Contents

Foreword **The Plastics Pipe Institute Handbook of Polyethylene Pipe**

Chapter 1 **Introduction** 5
- Features and Benefits of PE Pipe 6
- References 13

Chapter 2 **Inspections, Tests and Safety Considerations**

- Introduction 15
- PE Piping in the Field 16
  - Packaging for Commercial Transport 16
  - Receiving Inspection 18
  - Checking and Inspecting the Order 19
  - Receiving Report & Reporting Damage 19
  - Field Handling 20
    - Handling Equipment 21
    - Unloading Site 22
    - Unloading Bulk Packaged Pipe, Fittings and Fabrications 22
    - Unloading Large Fabrications, Manholes and Tanks 22
  - Pre-Installation Storage 22
    - Pipe Stacking Heights 23
  - Exposure to UV and Weather 24
  - Cold Weather Handling 25
- General Considerations Before and During Installation 25
  - Pre-Construction 25
    - Joining and Connections 25
    - Cleaning Before Joining 27
    - Field Fusion Joining 27
  - During Construction and Installation 28
    - Damage Inspections 28
    - Butt Fusion Joint Quality 28
    - Soil Tests 29
    - Deflection Tests for ID controlled Pipes 30
- Post Installation 32
  - Leak Testing – Considerations for All Procedures 32
    - Pressure System Leak Testing – Hydrostatic 34
    - Pressure System Leak Testing – Pneumatic 35
    - Pressure System Leak Testing – Initial Service 36
    - Non-Pressure System Leak Testing 37
    - Non-Testable Systems 37
- Considerations for Post Start-Up and Operation 37
  - Disinfecting Water Mains 37

Cleaning 38
Squeeze-Off 38
References 41

Chapter 3 Material Properties

Introduction 43
PE Plastics 45
History of PE 46
Manufacture of PE 46
Polymer Characteristics 47
Density 47
Crystallinity 48
Molecular Weight 50
Effect of Molecular Weight Distribution on Properties 53
PE Piping Materials 55
Structural Properties 56
PE Pipe Material Designation Code Identifies the Standard Classification of Essential Properties 56
Stress/Strain Response and its Representation by Means of an Apparent Modulus 57
Apparent Modulus Under Compressive Stress 63
Stress/Fracture Behavior and the Determination of Working Strength 64
Establishing a PE's Long-Term Hydrostatic Strength (LTHS) and its Derivative, The Hydrostatic Design Basis (HDB) 66
Compensating for the Effect of Temperature on Working Strength 72
Compressive Strength 73
Evaluating the Resistance to Slow Crack Growth (SCG) of a Sharply Notched PE Specimen 73
Resistance to Pressure Surges 74
Reaction to Occasional Pressure Surges 75
Reaction to Frequently Occurring Pressure Surges 75
Other Engineering Properties 76
Mechanical Properties 76
Resistance to Rapid Crack Propagation 79
Abrasion Resistance 79
Thermal Properties 80
Coefficient of Expansion/Contraction 80
Thermal Conductivity 81
Specific Heat 81
Material Classification Properties 81
Density 82

Melt Index 82
Flexural Modulus 83
Tensile Strength at Yield 83
Color and UV Stabilization 84
Electrical Properties 85
Static Charge 85
Chemical Resistance 85
Permeability 88
Properties Related to Durability 90
Weatherability 90
Stabilization 90
Biological Resistance 91
Properties Related to Health and Safety Concerns 92
Toxicological 92
Health Effects 92
Flammability 92
Combustion Toxicity 93
References 93
Appendix A: Pipe Pressure Rating (PR) And Pressure Class (PC) 95
Appendix B: Apparent Elastic Modulus 99
Appendix C: Allowable Compressive Stress 102
Appendix D: Poisson's Ratio 102
Appendix E: Thermal Properties 103
Appendix F: Electrical Properties 103

Chapter 4 PE Pipe and Fittings Manufacturing
Introduction 105
Raw Materials Description 106
Extrusion Line 107
Raw Materials Handling 107
Extrusion Basics 108
Extruders 110
Breaker Plate/Screen Pack 110
Die Design 110
Pipe Sizing 112
Cooling 114
Pullers 114
Take-off Equipment 114
Saw Equipment and Bundling 115
Injection Molded Fittings 115
Fabricated Fittings 118
Thermoformed Fittings 119
Electrofusion Couplings 119
Injection Molded Couplings 119

Quality Control/Quality Assurance Testing 121
  Workmanship, Finish, and Appearance 121
  Dimensions 122
  Physical Property Tests 122
  Quality Assurance Summary 123
References 123

Chapter 5 Standard Specifications, Standard Test Methods and Codes for PE (Polyethylene) Piping Systems
Introduction 125
Standard Requirements for PE Piping Materials 126
  Standard PE Piping Material Designation Code 129
  Standard Equation for Determining the Major Stress Induced in a Pressurized Pipe 130
  Standard Diameters 132
  PE Pipe Standards are Simplified by the Use of Preferred Values 132
  Determining a PE's Appropriate Hydrostatic Design Stress (HDS) Category 134
  Determining the Appropriate Value of HDS 135
  A Widely Recognized Source of HDS Recommendations 138
Standard Specifications for Fittings and Joints 139
  General 140
  Codes, Standards and Recommended Practices for PE Piping Systems 141
  Plastics Pipe Institute (PPI) 141
    ISO 143
    NSF International 143
    AWWA 144
  Standard Plumbing Codes 145
  Other Codes and Standards 146
  Factory Mutual 146
References 147
Appendix 1 148
  Gas Pipe, Tubing and Fittings 150
  Installation 152

Chapter 6 Design of PE Piping Systems
Introduction 155

Section 1 Design Based on Required Pressure Capacity 157
Pressure Rating 157
  Pressure Rating for Fuel Gas Pipe 160
Pressure Rating for Liquid Flow Surge Pressure 161
  Controlling Surge Pressure Reactions 167

Section 2 **Hydraulic Design of PE Pipe** 168
Pipe ID for Flow Calculations 168
Flow Diameter for Outside Diameter Controlled Pipe 168
Pipe Diameter for ID Controlled Pipe 169
Fluid Flow in PE Piping 169
Head Loss in Pipes – Darcy-Weisbach/Colebrook/Moody 169
Pipe Deflection Effects 172
Head Loss in Fittings 173
Head Loss Due to Elevation Change 174
Pressure Flow of Water – Hazen-Williams Equation 175
Pipe Flow Design Example 176
Pressure Flow of Liquid Slurries 177
Particle Size 177
Solids Concentration and Specific Gravity 178
Critical Velocity 178
Compressible Gas Flow 182
Empirical Equations for Low Pressure Gas Flow 183
Gas Permeation 184
Gravity Flow of Liquids 185
Manning Flow Equation 186
Comparative Flows for Slipliners 188
Flow Velocity 189
Pipe Surface Condition, Aging 190

Section 3 **Buried PE Pipe Design** 191
Calculations 192
Installation Categories 193
Design Process 194
Earth, Live, and Surcharge Loads on Buried Pipe 195
Vertical Soil Pressure 195
Earth Load 196
Live Load 197
AASHTO Vehicular Loading 198
Impact Factor 199
Vehicle Loading through Highway Pavement (Rigid) 199
Railroad Loads 204
Surcharge Load 205
Installation Category 1: Standard Installation - Trench or Embankment 210
Pipe Reaction to Earth, Live, and Surcharge Loads 210
Ring Deflection 210
Apparent Modulus of Elasticity for Pipe Material, E 212
Ring Stiffness Constant, RSC 212
Modulus of Soil Reaction, E’ 213
Soil Support Factor, F_S 215
Lag Factor and Long-Term Deflection 216

        - Vertical Deflection Example 217
        - Deflection Limits 217
        - Compressive Ring Thrust 219
        - Allowable Compressive Stress 220
        - Ring Compression Example 220
        - Constrained (Buried) Pipe Wall Buckling 220
        - Luscher Equation for Constrained Buckling Below Ground Water Level 221
        - Constrained Buckling Example 223
- Installation Category #2: Shallow Cover Vehicular Loading 224
        - Shallow Cover Example 225
- Installation Category #3: Deep Fill Installation 226
        - Compressive Ring Thrust and the Vertical Arching Factor 227
    - Earth Pressure Example 228
    - Ring Deflection of Pipes Using Watkins-Gaube Graph 229
    - Example of the Application of the Watkins-Gaube Calculation Technique 232
        - Moore-Selig Equation for Constrained Buckling in Dry Ground 232
    - Critical Buckling Example 233
- Installation Category #4: Shallow Cover Flotation Effects 233
    - Design Considerations for Ground Water Flotation 234
    - Unconstrained Pipe Wall Buckling (Hydrostatic Buckling) 238
    - Ground Water Flotation Example 240

Section 4 **Thermal Design Considerations** 242

- Strength and Stress/Strain Behavior 242
- Thermal Expansion/Contraction Effects 243
- Unrestrained Thermal Effects 243
- End Restrained Thermal Effects 244
- Above Ground Piping Systems 245
- Buried Piping Systems 245
- Appendix A.1 249
- Appendix A.2 253
- Appendix A.3 261

Chapter 7 Underground Installation of PE Piping

- Introduction 265
- Flexible Pipe Installation Theory 266
- Terminology of Pipe Embedment Materials 266
- Engineered and Simplified Installation Guidelines for PE Pipe 268
    - Simplified Installation Guidelines for Pressure Pipe 268
    - Simplfied Step-by-Step Installation 269
        - Trenching 269
        - De-watering 269
        - Bedding 269

        Placing Pipe in Trench 270
        Pipe Embedment 270
        Leak Testing 270
        Trench Backfill 270
Engineered Installation Guidelines for PE Pipe 271
Deflection Control 271
    Deflection Limit 273
Pipe Embedment Materials 273
Classification and Supporting Strength of Pipe Embedment Materials 274
    Strength of Embedment Soil 274
    Embedment Classification Per ASTM D-2321 274
        Class I and Class II 274
        Migration 275
        Cement Stabilized Sand 276
        Class lIl and Class IVA 277
        Class IVB and Class V 277
    Compaction of Embedment Materials 277
        Density Requirements 277
        Compaction Techniques 278
        Compaction of Class I and II Materials 279
        Compaction of Class lIl and IV Materials 280
        Density Checks 280
    Trench Construction 280
        Trench Width 281
        Trench Length 282
        Stability of the Trench 282
        Stability of Trench Floor 283
        Stability of Trench Walls 284
        Portable Trench Shield 285
Installation Procedure Guidelines 286
    Trench Floor Preparation 287
    Backfilling and Compaction 289
    Backfill Placement 289
    Sunlight Exposure 291
    Cold (Field) Bending 291
    Installation of Pipe in Curves 292
    Transition from PE Pressure Pipe to Gasket Jointed Pipe 292
    Proper Burial of Fabricated PE Fittings 293
Inspection 295
References 295
Appendix 1 296
Appendix 2 296
Appendix 3 300

Chapter 8 Above-Ground Applications for PE Pipe

Introduction 305
Design Criteria 306
  Temperature 306
    Pressure Capability 307
  Low Temperature Extremes 307
    Expansion and Contraction 308
  Chemical Exposure 308
    Ultraviolet Exposure 309
  Mechanical Impact or Loading 309
Design Methodology 310
Pressure Capability 310
Expansion and Contraction 311
Installation Characteristics 314
On-Grade Installations 314
  Free Movement 315
  Restrained Pipelines 316
Supported or Suspended Pipelines 320
  Support or Suspension Spacing 320
Anchor and Support Design 323
Pressure-Testing 324
References 326

Chapter 9 PE Pipe Joining Procedures

Introduction 327
General Provisions 327
Thermal Heat Fusion Methods 327
  Butt Fusion 328
  Butt Fusion of PE Pipe Products with Different Wall Thicknesses 329
  Optional Bead Removal 329
  Saddle/Conventional Fusion 330
  Socket Fusion 331
  Equipment Selection 332
  Square and Prepare Pipe 332
  Heating 332
  Joining 332
  Cooling 333
Electrofusion (EF) 333
Heat Fusion Joining of Unlike PE Pipe and Fittings 335
Mechanical Connections 335
  Mechanical Compression Couplings for Small Diameter Pipes 336
  Stab Type Mechanical Fittings 336
Mechanical Bolt Type Couplings 337
Stiffener Installation Guidelines 338

Flanged Connections 340

PE Flange Adapters and Stub Ends 340

Flange Gasket 343

Flange Bolting 343

Flange Assembly 344

Special Cases 344

Mechanical Flange Adapters 345

Solid DI Sleeve Connections to PE pipe 345

PE Pipe Connection to DI or PVC Bell End 347

PE Bell Adapters to DI or PVC Pipe End 347

DI Valve with PE Ends 348

Dismantling Joint 348

Mechanical Joint (MJ) Adapters 349

Transition Fittings 349

Mechanical Joint Saddle Fittings 351

Restraint Methods 352

Wall Anchor 352

Mechanical Restraint Anchor 353

Buried Poly Anchor 354

Above Ground Pipeline Anchor 354

PE to PVC Slip-Joint Anchor Fitting 355

References 356

Chapter 10 **Marine Installations**

Introduction 359

Selection of an Appropriate Pipe Diameter 362

Determination of the Required DR or SDR 362

Determination of the Required Weighting, and of the Design and the Spacing of Ballast Weights 363

Maximum Weighting that Allows Weighted Pipe to be Floated into Place 363

Determining the Maximum Weighting that Still Allows PE Pipe to Float 365

Determining the Required Minimum Weighting for the Anchoring of a Submerged Pipe in its Intended Location 365

Ensuring that the Required Weighting shall not be Compromised by Air Entrapment 367

Determining the Spacing and the Submerged Weight of the Ballasts to be Attached to the Pipe 368

Design and Construction of Ballast Weights 369

Selection of an Appropriate Site for Staging, Joining and Launching the Pipe 371

Preparing the Land-to-Water Transition Zone and, when Required, the Underwater Bedding 372

Assembly of Individual Lengths of PE Pipe Into Long Continuous Lengths 372

Mounting the Ballasts on the Pipe 373
Launching the Pipeline into the Water 374
Submersion of the Pipeline Using the Float-and-Sink Method 377
Completing the Construction of the Land-to-Water Transition 381
Post-Installation Survey 381
Other Kinds of Marine Installations 381
    Winter Installations 381
    Installations in Marshy Soils 382
    Water Aeration Systems 382
    Dredging 382
    Temporary Floating Lines 383
References 384
Appendix A-1 384
Appendix A-2 386
Appendix A-3 392

Chapter 11 Pipeline Rehabilitation by Sliplining with PE Pipe
Introduction 397
Design Considerations 398
    Select a Pipe Liner Diameter 399
    Determine a Liner Wall Thickness 399
        Non-Pressure Pipe 399
        Pressure Pipe 403
        Other Loading Considerations 403
    Determine the Flow Capacity 404
    Design the Accesses 406
    Develop the Contract Documents 409
    The Sliplining Procedure 409
    Other Rehabilitation Methods 417
    Swagelining 418
    Rolldown 418
    Titeliner 418
    Fold and Form 418
    Pipe Bursting 418
    Pipe Splitting 418
References 419

Chapter 12 Horizontal Directional Drilling
Introduction 421
PE Pipe for Horizontal Directional Drilling 422
Horizontal Directional Drilling Process 422
    Pilot Hole 422
    Pilot Hole Reaming 423
    Drilling Mud 423

Pullback 424
Mini-Horizontal Directional Drilling 424
General Guidelines 424
Geotechnical Investigation 426
Geotechnical Data For River Crossings 426
Summary 427
Product Design: PE Pipe DR Selection 427
Design Considerations for Net External Loads 428
Earth and Groundwater Pressure 430
Stable Borehole - Groundwater Pressure Only 430
Borehole Deforms/Collapse with Arching Mobilized 431
Borehole Collapse with Prism Load 432
Combination of Earth and Groundwater Pressure 433
Live Loads 433
Hydrostatic Buckling or Collapse 434
Ring Deformation 434
Performance Limits 434
Performance Limits of HDD Installed Pipe 434
Viscoelastic Behavior 434
Ring Deflection (Ovalization) 435
Ring Deflection Due to Earth Load 436
Unconstrained Buckling 437
Wall Compressive Stress 438
Installation Design Considerations 439
Pullback Force 440
Frictional Drag Resistance 441
Capstan Force 442
Hydrokinetic Force 443
Tensile Stress During Pullback 444
External Pressure During Installation 449
Resistance to External Collapse Pressure During Pullback Installation 450
Bending Stress 450
Thermal Stresses and Strains 451
Torsion Stress 451
References 452
Appendix A 452
Appendix B 457

Chapter 13 **HVAC Applications for PE Pipe**

Introduction 463
Ground Source Heat Pump Systems 463
Types of Ground Heat Exchangers 464
Pipe Specifications and Requirements 466

Pipe Joining Methods 466
Pipe Installation 467
Pressure Testing Ground Heat Exchanger 468
Solar Applications 469
Features and Benefits 470
Collector Technologies 470
Precautions 471
Installation 472
References 472

Chapter 14 **Duct and Conduit**
Introduction 473
Conduit Specifications 473
  Applications 474
  Advantages of PE Conduit 474
  Installation 475
  Features 475
Material Selection 476
  Physical Properties 476
    Cell Classification 476
    Other Important Physical Properties 477
    Stabilization 478
    Colorants for Conduit 478
Design Considerations 479
  Conduit vs. Pipe 479
  Cable Dimension Considerations 479
  Conduit Wall Determination 480
  Installation Method vs. Short-Term and Long-Term Stress 481
  Below Ground Installations 482
    Open Trench / Continuous Trenching 482
    Direct Plow 483
    Conduit Network Pulling 484
    Horizontal Directional Bore 485
Installation Methods 486
  General Considerations 486
    Mechanical Stress 486
    Pulling Tension 486
    Bending Radii 486
  Underground Installation 487
  Trenching Methods 487
    Open Trench/Continuous Trench 487
    Digging the Trench 488
    Plowing 489
    Plowing Variations 489

        Directional Bores 490
        Installation into Existing Conduit 490
    Above Ground / Aerial 491
        Installation 491
Joining Methods 492
    Introduction 492
    General Provisions 493
    Mechanical Fittings 493
        Barbed Mechanical Fittings 494
        Threaded Mechanical Fittings 494
        Compression Fittings 494
        Expansion Joints 494
    Heat Fusion 495
        Butt Fusion Joining 495
        Socket Fusion Joining 495
        Electrofusion Joining 495
        Repair Operations 496
Cable Installation 496
    Pulling Cable into Conduit 496
    Cable Blowing or Jetting 497
    Cable Installed by the Conduit Manufacturer (Cable-in-Conduit) 498
Friction in Conduit Systems 498
    Definitions 498
    Friction Reduction 498
    Field Effects of Friction 500
    Placement Planning 501
Special Applications 502
    Corrugated Duct 502
Bridge Structures 503
    Underwater 503
    Premise (Flame Retardant) 503
    Electrical / Building Code (Conduit Entry Issues) 504
    Armored (Rodent and Mechanical Protection) 505
    Multi-Cell Conduit 505
References 506
Appendix A 506

Chapter 15 **General Guidelines for Repairing Buried PE Potable Water Pressure Pipes**

Introduction 515
Natural Gas Polyethylene Piping Systems 516
Municipal and Other Polyethylene Piping Systems 517
    Temporary Field Repairs with Full Circle Band Clamp 517
Permanent Field Repairs 518

Small Field Repairs 518
Saddle Fusion Repair 518
Electrofusion Patch Repair 519
Mechanical Fitting Repair 519
Large Field Repairs 521
Mechanical Fitting Repair 521
Repairs with Solid Sleeves 522
Flange Adapter Spool Repair 524
Electrofusion Spool Repair 526
Stiffener Installation Guidelines 528
Restraint Methods 530
Mechanical Repair Fitting Restraint 530
Mechanical Coupling Restraint 531
Repair Clamps 533
Squeeze-off 533

Chapter 16 **Pipe Bursting**
Introduction 535
History 536
Pipe Bursting and Trenchless Pipe Replacement Systems 537
Pneumatic Bursting Systems 537
Static Bursting Systems 538
Pipe Splitting 539
Pipe Reaming 540
Impactor Process 540
Old Pipe Material 541
New Pipe Material 541
When is Pipe Bursting a Preferred Solution? 542
Pipe Bursting Project Classification 544
Pipe Bursting Applicability and Limitations 545
Design Considerations 546
Pre-design Phase 546
Design Phase 548
Utility Survey 548
Investigation of Existing Pipe and Site Conditions 549
Insertion and Pulling Shaft Requirements 549
Soil Considerations in Pipe Bursting 550
Maximum Allowable Operating Pressure (MAOP) 551
Risk Assessment Plan 551
Ground Movement Associated with Pipe Bursting 553
Plans and Specifications 556
Submittals 557
Quality Control/Quality Assurance Issues 557
Dispute Resolution Mechanisms 558

Maximum Allowable Tensile Pull 558
Permitting Issues 561
Typical Bidding Form For a Pipe Bursting Project 562
Selection of Pipe SDR 563
Construction Considerations 565
Typical Pipe Bursting Operation Layout 566
Shoring The Insertion and Pulling Shafts. 567
Matching System Components to Reduce Risk of Failure 568
Toning for Utilities 568
By Pass Pumping Considerations 569
Dewatering Considerations 569
Ground Movement Monitoring Program 569
Pipe Connection to the Manhole 570
Pipe Connection to Other Pipes 573
Pipe Bursting Water Mains 573
Service Connections 574
Groves on the Outside Surface of the Pipe 576
As-Built Drawing 577
Contingency Plan 578
Safety Considerations 578
Cost Estimating 578
Potential Problems and their Possible Solutions 580
References 582

Glossary 585
Organizations and Associations 602
Abbreviations 609

Index 611

CHAPTER 1

Introduction

Since its discovery in 1933, PE has grown to become one of the world's most widely used and recognized thermoplastic materials.(1) The versatility of this unique plastic material is demonstrated by the diversity of its use and applications. The original application for PE was as a substitute for rubber in electrical insulation during World War II. PE has since become one of the world's most widely utilized thermoplastics. Today's modern PE resins are highly engineered for much more rigorous applications such as pressure-rated gas and water pipe, landfill membranes, automotive fuel tanks and other demanding applications.

Figure I Joining Large Diameter PE Pipe with Butt Fusion

PE's use as a piping material first occurred in the mid 1950's. In North America, its original use was in industrial applications, followed by rural water and then oil field production where a flexible, tough and lightweight piping product was needed to fulfill the needs of a rapidly developing oil and gas production industry. The success of PE's pipe in these installations quickly led to its use in natural gas distribution where a coilable, corrosion-free piping material could be fused in the field to assure a "leak-free" method of transporting natural gas to homes and businesses. PE's success in this critical application has not gone without notice and today it is the material of choice for the natural gas distribution industry. Sources now estimate that nearly 95% of all new gas distribution pipe installations in North America that are 12" in diameter or smaller are PE piping.(2)

The performance benefits of polyethylene pipe in these original oil and gas related applications have led to its use in equally demanding piping installations such as potable water distribution, industrial and mining pipe, force mains and other critical applications where a tough, ductile material is needed to assure long-term performance. It is these applications, representative of the expanding use of polyethylene pipe that are the principle subject of this handbook. In the chapters that follow, we shall examine all aspects of design and use of polyethylene pipe in a broad array of applications. From engineering properties and material science to fluid flow and burial design; from material handling and safety considerations to modern installation practices such as horizontal directional drilling and/or pipe bursting; from potable water lines to industrial slurries we will examine those qualities, properties and design considerations which have led to the growing use of polyethylene pipe in North America.

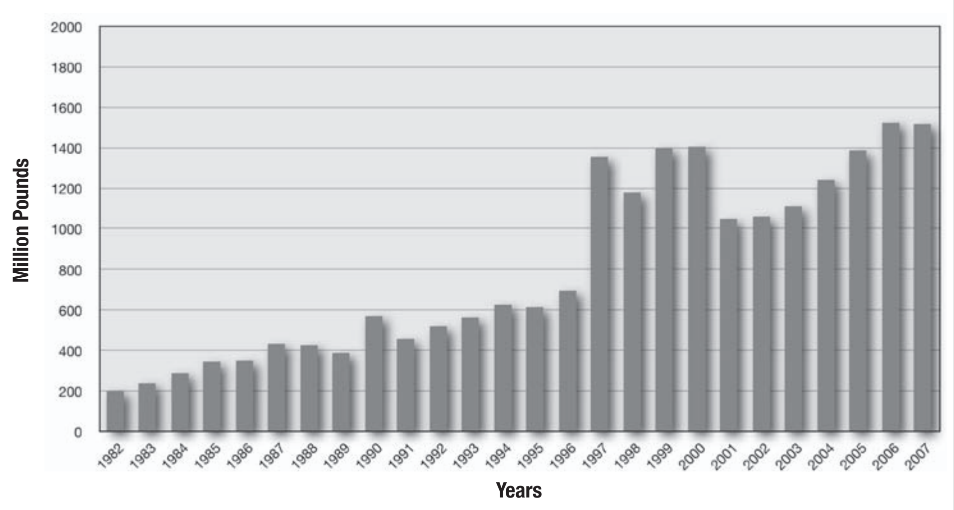


Figure 2 Historical Growth in North American HDPE Pipe Shipments[(3)]

Features and Benefits of PE Pipe

When selecting pipe materials, designers, owners and contractors specify materials that provide reliable, long-term service durability, and cost-effectiveness.

Solid wall PE pipes provide a cost-effective solution for a wide range of piping applications including natural gas distribution, municipal water and sewer, industrial, marine, mining, landfill, and electrical and communications duct applications. PE pipe is also effective for above ground, buried, trenchless, floating and marine installations. According to David A. Willoughby, P.O.E., "… one major reason for the growth in the use of the plastic pipe is the cost savings in installation, labor and equipment as compared to traditional piping materials. Add to this the potential for lower maintenance costs and increased service life and plastic pipe is a very competitive product."(4)

Natural gas distribution was among the first applications for medium-density PE (MDPE) pipe. In fact, many of the systems currently in use have been in continuous service since 1960 with great success. Today, PE pipe represents over 95% of the pipe installed for natural gas distribution in diameters up to 12" in the U.S. and Canada. PE is the material of choice not only in North America, but also worldwide. PE pipe has been used in potable water applications for almost 50 years, and has been continuously gaining approval and growth in municipalities. PE pipe is specified and/or approved in accordance with AWWA, NSF, and ASTM standards.

Some of the specific benefits of PE pipe are discussed in the parargraphs which follow.

- **Life Cycle Cost Savings** – For municipal applications, the life cycle cost of PE pipe can be significantly less than other pipe materials. The extremely smooth inside surface of PE pipe maintains its exceptional flow characteristics, and heat fusion joining eliminates leakage. This has proven to be a successful combination for reducing total system operating costs.
- **Leak Free, Fully Restrained Joints** – PE heat fusion joining forms leak-free joints that are as strong as, or stronger than, the pipe itself. For municipal applications, fused joints eliminate the potential leak points that exist every 10 to 20 feet when using the bell and spigot type joints associated with other piping products such as PVC or ductile iron. All these bell and spigot type joints employ elastomeric gasket materials that age over time and thus have the potential for leaks. As a result of this, the "allowable water leakage" for PE pipe is zero as compared to the water leakage rates of 10% or greater typically associated with these other piping products. PE pipe's fused joints are also self-restraining, eliminating the need for costly thrust restraints or thrust blocks while still insuring the integrity of the joint. Notwithstanding the advantages of the butt fusion method of joining, the engineer also has other available means for joining PE pipe and fittings such as electrofusion and mechanical fittings. Electrofusion fittings join the pipe and/or fittings together using embedded electric heating elements. In some situations, mechanical fittings may be required to facilitate joining to other piping products, valves or other system appurtenances. Specialized fittings for these purposes have been developed and are readily available to meet the needs of most demanding applications.
- **Corrosion & Chemical Resistance** – PE pipe will not rust, rot, pit, corrode, tuberculate or support biological growth. It has superb chemical resistance and is the material of choice for many harsh chemical environments. Although unaffected

by chemically aggressive native soil, installation of PE pipe (as with any piping material) through areas where soils are contaminated with organic solvents (oil, gasoline) may require installation methods that protect the PE pipe against contact with organic solvents. It should be recognized that even in the case of metallic and other pipe materials, which are joined by means of gaskets, protection against permeation is also required. Protective installation measures that assure the quality of the fluid being transported are typically required for all piping systems that are installed in contaminated soils.

- **Fatigue Resistance and Flexibility** – PE pipe can be field bent to a radius of about 30 times the nominal pipe diameter or less depending on wall thickness (12" PE pipe, for example, can be cold formed in the field to a 32-foot radius). This eliminates many of the fittings otherwise required for directional changes in piping systems and it also facilitates installation. The long-term durability of PE pipe has been extremely well researched. PE has exceptional fatigue resistance and when, operating at maximum operating pressure, it can withstand multiple surge pressure events up to 100% above its maximum operating pressure without any negative effect to its long-term performance capability.
- **Seismic Resistance** – The toughness, ductility and flexibility of PE pipe combined with its other special properties, such as its leak-free fully restrained heat fused joints, make it well suited for installation in dynamic soil environments and in areas prone to earthquakes.

Figure 3 Butt Fused PE Pipe "Arched" for Insertion into Directional Drilling Installation

- **Construction Advantages** – PE pipe's combination of light weight, flexibility and leak-free, fully restrained joints permits unique and cost-effective installation methods that are not practical with alternate materials. Installation methods such as horizontal directional drilling, pipe bursting, sliplining, plow and plant, and submerged or floating pipe, can greatly simplify construction and save considerable time and money on many installations. At approximately one-eighth the weight of comparable sized steel pipe, and with integral and dependable leakfree joining methods, installation is simpler, and it does not need heavy lifting equipment. PE pipe is produced in standard straight lengths to 50 feet or longer and coiled in diameters up through 6". Coiled lengths over 1000 feet are available in certain diameters. PE pipe can withstand impact much better than PVC pipe, especially in cold weather installations where other pipes are more prone to cracks and breaks. Because heat fused PE joints are as strong as the pipe itself, it can be joined into long runs conveniently above ground and later, installed directly into a trench or pulled in via directional drilling or using the re-liner process. Of course, the conditions at the construction site have a big impact on the preferred method of installation.
- **Durability** – PE pipe installations are cost-effective and have long-term cost advantages due to the pipe's physical properties, leak-free joints and reduced maintenance costs. The PE pipe industry estimates a service life for PE pipe to be, conservatively, 50-100 years provided that the system has been properly designed, installed and operated in accordance with industry established practice and the manufacturer's recommendations. This longevity confers savings in replacement costs for generations to come. Properly designed and installed PE piping systems require little on-going maintenance. PE pipe is resistant to most ordinary chemicals and is not susceptible to galvanic corrosion or electrolysis.

Figure 4 PE Pipe Weighted and Floated for Marine Installation

- **Hydraulically Efficient** – The internal surface of PE pipe is devoid of any roughness which places it in the “smooth pipe” category, a category that results in the lowest resistance to fluid flow. For water applications, PE pipe’s Hazen Williams C factor is 150 and does not change over time. The C factor for other typical pipe materials declines dramatically over time due to corrosion and tuberculation or biological build-up. Without corrosion, tuberculation, or biological growth PE pipe maintains its smooth interior wall and its flow capabilities indefinitely to insure hydraulic efficiency over the intended design life.
- **Temperature Resistance** – PE pipe’s typical operating temperature range is from 0°F to 140°F for pressure service. However, for non-pressure and special applications the material can easily handle much lower temperatures (e.g., to – 40°F and lower) and there are specially formulated materials that can service somewhat higher temperatures. Extensive testing and very many applications at very low ambient temperatures indicates that these conditions do not have an adverse effect on pipe strength or performance characteristics. Many of the PE resins used in PE pipe are stress rated not only at the standard temperature, 73° F, but also at an elevated temperature, such as 140°F. Typically, PE materials retain greater strength at elevated temperatures compared to other thermoplastic materials such as PVC. At 140° F, PE materials retain about 50% of their 73°F strength, compared to PVC which loses nearly 80% of its 73° F strength when placed in service at 140°F.(5) As a result, PE pipe materials can be used for a variety of piping applications across a very broad temperature range.

The features and benefits of PE are quite extensive, and some of the more notable qualities have been delineated in the preceding paragraphs. The remaining chapters of this Handbook provide more specific information regarding these qualities and the research on which these performance attributes are based.

Many of the performance properties of PE piping are the direct result of two important physical properties associated with PE pressure rated piping products. These are ductility and visco-elasticity. The reader is encouraged to keep these two properties in mind when reviewing the subsequent chapters of this handbook.

- **Ductility**

  Ductility is the ability of a material to deform in response to stress without fracture or, ultimately, failure. It is also sometimes referred to as increased strain capacity and it is an important performance feature of PE piping, both for above and below ground service. For example, in response to earth loading, the vertical diameter of buried PE pipe is slightly reduced. This reduction causes a slight increase in horizontal diameter, which activates lateral soil forces that tend to stabilize the pipe against further deformation. This yields a process that produces a soil-pipe Introduction 11 structure that is capable of safely supporting vertical earth and other loads that can fracture pipes of greater strength but lower strain capacity.

  Ductile materials, including PE, used for water, natural gas and industrial pipe applications have the capacity to safely handle localized stress intensifications that are caused by poor quality installation where rocks, boulders or tree stumps may be in position to impinge on the outside surface of the pipe. There are many other construction conditions that may cause similar effects, e.g. bending the pipe beyond a safe strain limit, inadequate support for the pipe, misalignment in connections to rigid structures and so on. Non- ductile piping materials do not perform as well when it comes to handling these types of localized high stress conditions.

Materials with low ductility or strain capacity respond differently. Strain sensitive materials are designed on the basis of a complex analysis of stresses and the potential for stress intensification in certain regions within the material. When any of these stresses exceed the design limit of the material, crack development occurs which can lead to ultimate failure of the part or product. However, with materials like PE pipe that operate in the ductile state, a larger localized deformation can take place without causing irreversible material damage such as the development of small cracks. Instead, the resultant localized deformation results in redistribution and a significant lessening of localized stresses, with no adverse effect on the piping material. As a result, the structural design with materials that perform in the ductile state can generally be based on average stresses, a fact that greatly simplifies design protocol.

To ensure the availability of sufficient ductility (strain capacity) special requirements are developed and included into specifications for structural materials intended to operate in the ductile state; for example, the requirements that have been established for “ductile iron” and mild steel pipes. On the other hand, ductility has always been a featured and inherent property of PE pipe materials. And it is one of the primary reasons why this product has been, by far, the predominant material of choice for natural gas distribution in North America over the past 30 plus years. The new or modern generation of PE pipe materials, also known as high performance materials, have significantly improved ductility performance compared to the traditional versions which have themselves, performed so successfully, not only in gas but also in a variety of other applications including, water, sewer, industrial, marine and mining since they were first introduced about 50 years ago.

For a more detailed discussion of this unique property of PE material, especially the modern high performance versions of the material, and the unique design benefits it brings to piping applications, the reader is referred to Chapter 3, Material Properties.

Visco-Elasticity

PE pipe is a visco-elastic construction material.(6) Due to its molecular nature, PE is a complex combination of elastic-like and fluid-like elements. As a result, this material displays properties that are intermediate to crystalline metals and very high viscosity fluids. This concept is discussed in more detail in the chapter on Engineering Properties within this handbook.

The visco-elastic nature of PE results in two unique engineering characteristics that are employed in the design of PE water piping systems, creep and stress relaxation.

- **Creep** is the time dependent viscous flow component of deformation. It refers to the response of PE, over time, to a constant static load. When PE is subjected to a constant static load, it deforms immediately to a strain predicted by the stressstrain modulus determined from the tensile stress-strain curve. At high loads, the material continues to deform at an ever decreasing rate, and if the load is high enough, the material may finally yield or rupture. PE piping materials are designed in accordance with rigid industry standards to assure that, when used in accordance with industry recommended practice, the resultant deformation due to sustained loading, or creep, is too small to be of engineering concern.
- **Stress relaxation** is another unique property arising from the visco-elastic nature of PE. When subjected to a constant strain (deformation of a specific degree) that is maintained over time, the load or stress generated by the deformation slowly decreases over time, but it never relaxes completely. This stress relaxation response to loading is of considerable importance to the design of PE piping systems. It is a response that decreases the stress in pipe sections which are subject to constant strain.

  As a visco-elastic material, the response of PE piping systems to loading is time-dependent. The apparent modulus of elasticity is significantly reduced by the duration of the loading because of the creep and stress relaxation characteristics of PE. An instantaneous modulus for sudden events such as water hammer is around 150,000 psi at 73°F. For slightly longer duration, but short-term events such as soil settlement and live loadings, the short-term modulus for PE is roughly 110,000 to 130,000 psi at 73° F, and as a long-term property, the apparent modulus is reduced to something on the order of 20,000-30,000 psi. As will be seen in the chapters that follow, this modulus is a key criterion for the long-term design of PE piping systems.

This same time-dependent response to loading also gives PE its unique resiliency and resistance to sudden, comparatively short-term loading phenomena. Such is the case with PE's resistance to water hammer phenomenon which will be discussed in more detail in subsequent sections of this handbook.

Summary

As can been seen from our brief discussions here, PE piping is a tough, durable piping material with unique performance properties that allow for its use in a broad range of applications utilizing a variety of different construction techniques based upon project needs. The chapters that follow offer detailed information regarding the engineering properties of PE, guidance on design of PE piping systems, installation techniques as well as background information on how PE pipe and fittings are produced, and appropriate material handling guidelines. Information such as this is intended to provide the basis for sound design and the successful installation and operation of PE piping systems. It is to this end, that members of the Plastics Pipe Institute have prepared the information in this handbook.

References:

1. *The History of Plastics.* (2005, May). www.americanplasticscouncil.org.
2. Mruk, S. (1985, November). Plastic Pipe in Gas Distribution Twenty-Five Years of Achievement, *Gas Industries.*
3. Shipments of PE Pipe, PPI Statistics Report. (2007). Plastics Pipe Institute, Irving, Texas.
4. Willoughby, D. A. (2002). *Plastic Piping Handbook*, McGraw-Hill Publications, New York.
5. PVC Pipe – Design and Installation. (2004). *AWWA Manual M-23*, American Water Works Association, Denver.
6. PE Pipe – Design and Installation. (2006). *AWWA Manual M-55*, American Water Works Association, Denver.

CHAPTER 2

Inspections, Tests and Safety Considerations

Scope

Once a PE piping system has been selected and designed for an application, the design is implemented by procuring the pipe, fittings and other necessary appurtenances, installing the system, and placing it in service. Piping installation involves people and machines in motion to move, assemble, install, inspect and test the piping system. Whenever moving machinery, piping parts, and personnel are engaged in piping system construction, safety must be a primary consideration. This chapter presents some of the inspections, tests and safety considerations related to installing PE piping, placing an installed system in service, and operating a PE piping system.

Cautionary statements are provided in this chapter, but this chapter does not purport to address all of the product applications, inspections, tests, or construction practices that could be used, nor all of the safety practices necessary to protect persons and property. It is the responsibility of the users of this chapter, installers, inspectors and operators of piping systems to establish appropriate safety and health practices, and to determine the applicability of regulatory limitations before any use, installation, inspection, test or operation.

Introduction

Generally, piping system installation begins with the arrival and temporary storage of pipe, fittings, and other goods required for the system. Assembly and installation follow, then system testing and finally, release for operation. Throughout the installation process, various inspections and tests are performed to ensure that the installation is in accordance with specification requirements and that the system when completed is capable of functioning according to its design specifications. In the selection, design, and installation of PE piping systems, professional engineering services, and qualified installers should be used.

PE piping products are integrated pipe and fitting systems for a broad range of commercial, municipal, utility and industrial applications. They may be buried, laid on the surface, supported above grade, installed underwater, or floated on the surface of lakes or rivers.

PE piping products are manufactured from 1/4" (6 mm) diameter through 120" (3050 mm) diameter under applicable industry standards (ASTM, AWWA, etc.) for pressure and non-pressure applications. As well, PE fittings, custom fabrications, special structures and appurtenances are available for full pressure rated, reduced pressure rated, or non-pressure rated applications.

Conventionally extruded PE pipes have homogeneous walls and smooth interior and exterior surfaces. Profile pipes are manufactured by extruding a profile over a mandrel. These pipes have smooth interiors, and may have a smooth or a profiled exterior.

Fittings, fabricated structures, tanks, and manholes are constructed for pressure, low pressure and non-pressure applications. Smaller size fittings are usually injection molded. Larger fittings, fabricated structures, tanks, and manholes are fabricated in manufacturer's facilities. Thermal joining techniques used for fabrication usually limit the design pressure capacity of the structure. Complex structures are generally not suitable for field fabrication.

PE Piping in the Field

After the piping system has been designed and specified, the piping system components must be procured. Typically, project management and purchasing personnel work closely together so that the necessary components are available when they are needed for the upcoming construction work.

Packaging for Commercial Transport

PE fittings, fabrications and pipe are shipped by commercial carriers who are responsible for the products from the time they leave the manufacturing plant until they are accepted by the receiver. Molded fittings and small fabrications and components are usually packaged in cartons. Large orders may be palletized. Large fabrications may require custom packaging. Commercial transport may be by parcel service or commercial carrier in enclosed vans or on flatbed trailers depending on packaging.

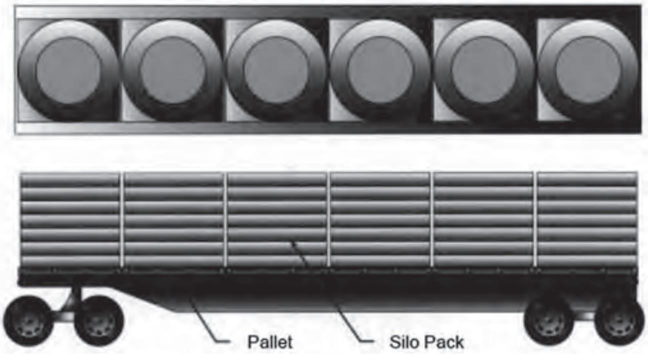


Figure 1 Typical Truckload of Coiled, Silo-Pack Pipe (40' Trailer)

PE pipe is produced in coils or in straight lengths and shipped on flatbed trailers. Coils are typically limited to 6-inch and smaller sizes. Coils may be laid flat and stacked together into silo packs, or may be individual large vertical coils, or may be reels of coiled pipe. Straight lengths are bundled together in bulk packs or loaded on the trailer in strip loads. Standard straight lengths for extruded pipe are 40 feet long; however, shorter lengths or lengths 60 feet long or longer depending on transportation restrictions may be produced. State transportation restrictions on length, height and width usually govern allowable load configurations. Higher freight costs may apply to loads that exceed length, height, or width restrictions. Although PE pipe is lightweight, weight limitations may restrict load size for very heavy wall or longer length pipe. Profile wall extruded pipes 96-inch ID (2438 mm ID) and 120-inch ID (3048 mm ID) will exceed 8 feet overall permissible width, and are subject to wide load restrictions.

Figures 1 through 3 are general illustrations of truckload and packaging configurations for conventionally extruded PE pipes. Actual truckloads and packaging may vary from the illustrations. "Nesting", or sliding a smaller pipe length inside a larger pipe, is generally not practiced for commercial flatbed loads because it is difficult to remove the inner pipe when the load is delivered at the jobsite, because nesting can result in an overweight load, and because most commercial flatbed trailers do not have structural bulkheads at both ends to prevent nested pipes from sliding out during acceleration or braking. Fully enclosed containers for overseas delivery can occasionally be nested. Occasionally, silos of small tubing sizes may be "nested" in silos of larger coiled pipe. Nested silos must have special packaging to lift the tubing silo out of the pipe silo. De-nesting should only be performed after the nested silos have been unloaded from the truck and placed on the ground.

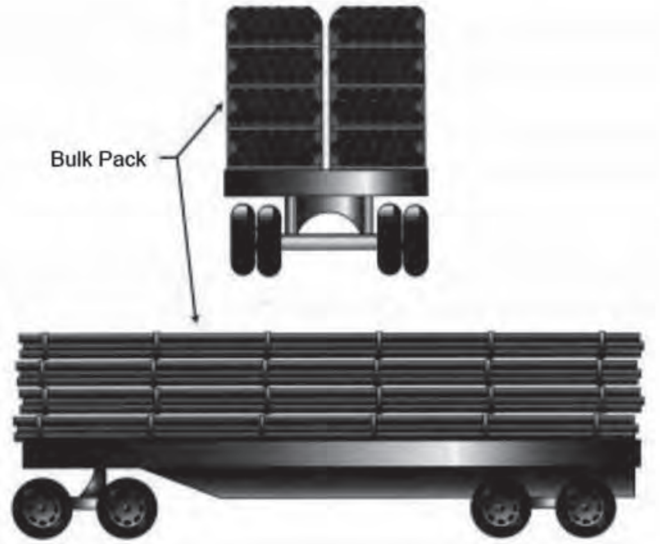


Figure 2 Typical Straight Length Bulk Pack Truckload

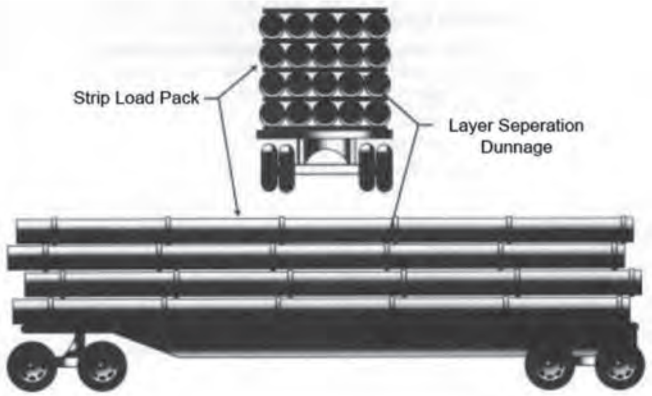


Figure 3 Typical Straight Length Strip Load Truckload

Occasionally, when coiled pipe silo packs and boxed fittings are shipped together, fitting cartons are placed in the center of the silo packs. Tanks, manholes, and large fittings and custom fabrications are usually loaded directly onto flatbed trailers.

Receiving Inspection

Few things are more frustrating and time consuming than not having what you need, when you need it. Before piping system installation begins, an important initial step is a receiving inspection of incoming products. Construction costs can be minimized, and schedules maintained by checking incoming goods to be sure the parts received are the parts that were ordered, and that they arrived in good condition and ready for installation.

Checking and Inspecting the Order

When a shipment is received, it should be checked to see that the correct products and quantities have been delivered in a condition that is suitable for installation. Several documents are used here. The Purchase Order or the Order Acknowledgment lists each item by its description, and the required quantity. The incoming load will be described in a Packing List which is attached to the load. The descriptions and quantities on the Packing List should match those on the Purchase Order or the Order Acknowledgment.

The carrier will present a Bill of Lading that generally describes the load as the number of packages the carrier received from the manufacturing plant. The Order Acknowledgment, Packing List, and Bill of Lading should all be in agreement. Any discrepancies must be reconciled among the shipper, the carrier, and the receiver. The receiver should have a procedure for reconciling any such discrepancies.

There is no substitute for visually inspecting an incoming shipment to verify that the paperwork accurately describes the load. Products are usually identified by markings on each individual product. These markings should be checked against the Order Acknowledgment and the Packing List. The number of packages and their descriptions should be checked against the Bill of Lading.

Before and during unloading, the load should be inspected for damage that may occur anytime products are handled. Obvious damage such as cuts, abrasions, scrapes, gouges, tears, and punctures should be carefully inspected. Manufacturers should be consulted for damage assessment guidelines. Product with damage that could compromise product performance should be segregated and a resolution discussed with the manufacturer.

When pipe installation involves saddle fusion joining, diesel smoke on the pipe outside surface may be a concern because it may reduce the quality of saddle fusion joints. Smoke damage is effectively prevented by covering at least the first third of the load with tarpaulins or by using truck tractors with low exhaust. If smoke tarps are required, they should be in place covering the load when it arrives.

Receiving Report & Reporting Damage

The delivering truck driver will ask the person receiving the shipment to sign the Bill of Lading, and acknowledge that the load was received in good condition. Any damage, missing packages, etc., should be noted on the bill of lading at that time.

Shipping problems such as damage, missing packages, document discrepancies, incorrect product, etc., should be reported to the product supplier immediately. Shipping claims must be filed within 7 days.

Field Handling

PE piping product transportation and handling is generally subject to governmental safety regulations such as OSHA in the United States or CCOSH in Canada. Persons transporting and handling PE piping products should be familiar with applicable governmental safety regulations. Additional PE pipe handling and transportation information is available in the PPI Material Handling Guide(1), and in handling and unloading recommendations from product manufacturers. The responsibility for safe transport and handling; however, rests primarily with persons that actually perform transport and handling activities.

Manufacturer handling and unloading recommendations are typically given to the truck driver when the load leaves the manufacturing plant with instructions for the truck driver to give the manufacturer's handling and unloading recommendations to jobsite personnel upon delivery.

Always observe applicable governmental safety regulations and manufacturer's handling and unloading recommendations when transporting or handling PE piping products in the field. Unsafe handling can result in damage to property or equipment, and be hazardous to persons in the area. Keep unnecessary persons away from the area during unloading and while handling pipe and piping components. See and be seen at all times. All persons involved in unloading and handling PE pipe and piping components should be sure that they can see all other persons and be seen by all other persons engaged in unloading and handling.

PE pipe is tough, lightweight, and flexible. Installation does not usually require high capacity lifting equipment. Pipe up to about 8" (219 mm) diameter and weighing roughly 6 lbs per foot (9 kg per m) or less can frequently be handled manually. Heavier, larger diameter pipe will require appropriate handling equipment to lift, move and lower the pipe. Pipe must not be dumped, dropped, pushed, or rolled into a trench.

Lengths of heat fused PE pipe may be cold bent in the field. The PE pipe manufacturer should be consulted for field bending radius recommendations. Field bending usually involves sweeping or pulling the pipe string into the desired bend radius, then installing permanent restraint such as embedment around a buried pipe, to maintain the bend. If used, temporary blocking should be removed before backfilling to avoid point loads against the pipe.

Considerable force may be required to field bend larger pipe, and the pipe may spring back forcibly if holding devices slip or are inadvertently released while bending. Observe appropriate safety precautions during field bending.

Handling Equipment

Unloading and handling equipment must be appropriate for the type of packaging, must be in safe operating condition, and must have sufficient capacity (load rating) to safely lift and move the product as packaged. Equipment operators should be trained and preferably, certified to operate the equipment. Safe handling and operating procedures must be observed.

Although PE piping components are lightweight compared to similar components made of metal, concrete, clay, or other materials, larger components can be heavy. Lifting and handling equipment must have adequate rated capacity to safely lift and move components. Equipment that lifts from the bottom of the load such as a forklift, or from above the load such as a crane, a side boom tractor, or an extension boom crane is used for unloading. Above the load lifting equipment may employ slings or slings and spreader bars to lift the load.

When using a forklift, or forklift attachments on equipment such as articulated loaders or bucket loaders, lifting capacity must be adequate at the load center on the forks. Forklift equipment is rated for a maximum lifting capacity at a distance from the back of the forks. If the weight-center of the load is farther out on the forks, lifting capacity is reduced.

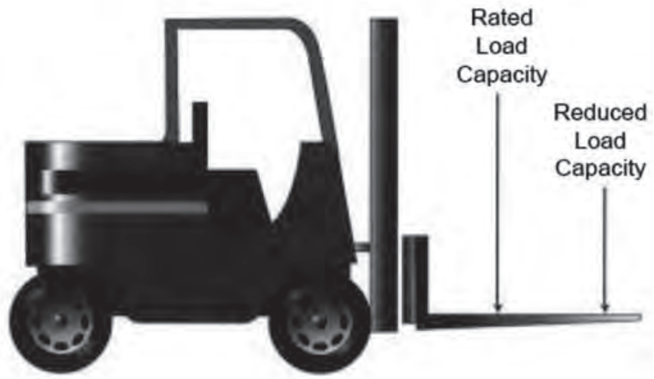


Figure 4 Forklift Load Capacity

Before lifting or transporting the load, forks should be spread as wide apart as practical, forks should extend completely under the load using fork extensions if necessary, and the load should be as far back on the forks as possible. During transport, a load on forks that are too short or too close together, or a load too far out on the forks, may become unstable and pitch forward or to the side, and result in damage to the load or property, or hazards to persons.

Above the load lifting equipment such as cranes, extension boom cranes, and side boom tractors, should be hooked to wide fabric choker slings that are secured around the load or to lifting lugs on the component. Wire rope slings and chains can damage components, can slip, and should not be used. Spreader bars should be used when lifting pipe or components longer than 20′. *Before use, inspect slings and lifting equipment. Equipment with wear or damage that impairs function or load capacity should not be used.*

Unloading Site

A suitable unloading site will be generally level and large enough for the carrier's truck, handling equipment and its movement, and for temporary load storage.

Unloading Bulk Packaged Pipe, Fittings and Fabrications

Silo packs and other palletized packages should be unloaded from the side or end with a forklift. Non-palletized pipe, fittings, fabrications, manholes, tanks, or other components should be unloaded from above with suitable lifting equipment and wide fabric slings, or from the side with a forklift.

Pipe, fittings, fabrications, tanks, manholes, and other components must not be pushed or rolled or dumped off the truck, or dropped.

Unloading Large Fabrications, Manholes and Tanks

Large fabrications, manholes and tanks should be unloaded using a wide web choker sling and lifting equipment such as an extension boom crane, crane, or lifting boom. The choker sling is fitted around the manhole riser or near the top of the tank. Do not use stub outs, outlets, or fittings as lifting points, and avoid placing slings where they will bear against outlets or fittings. Larger diameter manholes and tanks are typically fitted with lifting lugs. All lifting lugs must be used. *The weight of the manhole or tank is properly supported only when all lugs are used for lifting. Do not lift tanks or manholes containing liquids.*

Pre-Installation Storage

The size and complexity of the project and the components, will determine pre-installation storage requirements. For some projects, several storage or staging sites along the right-of-way may be appropriate, while a single storage location may be suitable for another job.

The site and its layout should provide protection against physical damage to components. General requirements are for the area to be of sufficient size to accommodate piping components, to allow room for handling equipment to get around them and to have a relatively smooth, level surface free of stones, debris, or other material that could damage pipe or components, or interfere with handling. Pipe may be placed on 4-inch wide wooden dunnage, evenly spaced at intervals of 4 feet or less.

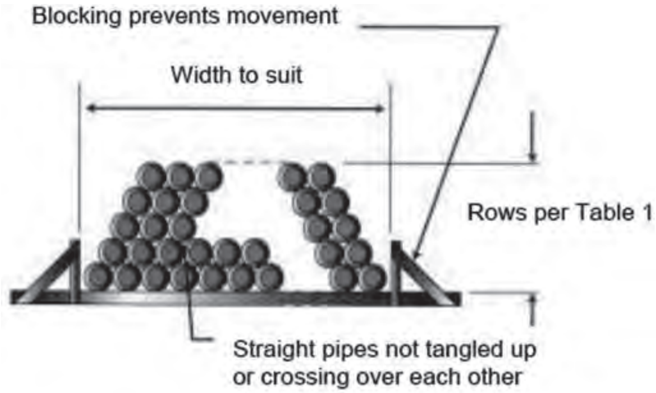


Figure 5 Loose Pipe Storage

Pipe Stacking Heights

Coiled pipe is best stored as-received in silo packs. Individual coils may be removed from the top of the silo pack without disturbing the stability of the remaining coils in the silo package.

Pipe received in bulk packs or strip load packs should be stored in the same package. If the storage site is flat and level, bulk packs or strip load packs may be stacked evenly upon each other to an overall height of about 6′. For less flat or less level terrain, limit stacking height to about 4′.

Before removing individual pipe lengths from bulk packs or strip load packs, the pack must be removed from the storage stack, and placed on the ground.

TABLE 1

Suggested Jobsite Loose Storage Stacking Height Limits for PE Pipe

Conventionally Extruded Solid Wall Pipe OD Size	Suggested Stacking Height Limits, Rows		Profile Wall Pipe ID Size (ASTM F 894[2])	Suggested Stacking Height, Rows
	DR Above 17	DR 17 & Below		
4	15	12	18	4
5	12	10	21	3
6	10	8	24	3
8	8	6	27	2
10	6	5	30	2
12	5	4	33	2
14	5	4	36	2
16	4	3	42	1
18	4	3	48	1
20	3	3	54	1
22	3	2	60	1
24	3	2	66	1
26	3	2	72	1
28	2	2	84	1
30	2	2	96	1
32	2	2	120	1
36	2	1		
42	1	1		
48	1	1		
54	1	1		
63	1	1		

Individual pipes may be stacked in rows. Pipes should be laid straight, not crossing over or entangled with each other. The base row must be blocked to prevent sideways movement or shifting. The interior of stored pipe should be kept free of debris and other foreign matter.

Exposure to UV and Weather

PE pipe products are protected against deterioration from exposure to ultraviolet light and weathering effects with antioxidants, and thermal and UV stabilizers. UV stabilization formulations for color products and for black products are different.

Color products use sacrificial UV stabilizers that are depleted by the UV energy absorbed. For this reason, unprotected outdoor storage for color products is generally about 2 years or less; however, some manufacturers may use UV stabilization formulations that allow longer unprotected outside storage. Where extended storage is anticipated, color products should be covered or measures should be taken to protect color product from direct UV exposure. Consult color product manufacturers for unprotected outdoor storage recommendations.

Black products contain at least 2% carbon black to shield the material against UV deterioration(3). Black products with and without stripes are generally suitable for outdoor storage without covering or protection against UV exposure. Products that are stored for many years may be affected by other environmental conditions or obsolescence due to improvements in materials or processes.

Cold Weather Handling

Temperatures near or below freezing will affect PE pipe by increasing stiffness and reducing resistance to impact damage. PE remains ductile at temperatures below -40ºF (-40ºC). In colder conditions, allow more time to conduct handling and installation procedures that bend and flex the pipe. Extra care should be taken not to drop pipe or fabricated structures, and to keep handling equipment and other things from forcefully impacting the pipe.

Ice, snow, and rain are not harmful to the material, but unsure footing and traction require greater care and caution to prevent damage or injury. Inclement weather can make pipe surfaces especially slippery. Do not walk on pipe.

General Considerations Before and During Installation

Pre-Construction

Inspections and tests begin before construction. Jobsite conditions dictate how piping may be installed and what equipment is appropriate for construction. Soil test borings and test excavations may be useful to determine soil bearing strength and whether or not native soils are suitable as backfill materials in accordance with project specifications.

In slipline or pipe bursting rehabilitation applications, the deteriorated pipeline should be inspected by remote TV camera to locate structurally deteriorated areas, obstructions, offset and separated joints, undocumented bends, and service connections.

The installer should carefully review contract specifications and plans. Different piping materials require different construction practices and procedures. These differences should be accurately reflected in the contract documents. Good plans and specifications help protect all parties from unnecessary claims and liabilities. Good documents also set minimum installation quality requirements, and the testing and inspection requirements that apply during the job.

Joining and Connections

For satisfactory material and product performance, system designs and installation methods rely on appropriate, properly made connections. An inadequate or improperly made field joint may cause installation delays, may disable or impair system operations, or may create hazardous conditions. Joining and connection methods will vary depending upon requirements for internal or external pressure, leak tightness, restraint against longitudinal movement (thrust load capacity), application and operation conditions, construction and installation requirements, and the products being joined.

PE pressure piping products are connected to themselves and to piping products from other materials using methods that seal and restrain against longitudinal thrust loads. These methods include butt, socket and saddle fusion, electrofusion couplings and saddles, and mechanical methods such as MJ Adapters, flanges, and restrained mechanical couplings.

In some circumstances, external restraint may be necessary for connections between PE and non-PE piping, such as for connections between butt-fused PE pressure pipe and bell and spigot joined PVC or ductile iron pipe. Longitudinal thrust forces that may develop in PE pressure pipe may be sufficient to disjoin unrestrained PVC or ductile iron joints that seal but do not restrain. To restrain longitudinal thrust forces, PE pressure pipe may be fitted with a wall anchor or electrofusion restraints to anchor against movement from longitudinal thrust forces.

PE non-pressure piping may require less or no restraint and may be connected using gasketed bell and spigot joints, extrusion welding, compression couplings, and various types of elastomeric seals. Sealed, unrestrained joints that may be suitable for non-pressure service are not suitable for PE pressure service.

Before using a joining or connection method, the limitations of the joining or connection method must be taken into account. Where a joining or connection method is suitable, the manufacturer's joining procedures, tools and components required to construct and install joints in accordance with manufacturer's recommendations should always be used.

Field connections are controlled by and are the responsibility of the field installer. Some joining procedures such as heat fusion, electrofusion and thermal welding require trained and qualified personnel. Some joining equipment such as larger butt fusion machines, saddle fusion and electrofusion equipment require persons that are properly trained in equipment operation. For regulated pipelines, the authority having jurisdiction may require certification of joining proficiency. Before heat fusion or electrofusion joining is performed at the jobsite, the contractor should obtain joining procedures and inspection criteria from the PE product manufacturer, and should obtain documentation of joining proficiency and qualification for persons making heat fusion or electrofusion joints. A discussion of joining and connecting PE piping products is presented in the Polyethylene Joining Procedures chapter in this handbook and in PPI TN-36(4).

Cleaning Before Joining

All field connection methods and procedures require component ends to be clean, dry, and free of detrimental surface defects before the connection is made. Contamination and unsuitable surface conditions usually produce an unsatisfactory connection. Gasketed joints may require appropriate lubrication.

Cleaning component ends before joining may require removing surface deposits to planning (facing), abrading or scraping the pipe surface. Surface dust and light soil may be removed by wiping the surfaces with clean, dry, lint free cloths. Heavier soil may be washed or scrubbed off with soap and water solutions, followed by thorough rinsing with clear water, and drying with dry, clean, lint-free cloths.

Before using chemical cleaning solvents, the user should know the potential risks and hazards and appropriate safety precautions should be taken. Hazard information is available from chemical manufacturer's instructions and the MSDS for the chemical. Some solvents may leave a residue on the pipe, or may be incompatible or deleterious when used with PE, for example, solvents that contain hydrocarbon liquids such as WD-40 or kerosene will contaminate the pipe and prevent heat fusion bonding. General information on PE compatibility with various chemicals is available in PPI Technical Report TR-19(5).

Surface damage that could detrimentally affect sealing or pipe performance generally requires removing the damaged section. See "Damage Inspections" below.

Field Fusion Joining

Heat fusion joining may be performed in any season and in hot or cold conditions. During inclement weather, a temporary shelter should be set-up around the joining operation to shield heat fusion operations from rain, frozen precipitation, and high wind conditions. Wind chill can reduce heating plate temperature or chill melted component ends before joining. If fusion joining operations cannot be protected against dust contamination during severe windblown dust conditions, joining may need to be temporarily suspended until conditions improve.

Most heat fusion equipment is electrically powered, but is not explosion proof. The fusion equipment manufacturer's instructions should be observed at all times and especially when heat fusion is to be performed in an atmosphere that may be volatile, such as coal or grain dust or in areas where gas or gas fumes may be present.

When installing large diameter PE pipe in a butt fusion machine, do not bend the pipe against an open fusion machine collet or clamp. The pipe may suddenly slip out of the open clamp, and cause injury or damage.

During Construction and Installation

Tests and inspections performed during construction may include damage inspections, butt fusion joint quality tests, soil tests, pipe deflection tests for ID controlled products such as extruded profile wall pipe, or pressure leak tests.

Damage Inspections

Damage such as cuts, scrapes, gouges, tears, cracks, punctures, and the like may occur during handling and installation. Damage may affect joint integrity or sealing, or may compromise pipeline performance. The following guidelines may be used to assess surface damage significance.

For PE pipelines, damage should not exceed about 10% of the minimum wall thickness required for the pipeline's operating pressure or the minimum wall thickness required to meet structural design requirements. Excessive damage generally requires removing the damaged section or reinforcement with a full encirclement repair clamp. Excessively deep cuts, abrasions or grooves cannot be repaired by using hot gas or extrusion welding to fill the damaged area with PE material because these methods do not provide sufficient bond strength for pressure service or to restore structural strength.

If damage is not excessive, the shape of the damage may be a consideration. Sharp notches and cuts may be dressed smooth so the notch is blunted. Blunt scrapes or gouges should not require attention. Minor surface abrasion from sliding on the ground or insertion into a casing should not be of concern.

Damage such as punctures and tears will generally require cutting the pipe to remove the damaged section and replacement with undamaged pipe. Small punctures may occasionally be repaired with patching saddles that are saddle fused or electrofused over the puncture.

Butt Fusion Joint Quality

Visual inspection is the most common butt fusion joint evaluation method for all sizes of conventionally extruded PE pipe. Visual inspection criteria for butt fusion joints should be obtained from the pipe manufacturer. Hydraulic butt fusion equipment is typically fitted for connection to data logging devices that can record equipment temperature, time and pressure conditions during joining. The record may be used to document equipment conditions when making field fusions, and to supplement field joining quality assurance using visual inspection and procedural oversight. Data logger records may be used to compare equipment operation during field fusion joining to data logger equipment operation records of properly made fusions (Butt fusion joining procedures are addressed in Chapter 9) where joint integrity has been verified.

To confirm joint integrity, operator procedure, and fusion machine set-up, fusion joints may be destructively tested. Destructive laboratory tests of tensile specimens prepared from butt fusion joined pipes may be performed per ASTM D 638(6) (standard tensile) or ASTM F 2634(7) (tensile impact). Tensile tests are usually compared to specimens without joints prepared from the parent pipe. Bent strap tests are usually limited to smaller pipe sizes. Bent strap test specimens from pipe with heavier walls require considerable bending force and attention to safety. Specially designed hydraulic press equipment may be used in the shop to conduct bend tests of heavy wall products. Bent strap tests in the shop or in the field require safety measures against inadvertent release, joint failure or springback during bending.

The bent strap test specimen is prepared by making a trial butt fusion and allowing it to cool to ambient temperature. A test strap that is at least 6" or 15 pipe wall thicknesses long on each side of the fusion, and about 1" or 1-1/2 wall thicknesses wide is cut out of the trial fusion pipe as illustrated in Figure 6. The strap is then bent so that the ends of the strap touch. Any disbondment at the fusion is unacceptable and indicates poor fusion quality. If failure occurs, fusion procedures and/or machine set-up should be changed, and a new trial fusion and bent strap test specimen should be prepared and tested. Field fusion should not proceed until a test joint has passed the bent strap test.

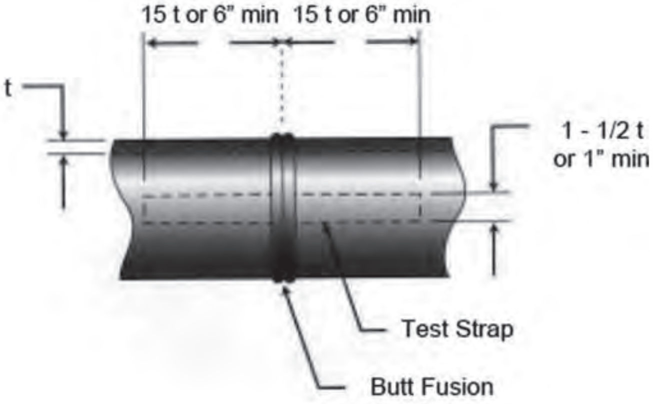


Figure 6 Bent Strap Test Specimen

Soil Tests

During buried pipe installation, work should be checked throughout the construction period by an inspector who is thoroughly familiar with the jobsite, contract specifications, materials, and installation procedures. Inspections should reasonably ensure that significant factors such as trench depth, grade, pipe foundation (if required), quality and compaction of embedment backfill, and safety are in compliance with contract specifications and other requirements. To evaluate soil stability, density and compaction, appropriate ASTM tests may be required in the contract specifications.

Deflection Tests for ID controlled Pipes

Deflection tests are typically based on an allowable percent vertical deflection of the pipe inside diameter. Deflection tests are generally limited to ID controlled PE piping such as extruded profile wall pipe. Conventionally extruded solid wall pipe is OD controlled so it is difficult if not impossible to determine a base ID for vertical deflection tests. Solid wall pipe extrusion also produces in a slight toe-in at the pipe ends. While internal fusion beads have negligible effects on fluid flows, the ID at butt fusions is reduced at butt fusions. For these reasons deflection testing is limited to ID controlled pipes and is not recommended for OD controlled conventionally extruded solid wall PE piping.

For ID controlled extruded profile pipes, pipe deflection may be used to monitor the installation quality. Improperly embedded pipe can develop significant deflection in a short time, thus alerting the installer and the inspector to investigate the problem. Inspection should be performed as the job progresses, so errors in the installation procedure can be identified and corrected.

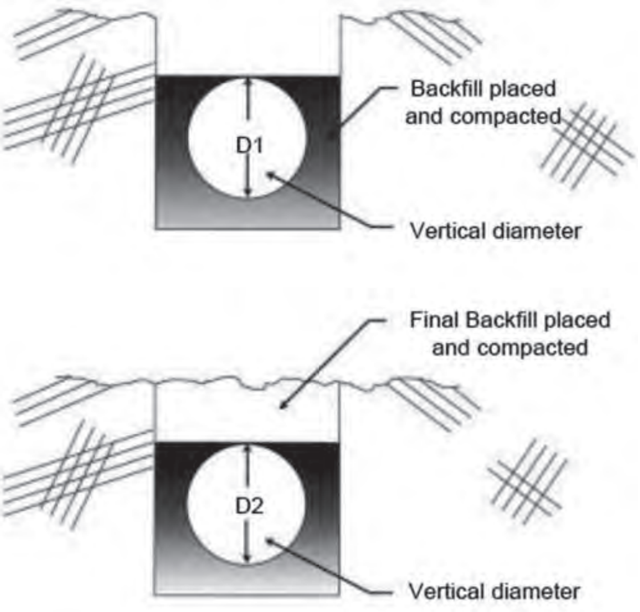


Figure 7 Determining Initial Deflection

Initial deflection checks of ID controlled extruded profile pipe may be performed after embedment materials have been placed and compacted. The inside diameter of the pipe is measured after backfill materials have been placed to the pipe crown, and compacted. This is D1. Then final backfill materials are placed and compacted, and the pipe inside diameter is measured again at the exact location where the prior measurement was taken. This is D2.

Percent initial deflection is calculated using the following:

(1)
$$\%\ Deflection = \left(\frac{D1\ -\ D2}{D1}\right)100$$

Where *D*1 and *D*2 are as defined above and depicted in Figure 7.

Another method to measure deflection is to pull a pre-sized mandrel (sewer ball) through the pipe. The mandrel should be sized so that if the pipe exceeds allowable deflection, the mandrel is blocked.

To properly size the mandrel, the allowable vertical diameter of the pipe must be established. It is necessary to account for pipe ID manufacturing tolerances and any ovality that may occur during shipping. Pipe base ID dimensions and tolerances should be obtained from the manufacturer. The maximum mandrel diameter is calculated as follows:

(2)
$$D_M = D - \left(\frac{Dy}{100}\right)$$

WHERE
D_M = maximum mandrel diameter, in
D = base pipe ID, in
y = allowable deflection, percent

(3)
$$D = D_i - \sqrt{A^2 + B^2}$$

D_i = nominal pipe ID, in
A = ID manufacturing tolerance, in

(4)
$$B = 0.03\,D_i$$

B = shipping ovality, in

For buried large diameter PE pipe that has been poorly backfilled, excessive deflection may be correctable using point excavation to remove backfill, then reinstalling embedment materials in accordance with recommended procedures.

Post Installation

Leak Testing – Considerations for All Procedures

The intent of leak testing is to find unacceptable joint leakage in pressure or non-pressure piping systems. If leaks exist, they may manifest themselves by leakage or rupture. Leak tests of pressure systems generally involve filling the system or a section of the system with a liquid or gaseous fluid and applying internal pressure to determine resistance to leakage. Leak tests of non-pressure systems typically involve testing sections of the system or individual joints using end plugs or bulkheads to determine resistance to leakage.

Safety is of paramount importance when conducting pressurized internal fluid leak tests. Although routinely performed, leak tests may be the very first time a newly installed system or repair will be subjected to stress.

- *Even at relatively low internal pressures, leak testing with a pressurized internal fluid can generate very high forces that can be dangerous or even fatal if suddenly released by the failure of a joint or a system component or a testing component.*
- *Always take safety precautions when conducting pressurized fluid leak tests.*
- *Restrain pipe, components and test equipment against movement in the event of failure. Joints may be exposed for leakage inspection provided that restraint is maintained.*
- *Keep persons not involved in testing a safe distance away while testing is being conducted.*

Liquids such as water are preferred as test fluids because less energy is released if something in the test section fails catastrophically. During a pressure leak test, energy (internal pressure) is applied to stress the test section. If the test fluid is an incompressible liquid such as water, the energy applied to pressurize the liquid transfers primarily to the pipe and components in the test section. However, if the test fluid is a compressible gas, energy is applied to compress the gas as well as to stress the piping section. If a catastrophic failure occurs during a pressurized liquid leak test, the overall applied energy is much lower, and energy dissipation is rapid. However, if catastrophic failure occurs during a pressurized gas test, energy release is many times greater, much more forceful and longer duration.

- Where hydrostatic testing is specified, never substitute compressed gas (pneumatic) for liquid (hydrostatic) testing.
- *Test pressure is temperature dependent.* If possible, test fluid and test section temperatures should be less than 80ºF (27ºC). At temperatures above 80ºF (27ºC), reduced test pressure is required. Contact the pipe manufacturer for technical assistance with elevated temperature pressure reduction. Sunlight heating of exposed PE pipe especially black PE pipe can result in high pipe temperature. Before applying test pressure, allow time for the test fluid and the test section to

temperature equalize. Hydrostatic leak tests typically use cooler liquids so the liquid filled test section will tend to equalize to a lower temperature near test liquid temperature. Compressed gases used in pneumatic leak tests do not have similar temperature lowering effects, so it is more likely that test pressures will have to be reduced due elevated temperature effects when conducting pneumatic leak tests. Bursting can result if test pressure is not reduced for elevated test section temperature.

- *Leak Test Pressure and Duration* – The maximum allowable leak test pressure and leak test time including initial expansion, and time at leak test pressure should be in accordance with equation (5) and Tables 1 and 2.

(5)

$$P_{(T)} = \frac{2 \times HDS \times F_t \times H_T}{(DR - 1)}$$

WHERE

$P_{(T)}$ = Leak Test Pressure, psi (MPa), for Leak Test Time, T
T = Leak Test Time, hours
HDS = PE material hydrostatic design stress for water at 73ºF (23ºC), psi (MPa)
F_t = PE material temperature reduction factor
H_T = Leak test duration factor for leak test time, T
DR = Pipe dimension ratio

TABLE 2
Leak Test Duration Factor, “H_T”

Leak Test Pressure, $P_{(T)}$, psi (MPa)	Leak Test Time, T, hours	Leak Test Duration Factor, H_T
$P_{(8)}$	≤ 8	1.50
$P_{(48)}$	≤ 48	1.25
$P_{(120)}$	≤ 120	1.00

TABLE 3
PE Material Hydrostatic Design Stress

PE Material Designation	HDS for Water at 73ºF (23ºC), psi (MPa)
PE2606 (PE2406)	630 (4.3)
PE2708	800 (5.5)
PE3608 (PE3408)	800 (5.5)
PE3710 & PE4710	1000 (6.9)

Various PE materials can have different elevated temperature performance. Consult the PE pipe manufacturer for the applicable temperature reduction factor, “Ft”.

Examples:

1. What is the maximum leak test pressure for a DR 11 PE4710 pipe for a 24 hour leak test where the pipe temperature is 125°F (52°C)?

   Answer: From Table 1, "H_T" = 1.25, and from Table 2, HDS = 1000 psi. The PE pipe manufacturer provided a temperature reduction factor, "F_t", of 0.70.

$$P_{(24)} = \frac{2 \times 1000 \times 0.70 \times 1.25}{(11-1)} = 175\, psi$$

2. What is the maximum leak test pressure for a DR 13.5 PE2606 pipe for a 6 hour leak test where the pipe temperature is 68°F (20°C)? For a 96 hour leak test?

   Answer: From Table 1, "H_T" = 1.50 for a 6 hour leak test, and "H_T" = 1.00 for a 96 hour leak test; from Table 2, HDS = 630 psi. The PE pipe manufacturer provided a temperature reduction factor, "F_t", of 1.00.

$$P_{(6)} = \frac{2 \times 630 \times 1.00 \times 1.50}{(13.5-1)} = 151.2\, psi$$

$$P_{(96)} = \frac{2 \times 630 \times 1.00 \times 1.00}{(13.5-1)} = 100.8\, psi$$

The piping manufacturer should be consulted before using pressure testing procedures other than those presented here. Other pressure testing procedures may or may not be applicable depending upon piping products and/or piping applications.

Pressure System Leak Testing – Hydrostatic

Hydrostatic pressure leak tests of PE pressure piping systems should be conducted in accordance with ASTM F 2164(8). The preferred hydrostatic testing liquid is clean water. Other non-hazardous liquids may be acceptable.

- *Restraint* –The pipeline test section must be restrained against movement in the event of catastrophic failure. Joints may be exposed for leakage examination provided that restraint is maintained.
- The testing equipment capacity and the pipeline test section should be such that the test section can be pressurized and examined for leaks within test duration time limits. Lower capacity testing and pressurizing equipment may require a shorter test section.

- Test equipment and the pipeline test section should be examined before pressure is applied to ensure that connections are tight, necessary restraints are in place and secure, and components that should be isolated or disconnected are isolated or disconnected. All low pressure filling lines and other items not subject to the test pressure should be disconnected or isolated.

For pressure piping systems where test pressure limiting components or devices have been isolated, or removed, or are not present in the test section, the maximum allowable test pressure for a leak test duration of 8 hours or less is 1.5 times the system design pressure at the lowest elevation in the section under test. If lower pressure rated components cannot be removed or isolated from the test section, the maximum test pressure is the pressure rating of the lowest pressure rated component that cannot be isolated from the test section. Test pressure is temperature dependent and must be reduced at elevated temperatures.

- The test section should be completely filled with the test liquid, taking care to bleed off any trapped air. Venting at high points may be required to purge air pockets while the test section is filling. Venting may be provided by bleed valves or equipment vents.
- The test procedure consists of initial expansion, and test phases. For the initial expansion phase, the test section is pressurized to test pressure and make-up test liquid is added as required to maintain maximum test pressure for four (4) hours. For the test phase, the test pressure is reduced by 10 psi. This is the target test pressure. If the pressure remains steady (within 5% of the target test pressure) for an hour, leakage is not indicated.
- If leaks are discovered, depressurize the test section before repairing leaks. Correctly made fusion joints do not leak. *Leakage at a butt fusion joint may indicate imminent catastrophic rupture. Depressurize the test section immediately if butt fusion leakage is discovered.* Leaks at fusion joints require the fusion joint to be cut out and redone.
- If the pressure leak test is not completed due to leakage, equipment failure, etc., the test section should be de-pressurized and repairs made. Allow the test section to remain depressurized for at least eight (8) hours before retesting.

Pressure System Leak Testing – Pneumatic

The Owner and the responsible Project Engineer should approve compressed gas (pneumatic) leak testing before use. Pneumatic testing should not be considered unless one of the following conditions exists:

- The piping system is so designed that it cannot be filled with a liquid;

  or
- The piping system service cannot tolerate traces of liquid testing medium.

The pressurizing gas should be non-flammable and non-toxic.

- *Restraint* – The pipeline test section must be restrained against movement in the event of catastrophic failure. Joints may be exposed for leakage examination provided that restraint is maintained.
- Leak test equipment and the pipeline test section should be examined before pressure is applied to ensure that connections are tight, necessary restraints are in place and secure, and components that should be isolated or disconnected are isolated or disconnected. All low pressure filling lines and other items not subject to the leak test pressure should be disconnected or isolated.
- *Leak Test Pressure* – For pressure piping systems where test pressure limiting components or devices have been isolated, removed, or are not present in the test section, the maximum allowable test pressure is 1.5 times the system design pressure for a leak test duration of 8 hours or less. If lower pressure rated components cannot be removed or isolated, the maximum test pressure is the pressure rating of the lowest pressure rated component that cannot be isolated from the test section. Leak test pressure is temperature dependent and must be reduced at elevated temperatures.
- The pressure in the test section should be gradually increased to not more than one-half of the test pressure; then increased in small increments until the required leak test pressure is reached. Leak test pressure should be maintained for ten (10) to sixty (60) minutes; then reduced to the design pressure rating (compensating for temperature if required), and maintained for such time as required to examine the system for leaks.
- Leaks may be detected using mild soap solutions (strong detergent solutions should be avoided), or other non-deleterious leak detecting fluids applied to the joint. Bubbles indicate leakage. After leak testing, all soap solutions or leak detecting fluids should be rinsed off the system with clean water.
- If leaks are discovered, depressurize the test section before repairing leaks. Correctly made fusion joints do not leak. *Leakage at a butt fusion joint may indicate imminent catastrophic rupture. Depressurize the test section immediately if butt fusion leakage is discovered.* Leaks at fusion joints require the fusion to be cut out and redone.
- If the pressure leak test is not completed due to leakage, equipment failure, etc., the test section should be de-pressurized and repairs made. Allow the test section to remain depressurized for at least eight (8) hours before retesting.

Pressure System Leak Testing – Initial Service

An initial service leak test may be acceptable when other types of tests are not practical, or where leak tightness can be demonstrated by normal service, or when initial service tests of other equipment are performed. An initial service test may apply to systems where isolation or temporary closures are impractical, or where checking out pumps and other equipment affords the opportunity to examine the system for leakage prior to full scale operations.

- *Restraint* – The pipeline section to be tested must be restrained against movement in the event of catastrophic failure. Joints may be exposed for leakage examination provided that restraint is maintained.

Test equipment and the pipeline should be examined before pressure is applied to ensure that connections are tight, necessary restraints are in place and secure, and components that should be isolated or disconnected are isolated or disconnected. All low pressure filling lines and other items not subject to the test pressure should be disconnected or isolated.

- *Leak test fluid* – The initial service leak test fluid will usually be the liquid or gas being transported in the pipeline. The leak test fluid may or may not need to be purged or flushed from the system.
- *Leak Test Pressure* – The piping system should be gradually brought up to normal operating pressure, and held at operating pressure for at least ten (10) minutes. During this time, joints and connections should be examined for leakage.
- If leaks are discovered, depressurize the test section before repairing leaks. Correctly made fusion joints do not leak. Leaks at fusion joints require the fusion to be cut out and redone. *Leakage at a butt fusion joint may indicate imminent catastrophic rupture. Depressurize the test section immediately if butt fusion leakage is discovered.*

Non-Pressure System Leak Testing

Pressure testing of non-pressure systems such as sewer lines should be conducted in accordance with ASTM F 1417(9).

Non-Testable Systems

Some systems may not be suitable for pressure leak testing. These systems may contain non-isolatable components, or temporary closures may not be practical. Such systems should be carefully inspected during and after installation. Inspections such as visual examination of joint appearance, mechanical checks of bolt or joint tightness, and other relevant examinations should be performed.

Considerations for Post Start-Up and Operation

Disinfecting Water Mains

Applicable procedures for disinfecting new and repaired potable water mains are presented in standards such as ANSI/AWWA C651(10) that uses liquid chlorine, sodium hypochlorite, or calcium hypochlorite to chemically disinfect the main. Disinfecting solutions containing chlorine should not exceed 12% active chlorine, because greater concentration can chemically attack and degrade PE.

Cleaning

Pipelines operating at low flow rates (around 2 ft/sec or less) may allow solids to settle in the pipe invert. PE has a smooth, non-wetting surface that resists the adherence of sedimentation deposits. If the pipeline is occasionally subject to higher flow rates, much of the sedimentation will be flushed from the system during these peak flows. If cleaning is required, sedimentation deposits can usually be flushed from the system with high pressure water.

Water-jet cleaning is available from commercial services. It usually employs high pressure water sprays from a nozzle that is drawn through the pipe system with a cable.

Pressure piping systems may be cleaned with the water-jet process, or may be pigged. Pigging involves forcing a resilient plastic plug (soft pig) through the pipeline. Soft pigs must be used with PE pipe. Scraping finger type or bucket type pigs may severely damage a PE pipe and must not be used. Usually, hydrostatic or pneumatic pressure is applied behind the pig to move it down the pipeline. Pigging should employ a pig launcher and a pig catcher.

A pig launcher is typically a tee assembly or a removable spool. In the tee assembly, the main flow is into the tee branch and out through a run outlet. The opposite tee run outlet is used to launch the pig. The pig is fitted into the opposite tee run; then the run behind the pig is pressurized to move the pig into the pipeline and downstream. In the removable pipe spool, the pig is loaded into the spool, the spool is installed into the pipeline, and then the pig is forced downstream. (Note – Fully pressure rated wyes suitable for pig launching are generally not available.)

A pig may discharge from the pipeline with considerable velocity and force. The pig catcher is a basket or other device at the end of the line to safely receive or catch the pig when it discharges from the pipeline.

Squeeze-Off

Squeeze-off (or pinch-off) is a means of controlling flow in smaller diameter PE pipe and tubing by flattening the pipe between parallel bars. Flow control does not imply complete flow stoppage in all cases. For larger pipes, particularly at higher pressures, some seepage is likely. If the situation will not allow seepage, then it may be necessary to vent the pipe between two squeeze-offs.

PE gas pipe manufactured to ASTM D 2513(11) is suitable for squeeze-off; however, squeeze-off practices are not limited to gas applications. Squeeze-off is applicable to PE pressure pipe up to 16" IPS, and up to 100 psi internal pressure, and conveying various gases or liquids. Larger sizes and higher pressures may be possible if suitable commercial equipment is available. Manufacturers of squeeze-off equipment should be consulted for equipment applicability, availability and capabilities.

Squeeze-off is applicable ONLY to PE pipe and tubing. The pipe or tubing manufacturer should be consulted to determine if squeeze-off is applicable to his product, and for specific squeeze-off procedures.

Squeeze-off tools should comply with ASTM F 1563(12). Typical squeeze-off tools use a manual mechanical screw or hydraulic cylinders, incorporate gap stops to prevent over-squeeze, and a mechanism to prevent accidental bar separation.

Closing and opening rate are key elements to squeezing-off without damaging the pipe. It is necessary to close slowly and release slowly, with slow release being more important. Squeeze-off procedures should be in accordance with ASTM F 1041(13) and should be qualified in accordance with ASTM F 1734(14).

Lower temperatures will reduce material flexibility and ductility, so in colder weather, closure and opening time must be slowed further.

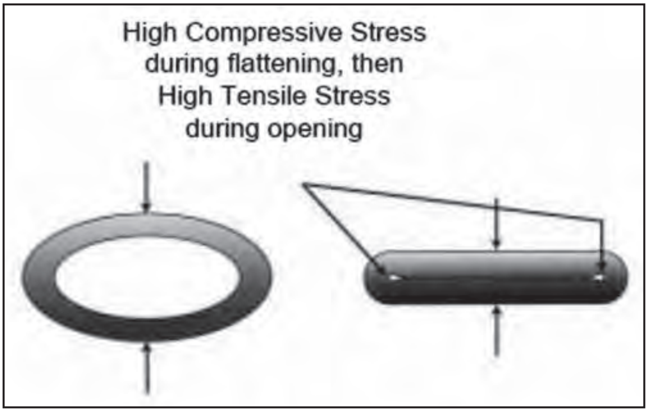


Figure 8 Squeeze-Off Stress

Testing of PE piping has shown that squeeze-off can be performed without compromising the expected service life of the system, or pipe can be damaged during squeeze-off. Damage occurs:

- If the manufacturer's recommended procedures are not followed, or
- If the squeeze is held closed too long, or

- From static electric discharge, or
- When closure stops are altered or circumvented, or
- By squeezing-off more than once in the same location.

Pipe known or suspected to have been damaged during squeeze-off should be removed from the system, or should be reinforced at the squeeze-off point using a full encirclement clamp and replacement repair scheduled.

Static Electricity Control – When pipe conveying a compressed gas is being flattened, the gas flow velocity through the flattened area increases. High velocity, dry gas, especially with particles present in the flow, can generate a static electric charge on pipe surfaces that can discharge to ground. *Before flattening the pipe, the tool should be grounded and procedures to control static charge build-up on pipe surfaces such as wetting surfaces with conductive fluids and applying conductive films or fabrics to ground should be employed.* Grounding and static control procedures should remain in place for the entire squeeze-off procedure.

Identify the squeezed-off area by wrapping tape around the pipe, or installing a full encirclement clamp over the area.

Squeeze-off procedures may be used for routine, scheduled changes to piping systems, or as an emergency procedure to control gasses or liquids escaping from a damaged pipe. For scheduled piping changes, ASTM F 1041 procedures that are qualified per ASTM F 1734 should be observed so that the pipe's service life is not compromised.

However, an emergency situation may require quickly flattening the pipe and controlling flow because the escaping fluid may be an immediate hazard of greater concern than damaging the pipe. *If an emergency situation requires rapid flattening, the pipe or tubing may be damaged.* When the emergency situation is resolved, a full encirclement clamp should be installed over the squeezed off area, and repair to replace the damaged pipe should be scheduled.

Conclusion

A successful piping system installation is dependent on a number of factors. Obviously, a sound design and the specification and selection of the appropriate quality materials are paramount to the long term performance of any engineered installation. The handling, inspection, testing, and safety considerations that surround the placement and use of these engineered products is of equal importance.

In this chapter, we have attempted to provide fundamental guidelines regarding the receipt, inspection, handling, storage, testing, and repair of PE piping products.

While this chapter cannot address all of the product applications, test and inspection procedures, or construction practices, it does point out the need to exercise responsible care in planning out these aspects of any job site. It is the responsibility of the contractor, installer, site engineer, or other users of these materials to establish appropriate safety and health practices specific to the job site and in accordance with the local prevailing codes that will result in a safe and effective installation.

References

1. PPI Material Handling Guide, Plastics Pipe Institute, Irving, TX.
2. ASTM F 894 Standard Specification for Polyethylene (PE) Large Diameter Profile Wall Sewer and Drain Pipe, ASTM, West Conshohocken, PA.
3. Gilroy, H.M., "Polyolefin Longevity for Telephone Service", Antec Proceedings, 1985.
4. PPI TN-36 General Guidelines for Connecting HDPE Potable Water Pressure Pipes to DI and PVC Piping Systems, Plastics Pipe Institute, Irving, TX.
5. PPI TR-19, Chemical Resistance of Thermoplastics Piping Materials, Plastics Pipe Institute, Irving, TX.
6. ASTM D 638 Standard Test Method for Tensile Properties of Plastics, ASTM, West Conshohocken, PA.
7. ASTM F 2634 Standard Test Method for Laboratory Testing of Polyethylene (PE) Butt Fusion Joints using Tensile-Impact Method, ASTM, West Conshohocken, PA.
8. ASTM F 2164 ASTM Standard Practice for Field Leak Testing of Polyethylene (PE) Pressure Piping Systems Using Hydrostatic Pressure, West Conshohocken, PA.
9. ASTM F 1417 Standard Test Method for Installation Acceptance of Plastic Gravity Sewer Lines Using Low Pressure Air, ASTM, West Conshohocken, PA.
10. AWWA C651 Standard for Disinfecting Water Mains, AWWA, Denver, CO
11. ASTM D 2513 Standard Specification for Thermoplastic Gas Pressure Pipe, Tubing and Fittings, ASTM, West Conshohocken, PA.
12. ASTM F1563, Standard Specification for Tools to Squeeze-off Polyethylene (PE) Gas Pipe or Tubing, West Conshohocken, PA.
13. ASTM F1041, Standard Guide for Squeeze-off of Polyethylene Gas Pressure Pipe or Tubing, West Conshohocken, PA.
14. ASTM F 1734 Standard Practice for Qualification of a Combination of Squeeze Tool, Pipe, and Squeeze-Off Procedures to Avoid Long-Term Damage in Polyethylene (PE) Gas Pipe, ASTM, West Conshohocken, PA.

Chapter 3

Material Properties

Scope

A principal objective of the following brief review of the nature of polyethylene (PE) piping materials, of their physical and chemical properties, and of their mechanical and engineering behavior, is to impart a basic understanding of the factors that lie behind the discussions and recommendations contained in this Handbook for the proper storage, handling, installation, design and operation of PE piping systems.

Also included in this Chapter is an Appendix that lists values for the more common engineering design properties of PE piping materials.

Introduction

A number of important performance advantages accounts for the widespread adoption of PE piping for so many pressure and non-pressure applications. A major one is PE's virtual freedom from attack by soils, and by ambient water and moisture. PE, being a non-conductor of electricity, is immune to the electrochemical based corrosion process that is induced by electrolytes such as salts, acids and bases. In addition, PE piping is not vulnerable to biological attack, and its smooth, non-stick inner surface results in low friction factors and exceptional resistance to fouling.

Another unique performance advantage is the flexibility of PE pipe. It allows for changes in direction with minimal use of fittings, facilitates installation, and makes it possible for piping up to about 6-inches in diameter to be offered in coils of longer lengths. A further one is strainability, a term denoting a capacity for high deformation without fracture. In response to earth loading a buried PE pipe can safely deflect and thereby gain additional and substantial support from the surrounding soil. So much so, that a properly installed PE pipe is capable of supporting earth fills and surface live loads that would fracture pipes that, although much stronger, can crack and fail at low strains. And, as proven by actual experience, PE pipe's high strainabilty makes it very resistive to seismic effects.

PE pipe and PE fittings can be joined to each other by thermal fusion processes which result in leak-proof bottle-tight joints that are as strong and as tough as the pipe itself. These advantages combine to make PE a preferred pipe for special applications, such as for horizontal directional drilling, for the renewal of old pipes by insertion, and for marine outfalls. For the first two named applications the butt-fusion process – which avoids the use of larger diameter couplings – enables installation to be conducted by pipe pulling and it permits the use of a larger diameter pipe.

Another recognized advantage of PE piping is its toughness. PE pipes, as well as the heat fusion joints in PE piping, greatly resist the propagation of an initial small failure into a large crack – a major reason for the overwhelming preference for PE piping for gas distribution applications. And, PE piping retains its toughness even at lower temperatures. In addition, PE piping exhibits very high fatigue resistance. Potential damage by repetitive variations in operating pressure (surges) is highly resisted.

Notwithstanding the above and various other advantages of PE piping, its successful design and application requires adequate recognition of its more complex stress/strain and stress/fracture behavior. PE piping does not exhibit the simple proportionality between stress and strain that is characteristic of metal pipes. And, its capacity to resist fracture is reduced as duration of loading is increased. In addition, these and its other mechanical properties exhibit a greater sensitivity to temperature and certain environments. Furthermore, the specific mechanical responses by a PE pipe can vary somewhat depending on the PE material from which it is made – mostly, depending on the nature of the PE polymer (e.g., its molecular weight, molecular weight distribution, degree of branching (density) but, also somewhat on the type and quantity of additives that are included in the piping composition. The particular behavior of the PE pipe that is selected for an application must be given adequate recognition for achieving an effective design and optimum quality of service. A brief explanation of the engineering behavior of PE and the listing of its more important properties is a major objective of this Chapter.

An additional objective of this Chapter is the presentation of values for the major properties that are used for material classification and piping design, and a brief description of the methods based on which these properties are determined.

PE Plastics

Plastics are solid materials that contain one or more polymeric substances which can be shaped by flow. Polymers, the basic ingredient of plastics, compose a broad class of materials that include natural and synthetic polymers. Nearly all plastics are made from the latter. In commercial practice, polymers are frequently designated as resins. For example, a PE pipe compound consists of PE resin combined with colorants, stabilizers, anti-oxidants or other ingredients required to protect and enhance properties during fabrication and service.

Plastics are divided into two basic groups, thermoplastics and thermosets, both of which are used to produce plastic pipe.

Thermoplastics include compositions of PE, polypropylene, and polyvinyl chloride (PVC). These can be re-melted upon the application of heat. The solid state of thermoplastics is the result of physical forces that immobilize polymer chains and prevent them from slipping past each other. When heat is applied, these forces weaken and allow the material to soften or melt. Upon cooling, the molecular chains stop slipping and are held firmly against each other in the solid state. Thermoplastics can be shaped during the molten phase of the resin and therefore can be extruded or molded into a variety of shapes, such as pipe, pipe fittings, flanges or valves.

Thermoset plastics are similar to thermoplastics prior to “curing,” a chemical reaction by which polymer chains are chemically bonded to each other by new cross-links. The curing is usually done during or right after the shaping of the final product. Cross-linking is the random bonding of molecules to each other to form a giant three-dimensional network. Thermoset resins form a permanent insoluble and infusible shape after the application of heat or a curing agent. They cannot be re-melted after they have been shaped and cured. This is the main difference between thermosets and thermoplastics. As heat is applied to a thermoset part, degradation occurs at a temperature lower than the melting point. The properties of thermosetting resins make it possible to combine these materials with reinforcements to form strong composites. Fiberglass is the most popular reinforcement, and fiberglass-reinforced pipe (FRP) is the most common form of thermoset-type pipe.

History of PE

The Imperial Chemical Company (ICI) in England first invented PE in 1933. The early polymerization processes used high-pressure (14,000 to 44,000 psi) autoclave reactors and temperatures of 200° to 600° F (93° to 316° C). The PE that came from these reactors was called "high pressure PE." It was produced in a free radical chain reaction by combining ethylene gas under high pressure with peroxide or a trace amount of oxygen.

The original process was dangerous and expensive, so other safer and less expensive processes were developed. PE produced at low pressure was introduced in the 1950's. These methods also afforded greater versatility in tailoring molecular structures through variations in catalysts, temperatures, and pressures.

Manufacture of PE

Polymers are large molecules formed by the polymerization (i.e. the chemical linking) of repeating small molecular units. To produce PE, the starting unit is ethylene, a colorless gas composed of two double-bonded carbon atoms and four hydrogen atoms (see Figure 1).

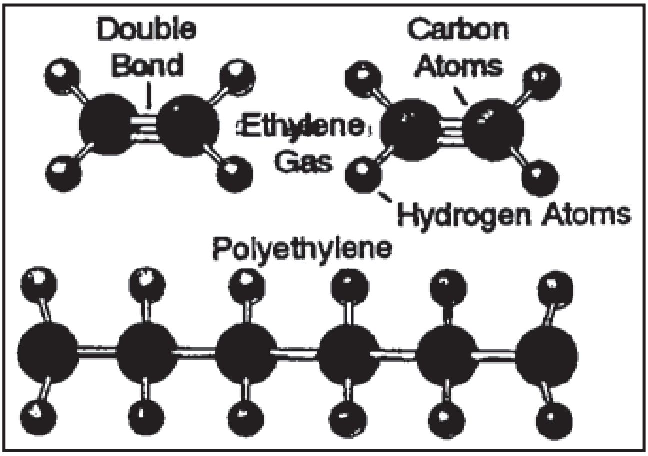


Figure 1 Manufacture of PE

There are currently three primary low-pressure methods for producing PE: gas-phase, solution and slurry (liquid phase). The polymerization of ethylene may take place with various types of catalysts, under varying conditions of pressure and temperature and in reactor systems of radically different design. Ethylene can also be copolymerized with small amounts of other monomers such as butene, propylene, hexene, and octene. This type of copolymerization results in small modifications in chemical structure, which are reflected in certain differences in properties, such as density, ductility, hardness, etc. Resins that are produced without comonomer are called homopolymers.

Regardless of process type, the chemical process is the same. Under reaction conditions, the double bond between the carbon atoms is broken, allowing a bond to form with another carbon atom as shown in Figure 1. Thus, a single chain of PE is formed. This process is repeated until the reaction is terminated and the chain length is fixed. PE is made by the linking of thousands of monomeric units of ethylene.

Polymer Characteristics

PE resins can be described by three basic characteristics that greatly influence the processing and end-use properties: density, molecular weight and molecular weight distribution. The physical properties and processing characteristics of any PE resin require an understanding of the roles played by these three major parameters.

Density

The earliest production of PE was done using the high-pressure process which resulted in a product that contained considerable "side branching." Side branching is the random bonding of short polymer chains to the main polymer chain. Since branched chains are unable to pack together very tightly, the resulting material had a relatively low density, which led to it being named low-density PE (LDPE).

As time passed and PEs of different degrees of branching were produced, there was a need for an industry standard that would classify the resin according to density. The American Society for Testing of Materials (ASTM) originally established the following classification system. It is a part of ASTM D1248, Standard Specification for Polyethylene Plastics Molding and Extrusion Materials(2,5). This standard has since been replaced by ASTM D 3350; ASTM D 1248 is no longer applicable to PE piping materials.

Type	Density
I	0.910 - 0.925 (low)
II	0.926 - 0.940 (medium)
III	0.941 - 0.959 (high)
IV	0.960 and above (high, homopolymer)

Type I is a low-density resin produced mainly in high-pressure processes. Also contained within this range are the linear-low-density polyethylenes (LLDPE), which represent a recent development in the PE area using low-pressure processes.

Type II is a medium density resin produced either by low- or high-pressure processes.

Types III and IV are high-density polyethylenes. Type III materials are usually produced with a small amount of a comonomer (typically butene or hexene) that is used to control chain branching. Controlled branching results in improved performance in applications where certain types of stresses are involved. Type IV resins are referred to as homopolymers since only ethylene is used in the polymerization process, which results in least-branched and highest-possible-density material. Figure 2 depicts the various molecular structures associated with each type of PE.

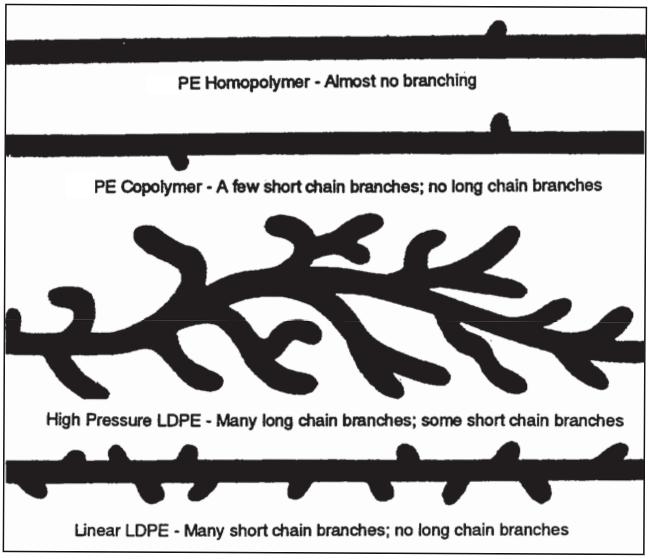


Figure 2 Chain Structure of PE

Crystallinity

The amount of side branching determines the density of the PE molecule. The more side branches, the lower the density. The packing phenomenon that occurs in PE can also be explained in terms of crystalline versus non-crystalline or amorphous regions as illustrated in Figure 3. When molecules pack together in tight formation, the intermolecular spacing is reduced.

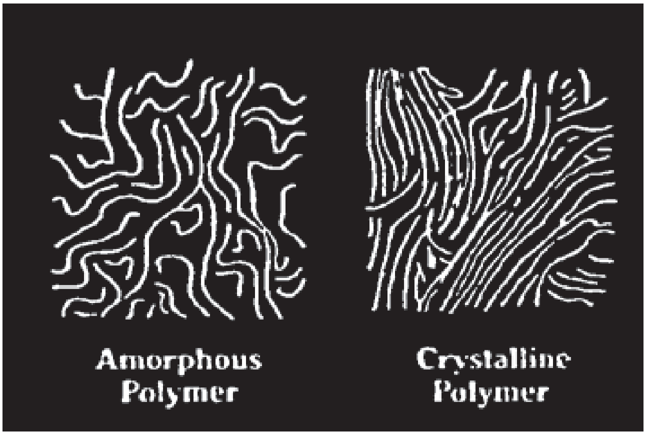
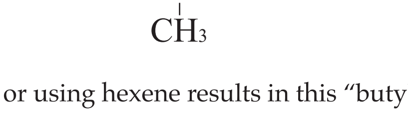


Figure 3 Crystallinity in PE

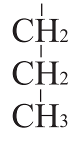
PE is one of a number of polymers in which portions of the polymer chain in certain regions align themselves in closely packed and very well ordered arrangements of polyhedral-shaped, microscopic crystals called spherulites. Other portions of the polymer chain lie in amorphous regions having no definite molecular arrangement. Since polyethylene contains both crystalline and amorphous regions, it is called a semicrystalline material. Certain grades of high density PE can consist of up to 90% crystalline regions compared to 40% for low density PE. Because of their closer packing, crystalline regions are denser than amorphous regions. Polymer density, therefore, reflects the degree of crystallinity.

As chain branches are added to a PE backbone through co-polymerization, the site and frequency of chain branches affect other aspects of the crystalline/amorphous network. This includes the site and distribution of spherulites, as well as the nature of the intermediate network of molecules that are between spherulites. For example, using butene as co-monomer results in the following "ethyl" side chain structure(8):



$$(\text{-CH}_2\text{-CH}_2\text{-}\underset{\substack{| \\ \text{CH}_2 \\ | \\ \text{CH}_3}}{\text{CH}_2}\text{-CH}_2\text{-CH}_2\text{-})n$$

or using hexene results in this "butyl" side chain:



$$(\text{-CH}_2\text{-CH}_2\text{-}\underset{\substack{| \\ \text{CH}_2 \\ | \\ \text{CH}_2 \\ | \\ \text{CH}_2 \\ | \\ \text{CH}_3}}{\text{CH}_2}\text{-CH}_2\text{-CH}_2\text{-})n$$

If two polymers were produced, one using butyl and the other hexene monomer, the polymer that contained the resultant butyl branches would have a lower density. Longer side branching reduces crystallinity and therefore lowers density. For high-density PE, the number of short chain branches is on the order of 3 to 4 side chains per 1,000 carbon atoms. It only takes a small amount of branching to affect the density.

Resin density influences a number of physical properties. Characteristics such as tensile yield strength and stiffness (flexural or tensile modulus) are increased as density is increased.

Molecular Weight

The size of a polymer molecule is represented by its molecular weight, which is the total of the atomic weights of all the atoms that make up the molecule. Molecular weight exerts a great influence on the processability and the final physical and mechanical properties of the polymer.

Molecular weight is controlled during the manufacturing process. The amount of length variation is usually determined by catalyst, conditions of polymerization, and type of process used. During the production of polyethylene, not all molecules grow to the same length. Since the polymer contains molecules of different lengths, the molecular weight is usually expressed as an average value.

There are various ways to express average molecular weight, but the most common is the number average (Mn) and weight average (Mw). The definitions of these terms are as follows:

Mn = Total weight of all molecules ÷ Total number of molecules

Mw = (Total weight of each size) (respective weights) ÷
Total weight of all molecules

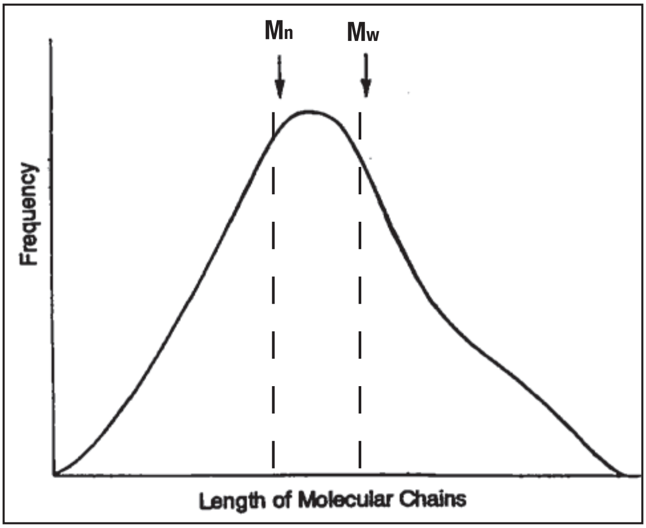


Figure 4 Typical Molecular Weight Distribution

Figure 4 illustrates the significance of these terms and includes other less frequently used terms for describing molecular weight.

Molecular weight is the main factor that determines the durability-related properties of a polymer. Long-term strength, toughness, ductility, and fatigue-endurance improve as the molecular weight increases. The current grades of highly durable materials result from the high molecular weight of the polymer.

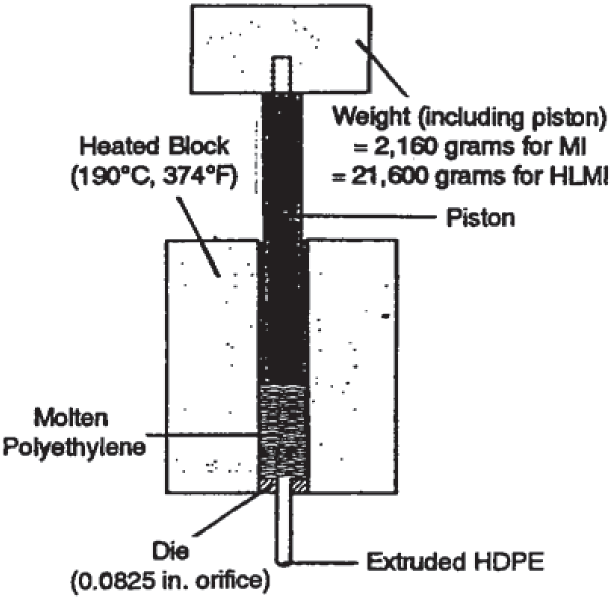


Figure 5 The Melt Flow Test (per ASTM D1238)

Molecular weight affects a polymer's melt viscosity or its ability to flow in the molten state. The standard method used to determine this "flowability" is the melt flow rate apparatus, which is shown in Figure 5. ASTM D1238, *Standard Test Method for Flow Rates of Thermoplastics by Extrusion Plastometer*(2), is the industry standard for measuring the melt flow rate. The test apparatus measures the amount of material that passes through a certain size orifice in a given period of time when extruded at a predetermined temperature and under a specified weight. The melt flow rate is the measured weight of material that passes through the orifice in ten minutes.
The standard nomenclature for melt flow rate, as described in ASTM D1238, lists the test temperature and weight used. A typical designation is condition 190/2.16 that indicates the test was conducted at a temperature of 190°C while using a 2.16-kg weight on top of the piston. Other common weights include: 5 kg, 10 kg, 15 kg and 21.6 kg.

The term "melt index"(MI) is the melt flow rate when measured under a particular set of standard conditions – 190°C/2.16 kg. This term is commonly used throughout the polyethylene industry.

Melt flow rate is a rough guide to the molecular weight and processability of the polymer. This number is inversely related to molecular weight. Resins that have a low molecular weight flow through the orifice easily and are said to have a high melt flow rate. Longer chain length resins resist flow and have a low melt flow rate. The melt flow rates of these very viscous (stiff) resins are very difficult to measure under the common conditions specified by this test. Therefore, another procedure is used where the weight is increased to 21.6 kg from the 2.16 kg weight used in the normal test procedure. This measurement is commonly referred to as the High Load Melt Index (HLMI) or 10X scale. There are other melt flow rate scales that use 5 kg, 10 kg or 15 kg weights.

There are various elaborate analytical techniques for determining molecular weight of a polymer. The melt flow rate gives a very quick, simple indication of the molecular weight. The more sophisticated methods include Gel Permeation Chromatography (GPC). The essence of GPC is to dissolve the polymer in a solvent and then inject the solution into a column (tubing). The column contains a porous packing material that retards the movements of the various polymer chains as they flow through the column under pressure. The time for the polymer to pass through the column depends upon the length of the particular polymer chain. Shorter chains take the longest time due to a greater number of possible pathways. Longer chain molecules will pass more quickly since they are retained in fewer pores. This method measures the distribution of the lengths of polymer chains along with the average molecular weight.

Effect of Molecular Weight Distribution on Properties

The distribution of different sized molecules in a polyethylene polymer typically follows the bell shaped normal distribution curve described by Gaussian probability theory. As with other populations, the bell shaped curve can reflect distributions ranging from narrow to broad. A polymer with a narrow molecular weight distribution (MWD) contains molecules that are nearly the same in molecular weight. It will crystallize at a faster, more uniform rate. This results in a part that will have less warpage.

A polymer that contains a broader range of chain lengths, from *short* to *long* is said to have a broad MWD. Resins with this type of distribution have good slow crack growth (SCG) resistance, good impact resistance and good processability.

Polymers can also have a bimodal shaped distribution curve which, as the name suggests, seem to depict a blend of two different polymer populations, each with its particular average and distribution. Resins having a bimodal MWD contain both very short and very long polyethylene molecules, giving the resin excellent physical properties while maintaining good processability. Figure 6 shows the difference in these various distributions.

The latest generation of high density PE pipe materials, known as high performance materials (e.g. PE 4710), are, for the most part, produced from bimodal resins. Pipe made from these materials are characterized by truly exceptional and unique resistance to slow crack growth (SCG), significantly improved long term performance, higher pressure ratings or increased flow capacity, and improved chemical resistance, all of which are achieved without compromising any of the other traditional benefits that are associated with the use of PE pipe.

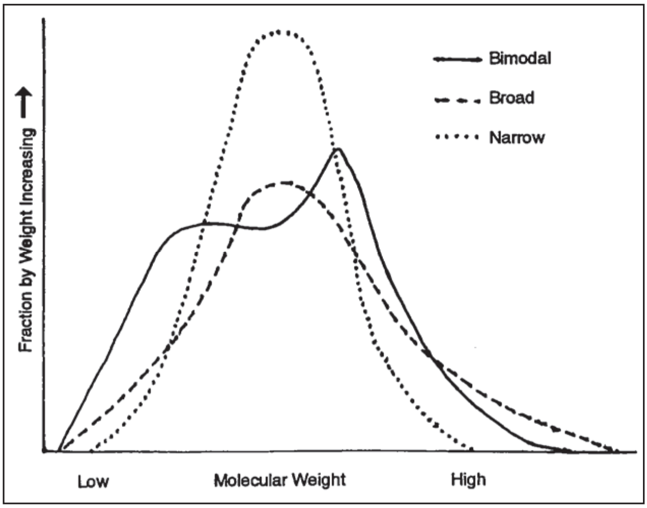


Figure 6 Molecular Weight Distribution

MWD is very dependent upon the type of process used to manufacture the particular polyethylene resin. For polymers of the same density and average molecular weight, their melt flow rates are relatively independent of MWD. Therefore, resins that have the same density and MI can have very different molecular weight distributions. The effects of density, molecular weight, and molecular weight distribution on physical properties are summarized in Table 1.

TABLE 1
Effects of Changes in Density, Melt Index, and Molecular Weight Distribution

Property	As Density Increases, Property	As Melt Index Increases, Property	As Molecular Wt. Distribution Broadens, Property
Tensile Strength (@ Yield)	Increases	Decreases	—
Stiffness	Increases	Decreases Slightly	Decreases Slightly
Impact Strength	Decreases	Decreases	Decreases
Low Temperature Brittleness	Increases	Increases	Decreases
Abrasion Resistance	Increases	Decreases	—
Hardness	Increases	Decreases Slightly	—
Softening Point	Increases	—	Increases
Stress Crack Resistance	Decreases	Decreases	Increases
Permeability	Decreases	Increases Slightly	—
Chemical Resistance	Increases	Decreases	—
Melt Strength	—	Decreases	Increases
Gloss	Increases	Increases	Decreases
Haze	Decreases	Decreases	—
Shrinkage	Increases	Decreases	Increases

PE Piping Materials

The Nature of PE Piping Materials

A PE piping material consists of a polyethylene polymer (commonly designated as the resin) to which has been added small quantities of colorants, stabilizers, anti-oxidants and other ingredients that enhance the properties of the material and that protect it during the manufacturing process, storage and service. PE piping materials are classified as thermoplastics because they soften and melt when sufficiently heated and harden when cooled, a process that is totally reversible and may be repeated. In contrast, thermosetting plastics become permanently hard when heat is applied.

Because PE is a thermoplastic, PE pipe and fittings can be fabricated by the simultaneous application of heat and pressure. And, in the field PE piping can be joined by means of thermal fusion processes by which matching surfaces are permanently fused when they are brought together at a temperature above their melting point.

PE is also classified as a semi-crystalline polymer. Such polymers (e.g., nylon, polypropylene, polytetrafluoroethylene), in contrast to those that are essentially amorphous (e.g., polystyrene, polyvinylchloride), have a sufficiently ordered structure so that substantial portions of their molecular chains are able to align closely to portions of adjoining molecular chains. In these regions of close molecular alignment crystallites are formed which are held together by secondary bonds. Outside these regions, the molecular alignment is much more random resulting in a less orderly state, labeled as amorphous. In essence, semi-crystalline polymers are a blend of a two phases, crystalline and amorphous, in which the crystalline phase is substantial in population.

A beneficial consequence of PE's semi-crystalline nature is a very low glass transition temperature (Tg), the temperature below which a polymer behaves somewhat like a rigid glass and above which it behaves more like a rubbery solid. A significantly lower Tg endows a polymer with a greater capacity for toughness as exhibited by performance properties such as: a capacity to undergo larger deformations before experiencing irreversible structural damage; a large capacity for safely absorbing impact forces; and a high resistance to failure by shattering or rapid crack propagation. These performance aspects are discussed elsewhere in this Chapter. The Tg for PE piping materials is approximately -130°F (-90°C) compared to approximately 221°F (105°C) for polyvinyl chloride and 212°F (100°C) for polystyrene, both of which are examples of amorphous polymers that include little or no crystalline content.

In the case of amorphous polymers, their melting temperature, the temperature at which a transition occurs between the rubbery solid and the liquid states, is not much higher than their Tg. Also for amorphous polymers, the transition between a rubbery solid and a viscous liquid is not very emphatic. This contrasts with semi-crystalline polymers, for which this transition corresponds with the melting of all crystallites, and above which a highly viscous liquid state is reached. This more emphatic transition in PE between the semi-crystalline solid and highly viscous liquid states facilitates manufacture, fabrication and field joining because it allows for more efficient 'welding' to be conducted – when in a liquid state the polymer molecules are able to more effectively diffuse into each other and thereby, form a monolithic structure. In contrast, the melting point of amorphous polymers is less defined and, across this melting point there is not as definite a transition between a rubbery, or plastic state, and a liquid viscous state.

Structural Properties

PE Pipe Material Designation Code Identifies the Standard Classification of Essential Properties

Standards for PE piping define acceptable materials in accordance with a standard designation code. This code, which is explained in greater detail in Chapter 5, has been designed for the quick identification of the pipe material's principal structural and design properties. As this section deals with this subject, it is appropriate to first describe the link between the code designations and these principal properties. For this purpose, and as an example, the significance of one designation, PE4710, is next explained.

- The letters PE designate that it is a polyethylene piping material.
- The first digit, in this example the number 4, identifies the PE resin's density classification in accordance with ASTM D3350, Standard Specification for Polyethylene Plastic Pipe and Fittings Materials (4).

  Certain properties, including stress/strain response, are dependent on a PE's crystalline content. An increase in this phase is reflected by an increase in density. An increase in density affects certain properties, for example an increase in tensile strength and stiffness. Also, a higher density results in changes to other properties. For this reason, the Table for Apparent Modulus that is included in the Appendix of this chapter lists values in accordance with the material's standard density classification. This ASTM standard classification can range from 2, the lowest value, to 4 the highest value.
- The second digit, in this example the number 7, identifies the material's standard classification for slow crack growth resistance – also, in accordance with ASTM D3350 – relating its capacity for resisting the initiation and propagation of slowly growing cracks when subjected to a sustained localized stress intensification.

  The standard classification for current commercial grades is either 6 or 7. The 6 denotes very high resistance and the 7 even higher. The test method for determining quality of resistance to SCG is described later in this chapter.
- The third and fourth digits combined, the number 10 in this example, denote the material's recommended hydrostatic design stress (HDS) for water at 73°F (23°C), in units of 100psi. In this example the number 10 designates the HDS is 1,000psi.

  There are two basic performance criteria based on which a recommended HDS is determined. The first is the material's long term hydrostatic strength (LTHS), a value that is required to comply with certain additional validation or substantiation requirements that are discussed later in this Chapter. The second is the material's quality of resistance to the initiation and growth of slowly growing cracks. An explanation of both of these criteria is included in this section. And, the standard method by which an LTHS is reduced into an HDS is explained in Chapter 5, "Standard Specifications, Test Methods and Codes for PE Piping Systems".

Stress/Strain Response and its Representation by Means of an Apparent Modulus

The potential range of the stress/strain response of a material is bounded by two extremes. At one extreme the response can be perfectly elastic; that is, in conformity to Hook's law whereby the magnitude of strain is always proportional to the magnitude of the applied stress. The resultant proportionality between stress and strain is labeled the modulus of elasticity. Elastic deformation is instantaneous, which means that total deformation (or strain) occurs at the instant the stress is applied. Upon the release of the external stress the deformation is instantaneously and totally recovered. This behavior is represented in Figure 7b as strain versus time for the instantaneous load-time curve depicted in Figure 7a. Under the modulus of elasticity concept, the stress/strain relationship is independent of duration of load application.

At the other extreme, under what is referred to as viscous behavior, deformation caused by the application of a stress is neither instantaneous nor proportional to the stress. Deformation is delayed and the rate and the final extent of deformation are dependent on the magnitude and the duration of the applied stress. Also, the deformation that occurs is not reversible after the stress is released. This response is depicted by Figure 7c.

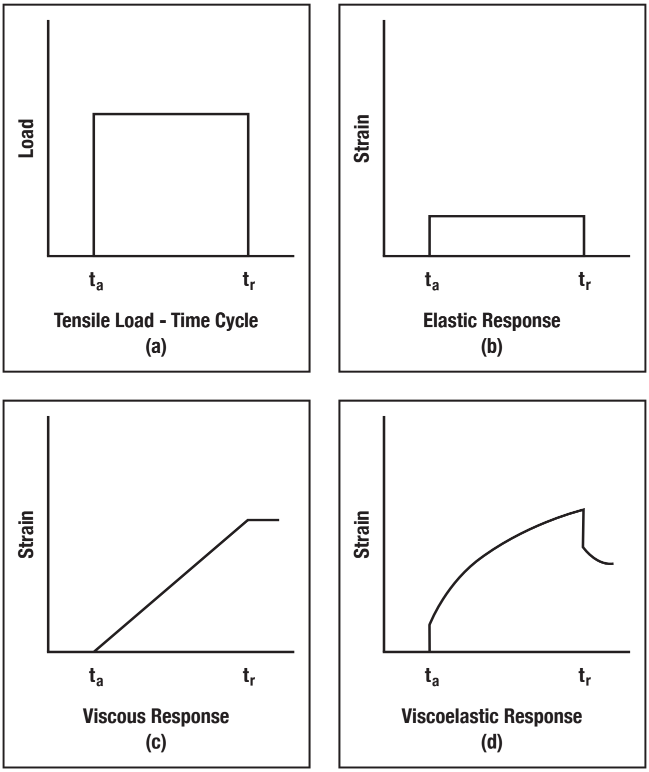


Figure 7 Strain Response (b-d) to a Load (a)

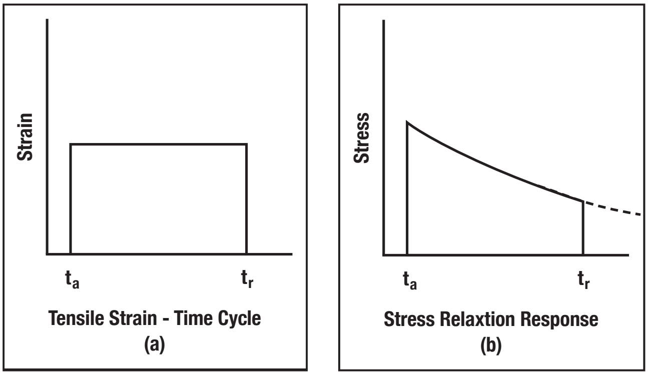


Figure 8 Stress Relaxation Response by a Viscoelastic Material

Viscoelastic behavior, which is depicted by Figure 7d, covers the intermediate region between these extremes. The imposition of a stress in the manner of Figure 7a results in a small instantaneous elastic strain that is then followed by a time-dependent strain. Upon removal of the stress there is a small elastic recovery of strain that is then followed by a time-dependent recovery. This time dependent recovery occurs more quickly for lower values of initial strain and more slowly for an initially larger strain. While the strain recovery may eventually be nearly total, there is almost always some remaining permanent deformation, which, again, is larger for an initially larger deformation.

Figure 7d illustrates viscoelastic response under the condition of constant tensile stress. However, if a strain is imposed and then kept constant, the initially required stress gradually decreases in the course of time. This reaction, which is illustrated by Figure 8, is called stress-relaxation. Stress relaxation is a beneficial response in situations where further deformation is either restrained or counteracted.

Models based on springs – which represent elastic response – and on dashpots –representing viscous response – have been developed to illustrate and to simulate the viscoelastic behavior of PE piping materials.(11 12) A simple one, known as the Maxwell model(29), is shown on the right side of Figure 9. In this model the lone spring represent the elastic reaction, the parallel arrangement of spring and dashpot represents the viscoelastic reaction and, the dashpot represents the viscous reaction.

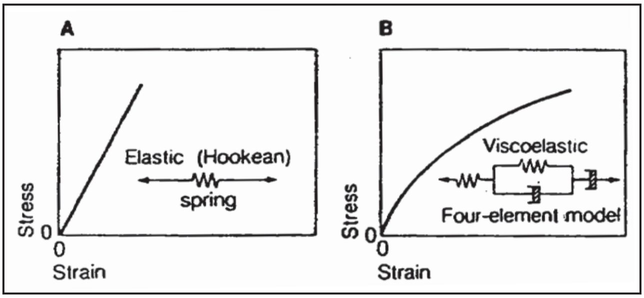


Figure 9 The Maxwell Model

A resultant stress/strain relationship for a viscoelastic/thermoplastic material is determined by a number of variables, principally the following:

1. The magnitude of the initial stress or strain (a larger stress or strain results in a larger viscous response)
2. The multi-axiality of the resultant stress (when a material is simultaneously pulled in more than one direction this inhibits its freedom to deform)
3. The duration of the sustained stress or of the sustained strain (increased duration results in a larger total response)
4. The temperature (it mostly affects the rate of the viscous response)
5. The environment (if an organic substance is adsorbed to some extent by PE, this may result in a plasticizing effect that mostly accelerates the viscous response – air and water are inert in this respect and they produce equivalent results)
6. Possible external restraints on the freedom to deform (e.g., the embedment around a buried pipe restricts free-creeping)

A frequently used method for evaluating the stress/strain response of PE piping materials is by means of tensile/creep tests that are conducted on test bars. In these tests, the specimens are subjected to a uni-axial stress and they are allowed to free-creep, meaning that their deformation is unrestrained. This combination of test parameters yields the maximum possible deformation under a certain sustained stress. When the logarithm of the strain (deformation) resulting from such tests is plotted against the logarithm of duration of loading it yields an essentially straight line for each level of sustained test stress. This behavior is illustrated by Figure 10. This essentially straight line behavior facilitates extrapolation of experimental results to longer durations of loading than covered by the data (the extrapolation is denoted by the dotted lines in Figure 10).

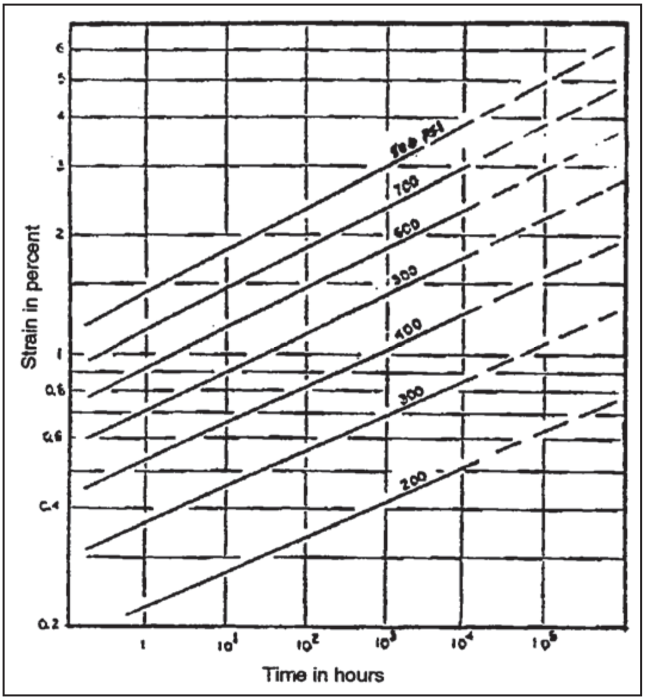


Figure 10 Typical Tensile Stress/Creep Response for a PE3XXX Piping Material When Subjected to a Sustained Uni-axial Tensile Stress, in Air at 73°F

Any point on a tensile/creep diagram, such as in Figure 10 gives a stress/strain ratio. To differentiate this ratio from the modulus of elasticity, which only applies to elastic behaving materials, it is designated as the apparent modulus under tension. For correct engineering use, a value of apparent modulus must identify the conditions under which that value has been established: the kind of stress (uni-axial versus bi- or multi-axial); the magnitude of the principal stress; the duration of stress application; the temperature; and, the test environment. Figure 11 illustrates the manner by which the apparent modulus of a PE3XXX material varies, at 73°F and in air, after different durations of sustained loading and in response to uni-axial stresses of different intensities.

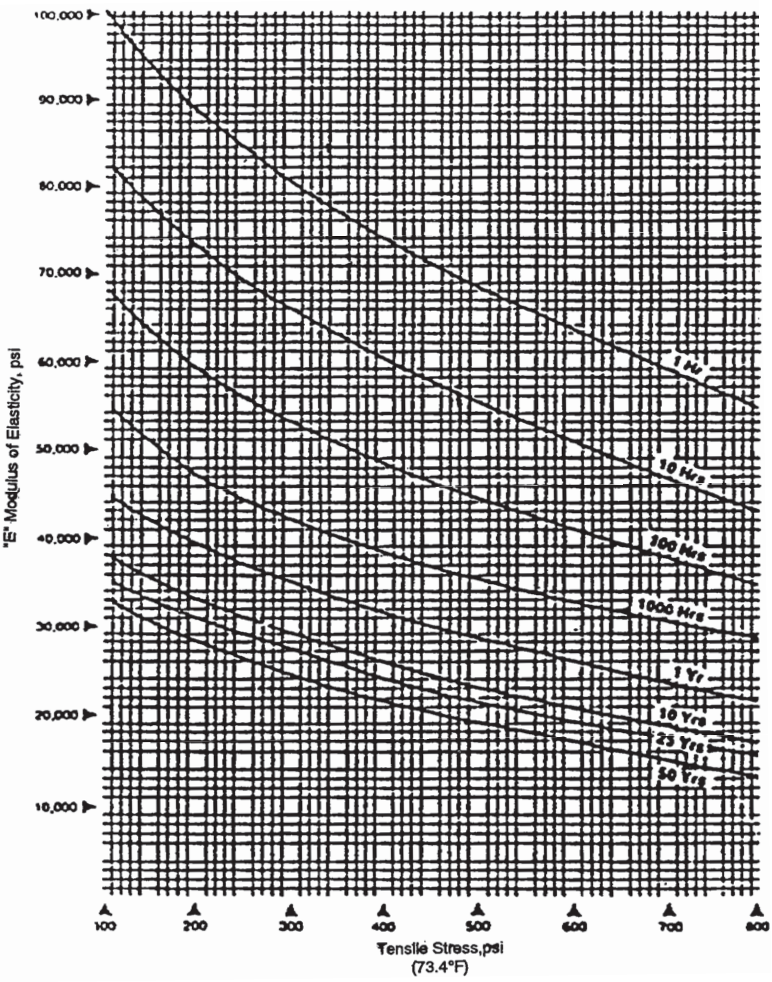


Figure 11 Apparent Modulus Versus Stress-Intensity for PE3XXX* Material when Evaluated Under Uni-Axial Stressing, In Air and at 73°F

* The PE3XXX designation covers all pipe materials that are made using a PE resin that meets the requirements for the Class 3 density classification, in accordance with ASTM D3350.

Apparent moduli have also been evaluated on pressurized pipe specimens by measuring the increase in pipe diameter as a function of pressure (stress) and time under pressure. In these tests the pipe specimen is subjected to bi-axial stressing – a circumferential stress and an axial stress that is about one-half of the magnitude of the circumferential stress. This combination of stresses works to restrain deformation. The result is an apparent modulus that is about 25% larger than that determined under uni-axial tension.

Analogous apparent moduli can also be derived from stress-relaxation data. However, the numerical difference between an apparent modulus derived from tensile creep data and one derived from stress relaxation data is generally small for typical working stresses and when the times under a continuous load, or strain, are matched. Accordingly, the two can be used interchangeably for common engineering design.

Apparent Modulus Under Compressive Stress

Apparent moduli can also be derived for the condition of compressive stress. Such a value tends to be somewhat larger because the resultant deformation causes a slight increase in the area that resists the applied stress. However, the resultant increase is generally small, allowing the tensile stress value to adequately and conservatively represent the compression state.

In summary

The apparent modulus concept has proven to be very useful and effective. Even though PE piping materials exhibit viscoelastic behavior, this concept allows for piping design to be conducted by means of the same equations that have been developed based on the assumption of elastic behavior. However, it is important to recognize that a value of an apparent modulus that is used for a design must adequately reflect the viscoelastic response that is expected to occur under the anticipated service conditions. In this regard it should be noted, as illustrated by Figure 11, that a value of apparent modulus is dependent not only on duration of loading but also, on stress intensity. However, in nearly all PE pipe applications the maximum stresses that are generated by reactions other than that which is caused by internal pressure – a reaction that, as shown by the section that follows, is treated as a separate design issue – are of a magnitude that seldom exceeds the range of about 300 to 400psi. Accordingly, the apparent modulus values within this stress range may be accepted as an appropriate and conservative value for general design purposes. This is the major consideration behind the design values that are presented in Table B.1.1 in the Appendix to this Chapter. It should also be recognized that the values in this table apply to the condition of uni-axial stressing. Thus, these values tend to be conservative because in most applications there exists some multi-axiality of stressing, a condition that leads to a somewhat larger apparent modulus.

There is one kind of operation that results in a temporary tensile stress that is significantly beyond the maximum range of 300-400psi for which Table B.1.1 applies. This is an installation by pipe pulling, a procedure that is the subject of Chapter 12. At the significantly greater uni-axial stresses that result under this installation procedure, the resultant apparent modulus is about 2/3rds of the values that are listed in Table B.1.1.

An aspect of Table B.1.1 worth noting is that it presents values in accordance with the standard density classification of the PE resin (the first numeral after the PE designation), in accordance with ASTM D3350 (Refer to Chapter 5 for a detailed explanation of the D3350 classification system). As discussed earlier in this Chapter, a higher resin density reflects a higher crystalline content. And, the higher the content, the greater a material's apparent modulus.

As mentioned earlier, the apparent modulus varies with temperature. Table B.1.2 in the Appendix to this Chapter lists multipliers for the converting of the apparent modulus for the base temperature of 73°F to another temperature of design interest.

Stress/Fracture Behavior and the Determination of Working Strength

Introduction

Successful design requires that the working strength of a material be defined in relation to the various conditions under which it is intended to be used and in recognition of its structural behavior. The working tensile strength of PE is affected by essentially the same variables that affect its stress/strain relationship, principally magnitude of load, duration of loading, temperature and environment. However, there is one important difference. Whereas strain response is in reaction to the nominal value (the so called bulk or, average value) of applied stress, fracture can result from either the effect of a nominal stress, or from that of a local intensified stress. Under an excessively large nominal stress PE continues to slowly deform until a sufficiently large deformation is reached at which the material begins to yield. Yielding is then quickly followed by structural failure. This failure mechanism, because it is preceded by yielding or plastic deformation, occurs in what is referred to as the ductile state.

In contrast, a locally intensified stress can sometimes lead to the initiation and subsequent propagation of a localized and very slowly growing crack. When the crack grows to a size that spans from the inside to the outside wall of a pressure pipe a leak is the end result. Even though a failure in PE pipe which results from slow crack growth (SCG) is greatly resistant of its propagation into a larger crack – a very beneficial feature of PE pipe – it is identified as brittle-like because it occurs absent of any localized yielding or plastic deformation. Such absence is symptomatic of the fracture process that occurs in what is known as the brittle state. The working strength of each commercial grade of PE pipe material is determined in consideration of both of these possible failure mechanisms.

In a pressure pipe application the major nominal stress is that which is induced by internal hydrostatic pressure. Accordingly, standards for pressure rated PE pipe require that each material from which a PE pipe is made have an experimentally established long-term hydrostatic strength (LTHS). The pressure rating of a PE pipe is based on this hydrostatic strength after it has been reduced to a hydrostatic design stress (HDS) by means of a design factor (DF) that gives adequate consideration to the additional nominal and localized stresses that can be generated by other conditions, as well as to the various other factors that can affect reliability and durability under actual service conditions. A discussion of these factors is included in Chapter 5 under the subtopic "Determining a PE's Appropriate Hydrostatic Design Stress (HDS) Category".

The methodology for establishing an HDS for PE pipe presumes that at the assigned value of HDS, and also under proper installation, the pipe shall operate in the ductile state. In other words, when it operates at its sustained pressure rating it also has sufficient reserve strength for safely absorbing anticipated add-on stresses, particularly localized stress intensifications. Normal stress increasing situations can result from scratches, gouges, changes in geometry (like those at fittings), rock impingements, etc.

The possible adverse effect by localized stress intensifications on the working strength of engineering materials is well recognized and is addressed by means of these two general strategies:

1. By recognizing a material's sensitivity to the effect of stress intensifications through

a) the application of a larger 'safety factor' when establishing a safe design stress; and, or,

b) by conducting pipe design not based on the average value of a major stress, but doing so in consideration of the maximum localized stress that may be generated, wherever it is expected to occur – for example, by the application of a special stress concentration factor. (31, 32)

2. By ensuring that the pipe material has the capacity to operate in the ductile state under the anticipated installation and service conditions. In this case pipe design can proceed on the basis of the nominal (average) value of a major stress.

The latter is the strategy that is employed for qualifying PE materials for piping applications. Because a design that is based on nominal stress presumes a capability for performing in the ductile state, PE piping standards require that the pipe material must not only have an established long-term hydrostatic strength (LTHS), but that it also has to exhibit a very high resistance to the development and growth of slowly growing cracks (SCG), the failure mechanism that may be initiated and then propagated by a localized stress intensification. These are two of three major considerations in the determination of the recommended hydrostatic design stress (HDS) of a PE piping material.

The determination of an HDS needs to also consider the potential effect on working strength by the add-on stresses of very temporary duration – those that result from pressure surges. This leads to a third consideration: The potential adverse effect on working strength by pressure surges.

The methods by which each of these three considerations – long term hydrostatic strength, resistance to slow crack growth and resistance to pressure surges – is evaluated, and the manner in how the results are considered for the establishment of an HDS, is briefly described in the sections that follow.

Establishing a PE's Long-Term Hydrostatic Strength (LTHS) and its Derivative, The Hydrostatic Design Basis (HDB)

It is well recognized that the working strength of materials that exhibit viscoelastic behavior – which includes not just thermoplastics but also other materials such as metals and ceramics at high temperatures – decreases with increased duration of loading (8, 13). For such materials their long-term working strength for a temperature and other condition of interest is determined based on the result of a sustained-stress versus time-to-rupture (i.e., a stress-rupture) evaluation. The working strength of PE materials is similarly evaluated and a standard protocol has been established for doing so.

The standard basis for determining an LTHS value for PE piping materials is from results of pressure testing in water, or air, for the base temperature of 73°F (23°C). However, many commercial grades of PE materials also have an LTHS that has been determined at an elevated temperature, generally 140°F (60°C). The determination of an LTHS involves three steps, as follows:

1. Circumferential (hoop) stress versus time-to -rupture data are obtained by means of longer-term sustained hydrostatic pressure tests that are conducted on pipe specimens made from the material under evaluation. This testing is performed in accordance with ASTM D1598, Time to Failure of Plastic Pipe Under Constant Internal Pressure(5). Sufficient stress-rupture data points are obtained for the adequate defining of the material's stress-rupture behavior from about 10hrs to not less than 10,000hrs.
2. The obtained data are then analyzed in accordance with ASTM D2837, Obtaining Hydrostatic Design Basis for Thermoplastic Pipe Materials,(5) to determine if it constitutes an acceptable basis for forecasting a PE's LTHS. To be acceptable, the data must satisfy the following two requirements:
    a. A statistical analysis of the stress-rupture data must confirm that a plot of the logarithm of circumferential (hoop) stress versus the logarithm of time-to-fail yields a straight line.

  b. An analysis of separately obtained elevated temperature stress-rupture data that are obtained on the same population of pipe specimens must validate the expectation that the above experimentally established straight line behavior shall continue significantly past the experimental period, through at least 100,000hrs (11.4 years). For the case of materials that are labeled high performance, it must be demonstrated that this straight line behavior shall continue through at least the 50-year intercept. This latter demonstration is labeled substantiation. A description of the validation and substantiation methods appears later in this discussion.

3. When both of the above (2a and 2b) requirements are satisfied this qualifies the mathematical representation of the stress-rupture behavior that is indicated by the experimental data. This mathematical model is then used for forecasting the average stress at which failure will occur at the 100,000hr intercept. The resultant value is labeled the long-term hydrostatic strength (LTHS) of the material under evaluation.

For purposes of simplifying standards that cover pressure rated pipes, an LTHS that is established by the above procedure is next reduced to one of a limited number of standard long-term hydrostatic strength categories, each of which is designated as a Hydrostatic Design Basis (HDB). The hydrostatic design stress (HDS) is then determined by applying an appropriate strength reduction factor – what is termed as the design factor (DF) – to the resultant HDB. The standard convention is to also express the DF in terms of a preferred number. The reduction of an HDB that is stated in terms of a preferred number by means of a DF that is also stated in terms of a preferred number results in an HDS that is always expressed in terms of a preferred number. The interested reader is referred to Chapter 5 for further information on the use of preferred numbers. A detailed description of the standard procedure for the reducing of an LTHS to an HDB, and the subsequent determination of an HDS, is included in Chapter 5, "Standard Specifications, Test Methods and Codes for PE Piping Systems".

It is important to recognize that because the LTHS is determined at the 100,000hr intercept this does not mean that the intended design life is only for that time period, essentially only about 11 years. This time intercept only represents the standard accepted basis for defining the PE material's LTHS. The design of a service life for a much longer period is one of the important functions of the DF, based on which an HDB (a categorized LTHS) is reduced to an HDS.

Once the HDS is determined for a particular material the standard pressure rating (PR), or pressure class (PC), for a pipe made from that material may be computed. The Appendix to this Chapter presents the equations that are used for this purpose as well as a table of the resultant PR's and PC's of pipes that are made to various dimension ratios (DR's).

The results of a stress-rupture evaluation of a PE pipe that has been produced from a high density material are presented in Figure 12. In this evaluation water was present inside and outside the pipe and the testing was conducted at a temperature of 20°C (68°F), and also at two elevated temperatures: 60 and 80°C (140 and 176°F). In this case all of the resultant data have been analyzed by means of a standard mathematical program[14] that also forecasts the long term strength of the PE material at each of these test temperatures. Two forecasts are shown: The higher line is a forecast of the mean value of strength; and, the lower line is a forecast of the lower predictive limit, the LPL. It can be observed that the 80°C data show that a "down-turn" occurs after about 2500hrs. At the lower test temperature of 60°C the downturn occurs about a log decade later. By taking into account the effect of temperature on this shift in strength, the mathematical program projects that for the tested material the straight line behavior at 20°C (68°F) shall continue beyond the 50 year intercept, considerably past the minimum 100,000 hours that is imposed by the validation requirement of ASTM D2837.

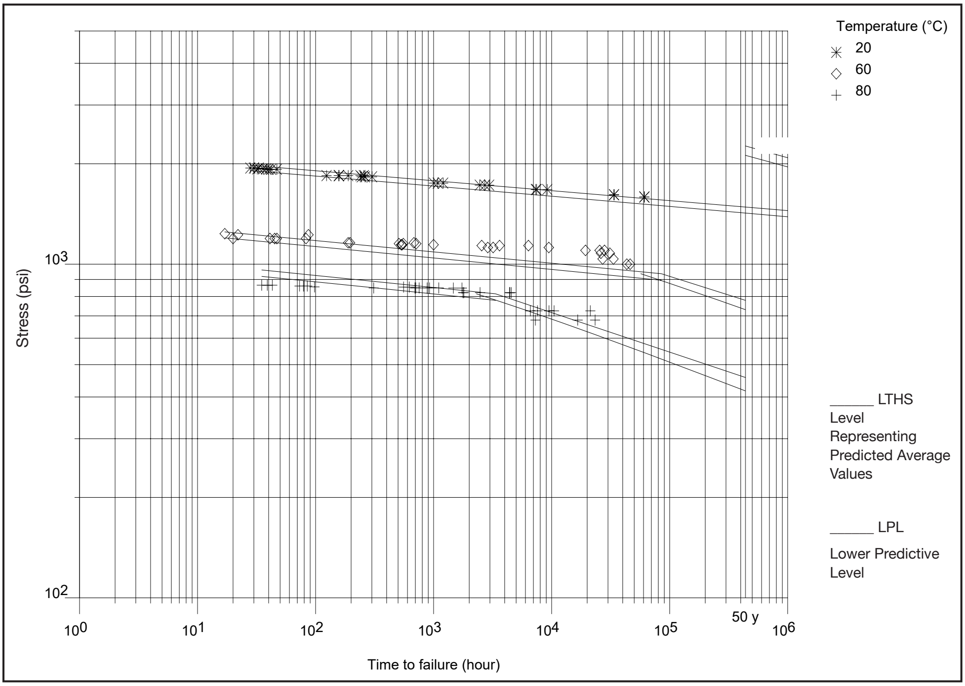


Figure 12 Stress-Rupture Characteristics of an HDPE Pipe Material Similar or Equivalent to PE 4710 (this is not a creep-rupture diagram and the 'higher performance' designation refers to the fact that there is no downturn even after 50 years.)

As already stated, a principal objective of the validation requirement is to confirm compliance to the expectation that the straight-line behavior that is exhibited by the experimental data shall continue through at least 100,000hrs. Should this expectation not be realized, then the LTHS as projected by the straight line assumption will be overstated. But, there is another important objective of the validation requirement. It has been determined that the shift to a down turn in the stress-rupture behavior of PE piping materials is the result of a shift in failure mechanism; from ductile to brittle-like. Studies show that brittle-like failures are the end result of a slow crack growth (SCG) mechanism that is initiated by localized stress intensifications that are generated at natural and normal flaws in the pipe material. In the case of PE materials the term flaws refer to very localized and quite normal discontinuities in structure, such as can be caused by gel particles, by residual catalyst, by transitions from crystallites to amorphous material. Materials that display high resistance to inherent flaws are also materials that offer high resistance to localized stress intensifications that are created by external factors. This observation on the effect of inherent flaws on working strength is in line with the behavior of other thermoplastics, as well as that of traditional materials. For example, if it were not for the presence of naturally occurring flaws the working strength of glass would be many times greater. An objective in the development of an engineering material is to minimize its vulnerability to inherent flaws; that is, to enhance its capacity to perform in the ductile state. This is the other important objective of the validation requirement.

A study conducted by the Plastics Pipe Institute (18) has shown that very good quality longer-term field performance is achieved by pipes that are made of PE materials for which the down turn in its ambient temperature stress-rupture behavior is predicted to occur beyond 100,000hrs. Such pipes have been shown to exhibit high resistance to stress increasing situations. In other words, these pipes have a capacity to continually operate in the ductile state. Based on this study, materials for which a downturn is predicted to occur prior to the 100,000hr intercept are excluded from pressure pipe applications. As discussed earlier in this section, it is important to, once again, emphasize that while the LTHS of a PE pipe material is based on its value at 100,000 hours (11.4 years) this does not define its design life.

The newer high performance PE pipe materials – for example the PE4710 materials – exhibit no downturn prior to the 50-year intercept. Because of this, and also because of a couple of additional performance requirements, these newer materials do not require as large a cushion to compensate for add-on stress and therefore, they can safely operate at a higher hydrostatic design stress. A discussion of this matter is included in Chapter 5.

Methodology for the validation of an LTHS

The validation requirement in ASTM D2837 is predicated on the finding that the kinetics of the slow crack growth process is in line with rate process theory(18, 20, 21, and 27). In accordance with this theory, which has been found to apply to many naturally occurring chemical and mechanical processes, the rate at which a process proceeds is a function of a driving force (e.g., concentration, pressure or, stress in the case of a fracture process) and temperature (which affects intensity of molecular activity). The following rate process based equation has been found to well model the experimentally established relationship between a pipe's time to failure under the SCG process and the magnitude of the applied stress and the temperature.

$$\text{(1)} \quad \text{Log } t = A + B/T + C\,(\log \delta)/T$$

WHERE

t = time to fail, hrs
T = absolute temperature, °R
δ = circumferential (hoop) stress, psi
A, B, and C = experimentally established coefficients

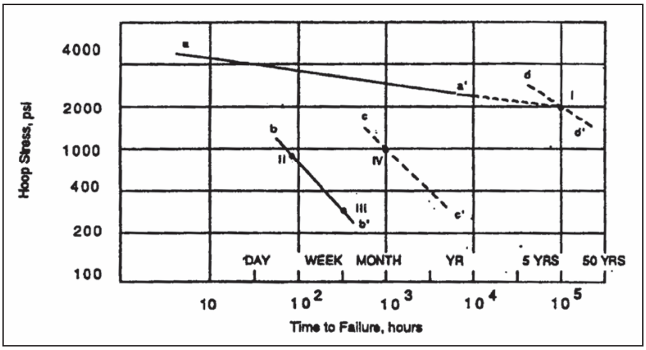


Figure 13 Hoop Stress vs Time to Failure

With reference to Figure 13 the following are the steps that comprise the validation procedure:

1. In accordance with ASTM D2837, evaluate pipe samples of a material of interest at the base temperature of 73.4°F (23°) so as to define the mathematical model that expresses the relationship between hoop stress and time-to-failure (Line a-a'). Then, based on this model compute the predicted value of average hoop stress that results in failure at the 100,000 hour intercept (Point I).
2. At an elevated temperature, but not higher than 194°F (90°C), establish a brittle failure line (line b-b') by the means of the following procedure:

a) Using at least six pipe test specimens, subject each specimen to a hoop stress that results in a brittle-like failure (a crack in the pipe wall with no visible sign of deformation) in the range of 100 to 500hrs. The determination of the best stress/temperature combination may require some preliminary trial and error experimentation. Determine the log average of the results (Point II).

b) Also using not less than six pipe specimens, select a hoop stress that is at least 75psi lower than that used in the above step. Testing under this condition should result in a failure time that ranges from 1,000 to about 2,000hrs. Determine the log average of the results (Point III).

3. Subject at least six pipe samples to the same sustained stress as used under condition 2-a, but conduct the testing at a temperature that is at least 27°F (15°C) lower. Continue this testing until failure of all specimens, or until the log average of the testing times (failures and non-failures) equals or exceeds the time predicted by the requirement that follows (Point IV).
4. To validate that the tested material is in compliance with the D2837 requirement that the straight-line that is depicted by the experimental data shall continue through at least 100,000 hours, the above determined log average failure time (point IV) must at the least equal a value that is predicted by the rate process equation (Equation 1) for which the coefficients A, B and C have been determined based on the experimentally established values of points I, II, and III. PE materials that fail to validate are considered unacceptable for pressure pipe applications.

A challenge in the application of the above method is the high resistance to brittle-like failure that is exhibited by modern PE piping materials. In consequence of this, failure times for these materials at the elevated test temperatures (such as Points III and IV in Figure 13 can be as long as thousands of hours. To achieve a more practical test time an alternate procedure has been established which is based on the Time-Temperature Superposition Principle. This principle is a derivative of the rate process theory. It essentially asserts that a certain stress-rupture performance that is exhibited at an elevated temperature is shifted to a longer time when the temperature is lowered. This shift is exhibited by lines b-b', c-c' and d-d' in Figure 13. Studies show that for PE piping materials of various kinds this shift is adequately represented by means of a common shift factor. Based on this common factor, tables have been established that specify the minimum times to failure at a specified stress and an elevated temperature that ensure the validation of an LTHS for 73.4°F (23°C). These Tables are published in PPI report TR-3. (22)

Substantiation: A Step Beyond Validation

Thanks to modern chemistry, PE piping materials have become available which exhibit outstanding resistance to slow crack growth. In consequence of this property these materials are very highly resistant to brittle-like failure, which results in a straight line stress-rupture behavior at ambient temperature that is predicted to exhibit no downturn prior to the 50-year intercept. This behavior is exhibited by Figure 12. In order to give standard recognition to this very beneficial aspect the substantiation requirement has been established. This requirement is essentially the same as validation, but the difference is that substantiation is the confirmation, also by means of supplementary testing, that the ductile stress-rupture behavior indicated by the experimental data is expected to continue through at least the 50-year intercept.

Compensating for the Effect of Temperature on Working Strength

Many evaluations have been conducted regarding the effect of a sustained temperature on a PE's LTHS. While results show that materials can be affected somewhat differently, they also show that over a range of about 30°F (17°C) above and below the base temperature of 73°F (23°C) the effect is sufficiently similar so that it can be represented by a common set of temperature compensating multipliers. Table A.2 in the Appendix to this chapter lists these common multipliers.

The Appendix also includes guidance for determining a multiplier, for a specific pipe material, for sustained temperatures that are above 100°F (38°C). This determination requires that the PE material from which the pipe is made have a recommended HDB for a temperature above 100°F (38°C), in addition to the universal requirement for pressure pipe applications to have an HDB for the base temperature of 73°F (23°C). This information may be obtained from the pipe supplier or, in the case where the commercial designation of the pipe material is known, it can be obtained by consulting a current copy of PPI Report TR-4. Earlier in this Chapter, the subject of HDB was discussed. For a more thorough discussion of the topic, the interested reader is referred to Chapter 5.

In addition, it is noted in this Appendix that certain standards, codes and manuals that are dedicated to certain applications may list temperature compensating multipliers that are either specific to the PE materials that are covered or, that reflect certain considerations that are unique to the application. For example, in water distribution applications the highest temperature is not sustained all year long. The operating temperature varies with the seasons. Therefore, in AWWA standards and manuals the temperature compensating multipliers apply to a **maximum** operating temperature – as contrasted to a temperature that is sustained – and the values recognize that because of seasonal variations the average operating temperature shall be somewhat below the maximum. Table A.2 in the Appendix presumes that the noted temperature shall be continually sustained. Accordingly, if a standard, code or manual includes a table of temperature de-rating multipliers, those multipliers take precedence over those in Table A.2 in the Appendix.

Compressive Strength

Unlike under the condition of tensile loading, which if excessive can result in a failure, a compressive loading seldom leads to a fracture. Instead, there is a resultant creep in compression, which causes a thickening of the areas resisting the stress, an effect that tends to reduce the true stress. If the stress is excessive failure can occur by yielding (excessive deformation) rather than by a fracture process. For these reasons, it is customary to report compressive strength as the stress required to deform a test sample to a certain strain. Recommended allowable compressive stress values are presented in Table C-1 in the Appendix to this Chapter.

Evaluating the Resistance to Slow Crack Growth (SCG) of a Sharply Notched PE Specimen

As mentioned earlier, a significant value of the validation and the substantiation requirements is that they work to exclude from piping applications those PE materials for which their long-term tensile strength and ductility may be compromised by a lower resistance to the slow crack growth mechanism, as it may be initiated by internal flaws (natural inhomogenities). And, as it was also mentioned earlier, this resistance to the effect of internal flaws is also a recognized index of a PE's resistance to the potentially adverse effect of external flaws. However, indications are that among different kinds of PE's there is not a consistent proportionality between the material's resistance to failure as initiated by internal flaws versus one that is initiated by external flaws. Thus, to more directly determine a PE's resistance to external flaws, ASTM F 1473, "Standard Test Method for Notch Tensile Test to Measure the Resistance to Slow Crack Growth of Polyethylene Pipes and Resins" (5) was developed. In this method a precisely notched specimen is subjected to a constant load in air that is maintained at a constant temperature of 80°C (176°F). This combination of conditions results in a failure time that can be measured in hours. The failure mechanism is at first, and for the greater part of the failure time, that of a slowly growing crack. When this crack reaches a major size it causes the remaining ligament to be subjected to a sufficiently higher stress such that the final break occurs by a ductile tearing. The total time-to-failure that covers both these mechanisms has been shown to be an index of the quality of a PE's resistance to SCG under actual service conditions.

A study sponsored by the Gas Research Institute (GRI) regarding the quality of long-term field performance of PE pipes versus their time-to-fail under test method ASTM F1473 indicates that 50 hours under this test results in an excellent service life. Or, in other words, this minimum time to failure ensures that under proper installation and operating conditions the pipe shall continue to operate in the ductile state. The lowest ASTM F1473 time to failure for current PE piping materials is 100hrs. This is designated by the numeral 6 in the second digit of the PE pipe material designation code (e.g., PE 3608). This minimum 100hr value includes a “safety” margin over the GRI determined “safe” value. However, many current materials qualify for the numeral 7 (e.g., PE4710), which designates a time to failure under this test in excess of 500 hours. This performance indicates a superior capacity for safely tolerating localized stress intensifications, which gives added assurance of a pipe’s capability to operate in the ductile state over its intended service life. This is one of the primary requirements that the higher performance PE piping materials must meet in order to qualify for a higher hydrostatic design stress rating. (See Chapter 5 for a discussion on establishing an HDS).

There are materials for which the time-to-fail, when tested under ASTM F1473, is in the thousands of hours. However, it should be kept in mind that under this method, as the time to fail increases, a larger share of this time-to-fail covers the ductile tearing phase, a phase that does not represent resistance to slow crack growth. (36) It also should be kept in mind that the objective of setting a minimum time-to-fail requirement is to achieve the beneficial effect of continued operation in the ductile state. Accordingly, when tested under ASTM F1473,a minimum 500 hour time–to-fail requirement has been established for higher performance PE materials, based on information that indicates materials that meet this requirement exhibit maximum efficacy in tempering potential adverse effects that may be caused by localized stress intensifications.

Resistance to Pressure Surges

As discussed earlier, the pressure rating and pressure class of a PE pipe is established based on the material’s long term hydrostatic strength (LTHS), a property that is determined under the condition of a sustained hydrostatic stress. Under actual service conditions pressure surges may occur, which can cause temporary rises in the hydrostatic stress above the sustained working stress. Such rises need to be limited to a value and a total number of occurrences that are safely tolerated by a pipe when it is operating at its working pressure. In the case of some pipe materials, the strength of which is affected by temporary pressure surges, their sustained pressure rating must be appropriately reduced. On the other hand, as evidenced by testing and proven by experience, PE pipe is very tolerant of the effect of pressure surges. Seldom is it necessary to lower a PE pipe’s static pressure rating to compensate for the effect of pressure surges.

Temporary rises in operating pressure may lead to either of these events:

1. The total stress that is induced by the combination of the static plus a surge pressure may reach a magnitude that exceeds the pipe’s hydrostatic strength thereby, causing the pipe to rupture.

2. A large number of surge pressure events coupled with their magnitude may, after some time, result in fatigue of the pipe material so as to cause a sufficient loss of its long-term hydrostatic strength (LTHS) that can lead to a premature failure.

These two events are distinguished by a major difference. The first event is the simple result of an applied stress that exceeds the pipe material's hydrostatic strength. But, the second one is the result of a gradual degradation of this strength by the effects of fatigue. This essential difference is recognized by the two kinds of allowances for sudden pressure surges for PE pipes that are presented in Chapter 6. One of these allowances is for occasional pressure surges, which do not induce fatiguing and, the other covers frequently occurring pressure surges that may result in fatiguing. PE pipe's reaction to each of these two different events is next discussed.

Reaction to Occasional Pressure Surges

PE's viscoelastic nature, which accounts for its decrease in hydrostatic strength with increased duration of loading also results in the opposite effect, an increased strength under decreased duration of loading. Occasional surge pressure events – such as may be caused by a power failure or other malfunction – result in a maximum hydrostatic stress that lasts for only a few seconds, at their longest. However, it should be noted that the short-term hydrostatic strength of PE pipe is more than twice its LTHS.

An evaluation of PE pipe's stress/strain behavior gives further support to its capacity for safely tolerating occasional pressure surges. When a PE pipe is subjected to an add-on stress of very short duration, the resultant additional strain is relatively small, as predicted by the higher apparent modulus that covers this situation (See previous discussion on apparent modulus). And, essentially all of this strain is elastic, meaning that as soon as the surge pressure is gone the added strain is reversed. Because this temporary strain is fully recovered the minimal pipe expansion that occurs during a short lived surge pressure event has no effect on the longer term creep expansion that occurs under the sustained stress that is induced by a steady operating pressure. In other words, surge pressure events of very short term duration have no adverse effect on a PE's long term hydrostatic strength (LTHS).

The above concepts have been confirmed by various studies and they are the basis for the allowances that are presented in Chapter 6.

Reaction to Frequently Occurring Pressure Surges

To a degree that can vary depending on circumstances, the strength of all materials may be adversely affected by fatigue. Modern PE's that meet current requirements for pressure pipe applications have been shown to exhibit very high resistance to fatigue. The primary parameters that affect the degree and the rate at which a material suffers irreversible damage through fatigue are the frequency and totality of the fatigue events as well as the amplitude of the change in stress that occurs under each event.

In PE, the fatigue mechanism that leads to a loss of long-term strength is that of an initial development of microcracks which under the effect of each cycle event slowly grow into larger cracks. It has been shown by various investigators that PE pipe materials which exhibit a very high resistance to slow crack growth under sustained pressure are also materials that exhibit a very high resistance to crack development and growth when subjected to cyclic stressing. In this regard the studies conducted by Bowman (7) on butt-fused PE piping systems are very informative. They show that even after millions of pressure cycling of substantial magnitude no damage has been detected in the tested systems. And the work by Marshall et al. (17) shows that properly installed pipe made from modern PE piping materials can safely withstand sustained periods of high frequency surging (from 1 to 50 cycles per hour) that result in temporary peak pressure of up to 200 percent of the pipe's static pressure rating with no indication of fatigue and no reduction in long-term serviceability. In a 1999 issue of Water Industry Information and Guidance Note, (35) the UK based Water Research Council concludes that for pipes made from high toughness PE materials (e.g., materials offering very high resistance to slow crack growth), fatigue de-rating is generally not required.

The allowances for frequently occurring pressure surges that are presented in Chapter 6 are conservatively based on the results of studies such as those mentioned in the above paragraph.

Other Engineering Properties

Mechanical Properties

Poisson's Ratio – Any stretching or compressing of a test specimen in one direction, due to uniaxial force (below the yield point) produces an adjustment in the dimensions at right angles to the force. A tensile force in the axial direction causes a small contraction in the lateral direction. The ratio of the decrease in lateral strain to the increase in axial strain is called Poisson's ratio (ν).

Poisson's ratio for PE has been found (10) to vary somewhat depending on the ultimate strain that is achieved, on temperature and on the density of the base resin. However, for typical working stresses, strains, and temperatures, an average value of 0.45 is applicable to all PE pipe materials regardless of their densities, and also for both short- and long-term durations of service. This value is also reported in the Appendix attached to this Chapter.

Impact Strength – The concept of impact strength covers at least two important properties:

1. The magnitude of a suddenly applied energy that causes the initiation and propagation of a crack. This is usually assessed by the results of tests on un-notched or, bluntly notched specimens.
2. The magnitude of a suddenly applied energy that causes a crack to rapidly propagate. This is usually assessed by means of very sharply notched specimens.

The results under the first assessment give an indication of a material's susceptibility to brittle fracture absent a source of localized stress concentration. The second assessment gives an indication of whether a material has useful resistance to shattering by the propagation of an existing crack or flaw. A recognized feature of PE materials is their very high resistance to crack initiation under very rapid loading. Consequently, impact tests on this material are always conducted on notched specimens.

The degree of resistance to impact loading depends on many factors that are not assessed by the impact test. They can include mode of impact loading, strain rate, multi-axiality of the stress field, localized stress concentrations, temperature and environment. However, impact test results have been shown to be of very helpful guidance in the selection of materials that can safely resist the potential adverse effects of impact loading. One of the exceptional features of PE pipe is its excellent impact resistance. This has been proven in the gas distribution application for which PE piping has been shown to resist failure by the rapid crack propagation mechanism.

Impact strength is a measure of the energy absorbed during the fracture or ductile deformation of a specimen of standard dimensions and geometry when subjected to a very rapid (impact) loading at a defined test temperature.

There are several types of impact tests that are used today. The most common one in the United States is the notched Izod test, which is illustrated in Figure 14. Notched specimens are tested as cantilever beams. The pendulum arm strikes the specimen and continues to travel in the same direction, but with less energy due to impact with the specimen. This loss of energy is called the Izod impact strength, measured in foot-pounds per inch of notch of beam thickness (ft-lb/in). Compared to other common true thermoplastic piping materials PE offers the highest Izod impact strengths. At ambient temperatures the resultant values exceed 20ft-lbs/in of notch compared to less than 10 for the other materials. And, many types of PE materials do not fail at all under this test.

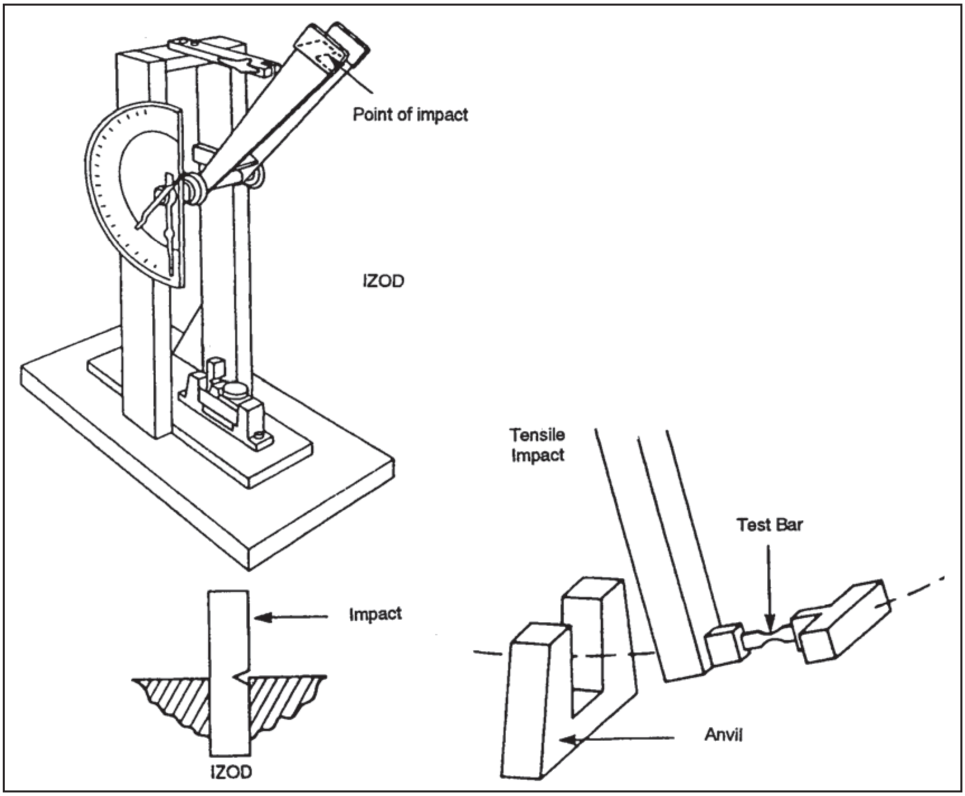


Figure 14 Izod Test

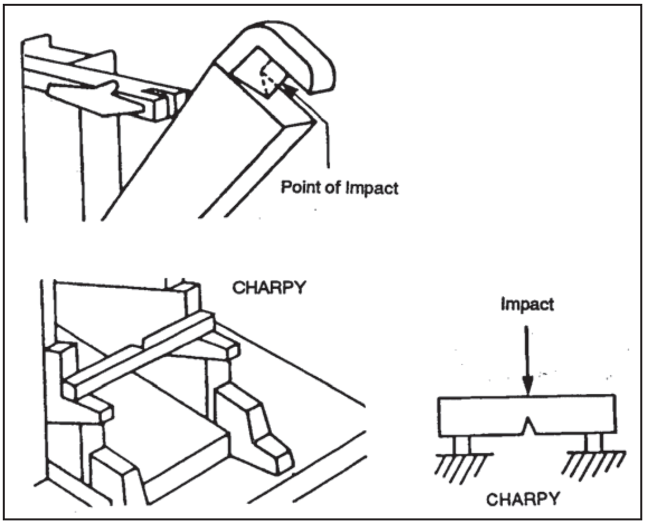


Figure 15 Charpy Test

The Charpy impact test, which is depicted in Figure 15, is widely used in Europe. The specimen is a supported beam, which is then struck with a pendulum. The loss of energy is measured in the same units as in the Izod impact test. At ambient temperature, current PE piping materials also resist failure under this test. ASTM D256, Standard Test Methods for Determining the Izod Pendulum Impact Resistance of Plastics and ASTM D 6110 Standard Test Method for Determining the Charpy Impact Resistance of Notched Specimens of Plastics describe these testing methods.

Resistance to Rapid Crack Propagation

The avoidance of the possibility of the occurrence of a rapid crack propagation (RCP) event in pipe is a very desirable design objective because the consequences of such an event can be very serious, especially when the piping is used for the transport of combustible materials. However, even when transporting an inert material like water an RCP kind of failure can result in a much larger loss of the fluid that is being conveyed as well as in more extensive damage to pipe and fittings. A recognized feature of PE piping is that “it leaks before it breaks”. This feature results from its high ductility and toughness. However, PE’s toughness decreases with decreasing temperature. Other factors that increase the possibility of an RCP event are: the nature of the fluid (compressible versus non-compressible), increasing pipe diameter, increasing wall thickness, and increasing operating pressure. In the case of the conveyance of non-compressible fluids, extensive experience shows that under proper installation and operation of thermally fused PE piping there is very little chance of an RCP event, very much less than with other common thermoplastics piping.

The defining of the exact material requirements and the pipe and operating parameters that will avoid the remote possibility of an RCP event is a complex matter that is still under study (15).

Abrasion Resistance

PE pipe is a frequent choice for the transport of granular or slurry solutions, such as sand, fly ash and coal. The advantage of polyethylene in these applications is its wear resistance, which for example when conveying fine grain slurries has been shown in laboratory tests to be three to five times greater than for steel pipe (37). PE pipe has elastic properties that under proper flow conditions allow particles to bounce off its surface. This feature combined with PE’s toughness results in a service life that exceeds that of many metal piping materials.

There are several factors that affect the wear resistance of a pipeline. The concentration, size and shape of the solid materials, along with the pipe diameter and flow velocity, are the major parameters that will affect the life of the pipeline.

The effects of velocity, particle size and solids concentration is discussed in Chapter 6 under the topic of "Pressure Flow of Liquid Slurries". A report by D. Richards (30) covers abrasion resistance factors that apply to dredge pipe applications.

Thermal Properties

Coefficient of Expansion/Contraction

A temperature increase or a decrease can induce a corresponding increase or decrease in the length of a pipe the movement of which is unconstrained. And, in the case of a constrained pipe it can induce the development of a longitudinal tensile or a compressive stress. Both these effects must be given adequate consideration for the proper installation, design and operation of PE piping system. Recommended procedures for dealing with potential reactions that can arise from temperature changes are addressed in various Chapters of this Handbook, but in particular in Chapters 6 (Design of PE Piping Systems), 8 (Above Ground Applications for PE Pipe), and 12 (Horizontal Directional Drilling). These procedures require that two essential properties be adequately defined: the pipe's linear coefficient of expansion/contraction; and, the pipe material's apparent modulus.

A property that distinguishes PE pipe from metallic pipe is that its coefficient of thermal expansion is about 10 times larger. This means a larger thermal expansion/contraction in the case of unconstrained pipe. However, another distinguishing feature is a much lower apparent modulus of elasticity. In the case of constrained pipe this leads to a much lower value of thermally induced longitudinal stresses, which greatly simplifies requirements for supporting and anchoring. The aspect of apparent modulus of elasticity has been covered earlier in this Chapter.

ASTM D696, *Standard Test Method for Coefficient of Linear Expansion of Plastics,* is normally used for the determination of this property. The evaluation is usually conducted on injection molded samples. But, it has been determined that the values that are obtained on samples that are machined from extruded pipe are somewhat smaller. And, it also has been noted that the value representing the diametrical expansion/contraction is about 85 to 90% of that which corresponds to the longitudinal expansion/contraction. This difference is attributed to a small anisotropy that results from the manufacturing process. It also has been noted that the value of this property is affected by resin density, an index of crystallinity. Materials made using resins that have a higher crystalline content (i.e., resins of higher density) have somewhat lower values for coefficient of thermal expansion. It has also been observed that within the practical range of normal operating temperatures there is little change in the value of this coefficient.

The resultant values of this property are presented in Table E.1 in the Appendix to this Chapter.

Thermal Conductivity

The capacity of PE materials to conduct heat is only about one hundredth of that of steel or copper. As reported by the values listed in Table E.1 in the Appendix, this capacity increases with resin density (i.e., with increased crystallinity) and it remains fairly constant over the typical range of working temperatures. (10)

Specific Heat

Over the range of typical working temperatures, the quantity of heat required to produce a unit temperature rise per unit mass of PE pipe material is about 46% of that for water. And, this capacity is little affected by resin density. In terms of traditional units, and as reported in Table E.1 found in the Appendix, the approximate value of the specific heat of PE piping compositions is 0.46 BTU/lb -°F.

Material Classification Properties

As discussed earlier in this Chapter, commercially available PE piping materials offer a range of properties that are tailored for optimizing certain aspects of engineering performance and ease of processing. For purposes of standardization, an identification system has been established which identifies the available PE piping materials based on important physical properties that can be used to distinguish one kind of PE from another.

This is the major objective of ASTM D3350, Standard Specification for Polyethylene Plastic Pipe and Fittings Material, (4) a document that is more fully described in Chapter 5. The discussion that follows focuses on a description of the primary properties that are recognized by this ASTM standard. A listing of these properties is included in the Table that follows. Also included in this table is the location in this Handbook in which a brief description of the subject property is presented. As indicated, two of the more important properties – Hydrostatic Strength Classification and Resistance to Slow Crack Growth – have already been described earlier in this Chapter. A brief description of the other properties is presented below.

TABLE 2
Primary Identification Properties for PE Piping Materials in Accordance with ASTM D3350

Property	Test Method	Where Discussed in this Chapter
Density of PE Resin	ASTM D1505, or D792	Under PE Piping Materials and In this Section
Melt Index	ASTM D1238	In this Section
Flexural Modulus	ASTM D790	In this Section
Tensile Strength at Yield	ASTM D638	In this Section
Resistance to Slow Crack Growth	ASTM F1473, or D1693	Under Structural Properties
Hydrostatic Strength Classification	ASTM D2837	Under Structural Properties
Color	Indicated by code letter	In this Section
UV Stabilizer	Indicated by code letter	In this Section

Density

The crystalline content of a PE resin is reflected by its density. As discussed earlier, the crystalline content exerts a major influence on the properties of a PE resin. This is recognized in the Appendix to this Chapter in which certain properties are somewhat different in accordance with the density of the resin that is used in the PE composition. Generally, as crystalline content increases so do stiffness (apparent modulus), tensile strength, and softening temperature. However, for a given kind of molecular structure there is a corresponding decrease in impact strength, and in low temperature toughness.

The accepted technique for obtaining a measure of a PE resin's crystalline content is to determine its density. A standard method for the measuring of density is ASTM D1505, *Test Method for Density of Plastics by the Density Gradient Technique* (2), or ASTM D792, *Test Methods for Density and Specific Gravity (Relative Density) of Plastics by Displacement* (2).

Melt Index

The melt index is a measure of the flowability of PE materials when in the molten state. This property is an accepted index to two important characteristics of a PE piping material: its processability; and the molecular weight of its primary constituent, the PE resin. A larger melt index denotes a lower melt viscosity, which means the material flows more freely in the molten state. However, a larger melt index also denotes a lower molecular weight, which tends to compromise certain long-term properties. Modern PE's are tailored so that at a resultant molecular weight and molecular weight distribution they remain quite processible while still offering very good long-term properties. Melt index is also important for joining by heat fusion, more information on which can found in PPI TR-33 and TR-41.

The method by which this property is determined is ASTM D1238, *Standard Test Method for Flow Rates of Thermoplastics by Extrusion Plastometer* (2). Under this method the melt index represents the amount of material that passes through a certain size orifice in a given period of time when extruded at a predetermined temperature and under a specified load.

Flexural Modulus

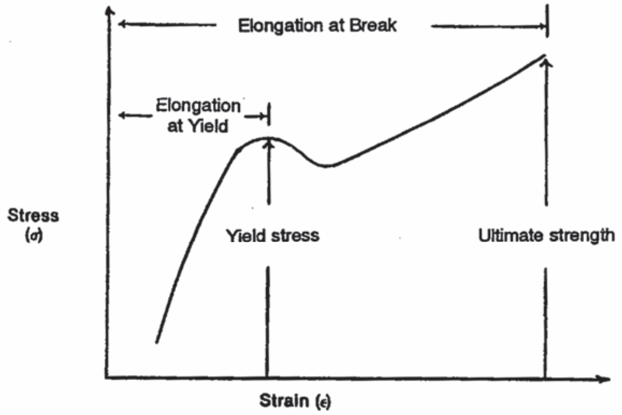
In this test a specimen is supported at both ends and a load is applied in the center at a specified crosshead rate. The flexural modulus is determined at the point when the strain in the outer fiber reaches a value of 2%. The modulus is the ratio of the stress in the outer fiber that results in the 2% strain. It has been determined that the flexural modulus is mainly affected by crystalline content (i.e., resin density) and to a lesser extent by other factors, such as molecular weight and molecular weight distribution, that help to determine size and distribution of crystallites. This property is primarily used for material characterization purposes.

The test method is ASTM D790, *Standard Test Methods for Flexural Properties of Unreinforced and Reinforced Plastics and Electrical Insulating Materials* (2). The particular version of this method that is used for PE materials and the conditions at which the testing is conducted is specified in ASTM D3350.

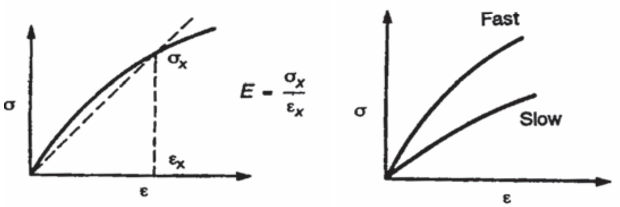
Tensile Strength at Yield

A traditional means for determining the strength of metals and other materials has been the tensile test, by which the stress/strain behavior of the material of interest is evaluated under a constant rate of straining. For most metals a point of interest is that at which yielding occurs – that is, the point at which there is a transition from elastic (reversible) to plastic (non-reversible) stress/strain response. This is because design with elastic materials seeks to ensure that only elastic deformation will result when a stress is applied.

Because of its viscoelastic nature, PE does not exhibit a true elastic region. As illustrated by Figure 16, although PE exhibits a yield point in the tensile test prior to this point the slope of its stress/strain curve decreases with increased strain. And, prior to yielding there is somewhat less than full reversibility in the strain that results from a certain stress. Also, as is illustrated by this Figure the stress strain curve is significantly affected by the rate of straining. Furthermore, the tensile behavior is also significantly affected by temperature. However, the stress at which yielding commences has been determined to be a useful measure for comparing PE piping materials. Because it has been determined that there is no proportionality between tensile strength at yield and long-term strength this property has limited value for design.



(a) Plot of results of tensile (stress-strain curve)



(b) Stress versus strain at constant crosshead rate

Figure 16 Stress vs Strain Curves Under Specified Conditions

However, it has been also determined that the extent to which a PE deforms in this test prior to failure is an index of the material's ductility under a sustained loading of very long duration. Accordingly, ASTM D3350 requires that all PE materials that are intended for pressure piping have a minimum extension at break of 500%.

The standard test method for determining a PE's tensile strength at yield is ASTM D638, *Standard Test Method for Tensile Properties of Plastics*(2). To provide a uniform basis for comparing different kinds of PE's ASTM D638 specifies the sample preparation procedure and it requires that this test be conducted at 23°C (73.4°F) and at a specified strain rate.

Color and UV Stabilization

ASTM D3350 also includes a code denoting the combination of color – natural, or colored, or black – and ultra violet (UV) stabilizer system that is used in the piping material. The specific requirement for a particular color and effectiveness of UV stabilization (e.g., at least six months of outdoor storage; or, for continuous above ground and outdoor use) is usually specified in the applicable pipe product standard.

Electrical Properties

Metals are very good electrical conductors because their atomic and crystalline structure makes available very many free electrons for participation in the conduction process. PE, along with most other polymers, is a poor conductor of electricity because of the unavailability of a large number of free electrons. Being a poor conductor, PE is a very good electrical insulator and is used as such in wiring and in many other electrical applications. Because it very poorly conducts electricity, PE also does not easily dissipate charges resulting from static electricity. Table F.1 in the Appendix to this Chapter lists the typical electrical properties of PE piping materials. In as much as the exact properties of a particular material can vary, interested readers requiring a more accurate representation should consult the pipe and/or pipe material manufacturer.

Static Charge

Since plastics are good insulators, they also tend to accumulate a static charge. PE pipe can acquire a static charge through friction. Sources of friction can be simply the handling of the pipe in during storage, shipping, or installation. Friction can also result from the flow of gas that contains dust or scale or from the pneumatic transport of dry materials. These charges can be a safety hazard if there is a possibility of a combustible leaking gas or of an explosive atmosphere. Such potential hazard should be dealt with prior to working on the pipeline.

A static charge in PE piping will remain in place until a grounding device discharges it. A ground wire will only discharge the static charge from its point of contact. The most effective method to minimize the hazard of a static electricity discharge is to maintain a conductive path to earth ground by applying a film of electrically conductive liquid (for example, water) to the pipe surface work area prior to handling. So that the conductive liquid does not dry out, cloth coverings that are kept moist with the conductive fluid or conductive films may also be wrapped around the pipe. Please refer to the pipe manufacturer for other suggestions.

Chemical Resistance

As indicated earlier in this Chapter, the standard property requirements for PE piping materials are established in an air or a water environment. When considering the use of a PE piping for the transport of another kind of material, the potential reaction by the piping to that material should first be established. This reaction depends on various factors, particularly the chemical or physical effect of the medium on PE, its concentration, the operating temperature, the period of contact and, the operating stress. PE, being a poor conductor of electricity, is immune to electrolytic corrosion such as can be caused by salts, acids and alkalis. However, strong oxidizing agents can attack the PE molecule directly and lead to a gradual deterioration of properties. Certain organic chemicals can be gradually absorbed by PE, through a process called solvation, causing some swelling, softening and a decrease in long-term strength that largely depends on the chemical configuration of the organic material, but is also affected by other operating variables.

A preliminary measure of the potential effect of a medium on the properties of PE is by means of the so called "soak" or "chemical immersion" test in which the PE is not subjected to any stressing. In this laboratory test, strips of PE material are soaked for different periods of time – generally, not longer than a month – in the medium of interest, which is maintained at a specified temperature. After certain soaking periods, changes are noted in appearance, dimensions, in weight gain or loss, and in strength properties – generally, in tensile strength at yield or elongation at break.

Results obtained by means of an immersion test are a useful guide for applications, such as drainage piping, in which the pipe is subject to only low levels of stressing. However, if the application is a pressurized system, then a more thorough investigation needs to be conducted over and beyond the immersion tests discussed. Please refer to PPI publication TR – 19, Chemical Resistance of Thermoplastics Piping Materials,(26) for more details. In this type of test the immersion period is of limited duration and the effect on strength is only checked by means of a short-term tensile strength test, which is recognized as not a sufficiently reliable indicator of how the tested medium may affect PE's long-term strength. The standard pressure ratings (PR) and standard pressure classes (PC) that are included in PE pipe standards that are issued by ASTM, AWWA and CSA are for the standard condition of water at 73°F. For the transport of other fluids these PR's or PC's may need to be de-rated if the fluid is known to cause a decrease in the pipe material's long-term strength in consequence of a slowly occurring chemical or physical action. Also, an additional de-rating may be applied in cases where a special consideration is in order – usually, when a greater safety margin is considered prudent because of either the nature of the fluid that is being conveyed or by the possible impact of a failure on public safety. The following is a general representation of the effect of different kinds of fluids on the long-term hydrostatic strength of PE pipe materials and the de-ratings, if any, that are normally applied in recognition of this effect:

- **Aqueous solutions of salts, acids and bases** – Because PE is immune to electrolytic attack these solutions have no adverse effect. Consequently, the PR or PC for water is also appropriate for the conveyance of these type materials.
- **Sewage and wastewater** – Normally, these fluids do not include components that affect PE. Therefore, for this case the PR and PC established for water is also appropriate.

- **Surface active agents (e.g., detergents), alcohols and glycols (including anti-freeze solutions)** – If these agents may be present in the fluid a precautionary measure is to specify PE pipe which is made from a material which exhibits very high resistance to slow crack growth (e.g., materials for which the second number in their standard designation code is either 6 or 7, such as PE2708, PE3608, PE3708, PE3710, PE4608, PE4708 and PE4710). For such materials no de-rating is needed.
- **Fluids containing oxidizing agents** – Strong oxidizers can gradually cause damage to PE material. The rate at which this damage occurs depends on the concentration and the chemical activity of the oxidizing agent. If the rate of damage on unprotected PE is low then PE pipe made from material that is adequately stabilized can be used. But, if the rate is high PE pipe may not be the most appropriate choice. Thus, the determination of the suitability of PE pipe and/or the extent to which it needs to be de-rated should be made on a case-by-case basis. For this purpose it is suggested that the reader contact PPI or its member companies for references regarding the known performance of PE pipes in similar applications.
- **Inert gases such as hydrogen, nitrogen and carbon dioxide** – These kinds of gases have no adverse effect and the PR or PC established for water is also appropriate.
- **Hydrocarbon gases of lower molecular weight, such as methane and hydrogen sulfide** – Studies and long-term experience show that the resultant long-term strength is at least equal to that established when using water or air as a test fluid. Therefore, no de-rating is required.
- **Vapors generated by liquefied petroleum gases (LPG)** – These vapors contain hydrocarbon gases of somewhat greater molecular weight, gases which because of their “plasticizing” or, “solvating” effect on PE tend to somewhat reduce PE’s long-term hydrostatic strength. To offset this possible reduction, the PR or PC for water is de-rated by the application of a factor of 0.80 or smaller.
- **Common hydrocarbons in the liquid state, such as those in LPG and fuel gas condensates, in crude oil, in fuel oil, in gasoline, in diesels fuels and in kerosene** – Because exposure to these liquids results in a larger “solvating” effect, the practice is either to de-rate PE pipe to a greater extent than for vapors or, if this de-rating is impractical, to use an alternate material. For crude oil application a de-rating factor of 0.50 is typically used.
- **Aromatic hydrocarbons** – Because aromatic hydrocarbons, such as benzene and toluene, have a much greater “solvating” effect, the use of PE should be avoided.

The above information, taken in conjunction with the results of immersion tests as covered in PPI’s TR-19 chemical resistance document,(26) is intended to give general guidance regarding the adequacy of a PE piping system for the transport of a specific medium under a particular set of operating conditions. The most reliable guidance is actual service experience under equivalent or similar conditions. PE piping manufacturers, PE material suppliers, and PPI can assist in obtaining this information.

The de-ratings that are mentioned above are only in recognition of the effect of a different fluid than water on the long-term strength of PE pipe. A further de-rating may be called for by a controlling standard or code because of additional considerations, most often for the maximizing of public safety. A designer should comply with the requirements of all applicable codes and standards.

An example of a more conservative de-rating is that by Title 49, Transportation, of the Code of Federal Regulations. The effect of a provision of Part 191 of this code, a part that covers transportation of natural and other fuel gases, is the requirement that the pressure rating of a PE pipe in natural gas service shall be 64% of the pressure rating which would be assigned to that pipe if it conveyed water, provided the water pressure rating is established using an HDS that has been determined based on a design factor (DF) of 0.50. This 64% de-rating is not in response to any adverse effect by natural gas – studies show that similar long-term strengths are obtained when using water or natural gas as the test pressure medium. It is applied mostly in consideration of public safety issues but also in consideration of the minor effect on PE by the small amount of additives that may be contained in fuel gases. There are additional restrictions imposed by this Code, such as the maximum pressure at which a PE pipe may be operated and the acceptable range of operating temperatures.

Another example of a conservative de-rating is that imposed by NFPA/ANSI 58, Standard for the Storage and Handling of Liquefied Petroleum Gases. This standard limits the operating pressure of PE pipe to a maximum of 30psig. The intent of this limitation is to ensure that the LPG gases that are being conveyed are always in the vapor and not in the liquid phase. This is because in the liquid state the constituents of LPG exercise a much more pronounced solvating effect. For further information the reader is referred to PPI publication TR-22, Polyethylene Piping Distribution Systems for Components of Liquid Petroleum Gases.

Permeability

The property of permeability refers to the passage of a substance from one side to the other side of a membrane. Polyethylene has very low permeability to water vapor but it does exhibit some amount of permeability to certain gases and other vapors. As a general rule the larger the vapor molecule or, the more dissimilar in chemical nature to polyethylene, the lower the permeability.

The other factors that affect the rate of permeation include: the difference in concentration, or in the partial pressure of the permeant between the two side of a membrane; the thickness of the membrane (e.g., the wall thickness of a pipe);

temperature; total area available for permeation; and any possible solvating effect by the permeant that can accelerated the rate of permeation.

Depending on the source of a permeant, permeation through a PE pipe can occur from the inside to the outside or, from the outside to the inside. This difference has different potential consequences that need to be recognized and, if significant they also need to be addressed. In the case of possible permeation from the inside the primary concern is the loss of some of the fluid that is flowing through the pipe. Studies show that this is not a problem with liquids. In the case of gases, it has been determined that when conveying methane the loss is so small that there is no problem involving transportation of natural gas. However, as shown in the Table that follows, the permeation rate of hydrogen is several times that of methane. Therefore, if hydrogen is a major constituent of a fuel gas the potential energy loss should be calculated.

The following gases are listed in order of decreasing permeability: sulfur dioxide; carbon dioxide; hydrogen; ethane; oxygen; natural gas; methane; air and nitrogen.

Most of the permeability is through the amorphous regions of the polymer, which is related to density, and to a lesser extent, molecular weight. An increase in density will result in a lower permeability. An increase in molecular weight will also slightly reduce the permeability. Table 3 shows permeation rate of methane and hydrogen through PE as a function of the density of the resin.(1)

TABLE 3

Approximate Gas Permeation Rate Through Polyethylene at Ambient Temperature

Piping Material	Permeation Rate, Ft^3-mil/ft^2-day-atm (The Ft^3 is @ Std. Temp. & Pressure. The Ft^2 refers to the outside surface area of the pipe)	
	Methane	Hydrogen
PE2XXX *	4.2×10^{-3}	21×10^{-3}
PE3XXX *	2.4×10^{-3}	16×10^{-3}
PE4XXX *	1.9×10^{-3}	14×10^{-3}

*PE 2XXX, PE3XXX and PE4XXX denotes all PE's that comply, respectively, to the density cell classification 2, or 3, or 4 in accordance with ASTM D3350

In the case of permeation that originates from the outside, most often it is caused by liquids that tend to permeate at much lower rates than gases, which generally do not cause a problem. However, even a low permeation rate – one that results in a "contamination" of only parts per billion – may affect the quality of the fluid that is being conveyed. This possibility is of concern when the pipe, no matter its type, is transporting potable water, and therefore, the issue is addressed by standards that cover this application. However, it is recognized by authorities that any pipe, as well as an elastomeric gasketed pipe joint, can be subjected to external permeation when the pipeline passes through contaminated soils. Special care should be taken when installing potable water lines through these soils regardless of the pipe material (concrete, clay, plastic, etc.). The Plastics Pipe Institute has issued Statement N – Permeation (28) that should be studied for further details.

Properties Related to Durability

Weatherability

All polymers (resins) are susceptible to gradual degradation when continually exposed to ultraviolet (UV) radiation in sunlight. (25) There are two effective means for protecting a resin against this effect. One is by the addition of a screen that blocks the penetration of UV rays into the material. The other is by the inclusion of a stabilizer that protects the material by chemical means.

For PE piping materials it has been shown that the most effective screen is achieved by the incorporation into the material of 2 to 3 % of finely divided carbon black, which also results in a black color. Experience and studies show that in outdoor applications such a material will retain its original performance properties for periods longer than 50-years. ASTM D3350, *Standard Specification for Polyethylene Plastic Pipe and Fittings Materials*, recognizes these materials by the inclusion of the code letter C in the material's cell classification.

However, in the case of buried and other kinds of applications in which the pipe shall not be exposed to sunlight indefinitely, the UV protection needs only to cover that time period during which the pipe may be handled and stored outdoors. In practice, this period is about two years. Protection for this period, and somewhat longer, is very effectively achieved by the incorporation into the PE material of a UV stabilizer. An advantage of using a stabilizer is that it allows the pipe to have another color than black. For example, yellow is an accepted color for gas distribution applications, blue for water and green for sewer and drain. The choice of a specific kind of colorant follows an evaluation that is intended to ensure that the chosen colorant does not interfere with the efficiency of the UV stabilizer. Standard ASTM D3350 identifies materials that contain both a UV stabilizer and a colorant by means of the code letter E.

Further information on this subject is presented in PPI Technical Report TR-18, *Weatherability of Thermoplastics Piping.* (25)

Stabilization

All PE piping materials include stabilizers in order to achieve two principal objectives. The first is to prevent the degradation of the resin during processing and thermal fusion, when melts are subjected to high temperatures. And the second is to protect the pipe during its service life from any deterioration in performance properties that could occur by gradual oxidation.

Exposure of polymers to high temperatures can induce the development of chemical reactions that can adversely affect performance properties. This degradation process results from the formation of free radicals that continue to react with PE, thereby producing a continuing degradation even after the material has been cooled. To prevent the continuation of this process heat stabilizers are added. These stabilizers work by reacting with initial products of degradation so as to form stable species that are incapable of further action.

At lower working temperatures there exists the possibility of a very slowly acting process of oxidative degradation, a process that can cause gradual degradation in performance properties. To counteract against this possibility antioxidants are added to the composition. These antioxidants can protect in a number of ways. A principal one is by deactivating hydroperoxide sites that are formed by oxidation. Most often, two kinds of antioxidants are used because of a synergism effect that substantially enhances the quality of protection.

There are several tests that have been developed which give a reliable guide on the quality of stabilizer and anti-oxidant protection that is included in a PE piping composition. One of these is the thermal stability test that is included in ASTM D3350. In this test a specimen of defined shape and size is heated in an oven, in air, at a predetermined rate of 10°C (18°F) per minute. Eventually, a point is reached at which the temperature rises much more rapidly than the predetermined rate. This point is called the induction temperature because it denotes the start of an exothermic reaction that results from the exhaustion of stabilizer and anti-oxidant protection. The higher the temperature, the more effective the protection. To qualify for a piping application a PE composition is required to exhibit an induction temperature of not less than 220°C (428°F).

Biological Resistance

Biological attack can be described as degradation caused by the action of microorganisms such as bacteria and fungi. Virtually all plastics are resistant to this type of attack. Once installed, polyethylene pipe will not be affected by microorganisms, such as those found in normal sewer and water systems. PE is not a nutrient medium for bacteria, fungi, spores, etc.

Research has shown that rodents and gnawing insects maintain their teeth in good condition by gnawing on objects. Various materials such as wood, copper, lead, and all plastics would fall prey to this phenomenon if installed in rodent-infested areas.

Termites pose no threat to PE pipe. Several studies have been made where PE pipe was exposed to termites. Some slight damage was observed, but this was due to the fact that the plastic was in the way of the termite's traveling pathway. PPI Technical Report TR-11, Resistance of Thermoplastic Piping Materials to Micro- and Macro-Biological Attack (24) has further information on this matter.

Properties Related to Health and Safety Concerns

Toxicological

Health Effects

The Food and Drug Administration (FDA) issues requirements for materials that may contact food, either directly or indirectly, under the Code of Federal Regulations (CFR) Title 21, parts 170 to 199. Most natural polyethylene resins do comply with these regulations.

Potable water piping materials, fittings, and pipe are currently tested according to the standards developed by the National Sanitation Foundation (NSF). The most recent standard to be written by the NSF is Standard 61, (19) *Drinking Water System Components – Health Effects.* It sets forth toxicological standards not only for plastics piping but also for all potable water system components. Compliance to these standards is a requirement of most States and/or governing authorities that have jurisdiction over water quality.

There are also other certification programs that are operated by independent laboratory and industrial organizations as well as governmental agencies. These are designed to assure compliance with applicable product standards. Amongst other requirements, these programs may include producer qualification, product testing, unannounced plant inspections and authorized use of compliance labels. Products failing to comply are then de-listed or withdrawn from the marketplace.

Flammability

After continuous contact with a flame, PE will ignite unless it contains a flame retardant stabilizer. Burning drips will continue to burn after the ignition source is removed. The flash ignition and self ignition temperatures of polyethylene are 645°F (341°C) and 660°F (349°C) respectively as determined by using ASTM D1929(3), *Standard Test Method for Ignition Properties of Plastics*. The flash point using the Cleveland Open Cup Method, described in ASTM D92(6), Standard Test method for Flash and Fire Points by Cleveland Open Cup, is 430°F (221°C). (9)

During PE pipe production, some fumes may be generated. If present, they can be an irritant and should be properly vented. Specific information and Material Safety Data Sheets (MSDS) are available from the PE resin manufacturer.

Combustion Toxicity

The combustion of organic materials, such as wood, rubber, and plastics, can release toxic gases. The nature and amount of these gases depends upon the conditions of combustion. For further information on combustion gases, refer to *Combustion Gases of Various Building Materials and Combustion Toxicity Testing from the Vinyl Institute.*(33,34)

The combustion products of polyethylene differ greatly from those of polyvinyl chloride (PVC). Polyethylene does not give off any corrosive gases such as hydrochloric acid, since it does not contain any chlorine in its polymer structure.

References

1. AGA Plastic Pipe Manual doe Gas Service (1985), American Gas Association, Arlington, VA.
2. ASTM Annual Book, Volume 08.01, Plastics (I), C177-D1600, ASTM International, West Conshohocken, PA.
3. ASTM Annual Book, Volume 08.02, Plastics, D1601-D3099, ASTM International, West Conshohocken, PA.
4. ASTM Annual Book, Volume 08.03, Plastics D3100-Latest, ASTM International, West Conshohocken, PA.
5. ASTM Annual Book, Volume 08.04, Plastics Pipe and building Products, ASTM International, West Conshohocken, PA.
6. ASTM Annual Book, Volume 0-5.01, Petroleum Products and Lubricants, ASTM International, West Conshohocken, PA.
7. Bowman, Jeremy, *The fatigue Response of Polyvinyl Chloride and Polyethylene Pipe Systems,* Proceedings Plastic Pipes VII, September 1988, Bath, England, The Plastics and Rubber Institute, UK.
8. Dieter, G. E. (1966), *Mechanical Metallurgy*, 3rd Edition, McGraw Hill Book Company, New York, NY.
9. Driscopipe Engineering Characteristics (1981), Phillips Driscopipe, Inc., Richardson, TX.
10. Final Report GRI-99/0192, *Technical Reference for Improved Design and Construction Practices to Account for Thermal Load in Plastic Pipelines*, Gas Research Institute, Chicago, IL.
11. Haag, J., Griffith (I1989, January), Measuring Viscoelastic Behavior, *American Laboratory*, No.1, 48-58.
12. Heger, F., R. Chambers, & A. Deitz (1982), *Structural Plastics Design Manual,* American Society of Civil Engineers, New York, NY.
13. Hertzberg, R. W. (1983), *Deformation and Fracture Mechanics of Engineering Materials*, 2nd Edition, J. Wiley & Sons, New York, NY.
14. ISO Standard 9080, Determination of Long-Term Hydrostatic Strength of Thermoplastics Materials in Pipe Form by Extrapolation, International Organization for Standardization.
15. Krishnaswamy, P. et al. (1986), *A Design Procedure and Test Method to Prevent Rapid Crack Propagation in Polyethylene Gas Pipe*, Batelle Columbus Report to the Gas Research Institute, Chicago, IL.
16. Lu X., Zhou Z., & Brown N. (1986), A Small Scale Laboratory Test that Relates to Rapid Crack Propagation in Gas Pipes, Proceedings of the Fourteenth Fuel Gas Pipe Symposium.
17. Marshall, G.P., Brogden, S., *Evaluation of the Surge and /Fatigue resistance of PVC and PE Pipeline Materials for Use in the U.K. Water Industry*, Proceedings Plastic Pipes X, Goteborg, Sweden (Sept., 1998).
18. Mruk, S. A. (1985), *Validating the Hydrostatic Design Basis of PE Piping Materials*, Proceedings of the Ninth Plastics Fuel Gas Pipe Symposium, 202-214.
19. NSF Standard 61, *Drinking Water System Components – Health Effects*, National Sanitation Foundation, Ann Arbor, MI.
20. Palermo, E.F. (1983), *Rate Process Method as a Practical Approach to a Quality Control Method for Polyethylene Pipe*, Proceedings of the Ninth Plastics Fuel Gas Pipe Symposium.
21. Palermo, E.F. & DeBlieu, I.K. (1985), *Rate Process Concepts applied to Hydrostatically Rating Polyethylene Pipe*, Proceedings of the Ninth Plastics Fuel Gas Pipe Symposium.
22. PPI Technical Report TR-3, *Policies and Procedures for Developing Recommended Hydrostatic Design Stresses for Thermoplastic Pipe Materials*, Plastics Pipe Institute, Irving, TX.
23. PPI Technical Report TR-4, *Recommended Hydrostatic Strengths and Design Stresses for Thermoplastics Pipe and Fittings Compounds*, Plastics Pipe Institute, Irving, TX.
24. PPI Technical Report TR-11, *Resistance of Thermoplastic Piping Materials to Micro- and Macro-Biological Attack*, Plastics Pipe Institute, Irving, TX.
25. PPI Technical Report TR-18, *Weatherabilty of Thermoplastics Piping*, Plastics Pipe Institute, Irving, TX.
26. PPI Technical Report TR-19, *Thermoplastics Piping for the Transport of Chemicals*, Plastics Pipe Institute, Irving, TX.
27. PPI Technical Note TN-16, Rate Process Method for Evaluating Performance of Polyethylene Pipe, Plastics Pipe Institute, Irving, TX.

28. PPI Statement N, *Pipe Permeation*, Plastics Pipe Institute, Irving, TX.
29. Powell, P.C., (1983), *Engineering with Polymers*, Chapman and Hall, New York, NY.
30. Richards, D., *Abrasion Resistance of Polyethylene Dredge Pipe*, US Army Engineer Waterways Experiment Station, Hydraulics Laboratory, Vicksburg, MS.
31. Rooke, D.P. & Cartwright, D.J., *Compendium of Stress Intensity Factors,* Her Majesty's Stationery Office, London, UK.
32. Sih, P.K. et al., *Handbook of Stress Intensity Factors for Researchers and Engineers*, Lehigh University, Bethlehem, PA.
33. Vinyl Institute Report on *Combustion Gases of Various Materials* (1987), Vinyl Institute, Washington, DC.
34. Vinyl Institute Report on Combustion Toxicity Testing (1986), Vinyl Institute, Washington, DC.
35. Water Industry Information and Guidance Note IGN 4-37-02, Design Against Surge and Fatigue Conditions for Thermoplastic Pipes (2006), Water Research Council, Blagrove, Swindon, Wilts, UK
36. Krishnaswamy, Rajendra K., *Analysis of Ductile and Brittle Failures from Creep Rupture Testing of High- Density Polyethylene (HDPE) Pipes*: Plastics Pipes XIII, Washington, DC, October 2-5, 2006.
37. Pankow, Virginia R., *Dredging Applications of High Density Polyethylene Pipe*, Hydraulics Laborat*ory*, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS 39180-0631, 1987

Appendix A
Pipe Pressure Rating (PR) And Pressure Class (PC)

A.1 - Standard Pipe Pressure Rating (PR) and Standard Pressure Class (PC) for 73°F (23°C)

Consensus standards for PE pipes intended for pressure applications define PE piping materials in accordance with their recommended hydrostatic design stress (HDS) for water, for the standard base temperature of 73°F (23°C). Most PE pipe standards also identify a pipe's resultant standard pressure rating (PR) or pressure class (PC) for water at 73°F (23°C). As discussed in Chapter 6, this standard PR or PC is determined based on the pipe material's recommended HDS, and the pipe's specified dimension ratio. Pressure ratings for pipes made to common dimension ratios are reproduced in Table A.1 (This is essentially the same Table as Table 6, in Chapter 5).

The pipe's PR or PC may be determined by means of either of the following relationships:

- For pipes made to controlled outside diameters – for which Do/t is defined as the dimension ratio (DR):

$$PR\ or,\ PC = \frac{2\ (HDS)}{[\frac{D_o}{t}-1]}$$

- For pipes made to controlled inside diameters – for which Di/t is defined as the inside diameter dimension ratio (IDR):

$$PR\ or,\ PC = \frac{2\ (HDS)}{[\frac{D_i}{t}+1]}$$

WHERE
PR **= Pressure Rating, psig (kPa)**
PC **= Pressure Class, psig (kPa)**
HDS **= Hydrostatic Design Stress, psi (kPa) = HDB (Hydrostatic Design Basis) x DF (Design Factor).**
For more details and discussion of each of these terms and the relationship between them, the reader is referred to Chapters 5 and 6.
D_o **= Specified outside pipe diameter, in (mm)**
D_i **= Specified inside pipe diameter, in (mm)**
t **= Specified minimum pipe wall thickness, in (mm)**

TABLE A.1
Standard Pressure Ratings (PR's) and Standard Pressure Classes (PC's), for Water for 73°F (23°C), for PE Pipes Made to Standard Dimension Ratios

Dimension Ratio (see Note 1)		Standard PR and Standard PC as a Function of the Pipe Material's Recommended Hydrostatic Design Stress (HDS) for Water, at 73°F (23°C)					
DR (Ratio = D_0/t (Applies to pipes made to controlled outside diameters- D_o)	**IDR (Ratio = D_i/t)** (Applies to pipes made to controlled inside diameters - D_i)	**HDS = 630psi (4.34MPa)**		**HDS = 800psi (5.52MPa)**		**HDS = 1000psi (6.90MPa)**	
		psig	**kPa**	**Psig**	**kPa**	**psig**	**kPa**
32.5	30.5	40	276	50	345	63	434
26.0	24.0	50	345	63	434	80	552
21.0	19.0	63	434	80	552	100	690
17.0	15.0	80	552	100	690	125	862
13.5	11.5	100	690	125	862	160	1103
11.0	9.0	125	862	160	1103	200	1379
9.0	7.0	160	1103	200	1379	250	1724
7.3	5.3	200	1379	250	1724	320	2206

Note 1: While the term, SDR (Standard Dimension Ratio), is an ANSI term, the pipe industry typically uses the term DR as shown in this table.

A.2 – Values for Other Temperatures

As discussed elsewhere in this and the other chapters of this Handbook (See Chapters 5 and 6), the long-term strength properties of PE pipe materials are significantly affected by temperature. In consequence of this, an operating temperature above the base temperature of 73°F (23°C) results in a decrease in a pipe material's HDS and therefore, in a pipe's PR or PC. Conversely, an operating temperature below the base temperature yields the opposite effect. There are three approaches, as follows, for compensating for the effect of temperature:

1. The application of a temperature compensating factor for operating temperatures that range between 40°F (4°C) and 100°F(38°C).

   While the effect of temperature on long-term strength is not exactly the same among the different commercially offered PE pipe materials, this effect is sufficiently similar over the temperature range covered by Table A.2 to allow for the establishment of the a common table of Temperature Compensation Multipliers. However, because some dissimilarity, though small, may exist, the reader is advised to consult with the pipe manufacturer to determine the most appropriate multiplier to apply in the particular application under consideration.

TABLE A.2

Temperature Compensating Multipliers for Converting a Base Temperature HDS or PR to HDS or PR for Another Temperature Between 40 and 100°F (4 and 38°C)

Maximum Sustained Temperature, °F (°C) (1)	Multiplier (2,3)
40 (4)	1.25
50 (10)	1.17
60 (15)	1.10
73 (23)	1.00
80 (27)	0.94
90 (32)	0.86
100 (38)	0.78

(1) Temporary and relatively minor increases in temperature beyond a sustained temperature have little effect on the long-term strength of a PE pipe material and thus, can be ignored.

(2) The multipliers in this table apply to a PE pipe that is made from a material having at least, an established hydrostatic design stress (HDS) for water, for 73°F (23°C). This HDS is designated by the last two numerals in the PE's standard designation code (e.g., the last two digits in PE4710 designate that the HDS for water, for 73°F (23°C), is 1,000psi – See Introduction and Chapter 5 for a more complete explanation.)

(3) For a temperature of interest that falls within any pair of listed temperatures the reader may apply an interpolation process to determine the appropriate multiplier.

2. In the case of PE pipes that are made from materials that have an established hydrostatic design basis (HDB) for water for both the base temperature of 73°F (23°C) and one higher temperature, the appropriate temperature multiplier for any in-between temperature may be determined by interpolation. Extrapolation above the range bounded by the higher temperature HDB is not recommended.

   Prior to the determination of an HDS, PR or PC for a temperature above 100°F (38°C) it should be first determined by contacting the pipe manufacturer that the pipe material is adequate for the intended application.

   There are many PE pipe materials for which an HDB has also been established for a higher temperature than the base temperature of 73°F (23°C), generally for 140°F (60°C) and, in a few cases for as high as 180°F (82°C). Information on the elevated temperature HDB rating that is held by the PE material from which a pipe is made can be obtained from the pipe supplier. In addition, PPI issues ambient and elevated temperature HDB recommendations for commercially available PE pipe materials. These recommendations are listed in PPI Technical Report TR-4, a copy of which is available via the PPI web site.

   The recognized equation for conducting the interpolation is as follows:

$$F_I = 1 - \frac{HDB_B - HDB_H}{HDB_B} \; \frac{\frac{1}{T_B} - \frac{1}{T_I}}{\frac{1}{T_B} - \frac{1}{T_H}}$$

WHERE

F_I = **Multiplier for the intermediate temperature T_I**
HDB_B = **Hydrostatic Design Basis (HDB) for the base temperature (normally, 73°F or 23°C), psi**
HDB_H =**Hydrostatic Design Basis (HDB) for the higher temperature, psi**
T_B = **Temperature at which the HDB_B has been determined, °Rankin (°F + 460)**
T_H = **Temperature at which the HDB_H has been determined, °Rankin (°F + 460)**
T_I = **Intermediate temperature, °R (°F + 460)**

Examples of the application of this equation are presented at the end of this Section.

3. By regulation. There are certain codes, standards and manuals that cover certain applications (e.g., AWWA water applications and gas distribution piping) that either list temperature compensating multipliers for approved products or, which define rules for their determination. For applications that are regulated by these documents their particular requirements take precedence. For example, AWWA standards C 901 and C 906 and manual M 55 which cover PE pressure class (PC) pipe include an abbreviated table of temperature compensation multipliers that differ slightly from what is presented here. The multipliers in the AWWA tables apply to temperature ranges typical for water applications and are rounded to a single decimal. The interested reader is advised to refer to these documents for more details.

Examples of the Application of the Interpolation Equation

Example – A PE pipe is made from a PE4710 material that has an established HDB of 1600psi for 73°F (533°R) and, an HDB of 1,000psi for 140°F (600°R). What is the temperature compensating multiplier for a sustained operating temperature of 120°F (580°R)?

For this case, $F_{120°F} = 1 - \frac{(1600-1000)}{1600} \frac{\left[\frac{1}{533}-\frac{1}{580}\right]}{\left[\frac{1}{533}-\frac{1}{600}\right]} = 0.73$

Appendix B
Apparent Elastic Modulus

B.1 – Apparent Elastic Modulus for the Condition of Either a Sustained Constant Load or a Sustained Constant Deformation

B.1.1 – Design Values for the Base Temperature of 73°F (23°C)

TABLE B.1.1
Apparent Elastic Modulus for 73°F (23°C)

Duration of Sustained Loading	Design Values For 73°F (23°C) (1,2,3)					
	PE 2XXX		PE3XXX		PE4XXX	
	psi	MPa	psi	MPa	psi	MPa
0.5hr	62,000	428	78,000	538	82,000	565
1hr	59,000	407	74,000	510	78,000	538
2hr	57,000	393	71,000	490	74,000	510
10hr	50,000	345	62,000	428	65,000	448
12hr	48,000	331	60,000	414	63,000	434
24hr	46,000	317	57,000	393	60,000	414
100hr	42,000	290	52,000	359	55,000	379
1,000hr	35,000	241	44,000	303	46,000	317
1 year	30,000	207	38,000	262	40,000	276
10 years	26,000	179	32,000	221	34,000	234
50 years	22,000	152	28,000	193	29,000	200
100 years	21,000	145	27,000	186	28,000	193

(1) Although there are various factors that determine the exact apparent modulus response of a PE, a major factor is its ratio of crystalline to amorphous content – a parameter that is reflected by a PE's density. Hence, the major headings PE2XXX, PE3XXX and, PE4XXX, which are based on PE's Standard Designation Code. The first numeral of this code denotes the PE's density category in accordance with ASTM D3350 (An explanation of this code is presented in Chapter 5).

(2) The values in this table are applicable to both the condition of sustained and constant loading (under which the resultant strain increases with increased duration of loading) and that of constant strain (under which an initially generated stress gradually relaxes with increased time).

(3) The design values in this table are based on results obtained under uni-axial loading, such as occurs in a test bar that is being subjected to a pulling load. When a PE is subjected to multi-axial stressing its strain response is inhibited, which results in a somewhat higher apparent modulus. For example, the apparent modulus of a PE pipe that is subjected to internal hydrostatic pressure – a condition that induces bi-axial stressing – is about 25% greater than that reported by this table. Thus, the Uni-axial condition represents a conservative estimate of the value that is achieved in most applications.

It should also be kept in mind that these values are for the condition of continually sustained loading. If there is an interruption or a decrease in the loading this, effectively, results in a somewhat larger modulus.

In addition, the values in this table apply to a stress intensity ranging up to about 400psi, a value that is seldom exceeded under normal service conditions.

B.1.2 – Values for Other Temperatures

The multipliers listed in Table B.1.2 when applied to the base temperature value (Table B.1.1) yield the value for another temperature.

TABLE B.1.2
Temperature Compensating Multipliers for Determination of the Apparent Modulus of Elasticity at Temperatures Other than at 73°F (23°C)
Equally Applicable to All Stress-Rated PE's (e.g., All PE2xxx's, All PE3xxx's and All PE4xxx's)

Maximum Sustained Temperature of the Pipe °F (°C)	Compensating Multiplier
-20 (-29)	2.54
-10 (-23)	2.36
0 (-18)	2.18
10 (-12)	2.00
20 (-7)	1.81
30 (-1)	1.65
40 (4)	1.49
50 (10)	1.32
60 (16)	1.18
73.4 (23)	1.00
80 (27)	0.93
90 (32)	0.82
100 (38)	0.73
110 (43)	0.64
120 (49)	0.58
130 (54)	0.50
140 (60)	0.43

B.2 – Approximate Values for the Condition of a Rapidly Increasing Stress OR Strain

B.2.1 – Values for the Base Temperature of 73°F (23°C)

TABLE B.2.1

Rate of Increasing Stress	Approximate Values of Apparent Modulus for 73°F (23°C)					
	For Materials Coded PE2XXX (1)		For Materials Coded PE3XXX (1)		For Materials Coded PE4XXX (1)	
	psi	MPa	psi	MPa	psi	MPa
"Short term" (Results Obtained Under Tensile Testing) (2)	100,000	690	125,000	862	130,000	896
"Dynamic" (3)	150,000psi (1,034MPa), For All Designation Codes					

(1) See Chapter 5 for an explanation of the PE Pipe Material Designation Code. The X's designate any numeral that is recognized under this code.

(2) Under ASTM D638, "Standard Test Method for Tensile Properties of Plastics", a dog–bone shaped specimen is subjected to a constant rate of pull. The "apparent modulus" under this method is the ratio of stress to strain that is achieved at a certain defined strain. This apparent modulus is of limited value for engineering design.

(3) The dynamic modulus is the ratio of stress to strain that occurs under instantaneous rate of increasing stress, such as can occur in a water-hammer reaction in a pipeline. This modulus is used as a parameter for the computing of a localized surge pressure that results from a water hammer event.

B.2.2 – Values for Other Temperatures

The values for other temperatures may be determined by applying a multiplier, as follows, to the base temperature value:

- For Short-Term Apparent Modulus – Apply the multipliers in Table B.1.2
- For Dynamic Apparent Modulus – Apply the multipliers in Table B.2.2

TABLE B.2.2
Dynamic Modulus, Temperature Compensating Multipliers

Temperature , °F (°C)	Multiplier
40 (4)	1.78
50 (10)	1.52
60 (16)	1.28
73.4 (23)	1.00
80 (27)	0.86
90 (32)	0.69
100 (38)	0.53
110 (43)	0.40
120 (49)	0.29

Appendix C
Allowable Compressive Stress

Table C.1 lists allowable compressive stress values for 73°F (23°C). Values for allowable compressive stress for other temperatures may be determined by application of the same multipliers that are used for pipe pressure rating (See Table A.2).

TABLE C.1
Allowable Compressive Stress for 73°F (23°C)

	Pe Pipe Material Designation Code (1)					
	PE 2406 PE 2708		PE3408 PE 3608 PE 3708 PE 3710 PE 4708		PE 4710	
	psi	MPa	psi	MPa	psi	MPa
Allowable Compressive Stress	800	5.52	1000	6.90	1150	7.93

(1) See Chapter 5 for an explanation of the PE Pipe Material Designation Code.

Appendix D
Poisson's Ratio

Poisson's Ratio for ambient temperature for all PE pipe materials is approximately 0.45.

This 0.45 value applies both to the condition of tension and compression. While this value increases with temperature, and vice versa, the effect is relatively small over the range of typical working temperatures.

Appendix E
Thermal Properties

TABLE E.1
Approximate Value of Thermal Property for Temperature Range Between 32 and 120°F (0 and 49°C)

Thermal Property	PE Pipe Material Designation Code (1)		
	PE2XXX	PE3XXX	PE4XXX
Coefficient of Thermal Expansion/Contraction (2) (in/in ·°F)	10×10^{-5}	9.0×10^{-5}	8.0×10^{-5}
Specific Heat BTU / LB - °F	0.46		
Thermal Conductivity (BTU · in /hr · sq. ft ·°F)	2.6	3.0	3.1

(1) See Chapter 5 for an explanation of the PE Pipe Material Designation Code. The X's designate any numeral that is recognized under this code.

(2) The thermal expansion coefficients define the approximate value of the longitudinal (axial) expansion/contraction that occurs in PE pipe. Because of a certain anisotropy that results from the extrusion process the diametrical expansion is generally lesser, resulting in a diametrical expansion/contraction coefficient that is about 85 to 90% of the axial value.

Appendix F
Electrical Properties

Table F.1 lists the approximate range of values of electrical properties for ambient temperatures for all commercially available PE pipe materials. The actual value for a particular PE piping material may differ somewhat in consequence, mostly, of the nature and quantity of additives that are included in the formulation. For example, formulations containing small quantities of carbon black – an electrical conductor – may exhibit slightly lower values than those shown in this table.

TABLE F.1
Approximate Range of Electrical Property Values for PE Piping Materials

Electrical Property	Test Method	Range of Property Value	
		Range	Unit
Volume Resistivity	–	$>10^{16}$	Ohms-cm
Surface Resistivity	–	$>10^{13}$	Ohms
Arc Resistance	ASTM D495	200 to 250	Seconds
Dielectric Strength	ASTM D149 (1/8 in thick)	450 to 1,000	Volts/mil
Dielectric Constant	ASTM D150 (60Hz)	2.25 to 2.35	–
Dissipation Factor	ASTM D150 (60Hz)	>0.0005	–

Chapter 4

PE Pipe and Fittings Manufacturing

Introduction

The essential steps of PE pipe and fitting production are to heat, melt, mix and convey the raw material into a particular shape and hold that shape during the cooling process. This is necessary to produce solid wall and profile wall pipe as well as compression and injection molded fittings.

All diameters of solid wall PE pipe are continuously extruded through an annular die. Whereas, for large diameter profile wall pipes, the profile is spirally wound onto a mandrel and heat-fusion sealed along the seams.

Solid wall PE pipe is currently produced in sizes ranging from 1/2 inch to 63 inches in diameter. Spirally wound profile pipe may be made up to 10 feet in diameter or more. PE pipe, both the solid wall type and the profile wall type, are produced in accordance with the requirements of a variety of industry standards and specifications such as ASTM and AWWA. Likewise, the PE fittings that are used with solid wall PE pipe are also produced in accordance with applicable ASTM standards. Refer to Chapter 5 for a list of the commonly used PE pipe standards.

Generally, thermoplastic fittings are injection or compression molded, fabricated using sections of pipe, or machined from molded plates. Injection molding is used to produce fittings up through 12 inches in diameter, and fittings larger than 12 inches are normally fabricated from sections of pipe. Refer to Chapter 5 for a list of the commonly used PE fittings standards.

ASTM F2206 Standard Specification for Fabricated Fittings of Butt-Fused Polyethylene (PE) Plastic Pipe, Fittings, Sheet Stock, Plate Stock, or Block Stock.

All of these pipe and fittings standards specify the type and frequency of quality control tests that are required. There are several steps during the manufacturing process that are closely monitored to ensure that the product complies with these rigorous standards. Some of these steps are discussed in the section of this chapter on quality control and assurance.

Pipe Extrusion

The essential aspects of a solid wall PE pipe manufacturing facility are presented in Figure 1. This section will describe the production of solid wall pipe from raw material handling, extrusion, sizing, cooling, printing, and cutting, through finished product handling. Details concerning profile wall pipe are also discussed in the appropriate sections.

Raw Materials Description

The quality of the starting resin material is closely monitored at the resin manufacturing site. As discussed in the chapter on test methods and codes in this handbook, a battery of tests is used to ensure that the resin is of prime quality. A certification sheet is sent to the pipe and fitting manufacturer documenting important physical properties such as melt index, density, ESCR (environmental stress crack resistance), SCG (slow crack growth), stabilizer tests, amongst others. The resin supplier and pipe manufacturer may agree upon additional tests to be conducted.

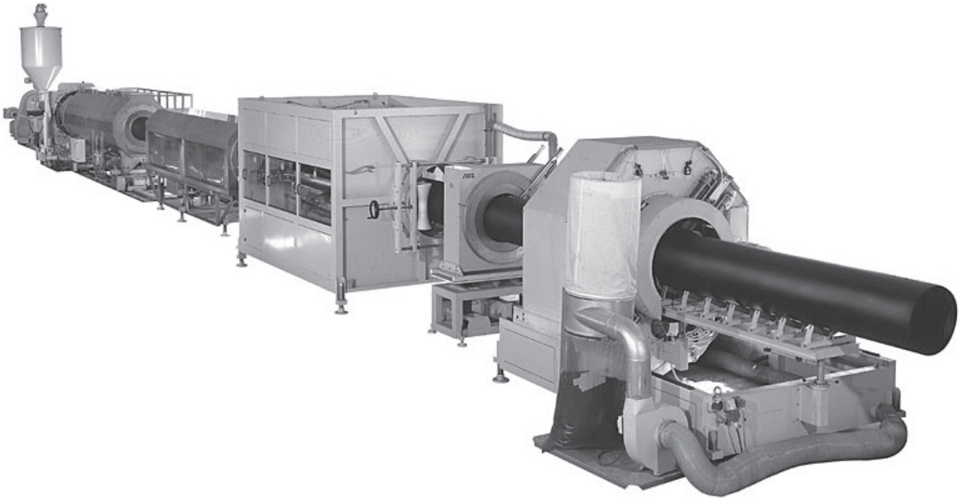


Figure 1 Typical Conventional Extrusion Line

Extrusion Line

The raw material, usually referred to as PE compound, is typically supplied to the pipe producer as non-pigmented pellets. PE pellets are stabilized for both heat and UV protection. Usually, color pigment is added to the pipe at the producer's facility. In North America, the most common colors are black and yellow. The choice of color will depend upon the intended application and the requirements of the pipe purchaser. Carbon black is the most common pigment used for water, industrial, sewer and above-ground uses. Yellow is reserved exclusively for natural gas applications, although black with yellow stripes is also permitted for this application. Other colors are used for telecommunications and other specialty markets.

All ASTM and many other industry standards specify that a PPI-listed compound shall be used to produce pipe and fittings for pressure pipe applications. A compound is defined as the blend of natural resin and color concentrate and the ingredients that make up each of those two materials. The pipe producer may not change any of the ingredients. In a listed compound, such as substituting a different color concentrate that could affect the long-term strength performance of the pipe. Any change to a listed formulation has to be pre-approved. These stringent requirements ensure that only previously tested and approved compounds are being used.

If the resin is supplied as a natural pellet, the pipe producer will blend a color concentrate with the resin prior to extrusion. In order to obtain a PPI Listing, each manufacturer producing pipe in this manner is required to submit data, according to ASTM 2837, to the PPI Hydrostatic Stress Board. A careful review of the data is made according to PPI Policy TR-3 (5) to assess the long-term strength characteristics of the in-plant blended compound. When those requirements are met, the compound qualifies for a Dependent listing and is listed as such in the PPI Publication TR-4 (6), which lists compounds that have satisfied the requirements of TR-3. Producers of potable water pipe are usually required to have the approval of the NSF International or an equivalent laboratory. NSF conducts un-announced visits during which time they verify that the correct compounds are being used to produce pipe that bears their seal.

Raw Materials Handling

After the material passes the resin manufacturer's quality control tests, it is shipped to the pipe manufacturer's facility in 180,000- to 200,000-pound capacity railcars, 40,000-pound bulk trucks, or 1000- to 1400-pound boxes.

Each pipe producing plant establishes quality control procedures for testing incoming resin against specification requirements. The parameters that are typically tested include: melt flow rate, density, moisture content and checks for contamination. Many resin producers utilize statistical process control (SPC) on certain key physical properties to ensure consistency of the product.

Resin is pneumatically conveyed from the bulk transporters to silos at the plant site. The resin is then transferred from the silos to the pipe extruder by a vacuum transfer system. Pre-colored materials can be moved directly into the hopper above the extruder. If a natural material is used, it must first be mixed homogeneously with a color concentrate. The resin may be mixed with the color concentrate in a central blender remote from the extruder or with an individual blender mounted above the extruder hopper. The blender's efficiency is monitored on a regular basis to ensure that the correct amount of color concentrate is added to the raw material.

Extrusion Basics

The function of the extruder is to heat, melt, mix, and convey the material to the die, where it is shaped into a pipe (8). The extruder screw design is critical to the performance of the extruder and the quality of the pipe. The mixing sections of the screw are important for producing a homogeneous mix when extruding blends. A typical extruder is shown in Figure 2.

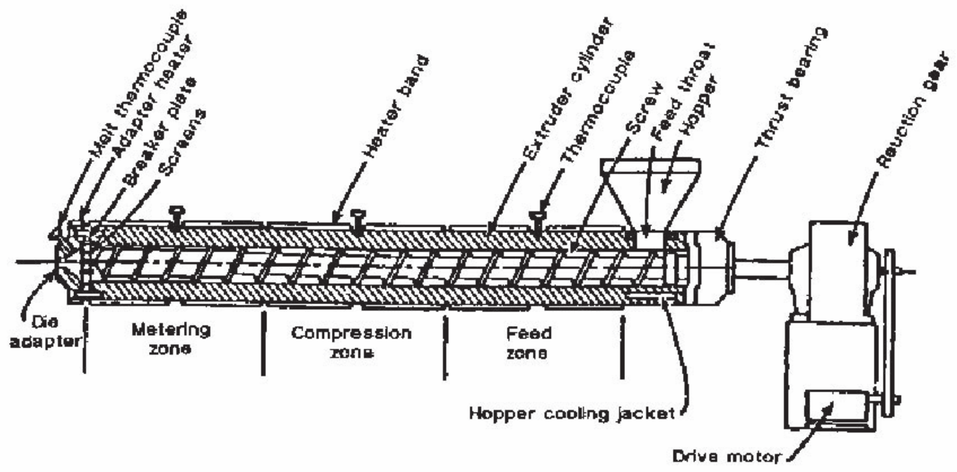


Figure 2 Typical Single-Stage, Single-Screw Extruder (Resin Flow from Right to Left)

There are many different types of screw designs (10), but they all have in common the features shown in Figure 3. Each screw is designed specifically for the type of material being extruded.

The extruder screw operates on the stick/slip principle. The polymer needs to stick to the barrel so that, as the screw rotates, it forces the material in a forward direction.

In the course of doing this, the polymer is subjected to heat, pressure and shear (mechanical heating). The extent to which the material is subjected to these three conditions is the function of the screw speed, the barrel temperature settings and the screw design. The design of the screw is important for the production of high quality pipe.

Figure 3 Typical Extrusion Screw

If a natural resin and concentrate blend is used, the screw will also have to incorporate the colorant into the natural resin. Various mixing devices are used for this purpose as shown in Figure 4. They include mixing rings or pins, fluted or cavity transfer mixers, blister rings, and helix shaped mixers, which are an integral part of the screw.

The pipe extrusion line generally consists of the extruder, die, cooling systems, puller, printer, saw and take-off equipment. Each of these items will be addressed in the following section.

Figure 4 Typical Resin Mixing Devices

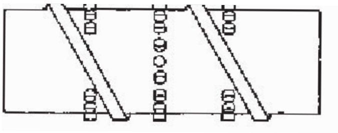


Figure 4.1 Mixing Pins

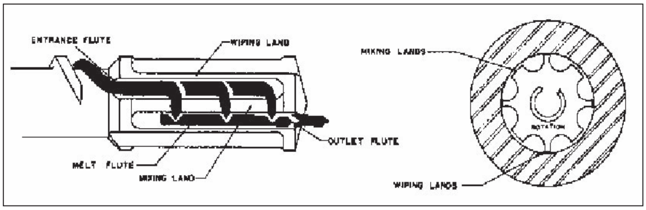


Figure 4.2 Fluted Mixer

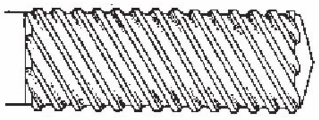


Figure 4.3 Helical Mixer

Extruders

An extruder is usually described by its bore size and barrel length. Pipe extruders typically have an inside diameter of 2 to 6 inches with barrel lengths of 20 to 32 times the bore diameter. The barrel length divided by the inside diameter is referred to as the L/D ratio. An extruder with an L/D ratio of 24:1 or greater provides adequate residence time to produce a homogeneous mixture.

The extruder is used to heat the raw material and then force the resulting melted polymer through the pipe extrusion die. The barrel of the machine has a series of four to six heater bands. The temperature of each band is individually controlled by an instrumented thermocouple. During the manufacturing process, the major portion of the heat supplied to the polymer is the shear energy generated by the screw and motor drive system. This supply of heat can be further controlled by applying cooling or heating to the various barrel zones on the extruder by a series of air or water cooling systems. This is important since the amount of heat that is absorbed by the polymer needs to be closely monitored. The temperature of the extruder melted polymer is usually between 390˚F and 450˚F, and it is also under high pressure (2000 to 4000 psi).

Breaker Plate/Screen Pack

The molten polymer leaves the extruder in the form of two ribbons. It then goes through a screen pack which consists of one or more wire mesh screens, positioned against the breaker plate. The breaker plate is a perforated solid steel plate. Screen packs prevent foreign contaminants from entering the pipe wall and assist in the development of a pressure gradient along the screw. This helps to homogenize the polymer. To assist in the changing of dirty screen packs, many extruders are equipped with an automatic screen changer device. It removes the old pack while it inserts the new pack without removing the die head from the extruder.

Die Design

The pipe extrusion die supports and distributes the homogeneous polymer melt around a solid mandrel, which forms it into an annular shape for solid wall pipe (9). The production of a profile wall pipe involves extruding the molten polymer through a die which has a certain shaped profile.

The die head is mounted directly behind and downstream of the screen changer unless the extruder splits and serves two offset dies.

There are two common types of die designs for solid wall pipe; the spider die design and the basket die design. They are illustrated in Figure 5. These designs refer to the manner in which the melt is broken and distributed into an annular shape and also the means by which the mandrel is supported.

Figure 5 Typical Pipe Dies

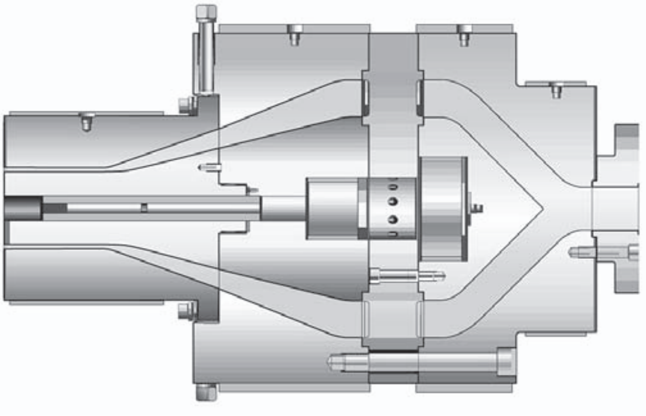


Figure 5.1 Pipe Die with Spider Design

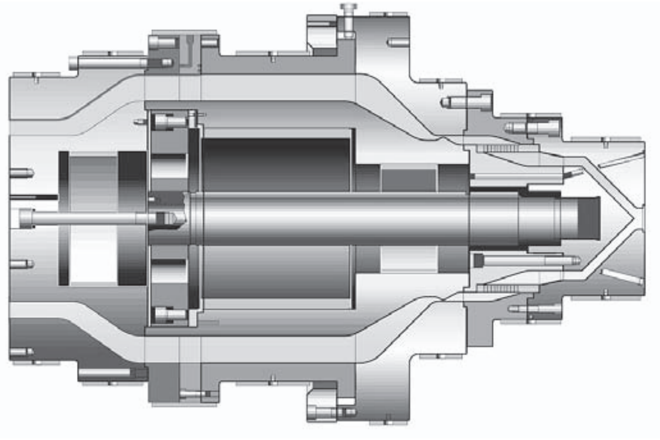


Figure 5.2 Pipe Die with Basket Design

In the spider die (Figure 5.1), the melt stream is distributed around the mandrel by a cone which is supported by a ring of spokes. Since the melt has been split by the spider legs, the flow must be rejoined.

Flow lines caused by mandrel supports should be avoided. This is done by reducing the annular area of the flow channel just after the spider legs to cause a buildup in die pressure and force the melt streams to converge, minimizing weld or spider lines. After the melt is rejoined, the melt moves into the last section of the die, called the land.

The land is the part of the die that has a constant cross-sectional area. It reestablishes a uniform flow and allows the final shaping of the melt and also allows the resin a certain amount of relaxation time. The land can adversely affect the surface finish of the pipe if it is too short in length. Typical land lengths are 15 to 20 times the annular spacing.

The basket design (Figure 5.2) has an advantage over the spider die concerning melt convergence. The molten polymer is forced through a perforated sleeve or plate, which contains hundreds of small holes. Polymer is then rejoined under pressure as a round profile. The perforated sleeve, which is also called a screen basket, eliminates spider leg lines.

Pipe Sizing

The dimensions and tolerances of the pipe are determined and set during the sizing and cooling operation. The sizing operation holds the pipe in its proper dimensions during the cooling of the molten material. For solid wall pipe, the process is accomplished by drawing the hot material from the die through a sizing sleeve and into a cooling tank. Sizing may be accomplished by using either vacuum or pressure techniques. Vacuum sizing is generally the preferred method.

In the vacuum sizing system, molten extrudate is drawn through a sizing tube or rings while its surface is cooled enough to maintain proper dimensions and a circular form. The outside surface of the pipe is held against the sizing sleeve by vacuum. After the pipe exits the vacuum sizing tank, it is moved through a second vacuum tank or a series of spray or immersion cooling tanks.

Figure 6 External Sizing Systems

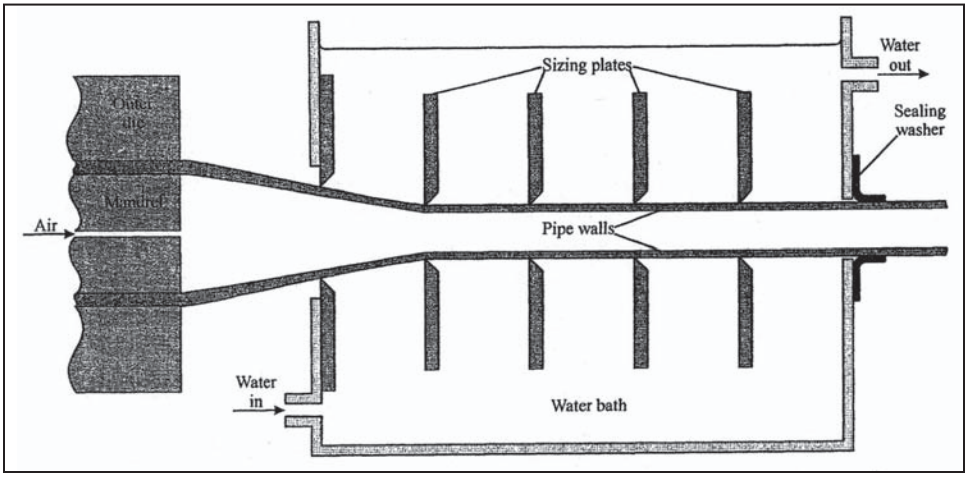


Figure 6.1 Vacuum Tank Sizing (11)

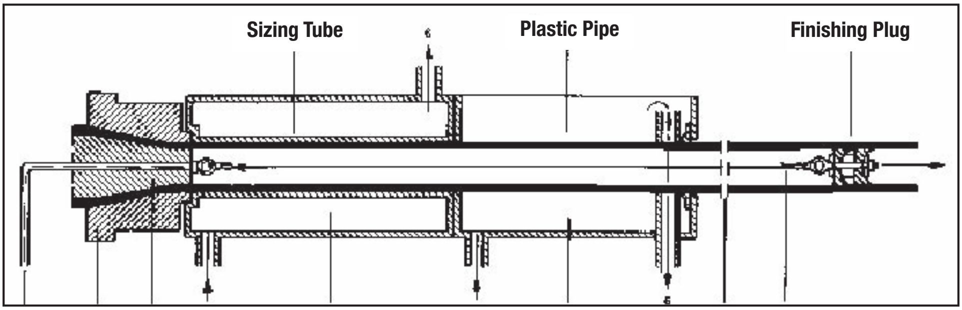


Figure 6.2 Internal (Pressure) Sizing for Small and Medium Pipe Diameters

In the pressure sizing system, a positive pressure is maintained on the inside of the pipe by the use of a plug attached to the die face by a cable or, on very small bore pipe, by closing or pinching off the end of the pipe. The pressure on the outside of the pipe remains at ambient and the melt is forced against the inside of the calibration sleeve with the same results as in the vacuum system.

The production of very large diameter profile pipe, up to 10 feet in diameter, uses mandrel sizing. In one form of this process, the extruded profile is wrapped around a mandrel. As the mandrel rotates, the extruded profile is wrapped such that each turn overlaps the previous turn. In some other techniques, the turns are not overlapped. A typical profile wall PE pipe is shown in Figure 7.

Figure 7 Typical PE Profile Wall Pipe from ASTM Standard F894

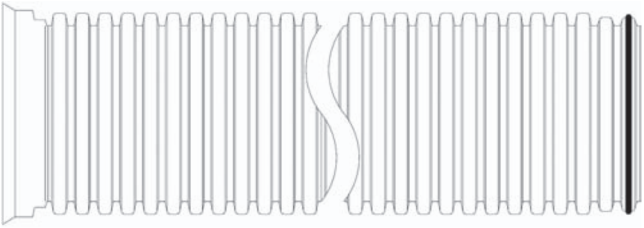


Figure 7.1 Laying Lengths

Figure 7.2 Typical Profile Wall Section Showing Bell End (right) and Spigot End (left)

Cooling

For either the vacuum or pressure sizing technique, the pipe must be cool enough so that it maintains its circularity before it exits the cooling tank. Various methods of cooling are utilized to remove the residual heat out of the PE pipe. Depending upon the pipe size, the system may use either total immersion or spray cooling. Spray cooling is usually applied to large diameter pipe where total immersion would be inconvenient. Smaller diameter pipe is usually immersed in a water bath. Cooling water temperatures are typically in the optimum range of 40° to 50°F (4° to 10°C). The total length of the cooling baths must be adequate to cool the pipe below 160°F (71°C) in order to withstand subsequent handling operations.

Residual stresses generated by the cooling process within the pipe wall are minimized by providing annealing zones.(4) These zones are spaces between the cooling baths which allow the heat contained within the inner pipe wall to radiate outward and anneal the entire pipe wall. Proper cooling bath spacing is important in controlling pipe wall stresses. Long-term pipe performance is improved when the internal pipe wall stresses are minimized.

Pullers

The puller must provide the necessary force to pull the pipe through the entire cooling operation. It also maintains the proper wall thickness control by providing a constant pulling rate. The rate at which the pipe is pulled, in combination with the extruder screw speed, determines the wall thickness of the finished pipe. Increasing the puller speed at a constant screw speed reduces the wall thickness, while reducing the puller speed at the same screw speed increases the wall thickness.

Standards of ASTM International and other specifications require that the pipe be marked at frequent intervals. The markings include nominal pipe size, type of plastic, SDR and/or pressure rating, and manufacturer's name or trademark and manufacturing code. The marking is usually ink, applied to the pipe surface by an offset roller. Other marking techniques include hot stamp, ink jet and indent printing. If indent printing is used, the mark should not reduce the wall thickness to less than the minimum value for the pipe or tubing, and the long-term strength of the pipe or tubing must not be affected. The mark should also not allow leakage channels when gasket or compression fittings are used to join the pipe or tubing.

Take-off Equipment

Most pipe four inches or smaller can be coiled for handling and shipping convenience. Some manufacturers have coiled pipe as large as 6 inch. Equipment allows the pipe to be coiled in various lengths. Depending upon the pipe diameter, lengths of up to 10,000 feet are possible. This is advantageous when long uninterrupted lengths of pipe are required - for example, when installing gas and water pipes.

Saw Equipment and Bundling

Pipe four inches or more in diameter is usually cut into specified lengths for storage and shipping. Typical lengths are 40 to 50 feet, which can be shipped easily by rail or truck. The pipe is usually bundled before it is placed on the truck or railcar. Bundling provides ease of handling and safety during loading and unloading.

Fittings Overview

The PE pipe industry has worked diligently to make PE piping systems as comprehensive as possible. As such, various fittings are produced which increase the overall use of the PE piping systems. Some typical fittings are shown in Figure 8.

PE fittings may be injection molded, fabricated or thermoformed. The following section will briefly describe the operations of each technique.

Injection Molded Fittings

Injection molded PE fittings are manufactured in sizes through 12-inch nominal diameter. Typical molded fittings are tees, 45° and 90° elbows, reducers, couplings, caps, flange adapters and stub ends, branch and service saddles, and self-tapping saddle tees. Very large parts may exceed common injection molding equipment capacities, so these are usually fabricated.

Equipment to mold fittings consists of a mold and an injection molding press, as shown in Figure 9. The mold is a split metal block that is machined to form a part-shaped cavity in the block. Hollows in the part are created by core pins shaped into the part cavity. The molded part is created by filling the cavity in the mold block through a filling port, called a gate. The material volume needed to fill the mold cavity is called a shot.

The injection molding press has two parts; a press to open and close the mold block, and an injection extruder to inject material into the mold block cavity. The injection extruder is similar to a conventional extruder except that, in addition to rotating, the extruder screw also moves lengthwise in the barrel. Injection molding is a cyclical process. The mold block is closed and the extruder barrel is moved into contact with the mold gate. The screw is rotated and then drawn back, filling the barrel ahead of the screw with material. Screw rotation is stopped and the screw is rammed forward, injecting molten material into the mold cavity under high pressure. The part in the mold block is cooled by water circulating through the mold block. When the part has solidified, the extruder barrel and mold core pins are retracted, the mold is opened, and the part is ejected.

Typical quality inspections are for knit line strength, voids, dimensions and pressure tests. A knit line is formed when the molten PE material flows around a core pin and joins together on the other side. While molding conditions are set to eliminate the potential for voids, they can occur occasionally in heavier sections due to shrinkage that takes place during cooling. Voids can be detected nondestructively by using x-ray scans. If this is not available, samples can be cut into thin sections and inspected visually.

Figure 8 Typical PE Pipe Fittings

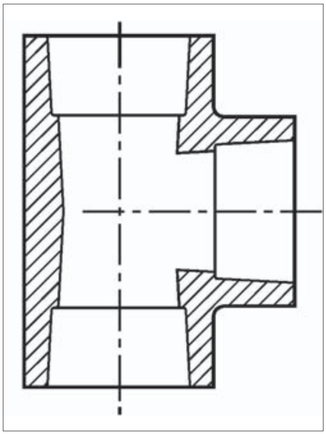


Figure 8.1 Socket Tee

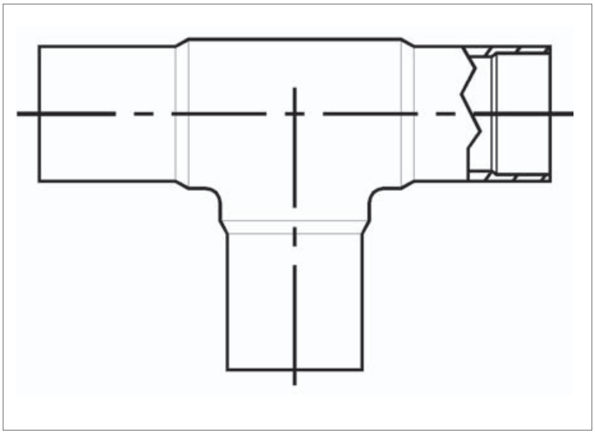


Figure 8.2 Butt Tee

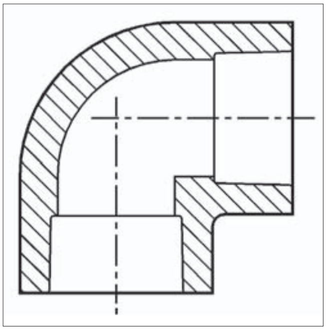


Figure 8.3 90° Socket Elbow

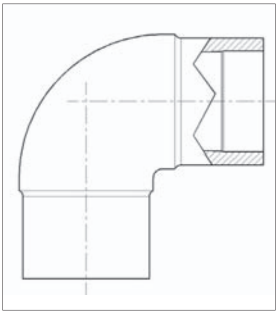


Figure 8.4 90° Butt Elbow

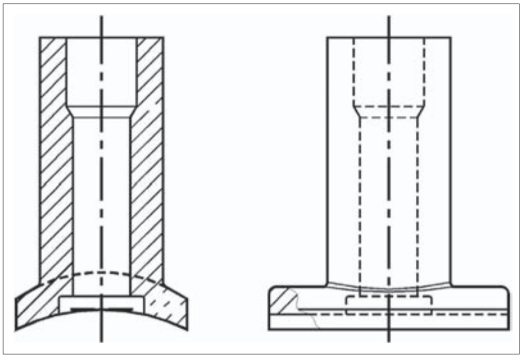


Figure 8.5 Saddle Fusion Fittings

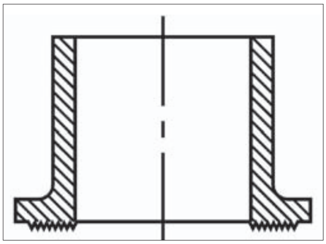


Figure 8.6 Butt Flange Adapter/Stub End

a. injection stage
b. freeze time with follow-up pressure
c. demoulding of finished article

1. locking mechanism
2. moving mounting plate
3. mold cavity plate
4. mold core plate
5. stationery mounting plate
6. plasticating cylinder
7. feed hopper
8. hydralic motor (screw drive)
9. hydralic cylinder of injection unit
10. pressure gauge
11. follw-up pressure limit switch
12. screw stroke adjusment

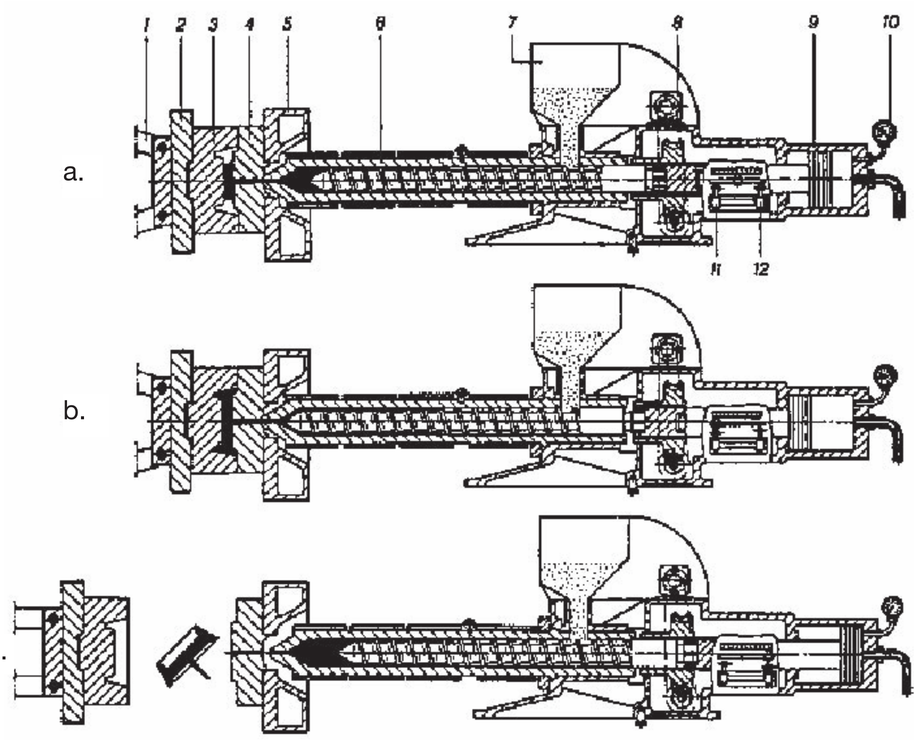


Figure 9 Construction and Mode of Operation of a Reciprocating Screw Injection Unit (Courtesy of Hoechst Celanese Corporation)

Fabricated Fittings

Fully pressure-rated, full bore fabricated fittings are available from select fittings fabricators. Fabricated fittings are constructed by joining sections of pipe, machined blocks, or molded fittings together to produce the desired configuration. Components can be joined by butt or socket heat fusion, electrofusion, hot gas welding or extrusion welding techniques. It is not recommended to use either hot gas or extrusion welding for pressure service fittings since the resultant joint strength is significantly less than that of the other heat fusion joining methods.

Fabricated fittings designed for full pressure service are joined by heat fusion and must be designed with additional material in regions of sharp geometrical changes, regions that are subject to high localized stress. The common commercial practice is to increase wall thickness in high-stress areas by fabricating fittings from heavier wall pipe sections. The increased wall thickness may be added to the OD, which provides for a full-flow ID; or it may be added to the ID, which slightly restricts ID flow. This is similar to molded fittings that are molded with a larger OD, heavier body wall thickness. If heavy-wall pipe sections are not used, the conventional practice is to reduce the pressure rating of the fitting. The lowest-pressure-rated component in a pipeline determines the operating pressure of the piping system.

Various manufacturers address this reduction process in different manners. Reinforced over-wraps are sometimes used to increase the pressure rating of a fitting. Encasement in concrete, with steel reinforcement or rebar, is also used for the same purpose. Contact the fitting manufacturer for specific recommendations.

Very large diameter fittings require special handling during shipping, unloading, and installation. Precautions should be taken to prevent bending moments that could stress the fitting during these periods. Consult the fittings manufacturer for specifics. These fittings are sometimes wrapped with a reinforcement material, such as fiberglass, for protection.

Thermoformed Fittings

Thermoformed fittings are manufactured by heating a section of pipe and then using a forming tool to reshape the heated area. Examples are sweep elbows, swaged reducers, and forged stub ends. The area to be shaped is immersed in a hot liquid bath and heated to make it pliable. It is removed from the heating bath and reshaped in the forming tool. Then the new shape must be held until the part has cooled.

Electrofusion Couplings

Electrofusion couplings and fittings are manufactured by either molding in a similar manner as that previously described for butt and socket fusion fittings or manufactured from pipe stock. A wide variety of couplings and other associated fittings are available from ½″ CTS thru 28″ IPS. Fittings are also available for ductile iron sized PE pipe. These couplings are rated as high as FM 200.

Electrofusion fittings are manufactured with a coil-like integral heating element. These fittings are installed utilizing a fusion processor, which provides the proper energy to provide a fusion joint stronger than the joined pipe sections. All electrofusion fittings are manufactured to meet the requirements of ASTM F-1055.

Injection Molded Couplings

Some mechanical couplings are manufactured by injection molding in a similar manner as previously described for butt and socket fusion fittings. The external

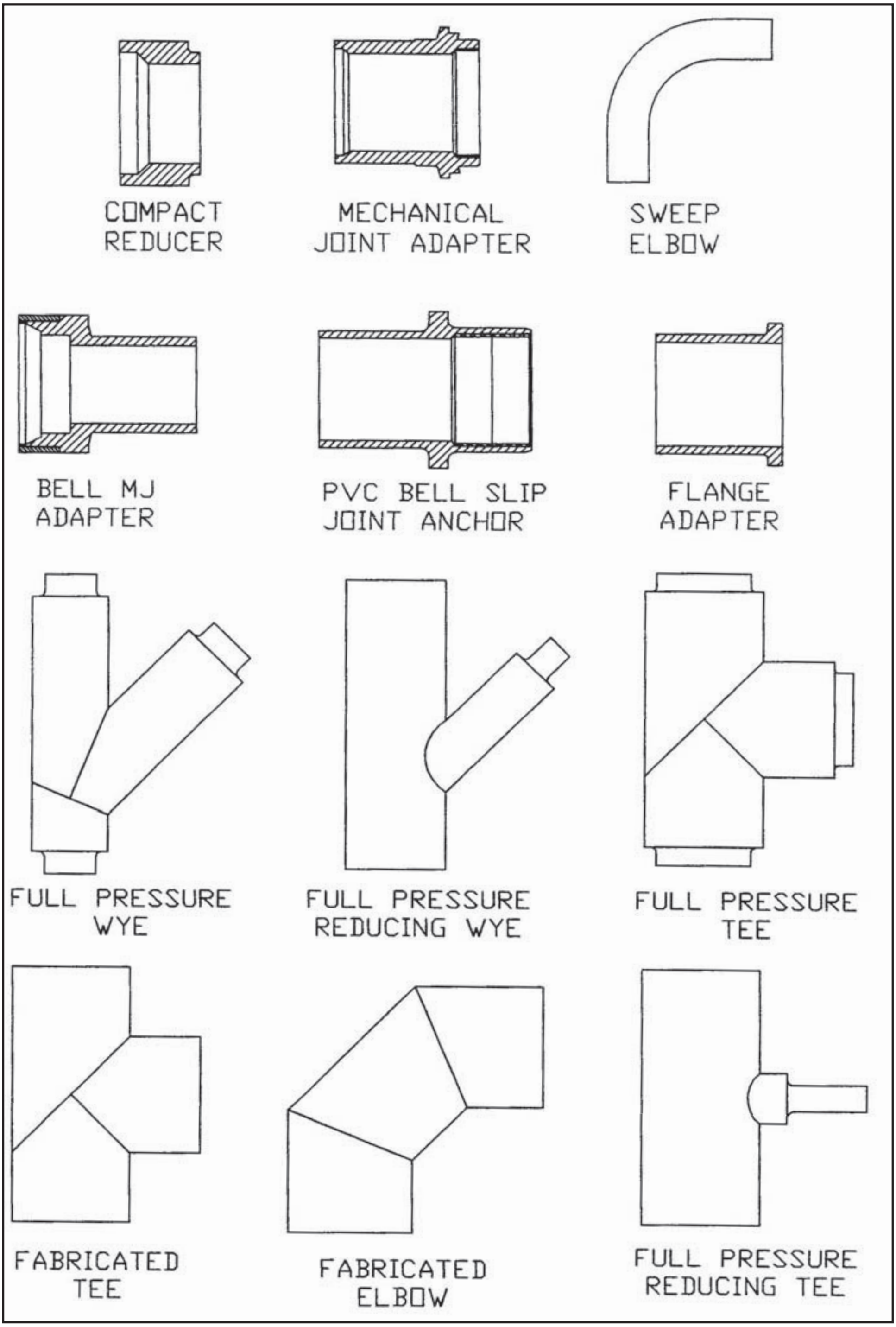


Figure 10 Typical Fabricated Fittings

coupling body is typically injection molded and upon final assembly will include internal components such as steel stiffeners, o-rings, gripping collets, and other components depending upon the design. A wide variety of coupling configurations are available including tees, ells, caps, reducers, and repair couplings. Sizes for joining PE pipe and tubing are typically from ½" CTS through 2" IPS. All injection molded couplings are manufactured to meet the requirements of ASTM D2513.

Quality Control/Quality Assurance Testing

Quality is engineered into the pipe and fitting product during the entire manufacturing process. The three phases of quality control for the pipe manufacturer involve the incoming raw material, the pipe or fitting production and the finished product. The combination of all three areas ensures that the final product will fulfill the requirements of the specification to which it was made.

Testing the incoming resin is the first step in the quality control program. It is usually checked for contamination, melt flow rate and density. Any resin that does not meet the raw material specification is not used for the production of specification-grade pipe or fitting.

During the manufacturing step, the pipe or fitting producer routinely performs quality control tests on samples. This verifies that proper production procedures and controls were implemented during production.

Once the product has been produced, it undergoes a series of quality assurance tests to ensure that it meets the minimum specifications as required by the appropriate standard. (See Handbook Chapter on Test Methods and Codes.)

The manufacturing specifications for piping products list the tests that are required. There are several quality control tests that are common in most ASTM PE standards. For gas service piping systems, refer to PPI Technical Report TR-32 (7) for a typical quality control program for gas system piping, or to the AGA Plastic Pipe Manual for Gas Service (1). The typical QC/QA tests found in most standards are described below.

Workmanship, Finish, and Appearance

According to ASTM product specifications, the pipe, tubing, and fittings shall be homogeneous throughout and free of visible cracks, holes, foreign inclusions, blisters, and dents or other injurious defects. The pipe tubing and fittings shall be as uniform as commercially practicable in color, opacity, density and other physical properties.

Dimensions

Pipe diameter, wall thickness, ovality, and length are measured on a regular basis to insure compliance with the prevailing specification. All fittings have to comply with the appropriate specification for proper dimensions and tolerances. All measurements are made in accordance with ASTM D2122, Standard Test Method of Determining Dimensions of Thermoplastic Pipe and Fittings (2).

Physical Property Tests

Several tests are conducted to ensure that the final pipe product complies to the applicable specification. Depending upon the specification, the type and the frequency of testing will vary. More details about industry standard requirements can be found in the chapter on specifications, test methods and codes in this Handbook.

The following tests, with reference to the applicable ASTM standard (2), are generally required in many product specifications such as natural gas service. The following list of tests was taken from the American Gas Association Manual for Plastic Gas Pipe (1) to serve as an example of typical tests for gas piping systems.

ASTM TESTS

Sustained Pressure	D1598
Burst Pressure	D1599
Apparent Tensile Strength	D2290

Neither the sustained pressure test or the elevated temperature pressure test are routine quality assurance tests. Rather, they are less frequently applied tests required by the applicable standards to confirm and assure that the established process system and materials being used produce quality product meeting the requirements of the standard.

There are other tests that are used that are not ASTM test methods. They are accepted by the industry since they further ensure product reliability. One such test, required by applicable AWWA Standards, is the Bend-Back Test (1) which is used to indicate inside surface brittleness under highly strained test conditions. In this test, a ring of the pipe is cut and then subjected to a reverse 180-degree bend. Any signs of surface embrittlement, such as cracking or crazing, constitute a failure. The presence of this condition is cause for rejection of the pipe.

Quality Assurance Summary

Through the constant updating of industry standards, the quality performance of the PE pipe and fitting industry is continually evolving. Each year, PPI and ASTM work to improve standards on plastic pipe which include the latest test methods and recommended practices. Resin producers, pipe extruders, and fittings manufacturers incorporate these revisions into their own QA/QC practices to insure compliance with these standards. In this way, the exceptional performance and safety record of the PE pipe industry is sustained.

Summary

This chapter provides an overview of the production methods and quality assurance procedures used in the manufacture of PE pipe and fittings. The purpose of this chapter is to create a familiarity with the processes by which these engineered piping products are made. Through a general understanding of these fundamental processes, the reader should be able to develop an appreciation for the utility and integrity of PE piping systems.

References

1. *AGA Plastic Pipe Manual for Gas Service*. (2001). Catalog No. XR0185, American Gas Association, Arlington, VA.
2. *Annual Book of ASTM Standards*. (2005). Volume 08.04, Plastic Pipe and Building Products, American Society for Testing and Materials, Philadelphia, PA.
3. Kamp, W., & H. D. Kurz. (1980). Cooling Sections in Polyolefin Pipe Extrusion, *Kunststoffe 70*, pp. 257-263, English Translation.
4. Policies and Procedures for Developing Hydrostatic Design Basis (HDB), Pressure Design Basis (PDB), Strength Design Basis (SDB), and Minimum Required Strength (MRS) Rating for Thermoplastic Piping Materials or Pipe (2005). Report TR-3, Plastics Pipe Institute, Irving, TX.
5. PPI Listing of Hydrostatic Design Basis (HDB), Strength Design Basis (SDB), Pressure Design Basis (PDB) and Minimum Required Strength (MRS) Ratings for Thermoplastic Piping Materials or Pipe (2005). Report TR-4, Plastics Pipe Institute, Irving, TX.
6. Recommended Minimum In-Plant Quality Control Program for Production of PE Gas Distribution Piping Systems. (1989). Report TR-32, Plastics Pipe Institute, Irving, TX.
7. Schiedrum, H. 0. (1974). The Design of Pipe Dies, *Plastverarbeiter*, No. 10, English Translation.
8. Rauwendaal, C. (1986). *Polymer Extrusion*, MacMillan Publishing Company, Inc., New York, NY.
9. *Screw and Barrel Technology*. (1985). Spirex Corporation, Youngstown, OH.
10. Peacock, Andrew J. (2000). *Handbook of PE*, Marcel Decker, Inc. New York, NY.

Chapter 5

Standard Specifications, Standard Test Methods and Codes for PE (Polyethylene) Piping Systems

Introduction

The specification, design and use of PE piping systems is addressed by a number of standard specifications, standard test methods and codes including those issued by ASTM International (ASTM), American Water Works Association (AWWA), and Canadian Standards Association (CSA) as well as Technical Reports (TR's) and Technical Notes (TN's) published by the Plastics Pipe Institute (PPI). A listing of the more frequently referenced standards, reports and recommendations is presented in the Appendix to this Chapter.

This Chapter covers topics relating to PE pipe of solid wall or of profile wall construction. These topics include:

1. Material specifications relating to properties and classifications of PE materials for piping applications.
2. Standard requirements relating to pipe pressure rating, dimensions, fittings and joints.
3. Codes, standards and recommended practices governing the application of PE pipe systems in a variety of end uses.

Readers seeking information on PE pipes of corrugated wall construction are invited to visit PPI's web site at http://plasticpipe.org/drainage/index.html

Standard Requirements for PE Piping Materials

As discussed in Chapter 3, polyethylene (PE) is a complex polymer with properties that can be optimized based on the desired end use. Such modifications are effected by choice of catalyst system, polymerization conditions and, the use of a small quantity of co-monomer (a monomer or monomers other than ethylene). All these changes allow PE to be tailor made to a wide range of processing and performance requirements.

For classifying this wide array of property variations that find use in piping applications, ASTM issued standard D 3350, “Standard Specification for Polyethylene Plastic Pipe and Fittings Materials”. This standard recognizes six properties that are considered important in the manufacture of PE piping, in the heat fusion joining of this material and, in defining its long-term performance capabilities. Each property is assigned into a “Cell” and, each cell consists of a number of “Classes”. A cell number covers a narrow range of the larger overall range that is covered by a property “cell”. These D 3350 property cells and classes are identified in Table 1.

TABLE 1

Cell Classification System from ASTM D 3350-06[1,2]

Property	Test Method	0	1	2	3	4	5	6	7	8
Density, g/cm3	D 1505	un-specified	0.925 or lower	>0.925 - 0.940	>0.940 - 0.947	>0.947 - 0.955	>0.955	—	specify value	—
Melt Index	D 1238	un-specified	>1.0	1.0 to 0.4	<0.4 to 0.15	<0.15	A	—	specify value	—
Flexural Modulus, MPa (psi), 2% secant	D 790	un-specified	<138 (<20,000)	138-<276 (20,000 to <40,000)	276-<552 (40,000 to <80,000)	552-<758 (80,000 to <110,000)	758-<1103 (110,000 to <160,000)	>1103 (>160,000)	specify value	—
Tensile strength at yield, MPa (psi)	D638	un-specified	<15 (<2000)	15- < 18 (2200-<2600)	18- <21 (2600-<3000)	21- <24 (3000-<3500)	24- <28 (3500-<4000)	>28 (>4000)	specify value	—
Slow Crack Growth Resistance I. ESCR	D1693	un-specified								
a. Test condition			A	B	C	C	—	—	—	specify value
b. Test duration, hours			48	24	192	600	—	—	—	
c. Failure, max. %			50	50	20	20	—	—	—	
Slow Crack Growth Resistance II. PENT (hours) Molded Plaque, 80°C, 2.4MPa, notch depth Table 1	F 1473	un-specified	—	—	—	10	30	100	500	specify value
Hydrostatic Strength Classification I. Hydrostatic design basis, MPa, (psi), (23°C)	D2837	NPR[B]	5.52 (800)	6.89 (1000)	8.62 (1250)	11.03 (1600)	—	—	—	—
Hydrostatic Strength Classification II. Minimum Required Strength, MPa (psi), (20°C)	ISO 12162	—	—	—	—	—	8 (1160)	10 (1450)	—	—

Notes to Table 1-A: Refer to 10.1.4.1 (ASTM D 3350) B: NPR = Not Pressure Rated, 1.) D 3350 is subject to periodic revisions, contact ASTM to obtain the latest version, 2.) The property and density are measured on the PE base resin; all the other property values are measured on the final compound.

In addition, by means of a Code letter, ASTM D3350 designates whether the material includes a colorant and also, the nature of the stabilizer that is included for protecting the material against the potential damaging effects of the ultraviolet (UV) rays in sunlight. Table 2 lists the Code letters that are used in D 3350 and what they reprsent.

TABLE 2

Code Letter Representation

Code Letter	Color and UV Stabilizer
A	Natural
B	Colored
C	Black with 2% minimum carbon black
D	Natural with UV stabilizer
E	Colored with UV stabilizer

For designating a PE material in accordance with ASTM D 3350 the cell number for each cell property is identified, and this is done in the same order as shown in Table 1. This is then followed by an appropriate Code letter to indicate color and stabilization as shown in Table 2. An example of this material designation system is presented in Table 3 for the case of a PE material having designation code PE445574C.

TABLE 3

Properties of a Cell number PE445574 Material

Digit Designating the Applicable Property Cell[1]	Class Number or Code Letter	Corresponding Value of Property (from Table1)
1st Digit – Density of PE base resin, gm/cm^3	4	>0.947 – 0.955
2nd Digit – Melt Index of compound, gm/10 minutes	4	<0.15
3rd Digit – Flexural Modulus of compound, psi (MPa)	5	110,000 - < 160,000 (758 - <1103)
4th Digit – Tensile Strength at Yield of compound, psi (MPa)	5	3,500 - <4,000 (24 - <28)
5th Digit – Resistance to Slow Crack Growth of compound (SCG), hrs.	7	500 minimum based on PENT test
6th Digit – Hydrostatic Design Basis for water at 73°F(23°C), psi of compound (MPa)	4	1600 (11.03)
Code Letter	C	Black with 2% minimum carbon black

(1) The density is that of the PE resin. All the other properties are determined on the final compounded material.

A PE material that complies with the Table 3 cell designation i.e. PE445574C would be a higher density (higher crystallinity), lower melt index (higher molecular weight) material that exhibits exceptionally high resistance to slow crack growth. In addition, it offers a hydrostatic design basis (HDB) for water at 73°F (23°C) of 1600 psi (11.03 MPa). Finally, it would be black and contain a minimum of 2% carbon black.

The cell classification system provides the design engineer with a very useful tool in specifying the requirements of PE materials for piping projects.

Standard PE Piping Material Designation Code

While all PE piping standards specify minimum material requirements based the on the cell requirements of ASTM D3350, a simpler, short-hand, ASTM recognized material designation code is commonly used for quickly identifying the most significant engineering properties of a PE pipe material. An important feature of this designation code is that it identifies the maximum recommended hydrostatic design stress (HDS) for water, at 73°F(23°C). Originally, this designation code was devised to only apply to materials intended for pressure piping. However, there is a recognition that even in non-pressure applications stresses are generated which makes it prudent to use a stress rated material. This has led to the common practice of using this material designation code for quickly identifying all PE piping materials intended for pipes of solid wall or, of profile wall construction.

This code is defined in ASTM F412, "Standard Terminology Relating to Plastic Piping Systems", under the definition for the term code, thermoplastic pipe materials designation. It consists of the ASTM approved abbreviation for the pipe material followed by four digits (e.g., PE4710). The information delivered by this code is as follows:

- The ASTM recognized abbreviation for the piping material. PE, in the case of polyethylene materials.
- The first digit identifies the density range of the base PE resin, in accordance with ASTM D3350, that is used in the material. As discussed in Chapter 3, the density of a PE polymer reflects the polymer's crystallinity which, in turn, is the principal determinant of the final material's strength and stiffness properties.
- The second digit identifies the compound's resistance to slow crack growth (SCG), also in accordance with ASTM D3350. A material's resistance to SCG relates very strongly to its long-term ductility, a property that defines the material's capacity for safely resisting the effects of localized stress intensifications.
- The last two numbers identify the compound's maximum recommended hydrostatic design stress (HDS) category (1) for water, at 73°F(23°C). This recommendation is established in consideration of various factors but, primarily the following: The capacity for safely resisting the relatively well distributed stresses that are generated only by internal pressure, and, the capacity for safely resisting add-on effects caused by localized stress intensifications.(1)

(1) More discussion on these topics later in this Chapter.

The Standard Designation Codes for materials which are recognized as of this writing by current ASTM, AWWA, CSA and other standards are listed in Table 4. This table gives a brief explanation of the significance of the code digits. It should be recognized that a new material may be commercialized which qualifies for a code designation that has not been recognized as of this writing. For a listing of the most current recognized code designations the reader is invited to consult the periodically updated PPI publication TR-4. Contact PPI via their website, www.plasticpipe.org

TABLE 4
Standard Designation Codes for Current Commercially Available PE Piping Compositions

Standard Designation Code	What the Digits in the Code Denote		
	The 1st Digit	The 2nd Digit	The last two Digits(1)
	Cell Number Based on the Density Cell In accordance with ASTM D3350 (See Table 1)	Cell Number Based on the Resistance to SCG Cell In accordance with ASTM D3350 (2) (See Table 1)	Recommended Standard Hydrostatic Design Stress (HDS) Category, for water, at 73°F (23°C) (psi)
PE2406	Cell number 2	Cell number 4	630
PE2708		Cell number 7	800
PE3408	Cell number 3	Cell number 4	800
PE3608		Cell number 6	
PE3708		Cell number 7	800
PE3710			1,000
PE4708	Cell number 4	Cell number 7	800
PE4710			1,000

(1) The last two digits code the Standard HDS Category in units of 100psi. For example, 06 is the code for 630psi and 10 is the code for 1,000psi.

(2) It should be noted that the lowest Cell number for SCG resistance for pipe is 4. Based on research and experience a rating of at least 4 has been determined as sufficient for the safe absorption of localized stresses for properly installed PE pipe.

Standard Equation for Determining the Major Stress Induced in a Pressurized Pipe

There are two major stresses which are induced in the wall of a closed cylindrical vessel, such as a pipe, when it is subjected to internal fluid pressure. One runs along the axis of the vessel, often called the axial (longitudinal) stress, and the other, which is often called the hoop stress, runs along its circumference. Since the magnitude of the hoop stress is about twice that of the axial stress the hoop stress is considered as the significant stress for purposes of pressure pipe design.

The hoop stress is not constant across a pipe’s wall thickness. It tends to be larger on the inside than on the outside of a pipe. And, this tendency is heightened in the case of materials having high stiffness and in thicker walled pipes. However, in the case of pipes made from thermoplastics – materials which are characterized by significantly lower stiffness than metals – it has long been accepted that the hoop stress is constant through the pipe’s wall thickness. For such case the so called thin-walled hoop stress equation is accepted as satisfactory and it has been adopted by standards which cover thermoplastics pipe. This equation, which more commonly is identified as the ISO (International Organization for Standardization) equation because it has been also adopted for thermoplastic pipes by that organization, is as follows:

(1) $$S = \frac{P}{2}\frac{D_m}{t}$$

WHERE

S **= Hoop stress (psi or, MPa)**
P **= Internal pressure (psi or, MPa)**
D_m **= Mean diameter (in or, mm)**
t **= minimum wall thickness, (in or, mm)**

Because PE pipe is made either to controlled outside diameters or in some cases, to controlled inside diameters the above equation appears in PE pipe standards in one of the following forms:

When the pipe is made to a controlled outside diameter:

(2) $$S = \frac{P}{2}\left[\frac{D_o}{t}-1\right]$$

Where Do is the average outside diameter

When the pipe is made to a controlled inside diameter:

(3) $$S = \frac{P}{2}\left[\frac{D_o}{t}+1\right]$$

Where Di is the average inside diameter

For purposes of pressure pipe design, the pipe's pressure rating (PR) is determined by the hydrostatic design stress (HDS) that is assigned to the material from which the pipe is made. Therefore, Equation (2) can be re-arranged and written in terms of HDS and as follows:

(4) $$PR = \frac{2\,(HDS)}{\left[\frac{D_o}{t}-1\right]}$$

Where PR is the pressure rating (psi or, MPa) and HDS is the hydrostatic design stress (psi or, MPa)

And, Equation (3) becomes:

(5) $$PR = \frac{2\,(HDS)}{\left[\frac{D_t}{t}+1\right]}$$

The term D_o/t is referred to as the *outside diameter dimension ratio* and the term D_i/t as the *inside diameter dimension ratio*. However, the convention in PE pipe standards is to limit these ratios to a standard few. The ASTM terms and abbreviations for these preferences are:

- *Standard Dimension Ratio (SDR)*, for a standard D_o/t dimension ratio
- *Standard Inside Diameter Ratio (SIDR)*, for a standard D_i/t dimension ratio

Standard Diameters

Standard specifications for PE pipe allow the pipe to be made to either controlled inside diameters or, to controlled outside diameters. The inside diameter system, applicable to small diameter sizes only, is intended for use with insert type fittings for which the pipe must have a predicable inside diameter, independent of pipe wall thickness. And the outside diameter systems are intended for use with fittings that require a predictable outside diameter, also independent of wall thickness.

There is but one standard inside diameter sizing convention, SIDR , and this system is based on the inside diameters of the Schedule 40 series of iron pipe sizes (IPS). But there are four standard outside diameter sizing conventions and these are as follows:

- The outside diameters specified for iron pipe sized (IPS) pipe
- The outside diameters specified for ductile iron pipe sizes (DIPS)
- The outside diameters specified for copper tubing sizes (CTS)
- The outside diameters specified by the International Standards Organization (ISO 161/1)

The scope of a consensus standard usually identifies the sizing convention system that is covered by that standard.

PE Pipe Standards are Simplified by the Use of Preferred Values

The most widely accepted standards for PE pipes are those that define pipes which when made to the same Dimension Ratio and from the same kind of material are able to offer the same pressure rating independent of pipe size (See Equations 4 and 5). These standards are commonly referred to as Dimension Ratio/Pressure Rated (DR-PR) so as to distinguish them from other standards, such as those based on Schedule 40 and 80 dimensioning, in which the Dimension Ratio varies from one size to the next.

For the purpose of limiting standard pressure ratings (PR) in DR-PR standards to just those few which adequately satisfy common application requirements these standards require that the Dimension Ratios be one of certain series of established preferred numbers. They also require that the pipe's pressure rating be determined based on a recognized HDS category that is also expressed in terms of a preferred number (See previous discussion on PE pipe material designation code). The preferred numbers for both are derived from the ANSI Preferred Numbers, Series 10. The Series 10 numbers get that name because ten specified steps are required to affect a rise from one power of ten to the next one. Each ascending step represents an increase of about 25% over the previous value. For example, the following are the ANSI specified steps between 10 and 100: are 10; 12.5; 16.0; 20.0; 25.0; 31.5; 40.0; 50.0; 63.0; 80.0; 100.

A beneficial feature of the use of preferred numbers is that when a preferred number is multiplied or, is divided by another preferred number the result is always a preferred number.

The table that follows lists the Standard Dimension Ratios, all based on preferred numbers, which appear in the various ASTM, AWWA and CSA DR-PR based standards for PE pipe.

TABLE 5
Standard Dimension Ratios (SDRs)

Based on Mean Diameter (D_m/t) (Same numerical value as ANSI Preferred Number, Series 10)	Based on Outside Diameter SDR = (D_o/t (Series 10 Number + 1)	Based on Inside Diameter SIDR = (D_i/t) (Series 10 Number – 1)
5.0	6.0	4.0
6.3	7.3	5.3
8.0	9.0	7.0
10.0	11.0	9.0
12.5	13.5	11.5
16.0	17.0	15.0
20.0	21.0	19.0
25.0	26.0	24.0
31.5	32.5	30.5
40.0	41.0	39.0
50.0	51.0	49.0
63.0	64.0	62.0

The recognized standard HDS categories for water, at 73°F (23°C), are: 630 psi (4.34 MPa); 800 psi (5.52 MPa); and 1,000psi (6.90 MPa) (See discussion under the heading, Standard PE Piping Material Designation Code).

And, the standard pressure ratings for water, at 73°F (23°C), which are commonly recognized by DR-PR standard specifications for PE pipe are as follows: 250; 200; 160; 125; 100; 80; 63; 50; and 40 psig. However, individual standards generally only cover a selected portion of this broad range.

The result of the use of these standard preferred number values is that a pipe's standard pressure rating (PR) is a consistent result, independent of pipe size, which simply depends on its standard dimension ratio and the standard HDS of the material from which the pipe was made. This relationship is shown in Table 6, as follows.

TABLE 6
Standard Pressure Ratings for Water, at 73°F (23°C), for SDR-PR Pipes, psig (1)

Standard Dimension Ratio		Standard Pressure Rating (psig) as a function of a Material's HDS for Water, at 73°F (23°C), psi		
SDR (In the Case of Pipes Made to Standard OD's)	SIDR (In the Case of Pipes Made to Standard ID's)	HDS = 630psi (4.34 MPa)	HDS = 800psi (5.52 MPa)	HDS = 1000psi (6.90 MPa)
32.5	30.5	40	50	63
26.0	24.0	50	63	80
21.0	19.0	63	80	100
17.0	15.0	80	100	125
13.5	11.5	100	125	160
11.0	9.0	125	160	200
9.0	7.0	160	200	250

(1) Note: The Standard Pressure Ratings are the calculated values using equations (4) and (5) but with a slight rounding-off so that they conform to a preferred number.

Although the adoption of preferred numbers by the ASTM, CSA and AWWA DR-PR based standards is very widespread, there are a few exceptions. In some DR-PR standards a non-preferred Diameter Ratio has been included so as to define pipes which offer a pressure rating that more closely meets a particular application requirement. In addition, where existing system conditions or special requirements may be better served by other than standard diameters or Standard Dimension Ratios many standards allow for the manufacture of custom sized pipe provided all the performance and quality control requirements of the standard are satisfied and also, provided the proposed changes are restricted to pipe dimensions and that these changes are mutually agreed upon by the manufacturer and the purchaser.

Determining a PE's Appropriate Hydrostatic Design Stress (HDS) Category

As stated earlier, the last two digits of the PE pipe material designation code indicate the material's maximum allowable HDS for water, at 73°F (23°C). This value of HDS is then used for the determining of a pipe's pressure rating. This practice of using an allowable stress, instead of basing design on a particular measure of strength that is reduced by a specified "factor of safety", is recognized by many standards and codes that cover other kinds of pipes and materials. One reason for avoiding the specifying of a factor of safety is that it is misleading because it implies a greater degree of safety than actually exists. This is because a particular laboratory measure of strength only defines a material's reaction to a certain kind of a major test stress whereas, in an actual installation a material can also be subjected to other add-on stresses which can have a significant effect on ultimate performance. To provide a satisfactory cushion against the effect of these add-on stresses the chosen measure of strength is reduced by an appropriate strength reduction factor. But, as can be appreciated, the magnitude of this factor needs to be greater than the resultant true factor of safety.

As discussed in Chapter 3, it is recognized that a very significant strength of PE pressure pipe is its long-term hoop strength based on which it resists the effects of sustained internal hydrostatic pressure. The manner by which this long-term hydrostatic strength (LTHS) is forecast and, the reduction of the resultant LTHS into one of a limited hydrostatic design basis (HDB) strength categories is also described in Chapter 3. As implied by its name, the HDB is a design basis the limitations of which need to be recognized when using it for the establishment of a hydrostatic design stress (HDS). This is done by the choice of an appropriate strength reduction factor. This factor has many functions, but one of the more important ones is the providing of a suitable cushion for the safe absorption of all stresses the pipe may see in actual service, not just the stresses upon which the material's HDB has been determined.

So as not to mistake this strength reduction factor for a true factor of safety it has been designated as a design factor (DF). Furthermore, this factor is a multiplier, having a value of less than 1.0, as compared to a factor of safety which normally is a divisor having a value greater than 1.0. For consistency in design, the DF's are also expressed in terms of a preferred number. Therefore, when an HDB – which is expressed in terms of a preferred number – is reduced by a DF – also, a preferred number – it yields an HDS that is always a preferred number. The resultant value of this HDS becomes part of the standard PE material code designation.

Determining the Appropriate Value of HDS

As explained in Chapter 3, HDB of a PE pipe material is determined on the basis of PE pipe samples that are only subjected to the relatively well distributed stresses that are generated by internal pressure. This test model does not expose the test pipe to other stresses, in particular to the very localized stresses that are intensified by external causes such as by stone impingement or, by scratches and gouges or, by geometric effects inherent in fittings and joints. Extensive field experience and studies indicate that in the case of certain older generation PE materials which have been shown to exhibit low resistance to slow crack growth (SCG) localized stress intensifications can initiate and then, propagate the growth of slowly growing cracks. After some time, when these cracks grow to a size where they span through a pipe's entire wall thickness the end result is a localized fracture. As is the case for traditional piping materials, and as it has been demonstrated to be also the case for plastics, the potential damaging effect of a localized stress intensification depends strongly on the material's ability to safely deform locally and thereby, blunt a nascent crack, a reaction that reduces the magnitude of the localized stress. A feature of modern high performance PE materials is that they offer this ability to a significantly high degree.

To avoid the chance of a failure by the slow crack mechanism a three-fold approach has proven to be very successful:

1. PE pipe, and for that matter, pipe made from any material needs to be handled, joined and installed so as to minimize the development of excessive localized stress intensifications. Requirements for proper handling, joining and installing of PE piping – which are not at all onerous – are covered by standards, guides and manuals issued by ASTM, AWWA and other organizations. They are also described in this Handbook.
2. PE piping materials need to offer adequate resistance to slow crack growth (SCG). All Current commercially available materials meet not less than Cell number 4 of the requirement for resistance to SCG Cell that is specified by ASTM D3350. However, the newer generation of high performance materials have far superior resistance to slow crack growth and therefore, qualify for the Cell number 7 requirement for this property(See Table 1).
3. The design factor (DF) based on which an HDB (hydrostatic design basis) is reduced to and HDS (hydrostatic design stress) needs to leave sufficient cushion for the safe absorption of stresses that are in addition to those upon which the HDB has been established. While the DF has many roles, this is one of the more important ones.

Over 40 years of actual experience and many studies regarding the fracture mechanics behavior of PE pipe materials have shown that when the first two approaches are in play – a principal objective of standards for PE piping – the establishment of an HDS by the reduction of an HDB by means of a DF = 0.50 results in a very reliable and very durable field performance. However, more recent developments in the manufacture of PE resin have resulted in the availability of higher performance PE's that offer exceptional resistance to SCG. These materials, which exceed the requirements for Cell number 7 of the SCG cell in ASTM 3350, have demonstrated that they have a significantly greater capacity for safely shedding-off localized stress intensifications. Consequently, the HDS for these materials does not need to provide the same cushion against localized stress intensifications as established for the traditional materials. It has been determined that for such high performance materials a DF of 0.63 is proven to be reliable.

For a PE pipe material to qualify as a high performance material it must be experimentally demonstrated that it meets the following three requirements:

1. By means of supplementary elevated temperature stress-rupture testing followed by a Rate Process Analysis of the test results it must be demonstrated that at 73°F (23°C) the slope of the stress regression line shall remain linear out to at least 50 years. This means that the failure mode of test samples remains in the ductile region for at least this same time period. This test protocol is referred to as the Substantiation requirement (See Chapter 3 for a discussion of Rate Process and Substantiation methodologies). Such performance at the higher test stresses is an indicator of a PE's very high resistance to SCG at the lower operating stresses.
2. The resistance to SCG of the composition must qualify it for Cell number 7 of the Slow Crack Growth Resistance Cell of ASTM D3350. To qualify, the failure time must exceed 500 hrs when the material is evaluated in accordance with method ASTM F1473. This is a fracture mechanics based method (Described in Chapter 3) which yields an index – one that has been calibrated against actual quality of longer-term field experience – of a PE's capacity for resisting localized stress intensifications that are caused by external (i.e., non-pressure) causes.
3. The LCL (lower confidence limit) ratio of the stress rupture data for these high performance materials has been raised to a minimum of 90 percent. This ratio represents the amount of scatter in the data; it means that the minimum predicted value of the LTS (long term strength) based on statistical analysis of the data shall not be less than 90 percent of it's average predicted value.

A PE material which qualifies for the second of these three requirements is identified by the number 7 as the second numeral in the PE pipe material designation code (For example, PE4710 and PE2708).

It should be evident from the above discussion that the HDS of a PE pipe material is not solely determined by its HDB, a measure of the material's capacity for resisting stresses induced by internal hydrostatic pressure. The HDS that is established needs also to reflect the material's capacity for safely shedding off add-on stresses. Thus, even if two PE pipe materials have the same HDB their allowable HDS's can be different. For this reason PE pipe standards designate a PE by its pipe material designation code, a code which both identifies the material's resistance to SCG and its recommended HDS (See Table 4). The pipe's pressure rating for the standard condition of water and 73°F (23°C) is derived from this HDS. Table A.2 in Chapter 3 (Appendix) lists factors for the determining of a pipe's pressure rating for other temperatures.

As pointed out in Item 3 under this Section's introductory paragraph, the DF has other important roles than just that of allowing for the safe absorption of other than the stresses that are induced by hydrostatic pressure. Included among these roles are the following:

- The hydrostatic design basis (HDB), upon which a DF is applied, is but a design basis that has been established based on a forecast of the average value of the material's hydrostatic strength at a loading that is continually sustained for 100,000hrs (11.4yrs). The DF must give recognition to the fact that a PE's minimum strength is actually somewhat below its predicted average and that the resultant HDS is intended for a loading duration that shall be substantially longer than 11.4 years.
- The forecasted value of a material's long-term hydrostatic strength (LTHS) is established using "perfect" test pipes that have not been subjected to the normal effects of handling and installation and that include no typical components of a piping system.
- The minimum value of material's long-term strength may somewhat vary due to normal variabilities in the processes that are used both in the manufacture of the pipe material and the pipe.
- The forecasted value of a material's LTHS has been established under conditions of constant pressure and temperature whereas in actual service these can vary.

A Widely Recognized Source of HDS Recommendations

Most PE pipe standards that are issued by ASTM establish PE pipe pressure ratings based on the HDS's that are recommended by the Hydrostatic Stress Board (HSB) of the Plastics Pipe Institute. This group has been issuing HDS recommendations for commercial grade materials since the early 1960's. The membership of the HSB is constituted of persons who are recognized experts in the technology of thermoplastic pressure pipe. These experts include representatives from material and pipe producers, testing laboratories, trade associations, a regulatory agency and private consultants. And, all major thermoplastic pipe materials are represented, including polyvinyl chloride (PVC), chlorinated PVC (CPVC), polyethylene (PE), and cross-linked PE (PEX).

The HDS recommendations that are issued by the HSB are based upon a close review of detailed longer-term stress rupture data and they take into account the various factors, as above discussed, that need to be considered when establishing an HDS. The HSB's policies regarding data requirements are presented in PPI publication TR-3, "Policies and Procedures for Developing Hydrostatic Design Basis (HDB), Hydrostatic Design Stresses (HDS), Pressure Design Basis (PDB), Strength Design Basis, and Minimum Required Strength (MRS) Ratings for Thermoplastic Pipe

Materials or Pipe”. A listing of HDS recommendations is offered in the periodically updated publication TR-4, “PPI Listing of Hydrostatic Design Basis (HDB), Hydrostatic Design Stress (HDS), Strength Design Basis (SDB), Pressure Design Basis (PDB) and Minimum Required Strength (MRS) Ratings for Thermoplastic Piping Materials”.

A current edition of both TR-2 and TR-4 can be found at the PPI website www.plasticpipe.org. Also available at this website are other reports, recommendations, notes and model specifications intended to assist users and designers in the optimum use of PE pipe. Each of these publications may be downloaded from this website.

Standard Specifications for Fittings and Joints

One of the best attributes of PE pipe is its ability to be joined by heat fusion (butt, socket and saddle). Butt fusion is performed by heating the ends of the pipe and/or fitting with an electrically heated plate at about 400°F until the ends are molten. The ends are then forced together at a controlled rate and pressure, and held until cooled. Performed properly, this results in a joint that is integral with the pipe itself, is totally leak-proof, and is typically stronger than the pipe itself. Heat fusion joining can also be used for connecting service lines to mains using saddle fittings — even while the main line is in service. Another type of heat fusion is electrofusion. The main difference between conventional heat fusion and electrofusion is the method by which heat is supplied. More complete details of the fusion joining procedure and other methods of joining PE pipe can be found in Chapter 9, “PE Pipe Joining Procedures”.

While heat fusion is a good method for joining PE pipe and fittings, mechanical fittings are another option. Mechanical fittings consist of compression fittings, flanges, or other types of manufactured transition fittings. There are many types and styles of fittings available from which the user may choose. Each offers its particular advantages and limitations for each joining situation the user may encounter.

The chapter on joining polyethylene pipe within this Handbook provides more detailed information on these procedures. It should be noted that, at this time, there are no known adhesives or solvent cements that are suitable for joining polyethylene pipes.

Joining of polyethylene pipe can be done by either mechanical fittings or by heat fusion. All joints and fittings must be designed at the same high level of performance and integrity as the rest of the piping system. For gas distribution systems, the installation of a plastic pipe system must provide that joining techniques comply with Department of Transportation 49 CFR 192 subpart F-Joining of Materials Other Than by Welding. The general requirements for this subpart are:

General

a. The pipeline must be designed and installed so that each joint will sustain the longitudinal pullout or thrust forces caused by contraction or expansion of the piping or by anticipated external or internal loading.

b. Each joint must be made in accordance with written procedures that have been proven by test or experience to produce strong, gas-tight joints.

c. Each joint must be inspected to ensure compliance with this subpart. Within 49 CFR 192 subpart F, 192.281 specifies selected requirements for plastic joints; 192.282 specifies requirements for qualifying joining procedures; 192.285 specifies qualifying persons to make joints; and 192.287 specifies inspection of joints.

Since PE fittings are also subjected to stresses they must also be produced from stress rated PE materials. However, since the geometry of the fittings is different from the pipe, the stress fields induced by internal pressure and by external causes are more complex. Because of this, there are no simple equations that can be used for the design of pressure rated fittings. The practice is to establish fitting pressure ratings by means of testing. Typically, the fitting will be rated to handle the same pressure as the pipe to which it is designed to be joined. If there is a question about the pressure rating of the fitting, the reader is advised to contact the manufacturer.

Specifications for socket, butt fusion, and electrofusion fittings that have been developed and issued by ASTM include:

- D 2683 “Standard Specification for Socket-Type Polyethylene Fittings for Outside Diameter-Controlled Polyethylene Pipe and Fittings.”
- D 3261 “Standard Specification for Butt Heat Fusion Polyethylene (PE) Plastic Fittings for Polyethylene Plastic Pipe and Tubing.”
- F 1055 “Electrofusion Type Polyethylene Fittings for Outside Diameter Controlled Polyethylene Pipe and Tubing.”
- D 2657 “Standard Practice for Heat Fusion Joining of Polyolefin Pipe and Fittings.”

Generic fusion procedures for PE pipe products have also been published by the Plastic Pipe Institute (PPI). They include, TR 33 “ Generic Butt Fusion Joining Procedure for Polyethylene Gas Pipe” and TR 41 “Generic Saddle Fusion Joining Procedure for Polyethylene Gas Pipe.” In addition to these standards and procedures, each manufacturer will have published joining procedures for their pipe and/or fittings. Some of the relevant standards that pertain to fitting performance or joining practices are listed in the Appendix.

Codes, Standards and Recommended Practices for PE Piping Systems

There are a large number of codes, standards and practices that apply to the use of PE piping. These consensus documents cover a broad range of applications for PE pipe and fittings. Some standards pertain to the product performance requirements for a specific application, while other standards are guidelines and practices detailing how a certain type of activity is to be performed. Some are test methods that define exactly how a particular test is to be run so that a direct comparison can be made between results. There are several organizations that issue standards, codes of practice, manuals, guides, and recommendations that deal with the manufacture, testing, performance, and use of PE pipe and fittings. Some of the major ones are discussed below. A more inclusive listing can be found in the Appendix of this chapter.

Plastics Pipe Institute (PPI)

The Plastics Pipe Institute is a trade association dedicated to promoting the proper and effective use of plastics piping systems. The assignment of a recommended hydrostatic design basis for a thermoplastic material falls under the jurisdiction of the Hydrostatic Stress Board - HSB - of the Plastics Pipe Institute. The Hydrostatic Stress Board has the responsibility of developing policies and procedures for the recommendation of the estimated long-term strength for commercial thermoplastic piping materials. The document most widely used for this is Technical Report-3, TR-3 "Policies and Procedures for Developing Hydrostatic Design Bases (HDB), Pressure Design Bases (PDB), Strength Design Bases (SDB), and Minimum Required Strengths (MRS) for Thermoplastic Piping Materials or Pipe." The material stress ratings themselves are published in TR-4, "PPI Listing of Hydrostatic Design Bases (HDB), Strength Design Bases (SDB), Pressure Design Bases (PDB) and Minimum Required Strengths (MRS) Ratings for Thermoplastic Piping Materials or Pipe." There are many other publications pertaining to various aspects of polyethylene pipe available from PPI such as: TN's - Technical Notes, TR's - Technical Reports, Model Specifications, and White Papers on specific positions addressed by the industry. Check the website www.plasticpipe.org for up-to-date publications.

It should be noted that while the Hydrostatic Stress Board (HSB) is a division of the Plastics Pipe Institute, involved in the development and issuance of policies, procedures, and listings of stress and pressure ratings for all thermoplastic pipe materials, PPI itself is an industry association focused on the promotion and effective and proper use of pipe primarily made from polyethylene (PE), cross linked polyethylene (PEX), and polyamide (POM) materials.

ASTM

ASTM International is a consensus standards writing organization, and has published standards for a multitude of materials, products, practices and applications. Those pertaining to polyethylene pipe are found in Volume 8.04 "Plastic Pipe and Building Products." ASTM employees do not write these standards; rather they are written by interested parties and experts within the industry who are members of ASTM. Most anyone can be a member of ASTM and participate in the standard writing process. Other standards, pertaining to plastics in general are found in other books within Volume 8 - 8.01, 8.02, or 8.03.

ASTM Standards pertaining to PE pipe can be a Standard Specification that defines the product requirements and performance for a specific application. It can also be a Standard Practice, which defines how a particular activity is to be performed, or a Standard Test Method, which defines how a particular test on PE pipe, fittings, or materials is to be done. While ASTM standards are mainly used in North America, many are also approved by the American National Standards Institute (ANSI) for international recognition, or are equivalent to an International Standards Organization (ISO) standard. When a manufacturer prints the ASTM Standard on a product, the manufacturer is certifying that the product meets all of the requirements of that standard.

The typical sections included in an ASTM Product Standard are:

Scope – what products and applications are covered under this standard.

Referenced Documents – what other standards or specifications are referenced in this standard.

Terminology – lists definitions that are specific to this standard.

Materials – defines material requirements for products that conform to this standard.

Requirements – details the performance requirements that the product must meet. This section will also contain dimensions.

Test Methods – details how the testing is to be performed to determine conformance to the performance requirements.

Marking – details the print that must be on the product. Includes the standard number, manufacturer's name, size, date of manufacture, and possibly the application such as "water." There may be other wording added to the print as the purchaser requires.

This is only a typical example of sections that may be included. While ASTM has defined protocol for product standards, each one may contain sections unique to that standard. Each standard should be reviewed individually for its requirements.

A listing of major ASTM standards pertaining to PE pipe and fittings is in the Appendix. Current publications of these standards can be found at the website www.astm.org.

ISO

The International Organization for Standardization (ISO) is a network of national standards institutes from 140 countries working in partnership with international organizations, governments, industry, business and consumer representatives.

The ISO committee having jurisdiction for development of plastics pipe standards is Technical Committee 138. The committee's stated scope is: Standardization of pipes, fittings, valves and auxiliary equipment intended for the transport of fluids and made from all types of plastic materials, including all types of reinforced plastics. Metal fittings used with plastics pipes are also included. The main committee has seven subcommittees devoted to specific issues.

TC 138 has 35 participating countries, including the United States and Canada, and 27 observer countries. For ISO matters the United States is represented by the American National Standards Institute (ANSI). Canadian representation is through the Standards Council of Canada (SCC). The United States representation has been passed through ANSI who had delegated it down to ASTM and, who in turn, had delegated it to the Plastics Pipe Institute.

NSF International

NSF International plays a vital role in the use of pipe and fittings for potable water and plumbing applications. NSF is an independent, not-for-profit organization of scientists, engineers, educators and analysts. It is a trusted neutral agency, serving government, industry and consumers in achieving solutions to problems relating to public health and the environment. NSF has three essential missions, as follows:

1. To issue standards that establish the necessary public health and safety requirements for thermoplastic piping materials and for piping products intended for use in the transport of potable water and for drainage and venting systems in plumbing applications.
2. To establish the appropriate test methods by which these requirements are evaluated.
3. To offer a certification program which affirms that a particular product which carries an NSF seal is in compliance with the applicable NSF requirements

NSF standards are developed with the active participation of public health and other regulatory officials, users and industry. The standards specify the requirements for the products, and may include requirements relating to materials, design, construction, and performance.

There are two NSF Standards that are of particular importance to the polyethylene pipe and fittings industry: Standard 14, "Plastic Piping components and Related Materials" and Standard 61, "Drinking Water System Components-Health Effects." Standard 14 includes both performance requirements from product standards and provisions for health effects covered in Standard 61. NSF Standard 14 does not contain performance requirements itself, but rather NSF will certify that a product conforms to a certain ASTM, AWWA, etc... product performance standard. In order to be certified for potable water applications under Standard 14, the product must also satisfy the toxicological requirements of Standard 61.

For products intended for potable water applications, it is also an option to be certified under Standard 61 only, without certifying the performance aspects of the product. In the early 1990's NSF separated the toxicological sections of Standard 14 into a new Standard 61. This was done for several reasons, but mainly to make it easier to bring new, innovative products to market without undue expense and time, while continuing to keep the public safe. This was a great benefit to the industry. Now manufacturers have a choice of staying with Standard 14 or switching to Standard 61. Many manufacturers who have in-house quality programs and the ability to perform the necessary tests switched to this new potable water certification option.

AWWA

The American Water Works Association (AWWA) is a leader in the development of water resource technology. These AWWA standards describe minimum requirements and do not contain all of the engineering and administrative information normally contained in a specification that is written for a particular project. AWWA standards usually contain options that must be evaluated by the user of the standard. Until each optional feature is specified by the user, the product or service is not fully defined. The use of AWWA standards is entirely voluntary. They are intended to represent a consensus of the water supply industry that the product described will provide satisfactory service.

There are currently two AWWA standards that pertain to polyethylene pipe: AWWA C901, "Polyethylene (PE) Pressure Pipe and Tubing, 1/2 inch through 3 inch, for Water Service" and AWWA C906, "Polyethylene (PE) Pressure Pipe and Fittings, 4 inch through 63 inches, for Water Distribution." Standard C901 addresses PE pressure pipe and tubing for use primarily as potable water service lines in the construction of underground distribution systems. It includes dimensions for pipe and tubing made to pressure classes of 80 psi, 100 psi, 125 psi, 160 psi and 250 psi.

This standard covers PE pipe in nominal sizes from ½ inch through 3 inch that are made to controlled outside-diameters based on iron pipe sizes i.e. (OD based IPS size) and also to controlled inside-diameter based on iron pipe sizes i.e. (ID based IPS size). It also covers tubing, ranging in size from ½ inch through 2 inch that conforms to the outside-diameter dimensions of copper tubing sizes (CTS). There are also sections on materials, testing and marking requirements; inspection and testing by manufacturer; and in-plant inspection by purchaser.

AWWA Standard C906 addresses larger diameter PE pressure pipe. The pipe is primarily intended for use in transporting potable water in either buried or above-ground installations. The standard covers 10 standard dimension ratios (SDR's) for nominal pipe sizes ranging from 4 inch through 63 inch. The available pipe sizes are limited by a maximum wall thickness of 3 inch. Pipe outside diameters (OD's) conform to the outside diameter dimensions of iron pipe sizes (IPS), ductile iron pipe size (DIPS), or those established by the International Standards Organization (ISO). Pressure class ratings range from 40 to 250 psig.

AWWA has also published a manual M55, "PE Pipe-Design and Installation". This manual is a design and installation guide for the use of polyethylene pipe in potable water applications. The manual supplements C901 and C906 and provides specific design recommendations as it relates to the use of PE pipe in potable water systems.

Standard Plumbing Codes

Piping systems used in buildings must meet standards that are recognized by the plumbing code adopted by the jurisdiction in which the building is to be located. Within the United States there are several "model" codes, any one of which can be used as the basis for a local jurisdiction's code. Most widely used model codes include the International Plumbing Code (IPC), produced by the International Code Council (ICC) and the Uniform Plumbing Code (UPC), produced by the International Association of Plumbing and Mechanical Officials (IAPMO). One of the model codes may be adopted in its entirety or modified by the jurisdiction. Some states adopt a statewide code which municipalities may or may not be allowed to amend based on state law. Both designers and contractors need to be familiar with the code that applies to a particular project with a specific jurisdiction.

ASME B31.3, Chemical Plant and Petroleum Refinery Piping Code

The proper and safe usage of plastics piping in industrial applications demands that close attention be paid in the design, selection and installation of such piping. Safe design rules and guidelines are set forth in the ASME B31.3 Piping Code. In this code the requirements for plastics piping, including those for PE, are placed in a separate Chapter V1, titled "Nonmetallic Piping and Piping Lined with Nonmetals".

Other Codes and Standards

There are several other codes and standards writing organizations which pertain to polyethylene pipe. These groups usually have a type of certification program for products to be used in a certain industry or application, and may or may not write their own performance standards. If they do not write their own standards, they will certify products to an existing standard such as ASTM, AWWA, etc. The certification process will normally consist of an initial application stating what specific products are requesting certification, an on-site inspection of the production facilities, and testing of the product to assure performance to the relevant product specification. This is followed up by annual random inspections and product testing.

The Canadian Standards Association (CSA) provides a good example of the type of compliance certification program that relates to the use of polyethylene pipe in both water (CSA B137.1) and gas distribution (C137.4) applications. CSA's certification of compliance to the standards to which a particular polyethylene pipe is made allows the producer of that product to place the CSA mark on the product. The presence of the mark assures the purchaser that the product has met the requirements of the CSA certification program and insures that the product meets the appropriate product specifications as determined by the audits and inspections conducted by the Canadian Standards Association.

Factory Mutual

Factory Mutual Research (FM), an affiliate of FM Global, is a non-profit organization that specializes in property loss prevention knowledge. The area that pertains to PE pipe is the FM Standard "Plastic Pipe and Fittings for Underground Fire Protection Service." Certification to this standard may be required by an insurance company for any PE pipe and fittings being used in a fire water system. FM Global requires an initial inspection and audit of production facilities to be assured that the facility has the proper quality systems in place similar to ISO 9000 requirements. Then testing of the pipe must be witnessed by an FM representative. This testing must pass the requirements set forth in the FM Standard for PE pipe. After initial certification, unannounced audits are performed on at least an annual basis. More information can be found at their website www.fmglobal.com, or by calling at (401) 275-3000.

Conclusion

PE resins are produced to cover a very broad range of applications. The physical performance properties of these various formulations of PE vary significantly making each grade suitable for a specific range of applications. To that end, the PE pipe industry has worked diligently to establish effective standards and codes which will assist the designer in the selection and specification of piping systems produced from PE materials which lend themselves to the type of service life sought. As such, the discussion which has been presented here should assist the designer and/or installer in his understanding of these standards and their significance relative to the use of these unique plastic piping materials.

Extensive reference has been made throughout the preceding discussion to standards writing or certifying organizations such as ASTM, AWWA, NSF, etc. The standards setting process is dynamic, as is the research and development that continues within the PE pipe industry. As such, new standards and revisions of existing standards are developed on an ongoing basis. For this reason, the reader is encouraged to obtain copies of the most recent standards available from these various standards organizations.

References

1. ASTM Annual Book of Standards, Volume 8.03 Plastics, (III): D 3100 - Latest, American Society for Testing and Materials, West Conshohocken, PA.
2. ASTM Annual Book of Standards, Volume 8.04 Plastic Pipe and Building Products, American Society for Testing and Materials, West Conshohocken, PA.
3. Plastics Pipe Institute, Various Technical Reports, Technical Notes, Model Specifications, Irving, TX.
4. NSF Standard 14, Plastic Piping Components and Related Materials , NSF International, Ann Arbor, MI.
5. NSF Standard 61, Drinking Water System Components - Health Effects, NSF International, Ann Arbor, MI.

Appendix 1
Major Standards, Codes and Practices

General

ASTM

D 3350	Polyethylene Plastics Pipe and Fittings Materials
D 1598	Time-to-Failure of Plastic Pipe Under Constant Internal Pressure
D 1599	Short-Time Hydraulic Failure Pressure of Plastic Pipe, Tubing and Fittings
D 2122	Determining Dimensions of Thermoplastic Pipe and Fittings
D 2837	Obtaining Hydrostatic Design Basis for Thermoplastic Pipe Materials
D 2488	Description and Identification of Soils (Visual-Manual Procedure)
D 2657	Heat-Joining Polyolefin Pipe and Fittings
D 2683	Socket Type Polyethylene Fittings for Outside Diameter Controlled Polyethylene Pipe and Tubing
F 412	Terminology Relating to Plastic Piping Systems
F 480	Thermoplastic Well Casing Pipe and Couplings Made in Standard Dimension Ratios (SDRs), SCH 40, and SCH 80
F 948	Time-to-Failure of Plastic Piping Systems and Components Under Constant Internal Pressure With Flow
F 1055	Electrofusion Type Polyethylene Fittings for Outside Diameter Controlled Polyethylene Pipe and Tubing
F 1248	Test Method for Determination of Environmental Stress Crack Resistance (ESCR) of Polyethylene Pipe
F1290	Electrofusion Joining Polyolefin Pipe and Fittings
F 1473	Notch Tensile Test to Measure the Resistance to Slow Crack Growth of Polyethylene Pipes and Resins
F 1533	Deformed Polyethylene (PE) Liner
F 1901	Polyethylene (PE) Pipe and Fittings for Roof Drain Systems
F 1962	Standard Guide for Use of Maxi-Horizontal Directional Drilling for Placement of Polyethylene Pipe or Conduit Under Obstacles, Including River Crossing
F 2164	Standard Practice for Field Leak Testing of Polyethylene (PE) Pressure Piping Systems Using Hydrostatic Pressure
F 2231	Standard Test Method for Charpy Impact Test on Thin Specimens of Polyethylene Used in Pressurized Pipes
F 2263	Standard Test Method for Evaluating the Oxidative Resistance of Polyethylene (PE) Pipe to Chlorinated Water
F 2620	Standard Practice for Heat Fusion Joining of Polyethylene Pipe and Fittings

PPI TECHNICAL REPORTS

TR-3	Policies and Procedures for Developing Hydrostatic Design Bases (HDB), Pressure Design Bases (PDB), Strength Design Bases (SDB), and Minimum Required Strengths (MRS) Ratings for Thermoplastic Piping Materials for Pipe
TR-4	PPI Listing of Hydrostatic Design Bases (HDB), Strength Design Bases (SDB), Pressure Design Bases (PDB) and Minimum Required Strength (MRS) Ratings for Thermoplastic Piping Materials or Pipe
TR-7	Recommended Methods for Calculation of Nominal Weight of Solid Wall Plastic Pipe
TR-9	Recommended Design Factors for Pressure Applications of Thermoplastic Pipe Materials
TR-11	Resistance of Thermoplastic Piping Materials to Micro- and Macro-Biological Attack
TR-14	Water Flow Characteristics of Thermoplastic Pipe
TR-18	Weatherability of Thermoplastic Piping Systems
TR-19	Thermoplastic Piping for the Transport of Chemicals
TR-21	Thermal Expansion and Contraction in Plastics Piping Systems
TR-30	Investigation of Maximum Temperatures Attained by Plastic Fuel Gas Pipe Inside Service Risers
TR-33	Generic Butt Fusion Joining Procedure for Polyethylene Gas Pipe
TR-34	Disinfection of Newly Constructed Polyethylene Water Mains
TR-35	Chemical & Abrasion Resistance of Corrugated Polyethylene Pipe
TR-36	Hydraulic Considerations for Corrugated Polyethylene Pipe
TR-37	CPPA Standard Specification (100-99) for Corrugated Polyethylene (PE) Pipe for Storm Sewer Applications
TR-38	Structural Design Method for Corrugated Polyethylene Pipe
TR-39	Structural Integrity of Non-Pressure Corrugated Polyethylene Pipe
TR-41	Generic Saddle Fusion Joining Procedure for Polyethylene Gas Piping

PPI TECHNICAL NOTES

TN-4	Odorants in Plastic Fuel Gas Distribution Systems
TN-5	Equipment used in the Testing of Plastic Piping Components and Materials
TN-6	Polyethylene (PE) Coil Dimensions
TN-7	Nature of Hydrostatic Stress Rupture Curves
TN-11	Suggested Temperature Limits for the Operation and Installation of Thermoplastic Piping in Non-Pressure Applications
TN-13	General Guidelines for Butt, Saddle and Socket Fusion of Unlike Polyethylene Pipes and Fittings
TN-14	Plastic Pipe in Solar Heating Systems
TN-15	Resistance of Solid Wall Polyethylene Pipe to a Sanitary Sewage Environment
TN-16	Rate Process Method for Projecting Performance of Polyethylene Piping Components
TN-17	Cross-linked Polyethylene (PEX) Tubing
TN-18	Long-Term Strength (LTHS) by Temperature Interpolation.
TN-19	Pipe Stiffness for Buried Gravity Flow Pipes
TN-20	Special Precautions for Fusing Saddle Fittings to Live PE Fuel Gas Mains Pressurized on the Basis of a 0.40 Design Factor
TN-21	PPI PENT test investigation
TN-22	PPI Guidelines for Qualification Testing of Mechanical Couplings for PE Pipes in Pressurized Water or Sewer Service
TN-23	Guidelines for Establishing the Pressure Rating for Multilayer and Coextruded Plastic Pipes
TN-35	General Guidelines for Repairing Buried HDPE Potable Water Pressure Pipes
TN-36	General Guidelines for Connecting HDPE Potable Water pressure Pipes to DI and PVC piping Systems
TN-38	Bolt Torque for Polyethylene Flanged Joints
TN-41	High Performance PE Material for Water Piping Applications

Gas Pipe, Tubing and Fittings

ASTM

D 2513	Thermoplastic Gas Pressure Pipe, Tubing and Fittings
F 689	Determination of the Temperature of Above-Ground Plastic Gas Pressure Pipe Within Metallic Castings
F 1025	Selection and Use of Full-Encirclement-Type Band Clamps for Reinforcement or Repair of Punctures or Holes in Polyethylene Gas Pressure Pipe
F 1041	Squeeze-Off of Polyolefin Gas Pressure Pipe and Tubing
F 1563	Tools to Squeeze Off Polyethylene (PE) Gas Pipe or Tubing
F 1734	Practice for Qualification of a Combination of Squeeze Tool, Pipe, and Squeeze-Off Procedure to Avoid Long-Term Damage in Polyethylene (PE) Gas Pipe
F 1924	Plastic Mechanical Fittings for Use on Outside Diameter Controlled Polyethylene Gas Distribution Pipe and Tubing
F 1948	Metallic Mechanical Fittings for Use on Outside Diameter Controlled Thermoplastic Gas Distribution Pipe and Tubing
F 1973	Factory Assembled Anodeless Risers and Transition Fittings in Polyethylene (PE) Fuel Gas Distribution Systems
F 2138	Standard Specification for Excess Flow Valves for Natural Gas Service

PPI

TR-22	Polyethylene Plastic Piping Distribution Systems for Components of Liquid Petroleum Gase
MS-2	Model Specification for Polyethylene Plastic Pipe, Tubing and Fittings for Natural Gas Distribution

OTHER STANDARDS FOR GAS PIPING APPLICATIONS

Title 49, CFR part 192	Transportation of Natural Gas and Other Gas by Pipe Line
AGA	AGA Plastic Pipe Manual for Gas Service (American Gas Association)
API	API Spec 15LE Specification for Polyethylene Line Pipe (American Petroleum Institute)

Water Pipe, Tubing and Fittings and Relatd Practices

ASTM

D 2104	Polyethylene (PE) Plastic Pipe, Schedule 40
D 2239	Polyethylene (PE) Plastic Pipe (SIDR-PR) Based on Controlled Inside Diameter
D 2447	Polyethylene (PE) Plastic Pipe, Schedules 40 to 80, Based on Outside Diameter
D 2609	Plastic Insert Fittings for Polyethylene (PE) Plastic Pipe
D 2683	Socket-Type Polyethylene Fittings for Outside Diameter-Controlled Polyethylene Pipe and Tubing
D 2737	Polyethylene (PE) Plastic Tubing
D 3035	Polyethylene (PE) Plastic Pipe (SDR-PR) Based on Controlled Outside Diameter
D 3261	Butt Heat Fusion Polyethylene (PE) Plastic Fittings for Polyethylene (PE) Plastic Pipe and Tubing
F 405	Corrugated Polyethylene (PE) Tubing and Fittings
F 667	Large Diameter Corrugated Polyethylene (PE) Tubing and Fittings
F 714	Polyethylene (PE) Plastic Pipe (SIDR-PR) Based on Controlled Outside Diameter
F 771	Polyethylene (PE) Thermoplastic High-Pressure Irrigation Pipeline Systems
F 810	Smooth Wall Polyethylene (PE Pipe for Use in Drainage and Waste Disposal Absorption Fields
F 982	Polyethylene (PE) Corrugated Pipe with a Smooth Interior and Fittings
F 894	Polyethylene (PE) Large Diameter Profile Wall Sewer and Drain Pipe
F 905	Qualification of Polyethylene Saddle Fusion Joints
F 1055	Electrofusion Type Polyethylene Fittings for Outside Diameter Controlled Polyethylene Pipe and Tubing
F 1056	Socket Fusion Tools for Use in Socket Fusion Joining Polyethylene Pipe or Tubing and Fittings
F 1759	Standard Practice for Design of High-Density Polyethylene (HDPE) Manholes for Subsurface Applications
F 2206	Standard Specification for Fabricated Fittings of Butt-Fused Polyethylene (PE) Plastic Pipe, Fittings, Sheet Stock, Plate Stock, or Block Stock

PPI

MS-3	Model Specification for Polyethylene Plastic Pipe, Tubing and Fittings for Water Mains and Distribution

AWWA

C 901	Polyethylene (PE) Pressure Pipe, Tubing, and Fittings, 1/2 inch through 3 inch for Water Service
C 906	Polyethylene (PE) Pressure Pipe and Fittings, 4 inch through 63 inch for Water Distribution
M 55	AWWA Manual 55: PE Pipe - Design and Installation

CSA

B 137.1	Polyethylene Pipe, Tubing and Fittings for Cold Water Pressure Services
B137.4	Polyethylene Piping Systems for Gas Services (Canadian Standards Association)

Installation

ASTM

D 2321	Underground Installation of Flexible Thermoplastic Sewer Pipe
D 2774	Underground Installation of Thermoplastic Pressure Piping
F 449	Subsurface Installation of Corrugated Thermoplastic Tubing for Agricultural Drainage or Water Table Control
F 481	Installation of Thermoplastic Pipe and Corrugated Tubing in Septic Tank Leach Fields
F 585	Insertion of Flexible Polyethylene Pipe into Existing Sewers
F 645	Selection, Design and Installation of Thermoplastic Water Pressure Pipe System
F 690	Underground Installation of Thermoplastic Pressure Piping Irrigation Systems
F 1176	Design and Installation of Thermoplastic Irrigation Systems with Maximum Working Pressure of 63 psi
F 1417	Test Method for Installation Acceptance of Plastic Gravity Sewer Lines Using Low-Pressure Air
F 1606	Standard Practice for Rehabilitation of Existing Sewers and Conduits with Deformed Polyethylene (PE) Liner
F 1668	Guide for Construction Procedures for Buried Plastic Pipe
F 1759	Standard Practice for Design of High-Density Polyethylene (HDPE) Manholes for Subsurface Applications
F 1743	Qualification of a Combination of Squeeze Tool, Pipe, and Squeeze-Off Procedures to Avoid Long-Term Damage in Polyethylene (PE) Gas Pipe
F 1804	Determine Allowable Tensile Load For Polyethylene (PE) Gas Pipe During Pull-in Installation
F 1962	Guide for Use of Maxi-Horizontal Directional Drilling for Placement of Polyethylene Pipe of Conduit Under Obstacles, Including River Crossings
F 2164	Standard Practice for Field Leak Testing of Polyethylene (PE) Pressure Piping Systems Using Hydrostatic Pressure

CONDUIT

F 2160	Standard Specification for Solid Wall High Density Polyethylene (HDPE) Conduit Based on Controlled Outside Diameter (OD)
F 2176	Standard Specification for Mechanical Couplings Used on Polyethylene Conduit, Duct, and Innerduct

AMERICAN SOCIETY OF AGRICULTURAL ENGINEERS

S376.1	Design, Installation and Performance of Underground, Thermoplastic Irrigation Pipelines

Chapter 6

Design of PE Piping Systems

Introduction

Design of a PE piping system is essentially no different than the design undertaken with any ductile and flexible piping material. The design equations and relationships are well-established in the literature, and they can be employed in concert with the distinct performance properties of this material to create a piping system which will provide very many years of durable and reliable service for the intended application.

In the pages which follow, the basic design methods covering the use of PE pipe in a variety of applications are discussed. The material is divided into four distinct sections as follows:

Section 1 covers Design based on Working Pressure Requirements. Procedures are included for dealing with the effects of temperature, surge pressures, and the nature of the fluid being conveyed, on the sustained pressure capacity of the PE pipe.

Section 2 deals with the hydraulic design of PE piping. It covers flow considerations for both pressure and non-pressure pipe.

Section 3 focuses on burial design and flexible pipeline design theory. From this discussion, the designer will develop a clear understanding of the nature of pipe/soil interaction and the relative importance of trench design as it relates to the use of a flexible piping material.

Finally, **Section 4** deals with the response of PE pipe to temperature change. As with any construction material, PE expands and contracts in response to changes in temperature. Specific design methodologies will be presented in this section to address this very important aspect of pipeline design as it relates to the use of PE pipe.

This chapter concludes with a fairly extensive appendix which details the engineering and physical properties of the PE material as well as pertinent pipe characteristics such as dimensions of product produced in accordance with the various industry standards.

Section 1
Design Based on Required Pressure Capacity

Pressure Rating

The methodology for arriving at the standard pressure rating, PR, for PE pipe is discussed in detail in Chapter 5. The terms pressure rating (PR), pressure class (PC), are used in various consensus standards from ASTM, AWWA, CSA and others to denote the pipe's capacity for safely resisting sustained pressure, and typically is inclusive of the capacity to resist momentary pressure increases from pressure surges such as from sudden changes in water flow velocity. Consensus standards may treat pressure surge capacity or allowances differently. That treatment may vary from the information presented in this handbook. The reader is referred to the standards for that specific information.

Equations 1-1 and 1-2 utilize the Hydrostatic Design Stress, HDS, at 73ºF (23ºC) to establish the performance capability of the pipe at that temperature. HDS's for various PE pipe materials are published in PPI TR-4, "PPI Listing of Hydrostatic Design Basis (HDB), Hydrostatic Design Stress (HDS), Strength Design Basis (SDB), Pressure Design Basis (PDB) and Minimum Required Strength (MRS) Ratings for Thermoplastic Piping Materials". Materials that are suitable for use at temperatures above 100ºF (38ºC) will also have elevated temperature Hydrostatic Design Basis ratings that are published in PPI TR-4.

The PR for a particular application can vary from the standard PR for water service. PR is reduced for pipelines operating above the base design temperatures, for pipelines transporting fluids that are known to have some adverse effect on PE, for pipelines operating under Codes or Regulations, or for unusual conditions. The PR may be reduced by application of a factor to the standard PR. For elevated temperature applications the PR is multiplied by a temperature factor, F_T. For special fluids such as hydrocarbons, or regulated natural gas, an environmental application factor, A_F, is applied. See Tables 1-2 and Appendix, Chapter 3.

The reader is alerted to the fact that the form of the ISO equation presented in Equations 1-1 and 1-2 has changed from the form of the ISO equation published in the previous edition of the PPI PE Handbook. The change is to employ HDS rather than HDB, and is necessitated by the additional ratings available for high performance materials. In the earlier form of the ISO equation, PR is given as a function of the HDB, not the HDS as in Equations 1-1 and 1-2. This difference is significant and can result in considerable error if the reader uses the Environmental Applications Factors given in Table 1-2 as the "Design Factor" in the HDB form of the ISO equation.

(1-1)

$$PR = \frac{2\ HDS\ F_T\ A_F}{(DR\text{-}1)}$$

(1-2)

$$PR = \frac{2\ HDS\ F_T\ A_F}{(IDR+1)}$$

WHERE

PR **= Pressure rating, psi**

HDS **= Hydrostatic Design Stress, psi (Table 1-1)**

A_F = Environmental Application Factor (Table 1-2)

NOTE: The environmental application factors given in Table 1-2 are not to be confused with the Design Factor, DF, used in previous editions of the PPI Handbook and in older standards.

F_T = Service Temperature Design Factor (See Appendix to Chapter 3)

DR **= OD -Controlled Pipe Dimension Ratio**

(1-3)

$$DR = \frac{D_O}{t}$$

D_O **= OD-Controlled Pipe Outside Diameter, in.**

t **= Pipe Minimum Wall Thickness, in.**

IDR **= ID -Controlled Pipe Dimension Ratio**

(1-4)

$$IDR = \frac{D_I}{t}$$

D_I **= ID-Controlled Pipe Inside Diameter, in.**

TABLE 1-1
Hydrostatic Design Stress and Service Temperatures

Property	**Standard**	**PE 2606, PE2706**	**PE 2708, PE 3608, PE 3708, PE 4608**	**PE 3710, PE 4710**
Hydrostatic Design Stress, HDS at 73°F (23°C)	ASTM D2837 & PPI TR-3	630 psi (4.6 MPa)	800 psi (5.5 MPa)	1000 psi (6.9 MPa)
Maximum recommended operating temperature for Pressure Service*	-	140°F (60°C)	140°F (60°C)	140°F (60°C)
Maximum recommended operating temperature for Non-Pressure Service	-	180°F (82°C)	180°F (82°C)	180°F (82°C)

* Some PE piping materials are stress rated at temperatures as high as 180°F. For more information regarding these materials and their use, the reader is referred to PPI, TR-4.

The Hydrostatic Design Stress, HDS, is the safe long-term circumferential stress that PE pipe can withstand. It is derived by applying an appropriate design factor, DF, to the Hydrostatic Design Basis, HDB. The method for establishing the Hydrostatic Design Stress for PE pipe is described in Chapters 3 and 5.

At the time of this printing, AWWA is in the process of revising AWWA C906 to incorporate PE4710 material and to use the HDS values in Table 1-1. The version in effect at the time of this printing, AWWA C906-07, limits the maximum Hydrostatic Design Stress to 800 psi for HDPE and to 630 psi for MDPE. AWWA C901-08 has been revised to incorporate the materials listed in Table 1-1.

The Environmental Application Factor is used to adjust the pressure rating of the pipe in environments where specific chemicals are known to have an effect on PE and therefore require derating as described in Chapter 3. Table 1-2 gives Environmental Applications Factors, A_F, which should only be applied to pressure equations (see Equations 1-1 and 1-2) based on the HDS, not the HDB.

TABLE 1-2
PE Pipe Environmental Application Factors (A_F)*

Pipe Environment	Environmental Application Factor (A_F) at 73°F (23°C)
Water: Aqueous solutions of salts, acids and bases; Sewage; Wastewater; Alcohols; Glycols (anti-freeze solutions)	1.0
Nitrogen; Carbon dioxide; Methane; Hydrogen sulfide; Non-Federally regulated applications involving dry natural gas or other non-reactive gases	1.0
Fluids such as solvating/permeating chemicals in pipe or soil (typically hydrocarbons) in 2% or greater concentration, natural or other fuel-gas liquids condensates, crude oil, fuel oil, gasoline, diesel, kerosene, hydrocarbon fuels, wet gas gathering, multiphase oilfield fluids, LVP liquid hydrocarbons, oilfield water containing >2% hydrocarbons.	0.5

* Certain codes and standards include prohibitions and/or strength reduction factors relating to the presence of certain constituents in the fluid being transported. In a code controlled application the designer must ensure compliance with all code requirements.

When choosing the environmental applications factor (A_F), consideration must be given to Codes and Regulations, the fluid being transported, the external environment, and the uncertainty associated with the design conditions of internal pressure and external loads.

The pressure rating (PR) for PE pipe in water at 73°F over the range of typical DR's is given in Tables 1-3 A and 1-3 B in this chapter.

Pressure Rating for Fuel Gas Pipe

Compared to other common thermoplastic pipes, PE pipe can be used over a broader temperature range. For pressure applications, it has been successfully used from -40ºF (-40ºC) to 140ºF (60ºC). In the case of buried non-pressure applications it has been used for conveying fluids that are at temperatures as high as 180°F (82°C). See Table 1-1. For pressure applications above 80ºF (27ºC) the Service Temperature Design Factor is applied to determine the pressure rating. See Table A.2 in the Appendix to Chapter 3.

The pressure rating for gas distribution and transmission pipe in US federally regulated applications is determined by Title 49, Transportation, of The Code of Federal Regulations. Part 192 of this code, which covers the transportation of natural and other gases, requires that the maximum pressure rating (PR) of a PE pipe be determined based on an HDS that is equal to the material's HDB times a DF of 0.32. (See Chapter 5 for a discussion of the Design Factor, DF.) This is the equivalent of saying that for high density PE pipe meeting the requirements of ASTM D2513 the HDS is 500 psi at 73ºF and for medium density PE pipe meeting D2513 the HDS is 400 psi at 73ºF. There are additional restrictions imposed by this Code, such as the maximum pressure at which a PE pipe may be operated (which at the time of this writing is 125 psi for pipe 12-in and smaller and 100 psi for pipe larger than 12-in through 24-in.) and the acceptable range of operating temperatures. The temperature design factors for federally regulated pipes are different than those given in Table A.2 in the Appendix to Chapter 3. Consult with the Federal Regulations to obtain the correct temperature design factor for gas distribution piping.

At the time of this writing, there is an effort underway to amend the US federal code to reflect changes already incorporated in ASTM F714 and D3035. When amended, these changes will increase the pressure rating (PR) of pipe made with high performance PR resins - those that meet the higher performance criteria listed in Chapter 5 (see "Determining the Appropriate Value of HDS"), to be 25% greater than pressure ratings of pipe made with 'traditional' resins.

In Canada gas distribution pipe is regulated per CSA Z662-07. CSA allows a design factor of 0.4 to be applied to the HDB to obtain the HDS for gas distribution pipe.

PE pipe meeting the requirements of ASTM D2513 may be used for the regulated distribution and transmission of liquefied petroleum gas (LPG). NFPA/ANSI 58 recommends a maximum operating pressure of 30 psig for LPG gas applications involving polyethylene pipe. This design limit is established in recognition of the higher condensation temperature for LPG as compared to that of natural gas and, thus, the maximum operating pressure is recommended to ensure that plastic pipe is not subjected to excessive exposure to LPG condensates. The Environmental Application Factor for LP Gas Vapors (propane, propylene, and butane) is 0.8 with a maximum HDS of 800 psi at 73°F for HDPE and 630 psi for MDPE. For further information the reader is referred to PPI's TR-22, Polyethylene Piping Distribution Systems for Components of Liquid Petroleum Gases.

The pressure rating for PE gas gathering lines in the US may differ depending upon the class location (population density) of the gathering line. Gas gathering lines in Class 2, 3 and 4 locations are regulated applications and subject to US federal codes the same as gas distribution and transmission lines. Gas gathering lines in Class 1 locations are not regulated in accordance with US federal codes, and may be operated at service pressures determined using Equation 1-1. Non-regulated gas gathering lines may use PE pipe meeting ASTM F2619 or API 15LE, and may be larger than 24" diameter. PE pipe meeting ASTM D2513 is not required for non-regulated gas gathering lines.

In Canada, PE gas gathering lines are regulated in accordance with CSA Z662 Clause 13.3 and are required to meet API 15LE. PE gas gathering lines may be operated at service pressures equivalent to those determined using Equation 1-1.

Pressure Rating for Liquid Flow Surge Pressure

Surge pressure events, which give rise to a rapid and temporary increase in pressure in excess of the steady state condition, are the result of a very rapid change in velocity of a flowing liquid. Generally, it is the fast closing of valves and uncontrolled pump shutdowns that cause the most severe changes and oscillations in fluid velocity and, consequently in temporary major pressure oscillations. Sudden changes in demand can also lead to lesser but more frequent pressure oscillations. For many pipe materials repeated and frequent pressure oscillations can cause gradual and cumulative fatigue damage which necessitate specifying higher pressure class pipes than determined solely based on sustained pressure requirements. And, for those pipe materials a higher pressure class may also be required for avoiding pipe rupture under the effect of occasional but more severe high-pressure peaks. Two properties distinguish PE pipes from these other kinds of pipes. The first is that because of their lower stiffness the peak value of a surge pressures that is generated by a sudden change in velocity is significantly lower than for higher stiffness pipes such as metallic pipes. And, the second is that a higher pressure rating (PR), or pressure class (PC), is generally not required to cope with the effects of pressure surges. Research, backed by extensive actual experience, indicates that PE pipes can safely tolerate the commonly observed maximum peak temporary surge pressure of twice the steady state condition. Furthermore, the long-term strength of PE pipes is not adversely affected by repeated cyclic loading – that is, PE pipes are very fatigue resistant.

In the design of PE pipe, pressure surges are generally classified as Occasional pressure surges, Recurring pressure surges, and Negative pressures.

- Occasional surge pressures are caused by emergency operations such as fire flow or as a result of a malfunction, such as a power failure or system component failure, which includes pump seize-up, valve stem failure and pressure relief valve failure.
- Recurring surge pressures are inherent to the design and operation of a system. Recurring surge pressures can be caused by normal pump start up or shut down, normal valve opening and closing, and/or "background" pressure fluctuations associated with normal pipe operation.
- Negative pressure may be created by a surge event and cause a localized collapse by buckling. (Negative pressure may also occur inside flowing pipelines due to improper hydraulic design.)

In recognition of the performance behavior of PE pipes the following design principles have been adopted by AWWA for all PE pressure class (PC) rated pipes. These design principles, which are as follows, are also applicable to PE water pipes that are pressure rated (PR) in accordance with ASTM and CSA standards:

1. Resistance to Occasional Pressure Surges:

- The resultant total pressure – sustained plus surge – must not exceed 2.0 times the pipe's temperature compensated pressure rating (PR). See Tables 1-3 A and 1-3 B for standard surge allowances when the pipe is operated at its full rated pressure.
- In the rare case where the resultant total pressure exceeds 2.0 times the pipe's temperature adjusted PR, the pipe must be operated at a reduced pressure so that the above criterion is satisfied. In this event the pipe's reduced pressure rating is sometimes referred to as the pipe's "working pressure rating" (WPR), meaning that for a specific set of operating conditions (temperature, velocity, and surge) this is the pipe's pressure rating. AWWA uses the term WPR not just for a reduced pressure rating but for any pressure rating based on application specific conditions. Where the total pressure during surge does not exceed the standard allowance of 2.0 (occasional) and 1.5 (recurring) the WPR equals the temperature adjusted PR.
- The maximum sustained pressure must never exceed the pipe's temperature adjusted pressure rating (PR).

Example:

A PE pipe has a DR = 17 and is made from a PE4710 material. Accordingly, its standard pressure rating (PR) for water, at 73°F is 125 psi (See Table A.1 in Appendix to Chapter 3). The maximum sustained water temperature shall remain below 73°F. Accordingly, no temperature compensation is required and therefore, the pipe's initial WPR is equal to its standard PR or, 125 psi.

Let us first assume that the maximum occasional surge pressure shall never exceed 120 psi. Since a WPR of 125 psi plus a surge of 120 psi is less than 2 times 125 psi the pipe's initial WPR of 125 psi remains at that value.

Now let us assume a second case in which the maximum occasional surge pressure can be as high as 150 psi. This pressure plus the pipe's initial WPR of 125 psi result in a total momentary pressure of 275 psi, which is 25 psi above the limit of 2 x 125 psi = 250 psi. To accommodate this 25 psi excess it is necessary to reduce the pipe's initial WPR of 125 to a final WPR of 100 psi.

2. Resistance to Recurring Pressure Surges:

- The resultant total momentary pressure – sustained plus surge – must not exceed 1.5 times the pipe's temperature adjusted pressure rating (PR). See Tables 1-3 A and 1-3 B for standard surge allowance when the pipe is operated at its full rated pressure.
- In the rare case where the resultant total pressure exceeds 1.5 times the pipe's temperature adjusted PR the pressure rating must be reduced to the pipe's WPR so that the above criterion is satisfied.
- The maximum sustained pressure must never exceed the pipe's temperature adjusted PR.

3. Resistance to Localized Buckling When Subjected to a Negative Pressure Generated by a Surge Event

A buried pipe's resistance to localized buckling while under the combined effect of external pressure and a very temporary full vacuum should provide an adequate margin of safety. The design for achieving this objective is discussed in a later section of this chapter. It has been shown that a DR21 pipe can withstand a recurring negative pressure surge equal to a full vacuum at 73°F. Higher DR pipes may also be able to withstand a recurring negative surge equal to full vacuum if they are properly installed and have soil support. Their resistance may be calculated using Luscher's Equation presented later in this chapter.

Estimating the Magnitude of Pressure Surges

Regardless of the type of pipe being used surge or water hammer problems can be complex especially in interconnected water networks and they are best evaluated by conducting a formal surge analysis (See References 25 and 32). For all water networks, rising mains, trunk mains and special pump/valve circumstances a detailed surge analysis provides the best way of anticipating and designing for surge.

Absent a formal surge analysis, an estimate of the magnitude of a surge pressure can be made by evaluating the surge pressure that results from an anticipated sudden change in velocity in the water flowing inside a PE pipe.

An abrupt change in the velocity of a flowing liquid in a pipe generates a pressure wave. The velocity of the wave may be determined using Equation 1-5.

(1-5)

$$a = \frac{4660}{\sqrt{1 + \frac{K_{BULK}}{E_d}(DR - 2)}}$$

WHERE

a = **Wave velocity (celerity), ft/sec**

K_{BULK} = **Bulk modulus of fluid at working temperature (typically 300,000 psi for water at 73°F)**

E_d = **Dynamic instantaneous effective modulus of pipe material (typically 150,000 psi for all PE pipe at 73°F (23°C)); see Appendix to Chapter 3**

DR = **Pipe dimension ratio**

The resultant transient surge pressure, Ps, may be calculated from the wave velocity, a, and the sudden change in fluid velocity, ΔV.

(1-6)

$$P_s = a\left(\frac{\Delta V}{2.31g}\right)$$

WHERE

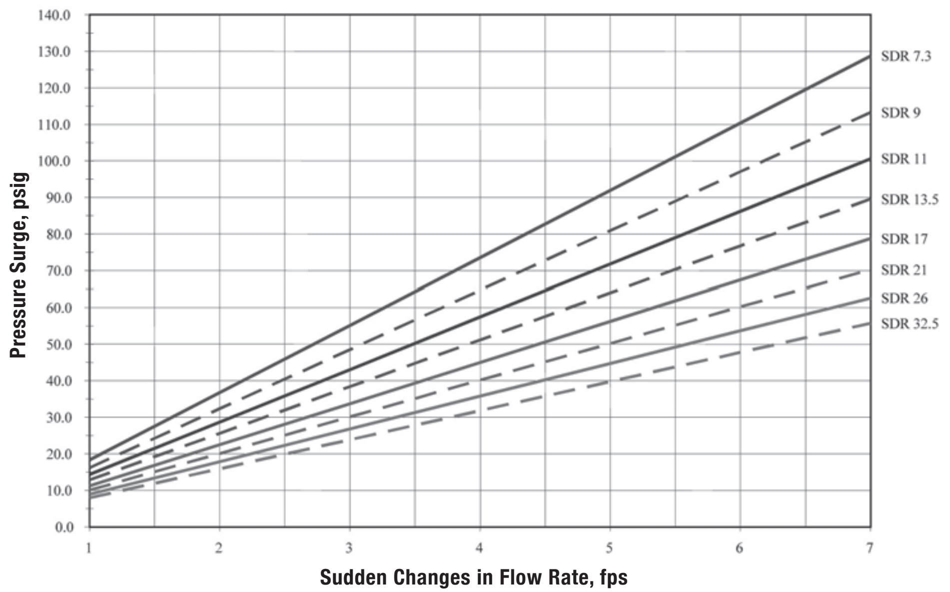
P_S = **Transient surge pressure, psig**

a = **Wave velocity (celerity), ft/sec**

ΔV = **Sudden velocity change, ft/sec**

g = **Constant of gravitational acceleration, 32.2 ft/sec^2**

Figure 1-1 represents the pressure surge curves for all PE pipes as calculated using Equations 1-5 and 1-6 for Standard Dimension Ratios (SDR's).



* A value of 150,000 psi and 300,000 psi were used for E_d and K, respectively.

**Calculated surge pressure values applicable to water at temperatures not exceeding 80°F (27°C).

Figure 1-1 Sudden Velocity Change vs. Pressure Surge for All PE Pipes

The surge pressure values in Figure 1-1 are based on a sudden change in velocity, which may more often be the case for events like a sudden pump shut-down or a rapid valve closure. A sudden shut-down or a rapid closure occurs faster than the "critical time" (the time it takes a pressure wave initiated at the beginning of a valve closing to return again to the valve). Under ordinary operations, during which valve closings and pump shut-downs are slower than the "critical time", the actual pressure surge is smaller than that in Figure 1-1. The "critical time" is determined by means of the following relationship:

(1-7) $$T_{CR} = 2L/a$$

WHERE

T_{CR} **= critical time, seconds**

L **= distance within the pipeline that the pressure wave moves before it is reflected back by a boundary condition, ft**

a **= wave velocity (celerity) of pressure wave for the particular pipe, ft/s. (See Equation 1-5)**

Generally, PE pipe's capacity for safely tolerating occasional and frequently occurring surges is such that seldom are surge pressures large enough to require a de-rating of the pipe's static pressure rating. Tables 1-3 A and 1-3 B show the maximum allowable sudden changes in water flow velocity (ΔV) that are safely tolerated without the need to de-rate the pressure rating (PR) or, the pressure class (PC), of a PE pipe. If sudden changes in velocity are expected to be greater than the values shown in these Tables, they then must be accommodated by lowering the pipe's static pressure rating. As previously discussed, the new rating is called the working pressure rating (WPR).The procedure for establishing a WPR has been discussed earlier in this Section.

TABLE 1-3A

Allowances for Momentary Surge Pressures Above PR or PC for Pipes Made From PE4710 and PE3710 Materials[1].

Pipe Standard Diameter Ratio (SDR)	Standard Static Pressure Rating (PR) or, Standard Pressure Class (PC) for water @ 73°F, psig	Standard Allowance for Momentary Surge Pressure Above the Pipe's PR or PC			
		Allowance for Recurring Surge		Allowance for Occasional Surge	
		Allowable Surge Pressure, psig	Resultant Allowable Sudden Change in Velocity, fps	Allowable Surge Pressure, psig	Resultant Allowable Sudden Change in Velocity, fps
32.5	63	32	4.0	63	8.0
26	80	40	4.5	80	9.0
21	100	50	5.0	100	10.0
17	125	63	5.6	125	11.2
13.5	160	80	6.2	160	12.4
11	200	100	7.0	200	14.0
9	250	125	7.7	250	15.4
7.3	320	160	8.7	320	17.4

1. AWWA C906-07 limits the maximum Pressure Class of PE pipe to the values shown in Table B. At the time of this printing C906 is being revised to allow PC values in Table A to be used for PE3710 and PE4710 materials. Check the latest version of C906

TABLE 1-3 B

Allowances for Momentary Surge Pressures Above PR or PC for Pipes Made from PE 2708, PE3408, PE3608, PE3708 and PE4708 Materials.

Pipe Standard Diameter Ratio (SDR)	Standard Static Pressure Rating (PR) or, Standard Pressure Class (PC), for Water @ 73°F, psig	Standard Allowance for Momentary Surge Pressure Above the Pipe's PR or PC			
		Allowance for Recurring Surge		Allowance for Occasional Surge	
		Allowable Surge Pressure, psig	Resultant Allowable Sudden Change in Velocity, fps	Allowable Surge Pressure, psig	Resultant Allowable Sudden Change in Velocity, fps
32.5	50	25	3.1	50	6.2
26	63	32	3.6	63	7.2
21	80	40	4.0	80	8.0
17	100	50	4.4	100	8.8
13.5	125	63	4.9	125	9.8
11	160	80	5.6	160	11.2
9	200	100	6.2	200	12.4
7.3	250	125	6.8	250	13.6

The surge pressure allowance in Table 1-3 A and 1-3 B are not the maximum surge limits that the pipe can safely withstand. Higher surge pressures can be tolerated in pipe where the working pressure rating (WPR) of the pipe is limited to a pressure less than the pressure rating (PR). This works because the combined total pressure for surge and for pumping pressure is limited to 1.5 times the PR (or PC) for recurring surge and 2.0 times the PR (or PC) for occasional surge. If the pumping pressure is less than the PR (or PC) then a higher surge than the standard allowance given in Table A and B is permitted. The maximum permitted surge pressure is equal to 1.5 x PR – WP for recurring surge and 2.0 x PR – WP for occasional surge, where WP is the pumping or working pressure of the pipeline. For example a DR21 PE4710 pipe with an operating pressure of 80 psi can tolerate a recurring surge pressure of 1.5 x 100 psi – 80 psi = 70 psi. Note that in all cases WP must be equal or less than PR.

Controlling Surge Pressure Reactions

Reducing the rate at which a change in flow velocity occurs is the major means by which surge pressure rises can be minimized. Although PE pipe is very tolerant of such rises, other non-PE components may not be as surge tolerant; therefore, the prudent approach is to minimize the magnitude of surge pressures by taking reasonable precautions to minimize shock. Hydrants, large valves, pumps, and all other hydraulic appurtenances that may suddenly change the velocity of a column of water should be operated slowly, particularly during the portion of travel near valve closing which has the larger effect on rate of flow. If the cause of a major surge can be attributable to pump performance – especially, in the case of an emergency stoppage – then, proper pressure relief mechanisms should be included. These can include traditional solutions such as by providing flywheels or by allowing the pumps to run backwards.

In hilly regions, a liquid flow may separate at high points and cause surge pressures when the flow is suddenly rejoined. In such cases measures should be taken to keep the pipeline full at all times. These can consist of the reducing of the flow rate, of the use at high points of vacuum breakers or, of air relief valve.

Also, potential surge pressure problems should be investigated in the design of pumping station piping, force mains, and long transmission lines. Proven and suitable means should be provided to reduce the effect of surges to a minimum that is practicable and economical. Although PE pipe is much more tolerant of the effect of sudden pressure increases traditional measures should be employed for the minimizing of the occurrence of such increases.

Section 2

Hydraulic Design of PE Pipe

This section provides design information for determining the required flow diameter for PE pipe. It also covers the following topics: general fluid flows in pipe and fittings, liquid (water and water slurry) flow under pressure, non-pressure(gravity) liquid flow, and compressible gas flow under pressure. Network flow analysis and design is not addressed. (1,2)

The procedure for piping system design is frequently an iterative process. For pressure liquid flows, initial choice of pipe flow diameter and resultant combinations of sustained internal pressure, surge pressure, and head loss pressure can affect pipe selection. For non-pressure systems, piping design typically requires selecting a pipe size that provides adequate reserve flow capacity and a wall thickness or profile design that sufficiently resists anticipated static and dynamic earthloads. This trial pipe is evaluated to determine if it is appropriate for the design requirements of the application. Evaluation may show that a different size or external load capacity may be required and, if so, a different pipe is selected then reevaluated. The Appendix to Chapter 3 provides engineering data for PE pipes made to industry standards that are discussed in this chapter and throughout this handbook.

Pipe ID for Flow Calculations

Thermoplastic pipes are generally produced in accordance with a dimension ratio (DR) system. The dimension ratio, DR or IDR, is the ratio of the pipe diameter to the respective minimum wall thickness, either OD or ID, respectively. As the diameter changes, the pressure rating remains constant for the same material, dimension ratio and application. The exception to this practice is production of thermoplastic pipe in accordance with the industry established SCH 40 and SCH 80 dimensions such as referenced in ASTM D 2447.

Flow Diameter for Outside Diameter Controlled Pipe

OD-controlled pipe is dimensioned by outside diameter and wall thickness. Several sizing systems are used including IPS, which specifies the same OD's as iron pipe sized (IPS) pipe: DIPS pipe which specifies the same OD's as ductile iron pipe; and CTS, which specifies the same OD's as copper tubing sizes. For flow calculations, inside diameter is calculated by deducting twice the average wall thickness from the specified outside diameter. OD-controlled pipe standards include ASTM D2513, ASTM D2737, ASTM D2447, ASTM D3035, ASTM F714, AWWA C901, AWWA C906 and API 15LE.(3,4,5,6,7,8,9,10) The Appendix to this chapter provides specific dimensional information for outside diameter controlled PE pipe and tubing that is made to dimension ratio (DR) requirements in accordance with a number of different ASTM, AWWA, CSA and API standards.

The average inside diameter for such pipes has been calculated using Equation 2-1. Typically, wall thickness is specified as a minimum dimension, and a plus 12% tolerance is applied. In this equation, the average ID is determined by deducting twice the average wall thickness (minimum wall thickness plus a tolerance of 6%) from the average outside diameter.

(2-1)

$$D_I = D_O - 2.12\left(\frac{D_O}{DR}\right)$$

WHERE

D_I **= pipe average inside diameter, in**

D_O **= specified average value of pipe outside diameter, in**

DR **= dimension ratio**

(2-2)

$$DR = \frac{D_O}{t}$$

t = pipe minimum wall thickness, in

Pipe Diameter for ID Controlled Pipe

Standards for inside diameter controlled pipes provide average dimensions for the pipe inside diameter that are used for flow calculations. ID-controlled pipe standards include ASTM D2104, ASTM D2239, ASTM F894 and AWWA C901. (11,12,13)

The terms “DR” and “IDR” identify the diameter to wall thickness dimension ratios for outside diameter controlled and inside diameter controlled pipe, respectively. When those ratios comply with standard values they are called “standard dimension ratios”, that is SDR or SIDR. A discussion of standard dimension ratios is included in Chapter 5.

Fluid Flow in PE Piping

Head Loss in Pipes – Darcy-Weisbach/Colebrook/Moody

Viscous shear stresses within the liquid and friction along the pipe walls create resistance to flow within a pipe. This resistance results in a pressure drop, or loss of head in the piping system.

The Darcy-Weisbach formula, Equation 2-3., and the Colebrook formula, Equation 2-6, are generally accepted methods for calculating friction losses due to liquids flowing in full pipes.(15,16) These formulas recognize dependence on pipe bore and pipe surface characteristics, liquid viscosity and flow velocity.

The Darcy-Weisbach formula is:

(2-3)

$$h_f = f \frac{L V^2}{d' 2g}$$

WHERE

h_f **= friction (head) loss, ft. of liquid**

L **= pipeline length, ft.**

d' **= pipe inside diameter, ft.**

V **= flow velocity, ft/sec.**

f **= friction factor (dimensionless, but dependent upon pipe surface roughness and Reynolds number)**

g **= constant of gravitational acceleration (32.2ft/sec^2)**

The flow velocity may be computed by means of the following equation

(2-4)

$$V = \frac{0.4085 \ Q}{D_1^{\ 2}}$$

WHERE

Q **= flow rate, gpm**

D_I **= pipe inside diameter, in**

Liquid flow in pipes will assume one of three flow regimes. The flow regime may be laminar, turbulent or in transition between laminar and turbulent. In laminar flow (Reynolds number, Re, below 2000), the pipe's surface roughness has no effect and is considered negligible. As such, the friction factor, *f*, is calculated using Equation 2-5.

(2-5)

$$f = \frac{64}{\text{Re}}$$

WHERE

Re **= Reynolds number, dimensionless = < 2000 for laminar flow, see Equation 2-7**

> 4000 for turbulent flow, see Figure 2-1

For turbulent flow (Reynolds number, Re, above 4000), the friction factor, *f*, is dependent on two factors, the Reynolds number and pipe surface roughness. The resultant friction factor may be determined from Figure 2-1, the Moody Diagram. This factor applies to all kinds of PE's and to all pipe sizes(17). In the Moody Diagram, relative roughness, ε/d (see Table 2-1 for ε) is used which is the ratio of absolute roughness to the pipe inside diameter. The friction factor may also be determined using the Colebrook formula. The friction factor can also be read from the Moody diagram with enough accuracy for calculation.

The Colebrook formula is:

(2-6)
$$\frac{1}{\sqrt{f}} = -2\log_{10}\left\{\frac{\varepsilon}{3.7\,d'} + \frac{2.51}{\mathrm{Re}\sqrt{f}}\right\}$$

For Formulas 2-5 and 2-6, terms are as previously defined, and:

ε **= absolute roughness, ft. (see Table 2-1)**
R_e **= Reynolds number, dimensionless (see Equation 2-5)**

Liquid flow in a pipe occurs in one of three flow regimes. It can be laminar, turbulent or in transition between laminar and turbulent. The nature of the flow depends on the pipe diameter, the density and viscosity of the flowing fluid, and the velocity of flow. The numerical value of a dimensionless combination of these parameters is known as the Reynolds number and the resultant value of this number is a predictor of the nature of the flow. One form of the equation for the computing of this number is as follows:

(2-7)
$$Re = \frac{3160\,Q}{k\,Di}$$

WHERE
Q **= rate of flow, gallons per minute**
k **= kinematic viscosity, in centistokes (See Table 2-3 for values for water)**
Di **= internal diameter of pipe, in**

When the friction loss through one size pipe is known, the friction loss through another pipe of different size may be found by:

(2-8)
$$h_{f2} = h_{f1}\left(\frac{d'_1}{d'_2}\right)^5$$

The subscripts 1 and 2 refer to the known and unknown pipes. Both pipes must have the same surface roughness, and the fluid must be the same viscosity and have the same flow rate.

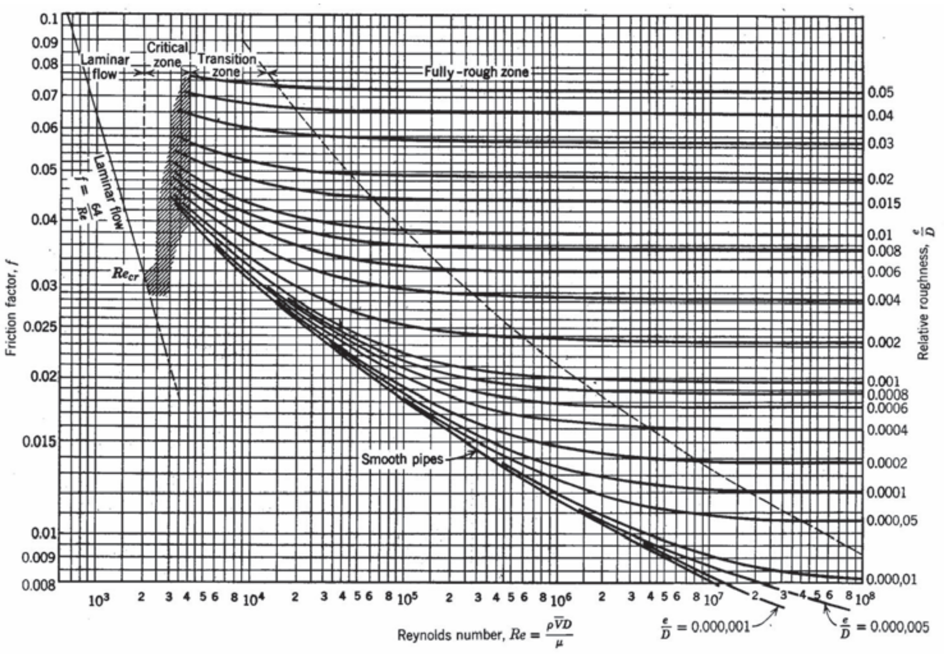
TABLE 2-1
Surface Roughness for Various New Pipes

Type of Pipe	‘ε’ Absolute Roughness of Surface, ft		
	Values for New Pipe Reported by Reference (18)	Values for New Pipe and Recommended Design Values Reported by Reference (19)	
		Mean Value	Recommended Design Value
Riveted steel	0.03 - 0.003	–	–
Concrete	0.01 – 0.001	–	–
Wood stave	0.0003 – 0.0006	–	–
Cast Iron – Uncoated	0.00085	0.00074	0.00083
Cast Iron – Coated	–	0.00033	0.00042
Galvanized Iron	0.00050	0.00033	0.00042
Cast Iron – Asphalt Dipped	0.0004	–	–
Commercial Steel or Wrought Iron	0.00015	–	–
Drawn Tubing	0.000005 corresponds to “smooth pipe”	–	–
Uncoated Stee	–	0.00009	0.00013
Coated Steel	–	0.00018	0.00018
Uncoated Asbestos – Cement	–		
Cement Mortar Relined Pipes (Tate Process)	–	0.00167	0.00167
Smooth Pipes (PE and other thermoplastics, Brass, Glass and Lead)	–	“smooth pipe” (0.000005 feet) (See Note)	“smooth pipe” (0.000005) (See Note)

Note: Pipes that have absolute roughness equal to or less than 0.000005 feet are considered to exhibit “smooth pipe” characteristics.

Pipe Deflection Effects

Pipe flow formulas generally assume round pipe. Because of its flexibility, buried PE pipe will deform slightly under earth and other loads to assume somewhat of an elliptical shape having a slightly increased lateral diameter and a correspondingly reduced vertical diameter. Elliptical deformation slightly reduces the pipe’s flow area. Practically speaking, this phenomenon can be considered negligible as it relates to pipe flow capacity. Calculations reveal that an elliptical deformation which reduces the pipe’s vertical diameter by 7% results in a flow reduction of approximately 1%.



Note for the Moody Diagram: D = pipe inside diameter, ft

Figure 2-1 The Moody Diagram

Head Loss in Fittings

Fluids flowing through a fitting or valve will experience a friction loss that can be directly expressed using a resistance coefficient, K′, which represents the loss in terms of an equivalent length of pipe of the same diameter.(20) As shown in the discussion that follows, this allows the loss through a fitting to be conveniently added into the system flow calculations. Table 2-2 presents K′ factors for various fittings.

Where a pipeline contains a large number of fittings in close proximity to each other, this simplified method of predicting flow loss may not be adequate due to the cumulative systems effect. Where this is a design consideration, the designer should consider an additional frictional loss allowance, or a more thorough treatment of the fluid mechanics.

The equivalent length of pipe to be used to estimate the friction loss due to fittings may be obtained by Eq. 2-9 where L_{EFF} = Effective Pipeline length, ft; D is pipe bore diameter in ft.; and K′ is obtained from Table 2-2.

(2-9) $$L_{EFF} = K'D$$

TABLE 2-2

Representative Fittings Factor, K', To Determine Equivalent Length of Pipe

Piping Component	K'
90° Molded Elbow	40
45° Molded elbow	21
15° Molded Elbow	6
90° Fabricated Elbow (3 or more miters)	24
90° Fabricated Elbow (2 miters)	30
90° Fabricated Elbow (1 miters)	60
60° Fabricated Elbow (2 or more miters)	25
60° Fabricated Elbow (1 miters)	16
45° Fabricated Elbow (2 or more miters)	15
45° Fabricated Elbow (1 miters)	12
30° Fabricated Elbow (2 or more miters)	8
30° Fabricated Elbow (1 miters)	8
15° Fabricated Elbow (1 miters)	6
Equal Outlet Tee, Run/Branch	60
Equal Outlet Tee, Run/Run	20
Globe Valve, Conventional, Fully Open	340
Angle Valve, Conventional, Fully Open	145
Butterfly Valve, >8", Fully Open	40
Check Valve, Conventional Swing	135

- K values are based on Crane Technical Paper No 410-C
- K value for Molded Elbows is based on a radius that is 1.5 times the diameter.
- K value for Fabricated Elbows is based on a radius that is approximately 3 times the diameter.

Head Loss Due to Elevation Change

Line pressure may be lost or gained from a change in elevation. For liquids, the pressure for a given elevation change is given by:

(2-10) $$h_E = h_2 - h_1$$

WHERE

h_E = Elevation head, ft of liquid

h_1 = Pipeline elevation at point 1, ft

h_2 = Pipeline elevation at point 2, ft

If a pipeline is subject to a uniform elevation rise or fall along its length, the two points would be the elevations at each end of the line. However, some pipelines may have several elevation changes as they traverse rolling or mountainous terrain. These pipelines may be evaluated by choosing appropriate points where the pipeline slope changes, then summing the individual elevation heads for an overall pipeline elevation head.

In a pipeline conveying liquids and running full, pressure in the pipe due to elevation exists whether or not liquid is flowing. At any low point in the line, internal pressure will be equal to the height of the liquid above the point multiplied by the specific weight of the liquid. If liquid is flowing in the line, elevation head and head loss due to liquid flow in the pipe are added to determine the pressure in the pipe at a given point in the pipeline.

Pressure Flow of Water – Hazen-Williams Equation

The Darcy-Weisbach method of flow resistance calculation may be applied to liquid and gases, but its solution can be complex. For many applications, empirical formulas are available and, when used within their limitations, reliable results are obtained with greater convenience. For example, Hazen and Williams developed an empirical formula for the flow of water in pipes at 60° F.

The Hazen-Williams formula for water at 60° F (16°C) can be applied to water and other liquids having the same kinematic viscosity of 1.130 centistokes which equals 0.00001211 ft^2/sec or 31.5 SSU (Saybolt Second Universal). The viscosity of water varies with temperature, so some error can occur at temperatures other than 60°F (16°C).

Hazen-Williams formula for friction (head) loss in feet of water head:

(2-11)

$$h_f = \frac{0.002083\,L}{{D_I}^{4.8655}}\left(\frac{100\,Q}{C}\right)^{1.85}$$

Hazen-Williams formula for friction (head) loss in psi:

(2-12)

$$p_f = \frac{0.0009015\mathrm{L}}{{D_I}^{4.8655}}\left(\frac{100\,Q}{C}\right)^{1.85}$$

Terms are as previously defined, and:

h_f **= friction (head) loss, ft. of water.**
p_f **= friction (head) loss, psi**
D_I **= pipe inside diameter, in**
C **= Hazen-Williams Friction Factor, dimensionless c = 150-155 for PE , (not related to Darcy-Weisbach friction factor, *f*)**
Q **= flow rate, gpm**

The Hazen-Williams Friction Factor, C, for PE pipe was determined in a hydraulics laboratory using heat fusion joined lengths of pipe with the inner bead present. Other forms of these equations are prevalent throughout the literature.(21) The reader is referred to the references at the end of this chapter.

TABLE 2-3
Properties of Water

Temperature, °F/°C	Specific Weight, lb/ft³	Kinematic Viscosity, Centistokes
32 / 0	62.41	1.79
60 / 15.6	62.37	1.13
75 / 23.9	62.27	0.90
100 / 37.8	62.00	0.69
120 / 48.9	61.71	0.57
140 / 60	61.38	0.47

Water flow through pipes having different Hazen-Williams factors and different flow diameters may be determined using the following equations:

(2-13)

$$\%flow = 100\left(\frac{D_{I2}}{D_{I1}}\right)^{2.63}\left(\frac{C_2}{C_1}\right)$$

Where the subscripts 1 and 2 refer to the designated properties for two separate pipe profiles, in this case, the pipe inside diameter (D_I in inches) of the one pipe (1) versus that of the second pipe (2) and the Hazen-Williams factor for each respective profile.

Pipe Flow Design Example

A PE pipeline conveying water at 60°F is 15,000 feet long and is laid on a uniform grade that rises 150 feet. What is the friction head loss in 4" IPS DR 17 PE 3408 pipe for a 50 gpm flow? What is the elevation head? What is the internal pressure at the bottom of the pipe when water is flowing uphill? When flowing downhill? When full but not flowing?

Using equation 2-12 and C = 150

$$p_f = \frac{0.0009015(15000)}{3.938^{4.8655}}\left(\frac{100(50)}{150}\right)^{1.85} = 11.3\,psi$$

To determine the elevation head, assume point 1 is at the bottom of the elevation, and point 2 is at the top. Using Equation 2-10,

$$h_E = 150 - 0 = 150\,ft\ of\ water$$

The specific weight of water at 60°F is 62.37 lb/ft^3 (see Table 2-3), which, for each foot of head exerts a pressure of 62.37 lb over a 1 ft square area, or a pressure of 62.37/144 = 0.43 lb/in^2. Therefore, for a 150 ft. head,

$$h_E = (150 - 0)0.43 = 64.5\,psig$$

When water is flowing, elevation head and the friction head are added. The maximum friction head acts at the source point, and the maximum elevation head at the lowest point. Therefore, when flowing uphill, the pressure, P, at the bottom is elevation head plus the friction head because the flow is from the bottom to the top.

$$P = h_E + p_f = 64.5 + 11.3 = 75.8\,psig$$

When flowing downhill, water flows from the top to the bottom. Friction head applies from the source point at the top, so the pressure developed from the downhill flow is applied in the opposite direction as the elevation head. Therefore,

$$P = h_E - p_f = 64.5 - 11.3 = 53.2\,psig$$

When the pipe is full, but water is not flowing, no friction head develops.

$$P = h_E + p_f = 64.5 + 0 = 64.5\,psig$$

Pressure Flow of Liquid Slurries

Liquid slurry piping systems transport solid particles entrained in a liquid carrier. Water is typically used as a liquid carrier, and solid particles are commonly granular materials such as sand, fly-ash or coal. Key design considerations involve the nature of the solid material, it's particle size and the carrier liquid.

Turbulent flow is preferred to ensure that particles are suspended in the liquid. Turbulent flow also reduces pipeline wear because particles suspended in the carrier liquid will bounce off the pipe inside surface. PE pipe has viscoelastic properties that combine with high molecular weight toughness to provide service life that can significantly exceed many metal piping materials. Flow velocity that is too low to maintain fully turbulent flow for a given particle size can allow solids to drift to the bottom of the pipe and slide along the surface. However, compared to metals, PE is a softer material. Under sliding bed and direct impingement conditions, PE may wear appreciably. PE directional fittings are generally unsuitable for slurry applications because the change of flow direction in the fitting results in direct impingement. Directional fittings in liquid slurry applications should employ hard materials that are resistant to wear from direct impingement.

Particle Size

As a general recommendation, particle size should not exceed about 0.2 in (5 mm), but larger particles are occasionally acceptable if they are a small percentage of the solids in the slurry. With larger particle slurries such as fine sand and coarser particles, the viscosity of the slurry mixture will be approximately that of the carrying liquid. However, if particle size is very small, about 15 microns or less, the slurry viscosity will increase above that of the carrying liquid alone. The rheology of fine particle slurries should be analyzed for viscosity and specific gravity before determining flow friction losses. Inaccurate assumptions of a fluid's rheological properties can lead to significant errors in flow resistance analysis. Examples of fine particle slurries are water slurries of fine silt, clay and kaolin clay.

Slurries frequently do not have uniform particle size, and some particle size non-uniformity can aid in transporting larger particles. In slurries having a large proportion of smaller particles, the fine particle mixture acts as a more viscous carrying fluid that helps suspend larger particles. Flow analysis of non-uniform particle size slurries should include a rheological characterization of the fine particle mixture.

Solids Concentration and Specific Gravity

Equations 2-14 through 2-17 are useful in determining solids concentrations and mixture specific gravity. Tables 2-4, 2-5, and 2-6 provide information about specific gravity and particle size of some slurries.

(2-14)
$$C_V = \frac{S_M - S_L}{S_S - S_L}$$

(2-15)
$$C_W = \frac{C_V S_S}{S_M}$$

(2-16)
$$S_M = C_V\left(S_S - S_L\right) + S_L$$

(2-17)
$$S_M = \frac{S_L}{1 - \frac{C_W\left(S_S - S_L\right)}{S_S}}$$

WHERE

S_L **= carrier liquid specific gravity**

S_S **= solids specific gravity**

S_M **= slurry mixture specific gravity**

C_V **= percent solids concentration by volume**

C_W **= percent solids concentration by weight**

Critical Velocity

As pointed out above, turbulent flow is preferred to maintain particle suspension. A turbulent flow regime avoids the formation of a sliding bed of solids, excessive pipeline wear and possible clogging. Reynolds numbers above 4000 will generally insure turbulent flow.

Maintaining the flow velocity of a slurry at about 30% above the critical settlement velocity is a good practice. This insures that the particles will remain in suspension thereby avoiding the potential for excessive pipeline wear. For horizontal pipes, critical velocity may be estimated using Equation 2-18.

Individual experience with this equation varies. Other relationships are offered in the literature. See Thompson and Aude (26). A test section may be installed to verify applicability of this equation for specific projects.

(2-18)

$$V_C = F_L \sqrt{2gd'\left(S_S - 1\right)}$$

Where terms are previously defined and

V_C **= critical settlement velocity, ft/sec**

F_L **= velocity coefficient (Tables 2-7 and 2-8)**

d' **= pipe inside diameter, ft**

An approximate minimum velocity for fine particle slurries (below 50 microns, 0.05 mm) is 4 to 7 ft/sec, provided turbulent flow is maintained. A guideline minimum velocity for larger particle slurries (over 150 microns, 0.15 mm) is provided by Equation 2-19.

(2-19)

$$V_{\min} = 14\sqrt{d'}$$

WHERE

V_{min} **= approximate minimum velocity, ft/sec**

Critical settlement velocity and minimum velocity for turbulent flow increases with increasing pipe bore. The relationship in Equation 2-20 is derived from the Darcy-Weisbach equation. (Equation 2-3)

(2-20)

$$V_2 = \frac{\sqrt{d'_2}}{\sqrt{d'_1}} V_1$$

The subscripts 1 and 2 are for the two pipe diameters.

TABLE 2-4
Scale of Particle Sizes

Tyler Screen Mesh	U.S. Standard Mesh	Inches	Microns	Class
–	–	1.3 – 2.5	33,000 – 63,500	Very coarse gravel
–	–	0.6 – 1.3	15,200 – 32,000	Coarse gravel
2.5	–	0.321	8,000	Medium gravel
5	5	0.157	4,000	Fine gravel
9	10	0.079	2,000	Very fine gravel
16	18	0.039	1,000	Very coarse sand
32	35	0.0197	500	Coarse sand
60	60	0.0098	250	Medium sand
115	120	0.0049	125	Fine sand
250	230	0.0024	62	Very fine sand
400	–	0.0015	37	Coarse silt
–	–	0.0006 – 0.0012	16 – 31	Medium silt
–	–	–	8 – 13	Fine silt
–	–	-	4 – 8	Very fine silt
–	–	–	2 – 4	Coarse clay
–	–	–	1 – 2	Medium clay
–	–	–	0.5 - 1	Fine clay

TABLE 2-5
Typical Specific Gravity and Slurry Solids Concentration (Water Slurries)

Material	Specific Gravity	Typical Solids Concentration	
		% by Weight	% by Volume
Gilsonite	1.05	40 –45	39 – 44
Coal	1.40	45 – 55	37 – 47
Sand	2.65	43 – 43	23 – 30
Limestone	2.70	60 – 65	36 – 41
Copper Concentrate	4.30	60 – 65	26 – 30
Iron Ore	4.90	–	–
Iron Sands	1.90	–	–
Magnetite	4.90	60 - 65	23 - 27

TABLE 2-6
Water-Base Slurry Specific Gravities

Concentration by Weight Percent, C_W	Solid Specific Gravity, S_S									
	1.4	1.8	2.2	2.6	3.0	3.4	3.8	4.2	4.6	5.0
5	1.01	1.02	1.03	1.03	1.03	1.04	1.04	1.04	1.04	1.04
10	1.03	1.05	1.06	1.07	1.07	1.08	1.08	1.08	1.08	1.09
15	1.04	1.07	1.09	1.10	1.11	1.12	1.12	1.13	1.13	1.14
20	1.05	1.10	1.12	1.14	1.15	1.16	1.17	1.18	1.19	1.19
25	1.08	1.13	1.16	1.18	1.20	1.21	1.23	1.24	1.24	1.25
30	1.09	1.15	1.20	1.23	1.25	1.27	1.28	1.30	1.31	1.32
35	1.11	1.18	1.24	1.27	1.30	1.33	1.35	1.36	1.38	1.39
40	1.13	1.22	1.28	1.33	1.36	1.39	1.42	1.44	1.46	1.47
45	1.15	1.25	1.33	1.38	1.43	1.47	1.50	1.52	1.54	1.56
50	1.17	1.29	1.38	1.44	1.50	1.55	1.58	1.62	1.64	1.67
55	1.19	1.32	1.43	1.51	1.58	1.63	1.69	1.72	1.76	1.79
60	1.21	1.36	1.49	1.59	1.67	1.73	1.79	1.84	1.89	1.92
65	1.23	1.41	1.55	1.67	1.76	1.85	1.92	1.98	2.04	2.08
70	1.25	1.45	1.62	1.76	1.88	1.98	2.07	2.14	2.21	2.27

TABLE 2-7
Velocity Coefficient, F_L (Uniform Particle Size)

Particle Size, mm	Velocity Coefficient, F_L			
	$C_V = 2\%$	$C_V = 5\%$	$C_V = 10\%$	$C_V = 15\%$
0.1	.76	0.92	0.94	0.96
0.2	0.94	1.08	1.20	1.28
0.4	1.08	1.26	1.41	1.46
0.6	1.15	1.35	1.46	1.50
0.8	1.21	1.39	1.45	1.48
1.0	1.24	1.04	1.42	1.44
1.2	1.27	1.38	1.40	1.40
1.4	1.29	1.36	1.67	1.37
1.6	1.30	1.35	1.35	1.35
1.8	1.32	1.34	1.34	1.34
2.0	1.33	1.34	1.34	1.34
2.2	1.34	1.34	1.34	1.34
2.4	1.34	1.34	1.34	1.34
2.6	1.35	1.35	1.35	1.35
2.8	1.36	1.36	1.36	1.36
≥ 3.0	1.36	1.36	1.36	1.36

TABLE 2-8
Velocity Coefficient, F_L (50% Passing Particle Size)

Particle Size, mm	Velocity Coefficient, F_L			
	C_V = 5%	C_V = 10%	C_V = 20%	C_V = 30%
0.01	0.48	0.48	0.48	0.48
0.02	0.58	0.59	0.60	0.61
0.04	0.70	0.72	0.74	0.76
0.06	0.77	0.79	0.81	0.83
0.08	0.83	0.86	0.86	0.91
0.10	0.85	0.88	0.92	0.95
0.20	0.97	1.00	1.05	1.08
0.40	1.09	1.13	1.18	1.23
0.60	1.15	1.21	1.26	1.30
0.80	1.21	1.25	1.31	1.33
1.0	1.24	1.29	1.33	1.35
2.0	1.33	1.36	1.38	1.40
3.0	1.36	1.38	1.39	1.40

Equation 2-3, Darcy-Weisbach, and Equations 2-11 and 2-12, Hazen-Williams, may be used to determine friction head loss for pressure slurry flows provided the viscosity limitations of the equations are taken into account. Elevation head loss is increased by the specific gravity of the slurry mixture.

(2-21)
$$h_E = S_M \left(h_2 - h_1\right)$$

Compressible Gas Flow

Flow equations for smooth pipe may be used to estimate compressible gas flow through PE pipe.

Empirical Equations for High Pressure Gas Flow

Equations 2-22 through 2-25 are empirical equations used in industry for pressure greater than 1 psig. Calculated results may vary due to the assumptions inherent in the derivation of the equation.

Mueller Equation

(2-22)
$$Q_h = \frac{2826\, D_I^{\,2.725}}{S_g^{\,0.425}} \left(\frac{p_1^{\,2} - p_2^{\,2}}{L}\right)^{0.575}$$

Weymouth Equation

(2-23)
$$Q_h = \frac{2034\, D_I^{\,2.667}}{S_g^{\,0.5}} \left(\frac{p_1^{\,2} - p_2^{\,2}}{L}\right)^{0.5}$$

IGT Distribution Equation

(2-24)

$$Q_h = \frac{2679\, D_I^{\,2.667}}{S_g^{\,0.444}} \left(\frac{p_1^{\,2} - p_2^{\,2}}{L} \right)^{0.555}$$

Spitzglass Equation

(2-25)

$$Q_h = \frac{3410}{S_g^{\,0.5}} \left(\frac{p_1^{\,2} - p_2^{\,2}}{L} \right)^{0.5} \left(\frac{D_I^{\,5}}{1 + \frac{3.6}{D_I} + 0.03\, D_I} \right)^{0.5}$$

WHERE

(Equations 2-22 through 2-25)

Q_h **= flow, standard ft³/hour**

S_g **= gas specific gravity**

p_1 **= inlet pressure, lb/in² absolute**

p_2 **= outlet pressure, lb/in² absolute**

L **= length, ft**

D_I **= pipe inside diameter, in**

Empirical Equations for Low Pressure Gas Flow

For applications where internal pressures are less than 1 psig, such as landfill gas gathering or wastewater odor control, Equations 2-26 or 2-27 may be used.

Mueller Equation

(2-26)

$$Q_h = \frac{2971\, D_I^{\,2.725}}{S_g^{\,0.425}} \left(\frac{h_1 - h_2}{L} \right)^{0.575}$$

Spitzglass Equation

(2-27)

$$Q_h = \frac{3350}{S_g^{\,0.5}} \left(\frac{h_1 - h_2}{L} \right)^{0.5} \left(\frac{D_I^{\,5}}{1 + \frac{3.6}{D_I} + 0.03\, D_I} \right)^{0.5}$$

Where terms are previously defined, and

h_1 **= inlet pressure, in H_2O**

h_2 **= outlet pressure, in H_2O**

Gas Permeation

Long distance pipelines carrying compressed gasses may deliver slightly less gas due to gas permeation through the pipe wall. Permeation losses are small, but it may be necessary to distinguish between permeation losses and possible leakage. Equation 2-28 may be used to determine the volume of a gas that will permeate through PE pipe of a given wall thickness:

(2-28)

$$q_P = \frac{K_P A_s \Theta P_A}{t'}$$

WHERE

q_P **= volume of gas permeated, cm^3 (gas at standard temperature and pressure)**

K_P **= permeability constant (Table 2-9);** units: $\frac{\text{Cm}^3\ \text{mil}}{100\ \text{in}^2\ \text{atm day}}$

A_s **= pipe outside wall area in units of 100 square inches**

P_A **= pipe internal pressure, atmospheres (1 atmosphere = 14.7 lb/in^2)**

Θ **= elapsed time, days**

t' **= wall thickness, mils**

TABLE 2-9

Permeability Constants [(28)]

Gas	K_P
Methane	85
Carbon Monoxide	80
Hydrogen	425

TABLE 2-10
Physical Properties of Gases (Approx. Values at 14.7 psi & 68ºF)

Gas	Chemical Formula	Molecular Weight	Weight Density, lb/ft^3	Specific Gravity, (Relative to Air) S_g
Acetylene (ethylene)	C_2H_2	26.0	0.0682	0.907
Air	–	29.0	0.0752	1.000
Ammonia	NH_3	17.0	0.0448	0.596
Argon	A	39.9	0.1037	1.379
Butane	C_4H_{10}	58.1	0.1554	2.067
Carbon Dioxide	CO_2	44.0	0.1150	1.529
Carbon Monoxide	CO	28.0	0.0727	0.967
Ethane	C_2H_6	30.0	0.0789	1.049
Ethylene	C_2H_4	28.0	0.0733	0.975
Helium	H_e	4.0	0.0104	0.138
Hydrogen Chloride	HCl	36.5	0.0954	1.286
Hydrogen	H	2.0	0.0052	0.070
Hydrogen Sulphide	H_2S	34.1	0.0895	1.190
Methane	CH_4	16.0	0.0417	0.554
Methyl Chloride	CH_3Cl	50.5	0.1342	1.785
Natural Gas	–	19.5	0.0502	0.667
Nitric Oxide	NO	30.0	0.0708	1.037
Nitrogen	N_2	28.0	0.0727	0.967
Nitrous Oxide	N_2O	44.0	0.1151	1.530
Oxygen	O_2	32.0	0.0831	1.105
Propane	C_3H_8	44.1	0.1175	1.562
Propene (Propylene)	C_3H_6	42.1	0.1091	1.451
Sulfur Dioxide	SO_2	64.1	0.1703	2.264
Landfill Gas (approx. value)	–	–	–	1.00
Carbureted Water Gas	–	–	–	0.63
Coal Gas	–	–	–	0.42
Coke-Oven Gas	–	–	–	0.44
Refinery Oil Gas	–	–	–	0.99
Oil Gas (Pacific Coast)	–	–	–	0.47
“Wet” Gas (approximate value)	–	–	–	0.75

Gravity Flow of Liquids

In a pressure pipeline, a pump of some sort, generally provides the energy required to move the fluid through the pipeline. Such pipelines can transport fluids across a level surface, uphill or downhill. Gravity flow lines, on the other hand, utilize the energy associated with the placement of the pipeline discharge below the inlet. Like pressure flow pipelines, friction loss in a gravity flow pipeline depends on viscous shear stresses within the liquid and friction along the wetted surface of the pipe bore.

Some gravity flow piping systems may become very complex, especially if the pipeline grade varies, because friction loss will vary along with the varying grade. Sections of the pipeline may develop internal pressure, or vacuum, and may have varying liquid levels in the pipe bore.

Manning Flow Equation

For open channel water flow under conditions of constant grade, and uniform channel cross section, the Manning equation may be used.(29,30) Open channel flow exists in a pipe when it runs partially full. Like the Hazen-Williams formula, the Manning equation is applicable to water or liquids with a kinematic viscosity equal to water.

Manning Equation

(2-29)
$$V = \frac{1.486}{n} r_H^{2/3} S_H^{1/2}$$

WHERE

V = flow velocity, ft/sec

n = roughness coefficient, dimensionless

r_H = hydraulic radius, ft

S_H = hydraulic slope, ft/ft

(2-30)
$$r_H = \frac{A_C}{P_W}$$

A_C = cross-sectional area of flow bore, ft^2

P_W = perimeter wetted by flow, ft

(2-31)
$$S_H = \frac{h_U - h_D}{L} = \frac{h_f}{L}$$

h_U = upstream pipe elevation, ft

h_D = downstream pipe elevation, ft

h_f = friction (head) loss, ft of liquid

L = length, ft

It is convenient to combine the Manning equation with

(2-32) $$Q = A_C V$$

To obtain

(2-33)
$$Q = \frac{1.486\, A_C}{n} r_H^{2/3} S_H^{1/2}$$

Where terms are as defined above, and

Q = **flow, ft^3/sec**

When a circular pipe is running full or half-full,

(2-34)
$$r_H = \frac{d'}{4} = \frac{D_I}{48}$$

WHERE

d' = **pipe inside diameter, ft**

D_I = **pipe inside diameter, in**

Full pipe flow in ft^3 per second may be estimated using:

(2-35)
$$Q_{FPS} = \left(6.136 \times 10^{-4}\right) \frac{D_I^{8/3} S_H^{1/2}}{n}$$

Full pipe flow in gallons per minute may be estimated using:

(2-36)
$$Q' = 0.275 \frac{D_I^{8/3} S_H^{1/2}}{n}$$

Nearly full circular pipes will carry more liquid than a completely full pipe. When slightly less than full, the perimeter wetted by flow is reduced, but the actual flow area is only slightly lessened. This results in a larger hydraulic radius than when the pipe is running full. Maximum flow is achieved at about 93% of full pipe flow, and maximum velocity at about 78% of full pipe flow. Manning's n is often assumed to be constant with flow depth. Actually, n has been found to be slightly larger in non-full flow.

TABLE 2-11

Values of n for Use with Manning Equation

Surface	n, typical design
PE pipe	0.009
Uncoated cast or ductile iron pipe	0.013
Corrugated steel pipe	0.024
Concrete pipe	0.013
Vitrified clay pipe	0.013
Brick and cement mortar sewers	0.015
Wood stave	0.011
Rubble masonry	0.021

Note: The n-value of 0.009 for PE pipe is for clear water applications.
An n-value of 0.010 is typically utilized for applications such as sanitary sewer, etc.

Comparative Flows for Slipliners

Deteriorated gravity flow pipes may be rehabilitated by sliplining with PE pipe. This process involves the installation of a PE liner inside of the deteriorated original pipe as described in subsequent chapters within this manual. For conventional sliplining, clearance between the liner outside diameter and the existing pipe bore is required to install the liner; thus after rehabilitation, the flow channel is smaller than that of the original pipe. However, it is often possible to rehabilitate with a PE slipliner, and regain all or most of the original flow capacity due to the extremely smooth inside surface of the PE pipe and its resistance to deposition or build-up. Because PE pipe is mostly joined by means of butt-fusion, this results in no effective reduction of flow diameter at joint locations Comparative flow capacities of circular pipes may be determined by the following:

(2-37)

$$\% \; flow = 100 \frac{Q_1}{Q_2} = 100 \frac{\left(\frac{D_{I1}^{\;8/3}}{n_1} \right)}{\left(\frac{D_{I2}^{\;8/3}}{n_2} \right)}$$

Table 2-12 was developed using Equation 2-36 where D_{I1} = the inside diameter (ID) of the liner, and D_{I2} = the original inside diameter of the deteriorated host pipe.

TABLE 2-12
Comparative Flows for Slipliners

Existing Sewer ID, in	Liner OD, in.	Liner DR 32.5			Liner DR 26			Liner DR 21			Liner DR 17		
		Liner ID, in.†	% flow vs. concrete	% flow vs. clay	Liner ID, in.†	% flow vs. concrete	% flow vs. clay	Liner ID, in.†	% flow vs. concrete	% flow vs. clay	Liner ID, in.†	% flow vs. concrete	% flow vs. clay
4	3.500	3.272	97.5%	84.5%	3.215	93.0%	80.6%	3.147	87.9%	76.2%	3.064	81.8%	70.9%
6	4.500	4.206	64.6%	56.0%	4.133	61.7%	53.5%	4.046	58.3%	50.5%	3.939	54.3%	47.0%
6	5.375	5.024	103.8%	90.0%	4.937	99.1%	85.9%	4.832	93.6%	81.1%	4.705	87.1%	75.5%
8	6.625	6.193	84.2%	73.0%	6.085	80.3%	69.6%	5.956	75.9%	65.8%	5.799	70.7%	61.2%
8	7.125	6.660	102.2%	88.6%	6.544	97.5%	84.5%	6.406	92.1%	79.9%	6.236	85.8%	74.4%
10	8.625	8.062	93.8%	81.3%	7.922	89.5%	77.6%	7.754	84.6%	73.3%	7.549	78.8%	68.3%
12	10.750	10.049	103.8%	90.0%	9.873	99.1%	85.9%	9.665	93.6%	81.1%	9.409	87.1%	75.5%
15	12.750	11.918	90.3%	78.2%	11.710	86.1%	74.6%	11.463	81.4%	70.5%	11.160	75.7%	65.6%
15	13.375	12.503	102.5%	88.9%	12.284	97.8%	84.8%	12.025	92.4%	80.1%	11.707	86.1%	74.6%
16	14.000	13.087	97.5%	84.5%	2.858	93.0%	80.6%	12.587	87.9%	76.2%	12.254	81.8%	70.9%
18	16.000	14.956	101.7%	88.1%	14.695	97.0%	84.1%	14.385	91.7%	79.4%	14.005	85.3%	74.0%
21	18.000	16.826	92.3%	80.0%	16.532	88.1%	76.3%	16.183	83.2%	72.1%	15.755	77.5%	67.1%
24	20.000	18.695	85.6%	74.2%	18.369	81.7%	70.8%	17.981	77.2%	66.9%	17.506	71.9%	62.3%
24	22.000	20.565	110.4%	95.7%	20.206	105.3%	91.3%	19.779	99.5%	86.2%	19.256	92.6%	80.3%
27	24.000	22.434	101.7%	88.1%	22.043	97.0%	84.1%	21.577	91.7%	79.4%	21.007	85.3%	74.0%
30	28.000	26.174	115.8%	100.4%	25.717	110.5%	95.8%	25.173	104.4%	90.5%	24.508	97.2%	84.2%
33	30.000	28.043	108.0%	93.6%	27.554	103.0%	89.3%	26.971	97.3%	84.3%	26.259	90.6%	78.5%
36	32.000	29.913	101.7%	88.1%	29.391	97.0%	84.1%	28.770	91.7%	79.4%	28.009	85.3%	74.0%
36	34.000	31.782	119.5%	103.6%	31.228	114.1%	98.9%	30.568	107.7%	93.4%	29.760	100.3%	86.9%
42	36.000	33.652	92.3%	80.0%	33.065	88.1%	76.3%	32.366	83.2%	72.1%	31.511	77.5%	67.1%
48	42.000	39.260	97.5%	84.5%	38.575	93.0%	80.6%	37.760	87.9%	76.2%	36.762	81.8%	70.9%
54	48.000	44.869	101.7%	88.1%	44.086	97.0%	84.1%	43.154	91.7%	79.4%	42.014	85.3%	74.0%
60	54.000	50.478	105.1%	91.1%	49.597	100.3%	86.9%	48.549	94.8%	82.1%	47.266	88.2%	76.5%

† Liner ID calculated per Equation 2-1.

Flow Velocity

Acceptable flow velocities in PE pipe depend on the specific details of the system. For water systems operating at rated pressures, velocities may be limited by surge allowance requirements. See Tables 1-3A and 1-3B. Where surge effects are reduced, higher velocities are acceptable, and if surge is not possible, such as in many gravity flow systems, water flow velocities exceeding 25 feet per second may be acceptable.

Liquid flow velocity may be limited by the capabilities of pumps or elevation head to overcome friction (head) loss and deliver the flow and pressure required for the application. PE pipe is not eroded by water flow. Liquid slurry pipelines may be subject to critical minimum velocities that ensure turbulent flow and maintain particle suspension in the slurry.

Gravity liquid flows of 2 fps (0.6 m/s) and higher can help prevent or reduce solids deposition in sewer lines. When running full, gravity flow pipelines are subject to the same velocity considerations as pressure pipelines.

Flow velocity in compressible gas lines tends to be self-limiting. Compressible gas flows in PE pipes are typically laminar or transitional. Fully turbulent flows are possible in short pipelines, but difficult to achieve in longer transmission and distribution lines because the pressure ratings for PE pipe automatically limit flow capacity and, therefore, flow velocity.

Pipe Surface Condition, Aging

Aging acts to increase pipe surface roughness in most piping systems. This in turn increases flow resistance. PE pipe resists typical aging effects because PE does not rust, rot, corrode, tuberculate, or support biological growth, and it resists the adherence of scale and deposits. In some cases, moderate flow velocities are sufficient to prevent deposition, and where low velocities predominate, occasional high velocity flows will help to remove sediment and deposits. As a result, the initial design capabilities for pressure and gravity flow pipelines are retained as the pipeline ages.

Where cleaning is needed to remove depositions in low flow rate gravity flow pipelines, water-jet cleaning or forcing a “soft” (plastic foam) pig through the pipeline are effective cleaning methods. Bucket, wire and scraper-type cleaning methods will damage PE pipe and must not be used.

Section 3
Buried PE Pipe Design

Introduction

This section covers basic engineering information for calculating earth and live-load pressures on PE pipe, for finding the pipe's response to these pressures taking into account the interaction between the pipe and its surrounding soil, and for judging that an adequate safety factor exists for a given application.

Soil pressure results from the combination of soil weight and surface loads. As backfill is placed around and over a PE pipe, the soil pressure increases and the pipe deflects vertically and expands laterally into the surrounding soil. The lateral expansion mobilizes passive resistance in the soil which, in combination with the pipe's inherent stiffness, resists further lateral expansion and consequently further vertical deflection.

During backfilling, ring (or hoop) stress develops within the pipe wall. Ring bending stresses (tensile and compressive) occur as a consequence of deflection, and ring compressive stress occurs as a consequence of the compressive thrust created by soil compression around the pipe's circumference. Except for shallow pipe subject to live load, the combined ring stress from bending and compression results in a net compressive stress.

The magnitude of the deflection and the stress depends not only on the pipe's properties but also on the properties of the surrounding soil. The magnitude of deflection and stress must be kept safely within PE pipe's performance limits. Excessive deflection may cause loss of stability and flow restriction, while excessive compressive stress may cause wall crushing or ring buckling. Performance limits for PE pipe are given in Watkins, Szpak, and Allman(1) and illustrated in Figure 3-1.

The design and construction requirements can vary somewhat, depending on whether the installation is for pressure or non-pressure service. These differences will be addressed later in this chapter and in Chapter 7, "Underground Installation of PE Pipe."

Calculations

Section 3 describes how to calculate the soil pressure acting on PE pipe due to soil weight and surface loads, how to determine the resulting deflection based on pipe and soil properties, and how to calculate the allowable (safe) soil pressure for wall compression (crushing) and ring buckling for PE pipe.

Detailed calculations are not always necessary to determine the suitability of a particular PE pipe for an application. Pressure pipes that fall within the Design Window given in AWWA M-55 "PE Pipe – Design and Installation" regarding pipe DR, installation, and burial depth meet specified deflection limits for PE pipe, have a safety factor of at least 2 against buckling, and do not exceed the allowable material compressive stress for PE. Thus, the designer need not perform extensive calculations for pipes that are sized and installed in accordance with the Design Window.

AWWA M-55 Design Window

AWWA M-55, "PE Pipe – Design and Installation", describes a Design Window. Applications that fall within this window require no calculations other than constrained buckling per Equation 3-15. It turns out that if pipe is limited to DR 21 or lower as in Table 3-1, the constrained buckling calculation has a safety factor of at least 2, and no calculations are required.

The design protocol under these circumstances (those that fall within the AWWA Design Window) is thereby greatly simplified. The designer may choose to proceed with detailed analysis of the burial design and utilize the AWWA Design Window guidelines as a means of validation for his design calculations and commensurate safety factors. Alternatively, he may proceed with confidence that the burial design for these circumstances (those outlined within the AWWA Design Window) has already been analyzed in accordance with the guidelines presented in this chapter.

The Design Window specifications are:

- Pipe made from stress-rated PE material.
- Essentially no dead surface load imposed over the pipe, no ground water above the surface, and provisions for preventing flotation of shallow cover pipe have been provided.
- The embedment materials are coarse-grained, compacted to at least 85% Standard Proctor Density and have an E′ of at least 1000 psi. The native soil must be stable; in other words the native soil must have an E′ of at least 1000 psi. See Table 3-7.
- The unit weight of the native soil does not exceed 120 pcf.
- The pipe is installed in accordance with manufacturer's recommendations for controlling shear and bending loads and minimum bending radius, and installed

in accordance with ASTM D2774 for pressure pipes or ASTM D2321 for non-pressure pipes.

- Minimum depth of cover is 2 ft (0.61 m); except when subject to AASHTO H20 truck loadings, in which case the minimum depth of cover is the greater of 3 ft (0.9 m) or one pipe diameter.
- Maximum depth of cover is 25 ft (7.62 m).

TABLE 3-1
AWWA M-55 Design Window Maximum and Minimum Depth of Cover Requiring No Calculations

DR	Min. Depth of Cover With H20 Load	Min. Depth of Cover Without H20 Load	Maximum Depth of Cover
7.3	3 ft	2 ft	25 ft
9	3 ft	2 ft	25 ft
11	3 ft	2 ft	25 ft
13.5	3 ft	2 ft	25 ft
17	3 ft	2 ft	25 ft
21	3 ft	2 ft	25 ft

* Limiting depths where no calculations are required. Pipes are suitable for deeper depth provided a sufficient E' (1,000 psi or more) is accomplished during installations. Calculations would be required for depth greater than 25 ft.

Installation Categories

For the purpose of calculation, buried installations of PE pipe can be separated into four categories depending on the depth of cover, surface loading, groundwater level and pipe diameter. Each category involves slightly different equations for determining the load on the pipe and the pipe's response to the load. The boundaries between the categories are not definite, and engineering judgment is required to select the most appropriate category for a specific installation. The categories are:

1. **Standard Installation-Trench or Embankment** installation with a maximum cover of 50 ft with or without traffic, rail, or surcharge loading. To be in this category, where live loads are present the pipe must have a minimum cover of at least one diameter or 18" whichever is greater. Earth pressure applied to the pipe is found using the prism load (geostatic soil stress). The Modified Iowa Formula is used for calculating deflection. Crush and buckling are performance limits as well. The Standard Installation section also presents the AWWA "Design Window."
2. **Shallow Cover Vehicular Loading Installation** applies to pipes buried at a depth of at least 18" but less than one pipe diameter. This installation category

uses the same equations as the Standard Installation but with an additional equation relating wheel load to the pipe's bending resistance and the soil's supporting strength.

3. **Deep Fill Installation** applies to embankments with depths exceeding 50 ft. The soil pressure calculation may be used for profile pipe in trenches less than 50 ft. The Deep Fill Installation equations differ from the Standard Installation equations by considering soil pressure based on armored, calculating deflection from the Watkins-Gaube Graph, and calculating buckling with the Moore-Selig Equation.
4. **Shallow Cover Flotation Effects** applies to applications where insufficient cover is available to either prevent flotation or hydrostatic collapse. Hydrostatic buckling is introduced in this chapter because of its use in subsurface design.

Section 3 of the Design Chapter is limited to the design of PE pipes buried in trenches or embankments. The load and pipe reaction calculations presented may not apply to pipes installed using trenchless technologies such as pipe bursting and directional drilling. These pipes may not develop the same soil support as pipe installed in a trench. The purveyor of the trenchless technology should be consulted for piping design information. See the Chapter on "PE Pipe for Horizontal Directional Drilling" and ASTM F1962, *Use of Maxi-Horizontal Directional Drilling (HDD) for Placement of Polyethylene Pipe or Conduit Under Obstacles, Including River Crossings* for additional information on design of piping installed using directional drilling.

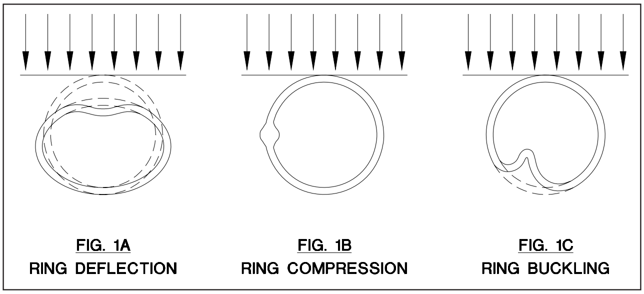


Figure 3-1 Performance Limits for Buried PE Pipe

Design Process

The interaction between pipe and soil, the variety of field-site soil conditions, and the range of available pipe Dimension Ratios make the design of buried pipe seem challenging. This section of the Design Chapter has been written with the intent of easing the designer's task. While some very sophisticated design approaches for buried pipe systems may be justified in certain applications, the simpler, empirical methodologies presented herein have been proven by experience to provide reliable results for virtually all PE pipe installations.

The design process consists of the following steps:

1. Determine the **vertical soil pressure** acting at the crown of the pipe due to earth, live, and surcharge loads.
2. Select a **trial pipe**, which means selecting a **trial dimension ratio (DR)** or, in the case of profile pipe, a **trial profile**.
3. Select an embedment material and degree of compaction. As will be described later, soil type and compaction are relatable to a specific **modulus of soil reaction value (E')** (Table 3-8). (As deflection is proportional to the combination of pipe and soil stiffness, pipe properties and embedment stiffness can be traded off to obtain an optimum design.)
4. For the trial pipe and trial modulus of soil reaction, **calculate** the deflection due to the vertical soil pressure. **Compare** the pipe deflection to the deflection limit. If deflection exceeds the limit, it is generally best to look at increasing the modulus of soil reaction rather than reducing the DR or changing to a heavier profile. Repeat step 4 for the new E′ and/or new trial pipe.
5. For the trial pipe and trial modulus of soil reaction, **calculate** the allowable soil pressure for wall crushing and for wall buckling. **Compare** the allowable soil pressure to the applied vertical pressure. If the allowable pressure is equal to or higher than the applied vertical pressure, the design is complete. If not, select a different pipe DR or heavier profile or different E′, and repeat step 5.

Since design begins with calculating vertical soil pressure, it seems appropriate to discuss the different methods for finding the vertical soil pressure on a buried pipe before discussing the pipe's response to load within the four installation categories.

Earth, Live, and Surcharge Loads on Buried Pipe

Vertical Soil Pressure

The weight of the earth, as well as surface loads above the pipe, produce soil pressure on the pipe. The weight of the earth or "earth load" is often considered to be a "dead-load" whereas surface loads are referred to as "surcharge loads" and may be temporary or permanent. When surcharge loads are of short duration they are usually referred to as "live loads." The most common live load is vehicular load. Other common surcharge loads include light structures, equipment, and piles of stored materials or debris. This section gives formulas for calculating the vertical soil pressure due to both earth and surcharge loads. The soil pressures are normally calculated at the depth of the pipe crown. The soil pressures for earth load and each surcharge load are added together to obtain the total vertical soil pressure which is then used for calculating deflection and for comparison with wall crush and wall buckling performance limits.

Earth Load

In a uniform, homogeneous soil mass, the soil load acting on a horizontal plane within the mass is equal to the weight of the soil directly above the plane. If the mass contains areas of varying stiffness, the weight of the mass will redistribute itself toward the stiffer areas due to internal shear resistance, and arching will occur. Arching results in a reduction in load on the less stiff areas. Flexible pipes including PE pipes are normally not as stiff as the surrounding soil, so the resulting earth pressure acting on PE pipe is reduced by arching and is less than the weight of soil above the pipe. (One minor exception to this is shallow cover pipe under dynamic loads.) For simplicity, engineers often ignore arching and assume that the earth load on the pipe is equal to the weight of soil above the pipe, which is referred to as the “prism load” or “geostatic stress.” Practically speaking, the prism load is a conservative loading for PE pipes. It may be safely used in virtually all designs. Equation 3-1 gives the vertical soil pressure due to the prism load. The depth of cover is the depth from the ground surface to the pipe crown.

(3-1) $$P_E = \mathrm{w}H$$

WHERE

P_E **= vertical soil pressure due to earth load, psf**
w **= unit weight of soil, pcf**
H **= depth of cover, ft**

UNITS CONVENTION: To facilitate calculations for PE pipes, the convention used with rigid pipes for taking the load on the pipe as a line load along the longitudinal axis in units of **lbs/lineal-ft** of pipe length is not used here. Rather, the load is treated as a soil pressure acting on a horizontal plane at the pipe crown and is given in units of **lbs/ft^2 or psf.**

Soil weight can vary substantially from site to site and within a site depending on composition, density and load history. Soil weights are often found in the construction site geotechnical report. The saturated unit weight of the soil is used when the pipe is below the groundwater level. For design purposes, the unit weight of dry soil is commonly assumed to be 120 pcf, when site-specific information is not available.

Generally, the soil pressure on profile pipe and on DR pipe in deep fills is significantly less than the prism load due to arching. For these applications, soil pressure is best calculated using the calculations that account for arching in the "Deep Fill Installation" section.

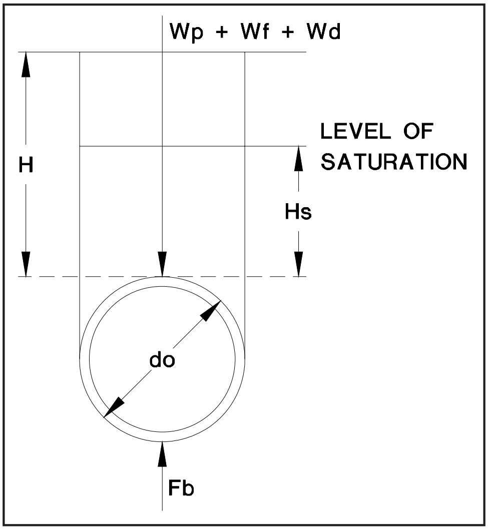


Figure 3-2 Prism Load

Live Load

Even though wheel loadings from cars and other light vehicles may be frequent, these loads generally have little impact on subsurface piping compared to the less frequent but significantly heavier loads from trucks, trains, or other heavy vehicles. For design of pipes under streets and highways, only the loadings from these heavier vehicles are considered. The pressure transmitted to a pipe by a vehicle depends on the pipe's depth, the vehicle's weight, the tire pressure and size, vehicle speed, surface smoothness, the amount and type of paving, the soil, and the distance from the pipe to the point of loading. For the more common cases, such as AASHTO, H20 HS20 truck traffic on paved roads and E-80 rail loading, this information has been simplified and put into Table 3-3, 3-4, and 3-5 to aid the designer. For special cases, such as mine trucks, cranes, or off-road vehicles, Equations 3-2 and 3-4 may be used.

The maximum load under a wheel occurs at the surface and diminishes with depth. PE pipes should be installed a minimum of one diameter or 18", whichever is greater, beneath the road surface. At this depth, the pipe is far enough below the wheel load to significantly reduce soil pressure and the pipe can fully utilize the embedment soil for load resistance. Where design considerations do not permit installation with at least one diameter of cover, additional calculations are required and are given in the section discussing “Shallow Cover Vehicular Loading Installation.” State highway departments often regulate minimum cover depth and may require 2.5 ft to 5 ft of cover depending on the particular roadway.

During construction, both permanent and temporary underground pipelines may be subjected to heavy vehicle loading from construction equipment. It may be advisable to provide a designated vehicle crossing with special measures such as temporary pavement or concrete encasement, as well as vehicle speed controls to limit impact loads.

The following information on AASHTO Loading and Impact Factor is not needed to use Tables 3-3 and 3-4. It is included to give the designer an understanding of the surface loads encountered and typical impact factors. If the designer decides to use Equations 3-2 or 3-4 rather than the tables, the information will be useful.

AASHTO Vehicular Loading

Vehicular loads are typically based on The American Association of State Highway and Transportation Officials (AASHTO) standard truck loadings. For calculating the soil pressure on flexible pipe, the loading is normally assumed to be an H20 (HS20) truck. A standard H20 truck has a total weight of 40,000 lbs (20 tons). The weight is distributed with 8,000 lbs on the front axle and 32,000 lbs on the rear axle. The HS20 truck is a tractor and trailer unit having the same axle loadings as the H20 truck but with two rear axles. See Figure 3-3. For these trucks, the maximum wheel load is found at the rear axle(s) and equals 40 percent of the total weight of the truck.
The maximum wheel load may be used to represent the static load applied by either a single axle or tandem axles. Some states permit heavier loads. The heaviest tandem axle loads normally encountered on highways are around 40,000 lbs (20,000 lbs per wheel). Occasionally, vehicles may be permitted with loads up to 50 percent higher.

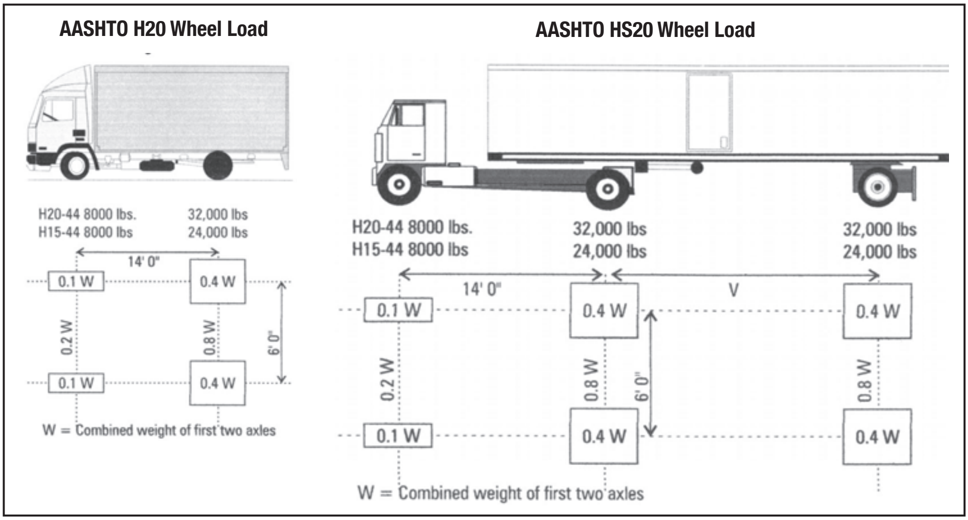


Figure 3-3 AASHTO H20 and HS20 Vehicle Loads

Impact Factor

Road surfaces are rarely smooth or perfectly even. When vehicles strike bumps in the road, the impact causes an instantaneous increase in wheel loading. Impact load may be found by multiplying the static wheel load by an impact factor. The factor varies with depth. Table 3-2 gives impact factors for vehicles on paved roads. For unpaved roads, impact factors of 2.0 or higher may occur, depending on the road surface.

TABLE 3-2
Typical Impact Factors for Paved Roads

Cover Depth, ft	Impact Factor, I_f
1	1.35
2	1.30
3	1.25
4	1.20
6	1.10
8	1.00

Derived from Illinois DOT dynamic load formula (1996).

Vehicle Loading through Highway Pavement (Rigid)

Pavement reduces the live load pressure reaching a pipe. A stiff, rigid pavement spreads load out over a large subgrade area thus significantly reducing the vertical soil pressure. Table 3-3 gives the vertical soil pressure underneath an H20 (HS20) truck traveling on a paved highway (12-inch thick concrete). An impact factor is incorporated. For use with heavier trucks, the pressures in Table 3-3 can be adjusted proportionally to the increased weight as long as the truck has the same tire area as an HS20 truck.

TABLE 3-3
Soil Pressure under H20 Load (12" Thick Pavement)

Depth of cover, ft.	Soil Pressure, lb/ft^2
1	1800
1.5	1400
2	800
3	600
4	400
5	250
6	200
7	175
8	100
Over 8	Neglect

Note: For reference see ASTM F7906. Based on axle load equally distributed over two 18 by 20 inch areas, spaced 72 inches apart. Impact factor included.

Vehicle Loading through Flexible Pavement or Unpaved Surface

Flexible pavements (or unpaved surfaces) do not have the bridging ability of rigid pavement and thus transmit more pressure through the soil to the pipe than given by Table 3-3. In many cases, the wheel loads from two vehicles passing combine to create a higher soil pressure than a single dual-tire wheel load. The maximum pressure may occur directly under the wheels of one vehicle or somewhere in between the wheels of the two vehicles depending on the cover depth. Table 3-4 gives the largest of the maximum pressure for two passing H20 trucks on an unpaved surface. No impact factor is included. The loading in Table 3-3 is conservative and about 10% higher than loads found by the method given in AASHTO Section 3, LRFD Bridge Specifications Manual based on assuming a single dual-tire contact area of 20 x 10 inches and using the equivalent area method of load distribution.

TABLE 3-4
Soil Pressure Under H20 Load (Unpaved or Flexible Pavement)

Depth of cover, ft.	Soil Pressure, lb/ft^2
1.5	2000
2.0	1340
2.5	1000
3.0	710
3.5	560
4.0	500
6.0	310
8.0	200
10.0	140

Note: Based on integrating the Boussinesq equation for two H20 loads spaced 4 feet apart or one H20 load centered over pipe. No pavement effects or impact factor included.

Off-Highway Vehicles

Off-highway vehicles such as mine trucks and construction equipment may be considerably heavier than H20 trucks. These vehicles frequently operate on unpaved construction or mine roads which may have very uneven surfaces. Thus, except for slow traffic, an impact factor of 2.0 to 3.0 should be considered. For off-highway vehicles, it is generally necessary to calculate live load pressure from information supplied by the vehicle manufacturer regarding the vehicle weight or wheel load, tire footprint (contact area) and wheel spacing.

The location of the vehicle's wheels relative to the pipe is also an important factor in determining how much load is transmitted to the pipe. Soil pressure under a point load at the surface is dispersed through the soil in both depth and expanse. Wheel loads not located directly above a pipe may apply pressure to the pipe, and this pressure can be significant. The load from two wheels straddling a pipe may produce a higher pressure on a pipe than from a single wheel directly above it.

For pipe installed within a few feet of the surface, the maximum soil pressure will occur when a single wheel (single or dual tire) is directly over the pipe. For deeper pipes, the maximum case often occurs when vehicles traveling above the pipe pass within a few feet of each other while straddling the pipe, or in the case of off-highway vehicles when they have closely space axles. The minimum spacing between the centerlines of the wheel loads of passing vehicles is assumed to be four feet. At this spacing for H20 loading, the pressure on a pipe centered midway between the two passing vehicles is greater than a single wheel load on a pipe at or below a depth of about four feet.

For design, the soil pressure on the pipe is calculated based on the vehicle location (wheel load locations) relative to the pipe that produces the maximum pressure. This generally involves comparing the pressure under a single wheel with that occurring with two wheels straddling the pipe. The Timoshenko Equation can be used to find the pressure directly under a single wheel load, whereas the Boussinesq Equation can be used to find the pressure from wheels not directly above the pipe.

Timoshenko's Equation

The Timoshenko Equation gives the soil pressure at a point directly under a distributed surface load, neglecting any pavement.

(3-2)

$$P_L = \frac{I_f W_w}{a_C}\left(1 - \frac{H^3}{(r_T{}^2 + H^2)^{1.5}}\right)$$

WHERE

P_L **= vertical soil pressure due to live load, lb/ft^2**

I_f **= impact factor**

W_W **= wheel load, lb**

a_C **= contact area, ft^2**

r_T **= equivalent radius, ft**

H **= depth of cover, ft**

The equivalent radius is given by:

(3-3)

$$r_T = \sqrt{\frac{a_C}{\pi}}$$

For standard H2O and HS20 highway vehicle loading, the contact area is normally taken for dual wheels, that is, 16,000 lb over a 10 in. by 20 in. area.

Timoshenko Example Calculation

Find the vertical pressure on a 24" PE pipe buried 3 ft beneath an unpaved road when an R-50 off-road truck is over the pipe. The manufacturer lists the truck with a gross weight of 183,540 lbs on 21X35 E3 tires, each having a 30,590 lb load over an imprint area of 370 in^2.

SOLUTION: Use Equations 3-2 and 3-3. Since the vehicle is operating on an unpaved road, an impact factor of 2.0 is appropriate.

$$r_T = \sqrt{\frac{370/144}{\pi}} = 0.90ft \qquad P_L = \frac{(2.0)(30,590)}{\frac{370}{144}}\left(1 - \frac{3^3}{(0.90^2 + 3^2)^{1.5}}\right)$$

$$P_L = 2890lb/ft^2$$

Boussinesq Equation

The Boussinesq Equation gives the pressure at any point in a soil mass under a concentrated surface load. The Boussinesq Equation may be used to find the pressure transmitted from a wheel load to a point that is not along the line of action of the load. Pavement effects are neglected.

(3-4)
$$P_L = \frac{3 I_f W_w H^3}{2\pi r^5}$$

WHERE

P_L **= vertical soil pressure due to live load lb/ft²**

W_W **= wheel load, lb**

H **= vertical depth to pipe crown, ft**

I_f **= impact factor**

r **= distance from the point of load application to pipe crown, ft**

(3-5)
$$r = \sqrt{X^2 + H^2}$$

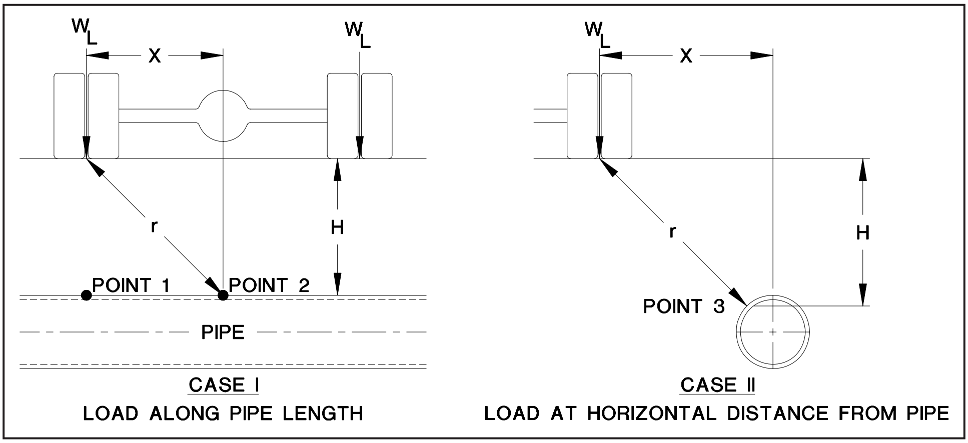


Figure 3-4 Illustration of Boussinesq Point Loading

Example Using Boussinesq Point Loading Technique

Determine the vertical soil pressure applied to a 12″ pipe located 4 ft deep under a dirt road when two vehicles traveling over the pipe and in opposite lanes pass each other. Assume center lines of wheel loads are at a distance of 4 feet. Assume a wheel load of 16,000 lb.

SOLUTION: Use Equation 3-4, and since the wheels are traveling, a 2.0 impact factor is applied. The maximum load will be at the center between the two wheels, so X = 2.0 ft. Determine r from Equation 3-5.

$$r = \sqrt{4^2 + 2.0^2} = 4.47\,ft$$

Then solve Equation 3-4 for PL, the load due to a single wheel.

$$P_L = \frac{3(2.0)(16{,}000)(4)^3}{2\pi(4.47)^5}$$

$$P_L = 548\ lb / ft^2$$

The load on the pipe crown is from both wheels, so

$$2\,P_L = 2(548) = 1096\ lb / ft^2$$

The load calculated in this example is higher than that given in Table 3-4 for a comparable depth even after correcting for the impact factor. Both the Timoshenko and Boussinesq Equations give the pressure applied at a point in the soil. In solving for pipe reactions it is assumed that this point pressure is applied across the entire surface of a unit length of pipe, whereas the actual applied pressure decreases away from the line of action of the wheel load. Methods that integrate this pressure over the pipe surface such as used in deriving Table 3-4 gives more accurate loading values. However, the error in the point pressure equations is slight and conservative, so they are still effective equations for design.

Railroad Loads

The live loading configuration used for pipes under railroads is the Cooper E-80 loading, which is an 80,000 lb load that is uniformly applied over three 2 ft by 8 ft areas on 5 ft centers. The area represents the 8 ft width of standard railroad ties and the standard spacing between locomotive drive wheels. Live loads are based on the axle weight exerted on the track by two locomotives and their tenders coupled together in doubleheader fashion. See Table 3-5. Commercial railroads frequently require casings for pressure pipes if they are within 25 feet of the tracks, primarily for safety reasons in the event of a washout. Based upon design and permitting requirements, the designer should determine whether or not a casing is required.

TABLE 3-5
Live Load Pressure for E-80 Railroad Loading

Depth of cover, ft.	Soil Pressure*, lb/ft^2
2.0	3800
5.0	2400
8.0	1600
10.0	1100
12.0	800
15.0	600
20.0	300
30.0	100
Over 30.0	Neglect

For referecne see ASTM A796. *The values shown for soil pressure include impact.

Surcharge Load

Surcharge loads may be distributed loads, such as a footing, foundation, or an ash pile, or may be concentrated loads, such as vehicle wheels. The load will be dispersed through the soil such that there is a reduction in pressure with an increase in depth or horizontal distance from the surcharged area. Surcharge loads not directly over the pipe may exert pressure on the pipe as well. The pressure at a point beneath a surcharge load depends on the load magnitude and the surface area over which the surcharge is applied. Methods for calculating vertical pressure on a pipe either located directly beneath a surcharge or located near a surcharge are given below.

Pipe Directly Beneath a Surcharge Load

This design method is for finding the vertical soil pressure under a rectangular area with a uniformly distributed surcharge load. This may be used in place of Tables 3-3 to 3-5 and Equations 3-3 and 3-5 to calculate vertical soil pressure due to wheel loads. This requires knowledge of the tire imprint area and impact factor.

The point pressure on the pipe at depth, H, is found by dividing the rectangular surcharge area (ABCD) into four sub-area rectangles (a, b, c, and d) which have a common corner, E, in the surcharge area, and over the pipe. The surcharge pressure, P_L, at a point directly under E is the sum of the pressure due to each of the four sub-area loads. Refer to Figure 3-5 A.

The pressure due to each sub-area is calculated by multiplying the surcharge pressure at the surface by an Influence Value, I_V. Influence Values are proportionality constants that measure what portion of a surface load reaches the subsurface point in question. They were derived using the Boussinesq Equation and are given in Table 3-6.

(3-6) $$P_L = p_a + p_b + p_c + p_d$$

WHERE

P_L = vertical soil pressure due to surcharge pressure, lb/ft^2

p_a = pressure due to sub-area a, lb/ft^2

p_b = pressure due to sub-area b, lb/ft^2

p_c = pressure due to sub-area c, lb/ft^2

p_d = pressure due to sub-area d, lb/ft^2

Pressure due to the surcharge applied to the i-th sub-area equals:

(3-7) $$p_i = I_V \, w_S$$

WHERE

I_V = Influence Value from Table 3-6

w_S = distributed pressure of surcharge load at ground surface, lb/ft^2

If the four sub-areas are equivalent, then Equation 3-7 may be simplified to:

(3-8) $$P_L = 4I_V \, w_S$$

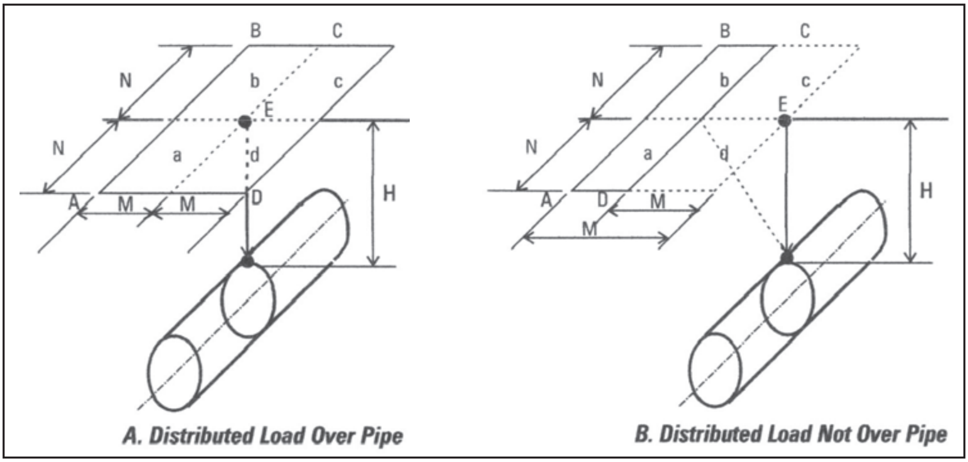
The influence value is dependent upon the dimensions of the rectangular area and upon the depth to the pipe crown, H. Table 3-6 Influence Value terms depicted in Figure 3-6, are defined as:

H = depth of cover, ft

M = horizontal distance, normal to the pipe centerline, from the center of the load to the load edge, ft

N = horizontal distance, parallel to the pipe centerline, from the center of the load to the load edge, ft

Interpolation may be used to find values not given in Table 3-6. The influence value gives the portion (or influence) of the load that reaches a given depth beneath the corner of the loaded area.



A. Distributed Load Over Pipe

B. Distributed Load Not Over Pipe

Figure 3-5 Illustration of Distributed Loads

TABLE 3-6

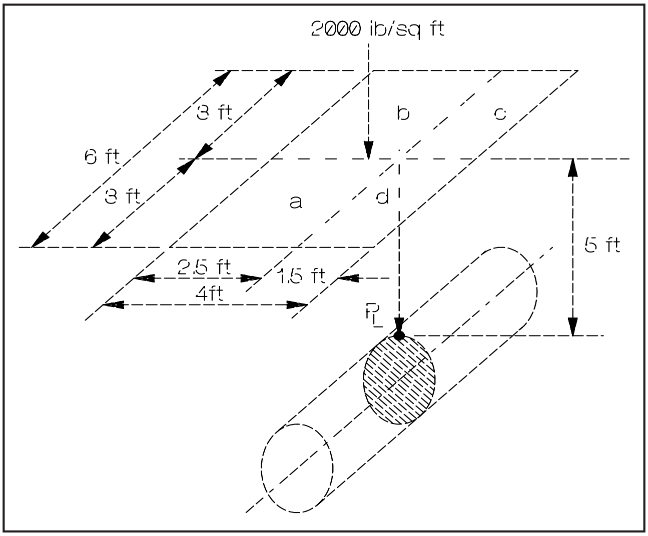
Influence Values, I_V for Distributed Loads*

	N/H													
M/H	**0.1**	**0.2**	**0.3**	**0.4**	**0.5**	**0.6**	**0.7**	**0.8**	**0.9**	**1.0**	**1.2**	**1.5**	**2.0**	∞
0.1	0.005	0.009	0.013	0.017	0.020	0.022	0.024	0.026	0.027	0.028	0.029	0.030	0.031	0.032
0.2	0.009	0.018	0.026	0.033	0.039	0.043	0.047	0.050	0.053	0.055	0.057	0.060	0.061	0.062
0.3	0.013	0.026	0.037	0.047	0.056	0.063	0.069	0.073	0.077	0.079	0.083	0.086	0.089	0.090
0.4	0.017	0.033	0.047	0.060	0.071	0.080	0.087	0.093	0.098	0.101	0.106	0.110	0.113	0.115
0.5	0.020	0.039	0.056	0.071	0.084	0.095	0.103	0.110	0.116	0.120	0.126	0.131	0.135	0.137
0.6	0.022	0.043	0.063	0.080	0.095	0.107	0.117	0.125	0.131	0.136	0.143	0.149	0.153	0.156
0.7	0.024	0.047	0.069	0.087	0.103	0.117	0.128	0.137	0.144	0.149	0.157	0.164	0.169	0.172
0.8	0.026	0.050	0.073	0.093	0.110	0.125	0.137	0.146	0.154	0.160	0.168	0.176	0.181	0.185
0.9	0.027	0.053	0.077	0.098	0.116	0.131	0.144	0.154	0.162	0.168	0.178	0.186	0.192	0.196
1.0	0.028	0.055	0.079	0.101	0.120	0.136	0.149	0.160	0.168	0.175	0.185	0.194	0.200	0.205
1.2	0.029	0.057	0.083	0.106	0.126	0.143	0.157	0.168	0.178	0.185	0.196	0.205	0.209	0.212
1.5	0.030	0.060	0.086	0.110	0.131	0.149	0.164	0.176	0.186	0.194	0.205	0.211	0.216	0.223
2.0	0.031	0.061	0.088	0.113	0.135	0.153	0.169	0.181	0.192	0.200	0.209	0.216	0.232	0.240
∞	0.032	0.062	0.089	0.116	0.137	0.156	0.172	0.185	0.196	0.205	0.212	0.223	0.240	0.250

* H, M, and N are per Figure 3-5.

Vertical Surcharge Example # 1

Find the vertical surcharge load for the 4′ x 6′, 2000 lb/ft2 footing shown below.



SOLUTION: Use equations 3-6 and 3-7, Table 3-6, and Figure 3-5. The 4 ft x 6 ft footing is divided into four sub-areas, such that the common corner of the sub-areas is directly over the pipe. Since the pipe is not centered under the load, sub-areas a and b have dimensions of 3 ft x 2.5 ft, and sub-areas c and d have dimensions of 3 ft x 1.5 ft.

Determine sub-area dimensions for M, N, and H, then calculate M/H and N/H. Find the Influence Value from Table 3-6, then solve for each sub area, p_a, p_b, p_c, p_d, and sum for P_L.

	Sub-area			
	a	**b**	**c**	**d**
M	2.5	2.5	1.5	1.5
N	3.0	3.0	3.0	3.0
M/H	0.5	0.5	0.3	0.3
N/H	0.6	0.6	0.6	0.6
I_V	0.095	0.095	0.063	0.063
p_i	190	190	126	126

Therefore: $P_L = 632$ lbs/ft^2

Pipe Adjacent to, but Not Directly Beneath, a Surcharge Load

This design method may be used to find the surcharge load on buried pipes near, but not directly below, uniformly distributed loads such as concrete slabs, footings and floors, or other rectangular area loads, including wheel loads that are not directly over the pipe.

The vertical pressure is found by first adding an imaginary loaded area that covers the pipe, then determining the surcharge pressure due to the overall load (actual and imaginary) based on the previous section, and finally by deducting the pressure due to the imaginary load from that due to the overall load.

Refer to Figure 3-5 B. Since there is no surcharge directly above the pipe centerline, an imaginary surcharge load, having the same pressure per unit area as the actual load, is applied to sub-areas c and d. The surcharge pressure for sub-areas a+d and b+c are determined, then the surcharge loads from the imaginary areas c and d are deducted to determine the surcharge pressure on the pipe.

(3-9) $$P_L = p_{a+d} + p_{b+c} - p_d - p_c$$

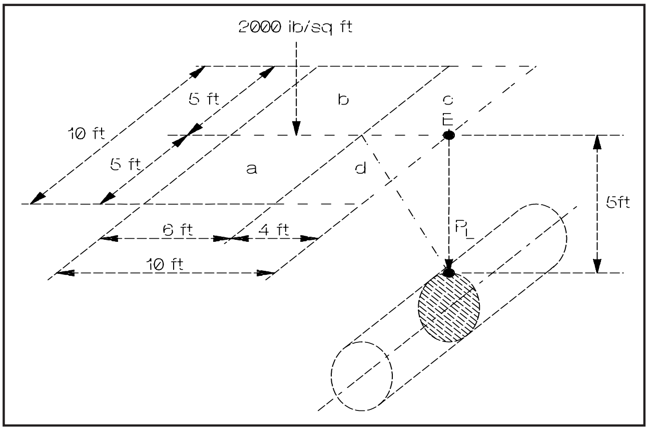
Where terms are as previously defined above, and

P_{a+d} **= surcharge load of combined sub-areas a and d, lb/ft^2**

P_{b+c} **= surcharge load of combined sub-areas b and c, lb/ft^2**

Vertical Surcharge Example # 2

Find the vertical surcharge pressure for the 6′ x 10′, 2000 lb/ft^2 slab shown below.



SOLUTION: Use Equations 3-7 and 3-9, Table 3-6, and Figure 3-5 B. The surcharge area is divided into two sub-areas, a and b. The area between the surcharge and the line of the pipe crown is divided into two sub-areas, c and d, as well. The imaginary load is applied to sub-areas c and d. Next, the four sub-areas are treated as a single surcharge area. Unlike the previous example, the pipe is located under the edge of the surcharge area rather than the center. So, the surcharge pressures for the combined sub-areas a+d and b+c are determined, and then for the sub-areas c and d. The surcharge pressure is the sum of the surcharge pressure due to the surcharge acting on sub-areas a+d and b+c, less the imaginary pressure due to the imaginary surcharge acting on sub-areas c and d.

	Sub-area			
	a + d	b + c	c	d
M	10	10	4	4
N	5	5	5	5
M/H	2.0	2.0	0.8	0.8
N/H	1.0	1.0	1.0	1.0
I_V	0.200	0.200	0.160	0.160
p_i	400	400	(320)	(320)

Therefore P_L = 160 lb/ft^2

Installation Category 1: Standard Installation - Trench or Embankment

Pipe Reaction to Earth, Live, and Surcharge Loads

Now might be a good time to review the "Design Process" that appeared earlier in Section 3. After calculating the vertical pressure applied to the pipe the next design step is to choose a trial pipe (DR or profile). Then, based on the Installation Category and the selected embedment and compaction, calculate the anticipated deflection and resistance to crush and buckling.

The Standard Installation category applies to pipes that are installed between 18 inches and 50 feet of cover. Where surcharge, traffic, or rail load may occur, the pipe must have at least one full diameter of cover. If such cover is not available, then the application design must also consider limitations under the Shallow Cover Vehicular Loading Installation category. Where the cover depth exceeds 50 ft an alternate treatment for dead loads is given under the Deep Fill Installation category. Where ground water occurs above the pipe's invert and the pipe has less than two diameters of cover, the potential for the occurrence of flotation or upward movement of the pipe may exist. See Shallow Cover Flotation Effects.

While the Standard Installation is suitable for up to 50 feet of cover, it may be used for more cover. The 50 feet limit is based on A. Howard's (3) recommended limit for use of E' values. Above 50 feet, the E' values given in Table B.1.1 in Chapter 3 Appendix are generally thought to be overly conservative as they are not corrected for the increase in embedment stiffness that occurs with depth as a result of the higher confinement pressure within the soil mass. In addition, significant arching occurs at depths greater than 50 feet.

The Standard Installation, as well as the other design categories for buried PE pipe, looks at a ring or circumferential cross-section of pipe and neglects longitudinal loading, which is normally insignificant. They also ignore the re-rounding effect of internal pressurization. Since re-rounding reduces deflection and stress in the pipe, ignoring it is conservative.

Ring Deflection

Ring deflection is the normal response of flexible pipes to soil pressure. It is also a beneficial response in that it leads to the redistribution of soil stress and the initiation of arching. Ring deflection can be controlled within acceptable limits by the selection of appropriate pipe embedment materials, compaction levels, trench width and, in some cases, the pipe itself.

The magnitude of ring deflection is inversely proportional to the combined stiffness of the pipe and the embedment soil. M. Spangler (4) characterized this relationship in the Iowa Formula in 1941. R. Watkins (5) modified this equation to allow a simpler approach for soil characterization, thus developing the Modified Iowa Formula. In 1964, Burns and Richards (6) published a closed-form solution for ring deflection and pipe stress based on classical linear elasticity. In 1976 M. Katona et. al. (7) developed a finite element program called CANDE (Culvert Analysis and Design) which is now available in a PC version and can be used to predict pipe deflection and stresses.

The more recent solutions may make better predictions than the Iowa Formula, but they require detailed information on soil and pipe properties, e.g. more soil lab testing. Often the improvement in precision is all but lost in construction variability. Therefore, the Modified Iowa Formula remains the most frequently used method of determining ring deflection.

Spangler's Modified Iowa Formula can be written for use with solid wall PE pipe as:

(3-10)

$$\frac{\Delta X}{D_M} = \frac{1}{144}\left(\frac{K_{BED}\,L_{DL}P_E + K_{BED}P_L}{\frac{2E}{3}\left(\frac{1}{DR-1}\right)^3 + 0.061F_S E'}\right)$$

and for use with ASTM F894 profile wall pipe as:

(3-11)

$$\frac{\Delta X}{D_I} = \frac{P}{144}\left(\frac{K_{BED}L_{DL}}{\frac{1.24(RSC)}{D_M} + 0.061F_S E'}\right)$$

WHERE

ΔX = **Horizontal deflection, in**

K_{BED} = **Bedding factor, typically 0.1**

L_{DL} = **Deflection lag factor**

P_E = **Vertical soil pressure due to earth load, psf**

P_L = **Vertical soil pressure due to live load, psf**

E = **Apparent modulus of elasticity of pipe material, lb/in^2**

E' =**Modulus of Soil reaction, psi**

F_S = **Soil Support Factor**

RSC = **Ring Stiffness Constant, lb/ft**

DR = **Dimension Ratio, OD/t**

D_M = **Mean diameter (D_I+2z or D_O-t), in**

z = **Centroid of wall section, in**

t = **Minimum wall thickness, in**

D_I = **pipe inside diameter, in**

D_O = **pipe outside diameter, in**

Deflection is reported as a percent of the diameter which can be found by multiplying 100 times $\Delta X/D_M$ or $\Delta X/D_I$. (When using RSC, the units of conversion are accounted for in Equation 3-11.)

Apparent Modulus of Elasticity for Pipe Material, E

The apparent modulus of PE is dependent on load-rate or, duration of laoding and temperature.Apparent elastic modulus values for high and medium density PE may be found in Table B.1.1 in Chapter 3 Appendix. These values can be used in Spangler's Iowa Formula. It has long been an industry practice to use the short-term modulus in the Iowa Formula for thermoplastic pipe. This is based on the idea that, in granular embedment soil, deformation is a series of instantaneous deformations consisting of rearrangement and fracturing of grains while the bending stress in the pipe wall is decreasing due to stress relaxation. Use of the short-term modulus has proven effective and reliable for corrugated and profile wall pipes. These pipes typically have pipe stiffness values of 46 psi or less when measured per ASTM D2412. Conventional DR pipes starting with DR17 or lower have significantly higher stiffness and therefore they may carry a greater proportion of the earth and live load than corrugated or profile pipe; so it is conservative to use the 50-year modulus for DR pipes that have low DR values when determining deflection due to earth load.

Vehicle loads are generally met with a higher modulus than earth loads, as load duration may be nearly instantaneous for moving vehicles. The deflection due to a combination of vehicle or temporary loads and earth load may be found by separately calculating the deflection due to each load using the modulus appropriate for the expected load duration, then adding the resulting deflections together to get the total deflection. When doing the deflection calculation for vehicle load, the Lag Factor will be one. An alternate, but conservative, method for finding deflection for combined vehicle and earth load is to do one calculation using the 50-year modulus, but separate the vertical soil pressure into an earth load component and a live load component and apply the Lag Factor only to the earth load component.

Ring Stiffness Constant, RSC

Profile wall pipes manufactured to ASTM F894, "Standard Specification for Polyethylene (PE) Large Diameter Profile Wall Sewer and Drain Pipe," are classified on the basis of their Ring Stiffness Constant (RSC). Equation 3-12 gives the RSC.

(3-12)

$$RSC = \frac{6.44\ EI}{D_M^2}$$

WHERE

E = Apparent modulus of elasticity of pipe material @73°F (See Chapter 3 Appendix)

I = Pipe wall moment of inertia, in^4/in ($t^3/12$, if solid wall construction)

z = Pipe wall centroid in

DI = Pipe inside diameter in

D_M = Mean diameter (DI + 2z or D_O-t), in

t = Minimum wall thickness, in

Modulus of Soil Reaction, E'

The soil reaction modulus is proportional to the embedment soil's resistance to the lateral expansion of the pipe. There are no convenient laboratory tests to determine the soil reaction modulus for a given soil. A. Howard (8) determined E' values empirically from numerous field deflection measurements by substituting site parameters (i.e. depth of cover, soil weight) into Spangler's equation and "back-calculating" E'. Howard developed a table for the Bureau of Reclamation relating E' values to soil types and compaction efforts. See Table 3-7. In back-calculating E', Howard assumed the prism load was applied to the pipe. Therefore, Table 3-7 E' values indirectly include load reduction due to arching and are suitable for use only with the prism load. In 2006, Howard published a paper reviewing his original 1977 publication from which Table 3-7 is taken. For the most part the recent work indicates that the E' values in Table 3-7 are conservative.

Due to differences in construction procedures, soil texture and density, pipe placement, and insitu soil characteristics, pipe deflection varies along the length of a pipeline. Petroff (9) has shown that deflection measurements along a pipeline typically fit the Normal Distribution curve. To determine the anticipated maximum deflection using Eq. 3-10 or 3-11, variability may be accommodated by reducing the Table 3-7 E' value by 25%, or by adding to the calculated deflection percentage the correction for 'accuracy' percentage given in Table 3-7.

In shallow installations, the full value of the E' given in Table 3-7 may not develop. This is due to the lack of "soil confining pressure" to hold individual soil grains tightly together and stiffen the embedment. Increased weight or equivalently, depth, increases the confining pressure and, thus, the E'. J. Hartley and J. Duncan (10) published recommended E' values based on depth of cover. See Table 3-8. These are particularly useful for shallow installations.

Chapter 7, "Underground Installation of PE Pipe" covers soil classification for pipe embedment materials and preferred methods of compaction and installation for selected embedment materials. Some of the materials shown in Table 3-7 may not be appropriate for all pipe installation. One example would be fine-grained soils in wet ground, which would not be appropriate embedment, under most circumstances, for either profile pipe or pipes with high DR's. Such limitations are discussed in Chapter 7.

TABLE 3-7

Values of E' for Pipe Embedment (See Howard (8))

Soil Type-pipe Embedment Material (Unified Classification System)[1]	E' for Degree of Embedment Compaction, lb/in^2			
	Dumped	**Slight,** **<85% Proctor, <40% Relative Density**	**Moderate, 85%-95% Proctor, 40%-70% Relative Density**	**High, >95% Proctor, >70% Relative Density**
Fine-grained Soils (LL > 50)[2] Soils with medium to high plasticity; CH, MH, CH-MH	No data available: consult a competent soils engineer, otherwise, use E' = 0.			
Fine-grained Soils (LL < 50) Soils with medium to no plasticity, CL, ML, ML-CL, with less than 25% coarse grained particles.	50	200	400	1000
Fine-grained Soils (LL < 50) Soils with medium to no plasticity, CL, ML, ML-CL, with more than 25% coarse grained particles; Coarse-grained Soils with Fines, GM, GC, SM, SC[3] containing more than 12% fines.	100	400	1000	2000
Coarse-grained soils with Little or No Fines GW, GP, SW, SP[3] containing less than 12% fines	200	1000	2000	3000
Crushed Rock	1000	3000	3000	3000
Accuracy in Terms of Percentage Deflection[4]	±2%	±2%	±1%	±0.5%

[1] ASTM D-2487, USBR Designation E-3
[2] LL = Liquid Limit
[3] Or any borderline soil beginning with one of these symbols (i.e., GM-GC, GC-SC).
[4] For ±1% accuracy and predicted deflection of 3%, actual deflection would be between 2% and 4%.

Note: Values applicable only for fills less than 50 ft (15 m). Table does not include any safety factor. For use in predicting initial deflections only; appropriate Deflection Lag Factor must be applied for long-term deflections. If embedment falls on the borderline between two compaction categories, select lower E' value, or average the two values. Percentage Proctor based on laboratory maximum dry density from test standards using 12,500 ft-lb/cu ft (598,000 J/m^2) (ASTM D-698, AASHTO T-99, USBR Designation E-11). 1 psi = 6.9 KPa.

TABLE 3-8
Values of E' for Pipe Embedment (See Duncan and Hartley(10))

Type of Soil	Depth of Cover, ft	E' for Standard AASHTO Relative Compaction, lb/in²			
		85%	90%	95%	100%
Fine-grained soils with less than 25% sand content (CL, ML, CL-ML)	0-5	500	700	1000	1500
	5-10	600	1000	1400	2000
	10-15	700	1200	1600	2300
	15-20	800	1300	1800	2600
Coarse-grained soils with fines (SM, SC)	0-5	600	1000	1200	1900
	5-10	900	1400	1800	2700
	10-15	1000	1500	2100	3200
	15-20	1100	1600	2400	3700
Coarse-grained soils with little or no fines (SP, SW, GP, GW)	0-5	700	1000	1600	2500
	5-10	1000	1500	2200	3300
	10-15	1050	1600	2400	3600
	15-20	1100	1700	2500	3800

Soil Support Factor, F_S

Ring deflection and the accompanying horizontal diameter expansion create lateral earth pressure which is transmitted through the embedment soil and into the trench sidewall. This may cause the sidewall soil to compress. If the compression is significant, the embedment can move laterally, resulting in an increase in pipe deflection. Sidewall soil compression is of particular concern when the insitu soil is loose, soft, or highly compressible, such as marsh clay, peat, saturated organic soil, etc. The net effect of sidewall compressibility is a reduction in the soil-pipe system's stiffness. The reverse case may occur as well if the insitu soil is stiffer than the embedment soil; e.g. the insitu soil may enhance the embedment giving it more resistance to deflection. The Soil Support Factor, F_S, is a factor that may be applied to E' to correct for the difference in stiffness between the insitu and embedment soils. Where the insitu soil is less stiff than the embedment, F_S is a reduction factor. Where it is stiffer, F_S is an enhancement factor, i.e. greater than one.

The Soil Support Factor, F_S, may be obtained from Tables 3-9 and 3-10 as follows:

- Determine the ratio B_d/D_O, where B_d equals the trench width at the pipe springline (inches), and D_O equals the pipe outside diameter (inches).
- Based on the native insitu soil properties, find the soil reaction modulus for the insitu soil, E'_N in Table 3-9.
- Determine the ratio E'_N/E'.
- Enter Table 3-10 with the ratios B_d/D_O and E'_N/E' and find F_S.

TABLE 3-9

Values of E'_N, Native Soil Modulus of Soil Reaction, Howard (3)

Native In Situ Soils				
Granular		Cohesive		E'_N (psi)
Std. Pentration ASTM D1586 Blows/ft	Description	Unconfined Compressive Strength (TSF)	Description	
> 0 - 1	very, very loose	> 0 - 0.125	very, very soft	50
1 - 2	very loose	0.125 - 0.25	very soft	200
2 - 4	very loose	0.25 - 0.50	soft	700
4 - 8	loose	0.50 - 1.00	medium	1,500
8 - 15	slightly compact	1.00 - 2.00	stiff	3,000
15 - 30	compact	2.00 - 4.00	very stiff	5,000
30 - 50	dense	4.00 - 6.00	hard	10,000
> 50	very dense	> 6.00	very hard	20,000
Rock	–	–	–	50,000

TABLE 3-10

Soil Support Factor, F_S

E'_N/E'	B_d/D_O 1.5	B_d/D_O 2.0	B_d/D_O 2.5	B_d/D_O 3.0	B_d/D_O 4.0	B_d/D_O 5.0
0.1	0.15	0.30	0.60	0.80	0.90	1.00
0.2	0.30	0.45	0.70	0.85	0.92	1.00
0.4	0.50	0.60	0.80	0.90	0.95	1.00
0.6	0.70	0.80	0.90	0.95	1.00	1.00
0.8	0.85	0.90	0.95	0.98	1.00	1.00
1.0	1.00	1.00	1.00	1.00	1.00	1.00
1.5	1.30	1.15	1.10	1.05	1.00	1.00
2.0	1.50	1.30	1.15	1.10	1.05	1.00
3.0	1.75	1.45	1.30	1.20	1.08	1.00
5.0	2.00	1.60	1.40	1.25	1.10	1.00

Lag Factor and Long-Term Deflection

Spangler observed an increase in ring deflection with time. Settlement of the backfill and consolidation of the embedment under the lateral pressure from the pipe continue to occur after initial installation. To account for this, he recommended applying a lag factor to the Iowa Formula in the range of from 1.25 to 1.5. Lag occurs in installations of both plastic and metal pipes. Howard (3, 11) has shown that the lag factor varies with the type of embedment and the degree of compaction. Many plastic pipe designers use a Lag Factor of 1.0 when using the prism load as it accounts for backfill settlement. This makes even more sense when the Soil Support Factor is included in the calculation.

Vertical Deflection Example

Estimate the vertical deflection of a 24" diameter DR 26 pipe produced from a PE4710 material that is installed under 18 feet of cover. The embedment material is a well-graded sandy gravel, compacted to a minimum 90 percent of Standard Proctor density, and the native ground is a saturated, soft clayey soil. The anticipated trench width is 42".

SOLUTION: Use the prism load, Equation 3-1, Tables 3-7, 3-9, and 3-10, and Equation 3-10. Table 3-7 gives an E′ for a compacted sandy gravel or GW-SW soil as 2000 lb/in^2. The Short-Term Apparent Modulus of Elasticity for PE 4710 material obtained from Table B.2.1 equals 130,000 psi. To estimate maximum deflection due to variability, this value will be reduced by 25%, or to 1500 lb/in^2. Table 3-9 gives an E'_N of 700 psi for soft clay. Since B_d/D equals 1.75 and E'_N/E' equals 0.47, F_S is obtained by interpolation and equal 0.60.

The prism load on the pipe is equal to:

$$P_E = (120)(18) = 2160 lb/ft^2$$

Substituting these values into Equation 3-10 gives:

$$\frac{\Delta X}{D_M} = \frac{2160}{144}\left(\frac{(0.1)(1.0)}{\frac{2(130{,}000)}{3}\left(\frac{1}{26-1}\right)^3 + (0.061)(0.60)(1500)}\right)$$

$$\frac{\Delta X}{D_M} = 0.025 = 2.5\,\%$$

Deflection Limits

The designer limits ring deflection in order to control geometric stability of the pipe, wall bending strain, pipeline hydraulic capacity and compatibility with cleaning equipment, and, for bell-and-spigot jointed pipe, its sealing capability. Only the limits for geometric stability and bending strain will be discussed here. Hydraulic capacity is not impaired at deflections less than 7.5%.

Geometric stability is lost when the pipe crown flattens and loses its ability to support earth load. Crown flattening occurs with excessive deflection as the increase in horizontal diameter reduces crown curvature. At 25% to 30% deflection, the crown may completely reverse its curvature inward and collapse. See Figure 3-1A. A deflection limit of 7.5% provides at least a 3 to 1 safety factor against reverse curvature.

Bending strain occurs in the pipe wall as a result of ring deflection—outer-fiber tensile strain at the pipe springline and outer-fiber compressive strain at the crown and invert. While strain limits of 5% have been proposed, Jansen (12) reported that, on tests of PE pipe manufactured from pressure-rated resins and subjected to soil pressure only, "no upper limit from a practical design point of view seems to exist for the bending strain." In other words, as deflection increases, the pipe's performance limit will not be overstraining but reverse curvature collapse.

Thus, for non-pressure applications, a 7.5 percent deflection limit provides a large safety factor against instability and strain and is considered a safe design deflection. Some engineers will design profile wall pipe and other non-pressure pipe applications to a 5% deflection limit, but allow spot deflections up to 7.5% during field inspection.

The deflection limits for pressurized pipe are generally lower than for non-pressurized pipe. This is primarily due to strain considerations. Hoop strain from pressurization adds to the outer-fiber tensile strain. But the internal pressure acts to reround the pipe and, therefore, Eq. 3-10 overpredicts the actual long-term deflection for pressurized pipe. Safe allowable deflections for pressurized pipe are given in Table 3-11. Spangler and Handy (13) give equations for correcting deflection to account for rerounding.

TABLE 3-11
Safe Deflection Limits for Pressurized Pipe

DR or SDR	Safe Deflection as % of Diameter
32.5	7.5
26	7.5
21	7.5
17	6.0
13.5	6.0
11	5.0
9	4.0
7.3	3.0

* Based on Long-Term Design Deflection of Buried Pressurized Pipe given in ASTM F1962.

Compressive Ring Thrust

Earth pressure exerts a radial-directed force around the circumference of a pipe that results in a compressive ring thrust in the pipe wall. (This thrust is exactly opposite to the tensile hoop thrust induced when a pipe is pressurized.) See Figure 3-1B. Excessive ring compressive thrust may lead to two different performance limits: crushing of the material or buckling (loss of stability) of the pipe wall. See Figure 3-1C. This section will discuss crushing, and the next section will discuss buckling.

As is often the case, the radial soil pressure causing the stress is not uniform around the pipe's circumference. However, for calculation purposes it is assumed uniform and equal to the vertical soil pressure at the pipe crown.

Pressure pipes often have internal pressure higher than the radial pressure applied by the soil. As long as there is pressure in the pipe that exceeds the external pressure, the net thrust in the pipe wall is tensile rather than compressive, and wall crush or buckling checks are not necessary. Whether one needs to check this or not can be quickly determined by simply comparing the internal pressure with the vertical soil pressure.

Crushing occurs when the compressive stress in the wall exceeds the compressive yield stress of the pipe material. Equations 3-13 and 3-14 give the compressive stress resulting from earth and live load pressure for conventional extruded DR pipe and for ASTM F894 profile wall PE Pipe:

(3-13)
$$S = \frac{(P_E + P_L)\,DR}{288}$$

(3-14)
$$S = \frac{(P_E + P_L)\,D_O}{288A}$$

WHERE

P_E = **vertical soil pressure due to earth load, psf**

P_L = **vertical soil pressure due to live-load, psf**

S = **pipe wall compressive stress, lb/in^2**

DR = **Dimension Ratio, D_O/t**

D_O = **pipe outside diameter (for profile pipe $D_O = D_I + 2H_P$), in**

D_I = **pipe inside diameter, in**

H_P = **profile wall height, in**

A = **profile wall average cross-sectional area, in^2/in**
(Obtain the profile wall area from the manufacturer of the profile pipe.)

(Note: These equations contain a factor of 144 in the denominator for correct units conversions.)

Equation 3-14 may overstate the wall stress in profile pipe. Ring deflection in profile wall pipe induces arching. The "Deep Fill Installation" section of this chapter discusses arching and gives equations for calculating the earth pressure resulting from arching, P_{RD}. P_{RD} is given by Equation 3-23 and may be substituted for PE to determine the wall compressive stress when arching occurs.

The compressive stress in the pipe wall can be compared to the pipe material allowable compressive stress. If the calculated compressive stress exceeds the allowable stress, then a lower DR (heavier wall thickness) or heavier profile wall is required.

Allowable Compressive Stress

Allowable long-term compressive stress values for the several PE material designation codes can be found in Appendix, Chapter 3.

The long-term compressive stress value should be reduced for elevated temperature pipeline operation. Temperature design factors used for hydrostatic pressure may be used. See temperature re-rating or adjustment factors in the Appendix, Chapter 3.

Ring Compression Example

Find the pipe wall compressive ring stress in a DR 32.5 PE4710 pipe buried under 46 ft of cover. The ground water level is at the surface, the saturated weight of the insitu silty-clay soil is 120 lbs/ft3.

SOLUTION: Find the vertical earth pressure acting on the pipe. Use Equation 3-1.

Although the net soil pressure is equal to the buoyant weight of the soil, the water pressure is also acting on the pipe. Therefore the total pressure (water and earth load) can be found using the saturated unit weight of the soil.

Next, solve for the compressive stress.

$$P_E = (120\ pcf)(46\ ft) = 5520\ psf$$

$$S = \frac{(5520\ lb / ft^2)(32.5)}{288} = 623\ lb / inch^2$$

The compressive stress is well below the allowable limit of 1150 psi for the PE4710 material given in the Appendix, Chapter 3.

Constrained (Buried) Pipe Wall Buckling

Excessive compressive stress (or thrust) may cause the pipe wall to become unstable and buckle. Buckling from ring compressive stress initiates locally as a large "dimple," and then grows to reverse curvature followed by structural collapse. Resistance to buckling is proportional to the wall thickness divided by the diameter raised to a power. Therefore the lower the DR, the higher the resistance. Buried pipe has an added resistance due to support (or constraint) from the surrounding soil.

Non-pressurized pipes or gravity flow pipes are most likely to have a net compressive stress in the pipe wall and, therefore, the allowable buckling pressure should be calculated and compared to the total (soil and ground water) pressure. For most pressure pipe applications, the fluid pressure in the pipe exceeds the external pressure, and the net stress in the pipe wall is tensile. Buckling needs only be considered for that time the pipe is not under pressure, such as during and immediately after construction and during system shut-downs and, in cases in which a surge pressure event can produce a temporary negative internal pressure. Under these circumstances the pipe will react much stiffer to buckling as its modulus is higher under short term loading. When designing, select a modulus appropriate for the duration of the negative external pressure. For pipe that are subjected to negative pressure due to surge, consideration should be given to selecting a DR that gives the pipe sufficient unconstrained collapse strength to resist the full applied negative pressure without support for the soil. This is to insure against construction affects that result in the embedment material not developing its full design strength.

This chapter gives two equations for calculating buckling. The modified Luscher Equation is for buried pipes that are beneath the ground water level, subject to vacuum pressure, or under live load with a shallow cover. These forces act to increase even the slightest eccentricity in the pipe wall by following deformation inward. While soil pressure alone can create instability, soil is less likely to follow deformation inward, particularly if it is granular. So, dry ground buckling is only considered for deep applications and is given by the Moore-Selig Equation found in the section, "Buckling of Pipes in Deep, Dry Fills".

Luscher Equation for Constrained Buckling Below Ground Water Level

For pipes below the ground water level, operating under a full or partial vacuum, or subject to live load, Luscher's equation may be used to determine the allowable constrained buckling pressure. Equation 3-15 and 3-16 are for DR and profile pipe respectively.

(3-15)

$$P_{WC} = \frac{5.65}{N}\sqrt{RB'E'\frac{E}{12(DR-1)^3}}$$

(3-16)

$$P_{WC} = \frac{5.65}{N}\sqrt{RB'E'\frac{EI}{D_M{}^3}}$$

WHERE

P_{WC} **= allowable constrained buckling pressure, lb/in^2**

N **= safety factor**

(3-17)

$$R = 1 - 0.33 \frac{H_{GW}}{H}$$

WHERE

R **= buoyancy reduction factor**

H_{GW} **= height of ground water above pipe, ft**

H **= depth of cover, ft**

(3-18)

$$B' = \frac{1}{1 + 4\, e^{(-0.065H)}}$$

WHERE

e **= natural log base number, 2.71828**

E' **= soil reaction modulus, psi**

E **= apparent modulus of elasticity, psi**

DR **= Dimension Ratio**

I **= pipe wall moment of inertia, in^4/in ($t^3/12$, if solid wall construction)**

D_M **= Mean diameter (D_I + 2z or D_O – t), in**

Although buckling occurs rapidly, long-term external pressure can gradually deform the pipe to the point of instability. This behavior is considered viscoelastic and can be accounted for in Equations 3-15 and 3-16 by using the apparent modulus of elasticity value for the appropriate time and temperature of the loading. For instance, a vacuum event is resisted by the short-term value of the modulus whereas continuous ground water pressure would be resisted by the 50 year value. For modulus values see Appendix, Chapter 3.

For pipes buried with less than 4 ft or a full diameter of cover, Equations 3-15 and 3-16 may have limited applicability. In this case the designer may want to use Equations 3-39 and 3-40.

The designer should apply a safety factor commensurate with the application. A safety factor of 2.0 has been used for thermoplastic pipe.

The allowable constrained buckling pressure should be compared to the total vertical stress acting on the pipe crown from the combined load of soil, and ground water or floodwater. It is prudent to check buckling resistance against a ground water level for a 100-year-flood. In this calculation the total vertical stress is typically taken as the prism load pressure for saturated soil, plus the fluid pressure of any floodwater above the ground surface.

For DR pipes operating under a vacuum, it is customary to use Equation 3-15 to check the combined pressure from soil, ground water, and vacuum, and then to use the unconstrained buckling equation, Equation 3-39, to verify that the pipe can operate with the vacuum independent of any soil support or soil load, in case construction does not develop the full soil support. Where vacuum load is short-term, such as during water hammer events two calculations with Equation 3-14 are necessary. First determine if the pipe is sufficient for the ground water and soil pressure using a long-term modulus; then determine if the pipe is sufficient for the combined ground water, soil pressure and vacuum loading using the short-term modulus.

Constrained Buckling Example

Does a 36″ SDR 26 PE4710 pipe have satisfactory resistance to constrained buckling when installed with 18 ft of cover in a compacted soil embedment? Assume ground water to the surface and an E′ of 1500 lb/in^2.

SOLUTION: Solve Equation 3-15. Since this is a long-term loading condition, the 50 year stress relaxation modulus for PE4710 material is given in the Appendix to Chapter 3 as 29,000 psi. Soil cover, H, and ground water height, H_{GW}, are both 18 feet. Therefore, the soil support factor, B′, is found as follows;

$$B' = \frac{1}{1+4e^{-(0.065)(18)}} = 0.446$$

and the bouyancy reduction factor, R, is found as follows:

$$R = 1 - 0.33\frac{18}{18} = 0.67$$

Solve Equation 3-15 for the allowable long-term constrained buckling pressure:

$$P_{WC} = \frac{5.65}{2}\sqrt{\frac{0.67(0.446)1500(29{,}000)}{12(26-1)^3}}$$

$$P_{WC} = 23.5\ psi = 3387\ psf$$

The earth pressure and ground water pressure applied to the pipe is found using Equation 3-1 (prism load) with a saturated soil weight. The saturated soil weight being the net weight of both soil and water.

$$P_E = (120)(18) = 2160\frac{lb}{ft^2}$$

Compare this with the constrained buckling pressure. Since P_{WC} exceeds P_E, DR 26 has satisfactory resistance to constrained pipe buckling.

Installation Category #2: Shallow Cover Vehicular Loading

The Standard Installation methodology assumes that the pipe behaves primarily as a "membrane" structure, that is, the pipe is almost perfectly flexible with little ability to resist bending. At shallow cover depths, especially those less than one pipe diameter, membrane action may not fully develop, and surcharge or live loads place a bending load on the pipe crown. In this case the pipe's flexural stiffness carries part of the load and prevents the pipe crown from dimpling inward under the load. Equation 3-19, published by Watkins (14) gives the soil pressure that can be supported at the pipe crown by the combination of the pipe's flexural stiffness (bending resistance) and the soil's internal resistance against heaving upward. In addition to checking Watkins' formula, the designer should check deflection using Equations 3-10 or 3-11, pipe wall compressive stress using Equations 3-13 or 3-14, and pipe wall buckling using Equations 3-15 or 3-16.

Watkins' equation is recommended only where the depth of cover is greater than one-half of the pipe diameter and the pipe is installed at least 18 inches below the road surface. In other words, it is recommended that the pipe regardless of diameter always be at least 18" beneath the road surface where there are live loads present; more may be required depending on the properties of the pipe and installation. In some cases, lesser cover depths may be sufficient where there is a reinforced concrete cap or a reinforced concrete pavement slab over the pipe. Equation 3-19 may be used for both DR pipe and profile pipe. See definition of "A" below.

(3-19)

$$P_{WAT} = \frac{12\mathrm{w}(KH)^2}{N_S D_O} + \frac{7387(I)}{N_S {D_O}^2 c}\left(S_{MAT} - \frac{\mathrm{w} D_O H}{288A}\right)$$

WHERE

P_{WAT} = **allowable live load pressure at pipe crown for pipes with one diameter or less of cover, psf**

w = **unit weight of soil, lb/ft^3**

D_O = **pipe outside diameter, in**

H = **depth of cover, ft**

I = **pipe wall moment of inertia (t^3/12 for DR pipe), in^4/in**

A = **profile wall average cross-sectional area, in^2/in, for profile pipe or wall thickness (in) for DR pipe (obtain the profile from the manufacturer of the profile pipe.)**

c = **outer fiber to wall centroid, in**

c = **H_P – z for profile pipe and c = 0.5t for DR pipe, in**

H_P = **profile wall height, in**

z = **pipe wall centroid, in**

S_{MAT} = **material yield strength, lb/in^2, Use 3000 PSI for PE3408**

N_S = **safety factor**

K = **passive earth pressure coefficient**

(3-20)
$$K = \frac{1 + \mathrm{SIN}(\phi)}{1 - \mathrm{SIN}(\phi)}$$

ϕ = **angle of internal friction, deg**

Equation 3-19 is for a point load applied to the pipe crown. Wheel loads should be determined using a point load method such as given by Equations 3-2 (Timoshenko) or 3-4 (Boussinesq).

When a pipe is installed with shallow cover below an unpaved surface, rutting can occur which will not only reduce cover depth, but also increase the impact factor.

Shallow Cover Example

Determine the safety factor against flexural failure of the pipe accompanied by soil heave, for a 36″ RSC 100 F894 profile pipe 3.0 feet beneath an H20 wheel load. Assume an asphalt surface with granular embedment.

SOLUTION: The live load pressure acting at the crown of the pipe can be found using Equation 3-4, the Boussinesq point load equation. At 3.0 feet of cover the highest live load pressure occurs directly under a single wheel and equals:

$$P_L = \frac{(3)(2.0)(16000)(3.0)^3}{2\pi(3.0)^5} = 1697\ psf$$

WHERE

I_f = **2.0**

W = **16,000 lbs**

H = **3.0 ft**

w = **120 pcf**

The live load pressure is to be compared with the value in Equation 3-19. To solve Equation 3-19, the following parameters are required:

I = **0.171 in^4/in**

A = **0.470 in^2/in**

H_P = **2.02 in (Profile Wall Height)**

D_O = **D_I+2*h = 36.00+2*2.02 = 40.04 in**

Z = **0.58 in**

C = **h-z = 1.44 in**

S = **3000 psi**

ϕ = **30 deg.**

Determine the earth pressure coefficient:

$$K = \frac{1+\sin(30)}{1-\sin(30)} = \frac{1+0.5}{1-0.5} = 3.0$$

The live load pressure incipient to failure equals:

$$P_{WAT} = \frac{(12)120(3.0 * 3.0)^2}{40.04} + \frac{7387 * 0.171}{40.04^2(1.44)}\left(3000 - \frac{120(40.04)3.0}{288 * 0.470}\right)$$

$$P_{WAT} = 2904 + 1584 = 4498\ psf$$

The resulting safety factor equals:

$$N = \frac{P_{WAT}}{p_L} = \frac{4498}{1697} = 2.65$$

Installation Category #3: Deep Fill Installation

The performance limits for pipes in a deep fill are the same as for any buried pipe. They include:

1. Compressive ring thrust stress
2. Ring deflection
3. Constrained pipe wall buckling

The suggested calculation method for pipe in deep fill applications involves the introduction of design routines for each performance limit that are different than those previously given.

Compressive ring thrust is calculated using soil arching. The arching calculation may also be used for profile pipe designs in standard trench applications. Profile pipes are relatively low stiffness pipes where significant arching may occur at relatively shallow depths of cover.

At a depth of around 50 feet or so it becomes impractical to use Spangler's equation as published in this chapter because it neglects the significant load reduction due to arching and the inherent stiffening of the embedment and consequential increase in E′ due to the increased lateral earth pressure applied to the embedment. This section gives an alternate deflection equation for use with PE pipes. It was first introduced by Watkins et al. (1) for metal pipes, but later Gaube extended its use to include PE pipes. (15)

Where deep fill applications are in dry soil, Luscher's equation (Eq. 3-15 or 3-16) may often be too conservative for design as it considers a radial driving force from ground water or vacuum. Moore and Selig(17) developed a constrained pipe wall buckling equation suitable for pipes in dry soils, which is given in a following section.

Considerable care should be taken in the design of deeply buried pipes whose failure may cause slope failure in earthen structures, or refuse piles or whose failure may have severe environmental or economical impact. These cases normally justify the use of methods beyond those given in this Chapter, including finite element analysis and field testing, along with considerable professional design review.

Compressive Ring Thrust and the Vertical Arching Factor

The combined horizontal and vertical earth load acting on a buried pipe creates a radially-directed compressive load acting around the pipe's circumference. When a PE pipe is subjected to ring compression, thrust stress develops around the pipe hoop, and the pipe's circumference will ever so slightly shorten. The shortening permits "thrust arching," that is, the pipe hoop thrust stiffness is less than the soil hoop thrust stiffness and, as the pipe deforms, less load follows the pipe. This occurs much like the vertical arching described by Marston.(18) Viscoelasticity enhances this effect. McGrath(19) has shown thrust arching to be the predominant form of arching with PE pipes.

Burns and Richard(6) have published equations that give the resulting stress occurring in a pipe due to arching. As discussed above, the arching is usually considered when calculating the ring compressive stress in profile pipes. For deeply buried pipes McGrath (19) has simplified the Burns and Richard's equations to derive a vertical arching factor as given by Equation 3-21.

(3-21)

$$VAF = 0.88 - 0.71\frac{S_A - 1}{S_A + 2.5}$$

WHERE

VAF **= Vertical Arching Factor**

S_A **= Hoop Thrust Stiffness Ratio**

(3-22)

$$S_A = \frac{1.43\, M_S\, r_{CENT}}{EA}$$

WHERE

r_{CENT} **= radius to centroidal axis of pipe, in**

M_S**= one-dimensional modulus of soil, psi**

E **= apparent modulus of elasticity of pipe material, psi (See Appendix, Chapter 3)**

A**= profile wall average cross-sectional area, in^2/in, or wall thickness (in) for DR pipe**

One-dimensional modulus values for soil can be obtained from soil testing, geotechnical texts, or Table 3-12 which gives typical values. The typical values in Table 3-12 were obtained by converting values from McGrath (20).

TABLE 3-12
Typical Values of M_S, One-Dimensional Modulus of Soil

Vertical Soil Stress[1] (psi)	Gravelly Sand/Gravels 95% Std. Proctor (psi)	Gravelly Sand/Gravels 90% Std. Proctor (psi)	Gravelly Sand/Gravels 85% Std. Proctor (psi)
10	3000	1600	550
20	3500	1800	650
40	4200	2100	800
60	5000	2500	1000
80	6000	2900	1300
100	6500	3200	1450

* Adapted and extended from values given by McGrath(20). For depths not shown in McGrath(20), the MS values were approximated using the hyperbolic soil model with appropriate values for K and n where n=0.4 and K=200, K=100, and K=45 for 95% Proctor, 90% Proctor, and 85% Proctor, respectively.

[1] Vertical Soil Stress (psi) = [soil depth (ft) x soil density (pcf)]/144

The radial directed earth pressure can be found by multiplying the prism load (pressure) by the vertical arching factor as shown in Eq. 3-23.

$$P_{RD} = (VAF)wH \tag{3-23}$$

WHERE

P_{RD} = **radial directed earth pressure, lb/ft²**

w = **unit weight of soil, pcf**

H = **depth of cover, ft**

The ring compressive stress in the pipe wall can be found by substituting P_{RD} from Equation 3-23 for P_E in Equation 3-13 for DR pipe and Equation 3-14 for profile wall pipe.

Earth Pressure Example

Determine the earth pressure acting on a 36" profile wall pipe buried 30 feet deep. The following properties are for one unique 36" profile pipe made from PE3608 material. Other 36" profile pipe may have different properties. The pipe's cross-sectional area, A, equals 0.470 inches²/inch, its radius to the centroidal axis is 18.00 inches plus 0.58 inches, and its apparent modulus is 27,000 psi. Its wall height is 2.02 in and its D_O equals 36 in +2 (2.02 in) or 40.04 in. Assume the pipe is installed in a clean granular soil compacted to 90% Standard Proctor (Ms = 1875 psi), the insitu soil is as stiff as the embedment, and the backfill weighs 120 pcf. (Where the excavation is in a stable trench, the stiffness of the insitu soil can generally be ignored in this calculation.) The following series of equations calculates the hoop compressive stress, S, in the pipe wall due to the earth pressure applied by the soil above the pipe. The earth pressure is reduced from the prism load by the vertical arching factor.

(From Equation 3-22)

$$S_A = \frac{1.43(1875\frac{lbs}{inch^2})(18.58\,inch)}{(28250\frac{lbs}{inch^2})(0.470\frac{inch^2}{inch})} = 3.93$$

(From Equation 3-21)

$$VAF = 0.88 - 0.71\frac{3.75-1}{3.75+2.5} = 0.56$$

(From Equation 3-23)

$$P_{RD} = 0.57(120\ pcf)(30\ ft) = 2016\frac{lb}{ft^2}$$

(From Equation 3-14)

$$S = \frac{P_{RD}D_O}{288A} = \frac{2052\,psf\,(40.04\,in)}{288\,(0.470\,in^2/in)} = 596\ psi \leq 1000\,psi$$

(Allowable compressive stress per Table C.1, Appendix to Chapter 3)

Ring Deflection of Pipes Using Watkins-Gaube Graph

R. Watkins$^{(1)}$ developed an extremely straight-forward approach to calculating pipe deflection in a fill that does not rely on E′. It is based on the concept that the deflection of a pipe embedded in a layer of soil is proportional to the compression or settlement of the soil layer and that the constant of proportionality is a function of the relative stiffness between the pipe and soil. Watkins used laboratory testing to establish and graph proportionality constants, called Deformation Factors, D_F , for the stiffness ranges of metal pipes. Gaube$^{(15, 16)}$ extended Watkins' work by testing to include PE pipes. In order to predict deflection, the designer first determines the amount of compression in the layer of soil in which the pipe is installed using conventional geotechnical equations. Then, deflection equals the soil compression multiplied by the D_F factor. This bypasses some of the inherent problems associated with using the soil reaction modulus, E′, values. The designer using the Watkins-Gaube Graph (Figure 3-6) should select conservative soil modulus values to accommodate variance due to installation. Two other factors to consider when using this method is that it assumes a constant Deformation Factor independent of depth of cover and it does not address the effect of the presence of ground water on the Deformation Factor.

To use the Watkins-Gaube Graph, the designer first determines the relative stiffness between pipe and soil, which is given by the Rigidity Factor, R_F. Equation 3-24 and 3-25 are for DR pipe and for profile pipe respectively:

(3-24)
$$R_F = \frac{12\,E_S\,(DR-1)^3}{E}$$

(3-25)
$$R_F = \frac{E_S D_m^{\,3}}{EI}$$

WHERE

DR = **Dimension Ratio**

E_S = **Secant modulus of the soil, psi**

E = **Apparent modulus of elasticity of pipe material, psi**

I = **Pipe wall moment of inertia of pipe, in^4/in**

D_m = **Mean diameter (D_I + 2z or D_O – t), in**

The secant modulus of the soil may be obtained from testing or from a geotechnical engineer's evaluation. In lieu of a precise determination, the soil modulus may be related to the one-dimensional modulus, M_S, from Table 3-12 by the following equation where μ is the soil's Poisson ratio.

(3-26)
$$E_S = M_S \frac{(1+\mu)(1-2\mu)}{(1-\mu)}$$

TABLE 3-13

Typical range of Poisson's Ratio for Soil (Bowles[21])

Soil Type	Poisson's Ratio, µ
Saturated Clay	0.4-0.5
Unsaturated Clay	0.1-0.3
Sandy Clay	0.2-0.3
Silt	0.3-0.35
Sand (Dense)	0.2-0.4
Coarse Sand (Void Ratio 0.4-0.7)	0.15
Fine-grained Sand (Void Ratio 0.4-0.7)	0.25

Next, the designer determines the Deformation Factor, D_F , by entering the Watkins-Gaube Graph with the Rigidity Factor. See Fig. 3-6. The Deformation Factor is the proportionality constant between vertical deflection (compression) of the soil layer containing the pipe and the deflection of the pipe. Thus, pipe deflection can be obtained by multiplying the proportionality constant D_F times the soil settlement. If D_F is less than 1.0 in Fig. 3-6, use 1.0.

The soil layer surrounding the pipe bears the entire load of the overburden above it without arching. Therefore, settlement (compression) of the soil layer is proportional to the prism load and not the radial directed earth pressure. Soil strain, ε_S, may be determined from geotechnical analysis or from the following equation:

(3-27)

$$\varepsilon_S = \frac{wH}{144E_S}$$

WHERE

w = **unit weight of soil, pcf**

H = **depth of cover (height of fill above pipe crown), ft**

E_S = **secant modulus of the soil, psi**

The designer can find the pipe deflection as a percent of the diameter by multiplying the soil strain, in percent, by the deformation factor:

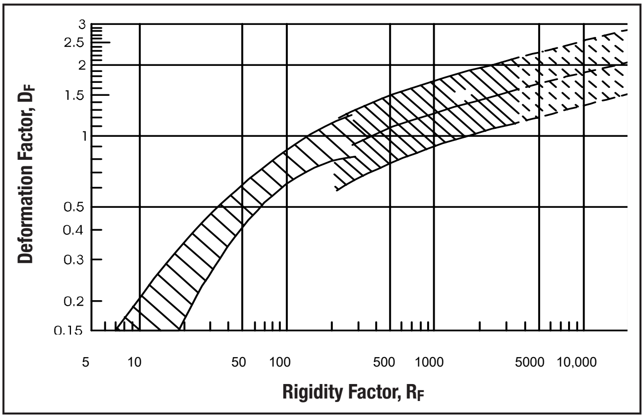


Figure 3-6 Watkins-Gaube Graph

(3-28)

$$\frac{\Delta X}{D_M}(100) = D_F \varepsilon_S$$

WHERE

$\Delta X/D_M$ **multiplied by 100 gives percent deflection.**

Example of the Application of the Watkins-Gaube Calculation Technique

Find the deflection of a 6″ SDR 11 pipe made from PE4710 materials under 140 ft of fill with granular embedment containing 12% or less fines, compacted at 90% of standard proctor. The fill weighs 75 pcf.

SOLUTION: First, calculate the vertical soil pressure equation, Eq. 3-1.

Eq. 3-1: $P_E = wH$

P_E **= (75lb/ft^3)(140 ft)**

P_E **= 10,500 lb/ft^2 or 72.9 psi**

The M_S is obtained by interpolation from Table 3-12 and equals 2700. The secant modulus can be found assuming a Poisson's Ratio of 0.30.

$$E_S = \frac{2700\, psi\,(1+0.30)(1-2(0.30))}{(1-0.30)} = 2005\, psi$$

The rigidity factor is obtained from Equation 3-24.

$$R_F = \frac{12\,(2005)\,(11-1)^3}{29,000} = 830$$

Using Figure 3-6, the average value of the deformation factor is found to be 1.2. The soil strain is calculated by Equation 3-27.

$$\varepsilon_S = \frac{75pcf * 140ft}{144 * 2005\frac{lbs}{inch^2}} * 100 = 3.6\%$$

The deflection is found by multiplying the soil strain by the deformation factor:

$$\frac{\Delta X}{D_M}(100) = 1.2 * 3.6 = 4.4\%$$

Moore-Selig Equation for Constrained Buckling in Dry Ground

As discussed previously, a compressive thrust stress exists in buried pipe. When this thrust stress approaches a critical value, the pipe can experience a local instability or large deformation and collapse. In an earlier section of this chapter, Luscher's equation was given for constrained buckling under ground water. Moore and Selig(17) have used an alternate approach called the continuum theory to develop design equations for contrained buckling due to soil pressure (buckling of embedded pipes). The particular version of their equations given below is more appropriate for dry applications than Luscher's equation. Where ground water is present, Luscher's equation should be used.

The Moore-Selig Equation for critical buckling pressure follows: (Critical buckling pressure is the pressure at which buckling will occur. A safety factor should be provided.)

(3-29)
$$P_{CR} = \frac{2.4\,\varphi\,R_H}{D_M}(EI)^{\frac{1}{3}}(E_S^*)^{\frac{2}{3}}$$

WHERE

P_{CR} **= Critical constrained buckling pressure, psi**

φ **= Calibration Factor, 0.55 for granular soils**

R_H **= Geometry Factor**

E **= Apparent modulus of elasticity of pipe material, psi**

I **= Pipe wall moment of Inertia, in^4/in (t^3/12, if solid wall construction)**

E_S***** **= E$_S$ /(1-μ)**

E_S **= Secant modulus of the soil, psi**

μ_S **= Poisson's Ratio of Soil (Consult a textbook on soil for values. Bowles (1982) gives typical values for sand and rock ranging from 0.1 to 0.4.)**

The geometry factor is dependent on the depth of burial and the relative stiffness between the embedment soil and the insitu soil. Moore has shown that for deep burials in uniform fills, R_H equals 1.0.

Critical Buckling Example

Determine the critical buckling pressure and safety factor against buckling for the 6″ SDR 11 pipe (5.987″ mean diameter) in the previous example.

SOLUTION:

$$E_S^* = \frac{2000}{(1-0.3)} = 2860\ \frac{lbs}{inch^2}$$

$$P_{CR} = \frac{2.4*0.55*1.0}{5.987}(29000\ *0.018)^{\frac{1}{3}}(2860)^{\frac{2}{3}} = 358\ \frac{lbs}{in^2}$$

Determine the Safety Factor against buckling:

$$S.F. = \frac{P_{CR}}{P_E} = \frac{358*144}{140*75} = 4.9$$

Installation Category #4: Shallow Cover Flotation Effects

Shallow cover presents some special considerations for flexible pipes. As already discussed, full soil structure interaction (membrane effect) may not occur, and live loads are carried in part by the bending stiffness of the pipe. Even if the pipe has sufficient strength to carry live load, the cover depth may not be sufficient to prevent the pipe from floating upward or buckling if the ground becomes saturated with ground water. This section addresses:

- Minimum soil cover requirements to prevent flotation
- Hydrostatic buckling (unconstrained)

Design Considerations for Ground Water Flotation

High ground water can float buried pipe, causing upward movement off-grade as well as catastrophic upheaval. This is not an issue for plastic pipes alone. Flotation of metal or concrete pipes may occur at shallow cover when the pipes are empty.

Flotation occurs when the ground water surrounding the pipe produces a buoyant force greater than the sum of the downward forces provided by the soil weight, soil friction, the weight of the pipe, and the weight of its contents. In addition to the disruption occurring due to off-grade movements, flotation may also cause significant reduction of soil support around the pipe and allow the pipe to buckle from the external hydrostatic pressure.

Flotation is generally not a design consideration for buried pipe where the pipeline runs full or nearly full of liquid or where ground water is always below the pipe invert. Where these conditions are not met, a quick “rule of thumb” is that pipe buried in soil having a saturated unit weight of at least 120 lb/ft^3 with at least 1½ pipe diameters of cover will not float. However, if burial is in lighter weight soils or with lesser cover, ground water flotation should be checked.

Mathematically the relationship between the buoyant force and the downward forces is given in Equation 3-30. Refer to Figure 3-7. For an empty pipe, flotation will occur if:

(3-30) $$F_B > W_P + W_S + W_D + W_L$$

WHERE

F_B **= buoyant force, lb/ft of pipe**

W_P **= pipe weight, lb/ft of pipe**

W_S **= weight of saturated soil above pipe, lb/ft of pipe**

W_D **= weight of dry soil above pipe, lb/ft of pipe**

W_L **= weight of liquid contents, lb/ft of pipe**

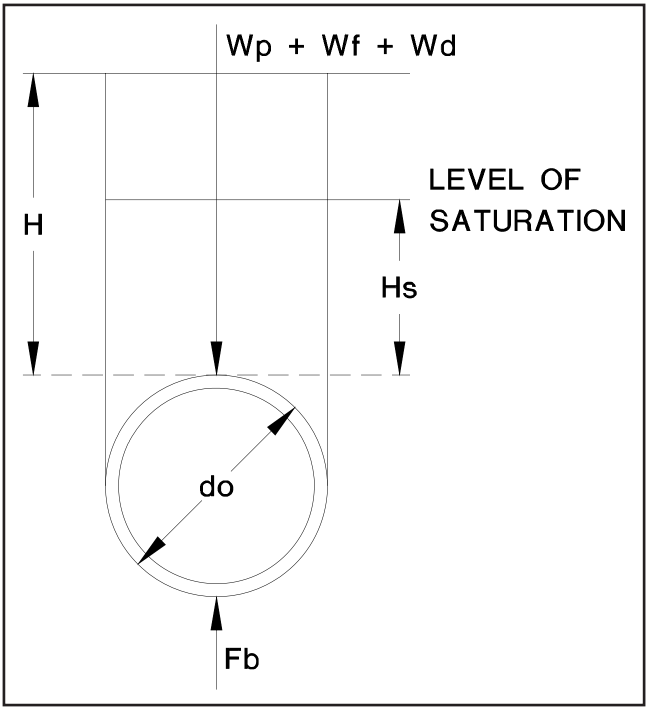


Figure 3-7 Schematic of Ground Water Flotation Forces

For a 1 ft length of pipe running empty and submerged, the upward buoyant force is:

(3-31)
$$F_B = \omega_G \frac{\pi}{4} d_O^2$$

WHERE

d_O **= pipe outside diameter, ft**

ω_G **= specific weight of ground water**

(fresh water = 62.4 lb/ft^3)

(sea water = 64.0 lb/ft^3)

The average pipe weight, W_P in lbs/ft may be obtained from manufacturers' literature or from Equation 3-32 or from the Table of Weights in the Appendix to this Chapter. This calculation is based on the use of a pipe material density of 0.955 gm/cc.

(3-32)
$$W_P = \pi d_O^2 \frac{(1.06\,DR - 1.12)}{DR^2} 59.6$$

Equation 3-33 gives the weight of soil per lineal foot of pipe.

(3-33) $$W_D = \omega_d (H - H_S) d_O$$

WHERE

ω_d **= unit weight of dry soil, pcf (See Table 3-14 for typical values.)**

H **= depth of cover, ft**

H_S **= level of ground water saturation above pipe, ft**

TABLE 3-14

Saturated and Dry Soil Unit Weight

Soil Type	Unit Weight, lb/ft³	
	Saturated, unit weight of ground water, pcf ω_S	Dry, the weight of saturated soil above the pipe, lbs per foot of pipe ω_d
Sands & Gravel	118-150	93-144
Silts & Clays	87-131	37-112
Glacial Till	131-150	106-144
Crushed Rock	119-137	94-125
Organic Silts & Clay	81-112	31-94

(3-34) $$W_S = (\omega_S - \omega_G)\left(\frac{d_O^{\,2}(4 - \pi)}{8} + d_O H_S\right)$$

WHERE

ω_S **= saturated unit weight of soil, pcf**

When an area is submerged, the soil particles are buoyed by their immersion in the ground water. The effective weight of submerged soil, (W_S – W_G), is the soil's saturated unit weight less the density of the ground water. For example, a soil of 120 pcf saturated unit weight has an effective weight of 57.6 pcf when completely immersed in water (120 - 62.4 = 57.6 pcf).

Equation 3-35 gives the weight per lineal foot of the liquid in a full pipe.

(3-35) $$W_L = \omega_L \frac{\pi d'^2}{4}$$

WHERE

W_L **= weight of the liquid in the pipe, lb/ft**

ω_L **= unit weight of liquid in the pipe, pcf**

and if half-full, the liquid weight is

(3-36)

$$W_L = \omega_L \frac{\pi d'^2}{8}$$

WHERE

ω_L **= unit weight of the liquid in the pipe, lb/ft3**

d' **= pipe inside diameter, ft**

For liquid levels between empty and half-full (0% to 50%), or between half-full and full (50% to 100%), the following formulas provide an approximate liquid weight with an accuracy of about ±10%. Please refer to Figure 3-8.

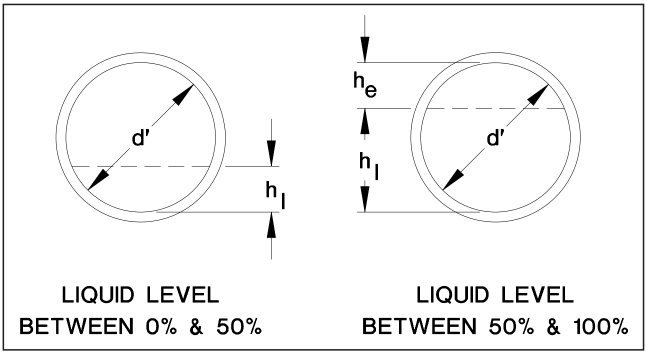


Figure 3-8 Flotation and Internal Liquid Levels

For a liquid level between empty and half-full, the weight of the liquid in the pipe is approximately

(3-37)

$$W_L = \omega_L \frac{4 h_l^3}{3} \sqrt{\frac{d' - h_l}{h_l} + 0.392}$$

WHERE

hl **= liquid level in pipe, ft**

For a liquid level between half-full and full, the weight of the liquid in the pipe is approximately

(3-38)

$$W_L = \omega_L \left(\frac{\pi d'^2}{4} - 1.573\, h_e \right)$$

WHERE

$$h_e = d' - h_l$$

Unconstrained Pipe Wall Buckling (Hydrostatic Buckling)

The equation for buckling given in this section is here to provide assistance when designing shallow cover applications. However, it may be used to calculate the buckling resistance of above grade pipes subject to external air pressure due to an internal vacuum, for submerged pipes in lakes or ponds, and for pipes placed in casings without grout encasement.

Unconstrained pipe are pipes that are not constrained by soil embedment or concrete encasement. Above ground pipes are unconstrained, as are pipes placed in a casing prior to grouting. Buried pipe may be considered essentially unconstrained where the surrounding soil does not significantly increase its buckling resistance beyond its unconstrained strength. This can happen where the depth of cover is insufficient to prevent the pipe from floating slightly upward and breaking contact with the embedment below its springline. Ground water, flooding, or vacuum can cause buckling of unconstrained pipe.

A special case of unconstrained buckling referred to as “upward” buckling may happen for shallow buried pipe. Upward buckling occurs when lateral pressure due to ground water or vacuum pushes the sides of the pipe inward while forcing the pipe crown and the soil above it upward. (Collapse looks like pipe deflection rotated 90 degrees.) A pipe is susceptible to upward buckling where the cover depth is insufficient to restrain upward crown movement. It has been suggested that a minimum cover of four feet is required before soil support contributes to averting upward buckling; however, larger diameter pipe may require as much as a diameter and a half to develop full support.

A conservative design for shallow cover buckling is to assume no soil support, and to design the pipe using the unconstrained pipe wall buckling equation. In lieu of this, a concrete cap, sufficient to resist upward deflection, may also be placed over the pipe and then the pipe may be designed using Luscher’s equation for constrained buckling.

Equations 3-39 and 3-40 give the allowable unconstrained pipe wall buckling pressure for DR pipe and profile pipe, respectively.

(3-39)

$$P_{WU} = \frac{f_O}{N_S} \frac{2E}{(1-\mu^2)} \left(\frac{1}{DR-1} \right)^3$$

(3-40)

$$P_{WU} = \frac{f_O}{N_S} \frac{24EI}{(1 - \mu^2) D_M^3}$$

WHERE

P_{WU} **= allowable unconstrained pipe wall buckling pressure, psi**

DR **= Dimension Ratio**

E **= apparent modulus of elasticity of pipe material, psi**

f_O **= Ovality Correction Factor, Figure 3-9**

N_S **= safety factor**

I **= Pipe wall moment of inertia, in4/in**

μ **= Poisson's ratio**

D_M **= Mean diameter, (DI + 2z or DO -t), in**

D_I **= pipe inside diameter, in**

z **= wall-section centroidal distance from inner fiber of pipe, in (obtain from pipe producer)**

Although buckling occurs rapidly, long-term external pressure can gradually deform the pipe to the point of instability. This behavior is considered viscoelastic and can be accounted for in Equations 3-39 and 3-40 by using the apparent modulus of elasticity value for the appropriate time and temperature of the specific application as given in the Appendix, Chapter 3. For Poisson's ratio, use a value of 0.45 for all PE pipe materials.

Ovality or deflection of the pipe diameter increases the local radius of curvature of the pipe wall and thus reduces buckling resistance. Ovality is typically reported as the percentage reduction in pipe diameter or:

(3-41)

$$\%DEFLECTION = 100\left(\frac{D_I - D_{MIN}}{D_I}\right)$$

WHERE

D_I **= pipe inside diameter, in**

D_{MIN} **= pipe minimum inside diameter, in**

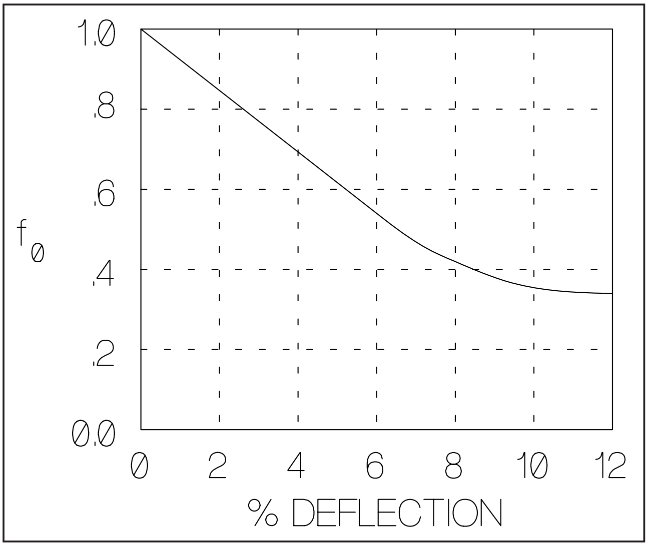


Figure 3-9 Ovality Compensation Factor, $f_Ø$

The designer should compare the critical buckling pressure with the actual anticipated pressure, and apply a safety factor commensurate with their assessment of the application. A safety factor of 2.5 is common, but specific circumstances may warrant a higher or lower safety factor. For large-diameter submerged pipe, the anticipated pressure may be conservatively calculated by determining the height of water from the pipe invert rather than from the pipe crown.

Ground Water Flotation Example

Find the allowable flood water level above a 10" DR 26 PE4710 pipe installed with only 2 ft of cover. Assume the pipe has 3 percent ovality due to shipping, handling, and installation loads.

SOLUTION: Use Equation 3-39. The pipe wall buckling pressure depends upon the duration of the water level above the pipe. If the water level is long lasting, then a long-term value of the stress relaxation modulus should be used, but if the water level rises only occasionally, a shorter term elastic modulus may be applied.

Case (a): For the long lasting water above the pipe, the stress relaxation modulus at 50 year, 73°F is approximately 29,000 lb/in^2 for a typical PE4710 material. Assuming 3% ovality (f_O equals 0.76) and a 2.5 to 1 safety factor, the allowable long-term pressure, P_{WU} is given by:

$$P_{WU} = \frac{(0.76)}{2.5}\frac{2\,(29{,}000)}{(1 - 0.45^2)}\left(\frac{1}{26 - 1}\right)^3 = 1.4\ psig\ (3.2\ ft\text{-}hd)$$

Case (b): Flooding conditions are occasional happenings, usually lasting a few days to a week or so. However, ground water elevations may remain high for several weeks following a flood. The 1000 hour elastic modulus value has been used to approximate the expected flood duration.

$$P_{WU} = \frac{(0.76)}{2.5}\frac{2(46{,}000)}{(1-0.45^2)}\left(\frac{1}{26-1}\right)^3 = 2.2\ psi = 5.2\ ft.\ (of\ head)$$

Section 4
Thermal Design Considerations

Introduction

Similar to all thermoplastics, the engineering behavior of PE can be significantly affected by temperature. An increase in temperature causes a decrease in strength and in apparent modulus. A decrease in temperature results in opposite effects. For effective pipeline design these effects must be adequately recognized.

In the case of pressure pipe the highest operating temperature is limited by the practical consideration of retaining sufficient long-term strength or maintaining the pressure rating that is sufficient for the intended application. That maximum temperature is generally 140°F (60°C). De-rating factors for up to 140°F are presented in the Appendix to Chapter 3. If higher temperatures are being considered, the pipe supplier should be consulted for additional information.

In the case of buried applications of non-pressure pipe, in which the embedment material provides a significant support against pipe deformation, the highest operating temperature can be higher –sometimes, as high 180°F (~82°C). The temperature re-rating factors for apparent modulus of elasticity, which are presented in the Appendix, Chapter 3, can be used for the re-rating of a pipe's 73°F pipe stiffness for any other temperature between -20 to 140°F (-29 to 60°C). For temperatures above 140°F the effect is more material dependent and the pipe supplier should be consulted.

A beneficial feature of PE pipe is that it retains much of its toughness even at low temperatures. It can be safely handled, installed and operated even in sub-freezing conditions. The formation of ice in the pipe will restrict or, stop flow but not cause pipe breakage. Although under sub-freezing conditions PE pipe is somewhat less tough it is still much tougher that most other pipe materials.

Strength and Stress/Strain Behavior

As discussed earlier in this Handbook, the engineering properties of PE material are affected by the magnitude of a load, the duration of loading, the environment and the operating temperature. And, also as discussed earlier, the standard convention is to report the engineering properties of PE piping materials based on a standard environment – which is water – and, a standard temperature – which is 73°F (23°C). A design for a condition that departs from this convention requires that an appropriate accommodation be made. This Section addresses the issue of the effect of a different temperature than that of the base temperature.

To properly consider the affect of temperature on strength and, on stress/strain properties this must be done based on actually observed long-term strength behavior. Tables which are presented in an Appendix to Chapter 3, list temperature adjustment factors that have been determined based on long-term evaluations.

Thermal Expansion/Contraction Effects

Fused PE pipe joints are fully restrained. The pipe and the fused joints can easily accommodate the stress induced by changes in temperature. In general thrust restraints and mechanical expansion joints are not required in a fully fused PE piping system. However, thrust restraint may be necessary where PE pipe is connection to other 'bell and spigot' end pipe. Design for this condition is addressed later in this chapter and in PPI's TN-36.

Because the coefficient of thermal expansion for PE is significantly larger than that of non-plastics, considerations relating to the potential effects of thermal expansion/contraction may include:

- Piping that is installed when it is warm may cool sufficiently after installation to generate significant tensile forces. Thus, the final connection should be made after the pipe has equilibrated to its operating temperature.
- Unrestrained pipe may shrink enough so that it pulls out from a mechanical joint that does not provide sufficient pull-out resistance. Methods used to connect PE pipe should provide restraint against pull-out that is either inherent to the joint design or additional mechanical restraint. See Chapter 9. (Note –specially designed thrust blocks may be needed to restrain movement when mechanical joints are in line with PE pipes.)
- Unrestrained pipe that is exposed to significant temperature swings will in some combination, expand and contract, deflect laterally, or apply compressive or tensile loads to constraints or supports.

A mitigating factor is PE's relatively low modulus of elasticity, which greatly reduces the thrust that is generated by a restrained expansion/contraction. This thrust imposes no problem on thermal fusion connections.

See Chapter 8 for additional information on designing above grade pipelines for thermal effects.

Unrestrained Thermal Effects

The theoretical change in length for an unrestrained pipe placed on a frictionless surface can be determined from Equation 4-1.

(4-1) $$\Delta L = L \alpha \Delta T$$

WHERE

ΔL = pipeline length change, ft

L = pipe length, ft

α = thermal expansion coefficient, in/in/°F

ΔT = temperature change,°F

The coefficient of thermal expansion for PE pipe material is approximately 1 x 10^{-4} in/in/˚F. As a "rule of thumb," temperature change for *unrestrained* PE pipe is about "1/10/100," that is, 1 inch for each 10˚F temperature change for each 100 foot of pipe. A temperature rise results in a length increase while a temperature drop results in a length decrease.

End Restrained Thermal Effects

A length of pipe that is restrained or anchored on both ends and one placed on a frictionless surface will exhibit a substantially different reaction to temperature change than the unrestrained pipe discussed above. If the pipe is restrained in a straight line between two points and the temperature decreases, the pipe will attempt to decrease in length. Because the ends are restrained or anchored, length change cannot occur, so a longitudinal tensile stress is created along the pipe. The magnitude of this stress can be determined using Equation 4-2.

(4-2) $$\sigma = E\,\alpha\,\Delta T$$

Where terms are as defined above, and

σ = longitudinal stress in pipe, psi

E = apparent modulus elasticity of pipe material, psi

The value of the apparent modulus of elasticity of the pipe material has a large impact on the calculated stress. As with all thermoplastic materials, PE's modulus, and therefore its stiffness, is dependent on temperature and the duration of the applied load. Therefore, the appropriate elastic modulus should be selected based on these two variables. When determining the appropriate time interval, it is important to consider that heat transfer occurs at relatively slow rates through the wall of PE pipe; therefore temperature changes do not occur rapidly. Because the temperature change does not happen rapidly, the average temperature is often chosen for the modulus selection.

(4-3) $$F = \sigma\,A_P$$

Where terms are as defined above, and

F = end thrust, lb

A_P = area of pipe cross section,(π/4)($DO^2 - Di^2$) in^2

Equations 4-2 and 4-3 can also be used to determine the compressive stress and thrust (respectively) from a temperature increase.

Although the length change of PE pipe during temperature changes is greater than many other materials, the amount of force required to restrain the movement is less because of its lower modulus of elasticity.

As pipeline temperature decreases from weather or operating conditions, a longitudinal tensile stress develops along the pipe that can be determined using Equation 4-2. The allowable tensile stress for pipe operating at its pressure rating is determined by the HDS for that temperature. The HDS is that of the pipe material for the base temperature at 73°F (23°C) times the temperature adjustment factor listed in Appendix, Chapter 3.

(4-4) $$\sigma_{allow} = HDS\ x\ F_T$$

WHERE

HDS = **Hydrostatic Design Stress, psi (Table 1-1)**

F_T = **Temperature factor (See Appendix, Chapter 3)**

Equation 4-3 is used to determine the thrust load applied to structural anchoring devices.

During temperature increase, the pipeline attempts to increase in length, but is restrained by mechanical guides that direct longitudinal compressive thrust to structural anchors that prevent length increase. This in turn creates a longitudinal compressive stress in the pipe and a thrust load against the structural anchors. The compressive stress that develops in the pipe and is resisted by the structural anchors is determined using Equation 4-2. Compressive stress should not exceed the allowable compressive stress per the Appendix in Chapter 3.

Above Ground Piping Systems

The design considerations for PE piping systems installed above ground are extensive and, therefore, are addressed separately in the Handbook chapter on above ground applications for PE pipe.

Buried Piping Systems

A buried pipe is generally well restrained by soil loads and will experience very little lateral movement. However, longitudinal end loads may result that need to be addressed.

Transitions to other pipe materials that use the bell and spigot assembly technique will need to be calculated using the thrust load as delivered by the pressure plus the potential of the load due to temperature changes. Merely fixing the end of the PE to the mating material may result in up stream joints pulling apart unless those connections are restrained. The number of joints that need to be restrained to prevent bell and spigot pull out may be calculated using techniques as recommended by the manufacturer of the alternate piping material. Equation 4-3 may be used to calculate the total thrust load due to temperature change.

Low thrust capacity connections to manholes or other piping systems as will be present in many no pressure gravity flow systems may be addressed via a longitudinal thrust anchor such as shown in Fig. 4-1. The size of the thrust block will vary depending on soil conditions and the thrust load as calculated via Equation 4-3.

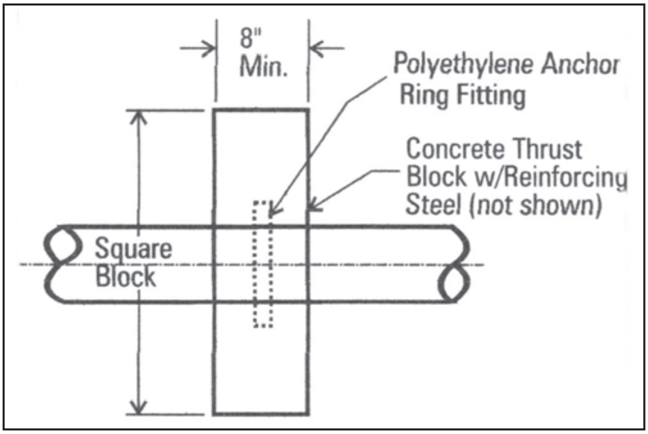


Figure 4-1 Longitudinal Thrust Anchor

Conclusion

The durability and visco-elastic nature of modern PE piping materials makes these products ideally suited for a broad array of piping applications such as: potable water mains and service lines, natural gas distribution, oil and gas gathering, force main sewers, gravity flow lines, industrial and various mining piping. To this end, fundamental design considerations such as fluid flow, burial design and thermal response were presented within this chapter in an effort to provide guidance to the piping system designer on the use of these tough piping materials in the full array of potential piping applications.

For the benefit of the pipeline designer, a considerable amount of background information and/or theory has been provided within this chapter. However, the designer should also keep in mind that the majority of pipeline installations fall within the criteria for the AWWA Design Window approach presented in Section 3 of this chapter. Pipeline installations that fall within the guidelines for the AWWA Window, may be greatly simplified in matters relating to the design and use of flexible PE piping systems.

While every effort has been made to be as thorough as possible in this discussion, it also should be recognized that these guidelines should be considered in light of specific project, installation and/or service needs. For this reason, this chapter on pipeline design should be utilized in conjunction with the other chapters of this Handbook to provide a more thorough understanding of the design considerations that may be specific to a particular project or application using PE piping systems. The reader is also referred to the extensive list of references for this chapter as additional resources for project and or system analysis and design.

References for Section 1

Kerr, Logan, "Water Hammer Problems in Engineering Design", Consulting Engineering, May 1985

Howard; A., "The Reclamation E' Table, 25 Years Later", Plastic Pipe XIII, Washington, D. C., Oct. 2-5, 2006.

Marshall, G. P., Brogden, S., "Evaluation of the Surge and Fatigue Resistances of PVC and PE Pipe Materials for use in the U.K. Water Industry", Plastics Pipe X, September '98, Gotenberg, Sweden.

UK Water Industry IGN 4-37-02, "Design Against Surge And Fatigue Conditions For Thermoplastics Pipes", March 1999.

References for Section 2

1. Jeppson, Roland W., Analysis of Flow in Pipe Networks, Ann Arbor Science, Ann Arbor, MI.
2. Distribution Network Analysis, *AWWA Manual M32,* American Water Works Association, Denver, CO.
3. ASTM D 2513, Standard Specification for Thermoplastic Gas Pipe, Tubing and Fittings, American Society for Testing and Materials, West Conshohocken, PA.
4. ASTM D 2737, Standard Specification for PE (PE) Tubing, American Society for Testing and Materials, West Conshohocken, PA.
5. ASTM D 2447, Standard Specification for PE (PE) Plastic Pipe, Schedules 40 and 80, Based on Outside Diameter, American Society for Testing and Materials, West Conshohocken, PA.
6. ASTM D 3035, Standard Specification for PE (PE) Plastic Pipe (DR-PR) Based on Controlled Outside Diameter, American Society for Testing and Materials, West Conshohocken, PA.
7. ASTM F 714, Standard Specification for PE (PE) Plastic Pipe (SDR-PR) Based on Controlled Outside Diameter, American Society for Testing and Materials, West Conshohocken, PA.
8. ANSI/AWWA C901, AWWA Standard for PE (PE) Pressure Pipe and Tubing, 1/2 In.(13 mm) Through 3 In. (76 mm) for Water Service, American Water Works Association, Denver, CO
9. ANSI/AWWA C906, AWWA Standard for PE (PE) Pressure Pipe and Fittings, 4 In. Through 63 In. for Water Distribution, American Water Works Association, Denver, CO.
10. API Specification 15LE, Specification for PE Line Pipe (PE), American Petroleum Institute, Washington DC.
11. ASTM D 2104, Standard Specification for PE (PE) Plastic Pipe, Schedule 40, American Society for Testing and Materials, West Conshohocken, PA.
12. ASTM D 2239, Standard Specification for PE (PE) Plastic Pipe (SIDR-PR) Based on Controlled Inside Diameter, American Society for Testing and Materials, West Conshohocken, PA.
13. ASTM F 894, Standard Specification for PE (PE) Large Diameter Profile Wall Sewer and Drain Pipe, American Society for Testing and Materials, West Conshohocken, PA.
14. PPI TR-22, PE Piping Distribution Systems for Components of Liquid Petroleum Gases, Plastics Pipe Institute, Irving, TX.
15. Nayyar, Mohinder L. (1992). *Piping Handbook* , 6th Edition, McGraw-Hill, New York, NY.
16. Iolelchick, I.E., Malyavskaya O.G., & Fried, E. (1986). *Handbook of Hydraulic Resistance*, Hemisphere Publishing Corporation.
17. Moody, L.F. (1944). *Transactions,* Volume 6, American Society of Mechanical Engineers (ASME), New York, NY.
18. Swierzawski, Tadeusz J. (2000). Flow of Fluids, Chapter B8, *Piping Handbook*, 7th edition, Mohinder L. Nayyar, McGraw-Hill, New York, NY.
19. Lamont, Peter A. (1981, May). Common Pipe Flow Formulas Compared with the Theory of Roughness, *Journal of the American Water Works Association*, Denver, CO.
20. Flow of Fluids through Valves, Fittings and Pipe. (1957). Crane Technical Paper No 410, the Crane Company, Chicago, IL.
21. Chen, W.F., & J.Y. Richard Liew. (2002). *The Civil Engineering Handbook*, 2nd edition, CRC Press, Boca Raton, FL.

22. Bowman, J.A. (1990). The Fatigue Response of Polyvinyl Chloride and PE Pipe Systems, Buried Plastics Pipe Technology, ASTM STP 1093, American Society for Testing and Materials, Philadelphia.
23. Marshall, GP, S. Brogden, & M.A. Shepherd, Evaluation of the Surge and Fatigue Resistance of PVC and PE Pipeline Materials for use in the UK Water Industry, Proceedings of Plastics Pipes X, Goteborg, Sweden.
24. Fedossof, F.A., & Szpak, E. (1978, Sept 20-22). Cyclic Pressure Effects on High Density PE Pipe, Paper presented at the Western Canada Sewage Conference, Regian, Saskatoon, Canada.
25. Parmakian, John. (1963). *Waterhammer Analysis*, Dover Publications, New York, NY.
26. Thompson, T.L., & Aude, T.C. (1980). Slurry Pipelines, *Journal of Pipelines*, Elsevier Scientific Publishing Company, Amsterdam.
27. *Handbook of Natural Gas Engineering*. (1959). McGraw-Hill, New York, NY.
28. *AGA Plastic Pipe Manual for Gas Service*. (2001). American Gas Association, Washington DC.
29. ASCE Manuals and Reports on Engineering Practice No. 60. (1982). Gravity Sewer Design and Construction, American Society of Civil Engineers, New York, NY.
30. Hicks, Tyler G. (1999). *Handbook of Civil Engineering Calculations*, McGraw-Hill, New York, NY.
31. PPI TR-14, Water Flow Characteristics of Thermoplastic Pipe, Plastics Pipe Institute, Irving, TX.
32. Kerr, Logan, Water Hammer Problems in Engineering Design, Consulting Engineering, May 1985.

References for Section 3

1. Watkins, R.K., Szpak, E., & Allman, W.B. (1974). Structural Design of PE Pipes Subjected to External Loads, Engr. Experiment Station, Utah State Univ., Logan.
2. AWWA (2006), PE Pipe Design and Installation, M55, American Water Works Association, Denver, CO.
3. Howard, A.K. (1996). *Pipeline Installation*, Relativity Printing, Lakewood, Colorado,ISBN 0-9651002-0-0.
4. Spangler, M.G. (1941). The Structural Design of Flexible Pipe Culverts, Bulletin 153, Iowa Engineering Experiment Station, Ames, IA.
5. Watkins, R.K., & Spangler, M.G. (1958). Some Characteristics of the Modulus of Passive Resistance of Soil—A Study in Similitude, Highway Research Board Proceedings 37:576-583, Washington.
6. Burns, J.Q., & Richard, R.M. (1964). Attenuation of Stresses for Buried Cylinders, Proceedings of the Symposium on Soil Structure Interaction, pp.378-392, University of Arizona, Tucson.
7. Katona, J.G., Forrest, F.J., Odello, & Allgood, J.R. (1976). CANDE—A Modern Approach for the Structural Design and Analysis of Buried Culverts, Report FHWA-RD-77-5, FHWA, US Department of Transportation.
8. Howard, A.K. (1977, January). Modulus of Soil Reaction Values for Buried Flexible Pipe, *Journal of the Geotechnical Engineering Division*, ASCE, Vol. 103, No GT 1.
9. Petroff, L.J. (1995). Installation Technique and Field Performance of PE, Profile Pipe, Proceedings 2nd Intl. Conference on the Advances in Underground Pipeline Engineering, ASCE, Seattle.
10. Duncan, J.M., & Hartley, J.D. (1982). Evaluation of the Modulus of Soil Reaction, E', and Its Variation with Depth, Report No. UCB/GT/82-02, University of California, Berkeley.
11. Howard, A.K. (1981). The USBR Equation for Predicting Flexible Pipe Deflection, Proceedings Intl. Conf. On Underground Plastic Pipe, ASCE, New Orleans, LA.
12. Janson, L.E. (1991). Long-Term Studies of PVC and PE Pipes Subjected to Forced Constant Deflection, Report No. 3, KP-Council, Stockholm, Sweden.
13. Spangler, M.G., & Handy, R.L. (1982). *Soil Engineering*, 4th ed., Harper & Row, New York.
14. Watkins, R.K. (1977). Minimum Soil Cover Required Over Buried Flexible Cylinders, Interim Report, Utah State University, Logan, UT.
15. Gaube, E. (1977, June). Stress Analysis Calculations on Rigid PE and PVC Sewage Pipes, *Kunstoffe,* Vol.67, pp. 353-356, Germany.
16. Gaube, E., & Muller, W. (1982, July). Measurement of the long-term deformation of PE pipes laid underground, *Kunstoffe*, Vol. 72, pp. 420-423, Germany.
17. Moore, I. D., & Selig, E. T. (1990). Use of Continuum Buckling Theory for Evaluation of Buried Plastic Pipe Stability, Buried Plastic Pipe Technology, ASTM STP 1093, Philadelphia.
18. Marston, A. (1930). Iowa Engineering Experiment Station, Bulletin No. 96.
19. McGrath, T. (1994). *Analysis of Burns & Richard Solution for Thrust in Buried Pipe*, Simpson Gumpertz & Heger, Inc, Cambridge, Mass.
20. McGrath, T.J. (1998). Replacing E' with the Constrained Modulus in Flexible Pipe Design, proceedings Pipeline Div. Conf. Pipelines in the Constructed Environment, ASCE, San Diego, CA.
21. Bowles, J.E. (1982). *Foundation Analysis and Design*, 3rd ed., McGraw-Hill Book Company, New York.

Appendix A.1

PIPE WEIGHTS AND DIMENSIONS (DIPS)

(Black)

OD			Pipe inside diameter (d)	Minimum Wall Thickness (t)	Weight (w)
Nominal in.	Actual in.	DR*	in.	in.	lb. per foot
		7	2.76	0.566	2.621
		9	3.03	0.440	2.119
		11	3.20	0.360	1.776
		13.5	3.34	0.293	1.476
3	3.960	15.5	3.42	0.255	1.299
		17	3.47	0.233	1.192
		21	3.56	0.189	0.978
		26	3.64	0.152	0.798
		32.5	3.70	0.122	0.644
		7	3.35	0.686	3.851
		9	3.67	0.533	3.114
		11	3.87	0.436	2.609
		13.5	4.05	0.356	2.168
4	4.800	15.5	4.14	0.310	1.909
		17	4.20	0.282	1.752
		21	4.32	0.229	1.436
		26	4.41	0.185	1.172
		32.5	4.49	0.148	0.946
		7	4.81	0.986	7.957
		9	5.27	0.767	6.434
		11	5.57	0.627	5.392
		13.5	5.82	0.511	4.480
6	6.900	15.5	5.96	0.445	3.945
		17	6.04	0.406	3.620
		21	6.20	0.329	2.968
		26	6.34	0.265	2.422
		32.5	6.45	0.212	1.954

OD			Pipe inside diameter (d)	Minimum Wall Thickness (t)	Weight (w)
Nominal in.	Actual in.	DR*	in.	in.	lb. per foot
		7	6.31	1.293	13.689
		9	6.92	1.006	11.069
		11	7.31	0.823	9.276
		13.5	7.63	0.670	7.708
8	9.050	15.5	7.81	0.584	6.787
		17	7.92	0.532	6.228
		21	8.14	0.431	5.106
		26	8.31	0.348	4.166
		32.5	8.46	0.278	3.361
		7	7.74	1.586	20.593
		9	8.49	1.233	16.652
		11	8.96	1.009	13.955
		13.5	9.36	0.822	11.595
10	11.100	15.5	9.58	0.716	10.210
		17	9.72	0.653	9.369
		21	9.98	0.529	7.681
		26	10.19	0.427	6.267
		32.5	10.38	0.342	5.056
		7	9.20	1.886	29.121
		9	10.09	1.467	23.548
		11	10.66	1.200	19.734
		13.5	11.13	0.978	16.397
12	13.200	15.5	11.39	0.852	14.439
		17	11.55	0.776	13.250
		21	11.87	0.629	10.862
		26	12.12	0.508	8.863
		32.5	12.34	0.406	7.151
		7	10.67	2.186	39.124
		9	11.70	1.700	31.637
		11	12.35	1.391	26.513
		13.5	12.90	1.133	22.030
14	15.300	15.5	13.21	0.987	19.398
		17	13.39	0.900	17.801
		21	13.76	0.729	14.593
		26	14.05	0.588	11.907
		32.5	14.30	0.471	9.607

OD			Pipe inside diameter (d)	Minimum Wall Thickness (t)	Weight (w)
Nominal in.	Actual in.	DR*	in.	in.	lb. per foot
		7	12.13	2.486	50.601
		9	13.30	1.933	40.917
		11	14.05	1.582	34.290
		13.5	14.67	1.289	28.492
16	17.400	15.5	15.02	1.123	25.089
		17	15.23	1.024	23.023
		21	15.64	0.829	18.874
		26	15.98	0.669	15.400
		32.5	16.26	0.535	12.425
		7	13.59	2.786	63.553
		9	14.91	2.167	51.390
		11	15.74	1.773	43.067
		13.5	16.44	1.444	35.785
18	19.500	15.5	16.83	1.258	31.510
		17	17.07	1.147	28.916
		21	17.53	0.929	23.704
		26	17.91	0.750	19.342
		32.5	18.23	0.600	15.605
		7	15.06	3.086	77.978
		9	16.51	2.400	63.055
		11	17.44	1.964	52.842
		13.5	18.21	1.600	43.907
20	21.600	15.5	18.65	1.394	38.662
		17	18.91	1.271	35.479
		21	19.42	1.029	29.085
		26	19.84	0.831	23.732
		32.5	20.19	0.665	19.147
		11	20.83	2.345	75.390
		13.5	21.75	1.911	62.642
		15.5	22.27	1.665	55.159
24	25.800	17	22.58	1.518	50.618
		21	23.20	1.229	41.495
		26	23.70	0.992	33.858
		32.5	24.12	0.794	27.317

OD			Pipe inside diameter (d)	Minimum Wall Thickness (t)	Weight (w)
Nominal in.	**Actual in.**	**DR***	**in.**	**in.**	**lb. per foot**
30	32.000	13.5	26.97	2.370	96.367
		15.5	27.62	2.065	84.855
		17	28.01	1.882	77.869
		21	28.77	1.524	63.835
		26	29.39	1.231	52.086
		32.5	29.91	0.985	42.023

* These DRs (7.3, 9, 11, 13.5, 17, 21, 26, 32.5) are from the standard dimension ratio (SDR) series established by ASTM F 412.51

Appendix A.2

PIPE WEIGHTS AND DIMENSIONS (IPS)

(BLACK)

OD			Pipe inside diameter (d)	Minimum Wall Thickness (t)	Weight (w)
Nominal in.	Actual in.	DR	in.	in.	lb. per foot
		7	0.59	0.120	0.118
		7.3	0.60	0.115	0.114
1/2	0.840	9	0.64	0.093	0.095
		9.3	0.65	0.090	0.093
		11	0.68	0.076	0.080
		11.5	0.69	0.073	0.077
		7	0.73	0.150	0.184
		7.3	0.75	0.144	0.178
3/4	1.050	9	0.80	0.117	0.149
		9.3	0.81	0.113	0.145
		11	0.85	0.095	0.125
		11.5	0.86	0.091	0.120
		7	0.92	0.188	0.289
		7.3	0.93	0.180	0.279
1	1.315	9	1.01	0.146	0.234
		9.3	1.02	0.141	0.227
		11	1.06	0.120	0.196
		11.5	1.07	0.114	0.188
		7	1.16	0.237	0.461
		7.3	1.18	0.227	0.445
		9	1.27	0.184	0.372
1 1/4	1.660	9.3	1.28	0.178	0.362
		11	1.34	0.151	0.312
		11.5	1.35	0.144	0.300
		13.5	1.40	0.123	0.259

OD			Pipe inside diameter (d)	Minimum Wall Thickness (t)	Weight (w)
Nominal in.	**Actual in.**	**DR**	**in.**	**in.**	**lb. per foot**
		7	1.32	0.271	0.603
		7.3	1.35	0.260	0.583
		9	1.45	0.211	0.488
1 1/2	1.900	9.3	1.47	0.204	0.474
		11	1.53	0.173	0.409
		11.5	1.55	0.165	0.393
		13.5	1.60	0.141	0.340
		15.5	1.64	0.123	0.299
		7	1.66	0.339	0.943
		7.3	1.69	0.325	0.911
		9	1.82	0.264	0.762
		9.3	1.83	0.255	0.741
2	2.375	11	1.92	0.216	0.639
		11.5	1.94	0.207	0.614
		13.5	2.00	0.176	0.531
		15.5	2.05	0.153	0.467
		17	2.08	0.140	0.429
		7	2.44	0.500	2.047
		7.3	2.48	0.479	1.978
		9	2.68	0.389	1.656
		9.3	2.70	0.376	1.609
		11	2.83	0.318	1.387
3	3.500	11.5	2.85	0.304	1.333
		13.5	2.95	0.259	1.153
		15.5	3.02	0.226	1.015
		17	3.06	0.206	0.932
		21	3.15	0.167	0.764
		26	3.21	0.135	0.623

OD			Pipe inside diameter (d)	Minimum Wall Thickness (t)	Weight (w)
Nominal in.	Actual in.	DR	in.	in.	lb. per foot
		7	3.14	0.643	3.384
		7.3	3.19	0.616	3.269
		9	3.44	0.500	2.737
		9.3	3.47	0.484	2.660
		11	3.63	0.409	2.294
4	4.500	11.5	3.67	0.391	2.204
		13.5	3.79	0.333	1.906
		15.5	3.88	0.290	1.678
		17	3.94	0.265	1.540
		21	4.05	0.214	1.262
		26	4.13	0.173	1.030
		32.5	4.21	0.138	0.831
		7	3.88	0.795	5.172
		7.3	3.95	0.762	4.996
		9	4.25	0.618	4.182
		9.3	4.29	0.598	4.065
		11	4.49	0.506	3.505
5	5.563	11.5	4.54	0.484	3.368
		13.5	4.69	0.412	2.912
		15.5	4.80	0.359	2.564
		17	4.87	0.327	2.353
		21	5.00	0.265	1.929
		26	5.11	0.214	1.574
		32.5	5.20	0.171	1.270
		7	4.62	0.946	7.336
		7.3	4.70	0.908	7.086
		9	5.06	0.736	5.932
		9.3	5.11	0.712	5.765
		11	5.35	0.602	4.971
6	6.625	11.5	5.40	0.576	4.777
		13.5	5.58	0.491	4.130
		15.5	5.72	0.427	3.637
		17	5.80	0.390	3.338
		21	5.96	0.315	2.736
		26	6.08	0.255	2.233
		32.5	6.19	0.204	1.801

OD			Pipe inside diameter (d)	Minimum Wall Thickness (t)	Weight (w)
Nominal in.	Actual in.	DR	in.	in.	lb. per foot
		7	6.01	1.232	12.433
		7.3	6.12	1.182	12.010
		9	6.59	0.958	10.054
		9.3	6.66	0.927	9.771
		11	6.96	0.784	8.425
8	8.625	11.5	7.04	0.750	8.096
		13.5	7.27	0.639	7.001
		15.5	7.45	0.556	6.164
		17	7.55	0.507	5.657
		21	7.75	0.411	4.637
		26	7.92	0.332	3.784
		7	7.49	1.536	19.314
		7.3	7.63	1.473	18.656
		9	8.22	1.194	15.618
		9.3	8.30	1.156	15.179
		11	8.68	0.977	13.089
10	10.750	11.5	8.77	0.935	12.578
		13.5	9.06	0.796	10.875
		15.5	9.28	0.694	9.576
		17	9.41	0.632	8.788
		21	9.66	0.512	7.204
		26	9.87	0.413	5.878
		32.5	10.05	0.331	4.742
		7	8.89	1.821	27.170
		7.3	9.05	1.747	26.244
		9	9.75	1.417	21.970
		9.3	9.84	1.371	21.353
		11	10.29	1.159	18.412
12	12.750	11.5	10.40	1.109	17.693
		13.5	10.75	0.944	15.298
		15.5	11.01	0.823	13.471
		17	11.16	0.750	12.362
		21	11.46	0.607	10.134
		26	11.71	0.490	8.269
		32.5	11.92	0.392	6.671

OD			Pipe inside diameter (d)	Minimum Wall Thickness (t)	Weight (w)
Nominal in.	Actual in.	DR	in.	in.	lb. per foot
		7	9.76	2.000	32.758
		7.3	9.93	1.918	31.642
		9	10.70	1.556	26.489
		9.3	10.81	1.505	25.745
		11	11.30	1.273	22.199
14	14.000	11.5	11.42	1.217	21.332
		13.5	11.80	1.037	18.445
		15.5	12.09	0.903	16.242
		17	12.25	0.824	14.905
		21	12.59	0.667	12.218
		26	12.86	0.538	9.970
		32.5	13.09	0.431	8.044
		7	11.15	2.286	42.786
		7.3	11.35	2.192	41.329
		9	12.23	1.778	34.598
		9.3	12.35	1.720	33.626
		11	12.92	1.455	28.994
16	16.000	11.5	13.05	1.391	27.862
		13.5	13.49	1.185	24.092
		15.5	13.81	1.032	21.214
		17	14.00	0.941	19.467
		21	14.38	0.762	15.959
		26	14.70	0.615	13.022
		7	12.55	2.571	54.151
		7.3	12.77	2.466	52.307
		9	13.76	2.000	43.788
		9.3	13.90	1.935	42.558
		11	14.53	1.636	36.696
18	18.000	11.5	14.68	1.565	35.263
		13.5	15.17	1.333	30.491
		15.5	15.54	1.161	26.849
		17	15.76	1.059	24.638
		21	16.18	0.857	20.198
		26	16.53	0.692	16.480
		32.5	16.83	0.554	13.296

OD			Pipe inside diameter (d)	Minimum Wall Thickness (t)	Weight (w)
Nominal in.	**Actual in.**	**DR**	**in.**	**in.**	**lb. per foot**
20	20.000	7	13.94	2.857	66.853
		7.3	14.19	2.740	64.576
		9	15.29	2.222	54.059
		9.3	15.44	2.151	52.541
		11	16.15	1.818	45.304
		11.5	16.31	1.739	43.535
		13.5	16.86	1.481	37.643
		15.5	17.26	1.290	33.146
		17	17.51	1.176	30.418
		21	17.98	0.952	24.936
		26	18.37	0.769	20.346
		32.5	18.70	0.615	16.415
22	22.000	9	16.82	2.444	65.412
		9.3	16.98	2.366	63.574
		11	17.76	2.000	54.818
		11.5	17.94	1.913	52.677
		13.5	18.55	1.630	45.548
		15.5	18.99	1.419	40.107
		17	19.26	1.294	36.805
		21	19.78	1.048	30.172
		26	20.21	0.846	24.619
		32.5	20.56	0.677	19.863
24	24.000	9	18.35	2.667	77.845
		9.3	18.53	2.581	75.658
		11	19.37	2.182	65.237
		11.5	19.58	2.087	62.690
		13.5	20.23	1.778	54.206
		15.5	20.72	1.548	47.731
		17	21.01	1.412	43.801
		21	21.58	1.143	35.907
		26	22.04	0.923	29.299
		32.5	22.43	0.738	23.638

OD			Pipe inside diameter (d)	Minimum Wall Thickness (t)	Weight (w)
Nominal in.	Actual in.	DR	in.	in.	lb. per foot
		11	22.60	2.545	88.795
		11.5	22.84	2.435	85.329
		13.5	23.60	2.074	73.781
		15.5	24.17	1.806	64.967
28	28.000	17	24.51	1.647	59.618
		21	25.17	1.333	48.874
		26	25.72	1.077	39.879
		32.5	26.17	0.862	32.174
		11	24.22	2.727	101.934
		11.5	24.47	2.609	97.954
		13.5	25.29	2.222	84.697
		15.5	25.90	1.935	74.580
30	30.000	17	26.26	1.765	68.439
		21	26.97	1.429	56.105
		26	27.55	1.154	45.779
		32.5	28.04	0.923	36.934
		13.5	26.97	2.370	96.367
		15.5	27.62	2.065	84.855
32	32.000	17	28.01	1.882	77.869
		21	28.77	1.524	63.835
		26	29.39	1.231	52.086
		32.5	29.91	0.985	42.023
		15.5	31.08	2.323	107.395
		17	31.51	2.118	98.553
36	36.000	21	32.37	1.714	80.791
		26	33.06	1.385	65.922
		32.5	33.65	1.108	53.186
		15.5	36.26	2.710	146.176
		17	36.76	2.471	134.141
42	42.000	21	37.76	2.000	109.966
		26	38.58	1.615	89.727
		32.5	39.26	1.292	72.392

OD			Pipe inside diameter (d)	Minimum Wall Thickness (t)	Weight (w)
Nominal in.	**Actual in.**	**DR**	**in.**	**in.**	**lb. per foot**
48	48.000	17	42.01	2.824	175.205
		21	43.15	2.286	143.629
		26	44.09	1.846	117.194
		32.5	44.87	1.477	94.552
54	54.000	21	48.55	2.571	181.781
		26	49.60	2.077	148.324
		32.5	50.48	1.662	119.668

Appendix A.3

List of Design Chapter Variables

υ	=	kinematic viscosity, ft^2/sec
ρ	=	fluid density, lb/ft^3
μ	=	dynamic viscosity, $lb\text{-}sec/ft^2$
Δ v	=	Sudden velocity change, ft/sec
a	=	Wave velocity (celerity), ft/sec
A_C	=	Cross-sectional area of pipe bore, ft^2
a_C	=	contact area, ft^2
A	=	profile wall average cross-sectional area, in^2/in, for profile pipe or wall thickness (in) for DR pipe
A_S	=	Area of pipe cross-section or $(\prod/4)\ (D_O^2 - D_i^2)$, in^2
A_P	=	area of the outside wall of the pipe, 100 in^2
C	=	Hazen-Williams Friction Factor, dimensionless ,see table 1-7.
c	=	outer fiber to wall centroid, in
C_V	=	percent solids concentration by volume
C_W	=	percent solids concentration by weight
D_A	=	pipe average inside diameter, in
DF	=	Design Factor, from Table 1-2
d’	=	Pipe inside diameter, ft
D_I	=	Pipe inside diameter, in
D_M	=	Mean diameter (DI+2z or D_O-t), in
D_{MIN}	=	pipe minimum inside diameter, in
D_o	=	pipe outside diameter, in
d_O	=	pipe outside diameter, ft
DR	=	Dimension Ratio, D_O/t
E	=	Apparent modulus of elasticity for pipe material, psi
e	=	natural log base number, 2.71828
E’	=	Modulus of soil reaction, psi
E_d	=	Dynamic instantaneous effective modulus of pipe material (typically 150,000 psi for PE pipe)
E_N	=	Native soil modulus of soil reaction, psi
E_S	=	Secant modulus of the soil, psi
E_S*	=	$E_S/(1-\mu)$
f	=	friction factor (dimensionless, but dependent upon pipe surface roughness and Reynolds number)
F	=	end thrust, lb
F_B	=	buoyant force, lb/ft
F_L	=	velocity coefficient (Tables 1-14 and 1-15)
f_O	=	Ovality Correction Factor, Figure 2-9
F_S	=	Soil Support Factor
F_T	=	Service Temperature Design Factor, from Table 1-11
g	=	Constant gravitational acceleration, 32.2 ft/sec^2
H_P	=	profile wall height, in
H	=	height of cover, ft
h_l	=	liquid level in the pipe, ft
H_{GW}	=	ground water height above pipe, ft
h_1	=	pipeline elevation at point 1, ft

h_1	=	inlet pressure, in H_2O
h_U	=	upstream pipe elevation, ft
h_2	=	pipeline elevation at point 2, ft
h_2	=	outlet pressure, in H_2O
d_D	=	downstream pipe elevation, ft
HDB	=	Hydrostatic Design Basis, psi
h_E	=	Elevation head, ft of liquid
h_f	=	friction (head) loss, ft. of liquid
H_S	=	level of ground water saturation above pipe, ft
I_V	=	Influence Value from Table 2-5
I	=	Pipe wall moment of inertia, in^4/in
IDR	=	ID -Controlled Pipe Dimension Ratio
I_f		impact factor
k	=	kinematic viscosity, centistokes
K_{BULK}	=	Bulk modulus of fluid at working temperature
K_{BED}	=	Bedding factor, typically 0.1
K	=	passive earth pressure coefficient
K’	=	Fittings Factor, Table 1-5
K_P	=	permeability constant (Table 1-13)
L_{EFF}	=	Effective Pipeline length, ft.
L	=	Pipeline length, ft
L_{DL}	=	Deflection lag factor
ΔL	=	pipeline length change, in
M	=	horizontal distance, normal to the pipe centerline, from the center of the load to the load edge, ft
M_s	=	one-dimensional modulus of soil, psi
n	=	roughness coefficient, dimensionless
N	=	horizontal distance, parallel to the pipe centerline, from the center of the load to the load edge, ft
N_S	=	safety factor
P	=	Internal Pressure, psi
P_W	=	perimeter wetted by flow, ft
p_1	=	inlet pressure, lb/in^2 absolute
p_2	=	outlet pressure, lb/in^2 absolute
P_A	=	pipe internal pressure, atmospheres (1 atmosphere = 14.7 lb/in^2)
PC	=	Pressure Class
P_{CR}	=	Critical constrained buckling pressure, psi
P_E	=	vertical soil pressure due to earth load, psf
P_f	=	friction (head) loss, psi
P_L	=	vertical soil pressure due to live load, psf
P_{OS}	=	Occasional Surge Pressure
P_{RD}	=	radial directed earth pressure, lb/ft^2
P_{RS}	=	Recurring Surge Pressure
P_s	=	Transient surge pressure, psig
P_{WAT}	=	Allowable live load pressure at pipe crowm for pipes with one diameter or less of cover, psf
P_{WC}	=	allowable constrained buckling pressure, lb/in^2
P_{WU}	=	allowable unconstrained pipe wall buckling pressure, psi

p_i	=	Pressure due to sub-area *i* lb/ft^2
Q	=	flow rate, gpm
Q_{FPS}	=	flow, ft^3/sec
Q_h	=	flow, standard ft^3/hour
q_P	=	volume of gas permeated, cm^3 (gas at standard temperature and pressure)
r_H	=	hydraulic radius, ft
r	=	distance from the point of load application to pipe crown, ft
R	=	buoyancy reduction factor
r_{CENT}	=	radius to centroidal axis of pipe, in
Re	=	Reynolds number, dimensionless
R_H	=	Geometry Factor
RSC	=	Ring Stiffness Constant, lb/ft
r_T	=	equivalent radius, ft
RF	=	Rigidity factor, dimensions
s	=	liquid density, gm/cm^3
S_H	=	hydraulic slope, ft/ft
S	=	pipe wall compressive stress, lb/in^2
S_{MAT}	=	material yield strength, lb/in^2
S_A	=	Hoop Thrust Stiffness Ratio
S_g	=	gas specific gravity
S_L	=	carrier liquid specific gravity
S_M	=	slurry mixture specific gravity
S_S	=	solids specific gravity
t	=	minimum wall thickness, in
t’	=	wall thickness, mils
T_{CR}	=	Critical time, seconds
V	=	flow velocity, ft/sec
VAF	=	Vertical Arching Factor
V_C	=	critical settlement velocity, ft/sec
ν	=	kinematic viscosity. ft^2/sec
V_{Min}	=	approximate minimum velocity, ft/sec
w	=	unit weight of soil, pcf
w	=	unit weight of soil, lb/ft^3
W_D	=	weight of dry soil above pipe, lb/ft of pipe
W_w	=	wheel load, lb
W_L	=	weight of liquid contents, lb/ft of pipe
W_L	=	weight of the liquid in contacts, lb/ft of pipe
WP	=	Working Pressure, psi
W_P	=	pipe weight, lb/ft of pipe
WPR	=	Working Pressure Rating, psi
w_S	=	distributed surcharge pressure acting over ground surface, lb/ft^2
W_S	=	weight of saturated soil above pipe, lb/ft of pipe
ζ	=	dynamic viscosity, centipoises
Z	=	Centroid of wall section, in
Z	=	Pipe wall centroid, in
Z_i	=	wall-section centroidal distance from inner fiber of pipe, in
α	=	thermal expansion coefficient, in/in/°F

ΔL	=	length change, in
ΔT	=	temperature change, °F
ΔX	=	Horizontal deflection, in
ΔV	=	Sudden velocity change., ft/sec
ε	=	absolute roughness, ft.
ε_S	=	Soil strain
Θ	=	elapsed time, days
μ_s	=	Poisson's Ratio of Soil
μ	=	Poisson's ratio
σ	=	longitudinal stress in pipe, psi
σ_{allow}	=	Allowable tensile stress at 73°F, lb/in
φ	=	Calibration Factor, 0.55 for granular soils change in psi
ω_D	=	unit weight of dry soil,lb/ft^3 (See Table 2-16 for typical values.)
ω_G	=	unit weight of groundwater lb/ft^3
ω_L	=	unit weight of liquid in the pipe, lb/ft^3
ω_S	=	unit weight of saturated soil, pcf lb/ft^3
ϕ	=	angle of internal friction, deg
Γ	=	Dynamic viscosity, lb-sec/ft^2

Chapter 7

Underground Installation of Polyethylene Piping

Introduction

Piping systems are prevalent throughout our everyday world. Most of us think of piping systems as underground structures used to convey liquids of one sort or another. To the novice, the concept of pipeline installation underground sounds relatively straight forward: a) dig a trench, b) lay the pipe in the trench, and c) fill the trench back in.

While this simplified perspective of pipeline construction may be appealing, it does not begin to address the engineering concepts involved in the underground installation of a pipeline. This chapter is written to assist in the development of a comprehensive understanding of the engineering principles utilized in the underground installation of polyethylene pipe.

In the pages which follow, the reader will be introduced to the concept of a pipe soil system and the importance that the soil and the design and preparation of the back-fill materials play in the long-term performance of a buried pipe structure. Specific terminology and design concepts relating to the underground installation of polyethylene pipe will be fully discussed. This will include fundamental guidelines regarding trench design and the placement and subsequent backfill of the polyethylene pipe.

This chapter is intended to assist the pipeline designer in the underground installation of polyethylene piping materials. This chapter is not intended as a substitute for the judgement of a professional engineer. Rather, it is felt that a comprehensive presentation of these design and installation principles may assist the engineer or designer in utilizing polyethylene pipe in a range of applications that require that it be buried beneath the earth.

Those individuals who are installing 24” diameter or smaller pressure pipe less than 16 feet deep are advised to see Appendix 1 which includes simplified installation guidelines. These guidelines were written to be used without review of this entire chapter; however, the installer of smaller pipes would benefit from a familiarity of the principles of pipe installation given in this chapter.

Appendix 2 contains a specification for large diameter (greater than 18”) gravity flow pipes. For these sizes it is advised that the installer read this chapter.

Flexible Pipe Installation Theory

Most PE piping is considered flexible. Flexible pipes include corrugated metal pipes, plastic pipes, and some steel and ductile pipes. These pipes deflect under load, such as the overburden load encountered when installed underground. The designer and installer of underground, flexible piping must utilize the soil to construct an envelope of supporting material around the pipe so that the deflection is maintained at an acceptable level. The extent to which the pipe depends on this enveloping soil for support is a function of the depth of cover, surface loading, and the SDR or Ring Stiffness of the pipe.

In general, the supporting envelope is built by surrounding the pipe with firm, stable material. This envelope is often referred to as the “embedment” (see figure 1). The amount of support provided by the embedment is directly proportional to its stiffness. For this reason, often the embedment material is compacted. The stiffness of the material placed above the pipe may also affect the pipe’s performance. Considerable load reduction may occur due to arching, that is the redistribution of stresses in the soil above and around the pipe which result in a shifting of load away from the pipe. The stiffer the backfill above the pipe, the more arching occurs.

The designer or installer will consider not only the embedment material but also the undisturbed in-situ soil surrounding the embedment and the ground water. The movement of the in-situ soil in the trench wall can reflect through the embedment and affect the pipe’s performance. Therefore, careful consideration must be paid to this material when planning and during installation. This will most likely affect the equipment involved in doing the installation and the installation procedure itself more so than the pipe design. Of particular significance are soft clays and wet, loose silts or sands. When these materials are encountered, unstable trenching can occur with considerable sloughing and loosening of the trench walls during excavation. Flexible pipe can be installed in such ground with limited deflection as long as attention is paid to the proper handling of these conditions.

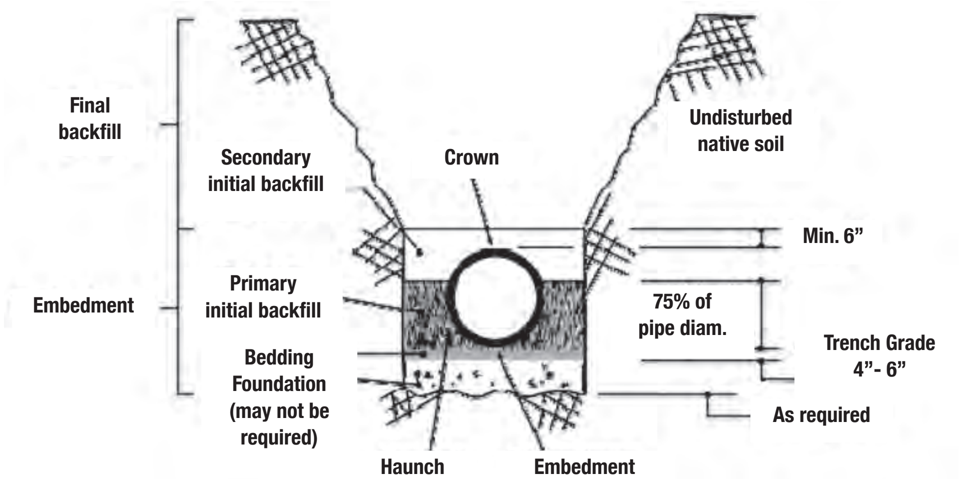


Figure 1 Pipe Trench

Note: When groundwater levels are expected to reach above pipe, the secondary initial backfill should be a continuation of the primary initial backfill in order to provide optimum pipe support. Minimum trench width will depend on site conditions and embedment materials.

Deflection Control

As described previously, the load carrying capability of a PE pipe can be greatly increased by the soil in which it is embedded if, as the pipe is loaded, the load is transferred from the pipe to the soil by a horizontal outward movement of the pipe wall. This enhances contact between pipe and soil and mobilizes the passive resistance of the soil. This resistance aids in preventing further pipe deformation and contributes to the support for the vertical loads. The amount of resistance found in the embedment soil is a direct consequence of the installation procedure. The stiffer the embedment materials are, the less deflection occurs. Because of this, the combination of embedment and pipe is often referred to as a pipe-soil system (see figure 2).

The key objective of a PE pipe installation is to limit or control deflection. (In this chapter the term “deflection” will mean a change in vertical diameter of the pipe, unless otherwise stated.) The deflection of a PE pipe is the sum total of two major components: the “installation deflection,” which reflects the technique and care by which the pipe is handled and installed; and the “service deflection,” which reflects the accommodation of the constructed pipe-soil system to the subsequent earth loading and other loadings.

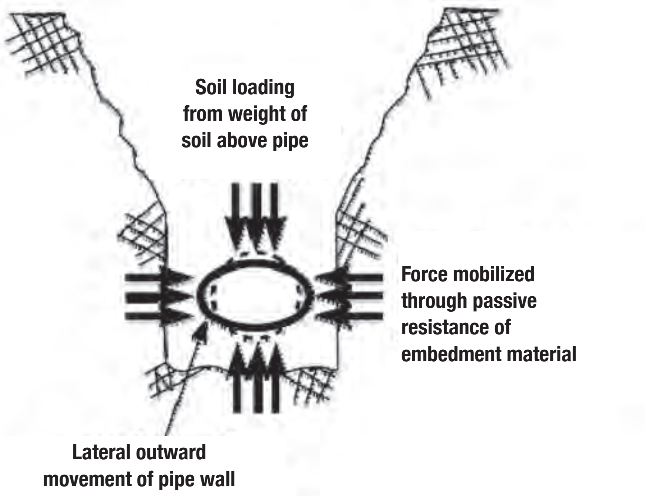


Figure 2 Mobilization of Enveloping Soil through Pipe Deformation

The "service deflection," which is usually a decrease in vertical pipe diameter, may be predicted by a number of reasonably well documented relationships, including those of Watkins and Spangler(1,2), or by use of a finite element analysis such as CANDE(1,2).

The "installation deflection" may be either an increase or decrease in vertical pipe diameter. An increase in vertical pipe diameter is referred to as "rise" and is usually a result of the forces acting on the pipe during compaction of the embedment beside it. Up to a point this may be beneficial in offsetting service deflection. Installation deflection is not predictable by any mathematical formula, although there are empirical methods for accounting for it(3).

Installation deflection is subject to control by the care used in the placement and compaction of the pipe embedment material in relation to the pipe's ring stiffness. For instance, compaction forces from hand operated air or gasoline tampers normally cause little rise, even when obtaining densities of 95 percent, but driving heavy loading equipment or driven compactors on the embedment while it is being placed beside the pipe may cause severe rise.

Commonly, deflection varies along the length of the pipeline due to variations in construction technique, soil type and loading. Field measurements illustrating this variability have been made by the U. S. Bureau of Reclamation and have been published by Howard(3). Typically, this variation runs around ±2 percent.

Acceptance Deflection

To evaluate and control the quality of a flexible pipe installation, many designers impose an “acceptance deflection” requirement. This is particularly important for gravity flow lines with high SDR pipe. Commonly, pressure pipes are not checked for deflection. The “acceptance deflection” is the maximum vertical pipe deflection permitted following installation. Typically, measurements are made only after most of the initial soil consolidation occurs, usually at least 30 days after installation. The design engineer sets the “acceptance deflection” based on the particular application and type of joints. Commonly, a deflection limit of 5 percent is used, although PE pipe in gravity applications can usually withstand much larger deflections without impairment. When deflection is measured past 30 days, it is common to allow for a higher percentage. (See section on “Inspection. ”)

Pipe Design Considerations

While control of pipe deflection is a key objective in the installation of PE pipe, deflection is not ordinarily the criterion that determines the selection of a specific pipe SDR or ring stiffness. For typical burial conditions most PE pipes, when properly installed, are adequately stiff to preclude excessive deflection. However, for gravity flow applications, the design may often be controlled by the pipe’s buckling resistance or the compressive thrust load in the pipe’s wall. The selection of pipe design and construction requirements should be based on anticipated site conditions including trench depth, hydrostatic pressure due to ground water, superimposed static or traffic load, and depth of cover.

Pipe Embedment Materials

The embedment is the material immediately surrounding the pipe. This material may be imported, such as a crushed stone, or it may be the material excavated from the trench to make room for the pipe. In this case, it is referred to as native soil.

The embedment material should provide adequate strength, stiffness, uniformity of contact and stability to minimize deformation of the pipe due to earth pressures. The earth pressure acting on the pipe varies around the pipe’s circumference (see figure 3). The pressure on the crown or top will typically be less than the free field stress as is the pressure at the invert or bottom of the pipe. Often, the highest pressure may be acting horizontally at the springline of the pipe, due to mobilization of passive pressure and arching.

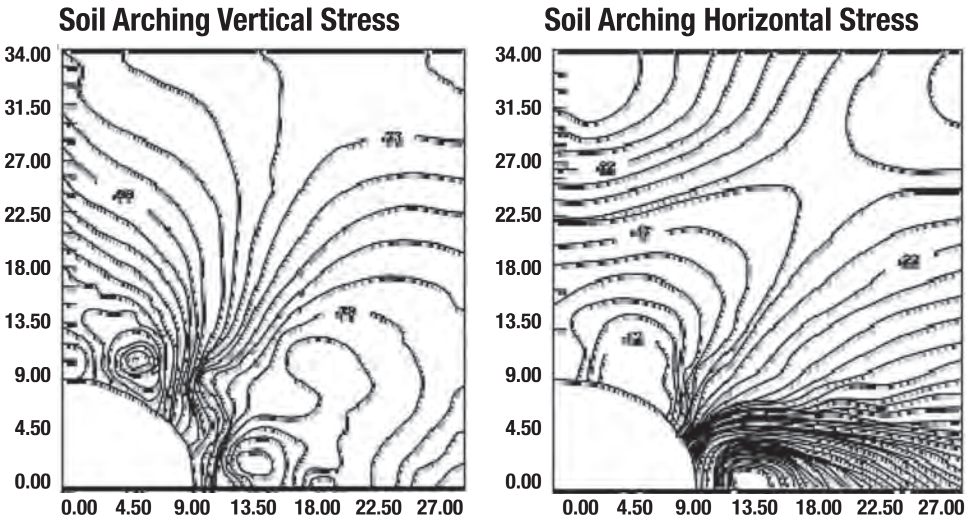


Figure 3 Stress Distribution for 18 in. HDPE pipe in soil box.

Because the earth pressure is acting around the circumference, it is important to completely envelop the pipe in embedment. (This may vary to a greater or lesser extent depending on the earth pressure, burial depth, and SDR.) To ensure that the embedment function should always be carried out under the anticipated job conditions, the design engineer will specify the permissible pipe embedment materials and their minimum acceptable density (compaction).

The properties of the in-situ (or native) soil into which the pipe is placed need not be as demanding as those for the embedment materials (unless it is used as the embedment material). The native soil may experience additional compression and deformation due to the horizontal pressure exerted by the pipe and transferred through the embedment material. This is usually a minor effect, but in some cases it can result in additional pipe deflection. This is most likely to occur where native soils are wet and loose, soft, or where native soil sloughs into the trench during excavation and is not removed. This effect is attenuated as the trench width (or width of embedment material) increases. Therefore, consideration must be given to the in-situ soil to ensure that it has adequate strength to permanently contain the embedment system. This is also discussed in a following section.

Terminology of Pipe Embedment Materials

The materials enveloping a buried pipe are generally identified, as shown by their function or location (see figure 1).

Foundation - A foundation is required only when the native trench bottom does not provide a firm working platform for placement of the pipe bedding material.

Bedding - In addition to bringing the trench bottom to required grade, the bedding levels out any irregularities and ensures uniform support along the length of the pipe.

Haunching - The backfill under the lower half of the pipe (haunches) distributes the superimposed loadings. The nature of the haunching material and the quality of its placement are one of the most important factors in limiting the deformation of PE pipe.

Primary Initial Backfill - This zone of backfill provides the primary support against lateral pipe deformation. To ensure such support is available, this zone should extend from trench grade up to at least 75 percent of the pipe diameter. Under some conditions, such as when the pipe will be permanently below the ground water table, the primary initial backfill should extend to at least 6 inches over the pipe.

Secondary Initial Backfill - The basic function of the material in this zone is to distribute overhead loads and to isolate the pipe from any adverse effects of the placement of the final backfill.

Final Backfill - As the final backfill is not an embedment material, its nature and quality of compaction has a lesser effect on the flexible pipe. However, arching and thus a load reduction on the pipe is promoted by a stiff backfill. To preclude the possibility of impact or concentrated loadings on the pipe, both during and after backfilling, the final backfill should be free of large rocks, organic material, and debris. The material and compaction requirements for the final backfill should reflect sound construction practices and satisfy local ordinances and sidewalk, road building, or other applicable regulations.

Classification and Supporting Strength of Pipe Embedment Materials

The burial of HDPE pipe for gravity flow applications is covered by ASTM D2321 "*Standard Practice for Underground Installation of Thermoplastic Pipe for Sewer and Other Gravity-Flow Applications*." ASTM 2774, "*Standard Practice for Underground Installation of Thermoplastic Pressure Piping*," covers water pipe and force mains.

Strength of Embedment Soil

When selecting embedment material, consideration should be given to how the grain size, shape, and distribution will affect its supporting strength. The following will help guide the designer or installer in making a choice. In general, soils with large grains such as gravel have the highest stiffness and thus provide the most supporting strengths. Rounded grains tend to roll easier than angular, or sharp grains, which tend to interlock, and resist shear better. Well graded mixtures of soils (GW, SW), which contain a good representation of grains from a wide range of sizes, tend to offer more resistance than uniform graded soils (GP, SP). (See Table 1 for symbol definitions.)

Aside from the grain characteristics, the density has the greatest effect on the embedment's stiffness. For instance, in a dense soil there is considerable interlocking of grains and a high degree of grain-to-grain contact. Movement within the soil mass is restricted as the volume of the soil along the surface of sliding must expand for the grains to displace. This requires a high degree of energy. In a loose soil, movement causes the grains to roll or to slide, which requires far less energy. Thus, loose soil has a lower resistance to movement. Loose soil will permit more deflection of pipe for a given load than a dense soil.

When a pipe deflects, two beneficial effects occur.

1. The pipe pushes into the embedment soil and forces the soil to start moving. As this occurs, a resistance develops within the soil which acts to restrain further deflection.

2. Vertical deflection results in a reduction in earth load transmitted to the pipe due to the mobilization of arching.

Embedment Classification Per ASTM D-2321

Pipe embedment materials have been grouped by ASTM D-2321, *"Underground Installation of Flexible Thermoplastic Sewer Pipe,"* into five embedment classes according to their suitability for that use.

TABLE 1
Embedment Classes per ASTM D-2321

Class	Soil Description	Soil Group Symbol	Average Value of E'			
			Dumped	Degree of Compaction of Embedment Mateial[1] (Standard Proctor)		
				Slight 85%	Moderate 90%	Heavy <95%
IA	Manufactured aggregate, angular open-graded and clean. Includes crushed stone, crushed shells.	None	500	1000	2000	3000
IB	Processed aggregate, angular dense-graded and clean. Includes Class IA material mixed with sand and gravel to minimize migration	None	200	1000	2000	3000
II	Coarse-grained soils, clean. Includes gravels, gravel-sand mixtures, and well and poorly graded sands. Contains little to no fines (less than 5% passing #200).	GW, GP, SW, SP	200	1000	2000	3000
II	Coarse-grained soils, borderline clean to "with fines." Contains 5% to 12% fines (passing #200).	GW- GC SP-SM	200	1000	5000	3000
III	Coarse-grained soils containing 12% to 50% fines. Includes clayey gravel, silty sands, and clayer sands.	GM, GC, SM, SC	100	200	1000	2000
IVA	Fine-grained soils (inorganic). Includes inorganic silts, rock flour, silty-fine sands, clays of low to medium plasticity, and silty or sandy clays.	ML, CL	50	200	400	1000
IVB	Fine-grained soils (inorganic). Includes diatomaceous silts, elastic silts, fat clays.	MH, CH	No data available: consult a competent soils engineer. Otherwise use E' equals zero.			
V	Organic soils. Includes organic silts or clays and peat.	OL, OH, PT	No data avaliable: consult a competent soils engineer. Otherwise use E' equals zero.			

[1] E' values taken from Bureau of Reclamation table of average values and modified slightly herein to make the values more conservative.

The lower numbered classes have larger grain sizes and thus are more suitable as pipe embedment. The materials included in each class are identified in Table 1 and grouped in accordance with their classification per ASTM D-2487, *Standard Unified Soil Classifcation System* (USCS). (See Appendix III for a general discussion of soil classification.) A visual manual procedure for the field identification of soils is offered by ASTM D-2488.

The supporting strength of embedment materials roughly coincides with their embedment class. The supporting strength or stiffness of a soil material is represented by the modulus of soil reaction, E′. Based on extensive evaluation of field and laboratory performance of flexible pipes, the Bureau of Reclamation of the U. S. Department of the Interior has issued a table of Modulus of Soil Reaction Values. This tabulation of E′ values, which is reproduced with some modifications based on recent experience in Table 1, provides a measure of available soil support depending on the soil embedment class and its degree of compaction. As discussed above, generally speaking, the classes with finer soils offer less supporting strength. However, within any embedment class, increased compaction greatly improves a soil's supporting strength, hence the critical role of proper compaction, particularly with the finer-grained soils. To ensure that the pipe is always adequately supported, it is the general practice to use materials and degrees of compaction resulting in an E′ equal to or greater than 750 psi, although some applications may require higher or lower E′ values.

Use of Embedment Materials

The determination of requirements for embedment materials and their placement should take into consideration not only their relative supporting strength but also their stability under end use conditions, ease of placement and compaction, and cost and availability.

Class I and Class II

Class I and Class II soils are granular and tend to provide the maximum embedment support as illustrated by the high E′ values that can be achieved with them. Class I material is generally manufactured aggregate, such as crushed stone. Class II materials consist of clean sands and gravels and are more likely to be naturally occurring soils such as river deposits. Class I and Class II materials can be blended together to obtain materials that resist migration of finer soils into the embedment zone (as will be explained below.) In addition, Class I and II materials can be placed and compacted over a wide range of moisture content more easily than can other materials. This tends to minimize pipe deflection during installation. The high permeability of open-graded Class I and II materials aids in de-watering trenches, making these materials desirable in situations such as rock cuts where water problems may be encountered. This favorable combination of characteristics leads many designers to select these materials over others when they are readily and economically available.

Maximum aggregate size of Class I and Class II materials when used next to the pipe (i. e. , bedding, haunching and initial backfill) should not be larger than those given in Table 2 below. (Larger stones up to 1½ inches have been successfully used, but they are difficult to shovel slice and compact.) The smaller the rock size, the easier it is to place in the haunches. Maximum size for the foundation material is not restricted except that it should be graded to prevent the bedding stone from migrating into it.

TABLE 2
Maximum Particle Size vs. Pipe Size

Nominal Pipe Size (in.)	Maximum Particle Size (in.)
2 to 4	½
6 to 8	¾
10 to 15	1
16 and larger	1 ½

Migration

When the pipe is located beneath the ground water level, consideration must be given to the possibility of loss of side support through soil migration (the conveying by ground water of finer particle soils into void spaces of coarser soils). Generally, migration can occur where the void spaces in the embedment material are sufficiently large to allow the intrusion of eroded fines from the trench side walls.

For migration to occur, the in-situ soil must be erodible. Normally, erodible soils are fine sand and silts and special clays known as dispersive clays. (Most clays have good resistance to dispersion.) This situation is exacerbated where a significant gradient exists in the ground water from outside of the trench toward the inside of the trench; i. e. , the trench must act as a drain. (Seasonal fluctuations of the ground water level normally do not create this condition.)

For such anticipated conditions, it is desirable when using granular materials (Class I and II) to specify that they be angular and graded to minimize migration. Rounded particles have a tendency to flow when a considerable amount of water exists and material with a high void content provides "room" for migrating particles. The Army Corps of Engineers developed the following particle size requirements for properly grading adjacent materials to minimize migration:

(1) $$D_{15}^{E} < 5D_{85}^{A}$$

(2) $$D_{50}^{E} \geq 25D_{85}^{A}$$

Where the D_{15}, D_{50} and D_{85} are the particle sizes from a particle size distribution plot at 15%, 50% and 85%, respectively, finer by weight and where D^{E} is the embedment soil and D^{A} is the adjacent in-situ soil.

Another approach to preventing migration is to use geotextile separation fabrics. The fabric is sized to allow water to flow but to hold embedment materials around the pipe. Figure 4 shows a typical installation.

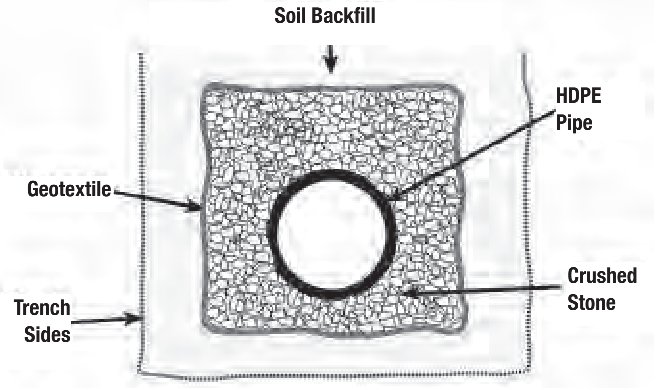


Figure 4 Installation of Geotextile Separation Fabrics

Cement Stabilized Sand

One special case of Class II material is Cement Stabilized Sand. Cement Stabilized Sand, once cured, is generally considered to give the same or better supporting strength as compacted Class I material. Cement Stabilized Sand consists of sand mixed with 3-5 percent cement. To achieve proper density, the material is placed with compaction rather than poured as with concrete. The material must be placed moist (at or near optimum moisture content) and then compacted in lifts as a Class II material. (The optimum moisture content is that moisture content at which a material can achieve its highest density for a given level of compaction.) If desired, deflection can be reduced if the cement sand embedment material is allowed to cure overnight before placement of backfill to grade. If the trench is backfilled immediately, cement sand will give the same support as a Class II material, but the lag factor will be reduced. Cement sand is usually placed in both the primary initial and secondary initial backfill zones (see figure 1).

Class III and Class IVA

Class lIl and Class IVA materials provide less supporting stiffness than Class I or II materials for a given density or compaction level, in part because of the increased clay content. In addition, they require greater compactive effort to attain specified densities and their moisture content must be closely controlled within the optimum limit. (The optimum moisture content is that moisture content at which a material can achieve its highest density for a given level of compaction.) Placement and compaction of Class IVA materials are especially sensitive to moisture content. If the Class IVA material is too wet, compaction equipment may sink into the material; if the soil is too dry, compaction may appear normal, but subsequent saturation with ground water may cause a collapse of the structure and lead to a loss of support.

Typically, Class IVA material is limited to applications with pressure pipe at shallow cover.

Class IVB and Class V

Class IVB and Class V materials offer hardly any support for a buried pipe and are often difficult to properly place and compact. These materials are normally not recommended for use as pipe embedment unless the pipe has a low SDR (or high ring stiffness), there are no traffic loads, and the depth of cover is only a few feet. In many cases the pipe will float in this type of soil if the material becomes saturated.

Compaction of Embedment Materials

Compaction criteria for embedment materials are a normal requirement in flexible pipe construction. Compaction reduces the void space between individual grains and increases the embedment density, thereby greatly improving pipe load carrying ability while reducing deflection, settlement, and water infiltration problems. Compaction of the embedment often will increase the stiffness of the in-situ soil and provide a sort of pre-stressing for the embedment and in-situ soils. Because of these benefits compaction should be considered on all projects.

Density Requirements

The required degree of compaction for an installation will be set by the designer in consideration of height of cover, extent of live loading, water table elevation and soil properties. Generally, the "moderate" compaction requirements listed in Table 1 are quite satisfactory. When compacting to this "moderate" level, it is suggested that the minimum target values for field measured densities be set as 90 percent Standard Proctor Density. This field density requirement will ensure that the actual densities will always be within the "moderate" range presented in Table 1. The applicable method for measuring density, ASTM D-2029, *Test for Relative Density of Cohesionless Soils*, or ASTM D-698*, Tests For Moisture-Density Relations of Soils and Soil-Aggregate Mixtures*, will be determined by the nature of the embedment material. Generally, the density of granular soils is determined using either test, whereas that of fine grained materials is determined by ASTM D-98. See Appendix 3 for a discussion of the difference between density and compaction and a discussion of the various test methods.

Compaction Techniques

Compaction of the embedment material should be performed by the most economical method available, consistent with providing uniform compaction and attaining the minimum specified density. Typical equipment used for compaction are hand held tamping bars (see figure 5), gasoline driven impact tampers ("whackers"), vibratory plates, and air driven impact tampers ("pogo sticks"). With crushed stone, some degree of densification can be achieved by the technique of shovel slicing, which consists of cutting the soil with a shovel.

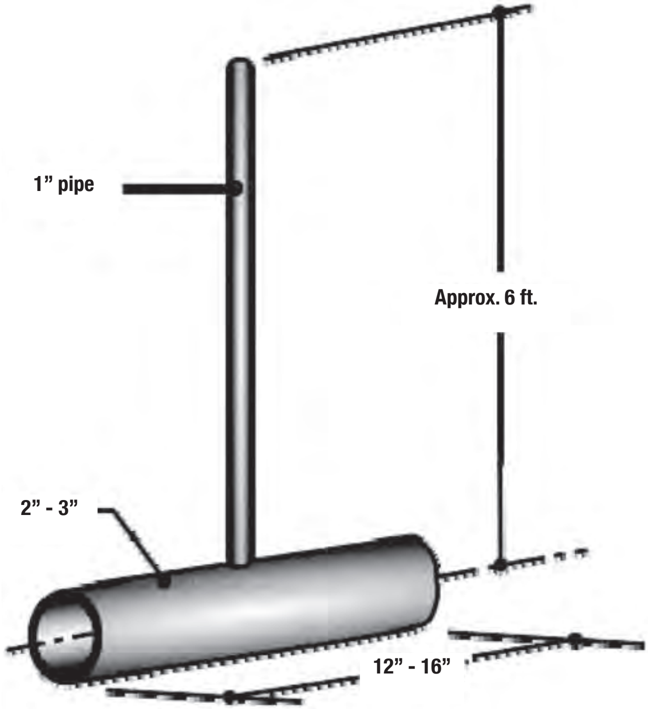


Figure 5 Tamping Tool

Compaction of the haunching material can best be accomplished by hand with tampers or suitable power compactors, taking particular care in the latter case not to disturb the pipe from its line and grade. In 36" and larger pipe, hand tampers are often used to reach under the haunches; they are then followed up with power compaction alongside the pipe.

When compacting the embedment near the pipe with impact-type tampers, caution should be taken to not allow direct contact of the equipment with the pipe. Avoid use of impact tampers directly above the pipe until sufficient backfill (usually 12") has been placed to ensure no local deformation of the pipe. Compaction of the embedment material alongside the pipe should not cause pipe to lift off of grade, but if upward movement occurs, reduce the compaction level below the springline or move the compactor away from the pipe toward the side of the trench.

Compaction of primary initial backfill should be conducted at, or near, the material's optimum moisture content. The backfill should be placed in layers, or lifts, that are brought up evenly on both sides of the pipe, otherwise the pipe could be moved off alignment. Each lift should be thoroughly compacted prior to placement of the next layer. The maximum lift height that will allow development of uniform density will vary depending on the material, its moisture content, and compactive effort. In general, maximum lifts of approximately 12 inches for Class I, 8 inches for Class II, and 6 inches for all others are adequate.

Compaction of Class I and II Materials

Compaction by vibration is most effective with granular (Class I and II) materials. Compaction of stone does not deform the stone but it does move it into a more compact or dense arrangement. In cases where the engineer specifies a minimum soil density of 90 percent of Standard Proctor or higher, as for installations under deep cover, mechanical compaction of Class I materials will be required. Impact tampers will also increase the density of Class I and II materials, primarily due to vibration. Impact tamping also acts to drive the embedment into the in-situ soil, which stiffens the trench wall interface. For this reason, impact compaction of Class I material should be considered for any application where the pipe will be below the ground water table or where the stability of the in-situ soil is in question.

An alternate method of achieving compaction with Class I materials is shovel slicing. Materials having been shovel sliced thoroughly will generally yield a modulus of around 1000 psi. The effectiveness of this method depends on the frequency of slicing along the length of the pipe. This technique should be limited to dry or firm (or better) in-situ soils. Where Class I materials are dumped around the pipe without any compactive effort (or shovel slicing), E's may be considerably lower than those given in the Bureau of Reclamation table. This is especially the case in wet or loose ground. A few passes with a vibratory compactor will increase the density and modulus of soil reaction.

Mechanical compaction of Class II materials can be aided by slight wetting. When so doing, care must be taken not to saturate the material or flood the trench, particularly when the native trench material does not drain freely. Flooding can result in flotation of the pipe.

Compaction by saturation, also called flooding or water tamping, is sometimes used to compact Class II materials. This method of compaction rarely yields Proctor densities greater than 75 percent, and therefore it will generally not give an E' of 750 psi or higher. Flooding is only suited for those applications where the pipe has sufficient internal supporting strength for the design load and does not depend on the soil for side support. (When considering this method for embedment that must provide side support, a geotechnical engineer should be consulted.) Compaction by saturation is limited to applications where both the embedment soil and in-situ soil are free draining. Compaction should be done in lifts not exceeding the radius of the pipe or 24 inches, whichever is smaller. Only enough water should be placed to saturate the material. It should be determined through proper monitoring that the desired level of compaction is being attained in each lift. Compaction by saturation should not be used in freezing weather. Water jetting, or the introduction of water under pressure to the embedment material, should not be used with plastic pipe.

Compaction of Class III and IV Materials

Compaction by impact is usually most effective with Class lII and Class IVa materials. The use of mechanical impact tampers is most practical and effective. Depending on the embedment material, its moisture content, and lift height, several compaction passes may be required. A maximum lift height of 6 inches should be used when compacting by impact. Embedment density should be suitably monitored to ensure that specification requirements are met.

Density Checks

It is prudent to routinely check density of the embedment material. Typically, several checks are made during start-up of the project to ensure that the compaction procedure is achieving the desired density. Random checks are subsequently made to verify that the materials or procedures have not changed. Checks should be made at different elevations of the embedment material to assure that the desired compaction is being achieved throughout the embedment zone.

Trench Construction

Trenches should be excavated to line and grade as indicated by contract documents and in accordance with applicable safety standards. Excavation should precede upgrade. Excessive runs of open trench should be avoided to minimize such problems as trench flooding, caving of trench walls and the freezing of trench bottom and backfill material, and to minimize hazards to workmen and traffic. This can be accomplished by closely coordinating excavation with pipe installation and backfilling.

Principal considerations in trench construction are trench width, stability of the native soil supporting and containing the pipe and its embedment soil, stability of trench walls, and water accumulation in the trench. When encountering unstable soils or wet conditions, they should be controlled by providing an alternate foundation, sloping or bracing the trench walls, de-watering the trench bottom, or some other such measure.

Trench Width

Since flexible pipe has to support, at most, only the weight of the “prism” or vertical column of soil directly over the pipe, the precaution of keeping the trench as narrow as possible is not the concern that it is for a rigid pipe, which can be subjected to the weight of the soil beside the prism as well as the prism itself. With PE pipe, widening the trench will generally not cause a loading greater than the prism load on the pipe. Trench width in firm, stable ground is determined by the practical consideration of allowing sufficient room for the proper preparation of the trench bottom and placement and compaction of the pipe embedment materials, and the economic consideration of the costs of excavation and of imported embedment materials. Trench width in firm, stable ground will generally be determined by the pipe size and the compacting equipment used. The following table gives minimum trench width values.

The trench width may need to be increased over the values in Table 3 to allow for sufficient clearance between the trench sidewalls and the pipe for compaction equipment. Typically for large diameter pipe (18" and larger), this required clearance will vary from 12 to 18 inches. If two or more pipes are laid in the same trench, sufficient space must be provided between the pipes so that embedment material can be compacted.

TABLE 3
Minimum Trench Width in Stable Ground

Nominal Pipe Size (in.)	MinimumTrench Width (in.)
3 to 16	Pipe O. D. + 12
18 to 42	Pipe O. D. + 18
48 and larger	Pipe O. D. + 24

Trench Length

Table 4 lists the recommended lengths of trench openings for each placement of continuous lengths of fused pipe, assembled above the trench. When the trench sidewalls are significantly sloped, somewhat shorter trench openings may be used. When space or ground conditions do not permit these suggested trench openings, the pipe lengths may be joined within the trench, using a joining machine or flanged couplings. When bell-and-spigot jointed pipe or flange-end pipe is used, the trench opening needs to be only long enough to accommodate placement and assembly of a single pipe length.

TABLE 4
Suggested Length of Minimum Trench Opening (Feet) for Installation of Joined Lengths of Polyethylene Pipe

Nominal Pipe Size (in.)	Depth of Trench (Feet)					
	3	5	7	9	11	13
½ to 3	15	20	25	30	35	40
4 to 8	25	30	35	40	45	50
10 to 14	35	40	45	50	55	60
16 to 22	45	50	55	60	65	70
24 to 42	-	60	65	70	75	80
48	-	-	80	90	100	110

Stability of the Trench

Although the native soil in which PE pipe is installed need not be as strong and stiff as the pipe embedment materials, it should provide adequate support and stable containment of the embedment material so that the density of the embedment material does not diminish. If the trenching conditions present construction problems such as trench sidewalls that readily slough or a soft trench floor that will not support workers or compaction, it is termed unstable. The instability is usually a condition of the trench and not the soil. Most often the primary cause of the instability is high groundwater, not the soil. Even soft or loose soils can provide good support for the pipe if they are confined. The problem with unstable conditions generally occurs during the installation. When the trench is opened where groundwater is present, most soils, except firm, cohesive soils (firm clays) or cemented soils, tend to slough off the trench wall. This results in a trench that keeps widening, with loose material falling into the trench floor.

Soil formations that commonly lead to unstable trenching conditions include materials with fine grain soils (silts or clays) saturated with water and uncemented sands saturated with water. In some cases, where the soil has an extremely high water content, such as with peat or with clay (or silt) having a water content beyond the liquid limit, the soil behaves “hydraulically”, that is, the water in the soil controls the soil’s behavior. Here, the backfill must be designed to sustain all the pressure from the pipe without support from the in-situ soil. These conditions may occur in saturated fine grained soils where the unconfined compressive strength of the soil is less than 500 psf, or in saturated, sandy soils where the standard penetration value, N, is less than 6 blows per ft. In this case, an engineering evaluation should be made to determine the necessity for special procedures such as a “wide” trench or permanent trench sheeting of the trench width.

As mentioned above, most trench stability problems occur in trenches that are excavated below the groundwater level. (However, the designer and the contractor should keep in mind that all trenches pose the risk of collapse and therefore workers should not be in trenches that are not adequately braced or sloped.) Stability can be improved by lowering the water table through deep wells, well-points, or other such means. In some ground the permeability is such that the only option is to remove the water after it has seeped out of the trench walls. Here the contractor will use underdrains or sumps on the trench floor. De-watering should continue throughout the pipe laying operation until sufficient cover is placed over the pipe so that it will not float.

Stability of Trench Floor

Trench floor stability is influenced by the soils beneath the trench. The floor must be stable in order to support the bedding material. A stable bedding minimizes bending of the pipe along its horizontal axis and supports the embedment enveloping the pipe. Generally, if the trench floor can be walked on without showing foot prints it is considered stable.

In many cases the floor can be stabilized by simply dewatering. Where dewatering is not possible or where it is not effective, stabilization of the trench floor may be accomplished by various cost-effective methods which can be suited to overcome all but the most difficult soil conditions. Included among these are the use of alternate trench foundations such as wood pile or sheathing capped by a concrete mat, or wood sheathing with keyed-in plank foundation; stabilization of the soil by the use of special grout or chemicals; geofabric migration barriers; or ballasting (undercutting). A cushion of bedding material must be provided between any special foundation and the pipe. Permanently buried timber should be suitably treated.

Stabilization by ballasting (undercutting) is the removal of a sufficient quantity of undesirable material. This technique is frequently employed to stabilize randomly encountered short sections of unstable soil. The extent of required over-excavation and details of accompanying construction requirements will be determined by the engineer in consideration of the qualities of the unstable soil and the specific design requirements. The following are general guidelines:

The trench bottom should be over-excavated over the full trench width from 18 to 36 inches below the pipe grade (depending on the soil strength and pipe diameter) and then brought back to grade with a foundation of ballast material topped with Class I material. An appropriate bedding should then be placed on the foundation. The grading of the foundation material should be selected so that it acts as an impervious mat into which neither the bedding, other embedment material, nor the surrounding native soil will migrate.

These guidelines are suitable for most situations except for extremely weak soils (such as quicksands, organic silts, and peats) which may call for further overexcavation, or other special treatment.

Stability of Trench Walls

In order to control deflection, the embedment material must be placed from undisturbed trench sidewall to undisturbed trench sidewall. Where trench walls are unstable, it may be necessary to use trench shields, bracing, or permanent sheeting to achieve a stable sidewall while installing the pipe. Where material sloughs into the trench it should be removed. This technique often leads to widening the trench.

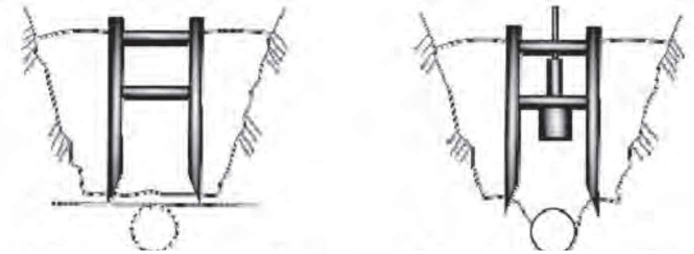
Walls of trenches below the elevation of the crown of the pipe should be maintained as vertical as possible. The shape of the trench above the pipe will be determined by the stability of the trench walls, excavation depth, surface loadings near the trench, proximity of existing underground structures, presence of groundwater or runoff water, safety and practical considerations. These will determine if the trench walls may be vertical, excavated with slope or benched sides, or shored. When trench walls are shored or otherwise stabilized, the construction scheme must allow for the proper placement and compaction of pipe embedment materials. Some suggested trench construction schemes follow. The final procedure must be in compliance with all applicable safety regulations.

Sloping of trench walls in granular and cohesionless soils should be provided whenever the walls are more than about four feet in depth or otherwise required by state, local or federal regulations. For safety, if the walls are not sloped, they should be stabilized by alternate means such as shoring or bracing. The slope should be no greater than the angle of repose of the materials being excavated and should be approved by the engineer.

Shoring or bracing will frequently be required in wet fine grained cohesive type soils and clays. Bracing or sheathing that is constructed of treated timber, steel or other acceptable material may be used to stabilize trench walls either permanently or temporarily. Wherever possible, sheathing and bracing should be installed so that its bottom extends no lower than about one-quarter of the pipe diameter below the pipe crown. When so installed, pulling the sheathing will minimally disturb the embedment material and the side support it provides. Sheathing that is installed to project below the pipe springline should be left in place unless, as with some thinner sheathing, it is designed to be pulled and removed without disturbing the embedment next to the pipe. In this case, the trench width should be increased by 12 to 24 inches depending on the pipe diameter to allow for minor disturbance to the embedment near the sheathing. Vibratory placement or extraction of sheeting is not advised. This method can cause severe disturbance to the bedding and liquefaction of the surrounding soils. Where steel sheet piling is used as sheathing and is to be removed or pulled, to minimize disturbance to the pipe embedment, it should be installed so that it is not closer than one pipe diameter or 18 inches, whichever is larger, from either side of the pipe. The void left by removal of the sheathing should be filled with embedment material.

Portable Trench Shield

Portable trench shields or boxes which provide a moveable safe working area for installing pipe can be used with flexible pipe. However, the installation technique of flexible pipe with the shield is not the same as it is for rigid pipe. In order to use the shield with PE pipe, all excavation of the trench below the pipe crown elevation should be done from inside of the shield. That is, the backhoe operator should dig inside of the shield and force the shield down as soil is removed. (The technique of digging out a large hole to pipe invert grade then sliding the shield into it will result in excess deflection of PE pipe.) After placing the pipe in the trench, embedment material should be placed in lifts and the shield vertically raised after each lift is placed so that workers can shovel embedment material under the shield to fill the void created by the shield wall. Figure 6 illustrates the steps used with a Portable Trench Shield.



A. Excavate and lower shield to pipe crown

B. Excavate below pipe crown from within shield

C. Place embedment

D. Lift shield in steps as embedment is placed

Figure 6 Installing PE Pipe with a Portable Trench Shield

If trench soil quality and applicable safety regulations permit, it is best to use shields that are placed with no portion of their sides extending lower than one-quarter of a pipe diameter below the pipe crown. This minimizes the amount of lifting required and precludes the possibility for disturbing embedment materials. If the sides of the trench box or shield do project below this point, then the box should be lifted vertically as described above, before moving along the trench.

The minimum inside clear width of the box, or shield, should allow for the minimum trench width requirements for the pipe to be satisfied plus an additional 12 to 24 inches depending on the pipe diameter.

Installation Procedure Guidelines

The following guidelines for the installation of PE pipe are based on the discussions of the previous sections. The reader is advised to see PPI Technical Report TR31 for more specific installation recommendations for solid wall SDR pipe. If the reader is interested in installing 24" or smaller pipes at 16 feet or less, see Appendix 1.

The installation procedure discussed in this section consists of trench floor preparation, providing a sufficiently stable working platform, and meeting the design grade requirements. Following pipe placement, backfill material which has been selected with regards to potential material migration, required density, depth of cover, weight of soil and surcharge loads is installed as follows:

1. Bedding material is placed and leveled.
2. Haunching is placed and, if required, compacted so as not to disturb the pipe from its line and grade.
3. The remainder of the primary initial backfill is placed and, if required, compacted in lifts.
4. Secondary backfill is used to protect the pipe during the final backfilling operation and also to provide support for the top portion of the pipe.
5. The final backfill may consist of any qualifying material that satisfies road construction or other requirements and, when required, must be compacted.

Trench Floor Preparation

The trench floor must have sufficient stability and load-bearing capacity to present a firm working platform during construction to maintain the pipe at its required alignment and grade and sustain the weight of the fill materials placed around and over the pipe. The trench bottom should be smooth and free from sloughed sidewall material, large stones, large dirt clods, frozen material, hard or soft spots due to rocks or low-bearing-strength soils, and any other condition that could lead to non-uniform or unstable support of the pipe. The trench bottom must be kept dry during installation of the pipe and the embedment materials. All foundation and bedding materials must be placed and compacted according to the design requirements. Such materials should be selected to provide the necessary migration control when required.

Over-excavation of the trench floor by more than 6 inches beyond grade requires that the over-excavation be filled with acceptable embedment material that is compacted to a density equal to that of the embedment material. If the over excavation exceeds 12 inches, it should be brought to proper grade with a suitably graded Class I or II material that is compacted to the same density as that of the native soil but not less than the density requirements for the embedment materials.

In stable soils the trench floor should be undercut by machine and then brought up to proper grade by use of a well-leveled bedding consisting of a 4 to 6-inch layer of embedment material. This material should be compacted by mechanical means to at least 90 percent Standard Proctor Density. Class I material may be shovel sliced where the depth of cover permits.

In unstable soils that may be too soft, of low load-bearing capacity or otherwise inadequate, the trench bottom must first be stabilized by soil modification, by providing an alternate foundation, or by the removal of the undesirable material and replacement with stable foundation material. A cushion of at least 4 inches of compacted bedding should be provided between any special foundation and the pipe. Adequacy of trench bottom stability is difficult to evaluate by visual observation and is therefore best determined by soil tests or at the site during installation. However, a warning of a potentially unstable soil condition is given by a trench bottom that cannot support the weight of workmen.

Uneven soil support conditions, where the grade line traverses both soft and hard spots, requires special consideration. Ballasting is the most frequently employed technique to deal with randomly encountered short sections of soft soils.

When differential conditions of pipe support might occur, such as in transitions from manholes to trench or from hard to soft soils, a transition support region should be provided to ensure uniform pipe support and preclude the development of shear, or other concentrated loading on the pipe. The following procedure may be used:

The soil next to the more rigid support is over-excavated to a depth of not less than 12 inches over a distance of 2 pipe diameters along the pipe line; over the next 2 diameters away from the rigid support, the depth of over-excavation is gradually decreased until it meets the normal trench depth. See Figures 7 and 8. Pipe grade is then restored by the addition of granular material that is compacted. In the case of connections to manholes and buildings, the distance of over-excavation along the pipe length should be no less than required to reach undisturbed soil.

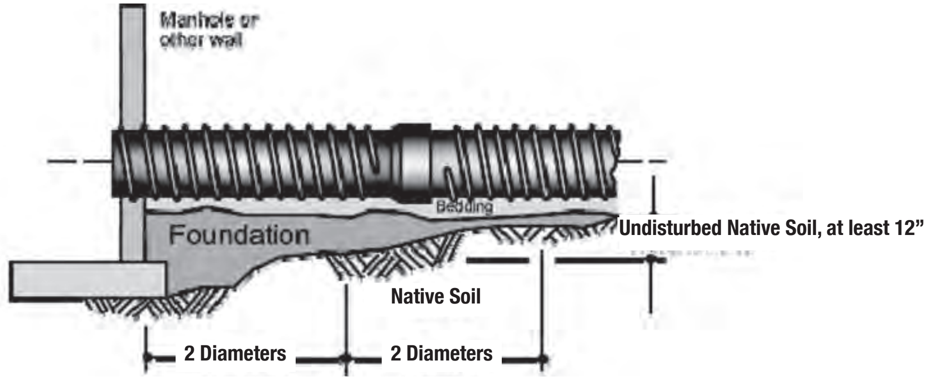


Figure 7 Pipe Support in Transition from Rigid Support to Normal Trench Support

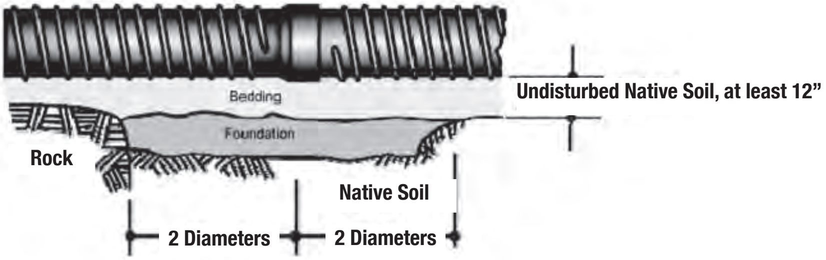


Figure 8 Proper Transition from Rock Trench Bottom to Normal Trench Support

Backfilling and Compaction

Backfilling should follow pipe placement and assembly as closely as possible. Such practice prevents the pipe from being shifted out of line by cave-ins, protects the pipe from external damage, eliminates pipe lifting due to flooding of open trench and in very cold weather lessens the possibility of backfill material becoming frozen. The quality of the backfill materials and their placement and compaction will largely determine the pipe's ultimate deformation and alignment. Backfill material should be selected with consideration of potential material migration to, or from, the trench wall and other layers of embedment material. Under most circumstances, compaction will be required for all material placed in the trench from 6 inches beneath the pipe to at least 6 inches above the pipe.

The required density of the bedding, haunching and the primary and secondary initial backfill material will depend on several considerations such as depth of cover, weight of soil, and surcharge loads. The minimum density for these materials should be equal to 85 percent Standard Proctor Density for Class I and II materials or 90 percent Standard Proctor Density for Class III or IVa materials. For Class II,III, and IVa materials, compaction will always be required to obtain these densities.

Class I material placed by shovel slicing will generally have a minimum density of 85 percent Standard Proctor; however, its E′ may not be greater than 750 psi. Just dumping Class I material into the trench may produce densities near 85 percent. However, except in shallow cover without live loads, this method will normally not provide adequate support to the pipe as voids may exist under the pipe haunches or elsewhere in the material.

Backfill Placement

Bedding performs a most important function in that it levels out any irregularities in the trench bottom, assuring uniform support and load distribution along the barrel of each pipe section and supports the haunching material. A mat of at least 6 inches of compacted embedment material will provide satisfactory bedding.

Haunching material must be carefully placed and compacted so as not to disturb the pipe from its line and grade while ensuring that it is in firm and intimate contact with the entire bottom surface of the pipe. Usually a vibratory compactor has less tendency to disturb the pipe than an impact tamper.

Primary initial backfill should be placed and compacted in lifts evenly placed on each side of the pipe. The lifts should not be greater than 12 inches for Class 1, 8 inches for Class II, and 6 inches for Class III and IVa materials. The primary initial backfill should extend up to at least three-quarters of the pipe diameter to perform its function of pipe side support as shown in figure 2. If the construction does not call for the use of a secondary initial backfill, then the primary layer should extend to not less than 6 inches above the pipe crown. In any location where the pipe may be covered by existing or future groundwater, the primary initial backfill should extend up to at least 6 inches over the pipe crown for pipe up to 27-inch diameter and to at least 12 inches over the pipe for larger pipe.

Secondary initial backfill serves to protect the pipe during the final backfilling operation and to provide support to the top portion of the pipe. Secondary initial backfill should extend to 6 inches above pipe for pipe up to 24 inches and to 12 inches for larger pipe. These depths can be modified slightly depending on the depth of burial, groundwater level, and type of native soil. Compaction of this layer should be to the same extent as that specified for the primary initial backfill. If the final backfill material contains large rock (boulder or cobble size) or clumps, then 18 inches of cushion material should be provided in the secondary initial backfill. Secondary initial backfill may consist of a different material than the primary initial backfill; however, in most cases, it should be a material that will produce an E′ of at least 750 psi.

The final backfill may consist of any material that satisfies road construction or other requirements. The material must be free of large stones or other dense hard objects which could damage the pipe when dropped into the trench or create concentrated pipe loading. The final backfill may be placed in the trench by machines.

There should be at least one foot of cover over the pipe before compaction of the final backfill by the use of self-powered compactors. Construction vehicles should not be driven over the pipe until a three foot cover of properly compacted material is placed over the pile.

When backfilling on slopes, the final backfill should be well compacted if there is any risk of the newly backfilled trench becoming a "french drain." Greater compaction may be achieved by tamping the final backfill in 4 inch layers all the way from the top of the initial backfill to the ground or surface line of the trench. To prevent water from undercutting the underside of the pipe, concrete collars keyed into the trench sides and foundation may be poured around the pipe or a polyethylene waterstop can be fabricated onto the pipe.

Proper Burial of HDPE Fabricated Fittings

A common question is "Does the installation of heat fused polyethylene solid wall pipe and fittings need thrust blocks?" The simple answer to this question is that heat fused HDPE pipe and fittings are a monolithic structure which does not require thrust blocks to restrain the longitudinal loads resulting from pipe pressurization.

Since fittings are part of the monolithic structure no thrust blocks are needed to keep the fittings from separating from the HDPE pipe. Bell and spigot piping systems must have thrust blocks or restrained joints to prevent separation of pipe from fittings when there is a change of direction.

Pipe movement due to elastic deformation, thermal expansion/contraction, etc. is not detrimental to HDPE pipe, but pipe movement or the attachment of valves or other appurtenances used with HDPE pipe systems can cause excessive loads. Proper backfill prevents excessive loads in most situations.

Common fittings, elbows and equal tees normally require the same backfill as specified for the pipe. When service connections are made from HDPE water mains, no special compaction is required. When service connections are made under an active roadway, 95% Standard Proctor density is normally required around the pipe and the service connection.

In water systems and fire protection piping systems, reducing tees are frequently used to connect from the main to valves and hydrants. The attached drawing shows the use of concrete support pads, thrust blocks on hydrants, self restrained HDPE MJ adapters and sand stabilized with cement around the reducing tee. While no true thrust blocks are on the HDPE pipe or fittings in this arrangement, the sand stabilized with cement provides proper support for the reducing tee. Compaction of the soil around these fittings is difficult and the use of sand stabilized with cement or flowable fill is usually easy.

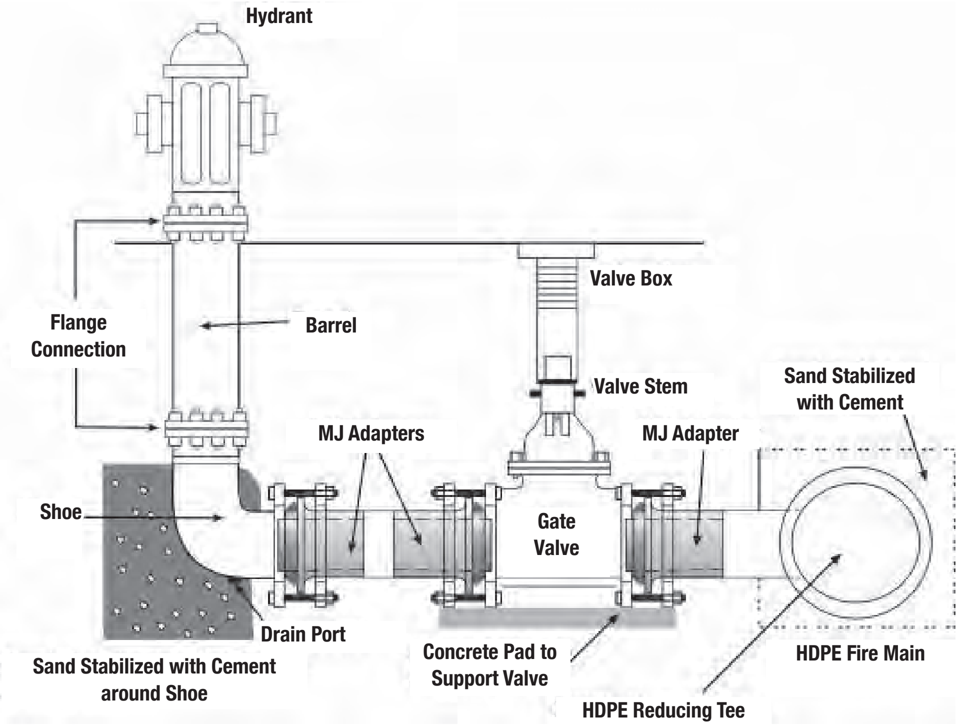


Figure 9 Mechanical Joint (MJ) Adaptor

As with all piping systems, proper compaction of the soil around pipe and fittings is important. In water and/or fire protection systems, when in-situ embedment materials can be compacted to a Standard Proctor density of 85% for installation outside of roadways or 95% Standard Proctor density in roadways, these materials should be used. When in-situ materials do not provide proper support, then sand stabilized with cement or flowable fill should be used.

Figure 9 shows an HDPE self-restrained mechanical joint (MJ) adapter being used to connect to the valve. When large reducing tees or equal tees are used, MJ adapters, flanges or electrofusion couplings should be fused to the reducing tees before it is placed in the trench. The direct connection of long pipe sections or valves can create bending loads on the leg of the reducing tee. The use of MJ's, flanges or electrofusion couplings on the reducing leg of the tee makes installation of reducing tees easier and safer while preventing stresses on the tee.

Inspection

One principal function of the inspector is to insure that the pipe meets the acceptance deflection specified by the engineer. Besides seeing that the installation practice of the contractor meets the specification, the inspector should periodically make deflection measurements of the pipe. Where the pipe can be accessed, inspection can be as simple as going through the pipe and taking diameter measurements. For smaller pipe, a mandrel or deflection measuring device can be pulled through the pipe.

Good installation practice consists of frequent deflection checks at the beginning of the project or anywhere there is a significant change in the installation procedure, soil formation, or materials. A prudent contractor will check deflection every 100 or 200 feet under these circumstances. After the contractor is confident in the procedure, the frequency of inspection can be relaxed.

Typically, acceptance deflection is measured after the pipe has been installed for at least 30 days. This gives the soil time to settle and stabilize. Where pipe exceeds its acceptance limit, it should be uncovered and the embedment material should be replaced and compacted.

References

1. Watkins, R. K. (1975). *Buried Structures*, Foundation Engineering Handbook (edited by H. F. Winterkom and H. Y. Fang), Van Nostrand Reinhold Co., New York, NY.
2. Spangler, M. G. (1951). *Soil Engineering,* International Textbook Co., Scranton, PA.
3. Howard, A. K. (1981). *The USBR Equation for predicting Flexible Pipe Deflection,* Proc. Int. Conf. on Underground Plastic Pipe, ASCE, New Orleans, LA.
4. Howard, A. K. (1972, January). *Modulus of Soil reaction Values for buned Flexible Pipe,* Joumal of the Geotechnical Engineering Division, ASCE, Vol. 103, No. GT1, pp. 3346.

Appendix 1

Simplified Installation Guidelines for Pressure Pipe

(Small diameter pressure pipes usually have adequate stiffness and are usually installed in such shallow depths that it is unnecessary to make an internal inspection of the pipe for deflection.)

A quality job can be achieved for most installations following the simple steps that are listed below. These guidelines apply where the following conditions are met:

1. Pipe Diameter of 24-inch or less
2. SDR equal to or less than 26
3. Depth of Cover between 2. 5 feet and 16 feet
4. Groundwater elevation never higher than 2 feet below the surface
5. The route of the pipeline is through stable soil

Stable soil is an arbitrary definition referring to soil that can be cut vertically or nearly vertically without significant sloughing, or soil that is granular but dry (or de-watered) that can stand vertical to at least the height of the pipe. These soils must also possess good bearing strength. (Quantitatively, good bearing capacity is defined as a minimum unconfined compressive strength of 1000 psf for cohesive soils or a minimum standard penetration resistance of 10 blows per ft for coarse grained soils.) Examples of soils that normally do not possess adequate stability for this method are mucky, organic, or loose and wet soils.

Where the above conditions are met, the specifier can write installation specifications from the following steps. The specifier should insure that all OSHA, state and local safety regulations are met.

The following are general guidelines for the installation of PE pipe. Other satisfactory methods or specifications may be available. This information should not be substituted for the judgment of a professional engineer in achieving specific requirements.

Simplfied Step-by-Step Installation

Trenching

Trench collapses can occur in any soil and account for a large number of worker deaths each year. In unbraced or unsupported excavations, proper attention should be paid to sloping the trench wall to a safe angle. Consult the local codes. All trench shoring and bracing must be kept above the pipe. (If this is not possible, consult the more detailed installation recommendations.) The length of open trench required for fused pipe sections should be such that bending and lowering the pipe into the ditch does not exceed the manufacturer's minimum recommended bend radius and result in kinking. The trench width at pipe grade should be equal to the pipe outer diameter (O. D.) plus 12 inches.

De-watering

For safe and proper construction the groundwater level in the trench should be kept below the pipe invert. This can be accomplished by deep wells, well points or sump pumps placed in the trench.

Bedding

Where the trench bottom soil can be cut and graded without difficulty, pressure pipe may be installed directly on the prepared trench bottom. For pressure pipe, the trench bottom may undulate, but must support the pipe smoothly and be free of ridges, hollows, and lumps. In other situations, and for gravity drain or sewer pipe, bedding may be prepared from the excavated material if it is rock free and well broken up during excavation. For gravity flow systems, the trench bottom should be graded evenly. The trench bottom should be relatively smooth and free of rock. When rocks, boulders, or large stones are encountered which may cause point loading on the pipe, they should be removed and the trench bottom padded with 4 to 6 inches of tamped bedding material. Bedding should consist of free-flowing material such as gravel, sand, silty sand, or clayey sand that is free of stones or hard particles larger than one-half inch.

Pipe Embedment

Figure 1 shows trench construction and terminology. Haunching and initial backfill are considered trench embedment materials. The embedment material should be a coarse grained soil, such as gravel or sand, or a coarse grained soil containing fines, such as a silty sand or clayey sand. The particle size should not exceed one-half inch for 2 to 4-inch pipe, three-quarter inch for 6 to 8-inch pipe and one inch for all other sizes. Where the embedment is angular, crushed stone may be placed around the pipe by dumping and slicing with a shovel. Where the embedment is naturally occurring gravels, sands and mixtures with fines, the embedment should be placed in lifts, not exceeding 6 inches in thickness, and then tamped. Tamping should be accomplished by using a mechanical tamper. Compact to at least 85 percent Standard Proctor density as defined in ASTM D-698. Under streets and roads, increase compaction to 95 percent Standard Proctor density.

Pressure Testing

If a pressure test is required, it should be conducted after the embedment material is placed.

Trench Backfill

The final backfill may consist of the excavated material, provided it is free from unsuitable matter such as large lumps of clay, organic material, boulders or stones larger than 8 inches, or construction debris. Where the pipe is located beneath a road, place the final backfill in lifts as mentioned earlier and compact to 95 percent Standard Proctor Density.

Appendix 2

Guidelines for Preparing an Installation Specification General Requirements

General Requirements

Subsurface conditions should be adequately investigated and defined prior to establishing final project specifications. Subsurface investigations are necessary to determine types of soil that are likely to be encountered during construction, existence of rock, thickness of strata layers, relative quality of strata layers, presence of other utilities, and presence of ground water. These findings are useful both in specifying the proper pipe for an application and in planning construction procedures.

Prior to start of construction the on-site surface conditions, including water run-off, traffic and other problems should be appraised by on-site inspections of the proposed pipeline location. Addtionally, all the construction documents, including plans, subsoil information and project specifications should be reviewed. All required permits should be obtained and arrangements made to insure compliance with all applicable federal, state, and local safety regulations.

The installation should be checked throughout the construction period by an inspector who is thoroughly familiar with the contract specifications, materials and installation procedures. The inspection should ensure that significant factors such as trench depth, width, grade, pipe foundation, quality and compaction of embedment and backfill comply with contract requirements.

The following specification may be used for most gravity drain projects in stable or de-watered trenches. Where special methods of stabilization are required as discussed previously, a more detailed specification may be required.

Guide Specification High Density Polyethylene (Hdpe) Gravity-drain Pipe (F-894 Pipe)

Various construction techniques can be used for installing PE pipe. The techniques described below are considered satisfactory, but there may be other techniques which will work equally as well. The information below is considered reliable, but the author makes no warranty, expressed or implied, as to the content, and disclaims all liability therefor. This information should not be substituted for the judgment of a professional engineer in achieving specific requirements.

General

Scope

The work covered by this section includes furnishing all labor, equipment, and materials required to supply, install, and test high-density polyethylene (HDPE) pipe, including accessories, as shown on the drawings and/or specified herein.

Quality Assurance

- The Contractor shall submit to the Engineer in writing that the pipe furnished under this specification is in conformance with the material and mechanical requirements specified herein.
- Each HDPE pipe length shall be clearly marked with the following:

1. Manufacturer's Name
2. Pipe Size
3. SDR or Ring Stiffness Constant Classification
4. Production Code Designating Plant Location, Machine, and Date of Manufacture

Shop Drawings

Complete shop drawings on all piping and accessories shall be submitted to the Engineer.

Storage

All pipe and accessories shall be stored on flat, level ground with no rocks or other objects under the pipe.

The maximum recommended stacking height for HDPE pipe is given in Table A2. 1

TABLE A2. 1
Allowable Stacking Heights for F-894 Pipe

Nominal Pipe Size	Number of Rows High
18	4
21	4
24	3
27	3
30	3
33	2
36	2
42	2
48	1
54	1
<54	1

Products

General

Apart from the structural voids and hollows associated with some profile wall designs, the pipe and fittings shall be homogenous throughout and free from visible cracks, holes, foreign inclusions or other injurious defects. The pipe shall be as uniform as commercially practical in color, opacity, density, and other physical properties.

High-Density Polyethylene (HDPE) Pipe

HDPE Profile wall pipe and fittings shall be manufactured in accordance with the requirements of (Engineer: specify appropriate ASTM designation here. For profile pipe designate ASTM F 894-85. For solid wall DR pipe designate ASTM F 714.)

HDPE profile wall pipe shall be made from a plastic compound meeting the requirements of Type III, Class C, Category 5, Grade P34 as defined in ASTM D 1248 and with an established hydrostatic design basis (HDB) of not less than 1250 psi for water at 73.4°F, determined in accordance with method ASTM D 2837. Materials meeting the requirements of cell classification PE 345464C or higher cell classification in accordance with ASTM D-3350 are also suitable. (Engineer: specify appropriate HDB and Cell class as underlined above.)

Material other than those specified above may be used as part of the profile wall construction, for example, as a core tube to support the shape of the profile during the processing, provided that these materials are compatible with the PE material, are completely encapsulated in the finished product, and in no way compromise the performance of the PE pipe product in the intended use.

Execution

Pipe Laying

A. Before the sewer pipe is placed in position in the trench, the bottom and sides of the trench shall be carefully prepared, the required bedding placed, and bracing and sheeting installed where required. The trench shall be excavated to the dimensions shown on the Engineer's drawings. Each pipe shall be accurately placed to the line and grade called for on the drawings. Grade shall be controlled by a laser beam or batter boards and a Mason's line. All equipment for maintaining grade shall be furnished by the Contractor.

B. All pipe and fittings shall be inspected before they are installed.

C. Pipe laying shall proceed upgrade, starting at the lower end of the grade with the bells uphill.

D. If the trench bottom does not provide a firm and stable working platform, sufficient material shall be removed and replaced with approved compacted materials to provide a firm foundation for the pipe.

E. Pipe trenches shall be kept free from water during pipe laying, jointing and until sufficient backfill has been placed to prevent flotation of the pipe. The minimum height of backfill to prevent flotation may be obtained from the Engineer. The Contractor may use sump pumps, well points, or other devices to remove water from the trench bottom. Small puddles that are no closer than 4" from the bottom of the pipe are acceptable. The contractor shall provide ample means and devices to promptly remove and dispose of all water from any source entering the trench.

F. No connection shall be made where joint surfaces and joint materials have been soiled by dirt in handling until such surfaces are thoroughly cleaned by washing and wiping.

G. As the work progresses, the interior of all pipes shall be kept clean. After each line of pipe has been laid, it shall be carefully inspected and all soil, trash, rags, and other foreign matter removed from the interior.

H. Backfilling of trenches shall be started immediately after the pipe is placed in the trench.

I. If the Engineer determines that no groundwater will be encountered or that the maximum height of the groundwater level (from seepage or other groundwater movement through the existing soil formation or the pipe trench) will not exceed the springline of the pipe during the service life of the line, the pipe shall be backfilled according to detail drawing Figure A1 titled "Dry Installation Bedding Requirements. "

J. If the Engineer determines that groundwater will be encountered or that the ground water level is anticipated to exceed the springline of the pipe during the service life of the line, backfill pipe according to the detail drawing Figure A2, titled "Wet Installation Bedding Requirements. "

K. Shoring, sheeting, or trench shields shall be utilized in such a manner as to minimize disturbance of the backfill material beneath the pipe crown. Trench sheeting that extends below the crown should either be left permanently in place or consist of adequately supported steel sheets 1" (one inch) thick or less which can be extracted with minimal disturbance to the pipe embedment. Where moveable trench shields are used, the following steps shall be followed unless an alternate technique that does not disturb the pipe embedment can be demonstrated:

   1. Excavation of the trench below the elevation of the pipe crown shall be done from inside of the trench shield to prevent the accumulation of loose or sloughed material along the outside of the shield. Excavation of the trench ahead of the shield at an elevation below the pipe crown is not permitted unless approved by the Engineer.

   2. After laying the pipe in the trench, bedding and pipe embedment shall be placed in lifts and the shield must be lifted in steps. As the shield is lifted, embedment material shall be shoveled under the shield so as to fill all voids left by the removal of the shield.

L. Bedding Material. Bedding material to be selected by Engineer. (Note to Engineer: Bedding material to be selected by evaluating depth of cover and E′ required to control deflection and buckling.)

When E' = 1,000 is required:
Specify Class I material shovel sliced to a minimum density of 85 percent Standard Proctor, or Class II material with mechanical compaction to a minimum density of 90 percent Standard Proctor, or Class III material with mechanical compaction to a minimum density of 90 percent Standard Proctor. (Embedment Classes are defined in ASTM D-2321.)

When E' = 2,000 is required:
Specify Class I or Class II material with mechanical compaction to a minimum density of 90 percent Standard Proctor.

When E' = 3,000 is required:
Specify Class I material with mechanical compaction to a minimum density of 90 percent Standard Proctor.

M. Backfill material placed under the pipe haunches shall be thoroughly shovel sliced along the length of the pipe.

N. Where compaction of backfill materials is required, compact by mechanical means. Suitable mechanical means includes vibratory sleds, gasoline driven impact tampers, and air driven impact tampers or other approved means. Compact to a minimum of 90 percent Standard Proctor or as required by the Engineer.

O. Pipe embedment soil shall be placed in lifts as follows:

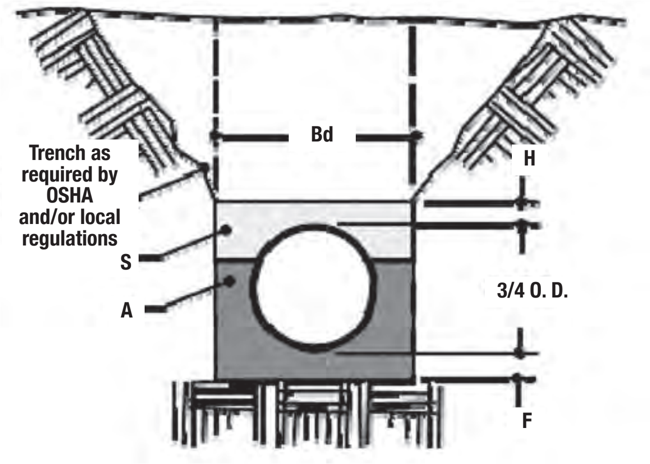
- Lift thickness for Class I material shall not exceed 12 inches.
- Lift thickness for Class II material shall not exceed 8 inches.
- Lift thickness for Class III material shall not exceed 6 inches.

P. After completing backfill in the pipe zone, the trench shall be backfilled to grade with native soil. Where pipe is located beneath streets, compact backfill to a minimum of 95 percent Standard Proctor or otherwise as directed by the Engineer. HDPE profile pipe shall not be subject to a roller or wheel loads until a minimum of one pipe diameter or 36″ (whichever is larger) of backfill has been placed over the top of the pipe and a hydrohammer shall not be used until a minimum depth of one pipe diameter or 48″ (whichever is larger) of backfill has been placed over the top of the pipe.

Connections

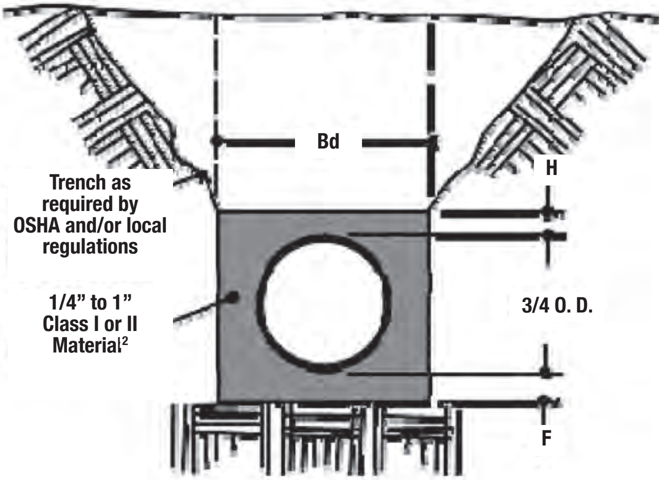
A Connections to existing lines shall be made by coupling a piece of smooth O. D. HDPE pipe to the existing line. The coupling shall be a flexible elastomeric boot with stainless steel clamps. The coupling is to be encased in cement-stabilized sand, grout, or concrete.

B. Connections to concrete manholes shall be made using smooth O. D. pipe and water stops, profile pipe cast into the concrete, or via elastomeric sleeves or gaskets precast in the manhole. Since the particular technique used is highly dependent on the construction method, these connections cannot be guaranteed by the manufacturer to be leak free.



A = ¼” to 1” Class I, II, or III Material
If cover < 18 ft – shovel slice
If cover > 18 ft – compact to at least 90% Standard Proctor per ASTM D-698
If cover > 24 ft – use wet installation bedding requrirements (Figure A2).
S = Selected earth backfill compacted to at least 90% Standard Proctor per ASTM D-698.
H = 6 inches for 18” to 36” pipe
= 12 inches for 42” to 84” pipe
= 18 inches for 96” to 120” pipe
F = 4 inches for 18” to 36” pipe
= 6 inches for 42” to 84” pipe
= 8 inches for 96” to 120” pipe
Bd = OD + 18”– see Table 3
= OD + 18 inches for 18” to 36” pipe
= OD + 24 for 36” to 60” pipe
= OD + 36 for 66” to 84” pipe
= OD + 48 for 96” to 120” pipe

Figure A1 Dry[1] Installation Bedding Requirements for HDPE Profile Wall Pipe
([1]Pipe springline elevation permanently above groundwater)



Compact Class I or Class II Material² to a minimum of 90% Standard Proctor per ASTM D-698.

H = 6 inches for 18" to 36" pipe
= 12 inches for 42" to 84" pipe
= 18 inches for 96" to 120" pipe
F = 4 inches for 18" to 36" pipe
= 6 inches for 42" to 84" pipe
= 8 inches for 96" to 120" pipe
Bd = OD + 18" – see Table 3
= OD + 18 inches for 18" to 36" pipe
= OD + 24 for 36" to 60" pipe
= OD + 36 for 66" to 84" pipe
= OD + 48 for 96" to 120" pipe
See section in this appendix titled "Pipe Laying"

Figure A2 Wet[1] Installation Bedding Requirements for HDPE Profile Wall Pipe
([1]Pipe springline elevation permanently above groundwater)
([2]Selection of bedding material to be made by Engineer based on pipe design requirements)
See section in this appendix titled "Pipe Laying."

C. Connections to HDPE manholes shall be made using closure pieces with shoulder gaskets.

Pipe Tunnels and Casing

A. The annular space between HDPE pipe and the casing pipe shall be filled with concrete grout. (Engineer: Grout is required where the pipe's allowable hydrostatic buckling resistance is less than the water pressure created by groundwater entering the casing.) The Contractor's procedure for placing the grout shall be approved by the Engineer. After installation of pipe in casing, the casing shall be kept dewatered until grouting is completed. Grout shall be placed by gravity flow only. Do not pressure grout PE pipe in a casing.

Inspection and Testing

A. After completion of any section of sewer, the grades, joints, and alignment shall be true to line and grade. There shall be no visual leakage, and the sewer shall be completely free from any cracks and from protruding joint materials, deposits of sand, mortar or other materials on the inside to the satisfaction of the Engineer.

B. At the Engineer's request, a deflection test shall be performed by the Contractor. The deflection can be measured mechanically by a mandrel or manually using an extension ruler. The final deflection test shall not be made on a section of sewer until all the backfill on that section has been in place for 30 days. However, the Contractor shall perform the deflection test on the first 300 – 400 feet of pipe after it has been backfilled in order to verify that the installation procedures are adequate to meet the requirements of the contract. No additional pipe shall be laid until this test has been successfully completed. Pipe deflection may be determined by direct vertical measurement of no less than 4 equally spaced points in each pipe section or by pulling a mandrel.

For solid wall PE pipe, deflection shall not exceed 5 percent of the I. D. For profile pipe, deflection shall not exceed 5 percent of the base I. D. as indicated in Table A2. 2.

All excess deflections shall be corrected. The Contractor shall correct the deficiency and retest the pipe.

TABLE A2. 2
Minimum Acceptable Diameter

Nominal Pipe Size (in.)	Base I. D. (in.)	Minimum Acceptable Diameter 5% of Base I. D. (in.)
18	17.34	16.47
21	20. 26	19.25
24	2319	22.03
27	26.11	24.80
30	29.02	27.57
33	31.94	30.34
36	34.86	33.12
42	40.67	38.64
48	46.48	44.16
54	52.29	49.68
60	58.10	55.20
66	63.91	60.71
72	69.72	66.23
84	81.34	77.27
96	92.96	88.31

C. The Contractor shall conduct either an infiltration test or a water test for leakage as determined by the Engineer. Testing shall be conducted in accordance with all applicable safety standards.

1. **Infiltration Test**
   Infiltration shall not exceed 50 gallons per 24 hours per inch of diameter per mile of sewer. Contractor shall furnish all supplies, materials, labor, service, etc. , needed to make infiltration or exfiltration tests including water. No separate payment will be made for equipment, supplies, material, water, or services.

   Any leakage, including active seepage, shall be corrected where such leakage exists until the pipeline meets the requirements of the allowable leakage specifications.

   Infiltration tests shall be made when groundwater level is 18 inches or more above the top of the outside of the pipe.

2. **Water Test**
   When normal groundwater does not stand at a level outside the pipe so as to enable infiltration tests to be made to the satisfaction of the Engineer, the Contractor shall make exfiltration tests by filling the pipe or sections thereof with water to a head of not less than 2 ft. above the top of the outside of the pipe and observing the amount of water required to maintain this level.

Cleanup

A. After completing each section of the sewer line, the Contractor shall remove all debris, construction materials, and equipment from the site of the work, then grade and smooth over the surface on both sides of the line and leave the entire right-of-way in a clean, neat, and serviceable condition.

Appendix 3

Basic Soil Concepts For Flexible Pipe Installation

Soil Classification

The embedment soil surrounding a flexible pipe prevents pipe from deflecting through its shear strength and stiffness. Shear strength enables the soil to resist distortion much like a solid body. Shear strength, or shear resistance as it is often called, arises from the structure of the soil's fabric. Soil is an assemblage of (1) mineral particles such as silica or aluminum silicates, (2) water, and (3) air. Mineral particles can range in size from the large, such as boulders, to the microscopic, such as the colloidal particles making up clay. The size of the individual soil particles or grains has a significant effect on the soil's behavior. Embedment soil is classified as either "fine" grained or "coarse" grained.

Fine Grain Soil (Clay and Silt)

Very small (colloidal) size soil particles are capable of absorbing large quantities of water, as much as 10 times their own weight. These particles attract each other to produce a mass which sticks together. This property is called cohesion or plasticity. Soils containing such particles are referred to as "cohesive" and include clayey soils. Cohesion gives clayey soils resistance to shear. The strength of clayey soils is dependent on the amount of water within the soil. As the content of water increases, the shear resistance decreases. Therefore, when using clays as pipe embedment beneath the ground water level, one must examine its sensitivity to water. Fat clays (CH), which are highly expansive, usually make poor embedment materials. (CH is the USCF soil classification symbol for fat clay.) Lean clays (CL), or other clays having relative low sensitivity to water, sometimes can be used for embedment.

While silts possess little to no cohesion, they are composed of very fine grains, which makes them behave somewhat like clay in that they can contain a high percentage of water. It is also common for silt and clay to occur together. Therefore, the general classification schemes for pipe embedment usually treat silts and clays similarly. (USCF symbols for inorganic silts are ML and MH, and for organic silts OL and OH.)

Coarse Grain Soils

Assemblages of larger-sized particles such as sands (S) and gravels (G) do not exhibit plasticity. Water has less effect on these materials. These soils are called “cohesionless” or “granular. ” Normally, cohesionless soils have high shear resistances. When a mass of cohesionless soil is sheared, individual grains either roll, slide, fracture, or distort along the surface of sliding. Likewise, many cohesive soils contain grains of sand, so they can exhibit significant shear resistance. These materials make excellent embedment in wet or dry conditions.

Density and Compaction

When discussing the installation of embedment material, two terms are use extensively. They are compaction and density. These terms are defined, herein, to assist the reader.

Density refers to the weight of a particular volume of soil As discussed above, soil consists of three materials or phases: a mineral phase, water, and air. As the soil is compacted, the mineral phase may undergo some change, but typically the air and water are expelled from the soil and the overall volume is reduced. The weight of the mineral phase stays the same. Thus, a given weight of mineral phase occupies a smaller volume after compaction. Typically, when densities are given, they are based on the dry unit weight of the soil (which is the weight of the mineral phase only) occupying a given volume, say a cubic foot.

Compaction, on the other hand, refers to the amount of energy imparted into the soil to reduce its volume. Typically, more energy, often called compactive effort, is required to increase the density of a fine grain soil than a coarse grain soil. One reason for this is that the fine grain soil has cohesion which must be overcome in order for the mineral phase particles to be pushed closer together. Another reason is that it is harder to force the water out of a fine grain material because of its low permeability.

Methods of Measuring Density

There are two general categories of density measures. One method involves imparting a standard amount of energy into the soil, say a fixed number of blows with a specified weight. The Standard and Modified Proctor density tests are such methods. The other measure involves comparing the in-place density with the most dense and least dense arrangement that can be achieve with that soil. An example of this method is the Relative Density test.

The Proctor Density is the most common method used with pipe embedment and will be discussed in somewhat more detail. Typically, a soil sample is taken from the embedment material and tested in the laboratory, where a precisely defined amount of compaction energy is applied to it, which compacts the sample to its

Proctor density. (This amount of energy is defined by the particular Proctor test, whether it is the Standard Proctor defined in ASTM D-698 or the Modified Proctor defined in ASTM D-1599. It is essentially independent of the soil type.) The sample is then dried and its density measured. This density is the standard for this material and is considered to be 100 percent of the Proctor density. The technician then makes measurement of the density (dry unit weight per cubic ft.) of the compacted embedment in the field using, say, the nuclear density gauge. That density can then be compared with the density obtained in the laboratory. The comparison is usually expressed in percent. Typically, the field density must be at least 90 percent of the laboratory density. In this case, we would say the minimum density is 90 percent of the Proctor.

For pipe installation, the important factor is soil stiffness. If two soils are compacted to the same Proctor density, that does not mean that the two soils provide equal supporting stiffness for the pipe. A crushed stone at 90 percent Proctor will be much stiffer than a clay compacted to 90 percent Proctor. This fact is illustrated by the different E′ values assigned to these materials at these densities. In the case of the crushed stone its E′ equals 3000 psi, whereas the clay has an E′ of only a 1000 psi. Methods used to measure soil stiffness such as the California Bearing Ratio test are not convenient for field testing of pipe Therefore, it is common to measure and monitor density.

Comparison of Installation of Rigid and Flexible Pipe

The underground installation of PE piping is similar to the installation of other piping materials. The performance of the pipe will depend on the quality of the installation. Most PE piping is considered flexible, which means that the pipe will depend to some extent on the support of the embedment soil. Often the installation of flexible pipe is contrasted with the installation of rigid pipe, but general requirements for both types of pipe are similar. A narrow trench keeps loads on both types of pipe at a minimum. Both pipes require firm, stable bedding and uniform support under the haunches. The major difference between the two types of pipes is that the flexible pipe requires side support, whereas the rigid pipe does not. Side support comes from the placement of firm, stable material beside the pipe. Often this is the same material used beside the rigid pipe with the exception that the material must be compacted. Sufficient space alongside the pipe must be provided for compacting the embedment material. The trench backfill placed above the pipe can be treated in the same manner for both flexible and rigid pipe. The denser the material above the pipe, the smaller the load applied to the pipe.

PE pipe interacts advantageously with the embedment soil. The viscoelastic properties of PE and most soils are similar. As the pipe deflects, much of the earth is transmitted by arching action to the soil around the pipe. Thus the need for stable soil beside the pipe. Rigid pipe is typically manufactured from materials that are not compliant with soil deformation. As the soil settles, load accumulates on the rigid pipe. If this load exceeds the pipe materials' yield strength, the pipe will fail by a sudden rupture or crack. PE is a ductile material that can yield. Under excessive loads, PE pipe will deform without cracking. The deformation is often sufficient to relieve the accumulated stresses, so performance is not interrupted.

Deflection is usually the main criterion for judging the performance of a flexible pipe. Pipes that deflect have two advantages over rigid pipe: (1) the deflection permits the release of accumulated stresses which promotes arching and causes a more uniform distribution of earth pressure around the pipe and (2) the deflection affords a convenient method of inspecting the quality of the installation - generally the less deflection the better the installation.

Chapter 8

Above-Ground Applications for PE Pipe

Introduction

In above ground applications PE piping may be suspended or cradled in support structures or, it may simply be placed directly on the ground surface. These types of installations may be warranted by any one of several factors. One is the economic considerations of a temporary piping system. Another is the ease of inspection and maintenance. Still another is simply that prevailing local conditions and even the nature of the application itself may require that the pipe be installed above ground.

PE pipe provides unique joint integrity, toughness, flexibility, and low weight. These factors combine to make its use practical for many "above-ground" applications. This resilient material has been used for temporary water lines, various types of bypass lines, dredge lines, mine tailings, and fines-disposal piping. PE pipe is used for slurry transport in many industries such as those that work with kaolins and phosphates. The ease of installation and exceptional toughness of PE pipe often make it practical for oil and gas collection. The economics and continued successful performance of this unique piping material is evident despite the extreme climatic conditions that may sometimes exist in some of these diverse applications.

This chapter presents design criteria and prevailing engineering methods that are used for above-ground installation of PE pipe. The effects of temperature extremes, chemical exposure, ultraviolet radiation, and mechanical impact are discussed in detail. Engineering design methodology for both "on-grade" and suspended or cradled PE pipe installations are presented and illustrated with typical sample calculations. All equations in the design methodology were obtained from published design references. These references are listed so the designer can verify the applicability of the methodology to his particular project. Additional installation considerations are also discussed.

Design Criteria

Conditions and effects which can influence the behavior and thus, the design of above ground PE piping systems include:

- Temperature
- Chemical exposure
- Ultraviolet radiation
- Potential mechanical impact or loading
- Internal Pressure

Figure 1 Above-Ground Installation of PE Pipe in a Wyoming Mining Operation

Temperature

The diversity of applications for which PE pipes are used in above-ground applications reflects the usable temperature range for this material. Above-grade installations are usually exposed to demanding fluctuations in temperature extremes as contrasted to a buried installation where system temperatures can be relatively stable. Irradiation by sunlight, seasonal changes, and day-to-night transitions can impose a significant effect on any piping material installed above the ground.

As a general rule, PE pipe for pressure applications can be safely used at temperatures as low as -40°F (-40°C) and as high as 140°F (60°C). For non-pressure service, the allowable temperature range widens up to 180°F (82°C). There are a few PE piping materials that have qualified for a pressure rating at 180°F. The interested reader is advised to consult with the PPI for more information on these materials. However, PE is a thermoplastic material and, as such, these extremes impact the engineering properties of the piping. Additional information in this regard is available within the engineering properties chapter of this handbook.

Pressure Capability

Because above ground installations of PE piping can be subject to exposures to wider temperature and pressure fluctuations and, sometimes also to effects of different environments, careful attention should be paid in the selection of PE piping which has an appropriate pressure rating for the anticipated temperature and environmental exposure. A detailed discussion of these issues is included in Chapters 6.

Low Temperature Extremes

Generally speaking, the limitation for extremely low environmental service temperature is the potential for embrittlement of the material. Note, however, that most PE piping materials tested at extremely low temperatures have shown no indication of embrittlement.

The effect of low temperature on PE pipe is unique. As discussed in Chapter 3 and as shown in tables in the Appendix of Chapter 3, the apparent modulus of elasticity increases as temperatures are lowered. In effect, the pipe becomes stiffer but retains its ductile qualities. The actual low temperature embrittlement of most PE is below -180°F (-118°C). In actual practice, PE pipe has been used in temperatures as low as -75°F (-60° C).(4.5) Obviously, service conditions at these extremes may warrant insulation to prevent heat loss and freezing of the material being conveyed.

It should be noted that in extreme service applications operating at high pressure and increasingly lower temperature that the ability of some PE piping materials to absorb and dissipate energy such as that associated with sudden impact may be compromised. In these situations, it is possible that, with the addition of a sustaining or driving force, a through-wall crack can form which is capable of traveling for significant distances along the longitudinal axis of the pipe. This phenomenon is generally referred to as rapid crack propagation or RCP, and can occur in any pressure piping or pressure vessel design regardless of the material of manufacture.

This type of phenomenon is generally not experienced in PE in liquid transport applications as the energy dissipation associated with the sudden release of fluid from the pipe mediates the driving force required to sustain the crack. Gas or compressed air handling applications do not provide for the dissipation of energy and, as such, a driving or sustaining force is a potential possibility. For these reasons, the operation of PE pipe above ground in extremely cold environments (<32°F) should be carefully researched in light of the potential application and prevailing service conditions. The reader is referred to the pipe manufacturer for additional information regarding RCP and specific design measurers for above ground, cold weather installations.

Expansion and Contraction

The coefficient of linear expansion for unrestrained PE pipe is approximately ten times that of metal or concrete. The end result is that large changes in the length of unrestrained PE piping may occur due to temperature fluctuations. While the potential for expansion (or contraction) is large when compared with that of metal, concrete, or vitrified clay pipe, note that the apparent modulus of elasticity for PE is substantially lower than that of these alternative piping materials. This implies that the degree of potential movement associated with a specific temperature change may be higher for the PE, but the stress associated with restraint of this movement is significantly less. The end result is that the means of restraint required to control this movement potential is often less elaborate or expensive. The stresses imposed by contraction or expansion of a PE piping system are usually on an order of 5% to 10% of those encountered with rigid piping materials.

Chemical Exposure

Standard pressure ratings for PE pipe are for water at 73°F (23°C). Also, as is well established, in common installations either below or above ground, PE pipe will not rust, rot, corrode or be subject to galvanic corrosion. However, if the pipe is intended for the conveyance of a fluid other than water or, if it is intended to be installed in a chemically aggressive environment, consideration should be given to the appropriateness of the assigned standard pressure rating. Continuous exposure to certain substances can result in a reduction in the long-term strength of the PE material due to chemical attack or adsorption.

In some cases, such as with strong oxidizing or other agents that chemically attack PE, a gradual and irreversible reduction in strength may seriously compromise performance properties. In these cases the useful service life depends on the chemical aggressiveness of the agent, its concentration, total time of exposure and temperature. There are many cases where even though there is gradual chemical attack, PE pipe still offers sufficiently long life and is the most economical alternative.

In cases where PE piping is exposed to liquid hydrocarbons, a small adsorption of these materials into the pipe wall can occur which may result in a decrease in long-term strength. The effect is limited by the maximum amount of hydrocarbon that can be adsorbed which depends on the nature of the hydrocarbon and the temperature of the service. This effect on long-term strength is generally limited because hydrocarbon adsorption does not attack PE’s chemical structure. Further, it should be noted that adsorption may slowly reverse when exposure to the hydrocarbon is decreased or removed. For lighter weight hydrocarbons such as condensates of gaseous hydrocarbons, adsorption reversal may occur within weeks or months after removal from exposure. However, the reverse adsorption of heavier liquid hydrocarbons may be so slow that the effect may be considered permanent. Exposure to most gaseous hydrocarbons is not known to reduce the long term strength of PE.

Finally, heat fusion joining between pipes after adsorption of liquid hydrocarbons can be affected. The presence of adsorbed liquid hydrocarbons in the pipe wall can result in low-strength heat fusion joining because the adsorbed hydrocarbons will liquefy and then vaporize when heated and reduce or prevent melt fusion. Hydrocarbon contamination is usually identified by a bubbly or pockmarked melt appearance upon heater plate removal. Because the strength and reliability of hydrocarbon contaminated joints is suspect, mechanical joining methods are used in these situations. The strength and reliability of heat fusion joints made before hydrocarbon adsorption is not affected

Ultraviolet Exposure

When PE pipe is utilized outdoors in above-ground applications, it will be subjected to extended periods of direct sunlight. The ultraviolet component in sunlight can produce a deleterious effect on the PE unless the material is sufficiently protected. Weathering studies have shown that pipe produced with a minimum 2.0% concentration of finely divided and evenly dispersed carbon black is protected from the harmful effects of UV radiation for indefinite periods of time.(18) PE pipe that is protected in this manner is the principal material selected for above-ground installations. Black pipe (containing 2.0% minimum carbon black) is normally recommended for above-ground use. Consult the manufacturer's recommendations for any non-black pipe that is either used or stored above ground.

Mechanical Impact or Loading

Any piping material that is installed in an exposed location is subject to the rigors of the surrounding environment. It can be damaged by the movement of vehicles or other equipment, and such damage generally results in gouging, deflecting or flattening of the pipe surfaces. If an above-ground installation must be located in a region of high traffic or excessive mechanical abuse (along a roadway, etc.), the pipe requires extra protection. It may be protected by building a berm or by encasing the pipe where damage is most likely. Other devices may be used, as appropriate to the situation. Design criteria for the installation of buried flexible thermoplastic pipe should be used for those areas where the above-ground PE system must pass under a roadway or other access, and where an underground installation of a portion of the system is necessary.(7,8) In general, in a pressurized installation in which any section of PE pipe has been gouged in excess of 10% of the minimum wall thickness, the gouged portion should be removed and replaced. This has long been an established procedure in the use of smaller diameter (up to 16-inch) PE pipe in natural gas applications. However, it is noted that this rule only applies to smaller size pipe.

Therefore, for any gouges or damage to larger pipe sizes with thicker walls, the user is advised to consult the manufacturer for assistance. When the PE pipe has been excessively or repeatedly deflected or flattened, it may exhibit stress-whitening, crazing, cracking, or other visible damage, and any such regions should be removed and replaced with new pipe material.

Design Methodology

As previously discussed, above-ground piping systems can be subjected to variations in temperature. These temperature fluctuations can impact the pressure capability of the exposed piping to some degree. The possible effects resulting from expansion and contraction characteristics of PE pipe must also be addressed in light of the anticipated variations in temperature. Further, the installation characteristics of the proposed above-ground system must be analyzed in some detail. Each of these concerns will be briefly discussed in the sections which follow. This discussion will be supplemented and facilitated with a few example calculations.

Pressure Capability

As mentioned earlier, the design of PE piping for internal pressure service is covered in significant detail in Chapter 6 of this Handbook. In addition, the Appendix to Chapter 3 contains a table of re-rating factors that can be applied to arrive at the appropriate pressure rating for the application under consideration.

Likewise, where the apparent modulus of elasticity of the pipe material is a consideration, the reader is referred to the modulus tables and associated temperature re-rating factors also found in Appendix, Chapter 3.

The following four example calculations are being presented to illustrate the effect of temperature on various design considerations for hypothetical above- ground PE pipe installations.

EXAMPLE 1

What is the pressure capability of an SDR 11 series of PE 4710 PE pipe used to transport water at 73°F (23°C)?
From Chapter 5,

$$P = 2\,(HDS)\,(F_T)\,/\,(\,SDR\text{ -}1\,)$$

WHERE

HDS = **Hydrostatic Design Stress for PE Material at 73ºF (23ºC). For PE4710 = 1000 psig**

F_T = **Temperature Re-rating Design Factor; at 73ºF, F_T = 1.0 per Appendix, Chapter 3.**

P = **2(1000)(1.0) / (11-1) = 200psig at 73ºF**

What is this pipe's pressure capability at 100°F (38°C)?
From Appendix, Chapter 3, F_T at 100°F = 0.78

$$P = 2(1000)\ (0.78)/(11\ \text{-}1) = 156 \text{ psig at } 100°\text{F}$$

Example 1 assumes that exposure of the pipe to sunlight, combined with the thermal properties of the material flowing within the pipe, has resulted in a normal average operating temperature for the system at 100°F (38°C). Exposure of the pipe to direct sunlight can result in high, up to about 150°F outside surface temperatures, particularly if the pipe is black.(9) In the majority of cases, the material flowing within the pipe is substantially cooler than the exterior of the exposed above-ground pipe. The cooler nature of the material flowing through the pipe tends to moderate the outside surface temperature of the exposed pipe. This results in a pipe wall temperature that is intermediate between that of the outside surface of the pipe and that of the flow stream. Obviously, the longer the period of irradiation of the pipe by sunlight, the greater the potential will be to raise the temperature of the flow stream.

Several texts related to temperature design criteria and flow are included in the literature references of this chapter.(10,11)

In addition, the reader is referred to Chapters 3 and 6 for more detailed information on the topic of the pressure ratings of the different PE materials designation codes and applicable temperature re-rating factors.

Expansion and Contraction

As noted in the Design Criteria section of this chapter, temperature changes can produce a substantial change in the physical dimensions of PE pipe. This is evidenced by a coefficient of expansion or contraction that is notably higher than that of many other piping materials. The design methodology for above-ground installation must take this potential for expansion or contraction into consideration.

The expansion or contraction for an unrestrained PE pipe can be calculated by using the following Equation.

Pipe Length vs. Temperature Change

(3) $$\Delta L = \alpha\,(T_2 - T_1)\,L$$

WHERE

ΔL **= Theoretical length change (in.)**

ΔL**>0 is expansion**

ΔL**<0 is contraction**

α **= Coefficient of linear expansion, see Appendix, Chapter 3**

T_1 **= Initial temperature (°F)**

T_2 **= Final temperature (°F)**
L **= Length of pipe (in.) at initial temperature,** T_1

EXAMPLE 2

A 100 foot section of 10-inch (10.75-inch OD) SDR 11 (PE 4710 pipe) is left unrestrained overnight. If the initial temperature is 70°F (21°C), determine the change in length of the pipe section at dawn the next morning if the pipe stabilizes at a nighttime temperature of 30°F (-1°C).

Using Equation 3,

$$\Delta L = (8.0 \times 10^{-5})(30° - 70°)(100 \text{ ft})(12 \text{ in/ft}) = -3.84 \text{ Inches}$$

The negative sign indicates a contraction, so the final length is 99 ft., 8.16 in.

As shown in Example 2, the contraction or expansion due to temperature change can be quite significant. However, this calculated change in length assumes both an unrestrained movement of the pipe and an instantaneous drop in temperature. Actually, no temperature drop is instantaneous, and obviously, the ground on which the pipe is resting creates a retarding effect on the theoretical movement due to friction. Practical field experience for PE pipe has shown that the actual contraction or expansion that occurs as a result of temperature change is approximately one-half that of the theoretical amount.

Field experience has also shown that changes in physical length are often further mitigated by the thermal properties or heat-sink nature of the flow stream within the pipe. However, conservative engineering design warrants that consideration be given to the effects of temperature variation when the flow stream is static or even when there is no flow stream.

In cases where PE pipe will be exposed to temperature changes, it is common practice to control the pipe movement by judiciously placing restraining devices. Typical devices include tie-down straps, concrete anchors, thrust blocks, etc. The anchor selection must consider the stresses developed in the pipe wall and the resultant loads that are generated as a result of the anticipated temperature changes. While Equations 4 and 5 provide examples of how to calculate generated loads and stress, the Equations are not all inclusive.

(4) Longitudinal Stress vs. Temperature Change

$$\sigma_T = \alpha (T_2 - T_1) E$$

WHERE

σ_T = **Theoretical longitudinal stress (psi)(Negative for contraction; positive for expansion)**

α = **Coefficient of expansion or contraction (see Eq. 3)**

T_1 = **Initial temperature (°F)**

T_2 = **Final temperature (°F)**

E = **Apparent short-term modulus of elasticity (see Appendix, Chapter 3) at average temperature (T_m)**

T_m = **(T_2 + T_1)/2**

(5) Longitudinal Force vs. Temperature Change

$$F_T = \sigma_T (A)$$

WHERE

F_T = **Theoretical longitudinal force (lbs)**

σ_T = **Theoretical longitudinal stress (psi) from Eq. 4**

A = **Pipe wall cross-sectional area (in^2)**

EXAMPLE 3

Assuming the same conditions as Example 2, what would be the potential maximum theoretical force developed on the unrestrained end of the 100 foot section if the other end is restrained effectively? Assume that the cross-sectional area of the pipe wall is approximately 30 in^2, the temperature change is instantaneous, and the frictional resistance against the soil is zero.

$$\sigma_T = \alpha (T_2 - T_1) E$$

Note: This E (apparent modulus) value is the average of the materials value at each of the two temperatures used in this example calculation.

$$= (8.0 \times 10^{-5})(30° - 70°)(130{,}000 \times [1.65 + 1.00]/2)$$

$$= -551 \text{ psi}$$

$$F_T = (\sigma_T)(A)$$

$$= -551 \text{ psi} \times 30 \text{ in}^2$$

$$= -16{,}530 \text{ lbs}$$

As previously mentioned, for these conditions where the temperature change is gradual, the actual stress level is approximately half that of the theoretical value. This would account for an actual force at the free end of about -8,265 Ibs. To illustrate the differences between the expansion and contraction characteristics of PE pipe versus those of steel, consider the following example:

EXAMPLE 4

Assume the same conditions as Example 2 for 10-inch Schedule 40 steel pipe. The pipe wall has a cross-sectional area of 11.90 in^2, the value of α for steel is 6.5 x 10^{-6} in/in/°F, and the value of E for this material is 30,000,000. (14)

$$\sigma_T = \alpha_{steel} (T_2 - T_1) E$$

$$= (6.5 \times 10^{-6}) (30° - 70°) (3 \times 10^7)$$

$$= -7{,}800 \text{ psi}$$

$$F_T = (\sigma_T)(A)$$

$$= -7{,}800 \text{ psi} \times 11.90 \text{ in}^2$$

$$= -92{,}820 \text{ lbs}$$

Thus, as shown by Examples 3 and 4, even though the coefficient of thermal expansion is high in comparison to other materials, the comparatively low modulus of elasticity results in correspondingly reduced thermal stresses and generated loads.

These design considerations provide a general introduction to the understanding of temperature effects on PE pipe in above-ground applications. They do not include other factors such as the weight of the installed pipe, frictional resistance of pipe lying on-grade, or grade irregularities. All of these factors affect the overall expansion or contraction characteristics, and individual pipe manufacturers should be consulted for further detail.

Installation Characteristics

There are two basic types of above-ground installations. One of these involves "stringing-out" the pipe over the naturally-occurring grade or terrain. The second involves suspending the pipe from various support structures available along the pipeline right-of-way. Figure 2 illustrates some typical installations for both types. Each type of installation involves different design methodologies, so the installation types are discussed separately.

On-Grade Installations

As indicated previously, pipe subjected to temperature variation will expand and contract in response to temperature variations. The designer has two options available to counteract this phenomenon. Basically the pipe may be installed in an unrestrained manner, thus allowing the pipe to move freely in response to temperature change. Or the pipe may be anchored by some means that will control any change of physical dimensions; anchoring can take advantage of PE's unique stress relaxation properties to control movement and deflection mechanically.(12)

Free Movement

An unrestrained pipe installation requires that the pipe be placed on a bed or right-of-way that is free of material that may abrade or otherwise damage the exterior pipe surface. The object is to let the pipe "wander" freely without restriction or potential for point damage. This installation method usually entails "snaking" the PE pipe along the right-of-way. The excess pipe then allows some slack that will be taken up when the temperature drops and the pipe contracts.

Figure 2 Typical Above-Ground Installations with PE Pipe

Figure 2a On-grade Installation of PE Pipe in an Industrial Application. Note "snaking" along right of way.

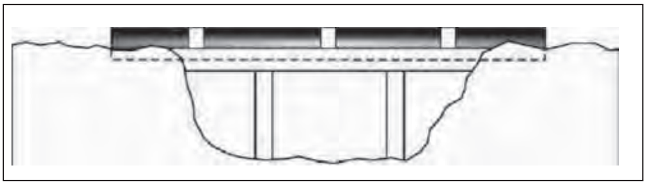


Figure 2b Continuous Support of PE Pipe at Ravine Crossing

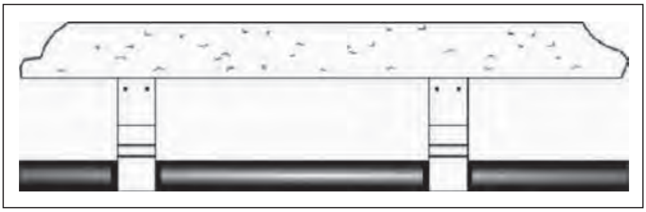


Figure 2c Intermittent Support of PE Pipe Suspended from Rigid Structure

In all likelihood, a free-moving PE pipe must eventually terminate at or connect to a rigid structure of some sort. It is highly recommended that transitions from free-moving PE pipe to a rigid pipe appurtenance be fully stabilized so as to prevent stress concentration within the transition connection.

Figure 3 illustrates some common methods used to restrain the pipe at a distance of one to three pipe diameters away from the rigid termination. This circumvents the stress-concentrating effect of lateral pipe movement at termination points by relieving the stresses associated with thermal expansion or contraction within the pipe wall itself.

Figure 3 Typical Anchoring Methods at Rigid Terminations of Free-Moving PE Pipe Sections

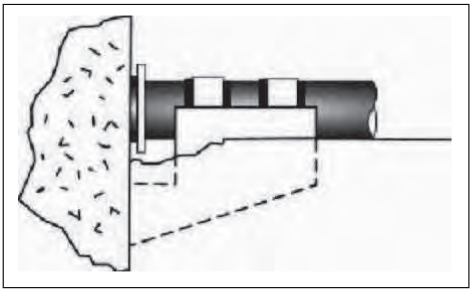


Figure 3a Connection to Concrete Vault Using Grade Beam

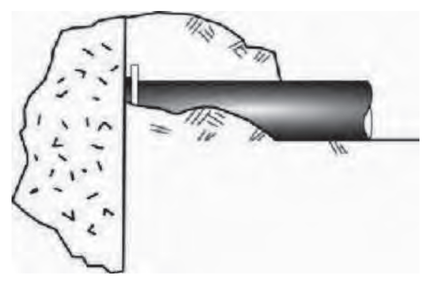


Figure 3b Connection to Rigid Structure Using Consolidated Earthen Berm

Restrained Pipelines

The design for an above-ground installation that includes restraint must consider the means by which the movement will be controlled and the anchoring or restraining force needed to compensate for, or control, the anticipated expansion and contraction stresses. Common restraint methods include earthen berms, pylons, augered anchors, and concrete cradles or thrust blocks.

The earthen berm technique may be either continuous or intermittent. The pipeline may be completely covered with a shallow layer of native earth over its entire length, or it may be stabilized at specific intervals with the earthen berms between the anchor locations. Typical earthen berm configurations are presented in Figure 4.

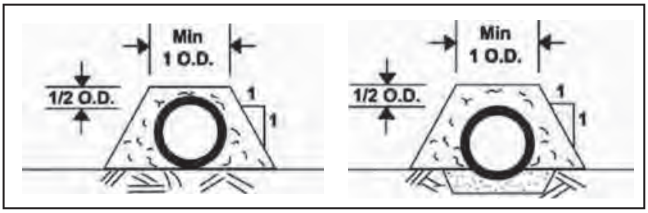


Figure 4 Earthern Berm Configurations

The continuous earthen berm serves not only to stabilize the pipe and restrain its movement but also to moderate temperature fluctuations. With less temperature fluctuation the tendency for pipe movement is reduced.

An intermittent earthen berm installation entails stabilization of the pipe at fixed intervals along the length of the pipeline. At each point of stabilization the above-ground pipe is encased with earthen fill for a distance of one to three pipe diameters. The economy of this method of pipeline restraint is fairly obvious.

Other means of intermittent stabilization are available which provide equally effective restraint of the pipeline with a greater degree of ease of operation and maintenance. These methods include pylons, augered anchors (13), or concrete cradles. These restraint techniques are depicted schematically in Figures 5 through 7.

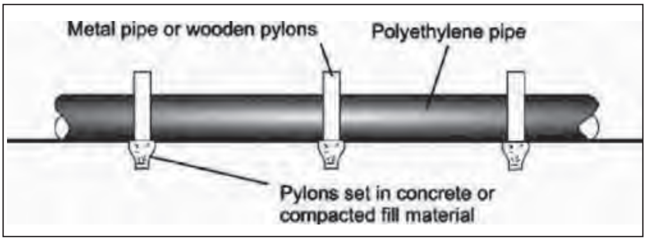


Figure 5 Pylon Type Stabilization

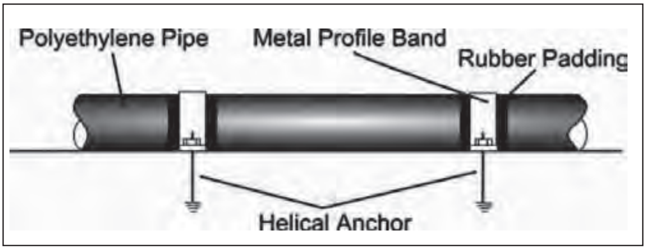


Figure 6 Augered Anchor Stabilization

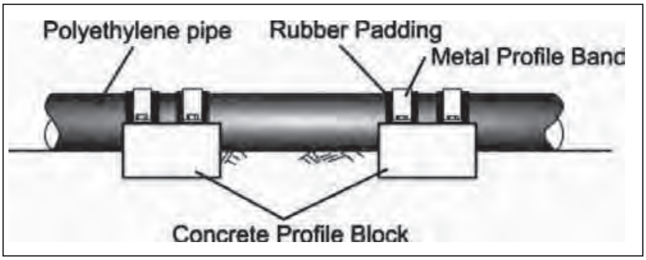


Figure 7 Concrete Cradle or Thrust Block Stabilization

A pipeline that is anchored intermittently will deflect laterally in response to temperature variations, and this lateral displacement creates stress within the pipe wall. The relationships between these variables are determined as follows:

Lateral Deflection (Approximate from Catenary Eq.)

$$(6)\ \Delta y = L\sqrt{0.5\,\alpha\,(\Delta T)}$$

WHERE

Δ_y = **Lateral deflection (in.)**

L = **Distance between anchor points (in.)**

α= **Coefficient of expansion/contraction; see Appendix, Chapter 3**

ΔT = **Temperature change (T_2 - T_1) in °F**

(7) Bending Strain Development

$$\varepsilon = \frac{D\sqrt{96\,\alpha\,(\Delta T)}}{L}$$

WHERE

ε = **Strain in pipe wall (%)**

D = **Outside diameter of pipe (in)**

α= **Coefficient of expansion/contraction; see Appendix, Chapter 3**

ΔT = **(T_2 - T_1) in °F**

L = **Length between anchor points (in)**

As a general rule, the frequency of stabilization points is an economic decision. For example, if lateral deflection must be severely limited, the frequency of stabilization points increases significantly. On the other hand, if substantial lateral deflection is permissible, fewer anchor points will be required, and the associated costs are decreased.

Allowable lateral deflection of PE is not without a limit. The upper limit is determined by the maximum permissible strain in the pipe wall itself. This limit is a conservative 5% for the majority of above-ground applications. It is determined by use of Equation 7 based on the assumption that the pipe is anchored between two posts at a distance L from each other. Equations 6 and 7 are used to determine the theoretical lateral deflection or strain in overland pipelines. Actual deflections and strain characteristics may be significantly less due to the friction imposed by the prevailing terrain, the weight of the pipe and flow stream, and given that most temperature variations are not normally instantaneous. These factors allow for stress relaxation during the process of temperature fluctuation.

EXAMPLE 5

Assume that a 10-inch (OD = 10.75) SDR 11 (PE 4710) pipe is strung out to grade and anchored at 100-foot intervals. What is the maximum theoretical lateral deflection possible, given a 50°F (27.8°C) temperature increase? What strain is developed in the pipe wall by this temperature change? What if the pipe is anchored at 50-foot intervals?

Calculations for 100-foot intervals:

$$\Delta y = L\sqrt{0.5\alpha\,(\Delta T)}$$

$$= 100 \times 12\,[0.5\,(8 \times 10^{-5})\,(50)]^{1/2}$$

$$= 53.7 \text{ inches lateral displacement}$$

$$\varepsilon = \frac{D\sqrt{96\alpha(\Delta T)}}{L}$$

$$= \frac{10.75\sqrt{(96)\,(8 \times 10^{-5})(50)}}{100(12)}$$

$$= 0.56\% \text{ strain}$$

Calculations for 50-foot intervals:

$$\Delta y = L\sqrt{0.5\alpha(\Delta T)}$$

$= 50 \times 12\,[0.5(8 \times 10^{-5})(50)]^{1/2}$

= 26.8 inches lateral displacement

$$\varepsilon = \frac{D\sqrt{96\alpha(\Delta T)}}{L}$$

$$= 10.75\,\frac{\sqrt{96\,(0.0001\,)\,(50)}}{50\,(\,12\,)}$$

= 1.11% strain

From the calculations in Example 5, it is apparent that lateral deflections which appear significant may account for relatively small strains in the pipe wall. The relationship between lateral deflection and strain rate is highly dependent on the selected spacing interval.

Supported or Suspended Pipelines

When PE pipeline installations are supported or suspended, the temperature and corresponding deflection characteristics are similar to those discussed above for unsupported pipelines with intermittent anchors. There are two additional parameters to be considered as well: beam deflection and support or anchor configuration.

Support or Suspension Spacing

Allowable spans for horizontal lines are principally influenced by the need to comply with these objectives:

- Keep the pipe bending stresses within suitable limits
- Limit deflections (sagging), if necessary for
  - Appearance
  - Avoiding pockets (to allow complete drainage)
  - Avoid interferences with other pipes or, items

In most cases, the limiting pipe spans which allow the above objectives to be met can readily be obtained from the equations which are presented below. These equations are based on the simple beam relationship.

(8) Support Spacing Requirements

$$L = \left(\frac{3\,(OD^4 - ID^4)\,\sigma_m \pi}{8qOD}\right)^{1/2}$$

WHERE

L = **Center-to-center span (in)**

OD = **Outside diameter (in)**

ID = **Inside diameter (in)**

σ_m = **Maximum allowable bending stress (psi); see Note below**

= 100 psi for pressurized pipelines

= 400 psi for non-pressurized pipelines

q = **Load per unit length (lb/in.)**

Note: A common and conservative design objective (in the case on non-pressure pipelines) is to limit the bending stress to one half of the PE pipe material's HDS for the maximum anticipated operating temperature. For pressure pipelines, the objective is to limit the bending stress to 1/8th of the HDS. For example, for a PE4710 material – one having an HDS of 1000psi for water for 73°F – the corresponding bending limits for 73°F would be 500 (for non-pressure) and 125psi (for pressure). And, for a different maximum operating temperature these limits would be modified in accordance with the temperature adjustment factors given in the Appendix to Chapter 3. Also, if environment is a factor this should also be recognized.

(9) Load per Unit Length

$$q = \frac{W}{12} + \frac{\pi\sigma(ID)^2}{6912}$$

WHERE

q = **Load per unit length (lb/in)**

W = **Weight of pipe (lbs/ft)**

σ = **Density of Internal fluid (lb/ft^3)**

π = **3.1416**

This calculation gives a conservative estimate of the support span in cases where the pipe is not completely restrained by the supports. (The pipe is free to move within the supports.) A more complex analysis of the bending stresses in the pipe may be performed by treating the pipe as a uniformly loaded beam with fixed ends. The actual deflection that occurs between spans may be determined on the basis of this type of analysis, as shown in Equation 10.

(10) Simple Beam Deflection Analysis(14,15) Based on Limiting Deflection

$$d = \frac{fqL^4}{E_L I}$$

WHERE

d = **Deflection or sag (in)**

f = **Deflection Coefficient, (Refer to Table 2)**

L = **Span length (in)**

q = **Load per unit length (lb/in)**

E_L **= Apparent long-term modulus of elasticity at average long-term temperature from Appendix, Chapter 3**
I **= Moment of inertia (in^4)**
= $(\pi/64)(OD^4 - ID^4)$

Simple beam analysis reflects the deflection associated with the proposed support spacing configuration and the apparent modulus of elasticity at a given service temperature. It does not take into consideration the increased or decreased deflection that may be attributed to expansion or contraction due to thermal variations. These phenomena are additive - Equation 11 illustrates the cumulative effect.

(11) Cumulative Deflection Effects

Total deflection = beam deflection + thermal expansion deflection

$$= d + \Delta y$$

$$d = \frac{fqL^4}{E_L I} + L\sqrt{0.5\alpha(\Delta T)}$$

Simple beam analysis assumes one support point at each end of a single span. Most supported pipelines include more than one single span. Normally, they consist of a series of uniformly spaced spans with relatively equal lengths. The designer may analyze each individual segment of a multiple-span suspended pipeline on the basis of simple beam analysis. However, this approach may prove overly conservative in the majority of multiple-span supported pipelines. Equation 12 presents a more realistic approach to deflection determination on the basis of continuous beam analysis.

(12) Continuous Beam Analysis

$$d = \frac{fqL^4}{E_L I}$$

WHERE

d **= Deflection or sag (in)**
f **= Deflection coefficient (Refer to Table 2)**
q **= Load per unit length (lbs/in)**
L **= Span length (in)**
E_L **= Apparent long-term modulus of elasticity at average long-term temperature from Appendix, Chapter 3**
I **= Moment of inertia (in^4)**
= $(\pi/64)(OD^4 - ID^4)$

The deflection coefficient, f, is a function of the number of spans included and whether the pipe is clamped securely, fixed, or simply guided (not fixed) within the supports. Practical values for the deflection coefficient, f, are provided in Table 2.

TABLE 2
Deflection Coefficients, f, for Various span Configurations [17]

1 Span	2 Spans	3 Spans	4 Spans
N-N	N-N-N	N-N-N-N	N-N-N-N-N
		1 2 1	1 2 2 1
f=0.013	f=0.0069	f1=0.0069	f1=0.0065
		f2=0.0026	f2=0.0031
F–N	F-N-N	F-N-N–N	F-N-N-N-N
	1 2	1 2 2	1 2 2 2
f=0.0054	f=0.0026	f1=0.0026	f1=0.0026
	f2=0.0054	f2=0.0054	f2=0.0054
F-F	F-N-F	F-N-N-F	F-N-N-N-F
		1 2 1	1 2 2 1
f=0.0026	f=0.0026	f1=0.0026	f1=0.0026
		f2=0.0031	f2=0.0031
	F-F-F	F-F-F-F	F-F-F-F-F
	f=0.0026	f=0.0026	f=0.0026
F = Fixed Securely N = Not Fixed			

As was the case for simple beam analysis, continuous beam analysis addresses the deflection resulting from a given span geometry at a specified service temperature. The equation does not take into consideration the additional deflection associated with expansion or contraction due to temperature variations. Equation 13 combines the effect of deflection due to span geometry (using continuous beam analysis) with deflection resulting from expansion due to a temperature increase. A total span deflection of ½ to 1 inch is generally considered as a maximum.

(13) Total Span Deflection Based on Continous Beam Analysis and Thermal Response

$$\text{Total Deflection (in)} = \frac{fqL^4}{E_L I} + L\sqrt{0.5\alpha(\Delta T)}$$

WHERE

f = **Deflection Coefficient (Refer to Table 2)**
q = **Load per unit length from Eq. 9 (lbs/in)**
L = **Span length from Eq. 8 (in)**
E_L = **Apparent long-term modulus of elasticity at average long-term temperature from Appendix, Chapter 3**
I = **Moment of inertia (in.^{4})**
= **$(\pi/64)(OD^4 - ID^4)$**

Anchor and Support Design

Proper design of anchors and supports is as important with PE piping as it is with other piping materials. A variety of factors must be considered.

Some installations of PE pipe have the pipe lying directly on the earth's surface. In this type of installation, the surface under the pipe must be free from boulders, crevices, or other irregularities that could create a point-loading situation on the pipe.

On-grade placement over bed rock or "hard pan" should be avoided unless a uniform bed of material is prepared that will cushion the pipe. If the PE pipe rests directly on a hard surface, this creates a point loading situation and can increase abrasion of the outer pipe surface as it "wanders" in response to temperature variations.

Intermittent pipe supports should be spaced properly, using the design parameters discussed in the preceding pages. Where excessive temperatures or unusual loading is encountered, continuous support should be considered.

Supports that simply cradle the pipe, rather than grip or clamp the pipe, should be from one-half to one-pipe diameter in length and should support at least 120 degrees of the pipe diameter. All supports should be free from sharp edges.

The supports should have adequate strength to restrain the pipe from lateral or longitudinal deflection, given the anticipated service conditions. If the design allows free movement during expansion, the sliding supports should provide a guide without restraint in the direction of movement. If on the other hand, the support is designed to grip the pipe firmly, the support must either be mounted flexibly or have adequate strength to withstand the anticipated stresses.

Heavy fittings or flanges should be fully supported and restrained for a distance of one full pipe diameter, minimum, on both sides. This supported fitting represents a rigid structure within the flexible pipe system and should be fully isolated from bending stresses associated with beam sag or thermal deflection.

Figure 8 includes some typical pipe hanger and support arrangements that are appropriate for use with PE pipe, and Figure 9 shows some anchoring details and cradle arrangements.

Pressure-Testing

It is common practice to pressure-test a pipe system prior to placing it in service. For the above-ground systems described in this chapter, this test should be conducted hydrostatically. Hydrostatic testing procedures are described in a number of publications, including PPI Technical Report 31.(8) The Plastics Pipe Institute does not recommend pneumatic pressure testing of an above-ground installation.(16) An ASTM test method for leakage testing of PE pipe installations is under development and may be applicable. The reader is also advised to refer to Chapter 2 of this Handbook where the subject of pressure testing of installed PE pipe systems is covered in greater detail.

Figure 8 Typical Pipe Hangers and Supports

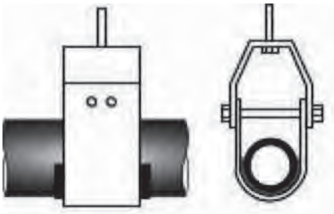


Figure 8.1 Pipe Stirrup Support

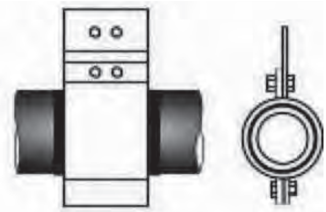


Figure 8.2 Clam Shell Support

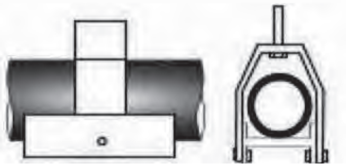


Figure 8.3 Suspended I-Beam or Channel-Continuous Support

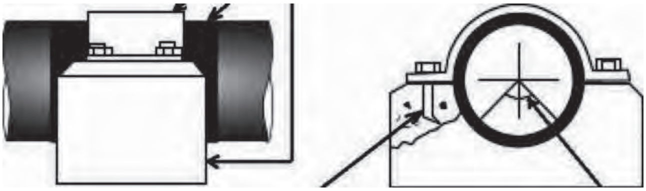


Figure 9 Typical Anchoring and Cradling Details

Conclusion

PE pipe has been used to advantage for many years in above-ground applications. The unique light weight, joint integrity, and overall toughness of PE has resulted in the above-ground installation of PE pipe in various mining, oil, gas production and municipal distribution applications. Many of these systems have provided years of cost-effective service without showing any signs of deterioration.

The key to obtaining a quality above-ground PE piping system lies in careful design and installation. This chapter is intended to serve as a guide by which the designer and/or installer may take advantage of the unique properties of PE pipe for these types of applications. In this way, excellent service is assured, even under the demanding conditions found with above-ground installations.

References

1. ASTM D2837, Standard Method for Obtaining the Hydrostatic Design Basis for Thermoplastic Materials, *Annual Book of Standards*, American Society for Testing and Materials (ASTM), Philadelphia, PA,
2. Plastics Pipe Institute, Report TR-3, Policies and Procedures for Developing Recommended Hydrostatic Design Stresses, Irving, TX.
3. ASTM D3035, Standard Specifications for PE (PE) Plastic Pipe (DR-PR) Based on Controlled Outside Diameter, *Annual Book of Standards*, American Society for Testing and Materials ASTM), Philadelphia, PA,
4. Arctic Town Gets Royal Flush. (1984, January 5). *Engineering News Record*, New York.
5. Bringing Modern Utilities to Town Beyond the Arctic Circle. (1985, December). *Public Works*.
6. Plastics Pipe Institute. (1991). Report TR19, Thermoplastic Piping for the Transport of Chemicals,Irving, TX.
7. ASTM D2321, Standard Practice for Underground Installation of Flexible Thermoplastic Sewer Pipe, *Annual Book of Standards*, American Society for Testing and Materials (ASTM), Philadelphia, PA,
8. Plastics Pipe Institute. (1988). Report TR-31, Underground Installation of Polyolefin Piping, Irving, TX.
9. Gachter, R., & H. Muller. (1983). *Plastics Addition Handbook*, McMillan Publishing Co., New York, NY.
10. Parker, J. D., James H. Boggs, & Edward F. Click. (1969). *Introduction to Fluid Mechanics and Heat Transfer*, Addison-Wesley Publishing Co., Reading, MA.
11. VanWylen, Gordon J., & Richard E. Sonntag. (1973). *Fundamentals of Classical Thermodynamics*, John Wiley & Sons, New York, NY.
12. Ferry, John D. (1982). Viscoelastic Properties of Polymers, John Wiley & Sons, New York, NY, 1980. *Pipeline Anchoring Encyclopedia*, A. B. Chance Company Bulletin 30-8201.
13. *Pipeline Anchoring Encyclopedia*. (1982). A. B. Chance Company bulletin 30-8201.
14. Engineering in Training Reference Manual, 8th edition, M.R. Lindeburg, Professional Publications, Belmont, CA, 2002.
15. Moffat, Donald W. (1974). *Plant Engineering Handbook of Formulas, Charts, and Tables*, Prentice-Hall, Inc., Englewood Cliffs, NJ.
16. Plastics Pipe Institute. (1989). *Recommendation B. Thermoplastic Piping for the Transport of Compressed Air or Other Compressed Cases*, Irving, TX.
17. *Manual of Steel Construction*, 6th Edition, American Institute of Steel Construction, Chicago, IL.
18. Gilroy, H. M., *Polyolefin Longevity for Telephone Service*, AT&T Bell Laboratories, Murray Hill, NJ.

References, Equations

Eq 1. The Plastics Pipe Institute. (1976). *Plastics Piping Manual*, Wayne.
Eq 2. *Managing Corrosion with Plastics*. (1983). Volume 5, National Association of Corrosion Engineers.
Eq 3. Roark Raymond J., & Warren C. Young. (1973). *Formulas for Stress & Strain*, McGraw-Hill Co., New York, NY.
Eq 4. Ibid.
Eq 5. Baumeister, T., & L. S. Marks. (1967). *Standard Handbook for Mechanical Engineers*, 7th Edition, McGraw-Hill Book Co., New York, NY.
Eq 6. Roark, Raymond J., & Warren C. Young. (1973). *Formulas for Stress & Strain*, McGraw-Hill Book Co., New York, NY.
Eq 7. Crocker. (1945). *Piping Handbook*, Grunnell Co., Providence, RI.
Eq 8. This is a basic equation utilized to determine the total weight of a pipe filled with fluid.
Eq 9. Shigley, J. E. (1972). *Mechanical Engineering Design*, 2nd Edition, McGraw-Hill Book Co., New York.
Eq 10. Ibid.
Eq 11. Ibid.
Eq 12. Ibid.

Chapter 9

PE Pipe Joining Procedures

Introduction

An integral part of any pipe system is the method used to join the system components. Proper engineering design of a system will take into consideration the type and effectiveness of the techniques used to join the piping components and appurtenances, as well as the durability of the resulting joints. The integrity and versatility of the joining techniques used for PE pipe allow the designer to take advantage of the performance benefits of PE in a wide variety of applications.

General Provisions

PE pipe or fittings are joined to each other by heat fusion or with mechanical fittings. PE pipe may be joined to other pipe materials by means of compression fittings, flanges, or other qualified types of manufactured transition fittings. There are many types and styles of fittings available from which the user may choose. Each offers its particular advantages and limitations for each joining situation the user may encounter. Contact with the various manufacturers is advisable for guidance in proper applications and styles available for joining as described in this document. The joining methods discussed in this chapter cover both large and small diameter pipe. Large diameter PE pipe is considered to be sizes 3″ IPS (3.500″ OD, Iron Pipe Size) and larger. All individuals involved in the joining PE pipe systems, whether it be using the typical heat fusion methods or employing mechanical connections, should be fully trained and qualified in accordance with applicable codes and standards and/or as recommended by the pipe or fitting manufacturer. Those assigned to making joints in PE pipe for gas applications must meet the additional requirement of compliance with U.S. Department of Transportation Pipeline Safety Regulations(10). The equipment used in the process of making heat fused joints must be designed to operate for the selected pipe and fusion procedures. Additionally, the equipment should be well maintained and capable of operating to specification.

Thermal Heat Fusion Methods

There are three types of conventional heat fusion joints currently used in the industry; Butt, Saddle, and Socket Fusion. Additionally, electrofusion (EF) joining is available with special EF couplings and saddle fittings.

The principle of heat fusion is to heat two surfaces to a designated temperature, then fuse them together by application of a sufficient force. This force causes the melted materials to flow and mix, thereby resulting in fusion. When fused according to the pipe and/or fitting manufacturers' procedures, the joint area becomes as strong as, or stronger than, the pipe itself in both tensile and pressure properties and properly fused joints are absolutely leak proof. As soon as the joint cools to near ambient temperature, it is ready for handling. The following sections of this chapter provide a general procedural guideline for each of these heat fusion methods.

Butt Fusion

The most widely used method for joining individual lengths of PE pipe and pipe to PE fittings is by heat fusion of the pipe butt ends as illustrated in Figure 1. This technique produces a permanent, economical and flow-efficient connection. Quality butt fusion joints are produced by using trained operators and quality butt fusion machines in good condition.

The butt fusion machine should be capable of:

- Aligning the pipe ends
- Clamping the pipes
- Facing the pipe ends parallel and square to the centerline
- Heating the pipe ends
- Applying the proper fusion force

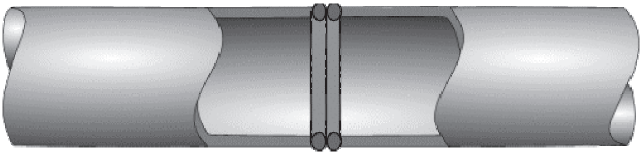


Figure 1 A Standard Butt Fusion Joint

The six steps involved in making a butt fused joint are:

1. Clean, clamp and align the pipe ends to be joined
2. Face the pipe ends to establish clean, parallel surfaces, perpendicular to the center line
3. Align the pipe ends
4. Melt the pipe interfaces
5. Join the two pipe ends together by applying the proper fusion force
6. Hold under pressure until the joint is cool

Butt Fusion of PE Pipe Products with Different Wall Thicknesses

PE pipes of the same outside diameter but having different specified wall thicknesses, that is, different DR designations, may be butt fused to each other under special conditions. Since this represents a special situation, it is subject to limitations. Therefore, the user is advised to consult with the pipe manufacturer to determine if the special procedures can be applied to the pipe components involved in the particular installation in question. If so, a written copy of the applicable assembly recommendations should be obtained.

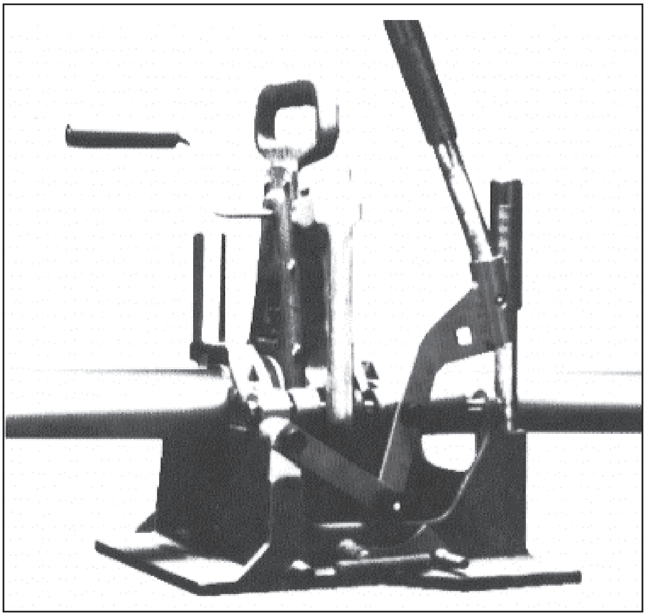


Figure 2 Typical Butt Fusion Machine for Smaller Diameter Pipe
(Butt Fusion machines are available to fuse pipe up to 65 inches in diameter)

Most pipe manufacturers have detailed parameters and procedures to follow. The majority of them helped develop and have approved the PPI Technical Report TR-33 for the generic butt fusion joining procedure for PE pipe (15) and ASTM F 2620.

Optional Bead Removal

In some pipe systems, engineers may elect to remove the inner or outer bead of the joint. External, or both beads are removed with run-around planing tools, which are forced into the bead, then drawn around the pipe. Power planers may also be used, but care must be taken not to cut into the pipe's outside surface.

It is uncommon to remove internal beads, as they have little or no effect on flow, and removal is time-consuming. Internal beads may be removed from pipes after each fusion with a cutter fitted to a long pole. Since the fusion must be completely cooled before bead removal, assembly time is increased slightly.

Saddle/Conventional Fusion

The conventional technique to join a saddle to the side of a pipe, illustrated in Figure 3, consists of simultaneously heating both the external surface of the pipe and the matching surface of the “saddle” type fitting with concave and convex shaped heating tools until both surfaces reach proper fusion temperature. This may be accomplished by using a saddle fusion machine that has been designed for this purpose.

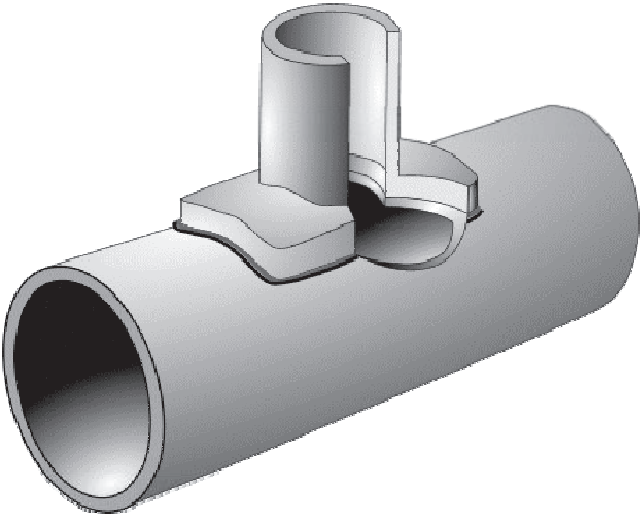


Figure 3 Standard Saddle Fusion Joint

Saddle fusion using a properly designed machine, provides the operator better alignment and force control, which is very important to fusion joint quality. The Plastics Pipe Institute recommends that saddle fusion joints be made only with a mechanical assist tool unless hand fusion is expressly allowed by the pipe and/or fitting manufacturer.(16)

There are eight basic sequential steps that are normally used to create a saddle fusion joint:

1. Clean the pipe surface area where the saddle fitting is to be located
2. Install the appropriate size heater saddle adapters

3. Install the saddle fusion machine on the pipe
4. Prepare the surfaces of the pipe and fitting in accordance with the recommended procedures
5. Align the parts
6. Heat both the pipe and the saddle fitting
7. Press and hold the parts together
8. Cool the joint and remove the fusion machine

Most pipe manufacturers have detailed parameters and procedures to follow. The majority of them helped develop and have approved the PPI Technical Report TR-41 for the generic saddle fusion joining procedure for PE pipe (16) and ASTM 2620.

Socket Fusion

This technique consists of simultaneously heating both the external surface of the pipe end and the internal surface of the socket fitting until the material reaches the recommended fusion temperature, inspecting the melt pattern, inserting the pipe end into the socket, and holding it in place until the joint cools. Figure 4 illustrates a typical socket fusion joint. Mechanical equipment is available to hold both the pipe and the fitting and should be used for sizes larger than 2" CTS to help attain the increased force required and to assist in alignment. Most pipe manufacturers have detailed written procedures to follow. The majority refer to ASTM F 2620.

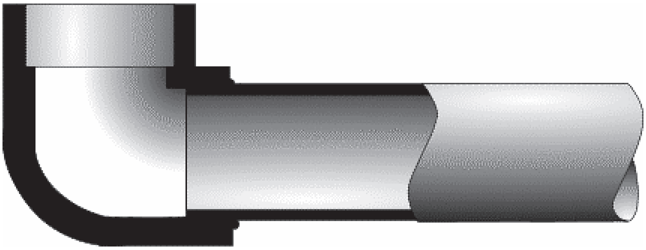


Figure 4 Standard Socket Fusion Joint

Follow these general steps when performing socket fusion:

1. Thoroughly clean the end of the pipe and the matching inside surface of the fitting
2. Square and prepare the pipe end
3. Heat the parts

4. Join the parts
5. Allow to cool

Equipment Selection

Select the proper size tool faces and heat the tools to the fusion temperature recommended for the material to be joined. For many years, socket fusion tools were manufactured without benefit of any industry standardization. As a result, variances of heater and socket depths and diameters, as well as depth gauges, do exist. More recently, ASTM F1056(7) was written, establishing standard dimensions for these tools. Therefore, mixing various manufacturers' heating tools or depth gauges is not recommended unless the tools are marked "F1056," indicating compliance with the ASTM specification and, thereby, consistency of tooling sizes.

Square and Prepare Pipe

Cut the end of the pipe square. Chamfer the pipe end for sizes 1¼"-inch diameter and larger. (Chamfering of smaller pipe sizes is acceptable and sometimes specified in the instructions.) Remove scraps, burrs, shavings, oil, or dirt from the surfaces to be joined. Clamp the cold ring on the pipe at the proper position, using the integral depth gauge pins or a separate (thimble type) depth gauge. The cold ring will assist in re- rounding the pipe and provide a stopping point for proper insertion of the pipe into the heating tool and coupling during the fusion process.

Heating

Check the heater temperature. Periodically verify the proper surface temperature using a pyrometer or other surface temperature measuring device. If temperature indicating markers are used, do not use them on a surface that will come in contact with the pipe or fitting. Bring the hot clean tool faces into contact with the outside surface of the end of the pipe and with the inside surface of the socket fitting, in accordance with pipe and fitting manufacturers' instructions.

Joining

Simultaneously remove the pipe and fitting from the tool using a quick "snap" action. Inspect the melt pattern for uniformity and immediately insert the pipe squarely and fully into the socket of the fitting until the fitting contacts the cold ring. Do not twist the pipe or fitting during or after the insertion, as is the practice with some joining methods for other pipe materials.

Cooling

Hold or block the pipe in place so that the pipe cannot come out of the joint while the mating surfaces are cooling. These cooling times are listed in the pipe or fitting manufacturer's instructions.

Electrofusion (EF)

This technique of heat fusion joining is somewhat different from the conventional fusion joining thus far described. The main difference between conventional heat fusion and electrofusion is the method by which the heat is applied. In conventional heat fusion joining, a heating tool is used to heat the pipe and fitting surfaces. The electrofusion joint is heated internally, either by a conductor at the interface of the joint or, as in one design, by a conductive polymer. Heat is created as an electric current is applied to the conductive material in the fitting. Figure 5 illustrates a typical electrofusion joint. PE pipe to pipe connections made using the electrofusion process require the use of electrofusion couplings.

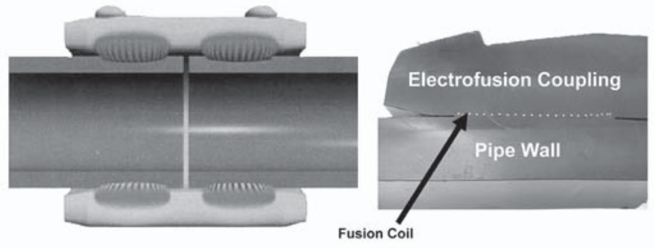


Figure 5 Typical Electrofusion Joint

General steps to be followed when performing electrofusion joining are:

1. Prepare the pipe (scrape, clean)
2. Mark the pipe
3. Align and restrain pipe and fitting per manufacturer's recommendations
4. Apply the electric current
5. Cool and remove the clamps
6. Document the fusion process

Prepare the Pipe (Clean and Scrape)

Assure the pipe ends are cut square when joining using electrofusion couplings. The fusion area must be clean from dirt or contaminants. This may require the use of water or 90% isopropyl alcohol (NO ADDITIVES OR NOT DENATURED). Next, the pipe surface in the fusion must be scraped, that is material must be removed to expose clean virgin material. This may be achieved by various special purpose tools available from the fitting manufacturer.

Mark the Pipe

Mark the pipe for stab depth of couplings or the proper fusion location of saddles. (Caution should be taken to assure that a non-petroleum marker is used.)

Align and Restrain Pipe or Fitting Per the Manufacturer's Recommendations

Align and restrain fitting to pipe per manufacturer's recommendations. Place the pipe(s) and fitting in the clamping fixture to prevent movement of the pipe(s) or fitting. Give special attention to proper positioning of the fitting on the prepared pipe surfaces. Large pipe diameters may need re-rounding prior to the electrofusion process.

Apply Electric Current

Connect the electrofusion control box to the fitting and to the power source (see Figure 6). Apply electric current to the fitting as specified in the manufacturer's instructions. Read the barcode which is supplied with the electrofusion fitting. If the control does not do so automatically, turn off the current when the proper time has elapsed to heat the joint properly.

Figure 6 Typical Electrofusion Control Box and Leads with Clamps and Fittings

Cool Joint and Remove Clamps

Allow the joint to cool for the recommended time. If using clamps, premature removal from the clamps and any strain on a joint that has not fully cooled can be detrimental to joint performance.

Consult the fitting manufacturer for detailed parameters and procedures.

Documenting fusion

The Electrofusion control box that applies current to the fitting also controls and monitors the critical parameters of fusion, (time, temperature, & pressure). The control box is a micro- processor capable of storing the specific fusion data for each joint. This information can be downloaded to a computer for documentation and inspection of the days work.

Heat Fusion Joining of Unlike PE Pipe and Fittings

Research has indicated that PE pipe and fittings made from unlike resins can be heat-fused together to make satisfactory joints. Some gas companies have been heat-fusion joining unlike PEs for many years with success. Guidelines for heat fusion of unlike materials are outlined in TN 13, issued by the Plastics Pipe Institute. Refer to Plastics Pipe Institute Technical Reports TR-33 and TR-41, ASTM F 2620 and the pipe and fitting manufacturers for specific procedures.

As mentioned earlier, fusion joints, whether they involve the conventional butt, socket or saddle heat fusion assembly procedures or the electrofusion procedure, should only be made by personnel fully trained and qualified in those procedures. The equipment used shall be designed to operate for the selected pipe and fusion procedures. The equipment should be well maintained and capable of operating to specification. In addition, it is important that only the specified or recommended joining procedures be followed at all times during assembly operations.

Mechanical Connections

As in the heat fusion methods, many types of mechanical connection styles and methods are available. This section is a general description of these types of fittings.

The Plastics Pipe Institute recommends that the user be well informed about the performance attributes of the particular mechanical connector being utilized. Fitting selection is important to the performance of a piping system. Product performance and application information should be available from the fitting manufacturer to assist in the selection process as well as instructions for use and performance limits, if any. Additional information for these types of products is also contained in a variety of specifications such as ASTM F1924, F1973, and AWWA C219.

PE pipe, conduit and fittings are available in outside diameter controlled Iron Pipe Sizes (IPS), Ductile Iron Pipe Sizes (DIPS), Copper Tubing Sizes (CTS) and Metric Sizes. There are also some inside diameter controlled pipe sizes (SIDR-PR). Before selecting mechanical fittings, establish which of the available piping system sizes and types are being installed to ensure proper fit and function. The pipe manufacturer can provide dimensional information, and the fitting manufacturer can advise on the correct fitting selection for the application.

Mechanical Compression Couplings for Small Diameter Pipes

This style of fitting comes in many forms and materials. The components, as depicted in Figure 7, are generally a body; a threaded compression nut; an elastomer seal ring or O-ring; a stiffener; and, with some, a grip ring. The seal and grip rings, when compressed, grip the outside of the pipe, effecting a pressure-tight seal and, in most designs, providing pullout resistance which exceeds the yield strength of the PE pipe. It is important that the inside of the pipe wall be supported by the stiffener under the seal ring and under the gripping ring (if incorporated in the design), to avoid deflection of the pipe. A lack of this support could result in a loss of the seal or the gripping of the pipe for pullout resistance. This fitting style is normally used in service lines for gas or water pipe 2" IPS and smaller. It is also important to consider that three categories of this type of joining device are available. One type provides a seal only, a second provides a seal and some restraint from pullout, and a third provides a seal plus full pipe restraint against pullout.

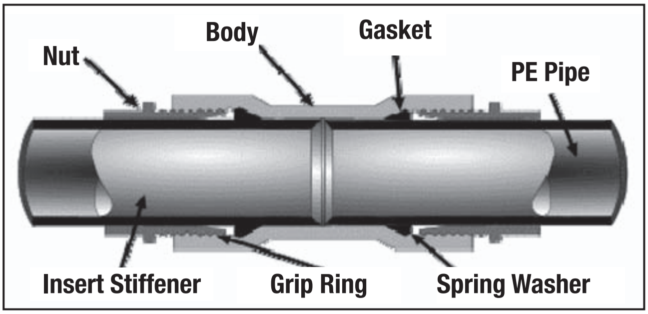


Figure 7 Typical Compression Nut Type Mechanical Coupling for Joining PE Pipe to PE Pipe

Stab Type Mechanical Fittings

Here again many styles are available. The design concept, as illustrated in Figure 8, is similar in most styles. Internally there are specially designed components including an elastomer seal, such as an "O" ring, and a gripping device to effect pressure sealing and pullout resistance capabilities. Self-contained stiffeners are included in this design. With this style fitting the operator prepares the pipe ends, marks the stab depth on the pipe, and "stabs" the pipe in to the depth prescribed for the fitting being used. These fittings are available in sizes from ½"CTS through 2" IPS and are all of ASTM D2513(2) Category I design, indicating seal and full restraint against pullout.

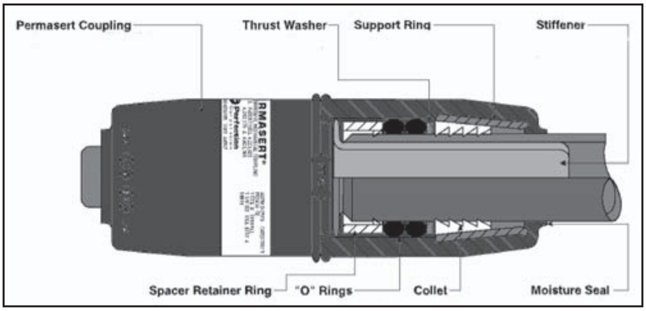


Figure 8 Stab Type Fitting

Mechanical Bolt Type Couplings

There are many styles and varieties of "Bolt Type" couplings available to join PE to PE or other types of pipe such as PVC, steel and cast iron in sizes from 1¼" IPS and larger. Components for this style of fitting are shown in Figure 9. As with the mechanical compression fittings, these couplings work on the general principle of compressing an elastomeric gasket around each pipe end to be joined, to form a seal. The gasket, when compressed against the outside of the pipe by tightening the bolts, produces a pressure seal. These couplings may or may not incorporate a grip ring, as illustrated, that provides pullout resistance sufficient to exceed the yield strength of the PE pipe. When PE pipe is pressurized, it expands a little and shortens slightly due to Poisson's effect. In a run of PE pipe, the cumulative shortening may be enough to cause separation of unrestrained mechanical joints that are in-line with the PE pipe. This can be a particular concern where transitioning from PE pipe to Ductile Iron pipe. Joint separation can be prevented by installing external joint restraints (gripping devices or flex restraints; see Figure 16) at mechanical connections, or by installing in-line anchors or a combination of both. Additional restraint mechanisms are available to supplement the pull resistance of these types of fittings if needed. The fitting manufacturer can help guide the user with that information. Use of a stiffener is needed in this fitting style to support the pipe under the area of the seal ring and any gripping devices incorporated for pullout resistance.

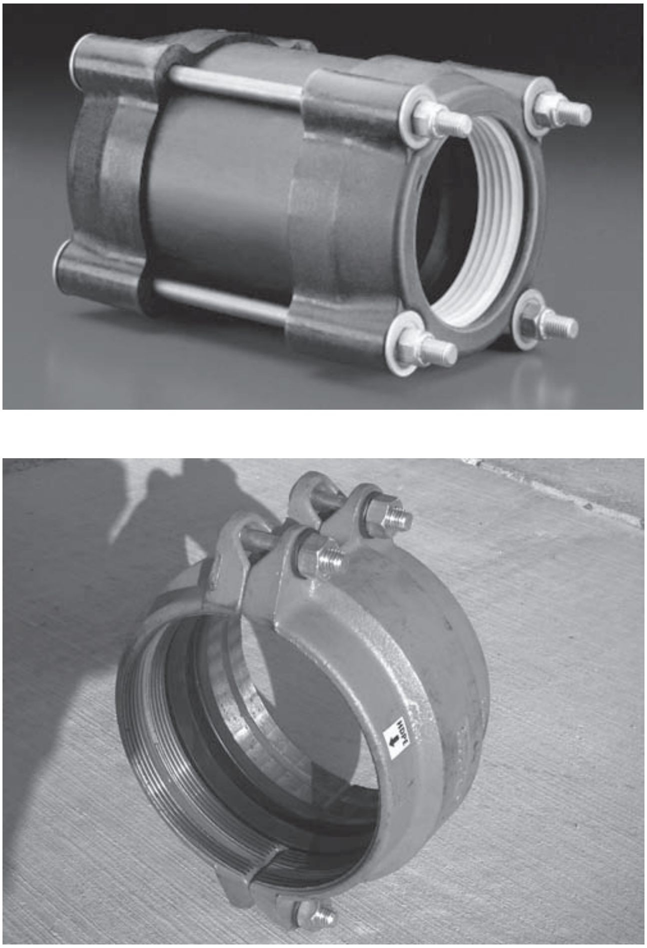


Figure 9 Mechanical Bolt Type Coupling for Joining Steel Pipe to PE or for Joining Two PE Pipes

Stiffener Installation Guidelines

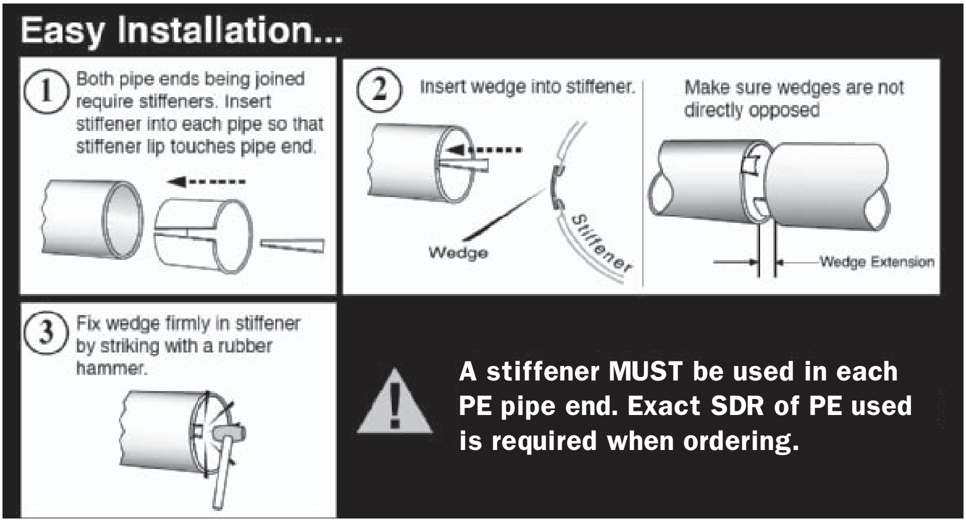
When connecting PE pipe to the bell end of a ductile iron or PVC pipe, it is recommended that a stiffener be added to the ID of the pipe to insure a good connection between the seal in the bell and the pipe. Check the pipe for toe in. If it is severe, cut the pipe back to remove it. If possible, have some means to press the stiffener into place. Lubricant will minimize the insertion effort required. A detergent or silicone grease is recommended.

There are two types of stiffeners available on the market. One type is a fixed diameter stiffener that matches the ID of the pipe being repaired (see Figure 10). Caution should be used when using fixed diameter stiffeners to be sure they are sized properly to obtain the proper press fit in the PE pipe. These are mainly used with smaller diameter service lines.

Figure 10 Fixed Diameter Stiffener for PE Pipe

Figure 11a Split Ring Stiffener for PE Pipe

The other type of stiffener is a split ring stiffener (see Figure 11a). These are normally made of stainless steel and provide a thin yet strong pipe wall reinforcement without disturbing the flow characteristic of the pipe. The easy installation instructions are shown in Figure 11b.



Easy Installation...

① Both pipe ends being joined require stiffeners. Insert stiffener into each pipe so that stiffener lip touches pipe end.

② Insert wedge into stiffener.

Make sure wedges are not directly opposed

③ Fix wedge firmly in stiffener by striking with a rubber hammer.

A stiffener MUST be used in each PE pipe end. Exact SDR of PE used is required when ordering.

Figure 11b Easy Installation Instructions

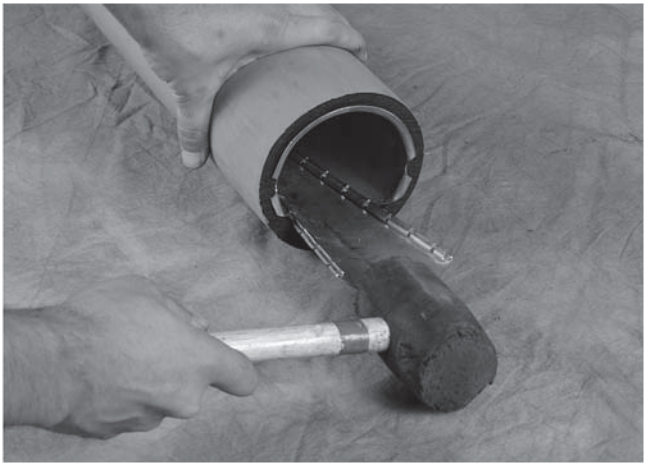


Figure 12 Install Split Ring Stiffener in PE Pipe

Flanged Connections

PE Flange Adapters and Stub Ends

When joining to metal or to certain other piping materials, or if a pipe section capable of disassembly is required, PE flange adapters, as depicted in Figures 13-15, are available. The "Flange Adapter" and its shorter version, the "Stub End," are designed so that one end is sized the same as the PE pipe for butt fusion to it. The other end has been especially made with a flange-type end that, provides structural support, which eliminates the need for a stiffener and, with the addition of a metal back-up ring, permits bolting to a similar flanged end connection — normally a 150-pound ANSI flange.(1)

The general procedures for joining would be:

1. Slip the metal ring onto the PE pipe section, far enough away from the end to avoid interference with operation of the butt fusion equipment.
2. If a stub end is used, first butt-fuse a short length of PE pipe to the pipe end of the stub end. If a "flange adapter" is used, the PE pipe-sized end is usually long enough that this step is unnecessary.
3. Butt fuse the flange adapter to the PE pipe segment.
4. The fusion bead may need to be removed to clear the back-up ring as it is moved against the flange.
5. Position the flanged face of the adapter at the position required so that the back-up ring previously placed on the PE pipe segment can be attached to the metal flange.
6. Install and tighten the flange bolts in a criss-cross pattern sequence (see TN 38), normally used with flange type connections, drawing the metal and PE flange faces evenly and flat. Do not use the process of tightening the flanges to draw the two sections of pipe together.

At lower pressure, typically 80 psi or less, a gasket is usually not required. At greater pressure, the serrated surface of the flange adapter helps hold the gasket in place. The flange face serration's should be individual closed concentric serration's as opposed to a continuous spiral groove which could act as a leak path. Standard Back-Up Rings are AWWA C207 Class D for 160 psi and lower pressure ratings, or Class 150 for higher pressure. Back-up ring materials are steel, primer coated steel, epoxy coated steel, or stainless steel. Ductile iron and fiberglass back-up ring materials are also available. In below ground service, coatings and cathodic protection may be appropriate to protect metal back-up rings from corrosion. One edge of the back-up ring bore must be rounded or chamfered. This edge fits against the back of the sealing surface flange.

An all-PE flange without a back-up ring is not recommended because PE flanges require uniform pressure over the entire sealing surface. Without a back-up ring, a PE flange will leak between the bolts.

Flange adapters differ from stub-ends by their overall length. A flange adapter is longer allowing it to be clamped in a fusion machine like a pipe end. The back-up ring is fitted to the flange adapter before fusion, so external fusion bead removal is not required.

A stub end is short and requires a special stub-end holder for butt fusion. Once butt fused to the pipe, the external bead must be removed so the back-up ring can be fitted behind the sealing surface flange. In the field, flange adapters are usually preferred over stub-ends.

Figure 13 Flange Adapter Assembly

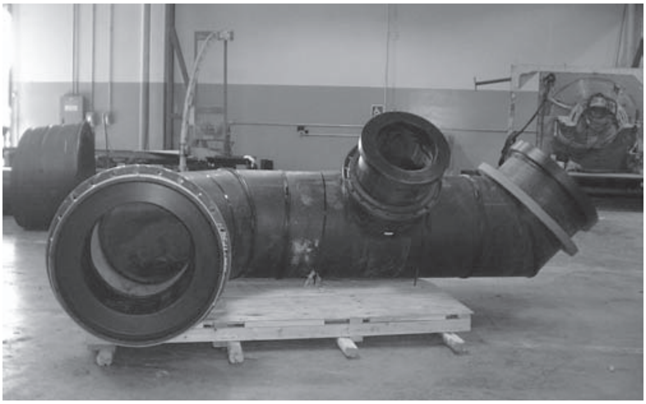


Figure 14 Fused Manifold Assembly with Flange Adapters and Back Up Rings

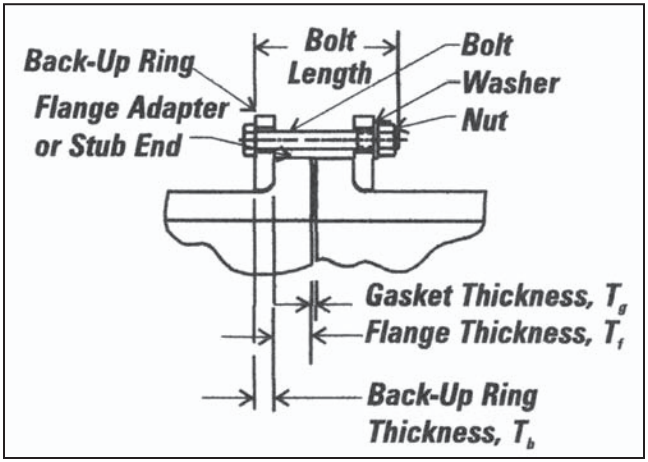


Figure 15 Flange Adapter Bolted Assembly Cross Section

Flange Gasket

A flange gasket may not be required between PE flanges. At lower pressures (typically 80 psi or less) the serrated flange sealing surface may be adequate. Gaskets may be needed for higher pressures and for connections between PE and non-PE flanges. If used, gasket materials should be chemically and thermally compatible with the internal fluid and the external environment, and should be of appropriate hardness, thickness and style. Elevated temperature applications may require higher temperature capability. Gasket thickness should be about 1/8”-3/16” (3-5mm) and about 60-75 Shore A hardness. Too soft or too thick gaskets may blow out under pressure. Overly hard gaskets may not seal. Common gasket styles are full-face or drop-in. Full-face style gaskets are usually applied to larger sizes, because flange bolts hold a flexible gasket in place while fitting the components together. Drop-in style gaskets are usually applied to smaller pipe sizes.

Flange Bolting

Mating flanges are usually joined together with hex bolts and hex nuts, or threaded studs and hex nuts. Bolting materials should have tensile strength equivalent to at least SAE Grade 3 for pressure pipe service, and to at least SAE Grade 2 for non-pressure service. Corrosion resistant materials should be considered for underground, underwater, or other corrosive environments. Flange bolts are sized 1/8” smaller than the blot hole diameter. Flat washers should be used between the nut and the back-up ring.

Flange bolts must span the entire width of the flange joint, and provide sufficient thread length to fully engage the nut.

Flange Assembly

Mating flanges must be aligned together before tightening. Tightening misaligned flanges can cause flange assembly failure. Surface or above grade flanges must be properly supported to avoid bending stresses. Below grade flange connections to heavy appurtenances such as valves or hydrants, or to metal pipes, require a support foundation of compacted, stable granular soil (crushed stone), or compacted cement stabilized granular backfill, or reinforced concrete. Flange connections adjacent to pipes passing through structural walls must be structurally supported to avoid shear loads.

Prior to fit-up, lubricate flange bolt threads, washers, and nuts with a non-fluid lubricant. Gasket and flange sealing surfaces must be clean and free of significant cuts or gouges. Fit the flange components together loosely. Hand-tighten bolts and re-check alignment. Adjust alignment if necessary. Flange bolts should be tightened to the same torque value by turning the nut. Tighten each bolt according to the patterns and torques recommended by the flange manufacturer. PE and the gasket (if used) will undergo some compression set. Therefore, retightening is recommended
about an hour or so after torquing to the final torque value the first time. In criss-cross pattern sequence, retighten each bolt to the final torque value. For high pressure or environmentally sensitive or critical pipelines, a third tightening, about 4 hours after the second, is recommended.

Special Cases

When flanging to brittle materials such as cast iron, accurate alignment, and careful tightening are necessary. Tightening torque increments should not exceed 10 ft.-lbs. PE flange adapters and stub ends are not full-face, so tightening places a bending stress across the flange face. Over-tightening, misalignment, or uneven tightening can break brittle material flanges.

When joining a PE flange adapter or stub end to a flanged butterfly valve, the inside diameter of the pipe flange should be checked for valve disk rotation clearance. The open valve disk may extend into the body of the flange adapter/stub end. Valve operation may be restricted if the pipe flange interferes with the disk. If disk rotation clearance is a problem, a tubular spacer may be installed between the mating flanges, or the pipe flange bore may be chamfered slightly. At the sealing surface, chamfering must not increase the flange inside diameter by more than 10%, and not extend into the flange more than 20% of the flange thickness. If spacer plates are used, the flange bolt length must be increased by the length of the spacer.

Mechanical Flange Adapters

Mechanical Flange Adapters are also available and are shown in Figure 16. This fitting combines the mechanical bolt type coupling shown in Figure 9 on one end with the flange connection shown in Figure 10 on the other. This fitting can provide a connection from flange fittings and valves to plain end pipes. The coupling end of this fitting must use a stiffener when used to join PE pipe. Mechanical flange adapters may or may not include a self-restraint to provide restraint against pipe pullout as part of the design. Alternative means of restraint should be used when joining PE pipe if the mechanical flange adapter does not provide restraint. Contact the manufacturer of these fittings for assistance in selecting the appropriate style for the application.

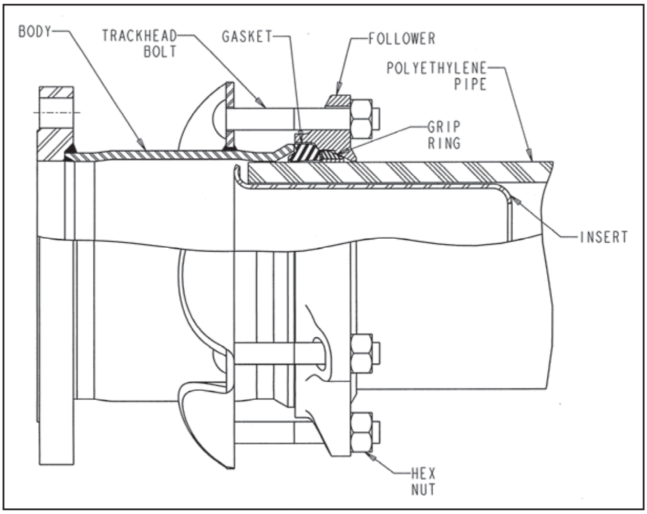


Figure 16 Bolt Type Mechanical Flange Adapter

Solid DI Sleeve Connections to PE pipe

Solid Sleeves are ductile iron fittings designed to connect DI/PVC pipe to other piping materials including PE pipe. They come in a variety of configurations depending on the application. Most solid sleeves have a flange or MJ hub to attach to the PE pipe. On the ductile iron pipe side, a Megalug flange is attached to the pipe and a gasket is installed over the pipe and into the sleeve before bolting the Megalug to the Sleeve flange. A standard PE MJ Adapter kit is used on the PE pipe side to complete the assembly. Be sure to use the manufacturer’s recommended bolting procedures for this assembly. (See Figure 17.)

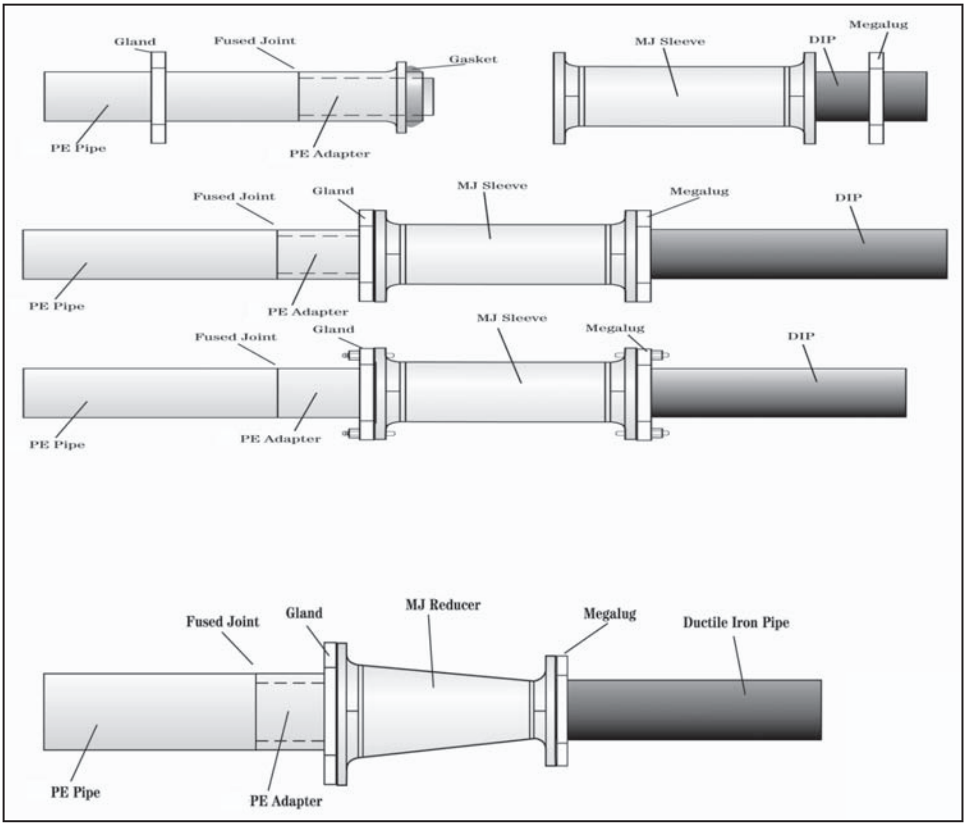


Figure 17 Solid DI Sleeve Connections to PE pipe

Another solid sleeve design is called a "One Bolt" Solid Sleeve and can be used to connect PE pipe to PVC or DI pipe. This is similar to a standard PE mechanical connector but has a special locking ring that grips the PE pipe to prevent pullout. It is recommended to use a stiffener inside the PE pipe, especially if the DR is more than 11. This connection can be installed very quickly in the field and may also be used for repair. Consult with the sleeve manufacturer for application and restraint advice.

Figure 18 One Bolt Solid Sleeve Connection

PE Pipe Connection to DI or PVC Bell End

Another method of restraining the above mentioned connection would be the use of a restraint harness and the attachment of flex restraint sections to the PE pipe. These flex restraint pieces are electro-fused to the PE pipe to achieve the proper stab depth in the PVC or DI bell and the restraint harness plate is attached behind them. The opposite end of the restraint harness is attached behind the DI/PVC hub. Install the PE pipe in the PVC/DI bell until it bottoms out on the flex restraints and tighten the tie rods to prevent the assembly from pulling apart. As discussed above: to maintain proper contact with the seal in the DI/PVC fitting, it is recommended that a stiffener be installed in the PE pipe end.

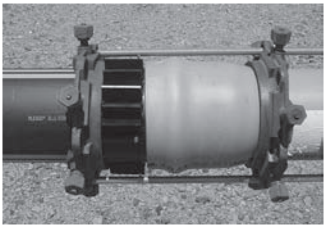


Figure 19 PE Pipe Connection to DI/PVC Bell End Using Flex Restraints on the PE Pipe

PE Bell Adapters to DI or PVC Pipe End

There are PE Bell Adapters available, up to 24" IPS, that are machined to the standard MJ Adapter internal configurations and have an external stainless steel backup ring installed to ensure positive seal contact. This connection incorporates a back-up flange behind the PE Adapter and a Mega-Lug flange on the PVC or DI pipe. Standard MJ seals and bolts are used to connect the assembly.

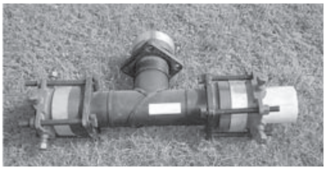


Figure 20 PE Bell Adapter to DI or PVC Pipe End

DI Valve with PE Ends

In most potable water systems, a valve is installed between the main and the hydrant. This can be fused in line using this special valve assembly with PE pipe installed on each side and available up to 12” pipe size. It has an PE ends installed on each side of the valve.

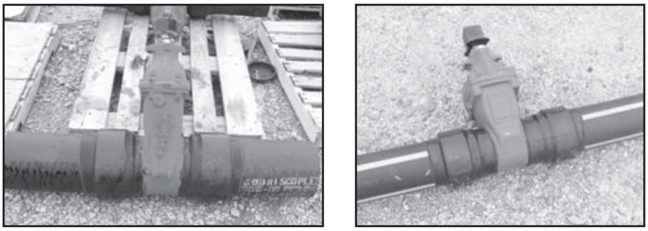


Figure 21 Ductile Iron Gate Valve with PE Ends

Dismantling Joint

Dismantling joints simplify installations and replacement of flanged fittings in retrofitting applications. Dismantling Joints provide the solution for adding, repairing or replacing flanged fittings within a flanged pipe system. In all applications, a restrained dismantling joint is required unless otherwise specified. (See Section titled Restraint Methods.)

Adjustable, slip joint design accommodates either wide gaps or close quarter installations and eliminates the need for precise measurements between flange connections. Available in sizes 2” and larger, for ductile iron or flanged PE piping systems. Standard flanges AWWA C207 Class D Flange. Other flanges are available upon request.

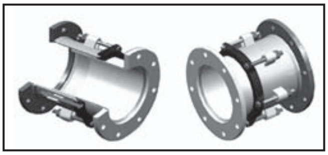


Figure 22 Dismantling Joint

Mechanical Joint (MJ) Adapters

PE pipe can be connected to traditional hydrants, valves and metal pipes using an MJ Adapter. A gland ring is placed behind the adapter before fusing, which can be connected to a standard ANSI/AWWA mechanical joint. When the gland ring is used, restraining devices are not required on the PE pipe.

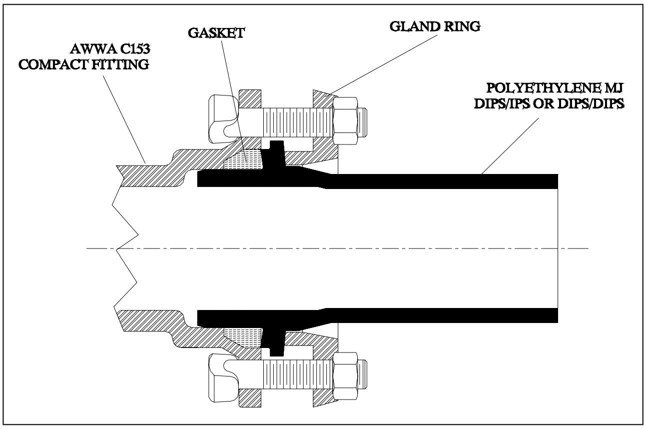


Figure 23 Typical Application of PE MJ Adapter

Transition Fittings

Other methods are available that allow joining of PE to metal. Transition fittings are available which are pre-assembled at the manufacturer's facility. These transition fittings are normally pull-out resistant, seal tight with pressure and have tensile values greater than that of the PE pipe part of a system. However, the user should insist on information from the manufacturer to confirm design capabilities or limitations. Transition fittings are available in all common pipe sizes and PE materials from CTS and larger with a short segment of PE pipe for joining to the PE pipe section. The metal end is available with a bevel for butt welding, with male or female pipe threads, or is grooved for a Victaulic(14) style, or flanged for connecting to an ANSI 150-pound flange.(1)

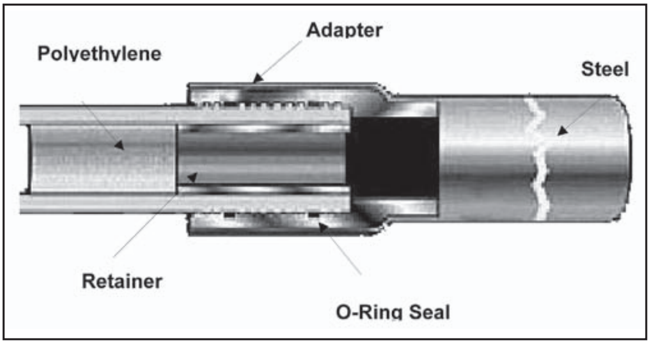


Figure 24 Standard Fitting for PE Pipe to Steel Pipe Transition

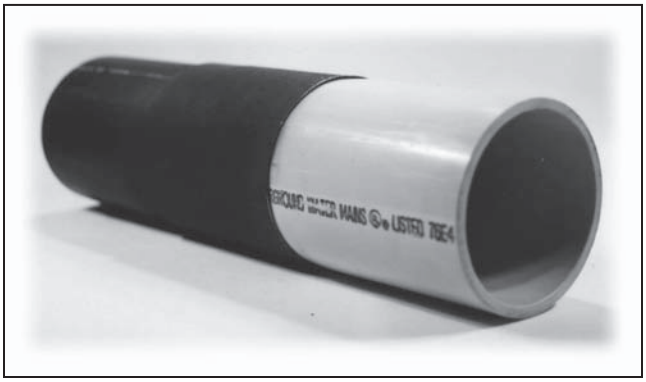


Figure 25 Transition Fitting - PE Pipe to PVC

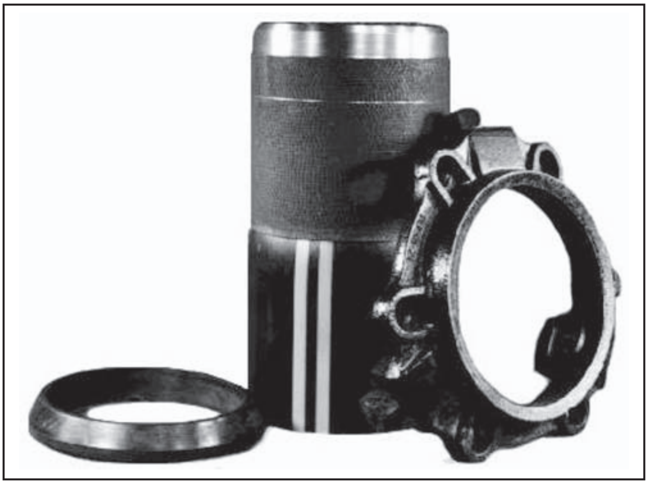


Figure 26 Transition Fitting - PE Pipe to DI with MJ Adapter

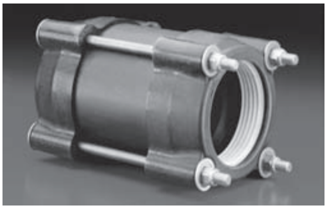


Figure 27 Hydrant Swivel Transition Fitting - PE Pipe to DI

Mechanical Joint Saddle Fittings

Mechanical joint saddle fittings have at least one mechanical joint which may connect the outlet to the service or branch pipe, or may connect the fitting base to the main, or both connections may be mechanical joints. Mechanical joint saddle fittings are made from PE, metals, and other materials.

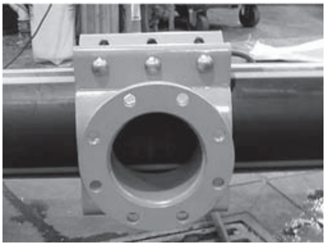


Figure 28 Mechanical Saddle

For mechanical joint outlets, the service or branch pipe is either supported with a tubular stiffener in the pipe ID, or the pipe end is fitted over a spigot (insert) end of the fitting. The outlet joint is completed using mechanical compression around the service or branch pipe OD. Depending upon design, gaskets may or may not be used. Observe the fitting manufacturer's instructions in making the outlet connection.

Plastic outlet pipes must be protected against shear or bending loads by installing protective sleeves or bridging sleeves, or special care must be taken to ensure that embedment materials are properly placed and compacted around the outlet.

The connection between the saddle base and the main may be by hot plate saddle fusion, or by electrofusion, or by mechanical connection. Hot plate saddle fusion and electrofusion have been previously discussed.

Mechanical saddle base connections are clamped or strapped to the side or top of the main pipe. Typically, gaskets or o-rings are used to seal between the saddle base and the main pipe OD surface to prevent leakage when the main wall is tapped. Once secured to the main per the fitting manufacturer's instructions, the main may be pierced to allow flow into the service or branch pipe.

Some mechanical joint saddle fittings can have an internal cutter to pierce the main pipe wall (Fig. 28). "Tapping tees or tapping saddles" (Fig. 29) are generally suitable for installation on a "live" or pressurized main (hot tapping). Branch saddles or service saddles that do not have internal cutters may also be hot tapped using special tapping equipment. Contact equipment manufacturer for information.

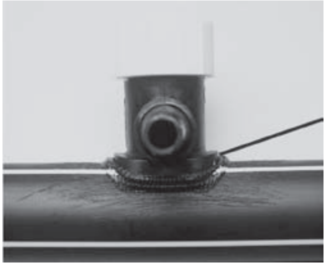


Figure 29 PE Tapping Tee with Cutter

Restraint Methods

A pipe section with fully restrained joints such as a long string of butt fused PE pipe will transmit Poisson effect pipe shortening from length to length through the restrained joints along the pipe string. Restrained joints include butt fusions, electro-fusions, socket fusions, bolted flange connections, MJ Adapter connections or other restrained mechanical connections. If an unrestrained bell and spigot or mechanical sleeve joint is in-line with the restrained section, the cumulative Poisson effect shortening and possible thermal expansion/contraction effect may cause in-line unrestrained joints or connections to be pulled apart. Therefore, unrestrained joints or mechanical connections that are in-line with fully restrained PE pipe must be either restrained or otherwise protected against pullout disjoining.

Wall Anchor

A typical pullout prevention technique is to restrain the transition connection by butt fusing a Wall Anchor in the PE pipeline close to the connection and pouring a concrete anchor around it as shown in Figure 30. Refer to the pipe manufacturer's recommendations on anchor size and pull out loads.

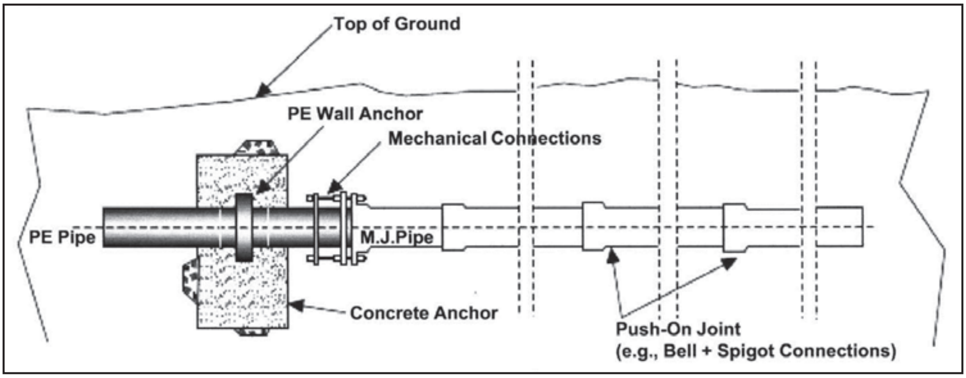


Figure 30 Wall Anchor Diagram

Another method of anchoring this connection is to electro-fuse several Flex Restraints to the PE pipe instead of butt fusing a wall anchor to the line as shown in Figure 31.

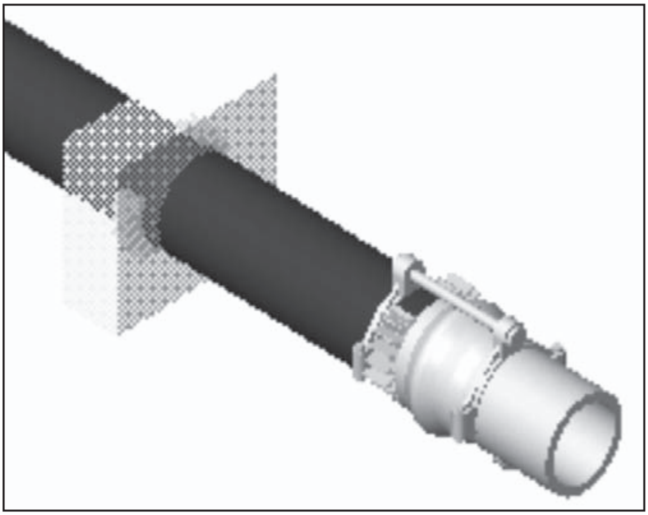


Figure 31 Flex Restraint Anchor

Mechanical Restraint Anchor

A typical pullout prevention technique is to restrain the transition connection and several non-PE bell and spigot joints down line from the transition connection as shown in Figure 32.

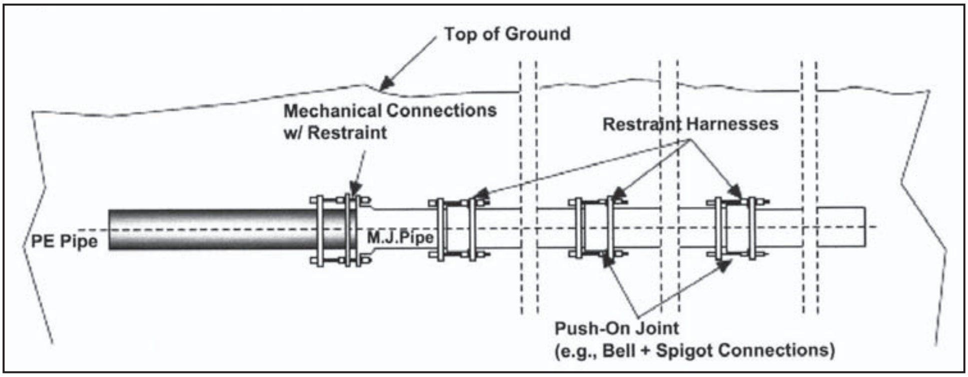


Figure 32 Mechanical Restraint of Existing Pipeline when Attaching to PE Pipe

Buried Poly Anchor

This product is designed to be buried in the soil and resist any linear movement that might occur with PE pipe without pouring a concrete anchor around it. In order to mobilize its buried anchoring restraint action, the Poly-Anchor simply requires at least 85% standard Proctor Density soil compaction in-situ to the top of the plate. Consult with the fitting manufacturer to ensure that the anchor size is adequate for the bearing capacity of the soil.

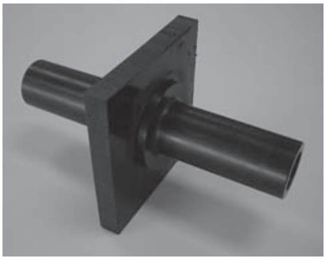


Figure 33 Buried Poly Anchor

Above Ground Pipeline Anchor

The above ground anchor fitting is commonly used to manage PE pipe from thermal expansion and contraction. The fitting is fused into the pipe-line, and a metal band (C-Clamp) is secured over the anchor fitting in the middle, and securely bolted to an I-beam, support bracket, or embedded into a concrete block up-to the spring-line with C-clamp over the pipe crown and bolted to the block . The metal band attaches the pipeline to the anchoring point; the OD rings prevent the pipeline from moving in expansion or contraction in either direction. The width of the center groove can be made as wide as required so as to get sufficient grip on the PE pipe for the thermal excursions expected.

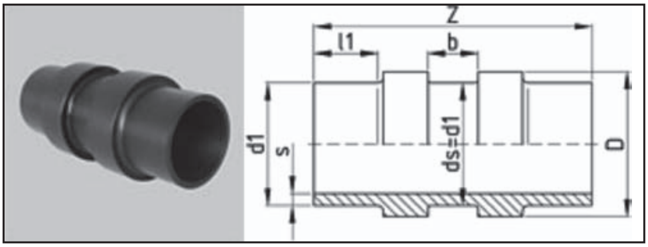


Figure 34 Above Ground Pipeline Anchor

PE to PVC Slip-Joint Anchor Fitting

A gasketed PVC pipe bell to plain end PE pipe should be restrained against PE thermal contraction and pressure thrust, to avoid possible long-term joint separation. The PVC-Bell slip-Joint Anchor Fitting (PVC-SJA Fitting) with internal stiffener to support gasket load, provides the restrained connection from PE pipe to bell-end PVC pipe. (For plain-end PVC, refer to Section titled PE Bell Adapters to DI or PVC Pipe End). When the restraint rings with tie-rod option is specified, the rods and rings are supplied separately from the SJA fitting.

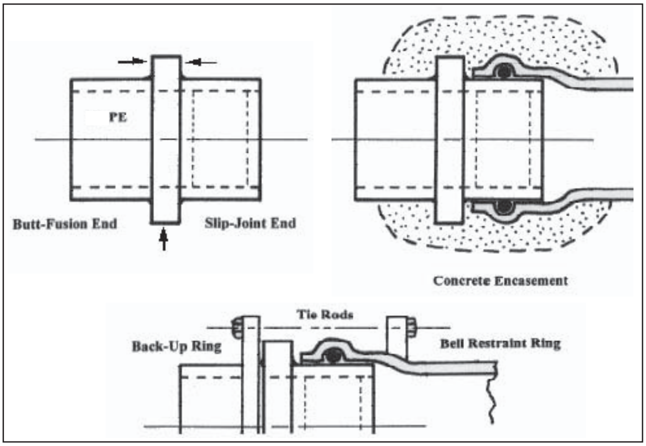


Figure 35 PE to PVC Slip-Joint Anchor Configurations

Summary

The applications for PE piping products continue to expand at an accelerating rate. Gas distribution lines, potable water systems, submerged marine installations, gravity and force main sewer systems, and various types of above-ground exposed piping systems are but a few of the installations for which PE pipe and fittings have been utilized.

As piping products applications expand, so does the use of new and existing joining methods expand.

A key element to this continued success is the diversity of methods available to join PE pipe and fittings. The integrity of the butt and socket fusion joining technique has been proven by the test of time in a variety of applications. The manufacturers of PE pipe and fittings have made every effort to make the systems as comprehensive as possible by producing a variety of fittings and components to insure compatibility with alternate piping materials and system appurtenances.

The purpose of this chapter has been to provide the reader with an overview of the various methods by which PE piping materials may be joined. As a result the reader has developed a further appreciation for the flexibility, integrity, and overall utility afforded in the design, installation, and performance of PE piping systems and components.

It should be noted that this chapter does not purport to address the safety considerations associated with the use of these procedures. Information on safe operating procedures can be obtained from the manufacturers of the various types of joining equipment or PE products.

References

1. ASME/ANSI B16.5. (1996). *American National Standard on Pipe Flanges and Flanged Fittings*, American National Standards Institute, New York, NY.
2. ASTM D2513, Standard Specifications for Thermoplastic Gas Pressure Pipe, Tubing, and Fittings, *Annual Book of Standards*, ASTM, West Conshohoken, PA.
3. ASTM F2620, " Standard Practice for Heat Fusion Joining of Polyethylene Pipe and Fittings, West Conshohoken, PA.
4. ASTM D3140, Standard Practice for Flaring Polyolefin Pipe and Tubing, *Annual Book of Standards*, ASTM, West Conshohoken, PA.
5. ASTM F894, Standard Specification for PE (PE) Large Diameter Profile Wall Sewer and Drain Pipe, *Annual Book of Standards*, ASTM, West Conshohoken, PA.
6. ASTM F1041, Standard Guide for Squeeze-Off of Polyolefin Gas Pressure Pipe and Tubing, *Annual Book of Standards*, ASTM, West Conshohoken, PA.
7. ASTM F1056, Standard Specification for Socket Fusion Tools for Use in Socket Fusion Joining PE Pipe or Tubing and Fittings, ASTM, West Conshohoken, PA.
8. AWWA C901, PE (PE) Pressure Pipe and Tubing, 1/2 in. Through 3 in., for Water Service, American Water Works Association, Denver, CO.
9. Caution Statement on Sidewall Heat Fusion Without Use of Mechanical Assist Tooling, *Statement T.* Plastics Pipe Institute, Irving, TX.
10. *Code of Federal Regulations*, Title 49, Part 192, Subpart F., Pipeline Safety Regulations, Washington, DC.
11. General Guidelines for the Heat Fusion of Unlike PE Pipes and Fittings, Report TN-13, Plastics Pipe Institute, Irving, TX.
12. *IAPMO*, International Association of Plumbing and Mechanical Officials, Walnut, CA.

13. PPFA. Plastics Pipe and Fittings Association, Glen Ellyn, IL.
14. *Victaulic General Catalog on Mechanical Piping Systems*. (1988). Victaulic Company of America, Easton, PA.
15. Generic Butt Fusion Procedure for PE Gas Pipe, PPI TR-33, Plastics Pipe Institute, Inc., Irving, TX.
16. Generic Saddle Fusion Procedure for PE Gas Pipe, PPI TR-41, Plastics Pipe Institute, Inc., Irving, TX.
17. AWWA C207: C207-07: Steel Pipe Flanges for Waterworks Service, Sizes 4 In. Through 144 In. (100 mm Through 3,600 mm), American Water Works Association, Denver, CO.
18. TN 38- Bolt Torque For Polyethylene Flanged Joints, Plastics Pipe Institute, Irving, TX.
19. TN 36- General Guidelines for Connecting PE Potable Water Pressure Pipes to DI and PVC Piping Systems, Plastics Pipe Institute, Irving, TX.

Chapter 10

Marine Installations

Introduction

Since the early 1960's, just a few years after its first introduction, polyethylene (PE) piping has been increasingly used for various marine applications such as effluent outfalls, river and lake crossings, and fresh and salt-water intakes. Immunity to galvanic corrosion is a major reason for selecting PE. The combination of air and water, but particularly seawater, can be very corrosive to ordinary metallic piping materials. But other beneficial features, as follows, combine to make PE piping particularly well-suited for marine applications:

Light weight – For a given pipe diameter and equivalent performance requirements, the weight of PE pipe is around one tenth of the weight of concrete pipe and less than one half that of cast iron. Handling of PE requires a minimum of heavy equipment.

It floats – Because PE's density is about 96% of that for fresh water, and about 94% of that for sea water, PE pipe floats even when full of water. Long lengths can be assembled on shore where the empty pipe may be weighted to an extent that allows air-filled pipe to be floated to its intended location, and in most cases, is also sufficiently weighted to keep it anchored at its final submerged location after the air has been replaced with water.

Integral, "bottle-tight" joints – By means of the butt fusion method, continuous lengths of PE pipe can be readily assembled without the need of mechanical fittings. The resultant heat fusion joints are as strong as the pipe, and they eliminate the risk of joint leakage.

Flexibility –The flexibility of PE pipe allows it to be gradually sunk and to adapt to the natural topography of underwater surfaces. This results in a more simplified sinking procedure, and it also means that the flexible pipeline can normally be placed directly on the natural bottom without any trenching or other form of preparation of continuous level support.

Ductility (strainability) – Because of its relatively high strain capacity, PE piping can safely adjust to variable external forces generated by wave and current action. High strain capacity also allows the PE piping to safely shift or bend to accommodate itself to altered bedding that can result by the underscouring that may sometimes occur with strong wave and current actions.

Conventional, non-flexible materials such as concrete or iron pipe can only afford relatively small deformations before risking leakage at, or structural failure of, the joints. As the exact magnitude of the maximum forces that can act on rigid pipes is difficult to predict, installations using piping that only allows relatively small deformation at the joints, or limited bending strain in the pipe, requires a large "safety factor," such as a relatively heavy loading to stabilize the pipe against movement, or the trenching of the pipe into sea bed sediments so as to stabilize it against movement that can result from heavy sea action. Such construction techniques tend to be more difficult, time-consuming and relatively expensive. In contrast, the flexibility and ductility of PE allows it to adapt to unconsolidated river and sea bottoms, and also to safely shift or bend under the forces resulting from occasionally strong currents or other actions. For most marine installations, PE piping needs only to be sufficiently weighted to keep it at the intended location and to prevent it from floating. This results in easier and less costly installations and in a submerged piping system that is capable of delivering very reliable and durable service. By choosing PE pipes, many projects have been accomplished which would not have been economically realistic with traditional piping materials. The lower overall cost of PE piping installations allows for the option of installing several small outfalls rather than one large one. Multiple outfalls can achieve greater environmental protection by the discharging of smaller quantities of effluent at separated points of discharge, and their use often results in lower onshore pretreatment costs.

A marine pipeline installation may involve considerable risk to the pipeline integrity both during installation and while in service. Guidance provided herein on the design and installation of PE piping is limited to those issues that are specific or are related to this material. It is not the intent of this chapter to cover the many other design, construction and safety issues that need to be considered in a marine installation.

The primary focus of this chapter is the design and installation of underwater lines by the “float-and-sink” method that is made possible through the use of the light-in-weight and flexible PE pipe. Under certain conditions – such as when it is not possible to delay navigation long enough to launch and sink a pipeline – it may be necessary, or it may be more practical, to use a variation of the “float-and-sink” method that is herein described. In one variation, one or more separate long-segments of the pipeline with a flange at each end are assembled and floated. These segments are then sunk, properly positioned and bolted together by divers. Another alternative method is the “bottom-pull” method, which is briefly described at the end of Step 8. However, regardless of which method is used, the general design and installation principles that apply to the “float-and-sink” method also apply to alternate methods.

Other marine applications for which PE piping has proven to be very suitable include temporary water surface pipelines, lines installed over marshy soils and lines used in dredging operations. These are described briefly. Design and installation for these marine applications are conducted in accordance with essentially the same criteria and principles as described for the “float-and-sink” method.

The Float-and-Sink Method – Basic Design and Installation Steps

In nearly all underwater applications, the design and installation of PE piping is comprised of the following basic steps:

1. Selection of an appropriate pipe diameter
2. Selection of an appropriate pipe SDR (i.e., an appropriate wall thickness) in consideration of the anticipated installation and operating conditions
3. Selection of the design, weight and frequency of spacing of the ballast weights that will be used to sink and then hold the pipe in its intended location
4. Selection of an appropriate site for staging, joining and launching the pipe

5. Preparing the land-to-water transition zone and, when required, the underwater bedding
6. Assembly of the individual lengths of pipe into a continuous string of pipe
7. Mounting of the ballast weights (This step may be done in conjunction with the next step.)
8. Launching the joined pipe into the water
9. Submersion of the pipeline into the specified location
10. Completion of the land-to-water transition

General guidance for the conduct of each of these steps follows. Since the specific conduct of each step can be affected by the choice of design and installation options discussed in other steps, the reader should review the entire chapter before deciding on the most applicable design and installation program.

Step 1 Selection of an Appropriate Pipe Diameter

Selection of an appropriate pipe diameter involves the estimation of the minimum flow diameter that is needed to achieve the design discharge rate. Guidance for doing this is provided in Chapter 6 of this Handbook.

A confirmation is then performed after the required pipe dimension ratio (DR) is determined in accordance with Step 2 which follows. Since the actual internal diameter of a pipe that is made to a standard outside diameter is dependent on the choice of pipe DR (see Table in the Appendix A.1 and A.2 in Chapter 6), the nominal pipe diameter/DR combination that is finally selected needs to have an actual inside diameter that is at least as large as the above determined minimum required flow diameter.

Step 2 Determination of the Required DR or SDR

The DR of the PE pipe, in combination with the pipe material's assigned maximum hydrostatic design stress, should allow the pipe to operate safely at the maximum anticipated sustained net internal pressure at the maximum anticipated operating temperature. Information, including temperature and environmental de-rating factors, for determining the appropriate pipe DR is presented in Chapter 6 and in Appendix, Chapter 3 of this Handbook. As an added "safety factor" it is common practice to pressure rate the pipe for the maximum anticipated operating temperature of either the internal or external environment, whichever is higher.

A check should be made to ensure that the selected pipe pressure rating is also sufficient to safely withstand any momentary pressure surges above normal operating pressure. Pressure surges tend to occur during pump start-ups or shut-downs, and also during sudden pump stops caused by emergencies, such as loss of power. Guidance for selecting a PE pipe with sufficient surge pressure strength is also presented in Chapter 6 of this Handbook.

A sudden pump stop can sometimes also result in flow separation, giving rise to a momentary reduction in pressure along some portion of the pipeline. Since underwater pipelines can be subject to relatively large external hydrostatic pressure, flow separation can sometimes lead to a significant net negative internal pressure. A check needs to be made to ensure that the pipe DR that has been selected based on maximum internal pressure considerations is also adequate to safely resist buckling, or pipe collapse, under the largest net negative internal pressure that could ever develop from whatever cause. Guidance for this design check is also provided in Chapter 6 of this Handbook. The ballast weights that are attached to PE pipe for purposes of its submersion also fulfill an important role as ring stiffeners that tend to enhance a pipe's inherent resistance to buckling. Common design practice is to accept this benefit as an added "safety factor," but not to directly consider it in the design procedure for selection of a pipe of appropriate ring stiffness.

Step 3 Determination of the Required Weighting, and of the Design and the Spacing of Ballast Weights

The determination of these parameters is made in accordance with the following sub-steps.

Step 3a Maximum Weighting that Allows Weighted Pipe to be Floated into Place

The buoyant or vertical lift force exerted by a submerged PE pipe is equal to the sum of the weight of the pipe and its contents minus the weight of the water that the pipe displaces. This relationship can be expressed mathematically as follows:

(1) $$F_B = [W_P + W_C] - W_{DW}$$

WHERE

F_B **= buoyant force, lbs/foot of pipe**

W_P **= weight of pipe, lbs/foot of pipe**

W_C **= weight of pipe contents, lbs/foot of pipe**

W_{DW} **= weight of water displaced by pipe, lbs/foot of pipe**

Since the density of PE (~59.6 lbs/cubic foot) is only slightly lower than that of fresh water (~62.3 lbs/cubic foot) the pipe contributes somewhat towards net buoyancy. However, the major lift force comes from the air-filled inner volume of the pipe. Since, for a pipe of given outside diameter, the size of the inner volume is determined by the pipe's wall thickness – the greater the thickness, the smaller the inner volume – and since a pipe's actual wall thickness can be expressed in terms of the pipe's diameter ratio (DR), Equation 1 can be rearranged as shown in Equation 2. The resultant net buoyancy force can be determined from the pipe's actual outside diameter, its DR (or SDR), the extent to which the pipe is filled with air, the density of the water into which the pipe is submerged, and the densities of the pipe and of the liquid inside the pipe:

(2)
$$F_B = \left[0.00545 D_o^2 \rho_w\right]\left[4.24\frac{(DR-1.06)}{(DR)^2}\frac{\rho_p}{\rho_w} + \left(1-\frac{2.12}{DR}\right)^2 (1-R)\frac{\rho_c}{\rho_w} - 1\right]$$

WHERE

F_B **= buoyant force, lbs/foot of pipe**

D_o **= external diameter of pipe, in**

D_R **= pipe dimension ratio, dimensionless**

R **= fraction of inner pipe volume occupied by air**

ρ_w **= density of the water outside the PE pipe, lbs/cu. ft**

ρ_p **= density of the pipe material, lbs/ cu. ft.**

ρ_c **= density of pipe contents, lbs/ cu. ft.**

The derivation of Equation 2 is presented in Appendix A-1. The reader is advised that Equation 2 does not consider lift forces that can result from water currents; refer to Appendix A-2 for further assistance with this topic.

A more succinct way of expressing the principle embodied in Equation 2 is as follows:

(3) $F_B = W_{DW}$ ["K"]

WHERE

W_{DW} **= 0.00545** $D_0^2 \rho_w$

Stated in words, the resultant buoyant force (F_B) is equal to the potential theoretical buoyant force (W_{DW}) times a buoyancy reduction factor ("K") that takes into account inner pipe volume, degree of air filling and the densities of the pipe and the liquid inside the pipe.

The manner by which the buoyancy reduction factor "K" is affected by a pipe's DR and the extent to which its inner pipe volume is filled with air, R, is indicated by the calculation results reported in Table 1. The values in this table have been computed based on the following densities: 62.3 lbs/ cu. ft for water both inside and outside the pipe, and 59.6 lbs/cu. ft for the PE pipe material. Using these K-values for approximation of the net buoyant force of a submerged pipeline in which a portion of the line is occupied by air greatly simplifies the calculations involved.

TABLE 1

Typical values of "K" in equation 3.0

"K" is the fraction of maximum potential buoyancy. The exact value of "K" is determined by the particular combination of pipe diameter ratio (SDR), pipe material and liquid densities and the extent (R) to which a PE pipe is filled with air*

Pipe SDR	Value of "K" as a function of R, the fraction of inner pipe volume that is occupied by air					
	R = 0.10	R = 0.15	R = 0.20	R = 0.25	R = 0.30	R =1.0 (100% Air)
9	-0.078	-0.107	-0.136	-0.166	-0.195	-0.604
11	-0.081	-0.113	-0.146	-0.178	-0.211	-0.667
13.5	-0.084	-0.119	-0.155	-0.190	-0.226	-0.723
17	-0.087	-0.125	-0.163	-0.202	-0.240	-0.776
21	-0.089	-0.130	-0.170	-0.210	-0.251	-0.817
26	-0.091	-0.133	-0.176	-0.218	-0.260	-0.850
32.5	-0.093	-0.137	-0.180	-0.224	-0.268	-0.879

* The "K" values in this table have been computed using Equation 2 and based on the following assumptions: a density of 62.3 lbs/cu ft for water outside and inside the pipe and 59.6 lbs/cu ft for the PE pipe material. The minus sign before each resultant value of "K" indicates a net upward, or buoyant force.

Step 3b Determining the Maximum Weighting That Still Allows PE Pipe To Float

When a PE pipe that is completely filled with air is weighted so that the submerged weighting is equal to W_{DW} (the weight of the water that is displaced by the outer volume of the pipe) times the appropriate value of "K" (e.g., the value given in the last column of Table 1), that pipe achieves neutral buoyancy – it neither sinks nor floats. Therefore, "K" represents the fraction of pipe displacement that, when counteracted by the placement of external weighting on the pipe, results in neutral buoyancy. With the objective in mind of facilitating a marine installation by the floating of a PE pipe so that it may readily be stored above water and then towed and maneuvered to its intended location, the weighting that is attached to the pipe needs to be limited to an amount that still allows an air-filled pipe to freely float on top of the water. To this end, the practice is to limit the weighting of an air-filled PE pipe to about 85% of the pipe displacement times the "K" value that corresponds to that pipe's DR and the densities of the pipe material and the water, for example, the "K" values reported in the last column of Table 1. This practice results in the limiting of the weighting of an air-filled pipe that is to be installed by the "float-and-sink" method to a maximum that can vary, depending on the pipe's DR, from about 57 to 75% of the pipe's displacement.

Step 3c Determining the Required Minimum Weighting for the Anchoring of a Submerged Pipe in its Intended Location

Fortunately, as indicated by analysis and confirmed by experience(1,2), in most cases a weighting of 25 to 50% of the pipe displacement is quite sufficient to maintain a properly anchored submerged PE pipe after it has been filled with water. The lower weighting has been found satisfactory in cases, like in lake crossings, where current and wave action are relatively mild, while the larger weighting is used in sea installations where sea actions are stronger. However, even for pipes that are exposed to normal sea conditions close to the shore, it has been found that a weighting of about 70% of the pipe displacement is quite satisfactory(1). As indicated by the values shown in Table 1, this extent of weighting still allows most PE pipes to float when air-filled.

In an article summarizing the state of the art in utilizing plastics pipe for submarine outfalls, Janson(3) reports that, based on past practical experience and theoretical studies, a 40-inch diameter PE ocean outfall line was installed in Sweden where, for depths greater than 40 feet, the pipe was weighted to 25% of its displacement; and in the surf zone, where the waves break and the water depth is about 10 feet, the loading was increased to 60% of the displacement. Closer to the shore, where wave action is at its strongest, it is common to protect the pipe by trenching it. In respect to trenched pipe, Janson also reports that, when a trench is refilled with fine-grained soil, the buried pipe can sometimes float from the trench, apparently a reaction resulting from the fluidization of the fill by strong wave action. This reference further reports that the possibility of floating from fine-grained backfill can be avoided by weighting the pipe to at least 40% of its displacement.

Calculation techniques have been developed for the determination of the required weighting of plastic pipes depending on anticipated current and wave action. A brief overview of the technical considerations upon which these calculations are based is included in Appendix A-2. References for further information are also provided.

In cases where it is indicated that the pipeline, or certain sections of the line, should be weighted to a greater extent than that which allows the pipe to float while filled with air, the attachment of the required ballast weights can be conducted in two stages: preliminary weighting is conducted so as to still allow the pipe to be floated into position, and then the additional required weights are added where required after the completion of the submerging of the pipe. Another option is to temporarily increase the pipe's buoyancy by the use of empty tanks or drums, or large blocks of rigid plastic foamed material that are then released as the pipe is being submerged. A further option, which is illustrated in Figure 1, is to attach the required ballast weights onto the pipe from a barge from which the pipe is slid to the bottom by means of a sled that has been designed to ensure that the bending of the pipe is less than that which might risk buckling (See the discussion on pipe submersion).

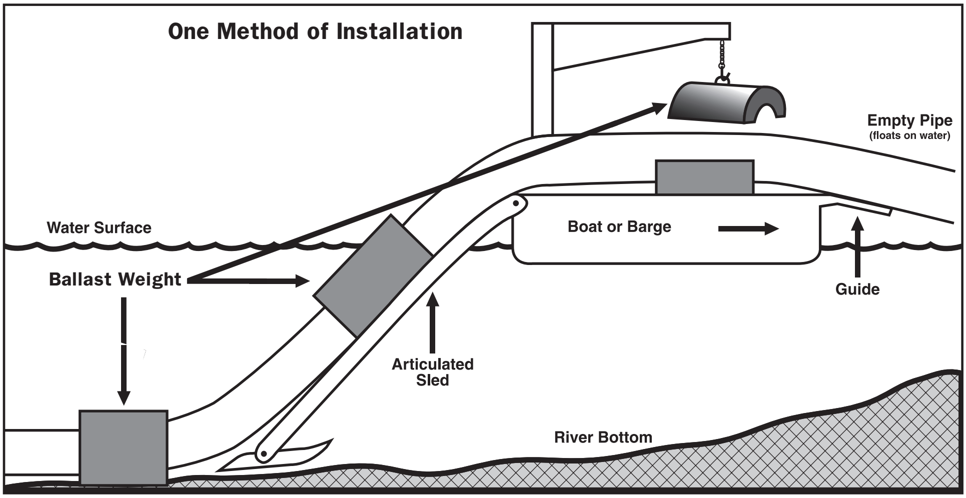


Figure 1 Submerging a heavily weighted pipe from a barge

Step 3d Ensuring that the Required Weighting Shall Not Be Compromised by Air Entrapment

As suggested by the "K" values in Table 1 that apply to pipes that are partially filled with air, even a modest amount of air entrapment can result in a lift force that can significantly reduce the quality of pipe anchorage. For example, if a pipeline is weighted to 25% of the water it displaces and in a section of that pipeline enough air accumulates to occupy just 10% of the pipe's inner volume, the lift produced by that amount of air will reduce the effective weighting in that portion of the pipeline to about only 15% of the pipe displacement. Such reduction is sure to compromise the stability of that pipe section against wave and current actions. Accordingly, one important objective in the design of the piping system to prevent the entrance and accumulation of air in all portions of the submerged section. In outfall systems, one effective means for achieving this objective is to utilize a surge or "drop" chamber into the system design, as illustrated in Figure 2. Another precautionary measure is to ensure that there are no localized high points along the submerged pipeline that could accumulate air or gases, particularly during periods of low or no flow rate.

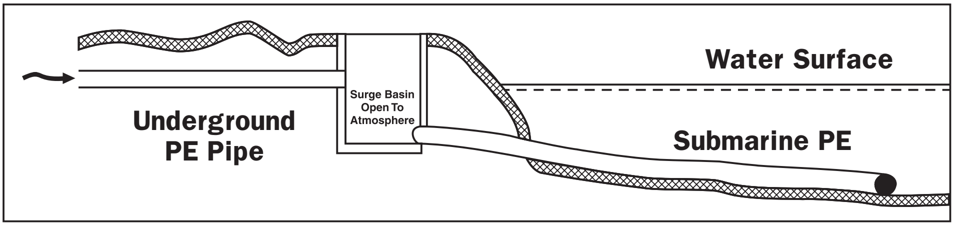


Figure 2 A surge chamber may be used to prevent air from entering a pipeline

In cases where the possibility of some accumulation of air or gas – which may be given off by chemical reactions – cannot be avoided, or where the line may at some time be emptied, it is necessary to add enough ballast weighting to offset the additional negative buoyancy so as to always hold the pipe in its intended location.

Step 3e Determining the Spacing and the Submerged Weight of the Ballasts To Be Attached to the Pipe

The objectives for limiting the spacing between ballast weights are essentially the same as those for establishing the support spacing requirements for above-ground suspended pipelines. In both cases the pipes are subject to a distributed loading – in the case of submerged pipelines, by the combined effect of current, lift and wave actions. The objective of the design is to limit resultant pipe deflection so that the resultant maximum fiber bending stresses and strains are within safe limits. An additional reason for limiting deflection in submerged pipelines is to reduce the chances of forming pockets in which air or gas can accumulate. The lift created by air-filled pockets can, if large enough, compromise the quality of the anchoring of the submerged pipe. Information on conducting the required calculations and on the appropriate limiting values for bending stress and strain is included in the chapter on design. Because of the concern of trapping air, support spacing for submerged pipes is normally delimited by allowable pipe deflection – considerably greater deflection would generally be permitted under the criteria of maximum bending stress or strain.

Listed in Table 2 are commonly used ballast spacings. To satisfy the objective for minimizing air entrapment, the spans in this table are somewhat shorter than for pipes that are suspended above ground. An added benefit of shorter spans is that they better distribute anchoring loads on the sea bottom, which often offers only moderate load bearing capacity. Additionally, these shorter spans minimize the chance of pipe shifting, help smooth out the submersion process and they lead to ballasts that are more manageable both in size and in weight.

TABLE 2
Commonly Used Values for the Spacing of Ballasts

Nominal Pipe Diameter, in	Approximate Spacing (L), ft
Up to 12	5 to 10
Over 12, up to 24	7.5 to 15
Over 24, up to 63	10 to 20

Source: AWWA M55, PE Pipe – Design and Installation, Chp 8: Installation, Denver, Colorado, USA

The required submerged weight of the ballasts can be determined from the following:

(4) $$B_W = W_S \times L$$

WHERE

B_W = weight of ballast in water, lbs

W_s = required submerged weighting by ballasts, lbs per foot

L = center to center spacing between ballasts, feet

The resultant dry weight of the ballast depends on the density of the ballast material as compared to that of the water into which the ballast is to be submerged:

(5) $$B_A = B_W \frac{\rho_B}{\left(\rho_B - \rho_W\right)}$$

WHERE

B_A = weight of ballast in air, lbs

ρ_B = density of ballast, lbs/cu. ft (~144 lbs/cu ft for plain concrete, ~ 150 for reinforced)

ρ_W = density of water, lbs/ cu ft (~62.3 lbs/cu ft for fresh water, ~64.0 lbs/cu ft for sea water)

Since the weight of a ballast cannot be closely predicted or readily adjusted, it is more practical to tune in the final weighting to the required value by adjusting the distance between ballasts of known weight. To this end the following formula, derived by combining Equations 4 and 5, may be used:

(6) $$L = \frac{B_A}{W_S} \frac{\left(\rho_B - \rho_W\right)}{\rho_B}$$

Step 3f Design and Construction of Ballast Weights

To prevent cracking of ballasts when handling, tightening and moving PE pipe, they are typically made of suitably reinforced concrete. Ballasts can be made to different shapes, although a symmetrical design such as round, square, or hexagonal is preferred to avoid twisting during submersion. Flat-bottomed ballasts are preferred if the submerged piping is likely to be subjected to significant currents, tides or wave forces because they help prevent torsional movement of the pipe.

Also, when such conditions are likely to occur, the ballasts should place the pipeline at a distance of at least one-quarter of the pipe diameter above the sea or river bed. The lifting force caused by rapid water movement that is at a right angle to a pipe that rests on, or is close to a sea or river-bed is significantly greater than that which acts on a pipe that is placed at a greater distance from the bed. This means that ballasts designed to give an open space between the pipe and the bed will give rise to smaller lifting forces.

For example, in accordance with the calculation procedure developed by Janson (See Appendix A-2), the lifting force that develops on a 12-in PE pipe that is resting directly on a sea bed and that is at an angle of 60° to the direction of a strong current that is flowing at a rate of about 10 feet per second is approximately 100 lbs per foot. When this pipe is raised above the sea bed so that the space between the bottom of the pipe and the sea bed is one-quarter of the pipe's outside diameter, the lifting force is reduced to about 25 lbs per foot.

The ballasts should comprise a top and bottom section that, when mated together over a minimum gap between the two halves, the resultant inside diameter is slightly larger than the outside diameter of the pipe. This slightly larger inside diameter is to allow the placement of a cushioning interlining to protect the softer PE pipe from being damaged by the hard ballast material. Another function of the interlining is to provide frictional resistance that will help prevent the ballasts from sliding along the pipe during the submersion process. Accordingly, slippery interlining material such as polyethylene film or sheeting should not be used. Some suggested interlining materials include several wraps of approximately 1/8-in thick rubber sheet or approximately ¼-in thick neoprene sponge sheet.

The purpose of the minimum gap between the two halves of the ballasts is to allow the two halves to be tightened over the pipe so as to effect a slight decrease in pipe diameter and thereby enhance the hold of the ballast on the pipe.

Additionally, experience has shown that in certain marine applications where tidal or current activity may be significant, it is feasible for the pipe to "roll" or "twist". This influence combined with the mass of the individual ballasts may lead to a substantial torsional influence on the pipe. For these types of installations, an asymmetric ballast design in which the bottom portion of the ballast is heavier than the upper portion of the ballast is recommended. Typical design considerations for this type of ballast are shown in Appendix A-3.

Suitable lifting lugs should be included in the top and bottom sections of the ballasts. The lugs and the tightening hardware should be corrosion resistant. Stainless steel strapping or corrosion-resistant bolting is most commonly used. Bolting is preferable for pipes larger than 8-in in diameter because it allows for post-tightening prior to submersion to offset any loosening of the gripping force that may result from stress-relaxation of the pipe material.

Examples of various successfully used ballast designs are shown in Appendix A-3.

Figure 3 Two-piece Concrete Anchors in Storage at Marine Job-Site

Step 4 Selection of an Appropriate Site for Staging, Joining and Launching the Pipe

The site for staging, joining and launching the pipe should preferably be on land adjacent to the body of water in which the pipeline is to be installed and near the point at which the pipe is to enter the water. Also, the site should be accessible to land delivery vehicles. If these requirements are not easily met, the pipe may be staged, joined and weighted at another more accessible location and then floated to the installation site. Long lengths of larger diameter PE pipe have been towed over substantial distances. However, considerable precautions should be exercised for insuring the stability of the towed materials in light of marine traffic, prevailing currents or impending weather considerations.

To facilitate proper alignment of the pipe-ends in the fusion machine and to leave enough room for the attachment of the ballast weights, the site near the water should be relatively flat. It is best to allow a minimum of two pipe lengths between the fusion joining machine and the water's edge. The site should also allow the pipe to be stockpiled conveniently close to the joining machine.

The ground or other surface over which the pipe is to be moved to the water should be relatively smooth and free of rocks, debris or other material that may damage the pipe or interfere with its proper launching. When launching a pipe with ballast weights already attached, provision should be made for a ramp or a rail skidway arrangement to allow the ballasts to move easily into the water without hanging up on the ground. As elaborated under the launching step, the end of a pipe that is moved into the water needs to be sealed to prevent water from entering and, thereby, compromising its capacity to float freely.

Step 5 Preparing the Land-to-Water Transition Zone and, When Required, the Underwater Bedding

At some point in time before the start of the submersion procedure, usually before the pipe is launched, a trench needs to be prepared in which to place the pipe between the point where it leaves the shore and the first underwater location beyond which the pipe is completely submerged without the need for external protection. The trench needs to be deep and long enough to protect the pipe from wave action, tidal scour, drifting ice and boat traffic. Special care should be employed in the design and construction of the land-to-water transition in ocean outfalls where occasional rough seas can result in very strong waves and in the scouring of the material below and around the pipe.

Unless weighted to a relatively high extent, say to at least 40% of the pipe displacement, a pipe lying in a land-to-water transition trench that has been filled with fine silt or sand could float up when that zone is subjected to strong wave action. One method of controlling this tendency would be to utilize increased weighting via enhanced ballast design. Alternatively, the submerged pipe could be placed on a bed of prepared backfill and subsequently surrounded by graded material in accordance with ASTM D2774, Standard Practice for Underground Installation of Thermoplastic Pressure Pipe. This ASTM standard provides that plastic pipe installed underground will be bedded and backfilled using material with a particle size in the range of ½” to 1 ½” depending on the outside pipe diameter. However, it may be necessary to place a layer of even larger particle sized fill (1 ½” to 4”) over the graded material to avoid movement of the stone backfill in some tidal zones or areas of strong current activity. Protection and stabilization of the pipe installation may be further enhanced by the placement of a 1 to 2 foot cover of blast rock over the completed installation.

With regard to the preparation of the underwater support generally, no dredging of filling needs to be carried out because the ballasts act to keep the pipe above the bottom material. The principal requirement is that the pipe should not rest or come in contact with large stones. To this end, larger stones that project above the bottom and that could come in contact with the pipe should be removed, as well as those that lie within about 3 pipe diameters on either side of the pipe.

Step 6 Assembly of Individual Lengths of PE Pipe Into Long Continuous Lengths

The butt fusion of individual lengths into a long string of pipe should be conducted by trained personnel and by means of appropriate equipment. The heat fusion parameters – e.g., temperature, interfacial pressure, heating and cooling times – should be as recommended by the pipe manufacturer for the particular pipe material and the joining conditions, including outdoor temperature and wind. (See Chapter 9 on PE Joining Procedures.)

Upon the completion of the heat fusing of an added individual length to the pipeline, the resultant longer pipe string is further moved into the water. As discussed elsewhere, the pipe should always be moved to the water using suitable mechanical equipment that will cause no damage to the pipe or to the pipe ends.

Ballast weights can be mounted before the pipe string reaches the water. If circumstances make it more practical, the ballasts can also be attached on the floating pipe from a floating barge by a scheme such as illustrated in Figure 4.

Step 7 Mounting the Ballasts on the Pipe

Since the process of heat fusing a new pipe section on a string of pipe usually takes less time than the attaching of ballasts, the later procedure can be quickened by increasing the number of work stations. It is also helpful to stockpile the ballasts adjacent to each work station. Adequate lift equipment needs to be on hand to move the ballasts from the stockpile to the pipe location and to lift the pipe to allow the ballasts to be positioned under it. This equipment can also be used to lift and pull the pipe into the water. A suitable ramp or skidway should be provided to move weighted pipe into the water with a minimum of drag. (See discussion on launching the pipeline.)

For mounting ballasts on the floating pipe it is necessary to have low-profile equipment such as a barge or raft that is of sufficient size to accommodate the required lifting equipment and to carry sufficient ballasts to allow for efficient operation. In this method the barge is brought alongside the floating pipe, the pipe is lifted to install one or more ballasts, and after their installation the pipe is returned to the water and a new section is moved onto the barge or the barge is advanced along the floating string of pipe. In either case, the working surface or platform of
the barge should be as close as possible to the water to reduce the need for a high lifting of the weighted pipe.

The steps involved in the mounting of ballasts include the following:

1. The placing of the protective/friction inducing material around the pipe. This can be done by first placing a pad over the lower half of the ballast and then placing a similar pad over the top of the pipe before the upper half of the ballast is lowered into position.
2. Lifting the pipe and positioning the lower half of the ballast under the pipe
3. Lowering the pipe so that it sits in the lower half of the ballast

4. Positioning and then lowering the upper half of the ballast so it sits on top of the pipe
5. Applying the strapping or tightening the bolts so that the ballasts are held fast to the pipe. (Note: before submersion, retightening of the bolts may be necessary to overcome any loss of gripping that may result from the stress-relaxation effect).

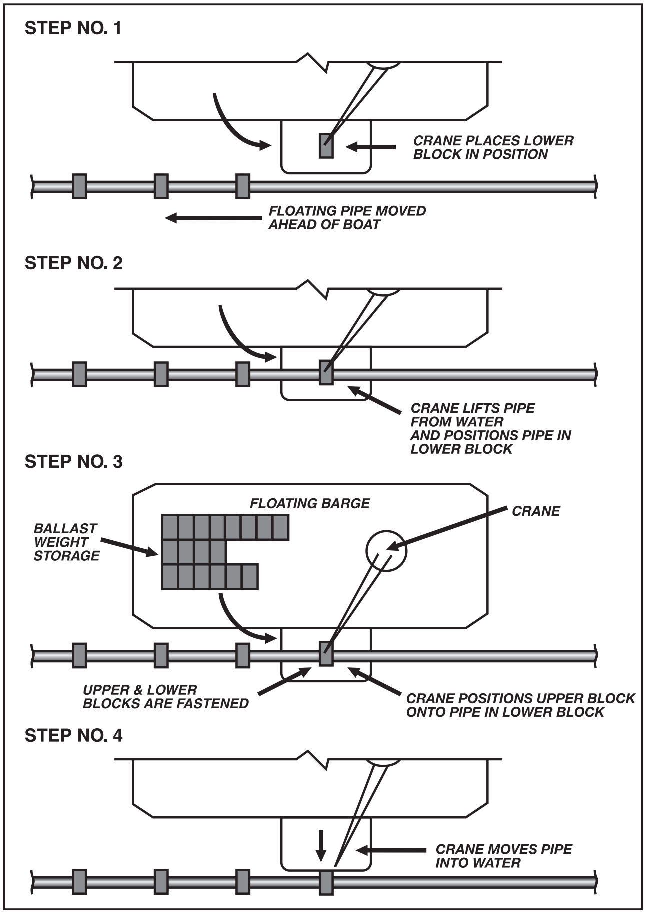


Figure 4 Installation of ballast weights from a raft or barge

Step 8 Launching the Pipeline into the Water

As previously cautioned, pipe that is launched into the water needs to have its ends closed, or its outlets located sufficiently high above the water, to prevent any water from entering the pipe. When the pipe is launched in the form of shorter strings of pipe that will later be joined to each other to produce the required overall length of submerged pipe, each separate section needs to have both ends sealed to prevent water from entering. In this respect, effluent outfall lines require special consideration.

Effluent outfalls usually terminate in one or more diffuser sections. Diffusers can be of different designs such as a “Y” or “T” outlet, a pipe length in which holes have been drilled on top of the pipe within 10 and 2 o’clock, or a pipe length onto which vertical risers consisting of short sections of smaller diameter PE pipe have been fused. Diffusers are often designed for connection to the pipe by means of flange assemblies. The connection can be made prior to launching, or by divers after the pipeline has been submerged. When a diffuser is attached prior to launching, it is necessary to float the diffuser higher up over the water by means of some additional buoyancy. This is necessary to prevent water from entering the pipe through the diffuser openings. This additional buoyancy is released as the pipe is sunk into position.

Extreme care should be taken in the submersion of a marine line with an engineered diffuser attached to the pipeline which is being sunk in place. The sinking process can create considerable stresses on the fittings that may be inherent to the design of the diffuser itself such as flanges, tees and/or other mechanical connections. A preferred method when placing a highly engineered diffuser into an HDPE marine pipeline is to first sink the flanged effluent pipe and then submerge the diffuser separately in easily controlled segments which may be connected to the main effluent pipe underwater using qualified diving contractors.

A pipe end that does not terminate in a diffuser section is best closed against entering water by attaching a blind flange assembly. The flange assembly consists of a PE stub end that is butt fused to the pipe end on which has been bolted a slip-on metal flange. A number of required tapped holes are drilled on the blind flange so as to allow for the installation of valves and other fittings required to control the sinking operation. (See the section on submersion of the pipeline.)

Figure 5 Unballasted PE Pipeline Being Floated Out to Marine Construction Barge Where Ballast Weights are Installed

Pipe with attached ballast weights should be moved into the water by means of a ramp or skidway arrangement that allows the ballasts to move easily into the water without hanging up on the ground. The ramp or skidway must extend sufficiently into the water so that when the pipe leaves this device the ballast weight is fully supported by the floating pipe. Pipe without ballast weights may be moved over the ground provided it is free of rocks, debris or any other material that may damage the pipe. When this is not practical, wooden dunnage or wooden rollers may be placed between the pipe and the ground surface.

The pipe should be moved using suitable equipment. The pipe may be moved by lifting and then pulling it using one piece of equipment while using another piece of equipment to simultaneously push the pipe from its inboard end. PE pipe should only be lifted using wide-band nylon slings, spreader slings with rope or band slings, or any other means that avoids the development of concentrated point loading. Under no conditions should the flange assemblies be used to pull the pipe.

Prior to the launching of the pipe into the water, a strategy should be worked out to control the floating pipeline as it moves into the water and to store it away from navigational traffic until such time as the entire length is ready for submerging. For this purpose, suitable marine equipment – such as boats that have adequate tugging power and maneuverability – may need to be on hand. Other means for controlling the pipe can be a system of heavy block anchors that are positioned on either side of the proposed site into which the pipe will be submerged. In the case of river crossings, a system of guide cables that are anchored on the opposite shore can serve to control the position of the pipeline, particularly when the pipeline is subject to strong river flow.

In the case of river crossings when navigational traffic prohibits the float-and sink procedure, a "bottom-pull" procedure, illustrated in Figure 6, has been successfully used. When using this procedure, only sufficient ballast is added to the pipe to ensure that the pipe follows the river bottom as it is winched from one shore to the other. After the completion of the "bottom-pull," additional ballast can be added or the pipeline can be adequately backfilled to produce the required anchoring and to offset any lift that may be created by currents or river flow.

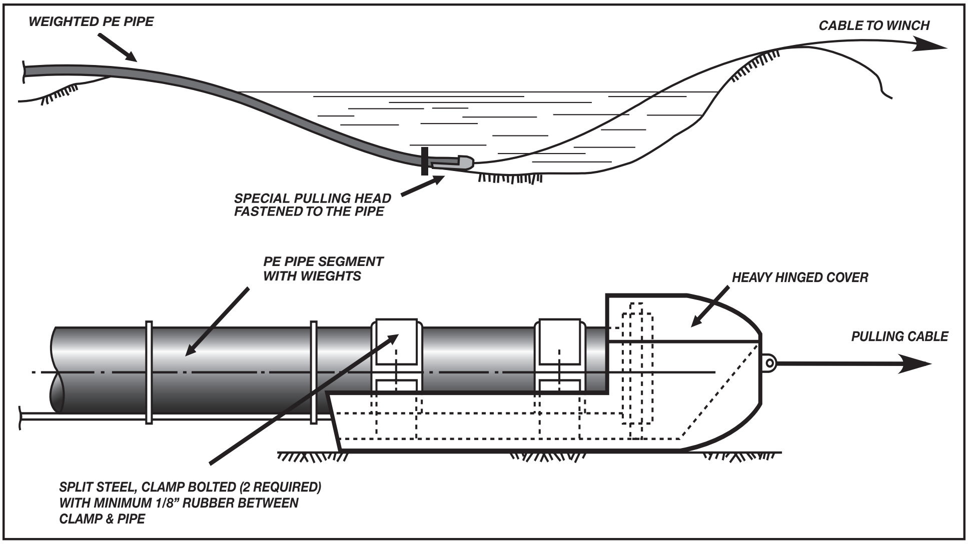


Figure 6 "Bottom-Pull" Installation of PE Pipe

Step 9 Submersion of the Pipeline Using the Float-and-Sink Method

To prepare the pipe for submersion, it is first accurately positioned over its intended location. The sinking operation basically consists of the controlled addition of water from the on-shore end of the pipe and the release of the entrapped air from the opposite end. The sinking is conducted so that it starts at the shore where the pipe enters the body of water and then gradually progresses into deeper waters. To achieve this, an air pocket is induced by lifting the floating pipe close to the shore. As the water is allowed to enter the pipe from the shore side, the added weight causes this initial air pocket to move outward and the intermediate section of pipe between the air pocket and the shore end to sink. As additional water is added, this pocket moves to deeper waters causing the sinking to progress to its terminal point in the body of water. This controlled rate of submersion minimizes pipe bending and it allows the pipeline to adjust and conform to the bottom profile so that it is evenly supported along its entire length (See Figure 7).

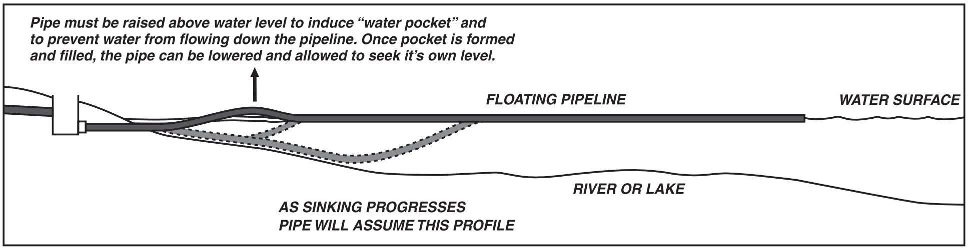


Figure 7 An induced water pocket initiates the submersion of the pipe and, as the pocket enlarges, it allows the submerging to gradually progress forward

A potential risk during the submersion operation is that, when the pipe sinking occurs too quickly, the bending of the pipe between the water-filled and air-filled portions may be sharp enough to risk the development of a kink, a form of localized pipe buckling. As a pipe is bent, its circumferential cross-section at the point of bending becomes increasingly ovalized. This ovalization reduces the pipe's bending moment of inertia, thus decreasing the bending force. Upon sufficient ovalization, a hinge or kink can form at the point of maximum bending an event that also leads to a sudden reduction of the bending force. Since the formation of a kink impedes the submersion process and can also compromise the pipe's flow capacity and structural integrity – in particular, the pipe's resistance to collapse under external pressure – it is essential that during submersion the bending of the pipeline be limited to an extent that will not risk the formation of a localized kink. The pipe bending radius at which buckling is in risk is given by the following expression:

(7)
$$R_b = D_o \frac{(DR - 1)}{1.12}$$

WHERE

R_b = **bending radius at which buckling can be initiated, in**

D_o = **outside pipe diameter, in**

DR = **pipe diameter ratio = average outside diameter divided by minimum wall thickness, dimensionless**

Janson's relationship for determination of minimum buckling radius (Eq. 7) was derived on the basis of a maximum pipe deflection (ovalization) due to bending of the pipe of 7% and a maximum strain limit in the pipe wall of 5%. In actuality, the short term strain limit for modern polyethylene pipe materials is somewhat higher, on the order of 7-10%. Further, we know that these pipe materials are capable of long-term service at higher degrees of ovalization in buried pipe installations. (Please refer to Chapter 6 of this Handbook.) As a result, the values presented in Table 3 are considered conservative guidelines for the short-term bending radius of polyethylene pipe during submersion of most marine pipelines. The designer may want to utilize a higher minimum bending radius to compensate for additional factors such as extremely strong currents, tidal activity, prevailing marine traffic, frequency of ballast placement, or other installation variables associated with a specific installation.

TABLE 3
Pipe Diameter Multipliers for the Determining of Minimum Bending Radii

Pipe DR	Multiplier*
11	8.9
13.5	11.2
17	14.3
21	17.8
26	22.3
32.5	28.1

* The minimum buckling radius of a pipe, in inches, is equal to the pipe's outside diameter, in inches, times the listed multiplier

It is essential that the water be introduced into the pipe at a controlled rate. This is done to ensure that the submersion process occurs at a rate that does not result in excessive localized pipe bending that could buckle the pipe. It also allows the pipe to settle properly on the bottom – thus avoiding any bridging between high spots which may make the pipe more vulnerable to movement when subjected to strong currents. Experience has shown that submerging the pipe at a rate in the range of about 800 to 1500 feet per hour has been found to be adequate for most cases. While the pipe is in the bent condition, long stoppage of the submersion procedure must be avoided. Consult with the pipe manufacturer and design engineer for specific submersion techniques for individual installations.

The risk of buckling can be minimized by applying a suitable pulling force during the submerging, such as illustrated by Figure 8.

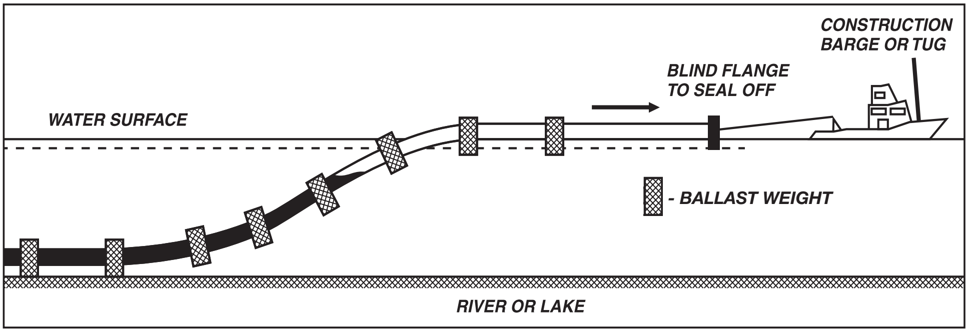


Figure 8 Pulling the pipe during submersion is a means for avoiding excessive bending that could risk buckling of the pipe

As water is being added at the shore-end of the pipe, air must be allowed to escape from the opposite end. In the case of outfall pipelines that terminate in one or more diffuser sections, the air is released through the diffuser outlets. When a pre-attached diffuser is used, it is necessary to support it with some additional buoyancy as a precaution against the water entering the pipe and causing that section of the pipeline to sink prematurely. Extreme care should be taken in the ballasting and submersion of elaborate diffuser systems that are sunk in concert with the main effluent pipe as the submersion process can create significant stresses on the tees, elbows or other fittings used in the design of the diffuser system. The preferred method is to submerge the flange or valved main effluent pipe and the diffuser separately and join the two sections underwater using qualified diving contractors.

When the end of a pipe that is being submerged terminates with a flange connection, air release can best be accomplished by installing a valved outlet in the blind flange outlet. To ensure that water will not enter through this outlet, a length of hose may be connected to the outlet, and the free end is held above water on a boat or by means of a float. After the completion of the submersion, a diver can remove the hose.

Should a problem be encountered during the submersion, the availability of a valved outlet on the outboard end of the pipeline allows the sinking procedure to be reversed. Compressed air can be pumped into the submerged line to push the water out and thus allow the line to be raised. Because compressed air packs a lot of potential energy – which, when suddenly released through a failure of a piping component, could present a serious safety hazard – the rule of thumb is to limit air pressure to not more than one-half the pipe’s pressure rating for water.

Under certain methods, such as the bottom-pull method that is described above, the necessary ballast to offset floatation during the installation of a water filled PE pipe can be of a temporary nature – for example, steel reinforcing bars that are strapped on the outside of the pipe. This temporary ballast can be removed after the installation of permanent anchoring. Permanent anchoring can consist of an appropriate quantity of stable backfill that is placed on pipe that has been installed in a trench, or it can consist of tie-down straps that are installed by augering or other procedures that result in the permanent anchoring of the pipeline. However, when considering an alternate means for anchoring a pipeline, it should be kept in mind that, as discussed earlier, a pipeline lying on the sea or river floor is subject to greater lift action by currents or waves than a pipeline that lies even a short distance above the bottom.

Step 10 Completing the Construction of the Land-to-Water Transition

After the pipeline has been submerged, the portion of the pipeline that has been lowered into a land-to-water transition trench should be backfilled with specified material and to the required depth of cover.

Post-Installation Survey

Upon completion of the installation of a submerged pipeline, it is advisable to have the complete line surveyed by a competent diver to ensure that:

- The pipeline is located within the prescribed right-of-way
- The ballasts holding the pipeline are all properly sitting on the bottom contour and that the line is not forced to bridge any changes in elevation
- The pipe is not resting on any rocks, debris or material that could cause damage
- Any auxiliary lines, such as hoses, ropes, buoyancy blocks or any other equipment used during the installation has been removed
- Where required, the pipe has been backfilled and the backfilling was done properly
- All other installation requirements established by the designer for the subject application have been complied with.

Other Kinds of Marine Installations

Because of its flexibility, light-weight and toughness PE piping has also emerged as a choice material for other types of marine applications. The basic design and installation principles described above for the “float-and-sink” method are, with some modifications, also valid for other types of marine applications. A brief description of some other kinds of marine applications is presented in the paragraphs that follow.

Winter Installations

Where ice conditions permit, PE pipe may be submerged from the surface of a frozen lake or river. After a long pipe length is assembled by means of heat fusion it can be easily pulled alongside the right-of-way. The heat fusion process needs to be performed in an adequately heated tent, or other shelter, to ensure fusion joint quality. Once the heat fusion has been completed, the ballast weights can be mounted. An ice trench is then cut with a saw, the ice blocks are moved out of the way and the pipeline is pushed into the trench. The submersion is carried out in accordance with the procedure previously described.

Installations in Marshy Soils

Installation of pipe in marshy or swampy soils represents one of the most demanding applications for any design engineer. Generally, marshy soils do not provide the firm and stable foundation that is required by rigid, more strain sensitive traditional piping materials.

Due to its flexibility and butt fusion joining technology, PE piping can readily adapt itself to shifting and uneven support without sacrifice of joint integrity. As soil conditions vary, the PE pipe can accommodate these irregularities by movement within the fluid-like soil envelope. Of course, care must be taken to consider any line, grade or external hydrostatic design requirements of the pipeline based on the operating conditions of the system. However, with these design aspects in mind, it is possible to utilize the engineering features of PE pipe to design a cost-effective and stable piping system that can provide years of satisfactory service in this highly variable environment.

In certain situations, the high water table that is characteristic of these soils can result in significant buoyant forces that may raise the pipe from the trench in which it has been installed. When this possibility presents itself, a ballast system may be designed using the same guidelines presented in this chapter which can prevent or minimize pipe flotation.

Water Aeration Systems

Smaller diameter submerged PE pipe, with small holes drilled into the top of the pipe has been used for the de-icing of marinas. Compressed air that bubbles out of these pipes raises warmer water that melts ice that forms on the water surface. When the system is operating, the submerged pipe is full of air, and the ballast weight design should be adequate to prevent the line from floating. Ballast also needs to be spaced frequently enough to minimize the upward deflection that results from the buoyancy force.

Dredging

PE piping is a natural choice for use in marine dredging operations. Its flexibility, combined with its light weight, buoyant nature and overall durability, provides for a piping material which has been successfully used for years in the demanding rigors of dredging operations. Generally, these types of applications require that the HDPE pipe be fused into manageable lengths that can be easily maneuvered within the dredge site. These individual lengths are then mechanically joined together using flanges or quick-connect type fittings to create a pipeline structure of suitable length for the project. As the dredge operation proceeds, pipe segments may be added or removed to allow for optimum transport of the dredge material.

Dredging operations can vary significantly in type of slurry, scale or operation and overall design. As such, a detailed analysis of dredge design using HDPE pipe is beyond the scope of this writing. However, the reader should note that as the particulate size and nature varies from project to project, it is possible to ballast the pipe so that it still floats and can be managed from the surface using tow boats or booms. This is accomplished by analysis of the composition of the dredge material and the design and attachment of suitable floats to the HDPE discharge or transport pipe.

Temporary Floating Lines

PE piping has also been used for temporary crossings of rivers and lakes. Its natural buoyancy allows a PE pipeline to float on or near the water surface. The principal design and installation requirement for floating line applications is to work out a system to maintain the pipe in its intended location when it is subject to currents, winds and wave action. To this end, cable restraints are generally used. The cables need to hold the pipe by means of stable collars that do not slip along the axis of the pipe and that cause no damage to the pipe material.

Conclusion

Modern HDPE piping materials are a natural choice for marine installations. The overall durability and toughness of these products, combined with the innovative and cost-effective installation methods that they facilitate, are compelling reasons for their use in effluent discharge systems, water intake structures and potable water or sanitary sewer force main marine crossings, as well as more temporary marine systems such as dredging operations.

The dependable butt fusion system of joining PE pipe, supplemented by the availability of a wide array of mechanical fittings, means that the design engineer has an abundance of tools available by which to design a leak-free piping system that lends itself to the most demanding marine installations. This same system of joining allows for the cost-effective installation of long lengths of pipe via the float and sink method, directional drilling or pull-in-place techniques. Utilizing the unique features of the PE piping system allows the designer to investigate installation methods that minimize the necessity of costly pipe construction barges or other specialized equipment. These same installation techniques may minimize the economic impact associated with marine traffic disruption.

This chapter provides an overall design perspective for some of the more typical applications of HDPE pipe in marine environments. Its intent is to provide the designer with a basic understanding of the utility that PE pipe brings to the designer of these challenging installations. More elaborate design investigation and methodology may be required depending on the specifics of the project under consideration. However, through a basic understanding of the benefits of PE pipe in marine installations and a fundamental understanding of the installation flexibility that they provide, it can be seen that PE pipe systems are a proven choice for modern, durable marine piping structures.

References

1. Janson, Lars-Eric. (1990, Sept 10-13). Review of Design and Experience With Thermoplastic Outfall Piping, ASTM STP 1093, Compendium of papers presented at the Buried Plastic Pipe Technology Symposium, Dallas, TX.
2. Berndtson, B. (1992, Sept 21-24). Polyethylene Submarine Outfall Lines, Paper presented at Plastics Pipes VIII, a symposium held in Koningshof, the Netherlands, and included in the Book of Proceedings for this symposium as published by The Plastics and Rubber Institute, London.
3. Janson, Lars-Eric. (1986). The Utilization of Plastic Pipe for Submarine Outfalls—State of The Art, *Water Science and Technology* ,Great Britain, Vol. 18, No. 11, pp 171-176.
4. Janson, Lars-Eric. (1996). *Plastics Pipe for Water Supply and Sewage Disposal,* published by Borealis, Sven axelsson AB/Affisch & Reklamtryck AB, Boras, Sewede.

Appendix A-1

Derivation of the Equation for the Determining of the Buoyant Force Acting on a Submerged PE Pipe (Equation 2 in the Text)

The first bracketed term in Equation 2, namely $[0.00545D^2_0\rho_W]$, is one commonly used form of the formula for obtaining a numerical value for the term W_{DW} in Equation 1, the weight of water that is displaced by the submerged PE pipe. This displaced weight is equivalent to the lift force acting on a submerged pipe that has an infinitely thin wall and that is completely filled with air. The sum of the three terms within the second set of brackets expresses the reduction of this potential lift force in consequence of the weight of the pipe (the first term) and that of its contents (the second term). As is evident from inspection of Equation 2, the extent to which the inner volume of a pipe is occupied by air (represented by the fraction R) exerts the more significant effect on resultant pipe buoyancy. Since a decrease in pipe DR (i.e., an increase in pipe wall thickness) results in a decrease in potential air volume space, a lower DR tends to reduce the potential buoyancy that can result from air filling.

1. The net buoyant (upward acting force) acting on a submerged PE pipe is:

(1) $$F_B = [W_p + W_c] - W_{DW}$$

WHERE

F_B **= buoyant force, lbs/foot of pipe**

W_p **= weight of pipe, lbs/foot of pipe**

W_c **= weight of pipe contents, lbs/foot of pipe**

W_{DW} **= weight of the water displaced by the pipe, lbs/foot of pipe**

2. W_p, the weight of pipe is:

$$W_p = V_p P_p$$

WHERE

V_p **= volume occupied by pipe material per foot of pipe**

P_p **= density of pipe material, lbs/ cu. ft**

Since $$V_p = \frac{\pi}{144} D_m t_a$$

WHERE

D_m **= mean pipe diameter of the pipe, in**

t_a **= average wall thickness, in**

And since $$DR = \frac{D_o}{t_m}$$

WHERE

D_o **= outside pipe diameter, in**

t_m **= minimum wall thickness, in**

Then, by assuming that the average wall thickness (t_a**) is 6% larger than the minimum (**t_m**), it can be shown that:**

(2) $$W_p = \frac{1.06\pi}{144}\left(\frac{D_o}{DR}\right)^2 (DR - 1.06)\rho_p$$

3. W_c, the weight of the pipe contents is equal to the volume occupied by the liquid inside the pipe times the density of the liquid:

$$W_c = V_L \rho_L$$

WHERE

V_L **= the volume occupied by the liquid, cu ft/linear ft**

P_L **= the density of the liquid inside the pipe, lbs/cu ft**

If the fraction of the inside volume of the pipe (V_I**) is expressed as** R **and as the formula for the inside volume is as follows:**

$$V_I = \frac{\pi D_I^2}{4} \frac{1}{144}$$

WHERE

D_I **= inside diameter of the pipe, in**

And also, since $D_I = D_o - 2t_a$ (where t_a is $1.06\ t_m$, as previously assumed) it can then be shown that:

(3)

$$Wc = \frac{\pi}{144}\frac{\rho_L}{4}\left[D_o\left(1-\frac{2.12}{DR}\right)\right]^2(1-R)$$

4. W_{DW}, the weight of the water displaced by the pipe is determined by means of the following formula:

(4)

$$W_{DW} = \frac{\pi D_o^2}{4}\frac{1}{144}\rho_W$$

WHERE

ρ_W **= the density of the displaced water, lbs/cu ft**

5. By substituting Equations 2, 3 and 4 into Equation 1, and by simplifying the resultant relationship, the following formula (Equation 2 in the text) is obtained:

$$F_B = \left[0.0054 D_o^2 \rho_W\right]\left[4.24\frac{(DR-1.06)}{(DR)^2}\frac{\rho_p}{\rho_w} + \left(1-\frac{2.12}{DR}\right)^2(1-R)\frac{\rho_c}{\rho_w} - 1\right]$$

Appendix A-2

Water Forces Acting on Submerged PE Piping

The following is a brief introduction to the technology for the estimating of the magnitude of the lateral forces that can act on a submerged pipe in consequence of water currents and wave action. As this technology is relatively complex and it is still emerging, the objective of this introduction is to provide basic information and references that can provide initial guidance for the proper design of PE piping for submerged applications. It is the responsibility of the designer to determine the design requirements and appropriate design protocol for the specific anticipated conditions and design requirements of a particular project. In addition to the information and references herein provided, the reader should consult the technical staff of PPI member companies for further information, including references to engineering companies that have experience in the use of PE piping for submerged applications.

Submerged pipes can be subject to lateral forces generated by currents or by wave action. A principal design objective is to ensure that the resultant lateral forces do not subject the pipe to excessive deflection, nor to fiber stresses or strains that could challenge the pipe material's capabilities. Thus, the capacity to estimate with some reasonable accuracy the potential maximum lateral stresses to which a submerged pipe may be subjected is an important element for achieving a successful design.

Currents impinging on a submerged pipe can cause two principal forces: a drag force in the direction of the current; and a vertical force at right angles to the drag force. The magnitude of these forces depends on the angle between the direction of the current flow and the pipe. They are at their maximum when the current flow is at a right angle to the pipe. As this angle (Θ) is reduced, the resultant force is reduced by $\sin^2 \Theta$.

For the purpose of estimating the drag and lift forces that a current can exert on a submerged pipe, Janson developed the graphical solution that is herein reproduced as Figure A-2-1. This graph is applicable to the condition where the current velocity, expressed in feet per second, times the pipe diameter, expressed in feet, is equals to or is greater than 0.5 m^2/sec (2.7 ft^2/sec).

Janson's nomagraph is based on the assumption that certain design variables are known. These design variables are as follows:

D **= external diameter of pipe, in meters (feet)**
l **= distance from the bottom, in meters (feet)**
u_m **= mean velocity of water, in m/sec (ft/sec)**
h **= depth of water, in meters (feet)**
k **= hydraulic roughness of the water bed, meters (feet)**
Θ **= angle between the direction of the current and that of the pipe, degrees**
λ **= ratio of l/h, dimensionless**
= 0 for pipe placed on seafloor or bed of body of water

Janson determined that for values of $D \times U_m > 0.50$ m^2/sec, a nomograph could be constructed which allowed for a relatively quick approximation of the drag and/or lift forces for which an underwater HDPE piping installation must be designed.

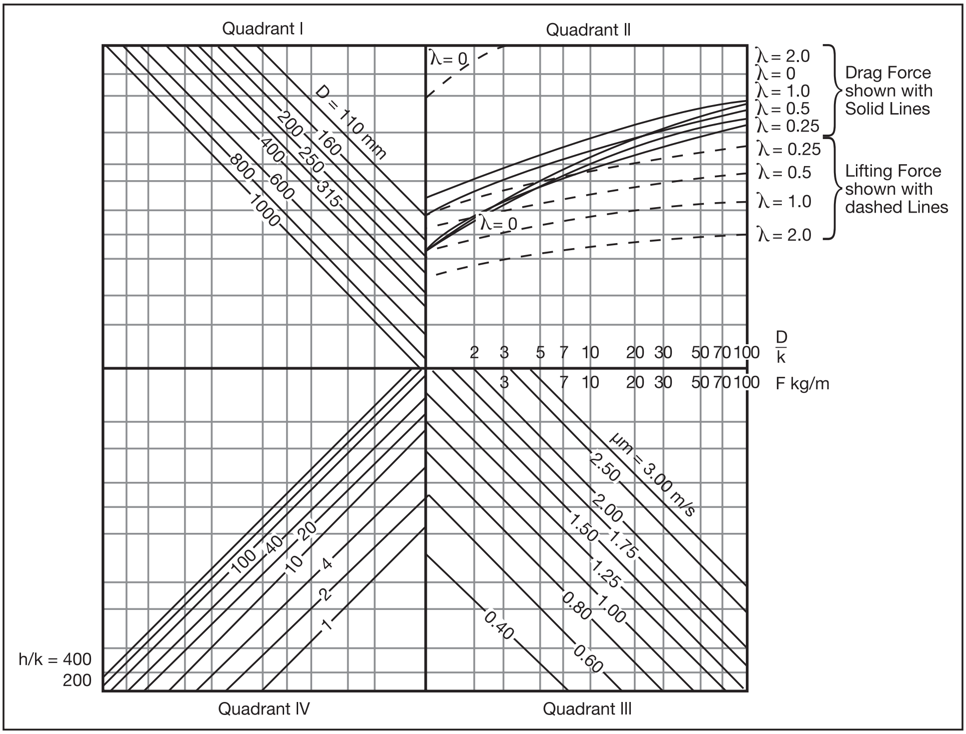


Figure A-2-1 Graph for the estimation of drag and lifting forces on underwater pipes when the flow rate of the current times the pipe diameter is 0.5 m^2/sec, or greater [(4)]

Consider the following example:

A 315 mm HDPE pipe is to be placed directly on the floor of a body of water that is flowing at approximately 3 m/sec and at 90 degrees to longitudinal axis of the pipe. The depth of the water is 10 meters and the pipe will be placed directly on a bed of gravel for which we will assume a hydraulic roughness of 10 cm.

Step 1 First, check to see if the nomograph is applicable

$$D \times u_m = 0.315 \text{ m} \times 3 \text{ m/sec} = 0.96 \text{ m}^2\text{/sec}$$

So, the nomograph can be utilized.

Step 2 Determine the two key dimensionless design ratios, D/k and h/k

GIVEN THAT

D **= 315 mm = 0.315 meter**

and

k **= 10 mm = 0.10 meter**

Then

D/k = **0.315 m / 0.10 m = 3.2**
h/k = **10 m / 0.10 m = 100**

Step 3 Determine the Drag Force

Utilizing the nomograph in Figure A-2-1, start at the horizontal axis between quadrant II and III. On the D/k axis locate the point 3.2 from the calculation in step 2. Draw a line vertically up to the solid curve (drag force) for $\lambda = 0$ (the pipe will rest on the bed of the body of water). Now draw a horizontal line from quadrant II into quadrant I to the line for diameter, in this case 315 mm. At the point of intersection with this line, draw another line downward to the line for h/k = 100 shown in quadrant IV. At that point of intersection, then draw another line horizontally back across to quadrant III to the line for flow velocity, in this example 3m/sec. From this point draw a line upward to the original axis and read drag velocity directly from nomograph. The result is 20 kg/m.

Step 4 Determine the Lift Force

Generally speaking, the lift force for a pipe laying on the floor of a body of water is eight times that of the drag force. In this case, the lift force generated is approximately 160 kg/m.

Alternatively, the lift force could have also been approximated from the nomograph by starting on the same axis between quadrant II and III and proceeding up to the dashed line for $\lambda = 0$ in quadrant II. The dashed line represent the curves for lift force relationships. From the intercept with the dashed curve for $\lambda = 0$, the procedure of is the same as that described for determination of the drag force from the nomograph.

Consider another example:

Now, using the scenario outlined in the preceding example, assume that the pipe is oriented in the water such that the angel of impact, θ, is 60 degrees.

Solution:

The revised angle of impact suggest that the drag force may be reduced by a factor, $\sin^2\theta$.

$$\text{Sin}^2\theta = \sin^2 60^\circ = 0.75.$$

Using this, we get a net drag force as follows:

$$\text{Drag Force}_{(90)} \times \text{Sin}^2\theta = 20 \text{ kg/m} \times 0.75 = 15 \text{ kg/m}$$

English Units

Janson's nomograph was originally published in metric units. However, the curves presented in quadrants II and IV are dimensionless. By converting quadrants I and III and the horizontal axis to English units then the nomograph may be used for pipe sized and installed accordingly. For ease of reference, Janson's nomograph is recreated using English units in figure A-2-2 below.

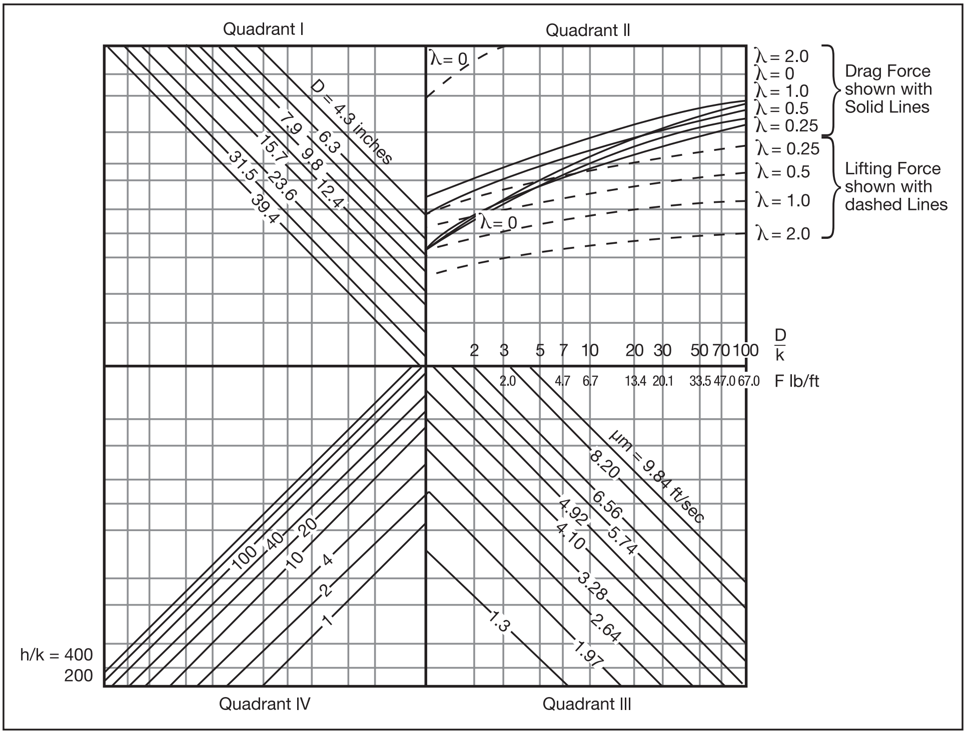


Figure A-2-2 Graph for the estimation of drag and lifting forces on underwater pipes when the flow rate of the current times the pipe diameter is 2.7 ft^2/sec, or greater

Consider the previous example restated in English units

A 12" IPS HDPE (325 mm) pipe is to be placed directly on the floor of a body of water that is flowing at approximately 9.8 ft/sec (3 m/sec) and at 90 degrees to longitudinal axis of the pipe. The depth of the water is 33 feet (10 meters) and the pipe will be placed directly on a bed of gravel for which we will assume a hydraulic roughness of 4 inches (10 cm).

Step 1 First, check to see if the nomograph is applicable

$$D \times u_m = 1 \text{ ft} \times 9.8 \text{ ft/sec} = 9.8 \text{ ft}^2\text{/sec} = 0.91 \text{ m}^2\text{/sec} > 0.50 \text{ m}^2\text{/sec}$$

So, the nomograph can be utilized.

Step 2 Determine the two key dimensionless design ratios, D/k and h/k

GIVEN THAT

D **= 12.75 inches = 1.06 foot**

and

k **= 4 inches = 0.33 foot**

Then

D/k **= 1.06/0.33 = 3.2**

h/k **= 33/ 0.33 m = 100**

Step 3 Determine the Drag Force

Utilizing the English version of the nomograph in Figure A-2-2, start at the horizontal axis between quadrant II and III. On the D/k axis locate the point 3.1 from the calculation in step 2. Draw a line vertically up to the solid curve (drag force) for $\lambda = 0$ (the pipe will rest on the bed of the body of water). Now draw a horizontal line from quadrant II into quadrant I to the line for diameter, in this case 12 inch. At the point of intersection with this line, draw another line downward to the line for h/k = 100 shown in quadrant IV. At that point of intersection, then draw another line horizontally back across to quadrant III to the line for flow velocity, in this example 9.8 ft/sec. From this point draw a line upward to the original axis and read drag velocity directly from nomograph. The result is 13.5 lbf/ft. The reader should keep in mind that this is only an approximation and is not intended to displace a more detailed engineering analysis of a specific marine installation design.

Step 4 Determine the Lift Force

As with the previous example, the lift force for a pipe laying on the floor of a body of water is eight times that of the drag force. In this case, the lift force generated is approximately 108 lbf/ft.

The lift force may be approximated from Figure A-2-2 by starting on the same axis between quadrant II and III and proceeding up to the dashed line for $\lambda = 0$ in quadrant II. The dashed line represent the curves for lift force relationships. From the intercept with the dashed curve for $\lambda = 0$, the procedure of is the same as that described for determination of the drag force from the nomograph.

APPENDIX A-3

Some Designs of Concrete Ballasts

Concrete ballast designs may take on a variety of different sizes, shapes and configurations depending on job-site needs, installation approach and/or availability of production materials. Table A-3-1 below provides some typical designs for concrete ballasts and details some suggested dimensional considerations based on pipe size, density of unreinforced concrete at 144 lb/ft^3 and per cent air entrapment in a typical underwater installation. The reader is advised to consider these dimensions and weights for reference purposes only after a careful analysis of the proposed underwater installation in accordance with the guidelines presented in this chapter.

TABLE A-3-1
Suggested Concrete Weight Dimensions (All dimensions in inches)

Nominal Pipe Size	Mean Outside Diameter (inches)	Spacing of Weights To Offset % Air (feet)			Approx. Weight of Concrete Block (pounds)		Approximate Block Dimensions (inches)						Bolt Dimensions (inches)	
		10%	15%	20%	In Air	In Water	"D"	"X"	"Y"	"T"	"S" (min)	"W"	Dia.	Length
3 IPS	3.50	10	6 ¾	5	12	7	4	9	3 ¾	2 ½	1 ½	2 ½	¾	12
4 IPS	4.50	10	6 ¾	5	20	10	5	11	4 ¾	2 ½	1 ½	3	¾	12
5 IPS	5.56	10	6 ¾	5	30	18	6	12	5 ¼	3 ½	1 ½	3	¾	12
6 IPS	6.63	10	6 ¾	5	35	20	7 ⅛	13	5 ¾	3 ½	1 ½	3	¾	12
7 IPS	7.13	10	6 ¾	5	45	26	7 ⅝	13 ½	6	4 ¼	1 ½	3	¾	12
8 IPS	8.63	10	6 ¾	5	55	30	9 ¼	15 ¼	6 ⅞	4 ¼	1 ½	3	¾	12
10 IPS	10.75	10	6 ¾	5	95	55	11 ¾	19 ¼	8 ⅝	4 ½	2	4	¾	12
12 IPS	12.75	10	6 ¾	5	125	75	13 ¼	21 ¼	9 ⅝	5	2	4	¾	13
13 IPS	13.38	10	6 ¾	5	175	100	13 ⅞	24	11	5 ¼	2	5	¾	13
14 IPS	14.00	15	10	7 ½	225	130	14 ½	24 ½	11 ¼	6 ½	2	5	1	13
16 IPS	16.00	15	10	7 ½	250	145	16 ½	26 ½	12 ¼	6 ½	2	5	1	13
18 IPS	18.00	15	10	7 ½	360	210	18 ½	28 ½	13 ¼	8 ¼	2	5	1	13
20 IPS	20.00	15	10	7 ½	400	235	20 ½	30 ½	14 ¼	8 ¼	2	6	1	13
22 IPS	22.00	15	10	7 ½	535	310	22 ½	34 ½	16 ¼	8 ½	2	6	1	13
24 IPS	24.00	15	13 ½	7 ½	610	360	24 ½	36 ½	17 ¼	8 ¾	2	6	1	13
28 IPS	28.00	20	13 ½	10	900	520	28 ½	40 ¼	19 ¼	11 ¼	2	6	1	13
32 M	31.59	20	13 ½	10	1140	660	32	44	21	12 ¼	2	6	1	13
36 IPS	36.00	20	13 ½	10	1430	830	36 ½	48 ½	23 ¼	13 ½	2	6	1	13
40 M	39.47	20	13 ½	10	1770	1020	40 ⅛	52	25	15 ¼	2	6	1	13
42 IPS	42.00	20	13 ½	10	1925	1125	42 ½	54 ½	26 ¼	15	2	6	1	13
48 IPS	47.38	20	13 ½	10	2500	1460	48 ¼	60 ¼	29 ⅛	17	2	6	1 ⅛	13
55 M	55.30	20	13 ½	10	3390	1980	55 ¾	68	33	18 ¾	2	6 ⅛	1 ⅛	15
63 M	63.21	20	13 ½	10	4450	2600	63 ¾	78	38	18 ½	2	7 ⅛	1 ⅛	15

Notes to Table A-3-1

1. Suggested underpad material: 1/8” black or red rubber sheet, 1/4” neoprene sponge padding width to be “T”+ 2” minimum to prevent concrete from contacting pipe surface.
2. Concrete interior surface should be smooth (3000 psi – 28 days).
3. Steele pipe sleeves may be used around the anchor bolts (1” for 3/4” bolt, etc.). Hot dip galvanize bolts, nuts, washers and sleeves.
4. A minimum gap, “S”, between mating blocks **must** be maintained to allow for tightening on the pipe.
5. To maintain their structural strength some weights are more than the required minimum.
6. Additional weight may be required for tide or current conditions.
7. Weights calculated for fresh water.
8. All concrete blocks should be suitably reinforced with reinforcing rod to prevent cracking during handling, tightening, and movement of weighted pipe.
9. See Table II for alternative weight design and suggested reinforcement for use with 28” to 48” HDPE pipe.

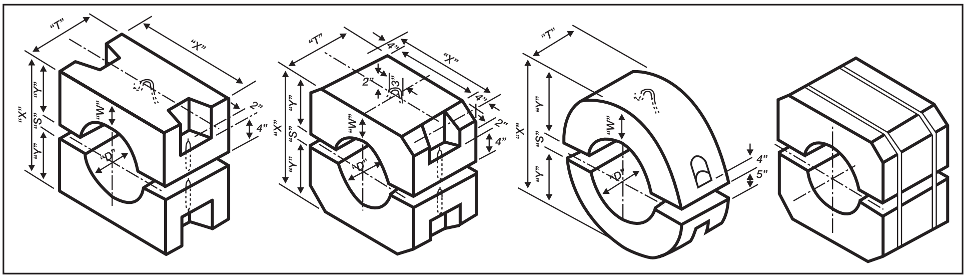


Figure A-3-1 Schematics of Concrete Ballast Designs

TABLE A-3-2

Suggested Dimensions and Reinforcing for Bottom-heavy Concrete Weights (For Extra Stability) All dimensions in inches

Nominal Pipe Size	Mean Outside Diameter (inches)	Spacing of Weights To Offset % Air (feet)			Approx. Weight of Concrete Block (pounds)		Approximate Block Dimensions (inches)						Bolt Dimensions (inches)	
		10%	15%	20%	In Air	In Water	“D”	“X”	“Y”	“Z”	“R”	“T”	Dia.	Length
28 IPS	28.00	20	13 ½	10	900	520	28 ½	44	19 ½	26 ½	48	7 ½	1	54
32 M	31.59	20	13 ½	10	1140	660	32 1/8	48	21	28	51	8 ½	1	57
36 IPS	36.00	20	13 ½	10	1430	830	36	52	23	30 ½	55 ½	9 3/8	1	61 ½
40 M	39.47	20	13 ½	10	1770	1020	40 1/8	56	25	33	60	10 ¼	1	66
42 IPS	42.00	20	13 ½	10	1925	1125	42 ½	59	26 ½	34 ½	63	10	1 1/8	69
48 M	47.38	20	13 ½	10	2500	1460	48 ¼	64	29	39	70	11 ½	1 1/8	76
55 M	55.30	20	13 ½	10	3390	1980	55 ¾	72	33	43	78	12 ¾	1 1/8	84
63 M	63.21	20	13 ½	10	4450	2600	63 ¾	80	37	47	86	14 ½	1 1/8	92

Notes to Table A-3-2

1. Minimum cover of rebar to be 2 ½”.
2. Rebar to be rail steel or equivalent.
3. Anchor bolt material to be ASTM A307.
4. It may be desirable to increase the amount of reinforcing used in the 55” and 63” pipe weights.
5. See recommended bore detail on the following page.

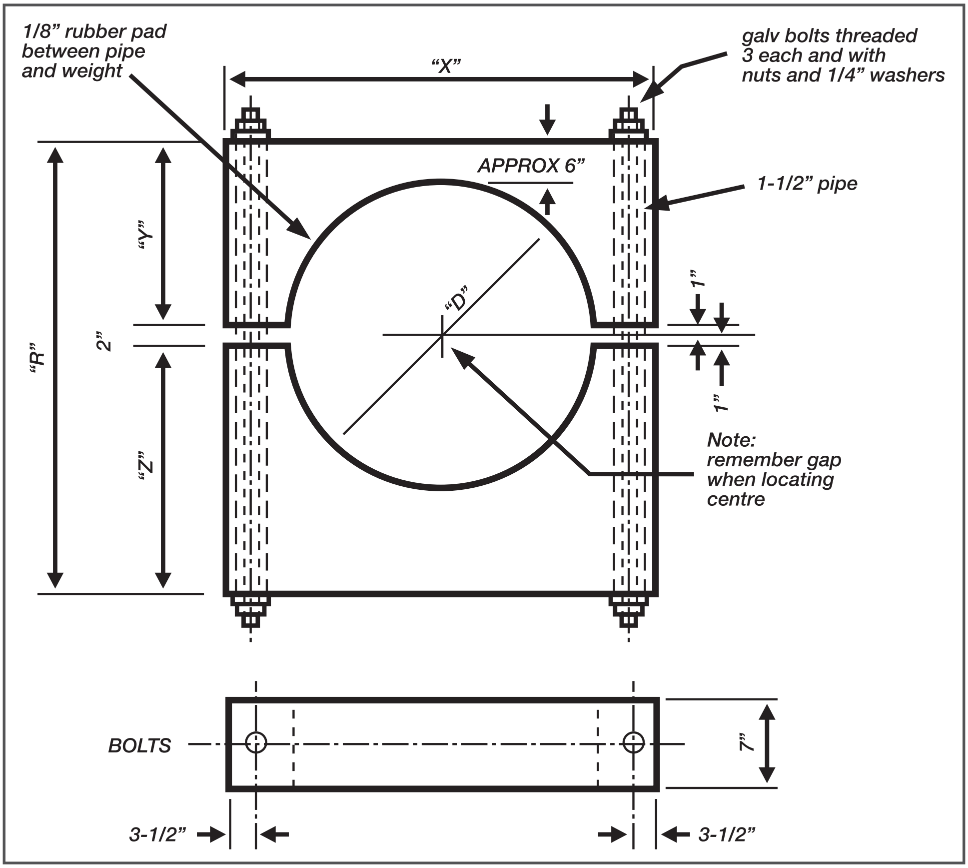


Figure A-3-2 Typical Detail of Concrete Ballast Showing 1-inch Gap Between Ballast Sections

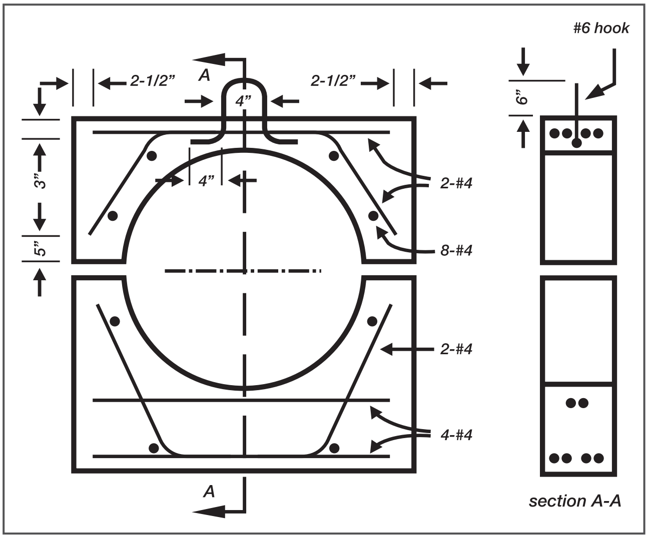


Figure A-3-3 Typical Rebar Detail in Concrete Ballast Design

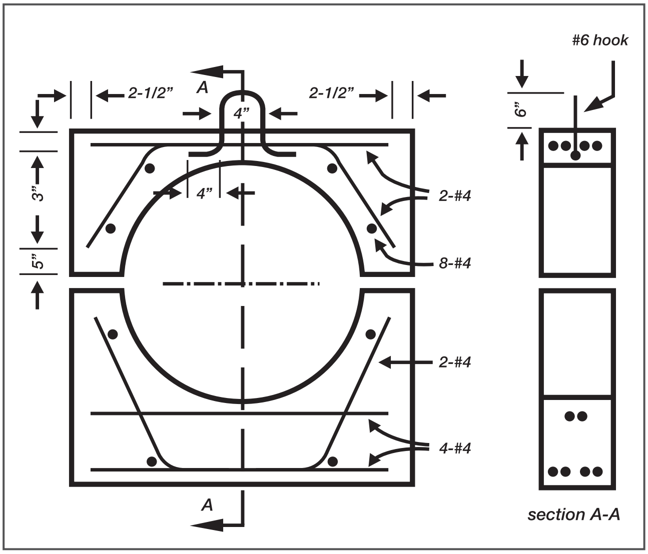


Figure A-3-4 Bore Detail for Concrete Ballast Design

Chapter 11

Pipeline Rehabilitation by Sliplining with PE Pipe

Introduction

An integral part of the infrastructure is the vast network of pipelines, conduits, and culverts in North America. These are among the assets we take for granted, since most are buried and we never see them. We do not see them deteriorate either, but we know that they do. Television inspection of the interiors of these systems often reveals misaligned pipe segments, leaking joints, or other failing pipe integrity.

The effects of continued deterioration of a pipeline could be quite drastic and costly. A dilapidated gravity sewer system permits substantial infiltration of groundwater, which increases the volume of flow and reduces the available hydraulic capacity of the existing line. So the old pipeline often increases treatment and transportation costs for the intended flow stream(24). Continued infiltration may also erode the soil envelope surrounding the pipe structure and cause eventual subsidence of the soil.

The case for positive-pressure pipelines is somewhat different, but the results are equally unacceptable. In this situation, continued leakage through the existing pipeline allows exfiltration of the contents of the flow stream that eventually leads to extensive property damage or water resource pollution. Also, in many cases, the contents of the flow stream are valuable enough that their loss through exfiltration becomes another economic factor. PE pipe provides an excellent solution to the problem of leaky joints, whether it is due to infiltration or to exfiltration. This is because the standard method of joining PE pipe uses a heat fusion process that results in a monolithic pipe system, that is, the joints are as strong as, and as leak free, as the pipe itself.

When the harmful results of pipeline deterioration become apparent, we must either find the most economical method that will restore the original function or abandon the failed system. Excavation and replacement of the deteriorating structure can prove prohibitively expensive and will also disrupt the service for which the original line is intended(18). An alternate method for restoration is "sliplining" or "insertion renewal" with polyethylene pipe. More than 30 years of field experience shows that this is a proven cost-effective means that provides a new pipe structure with minimum disruption of service, surface traffic, or property damage that would be caused by extensive excavation.

The sliplining method involves accessing the deteriorated line at strategic points within the system and subsequently inserting polyethylene pipe lengths, joined into a continuous tube, throughout the existing pipe structure. This technique has been used to rehabilitate gravity sewers(11, 24), sanitary force mains, water mains, outfall lines, gas mains(2, 13), highway and drainage culverts(18), and other piping structures with extremely satisfactory results. It is equally appropriate for rehabilitating a drain culvert 40-feet long under a road or straight sewer line with manhole access as far as ½ mile apart. The technique has been used to restore pipe as small as 1-inch, and there are no apparent maximum pipe diameters.

Mechanical connections are used to connect PE pipe systems to each other and to connect PE pipe systems to other pipe materials and systems. The reader can refer to the Handbook chapter that is titled 'Polyethylene Joining Procedures' for additional information on Mechanical Connections and Mechanical Joint (MJ) Adapters.

Design Considerations

The engineering design procedure required for a sliplining project consists of five straightforward steps:

1. Select a pipe liner diameter.
2. Determine a liner wall thickness.
3. Determine the flow capacity.
4. Design necessary accesses such as terminal manholes, headwall service and transition connections.
5. Develop the contract documents.

Select a Pipe Liner Diameter

To attain a maximum flow capacity, select the largest feasible diameter for the pipe liner. This is limited by the size and condition of the original pipe through which it will be inserted. Sufficient clearance will be required during the sliplining process to insure trouble-free insertion, considering the grade and direction, the severity of any offset joints, and the structural integrity of the existing pipe system.

The selection of a polyethylene liner that has an outside diameter 10% less than the inside diameter of the pipe to be rehabilitated will generally serve two purposes. First, this size differential usually provides adequate clearance to accommodate the insertion process. Second, 75% to 100% or more of the original flow capacity may be maintained. A differential of less than 10% may provide adequate clearance in larger diameter piping structures. It is quite common to select a 5% to 10% differential for piping systems with greater than 24-inch diameters, assuming that the conditions of the existing pipe structure will permit insertion of the liner.

Determine a Liner Wall Thickness

Non-Pressure Pipe

In the majority of gravity pipeline liner projects, the principal load that will act on the polyethylene pipe is the hydrostatic load that is created when the water table rises above the crown (top) of the liner.

The generic Love's equation (Eq. 1) shows that the ability of a free-standing pipe to withstand external hydrostatic loading is essentially a function of the pipe wall moment of inertia and the apparent modulus of elasticity of the pipe material. The critical buckling pressure, P_C, for a specific pipe construction can be determined by using equation Eq. 1.

(1) Love's Equation

$$P_c = \frac{24EI}{\left(1-\nu^2\right)\times D_m{}^3} \times f_0$$

WHERE

P_C = Critical buckling pressure, psi

E = Apparent modulus of elasticity (Refer to Appendix, Chapter 3, for the appropriate value for the Material Designation Code of the PE pipe being used and the applicable service conditions.)

I = Pipe wall moment of inertia, in^4/in

= $t^3/12$ for solid wall PE, where t = minimum wall thickness of the pipe, in

ν = Poisson's Ratio, 0.45 for all PE pipe materials

D_m = Mean diameter, inches (outside diameter minus one wall thickness)

f_0 = Ovality compensation factor, dimensionless (see Figure 1)

D = Pipe average outside diameter, in

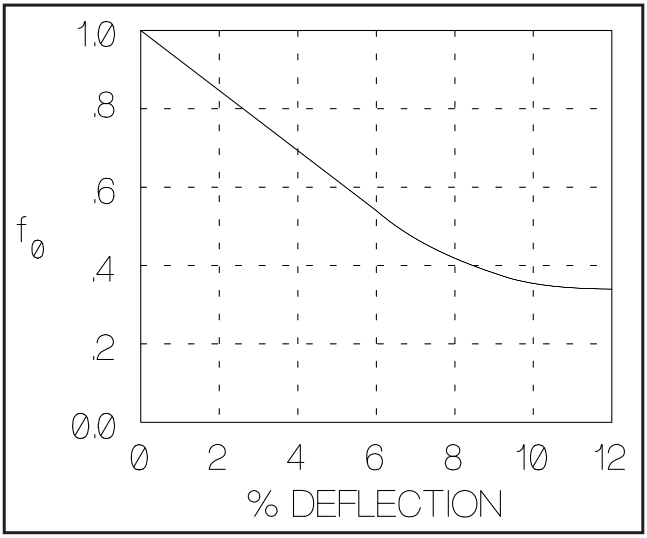


Figure 1 % Deflection vs. Ovality Correction Factor, f_0

$$\text{where } \% \text{ Deflection} = \frac{D - D_{min}}{D} \times 100$$

D_{min} = Pipe minimum diameter, in

To compute the buckling pressure of a dimension ratio (DR) series polyethylene pipe (i.e., a grouping of solid wall pipes of different diameters but with the same ratio of specified outside diameter to minimum wall thickness), the following variation of Love's equation(22), Eq. 2, is used.

(2) Love's Equation for DR Solid Wall Pipe

$$P_c = E \times \left(\frac{2}{1-\nu^2}\right) \times \left(\frac{1}{DR-1}\right)^3 \times f_o$$

WHERE

DR = Dimension ratio, dimensionless (OD/t)

OD = Actual outside diameter, inches

t = Minimum wall thickness, inches

The process of calculating the buckling resistance of a free-standing pipe is iterative in that, once the critical buckling resistance of a trial choice has been determined, it can be compared to the anticipated hydrostatic load. If the pipe's calculated buckling resistance is significantly larger than the anticipated hydrostatic loading, the procedure can be used to evaluate a lesser wall thickness (with the advantages of lighter weight materials and lower costs). The prudent practice is to select a design buckling resistance that provides an adequate safety factor (SF) over the maximum anticipated hydrostatic load.

(3) Safety Factor, SF

$$SF = \frac{P_c}{\text{Anticipated Hydrostatic Load}}$$

For an example of the calculations that can be made with Equations 2 and 3, consider a 22-inch DR 26 solid-wall polyethylene liner placed within a 24-inch clay tile pipe and subjected to a maximum excess hydrostatic load of 3 feet of water table.

1. Calculate the equivalent hydrostatic load in psi.
   Water load = 3 ft x 62.4 lb/ft^3 x 1 ft^2/144 in^2 = 1.3 psi

2. Calculate the critical buckling pressure, P_c, using Eq. 2 assuming the following variable values: $E = 28{,}200$ psi, $\nu = 0.45$ and $f_o = 0.79$

3. Calculate the Safety Factor, SF, from Eq. 3 for this load assumption.
   SF = 3.6/1.3 = 2.8

A safety factor of 2.0 or greater is often used for frequent or long-term exposure to such loads. If a larger safety factor is preferred, repeat the procedure for a heavier wall configuration or consider the enhancement of the pipe's buckling strength by the effects of external restraint.

Love's equation assumes that the liner being subjected to the indicated hydrostatic load is free-standing and is not restrained by any external forces. Actually, the existing pipe structure serves to cradle the flexible liner, enhancing its collapse resistance. Maximum external reinforcement can be provided, where required, by placing a stable load-bearing material such as cement, fly ash, polyurethane foam, or low-density grout in the annular space between the liner and the existing pipe. Studies show that filling the annular cavity will enhance the collapse resistance of a polyethylene pipe by at least a four-fold factor and often considerably more, depending on the load-bearing capabilities of the particular fill material. Contact the pipe suppliers for additional information.

For solid wall PE pipe, the significant variable that determines adequate wall stiffness is the pipe DR. It is a simple matter to specify the DR once the amount of the loading on the pipe is determined. A typical manufacturer's recommendation for safe long-term (50-year) external pressure loading might follow the guidelines in Table 1, which were derived according to the procedure shown in ASTM F585, Practice for Insertion of Flexible Polyethylene Pipe into Existing Sewers.

TABLE 1

Allowable Height[(1)] of Water Above DR Dimensioned Pipe at the Maximum Operating Temperature of 73°F (23°C)[(2)] and Under a Continuous Duration of Loading of 50-years[(3)]. Not Grouted vs. Grouted Pipe

Pipe Dimension Ratio (DR)	Height of water (feet) above pipe made from materials designated as PE 4XXX[(4)]		Height of water (feet) above pipe made from materials designated as PE 3XXX[(4)]	
	Not Grouted	Grouted	Not Grouted	Grouted
32.5	2.0	10.0	1.9	9.5
26	4.0	20.0	3.9	19.5
21	7.9	39.5	7.6	38.0
17	15.4	77.0	14.8	74.0
13.5	32.2	161.0	31.1	155.0
11	62.9	314.5	60.8	304.0

Notes:

(1) The values of allowable height were computed by means of equation (2) and under the following assumptions:
- The apparent modulus E is 28,000 psi for PE3XXX and 29,000 psi for PE4XXX materials at 73°F and for a 50-year load duration; refer to Appendix, Chapter 3 of this Handbook.
- The value of Poisson's ratio (μ) is 0.45
- The value of fo, the pipe ovality correction factor, is 0.75, which corresponds to a pipe deflection of 3%
- A safety factor of 2.0 was used. See preceding discussion on selecting an appropriate safety factor
- For grouted applications, the height of water above pipe was computed by multiplying by 5 the height obtained for the corresponding non-grouted applications.

(2) Table B.1.2 of the Appendix of Chapter 3 lists temperature adjusting factors which may be used to convert the above results to other maximum operating temperatures

(3) Values for apparent modulus for other periods of continuous loading are listed in Table B.1.1 in the Appendix to Chapter 3

(4) The first numeral after PE is the standard classification for the PE's density. The X's designate any recognized value for the other coded properties. See the section on Structural Properties of Chapter 3 for a detailed description of the PE piping material designation code.

The figures in this table represent a Safety Factor, SF, of 2.0 and a diametrical ovality of 3%. Grouted strength of the pipe was derived by applying a multiplier of 5 to the non-grouted value[(32)]. If the existing sewer will not provide structural integrity to earth and live loads, a more conservative Safety Factor should be used.

For profile wall pipe the variable that determines adequate wall stiffness is a function of the pipe wall moment of inertia and pipe inside mean diameter. The following equation can be used to estimate maximum allowable long-term (50-year) height of water above the pipe with no grout:

(4)
$$H = \frac{0.9 \times RSC}{D_m}$$

WHERE

H = Height of water, feet

RSC = Measured Ring Stiffness Constant

D_m = Mean diameter, inches

This equation contains a Safety Factor (SF) of 2.0 based on pipe with a maximum 3% deflection.

For grout with a minimum compressive strength of 500 psi at 24 hours (1,800 psi at 28 days), the allowable long-term (50-year) height of water above the pipe may be determined from the following equation:

(5)
$$H = 5 \times \frac{(0.9 \times RSC)}{D_m}$$

This equation contains a Safety Factor (SF) of 2.0.

Pressure Pipe

A liner, which will be exposed to a constant internal pressure or to a combination of internal and external stresses must be analyzed in a more detailed manner. The guidelines for a detailed loading analysis such as this are available from a variety of resources that discuss in detail the design principles concerned with underground installation of flexible piping materials.(3,15,16,19,26,29) The reader is also advised to refer to Chapters 3 and 6 of this Handbook for additional information on design principles and the properties applicable to the particular Material Designation Code of the PE pipe being used.

In those installations where the liner will be subjected to direct earth loading, the pipe/soil system must be capable of withstanding all anticipated loads. These include earth loading, hydrostatic loading, and superimposed loads. The structural stability of a polyethylene liner under these conditions is determined largely by the quality of the external support. For these situations, refer to any of the above referenced information sources that concern direct burial of thermoplastic pipe. A polyethylene liner that has been selected to resist hydrostatic loading will generally accommodate typical external loading conditions if it is installed properly.

Other Loading Considerations

Filling of the entire annular space is rarely required. If it is properly positioned and sealed off at the termination points, a polyethylene liner will eliminate the sluice path that could contribute to the continued deterioration of most existing pipe structures. With a liner, a gradual accumulation of silt or sediment occurs within the annular space, and this acts to eliminate the potential sluice path.

On occasion, deterioration of the original pipe may continue to occur even after the liner has been installed.(18) This situation may be the result of excessive ground-water movement combined with a soil quality that precludes sedimentation within the annular space. Soil pH and resistivity can also help deteriorate the host culvert or pipe. As a result, uneven or concentrated point loading upon the pipe liner or even subsidence of the soil above the pipe system may occur. This can be avoided by filling the annular space with a cement-sand mixture, a low-density grout material(10), or fly ash.

Determine the Flow Capacity

The third step in the sliplining process is to assess the impact of sliplining on the hydraulic capacity of the existing pipe system. This is accomplished by using commonly-accepted flow equations to compare the flow capacity of the original line against that of the smaller, newly-installed polyethylene liner. Two equations widely used for this calculation are the Manning Equation (Eq. 6) and the Hazen-Williams Approximation for other than gravity flow systems (Eq. 7).(2,5) The reader is referred to Chapter 6 of this Handbook, where the subject of fluid flow is covered extensively.

(6) Manning Equation for Gravity Flow

$$Q = \frac{1.486 \times A \times R^{0.667} \times S^{0.5}}{n}$$

WHERE

Q = Flow, ft^3/sec

A = Flow area, ft^2 (3.14 x ID^2/4)

R = Hydraulic radius, feet (ID/4 for full flow)

S = Slope, ft/ft

n = Manning flow factor for piping material, 0.009 for smooth wall PE

ID = Inside diameter, feet

For circular pipe flowing full, the formula may be simplified to

$$Q = \frac{0.463 \times ID^{2.667} \times S^{0.5}}{n}$$

(7) Hazen-Williams Approximation for Other Than Gravity Flow

$$H = \frac{1044 \times G^{1.85}}{C_H^{\ 1.85} \times ID^{4.865}}$$

WHERE

H = Friction loss in ft of H_2O/100 ft

G = Volumetric flow rate, gpm

= 2.449 x V x ID^2

V = Flow velocity, ft/sec

ID = Inside diameter, inches

C_H = Hazen Williams flow coefficient, dimensionless

= 150 for smooth wall polyethylene

The insertion of a smaller pipe within the existing system may appear to reduce the original flow capacity. However, in the majority of sliplining applications, this is not the case. The polyethylene liner is extremely smooth in comparison to most piping materials. The improved flow characteristic for clear water is evidenced by a comparatively low Manning Flow Coefficient, n of 0.009, and a Hazen-Williams coefficient, C_H, of 150.

While a reduction in pipe diameter does occur as a consequence of sliplining, it is largely compensated by the significant reduction in the Manning Flow Coefficient. As a result, flow capacity is maintained at or near the original flow condition.(18) Manning Flow Coefficients and Hazen-Williams Flow Coefficients for a variety of piping materials are listed in Table 2a and 2b. These factors may be used to approximate the relative flow capacities of various piping materials.

TABLE 2A

Typical Manning Flow Coefficients for Water Flowing through Common Piping Materials

Polyethylene (solid wall)	0.009
PVC	0.009
Cement-lined Ductile Iron	0.012
New Cast Iron, Welded Steel	0.014
Wood, Concrete	0.016
Clay, New Riveted Steel	0.017
Old Cast Iron, Brick	0.020
CSP	0.023
Severely Corroded Cast Iron	0.035

TABLE 2B

Typical Hazen-Williams Flow Coefficients for Water Flowing through Common Piping Materials(31)

Polyethylene (solid wall)	150
PVC	150
Cement-lined Ductile Iron	140
New Cast Iron, Welded Steel	130
Wood, Concrete	120
Clay, New Riveted Steel	110
Old Cast Iron, Brick	100
Severely Corroded Cast Iron	80

Quite often the hydraulic capacity of a gravity flow pipe can actually be improved by an insertion renewal. For example, consider the following illustrations of calculations using the Manning Equation (Eq. 6).

Calculation for Flow Rate, Q, through a 24-inch ID Concrete Pipe at 1% slope (1 ft/100 ft)

$$Q = \frac{1.486 \times 3.14 \times 1^2 \times 0.5^{0.667} \times 0.01^{0.5}}{0.016} = \mathbf{18.3\ ft^3/sec\ \ (8{,}248\ gpm)}$$

Calculation of Flow Rate, Q, through a 22-inch OD Polyethylene Pipe with a 20.65-Inch ID at 1% slope (1 ft/100 ft)

$$Q = \frac{1.486 \times 3.14 \times 0.8604^{2} \times 0.429^{0.667} \times 0.01^{0.5}}{0.009} = \mathbf{21.8\ ft^{3}/sec\ (9{,}800\ gpm)}$$

Comparison of the two calculated flow rates shows that sliplining this 24-inch concrete pipe with the smaller polyethylene pipe actually improves the capacity by 1,000 gallons per minute. This will often be the situation. Occasionally, the theoretical flow capacity of the liner may appear to be equivalent to or slightly less than that of the original system. In many such cases, the presence of the liner eliminates the infiltration associated with the deterioration of the original pipe and the corresponding burden this places on the existing flow capacity. So an apparently small reduction in theoretical flow capacity may, in reality, prove to be quite acceptable since it eliminates the infiltration and the effect this produces on available hydraulic capacity.

Design the Accesses

The polyethylene liner will need to be connected to existing system components or appurtenances. Proper planning for a rehabilitation project must include the specific engineering designs by which these connections will be made.

Gravity flow pipeline rehabilitation often requires that the individual liner lengths be terminated at manholes or concrete headwalls that already exist within the system that is being sliplined. The annular space at these locations must provide a water-tight seal against continued infiltration in the void area that exists between the liner and the original pipe where they connect to these structures.

Typically, the required seal can be made by compacting a ring or collar of Okum saturated with non-shrink grout into the void area to a distance equal to one-half to one full liner diameter. The annular space is then “dressed” with a non-shrink elastomeric grout. The face of the elastomeric grout may then be covered with a quick-set chemical-resistant concrete. The same concrete material may then be used to reconstruct an invert in the manhole. This type of seal is shown in Figure 2.

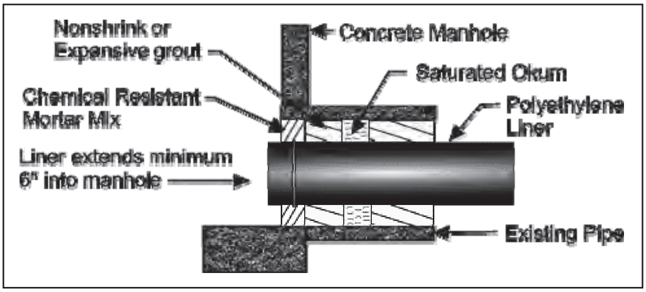


Figure 2 Typical Manhole Seal for Gravity Flow Applications

For those installations where a new manhole or headwall will be set, the amount of elastomeric grout may be minimized by fusing a water-stop or stub end onto the liner length before it is finally positioned. This fitting may then be embedded within the poured headwall or grouted into the new manhole. Some typical connecting arrangements for newly constructed appurtenances are shown in Figure 3. The connection described (water stop/wall anchor grouted in place) can also work on existing structures.

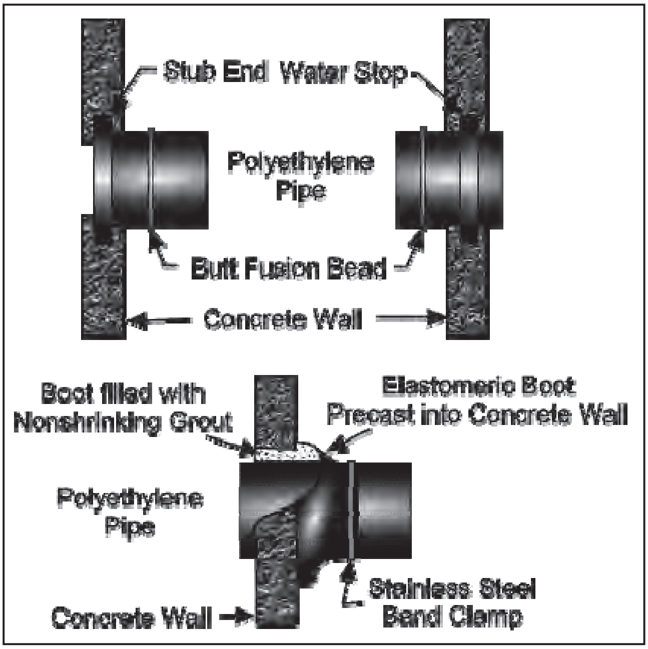


Figure 3 Newly Constructed Headwall or Manhole Placements

Deteriorated lateral service connections are a leading cause of infiltration in gravity flow pipelines.(19) An integral part of the insertion process is rebuilding these connections. This aspect of sliplining assures maximum reduction of infiltration, provides for long-term structural stability of the service, and minimizes the potential for continued deterioration of the existing pipe system.

Individual home services or other laterals may be connected to the liner by using any of several different connection methods. For example, upon relaxation of the liner, sanitary sewer connections may be made to the polyethylene liner by using a strap-on service saddle or a side-wall fusion fitting. Either of these options provides a secure water-tight connection to the liner and allows for effective renewal of the riser with no reduction in the inside diameter of the service. Both of these types of connection are shown in Figure 4.

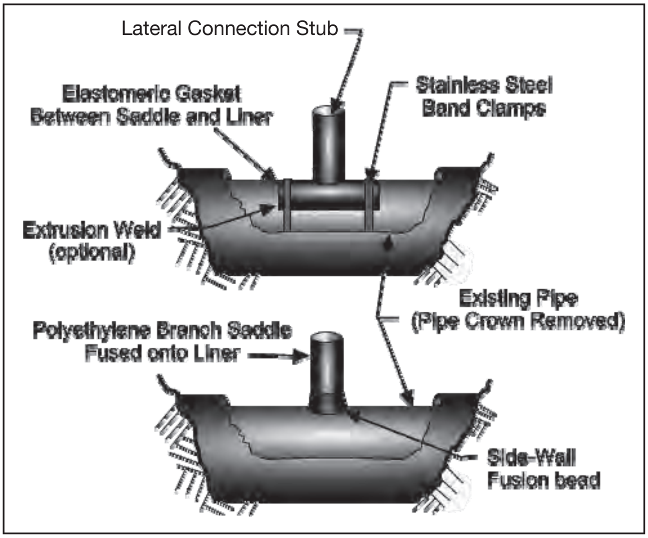


Figure 4 Lateral Service Connections for Sliplining Gravity Pipelines

Rehabilitation of pressure pipelines often requires that connections be made to lateral pressure-rated piping runs. Connections to these lines should be designed to insure full pressure capability of the rehabilitated system. Several alternatives are available to meet this requirement. These include in-trench fusion of molded or fabricated tees, sidewall fusion of branch saddles, insertion of spool pieces via electrofusion and insertion of low-profile mechanical connectors. One of these options is illustrated schematically in Figure 5. Performance requirements and installation parameters of the rehabilitation project most often dictate the selection of one specific connection design.

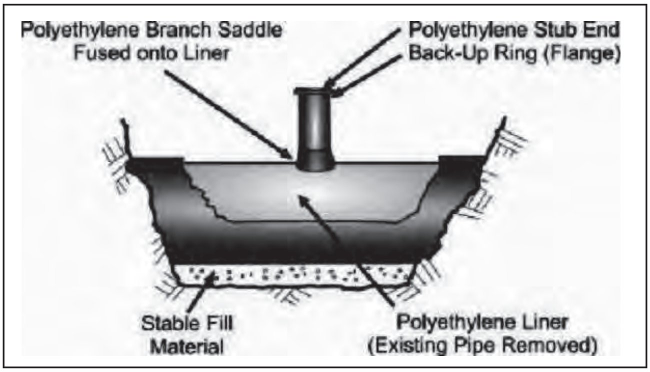


Figure 5 Typical Lateral Service Connection for Sliplining Pressure Pipelines

Develop the Contract Documents

When the rehabilitation design has been completed, attention will be focused on writing the specifications and contract documents that will ensure a successful installation. Reference documents for this purpose include: ASTM D3350(4), ASTM F585(5), ASTM F714(6), and ASTM F894.(7) To assist further in the development of these documents, a model sliplining specification is available from the Plastics Pipe Institute, "Guidance and Recommendations on the Use of Polyethylene (PE) Pipe for the Sliplining of Sewers."

The Sliplining Procedure

The standard sliplining procedure is normally a seven-step process. While the actual number of steps may vary to some degree in the field, the procedure remains the same for all practical purposes.(23,24) The procedures for rehabilitation of gravity and positive pressure pipelines are essentially the same. Some subtle differences become apparent in the manner by which some of the basic steps are implemented. The seven basic steps are as follows:

1. Inspect the existing pipe.
2. Clean and clear the line.
3. Join lengths of polyethylene pipe.
4. Access the original line.
5. Installation of the liner.
6. Make service and lateral connections.
7. Make terminal connections and stabilize the annular space.

1. Inspect the Existing Pipe

The first step for a sliplining project is the inspection of the existing pipe. This will determine the condition of the line and the feasibility of insertion renewal. During this step, identify the number and the locations of offset pipe segments and other potential obstructions.

Use a remote controlled closed circuit television camera to inspect the pipe interior. As the unit is pulled or floated through the original pipe, the pictures can be viewed and recorded with on-site television recording equipment.

2. Clean and Clear the Line

The existing pipeline needs to be relatively clean to facilitate placement of the polyethylene liner. This second step will ensure ease of installation. It may be accomplished by using cleaning buckets, kites or plugs, or by pulling a test section of polyethylene liner through the existing pipe structure.

Obviously, to attempt a liner insertion through a pipeline obstructed with excess sand, slime, tree roots or deteriorated piping components would be uneconomical or even impossible. Step 2 is often undertaken in conjunction with the inspection process of Step 1.

3. Weld Lengths of Polyethylene Pipe

Polyethylene pipe may be joined by butt fusion technology, gasketed bell and spigot joining methods, or by extrusion welding. The specific method to be used will be determined by the type of polyethylene pipe being inserted into the existing pipe structure. Solid wall polyethylene pipe is usually joined using butt fusion techniques. Polyethylene profile walled pipe, on the other hand, can be joined by integral gasketed bell and spigot joining methods or by the extrusion welding technique. Consult the manufacturer for the recommended procedure.

Butt Fusion — Solid Wall Pipe

Individual lengths of solid wall polyethylene pipe are joined by using the butt fusion process technique. The integrity of this joining procedure is such that, when it is performed properly, the strength of the resulting joint equals or exceeds the structural stability of the pipe itself. This facilitates the placement of a leak-free liner throughout the section of the existing system under rehabilitation.

The external fusion bead, formed during the butt fusion process, can be removed following the completion of joint quality assurance procedures by using a special tool prior to the insertion into the existing system. The removal of the bead may be necessary in cases of minimal clearance between the liner and the existing pipeline, but otherwise not required.

Pulling Lengths

Individual pulling lengths are usually determined by naturally occurring changes in grade or direction of the existing pipe system. Severe changes in direction that exceed the minimum recommended bending radius of the polyethylene liner may be used as access points. Likewise, severe offset joints, as revealed during the television survey, are commonly used as access points. By judicious planning, potential obstructions to the lining procedure may be used to an advantage.

There is a frequent question regarding the maximum pulling length for a given system. Ideally, each pull should be as long as economically possible without exceeding the tensile strength of the polyethylene material. It is rare that a pull of this magnitude is ever attempted. As a matter of practicality, pulling lengths are more often restricted by physical considerations at the job site or by equipment limitations.(23)

To ensure a satisfactory installation, the designer may want to analyze what is considered the maximum pulling length for a given situation. Maximum pulling length is a function of the tensile strength and weight of the polyethylene liner, the temperature at which the liner will be manipulated, the physical dimensions of the liner, and the frictional drag along the length of the polyethylene pipe liner.

Equations 8 and 9 are generally accepted for determination of the maximum feasible pulling length. One of the important factors in these calculations is the tensile strength of the particular polyethylene pipe product, which must be obtained from the manufacturer's literature.

(8) Maximum Pulling Force, MPF

$$MPF = f_y \times f_t \times T \times \pi \times OD^2 \left(\frac{1}{DR} - \frac{1}{DR^2} \right)$$

WHERE

MPF = Maximum pulling force, lb-force

f_y = Tensile yield design (safety) factor, 0.40

f_t = Time under tension design (safety) factor, 0.95*

T = Tensile yield strength, psi (Refer to Appendix, Chapter 3, for the appropriate value for the Material Designation Code of the PE pipe being used and the applicable service conditions.)

OD = Outside diameter, inches

DR = Dimension Ration, dimensionless

* The value of 0.95 is adequate for pulls up to 12 hours.

(9) Maximum Pulling Length, MPL

$$MPL = \frac{MPF}{W \times CF}$$

WHERE

MPL = Maximum straight pulling length on relatively flat surface, ft

MPF = Maximum pulling force, lb-force (Eq. 8)

W = Weight of pipe, lbs/ft

CF = Coefficient of friction, dimensionless

= 0.1, flow present through the host pipe

= 0.3, typical for wet host pipe

= 0.7, smooth sandy soil

Profile Wall Pipe

Profile wall PE pipe is available in the market place in different or unique wall constructions. Some of these products feature bell and spigot gasket type joint assembly; others are joined using one or more of the various heat fusion techniques such as, extrusion welding, butt fusion, and or electrofusion. The products having the bell and spigot gasketed joint arrangement must be pushed or "jacked" rather than pulled, into the line being rehabilitated. Because of this and the many other differences, it is not instructive or beneficial to try and cover all of these special products in this Handbook. Therefore, the reader who may have interest in learning more about the design and application of these products for pipeline rehabilitation service, is advised to consult directly with the product supplier.

4. Access the Original Line

Excavation of the access pits is the next step in the insertion renewal procedure. Access pits will vary considerably in size and configuration, depending on a number of project-related factors such as:

- Depth of the existing pipe
- Diameters of the liner and the existing pipe
- Stiffness of liner pipe
- Prevailing soil conditions
- Equipment availability
- Traffic and service requirements
- Job site geography

For example, a fairly large access pit may be required when attempting to slipline a large diameter system that is buried deep in relatively unstable soil. In contrast, the access pit for a smaller diameter pipeline that is buried reasonably shallow (5 to 8 feet) may be only slightly wider than the liner itself. In actual practice, the simpler situation is more prevalent. An experienced contractor will recognize the limiting factors at a particular job site and utilize them to the best economic advantage, thus assuring a cost-effective installation.

A typical access pit for sliplining with pre-fused or welded lengths of solid wall polyethylene pipe is illustrated in Figure 6. Figure 7 is a schematic of an access method that may be used with profile pipe.

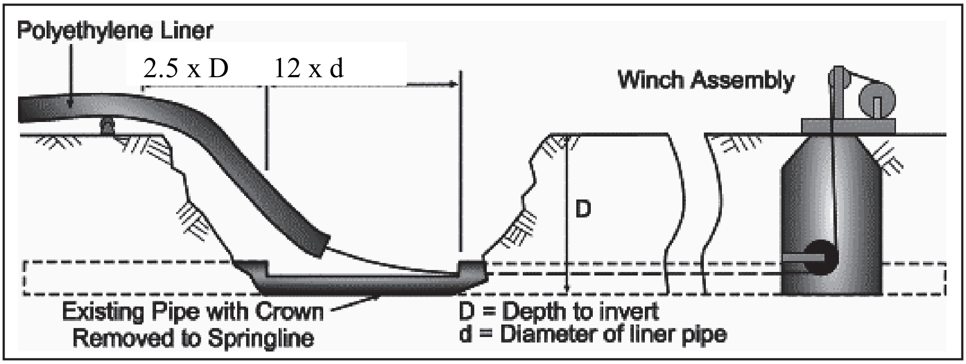


Figure 6 Typical Sliplining Access Pit for Prefused Lengths of Polyethylene Liner

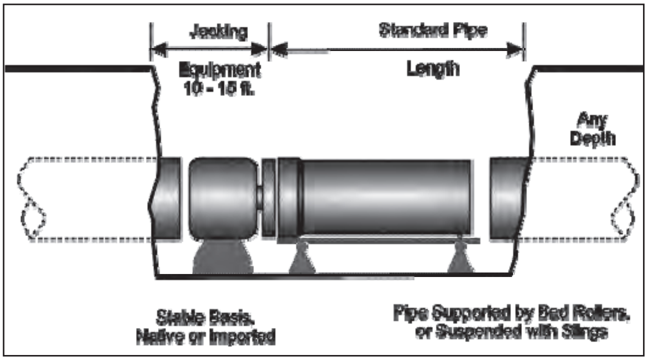


Figure 7 Typical Sliplining Access Pit for Bell and Spigot Polyethylene Liner

5. Installation of the Liner

Insertion of the polyethylene liner may be accomplished by one of several techniques. Prefused or welded lengths of solid wall polyethylene pipe may be "pulled" or "pushed" into place. Gasket-Jointed profile pipe, on the other hand, must be installed by the push method to maintain a water-tight seal.

The "Pulling" Technique

Prefused or welded lengths of polyethylene liner may be pulled into place by using a cable and winch arrangement. The cable from the winch is fed through the section of pipe that is to be sliplined. Then the cable is fastened securely to the liner segment, thus permitting the liner to be pulled through the existing pipe and into place.

Figure 6 is a schematic of an installation in which the liner is being pulled through the existing pipe from the left side toward a manhole at the right. This procedure requires some means, such as a pulling head, to attach the cable to the leading edge of the liner. The pulling head may be as simple or as sophisticated as the particular project demands or as economics may allow.

The pulling head may be fabricated of steel and fastened to the liner with bolts. They are spaced evenly around the circumference of the profile so that a uniform pulling force is distributed around the pipe wall. This type of fabricated pulling head will usually have a conical shape, aiding the liner as it glides over minor irregularities or through slightly offset joints in the old pipe system. The mechanical pulling head does not normally extend beyond the Outside Diameter (O.D.) of the polyethylene liner and is usually perforated to accommodate flow as quickly as possible once the liner is inserted inside the old system. Three practical styles of typical mechanical pulling heads are shown in Figure 8.

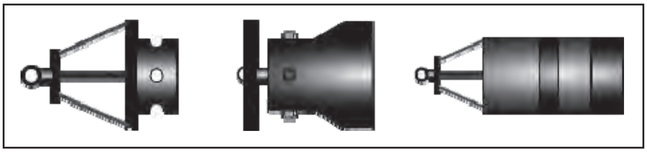


Figure 8 Fabricated Mechanical Pulling Heads

A less sophisticated but cost-effective approach is to fabricate a pulling head out of a few extra feet of liner that has been fused onto a single pipe pull. Cut evenly spaced wedges into the leading edge of the extra liner footage, making it look like the end of a banana being peeled. Collapse the ends toward the center and fasten them together with bolts or all-thread rods. Then attach the cable to secondary bolts that extend across the collapsed cross section. This simple technique is illustrated in Figure 9.

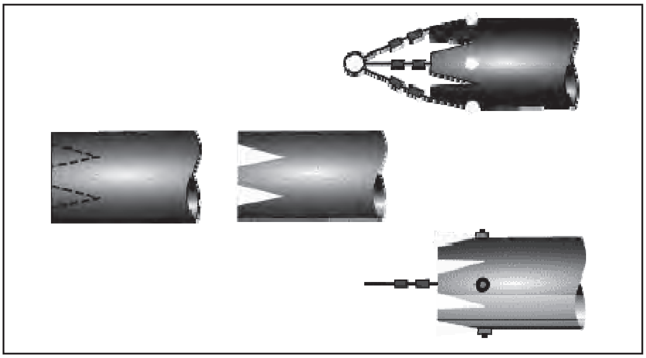


Figure 9 Field-Fabricated Pulling Heads

As the polyethylene liner is pulled into the pipeline, a slight elongation of the liner may occur. A 24-hour relaxation period will allow the liner to return to its original dimensions. After the relaxation period, the field fabricated pulling head may be cut off. It is recommended the liner be pulled past the termination point by 3-5%. This allows the liner to be accessible at the connection point after the relaxation period.

The pull technique permits a smooth and relatively quick placement of the liner within an old pipe system. However, this method may not be entirely satisfactory when attempting to install a large-diameter heavy-walled polyethylene pipe. This is especially true when the load requires an unusually large downstream winch. A similar problem may exist as longer and larger pulls are attempted so that a heavier pulling cable is required. When the pull technique is not practical, consider the advantages that may be offered by the push technique.

The "Push" Technique

The push technique for solid wall or welded polyethylene pipe is illustrated schematically in Figure 10. This procedure uses a choker strap, placed around the liner at a workable distance from the access point. A track-hoe, backhoe, or other piece of mechanical equipment pulls the choker to push the liner through the existing pipe. With each stroke of the backhoe, the choker grips the pipe and pushes the leading edge of the liner further into the deteriorated pipe. At the end of each stroke, the choker must be moved back on the liner, usually by hand. The whole process may be assisted by having a front-end loader or bulldozer simultaneously push on the trailing end of the liner segment.

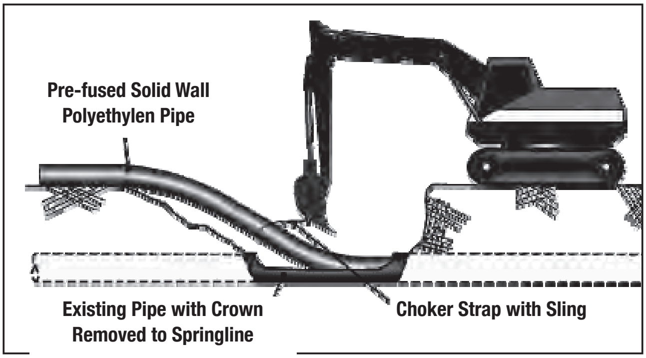


Figure 10 Pushing Technique for Solid Wall Polyethylene Pipe

Gasketed PE pipe requires the use of the push technique in order to keep the joints from separating, as well as to position the liner. The push technique for gasketed pipe is shown schematically in Figure 10. This process inserts the liner without the necessity for having a high capacity winch and cable system.

The Combination Technique

The pushing and pulling techniques can sometimes be combined to provide the most efficient installation method. Typically, this arrangement can be used when attempting the placement of unusually heavy walled or long lengths of polyethylene liner.

Flow Control

For most insertion renewal projects it is not necessary to eliminate the entire flow stream within the existing pipe structure. Actually, some amount of flow can assist positioning of the liner by providing a lubricant along the liner length as it moves through the deteriorated pipe structure. However, an excessive flow can inhibit the insertion process. Likewise, the disruption of a flow stream in excess of 50% of pipe capacity should be avoided.

The insertion procedure should be timed to take advantage of cyclic periods of low flow that occur during the operation of most gravity piping systems. During the insertion of the liner, often a period of 30 minutes or less, the annular space will probably carry sufficient flow to maintain a safe level in the operating sections of the system being rehabilitated. Flow can then be diverted into the liner upon final positioning of the liner. During periods of extensive flow blockage, the upstream piping system can be monitored to avoid unexpected flooding of drainage areas.

Consider establishing a flow control procedure for those gravity applications in which the depth of flow exceeds 50%. The flow may be controlled by judicious operation of pump stations, plugging or blocking the flow, or bypass pumping of the flow stream.

Pressurized piping systems will require judicious operation of pump stations during the liner installation.

6. Make Service and Lateral Connections

After the recommended 24-hour relaxation period following the insertion of the polyethylene liner, each individual service connection and lateral can be added to the new system. One common method of making these connections involves the use of a wrap-around service saddle. The saddle is placed over a hole that has been cut through the liner and the entire saddle and gasket assembly is then fastened into place with stainless steel bands. Additional joint integrity can be obtained by extrusion welding of the lap joint created between the saddle base and the liner. The service lateral can then be connected into the saddle, using a readily available flexible coupling(11). Once the lateral has been connected, following standard direct burial procedures can stabilize the entire area.

For pressure applications, lateral connections can be made using sidewall fusion of branch saddles onto the liner. As an alternate, a molded or fabricated tee may be fused or flanged into the liner at the point where the lateral connection is required (see Figures 3 and 4). Mechanical fittings are also a viable option; refer to Chapter 9, PE Joining Procedures, in this Handbook.

7. Make Terminal Connections and Stabilize the Annular Space Where Required

Making the terminal connections of the liner is the final step in the insertion renewal procedure. Pressurized pipe systems will require connection of the liner to the various system appurtenances. These terminal connections can be made readily through the use of pressure-rated polyethylene fittings and flanges with fusion technology. Several common types of pressurized terminal connections are illustrated in Figure 11. All of these require stabilization of the transition region to prevent point loading of the liner. Mechanical Joint (MJ) Adapters can be used. Refer to Chapter 9, PE Joining Procedures, in this Handbook.

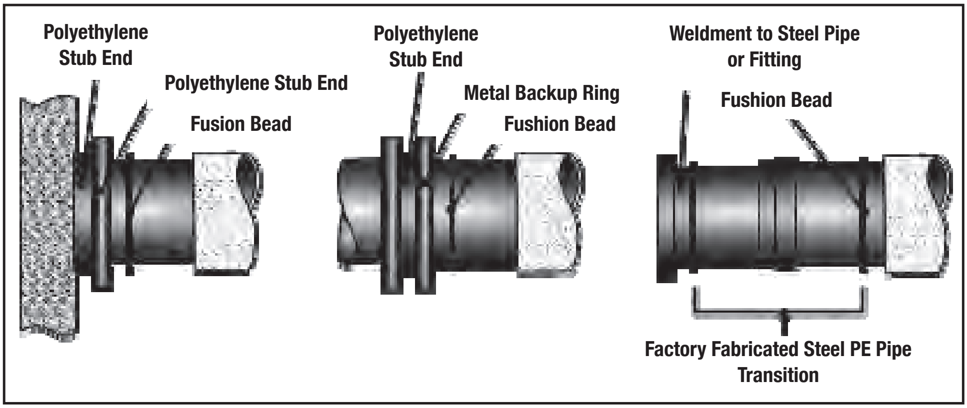


Figure 11 Terminal and Transition Connections for Pressurized Insertion Renewal Projects

Gravity lines do not typically require pressure-capable connections to the other system appurtenances. In these situations, the annular space will be sealed to prevent migration of ground water along the annulus and, ultimately, infiltration through the manhole or headwall connection. The typical method for making this type of connection is shown in Figure 11. Sealing materials should be placed by gravity flow methods so that the liner's buckling resistance is not exceeded during installation. Consideration should be given to the specific load bearing characteristics of the fill material in light of the anticipated loading of the liner.

Other Rehabilitation Methods

Rehabilitation by sliplining is only one (but probably the most popular) of a number of methods using polyethylene pipe currently available for pipeline rehabilitation. As mentioned in the introduction to this chapter, sliplining has been in use for more than thirty years.

Several other methods of rehabilitation that use polyethylene piping will be described briefly here. Please note that, due to rapidly advancing technology, this listing may become incomplete very quickly. Also note that any reference to proprietary products or processes is made only as required to explain a particular methodology.

Swagelining

A continuous length of polyethylene pipe passes through a machine where it is heated. It then passes through a heated die, which reduces the outside diameter (OD). Insertion into the original pipeline then follows through an insertion pit. The liner pipe relaxes (pressurization may be used to speed the process) until the OD of the liner matches the inside diameter (ID) of the original pipeline. Grouting is not required.

Rolldown

This system is very similar to swagelining except OD reduction is by mechanical means and expansion is through pressurization.

Titeliner

A system that is very similar to the swagelining and rolldown systems.

Fold and Form

Continuous lengths of polyethylene pipe are heated, mechanically folded into a "U" shape, and then coiled for shipment. Insertion is made through existing manholes. Expansion is by means of a patented heat/pressure procedure, which utilizes steam. The pipe is made, according to the manufacturer, to conform to the ID of the original pipeline; therefore, grouting is not required.

Pipe Bursting

A technique used for replacing pipes made from brittle materials, e.g. clay, concrete, cast iron, etc. A bursting head (or bursting device) is moved through the pipe, simultaneously shattering it, pushing the shards aside, and drawing in a polyethylene replacement pipe. This trenchless technique makes it possible to install pipe as much as 100% larger than the existing pipe.

Pipe Splitting

A technique, similar to pipe bursting, used for pipes made from ductile materials, e.g. steel, ductile iron, plastic, etc. A "splitter" is moved through the existing pipe, simultaneously splitting it with cutter wheels, expanding it, and drawing in a polyethylene replacement pipe. This trenchless technique is generally limited to replacement with same size or one pipe size (ie., 6" to 8") larger replacement pipe.

Summary

This chapter has provided an introductory discussion on the rehabilitation of a deteriorated pipe structure by insertion renewal with continuous lengths of polyethylene pipe. It also includes a brief description of other rehabilitation methods that utilize polyethylene piping. The sliplining or insertion renewal procedure is a cost-effective means by which a new pipeline is obtained with a minimum interference with surface traffic. An inherent benefit of the technology is the installation of a new, structurally sound, leak-free piping system with improved flow characteristics. The resulting pipe structure allows for a flow capacity at or near that of the deteriorating pipe system while eliminating the potential for infiltration or exfiltration. And the best feature of all is the vastly improved longevity of the PE pipe, especially compared to the decay normally associated with piping materials of the past.

The continuing deterioration of this country's infrastructure necessitates innovative solutions to persistent and costly problems. Insertion renewal, or sliplining, is a cost-effective means by which one aspect of the infrastructure dilemma may be corrected without the expense and long-term service disruption associated with pipeline replacement.

References

1. ASTM 1804, Standard Practice for Determining Allowable Tensile Load for Polyethylene (PE) Gas Pipe During Pull-In Installation, *Annual Book of Standards*, American Society for Testing and Materials (ASTM).
2. ASTM D2321, Standard Practices for Underground Installation of Flexible Thermoplastic Sewer Pipe, *Annual Book of Standards*, American Society for Testing and Materials (ASTM).
3. ASTM D2774, Standard Practices for Underground Installation of Thermoplastic Pressure Piping, *Annual Book of Standards*, American Society for Testing and Materials (ASTM).
4. ASTM D3350, Standard for Polyethylene Pipe and Fittings Materials, *Annual Book of Standards*, American Society for Testing and Materials (ASTM).
5. ASTM F585, Standard Practices for Insertion of Flexible Polyethylene Pipe into Existing Sewers, *Annual Book of Standards*, American Society for Testing and Materials (ASTM).
6. ASTM F714, Standard Specification for Polyethylene (SDR-PR) Based Outside Diameter, *Annual Book of Standards*, American Society for Testing and Materials (ASTM).
7. ASTM F894, Standard Specification for Polyethylene (PE) Large Diameter Profile Wall, Sewer and Drain Pipe, *Annual Book of Standards*, American Society for Testing and Materials (ASTM).
8. Diskin, Joe. (1987, May). Plastic Pipe Insertion, (NF), *Pipeline and Gas Journal*.
9. *Driscopipe System Design*. (1985, January). A Publication of Phillips Driscopipe, Inc.
10. Elastizell Product Catalog. (1984). *The Elastizell Advantage*. A Publication of the Plastizell Corporation of America.
11. *Existing Sewer Evaluation and Rehabilitation*. (1983). American Society of Civil Engineers and the Water Environment Federation, New York, NY.
12. *Fernco Product Catalog 185*. (1985, January). A Publication of Ferncom, Inc.
13. Gross, Sid. (1985, May). Plastic Pipe in Gas Distribution, Twenty-Five Years of Achievement, *Gas Industries*.
14. Gross, Sid. (1987, September). Choosing Between Liners for Sewer Rehabilitation, Public Works.
15. *Handbook of PVC Pipe*. (1978, February). A Publication of the Uni-Bell Plastic Pipe Association, Dallas, TX.
16. Howard, A.E., & Selander, C.E., (1977, September). Laboratory Load Tests on Buried Thermosetting, Thermoplastic and Steel Pipe, *Journal AWWA*.
17. Jenkins, C.F. & Kroll, A.E. (1981, March 30-April 1). External Hydrostatic Loading of Polyethylene Pipe, Proceedings of the International Conference on Underground Plastic Pipe, sponsored by the Pipeline Division of the American Society of Civil Engineers.
18. Lake, Donald W., Jr. (1979, December). Innovative Rehabilitation of Embankment Conduits. Paper presented to the 1984 winter meeting of the American Society of Agricultural Engineers.
19. Plastics Pipe Institute. (1979, September). Technical Report TR-31, Underground Installation of Polyolefin Piping.
20. *Polyolefin Piping*. (1985, May). A Publication of the Plastics Pipe Institute, Irving, TX.

21. *Recommended Specifications for Sewer Connection Rehabilitation*. (1984, January). A Publication of the National Society of Service Companies.
22. *Renewing Sewers with Polyolefin Pipe*. (1985, June). A Publication of the Plastics Pipe Institute, Irving, TX.
23. Sandstrum, S.D. (1986, August). Sewer Rehabilitation with Polyethylene Pipe. Paper presented at the Second Annual Sewer Maintenance and Rehabilitation Conference, Center for Local Government Technology, Oklahoma State University.
24. Schock, David B. (1982, August 6). New Pipes Do Job Better, *Mount Pleasant Morning Sun*.
25. Spangler, M.G. (1941). The Structural Design of Flexible Pipe Culverts, Bulletin 153, Iowa State Engineering Experiment Station.
26. *Spiral Engineered Systems*, A Publication of Spirolite, a Subsidiary of the Chevron Corporation.
27. Watkins, R.K. (1977). *Buried Structures*, Foundation Engineering Handbook, Utah State University.
28. Watkins, R.K. (1977). *Principles of Structural Performance of Buried Pipes*, Utah State University.
29. DOT FHWA-1P-85-15.
30. *Mark's Handbook for Mechanical Engineers*, 10th Edition.
31. Larock, B.E., Jeppson, R.W., & Watters, G.Z. (2000). *Hydraulics of Pipeline Systems*, Boca Raton: CRC Press.
32. Lo, King H., & Zhang, Jane Q. (1994, February 28-March 2). Collapse Resistance Modeling of Encased Pipes, Buried Plastic Pipe Technology: 2nd Volume, Papers presented at the ASTM symposium, New Orleans.

Chapter 12

Horizontal Directional Drilling

Introduction

The Horizontal Directional Drilling (HDD) Industry has experienced so much growth in the past two decades that HDD has become commonplace as a method of installation. One source reported that the number of units in use increased by more than a hundred-fold in the decade following 1984. This growth has been driven by the benefits offered to utility owners (such as the elimination of traffic disruption and minimal surface damage) and by the ingenuity of contractors in developing this technology. To date, HDD pipe engineering has focused on installation techniques, and rightfully so. In many cases, the pipe experiences its maximum lifetime loads during the pullback operation.

The purpose of this chapter is to acquaint the reader with some of the important considerations in selecting the proper PE pipe. Proper selection of pipe involves consideration not only of installation design factors such as pullback force limits and collapse resistance, but also of the long-term performance of the pipe once installed in the bore-hole. The information herein is not all-inclusive; there may be parameters not discussed that will have significant bearing on the proper engineering of an application and the pipe selection. For specific projects, the reader is advised to consult with a qualified engineer to evaluate the project and prepare a specification including recommendations for design and installation and for pipe selection. The reader may find additional design and installation information in ASTM F1962, “Standard Guide for Use of Maxi-Horizontal Directional Drilling for Placement of PE Pipe or Conduit Under Obstacles, Including River Crossings,” and in the ASCE Manual of Practice 108, “Pipeline Design for Installation by Directional Drilling.”

Background

Some of the earliest uses of large diameter PE pipe in directional drilling were for river crossings. These are major engineering projects requiring thoughtful design, installation, and construction, while offering the owner the security of deep river bed cover with minimum environmental damage or exposure, and no disruption of river traffic. PE pipe is suited for these installations because of its scratch tolerance and the fused joining system which gives a zero-leak-rate joint with design tensile capacity equal to that of the pipe.

To date, directional drillers have installed PE pipe for gas, water, and sewer mains; communication conduits; electrical conduits; and a variety of chemical lines. These projects involved not only river crossings but also highway crossings and right-of-ways through developed areas so as not to disturb streets, driveways, and business entrances.

PE Pipe for Horizontal Directional Drilling

This chapter gives information on the pipe selection and design process. It is not intended to be a primer on directional drilling. The reader seeking such information can refer to the references of this chapter. Suggested documents are the "Mini-Horizontal Directional Drilling Manual" (1) and the "Horizontal Directional Drilling Good Practices Guidelines" (2) published by the North American Society for Trenchless Technology (NASTT).

Horizontal Directional Drilling Process

Knowledge of the directional drilling process by the reader is assumed, but some review may be of value in establishing common terminology. Briefly, the HDD process begins with boring a small, horizontal hole (pilot hole) under the crossing obstacle (e.g. a highway) with a continuous string of steel drill rod. When the bore head and rod emerge on the opposite side of the crossing, a special cutter, called a back reamer, is attached and pulled back through the pilot hole. The reamer bores out the pilot hole so that the pipe can be pulled through. The pipe is usually pulled through from the side of the crossing opposite the drill rig.

Pilot Hole

Pilot hole reaming is the key to a successful directional drilling project. It is as important to an HDD pipeline as backfill placement is to an open-cut pipeline. Properly trained crews can make the difference between a successful and an unsuccessful drilling program for a utility. Several institutions provide operator-training programs, one of which is University of Texas at Arlington Center for Underground Infrastructure Research and Education (CUIRE). Drilling the pilot hole establishes the path of the drill rod ("drill-path") and subsequently the location of the PE pipe. Typically, the bore-head is tracked electronically so as to guide the hole to a pre-designed configuration. One of the key considerations in the design of the drill-path is creating as large a radius of curvature as possible within the limits of the right-of-way, thus minimizing curvature. Curvature induces bending stresses and increases the pullback load due to the capstan effect. The capstan effect is the increase in frictional drag when pulling the pipe around a curve due to a component of the pulling force acting normal to the curvature. Higher tensile stresses reduce the pipe's collapse resistance. The drill-path normally has curvature along its vertical profile. Curvature requirements are dependent on site geometry (crossing length, required depth to provide safe cover, staging site location, etc.) But, the degree of curvature is limited by the bending radius of the drill rod and the pipe. More often, the permitted bending radius of the drill rod controls the curvature and thus significant bending stresses do not occur in the pipe. The designer should minimize the number of curves and maximize their radii of curvature in the right-of-way by carefully choosing the entry and exit points. The driller should also attempt to minimize extraneous curvature due to undulations (dog-legs) from frequent over-correcting alignment or from differences in the soil strata or cobbles.

Pilot Hole Reaming

The REAMING operation consists of using an appropriate tool to open the pilot hole to a slightly larger diameter than the carrier pipeline. The percentage oversize depends on many variables including soil types, soil stability, depth, drilling mud, borehole hydrostatic pressure, etc. Normal over-sizing may be from 1.2 to 1.5 times the diameter of the carrier pipe. While the over-sizing is necessary for insertion, it means that the inserted pipe will have to sustain vertical earth pressures without significant side support from the surrounding soil.

Prior to pullback, a final reaming pass is normally made using the same sized reamer as will be used when the pipe is pulled back (swab pass). The swab pass cleans the borehole, removes remaining fine gravels or clay clumps and can compact the borehole walls.

Drilling Mud

Usually a "drilling mud" such as fluid bentonite clay is injected into the bore during cutting and reaming to stabilize the hole and remove soil cuttings. Drilling mud can be made from clay or polymers. The primary clay for drilling mud is sodium montmorillonite (bentonite). Properly ground and refined bentonite is added to fresh water to produce a "mud." The mud reduces drilling torque, and gives stability and support to the bored hole. The fluid must have sufficient gel strength to keep cuttings suspended for transport, to form a filter cake on the borehole wall that contains the water within the drilling fluid, and to provide lubrication between the pipe and the borehole on pullback. Drilling fluids are designed to match the soil and cutter. They are monitored throughout the process to make sure the bore stays open, pumps are not overworked, and fluid circulation throughout the borehole is maintained. Loss of circulation could cause a locking up and possibly overstressing of the pipe during pullback.

Drilling muds are thixotropic and thus thicken when left undisturbed after pullback. However, unless cementitious agents are added, the thickened mud is no stiffer than very soft clay. Drilling mud provides little to no soil side-support for the pipe.

Pullback

The pullback operation involves pulling the entire pipeline length in one segment (usually) back through the drilling mud along the reamed-hole pathway. Proper pipe handling, cradling, bending minimization, surface inspection, and fusion welding procedures need to be followed. Axial tension force readings, constant insertion velocity, mud flow circulation/exit rates, and footage length installed should be recorded. The pullback speed ranges usually between 1 to 2 feet per minute.

Mini-Horizontal Directional Drilling

The Industry distinguishes between mini-HDD and conventional HDD, which is sometimes referred to as maxi-HDD. Mini-HDD rigs can typically handle pipes up to 10″ or 12″ diameter and are used primarily for utility construction in urban areas, whereas HDD rigs are typically capable of handling pipes as large as 48″diamter. These machines have significantly larger pullback forces ranging up to several hundred thousand pounds.

General Guidelines

The designer will achieve the most efficient design for an application by consulting with an experienced contractor and a qualified engineer. Here are some general considerations that may help particularly in regard to site location for PE pipes:

1. Select the crossing route to keep it to the shortest reasonable distance.
2. Find routes and sites where the pipeline can be constructed in one continuous length; or at least in long multiple segments fused together during insertion.
3. Although compound curves have been done, try to use as straight a drill path as possible.
4. Avoid entry and exit elevation differences in excess of 50 feet; both points should be as close as possible to the same elevation.

5. Locate all buried structures and utilities within 10 feet of the drill-path for mini-HDD applications and within 25 feet of the drill-path for maxi-HDD applications. Crossing lines are typically exposed for exact location.
6. Observe and avoid above-ground structures, such as power lines, which might limit the height available for construction equipment.
7. The HDD process takes very little working space versus other methods. However, actual site space varies somewhat depending upon the crossing distance, pipe diameter, and soil type.
8. Long crossings with large diameter pipe need bigger, more powerful equipment and drill rig.
9. As pipe diameter increases, large volumes of drilling fluids must be pumped, requiring more/larger pumps and mud-cleaning and storage equipment.
10. Space requirements for maxi-HDD rigs can range from a 100 feet wide by 150 feet long entry plot for a 1000 ft crossing up to 200 feet wide by 300 feet long area for a crossing of 3000 or more feet.
11. On the pipe side of the crossing, sufficient temporary space should be rented to allow fusing and joining the PE carrier pipe in a continuous string beginning about 75 feet beyond the exit point with a width of 35 to 50 feet, depending on the pipe diameter. Space requirements for coiled pipe are considerably less. Larger pipe sizes require larger and heavier construction equipment which needs more maneuvering room (though use of PE minimizes this). The initial pipe side "exit" location should be about 50′ W x 100′ L for most crossings, up to 100′ W x 150′ L for equipment needed in large diameter crossings.
12. Obtain "as-built" drawings based on the final course followed by the reamer and the installed pipeline. The gravity forces may have caused the reamer to go slightly deeper than the pilot hole, and the buoyant pipe may be resting on the crown of the reamed hole. The as-built drawings are essential to know the exact pipeline location and to avoid future third party damage.

Safety

Safety is a primary consideration for every directionally drilled project. While this chapter does not cover safety, there are several manuals that discuss safety including the manufacturer's Operator's Manual for the drilling rig and the Equipment Manufacturer's Institute (EMI) Safety Manual: *Directional Drilling Tracking Equipment.* (3)

Geotechnical Investigation

Before any serious thought is given to the pipe design or installation, the designer will normally conduct a comprehensive geotechnical study to identify soil formations at the potential bore sites. The purpose of the investigation is not only to determine if directional drilling is feasible, but to establish the most efficient way to accomplish it. With this information the best crossing route can be determined, drilling tools and procedures selected, and the pipe designed. The extent of the geotechnical investigation often depends on the pipe diameter, bore length and the nature of the crossing. Refer to ASTM F1962, Guide for Use of Maxi-Horizontal Directional Drilling for Placement of Polyethylene Pipe or Conduit Under Obstacles, Including River Crossings (4) and ASCE MOP 108, Pipeline Design for Installation by Horizontal Directional Drilling (5) for additional information.

During the survey, the geotechnical consultant will identify a number of relevant items including the following:

a. Soil identification to locate rock, rock inclusions, gravelly soils, loose deposits, discontinuities and hardpan.

b. Soil strength and stability characteristics

c. Groundwater

(Supplemental geotechnical data may be obtained from existing records, e.g. recent nearby bridge constructions, other pipeline/cable crossings in the area.)

For long crossings, borings are typically taken at 700 ft intervals. For short crossings (1000 ft or less), as few as three borings may suffice. The borings should be near the drill-path to give accurate soil data, but sufficiently far from the borehole to avoid pressurized mud from following natural ground fissures and rupturing to the ground surface through the soil-test bore hole. A rule-of -thumb is to take borings at least 30 ft to either side of bore path. Although these are good general rules, the number, depth and location of boreholes is best determined by the geotechnical engineer.

Geotechnical Data For River Crossings

River crossings require additional information such as a study to identify river bed, river bed depth, stability (lateral as well as scour), and river width. Typically, pipes are installed to a depth of at least 20 ft below the expected future river bottom, considering scour. Soil borings for geotechnical investigation are generally conducted to 40 ft below river bottom.

Summary

The best conducted projects are handled by a team approach with the design engineer, bidding contractors and geotechnical engineer participating prior to the preparation of contract documents. The geotechnical investigation is usually the first step in the boring project. Once the geotechnical investigation is completed, a determination can be made whether HDD can be used. At that time, design of both the PE pipe and the installation can begin. The preceding paragraphs represent general guidance and considerations for planning and designing an HDD PE pipeline project. These overall topics can be very detailed in nature. Individual HDD contractors and consultant engineering firms should be contacted and utilized in the planning and design stage. Common sense along with a rational in-depth analysis of all pertinent considerations should prevail. Care should be given in evaluating and selecting an HDD contractor based upon successful projects, qualifications, experience and diligence. A team effort, strategic partnership and risk-sharing may be indicated.

Product Design: PE Pipe DR Selection

After completion of the geotechnical investigation and determination that HDD is feasible, the designer turns attention to selecting the proper pipe. The proper pipe must satisfy all hydraulic requirements of the line including flow capacity, working pressure rating, and surge or vacuum capacity. These considerations have to be met regardless of the method of installation. Design of the pipe for hydraulic considerations can be found in Chapter 6. For HDD applications, in addition to the hydraulic requirements, the pipe must be able to withstand (1) pullback loads which include tensile pull forces, external hydrostatic pressure, and tensile bending stresses, and (2) external service loads (post-installation soil, groundwater, and surcharge loads occurring over the life of the pipeline). Often the load the pipe sees during installation such as the combined pulling force and external pressure will be the largest load experienced by the pipe during its life. The remainder of this document will discuss the DR (Dimension Ratio) selection based on pullback and external service loads. (PE pipe is classified by DR. The DR is the “dimension ratio” and equals the pipe’s outer diameter divided by the minimum wall thickness.) A more detailed explanation of the DR concept is provided in Chapter 5.

While this chapter gives guidelines to assist the designer, the designer assumes all responsibility for determining the appropriateness and applicability of the equations and parameters given in this chapter for any specific application. Directional drilling is an evolving technology, and industry-wide design protocols are still developing. Proper design requires considerable professional judgment beyond the scope of this chapter. The designer is advised to consult ASTM F 1962, Guide for Use of Maxi-Horizontal Directional Drilling for Placement of Polyethylene Pipe or Conduit

Under Obstacles, Including River Crossings (4) when preparing an HDD design. This methodology is applied to designing municipal water pipe crossings as shown in Petroff (6).

Normally, the designer starts the DR selection process by determining the DR requirement for the internal pressure. The designer will then determine if this DR is sufficient to withstand earth, live, and groundwater service loads. If so, then the installation (pullback) forces are considered. Ultimately, the designer chooses a DR that will satisfy all three requirements: the pressure, the service loads, and the pullback load.

Although there can be some pipe wall stresses generated by the combination of internal pressurization and wall bending or localized bearing, generally internal pressure and external service load stresses are treated as independent. This is permissible primarily since PE is a ductile material and failure is usually driven by the average stress rather than local maximums. There is a high safety factor applied to the internal pressure, and internal pressurization significantly reduces stresses due to external loads by re-rounding. (One exception to this is internal vacuum, which must be combined with the external pressure.)

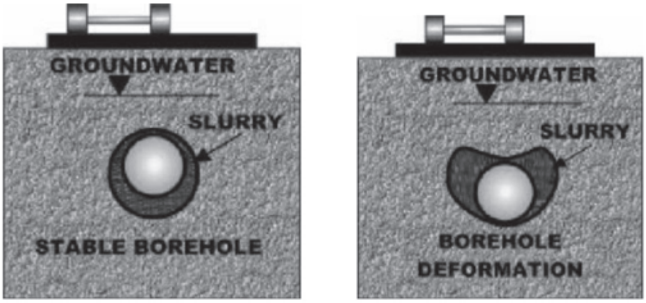


Figure 1 Borehole Deformation

Design Considerations for Net External Loads

This and the following sections will discuss external buried loads that occur on directionally drilled pipes. One important factor in determining what load reaches the pipe is the condition of the borehole, i.e. whether it stays round and open or collapses. This will depend in great part on the type of ground, the boring techniques, and the presence of slurry (drilling mud and cutting mixture). If the borehole does not deform (stays round) after drilling, earth loads are arched around the borehole and little soil pressure is transmitted to the pipe. The pressure acting on the pipe is the hydrostatic pressure due to the slurry or any groundwater present. The slurry itself may act to keep the borehole open. If the borehole collapses or deforms substantially, earth pressure will be applied to the pipe. The resulting pressure could exceed the slurry pressure unless considerable tunnel arching occurs above the borehole. Where no tunnel arching occurs, the applied external pressure is equal to the combined earth, groundwater, and live-load pressure. For river crossings, in unconsolidated river bed soils, little arching is anticipated . The applied pressure likely equals the geostatic stress (sometimes called the prism load). In consolidated soils, arching above the borehole may occur, and the applied pressure will likely be less than the geostatic stress, even after total collapse of the borehole crown onto the pipe. If the soil deposit is a stiff clay, cemented, or partially lithified, the borehole may stay open with little or no deformation. In this case, the applied pressure is likely to be just the slurry head or groundwater head.

In addition to the overt external pressures such as slurry head and groundwater, internal vacuum in the pipe results in an increase in external pressure due to the removal of atmospheric pressure from inside the pipe. On the other hand, a positive internal pressure in the pipe may mediate the external pressure. The following equations can be used to establish the net external pressure or, as it is sometimes called, the differential pressure between the inside and outside of the pipe.

Depending on the borehole condition, the net external pressure is defined by either Eq. 1 (deformed/collapsed borehole) or Eq. 2 (open borehole):

(1) $$P_N = P_E + P_{GW} + P_{SUR} - P_I$$

(2) $$P_N = P_{MUD} - P_I$$

WHERE

P_N **= Net external pressure, psi**

P_E **= External pressure due to earth pressure, psi**

P_{GW} **= Groundwater pressure (including the height of river water), psi**

P_{SUR} **= Surcharge and live loads, psi**

P_I **= Internal pressure, psi (negative in the event of vacuum)**

P_{MUD} **= Hydrostatic pressure of drilling slurry or groundwater pressure, if slurry can carry shear stress, psi**

(Earth, ground water, and surcharge pressures used in Eq. 1 are discussed in a following section of this chapter.)

(3) $$P_{MUD} = \frac{g_{MUD} H_B}{144}$$

WHERE

g_{MUD} **= Unit weight of slurry (drilling mud and cuttings), pcf**

H_B **= Elevation difference between lowest point in borehole and entry or exit pit, ft**

(144 is included for units conversion.)

When calculating the net external pressure, the designer will give careful consideration to enumerating all applied loads and their duration. In fact, most pipelines go through operational cycles that include (1) unpressurized or being drained, (2) operating at working pressure, (3) flooding, (4) shutdowns, and (5) vacuum and peak pressure events. As each of these cases could result in a different net external pressure, the designer will consider all phases of the line's life to establish the design cases.

In addition to determining the load, careful consideration must be given to the duration of each load. PE pipe is viscoelastic, that is, its effective properties depend on duration of loading. For instance, an HDD conduit resists constant groundwater and soil pressure with its long-term apparent modulus stiffness. On the other hand, an HDD force-main may be subjected to a sudden vacuum resulting from water hammer. When a vacuum occurs, the net external pressure equals the sum of the external pressure plus the vacuum. Since surge is instantaneous, it is resisted by the pipe's short-term apparent modulus,, which can be four times higher than the long-term apparent modulus.

For pressure lines, consideration should be given to the time the line sits unpressurized after construction. This may be several months. Most directionally drilled lines that contain fluid will have a static head, which will remain in the line once filled. This head may be subtracted from the external pressure due to earth/ groundwater load. The designer should keep in mind that the external load also may vary with time, for example, flooding.

Earth and Groundwater Pressure

Earth loads can reach the pipe when the borehole deforms and contacts the pipe. The amount of soil load transmitted to the pipe will depend on the extent of deformation and the relative stiffness between the pipe and the soil. Earth loading may not be uniform. Due to this complexity, there is not a simple equation for relating earth load to height of cover. Groundwater loading will occur whether the hole deforms or not; the only question is whether or not the slurry head is higher and thus may in fact control design. Thus, what loads reach the pipe will depend on the stability of the borehole.

The designer may wish to consult a geotechnical engineer for assistance in determining earth and groundwater loads, as the loads reaching the pipe depend on the nature of the soil.

Stable Borehole - Groundwater Pressure Only

A borehole is called stable if it remains round and deforms little after drilling. For instance, drilling in competent rock (rock that can be drilled without fracturing and collapsing) will typically result in a stable borehole. Stable boreholes may occur in some soils where the slurry exerts sufficient pressure to maintain a round and open hole. Since the deformations around the hole are small, soil pressures transmitted to the pipe are negligible. The external load applied to the pipe consists only of the hydrostatic pressure due to the slurry or the groundwater, if present. Equation 4 gives the hydrostatic pressure due to groundwater or drilling slurry. Standing surface water should be added to the groundwater.

(4)

$$P_{GW} = \frac{g_W H_W}{144}$$

WHERE

P_{GW} = **Hydrostatic fluid pressure due to ground and surface water, psi**

g_w = **Unit weight of water, pcf**

H_W = **Height to free water surface above pipe, ft (144 is included for correct units conversion.)**

Borehole Deforms/Collapse With Arching Mobilized

When the crown of the hole deforms sufficiently to place soil above the hole in the plastic state, arching is mobilized. In this state, hole deformation is limited. If no soil touches the pipe, there is no earth load on the pipe. However, when deformation is sufficient to transmit load to the pipe, it becomes the designer's chore to determine how much earth load is applied to the pipe. At the time of this writing, there have been no published reports giving calculation methods for finding earth load on directionally drilled pipes. Based on the successful performance of directionally drilled PE pipes, it is reasonable to assume that some amount of arching occurs in many applications. The designer of HDD pipes may gain some knowledge from the approaches developed for determining earth pressure on auger bored pipes and on jacked pipes. It is suggested that the designer become familiar with all of the assumptions used with these methods. For additional information on post installation design of directionally drilled pipelines see Petroff (9).

O'Rourke et. al. (7) published an equation for determining the earth pressure on auger bored pipes assuming a borehole approximately 10% larger than the pipe. In this model, arching occurs above the pipe similar to that in a tunnel where zones of loosened soil fall onto the pipe. The volume of the cavity is eventually filled with soil that is slightly less dense than the insitu soil, but still capable of transmitting soil load. This method of load calculation gives a minimal loading. The method published here is more conservative. It is based on trench type arching as opposed to tunnel arching and is used by Stein (8) to calculate loads on jacked pipe. In Stein's model, the maximum earth load (effective stress) is found using the modified form of Terzaghi's equation given by Eq. 6., Petroff (9). External groundwater pressure must be added to the effective earth pressure. Stein and O'Rourke's methods should only be considered where the depth of cover is sufficient to develop arching (typically exceeding five (5) pipe diameters), dynamic loads such as traffic loads are insignificant, the soil has sufficient internal friction to transmit arching, and conditions are confirmed by a geotechnical engineer.

Using the equations given in Stein, the external pressure is given below:

(5)
$$P_E = \frac{k\, g_{SE} H_C}{144}$$

(6)
$$k = \frac{1 - \exp\left(-2 \frac{K H_C}{B} \tan\left(\frac{\delta}{2} \right) \right)}{2 \frac{K H_C}{B} \tan\left(\frac{\delta}{2} \right)}$$

WHERE

P_E **= external earth pressure, psi**

g_{SE} **= effective soil weight, pcf**

H_C **= depth of cover, ft**

k **= arching factor**

B **= "silo" width, ft**

δ **= angle of wall friction, degrees (For HDD,** δ **= f)**

f **= angle of internal friction, degrees**

K **= earth pressure coefficient given by:**

$$K = \tan^2\left(45 - \frac{f}{2} \right)$$

The "silo" width should be estimated based on the application. It varies between the pipe diameter and the borehole diameter. A conservative approach is to assume the silo width equals the borehole diameter. (The effective soil weight is the dry unit weight of the soil for soil above the groundwater level, it is the saturated unit weight less the weight of water for soil below the groundwater level.)

Borehole Collapse with Prism Load

In the event that arching in the soil above the pipe breaks down, considerable earth loading may occur on the pipe. In the event that arching does not occur, the upper limit on the load is the weight of the soil prism ($P_E = g_{SE} H_C$) above the pipe. The prism load is most likely to develop in shallow applications subjected to live loads, boreholes in unconsolidated sediments such as in some river crossings, and holes subjected to dynamic loads. The "prism" load is given by Eq. 7.

(7)
$$P_E = \frac{g_{SE} H_C}{144}$$

WHERE

P_E **= earth pressure on pipe, psi**

g_{SE} **= effective weight of soil, pcf**

H_C **= soil height above pipe crown, ft**

(Note: 144 is included for units conversion.)

Combination of Earth and Groundwater Pressure

Where groundwater is present in the soil formation, its pressure must be accounted for in the external load term. For instance, in a river crossing one can assume with reasonable confidence that the directionally drilled pipe is subjected to the earth pressure from the sediments above it combined with the water pressure.

Case 1 Water level at or below ground surface

(8)
$$P_E + P_{GW} = \frac{g_B H_W + g_D (H_C - H_W) + g_W H_W}{144}$$

Case 2 Water level at or above ground surface (i.e. pipe in river bottom)

(9)
$$P_E + P_{GW} = \frac{g_B H_C + g_W H_W}{144}$$

WHERE

H_W **= Height of Ground water above pipe springline, ft**

H_C **= height of cover, ft**

g_B **= buoyant weight of soil, pcf**

g_W **= weight of water, pcf**

g_D **= dry unit weight of soil, pcf**

Live Loads

Wheel loads from trucks or other vehicles are significant for pipe at shallow depths whether they are installed by open cut trenching or directional drilling. The wheel load applied to the pipe depends on the vehicle weight, the tire pressure and size, vehicle speed, surface smoothness, pavement and distance from the pipe to the point of loading. In order to develop proper soil structure interaction, pipe subject to vehicular loading should be installed at least 18" or one pipe diameter (whichever is larger) under the road surface. Generally, HDD pipes are always installed at a deeper depth so as to prevent inadvertent returns from occurring during the boring.

The soil pressure due to live load such as an H20 wheel load can be found in Tables 3-3 and 3-4 in Chapter 6 or can be calculated using one of the methods in Chapter 6. To find the total pressure applied to the pipe, add the soil pressure due to live load, P_L, to the earth pressure, P_E. See Example 1 in Appendix A.

Performance Limits

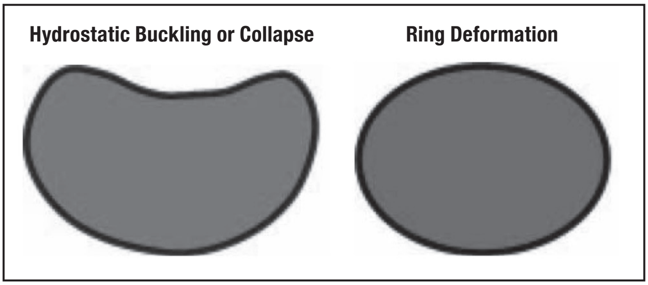


Figure 2 Performance Limits of HDD Pipe Subjected to Service Loads

Performance Limits of HDD Installed Pipe

The design process normally consists of calculating the loads applied to the pipe, selecting a trial pipe DR, then calculating the safety factor for the trial DR. If the safety factor is adequate, the design is sufficient. If not, the designer selects a lower DR and repeats the process. The safety factor is established for each performance limit of the pipe by taking the ratio of the pipe's ultimate strength or resistance to the applied load.

External pressure from earth load, groundwater, vacuum and live load applied to the HDD pipe produces (1) a compressive ring thrust in the pipe wall and (2) ring bending deflection. The performance limit of unsupported PE pipe subjected to compressive thrust is ring buckling (collapse). The performance limit of a PE pipe subjected to ring bending (a result of non-uniform external load, i.e. earth load) is ring deflection. See Figure 2.

Viscoelastic Behavior

Both performance limits are proportional to the apparent modulus of elasticity of the PE material. For viscoelastic materials like PE, the modulus of elasticity is a time-dependent property, that is, its value changes with time under load. A newly applied load increment will cause a decrease in apparent stiffness over time. Unloading will result in rebounding or an apparent gain in stiffness. The result is a higher resistance to short term loading than to long-term loading. Careful consideration must be given to the duration and frequency of each load, so that the performance limit associated with that load can be calculated using PE material properties representative of that time period. The same effects occur with the pipe's tensile strength. For instance, during pullback, the pipe's tensile yield strength decreases with pulling time, so the safe (allowable) pulling stress is a function of time under load, and temperature.

Typical safe pull tensile stress values for MDPE and HDPE are given in Table 1. Consult the manufacturer for specific applications. The values are given as a function of the duration of continuous loading. For pipe temperatures (not outside air temperatures) other than 73ºF, multiply the value in Table 1 by the temperature compensating multipliers found in Table B.1.2 of the Appendix to Chapter 3. The Safe Pull Load at 12 hours is given for a variety of pipe sizes and DR's in Tables 3 and 4 (3xxx material) and Tables 5 and 6 (4xxx material) in a following section, "Tensile Stress During Pullback".

TABLE 1
Safe Pull Tensile Stress @ 73º F

Duration (Hours)	Typical Safe Pull Stress (psi) @ 73ºF		
	PE2xxx (PE2406)	PE3xxx (PE3408)	PE4xxx (PE4710)
0.5	1100	1400	1500
1	1050	1350	1400
12	850	1100	1150
24	800	1050	1100

The safe pull stress is the stress at 3% strain. For strains less than 3% the pipe will essentially have complete strain recovery after pullback. The stress values in Table 1 were determined by multiplying 3% times the apparent tensile modulus from the Appendix to Chapter 3 adjusted by a 0.60 factor to account for the high stress level during pullback.

Ring Deflection (Ovalization)

Non-uniform pressure acting on the pipe's circumference such as earth load causes bending deflection of the pipe ring. Normally, the deflected shape is an oval. Ovalization may exist in non-rerounded coiled pipe and to a lesser degree in straight lengths that have been stacked, but the primary sources of bending deflection of directionally drilled pipes is earth load. Slight ovalization may also occur during pullback if the pipe is pulled around a curved path in the borehole. Ovalization reduces the pipe's hydrostatic collapse resistance and creates tensile bending stresses in the pipe wall. It is normal and expected for buried PE pipes to undergo ovalization. Proper design and installation will limit ovalization (or as it is often called "ring deflection") to prescribed values so that it has no adverse effect on the pipe.

Ring Deflection Due to Earth Load

As discussed previously, insitu soil characteristics and borehole stability determine to great extent the earth load applied to directionally drilled pipes. Methods for calculating estimated earth loads, when they occur, are given in the previous section on "Earth and Groundwater Pressure."

Since earth load is non-uniform around a pipe's circumference, the pipe will undergo ring deflection, i.e. a decrease in vertical diameter and an increase in horizontal diameter. The designer can check to see if the selected pipe is stiff enough to limit deflection and provide an adequate safety factor against buckling. (Buckling is discussed in a later section of this chapter.)

The soil surrounding the pipe may contribute to resisting the pipe's deflection. Formulas used for entrenched pipe, such as Spangler's Iowa Formula, are likely not applicable as the HDD installation is different from installing pipe in a trench where the embedment can be controlled. In an HDD installation, the annular space surrounding the pipe contains a mixture of drilling mud and cuttings. The mixture's consistency or stiffness determines how much resistance it contributes. Consistency (or stiffness) depends on several factors including soil density, grain size and the presence of groundwater. Researchers have excavated pipe installed by HDD and observed some tendency of the annular space soil to return to the condition of the undisturbed native soil. See Knight(11) and Ariaratnam(12). It is important to note that the researched installations were located above groundwater, where excess water in the mud-cuttings slurry can drain. While there may be consolidation and strengthening of the annular space soil particularly above the groundwater level, it may be weeks or even months before significant resistance to pipe deflection develops. Until further research establishes the soil's contribution to resisting deflection, one option is to ignore any soil resistance and to use Equation 10 which is derived from ring deflection equations published by Watkins and Anderson(13). (Coincidentally, Equation 10 gives the same deflection as the Iowa Formula with an E′ of zero.) Spangler's Iowa formula is discussed in Chapter 6. The design deflection limits for directionally drilled pipe are given in Table 2. Design deflection limits are for use in selecting a design DR. Field deflection measurements of directionally drilled pressure pipe are normally not made. Design deflection must be limited to control buckling resistance.

(10)
$$\frac{\Delta y}{D} = \frac{\frac{0.0125 P_E}{E}}{12\,(DR - 1)^3}$$

WHERE

Δy = **vertical ring deflection, in**

D = **pipe diameter, in**

P_E = **Earth pressure, psi**

DR = **Pipe Dimension Ratio**

E = **apparent modulus of elasticity, psi (Refer to Appendix, Chapter 3, Engineering Properties, for the appropriate value for the Material Designation Code of the PE pipe being used and the applicable service conditions)**

* To obtain ring deflection in percent, multiply $\Delta y/D$ by 100.

TABLE 2
Design Deflection Limits of Buried Polyehtylene Pipe, Long Term, %*

DR or SDR	**21**	**17**	**15.5**	**13.5**	**11**	**9**	**7.3**
Deflection Limit (% Δy/D) Non-Pressure Applications	7.5	7.5	7.5	7.5	7.5	7.5	7.5
Deflection Limit (%Δy/D) Pressure Applications	7.5	6.0	6.0	6.0	5.0	4.0	3.0

* Design deflection limits per ASTM F1962, Guide for Use of Maxi-Horizontal Directional Drilling for Placement of PE Pipe or Conduit Under Obstacles, Including River Crossings.

Unconstrained Buckling

Uniform external pressure applied to the pipe either from earth and live load, groundwater, or the drilling slurry creates a ring compressive hoop stress in the pipe's wall. If the external pressure is increased to a point where the hoop stress reaches a critical value, there is a sudden and large inward deformation of the pipe wall, called buckling. Constraining the pipe by embedding it in soil or cementitious grout will increase the pipe's buckling strength and allow it to withstand higher external pressure than if unconstrained. However, as noted in a previous section it is not likely that pipes installed below the groundwater level will acquire significant support from the surrounding mud-cuttings mixture and for pipe above groundwater support may take considerable time to develop. Therefore, until further research is available it is conservative to assume no constraint from the soil. The following equation, known as Levy's equation, may be used to determine the allowable external pressure (or negative internal pressure) for unconstrained pipe.

(11)
$$P_{UC} = \frac{2\,E}{(1 - \mu^2)} \left(\frac{1}{DR - 1}\right)^3 \frac{f_O}{N}$$

WHERE

P_{uc} = **Allowable unconstrained buckling pressure**

E = **Apparent modulus of elasticity, psi (Refer to Appendix, Chapter 3, Engineering Properties, for the appropriate value for the Material Designation Code of the PE pipe being used and the applicable service conditions.)**

μ = **Poisson's Ratio = 0.45 for all PE pipe materials**

DR = **Dimension Ratio (D_0/t), where D_0 =Outside Pipe Diameter and t = Minimum Wall Thickness**

f_o = **Ovality compensation factor (see figure 3)**

N = **Safety factor, generally 2.0 or higher**

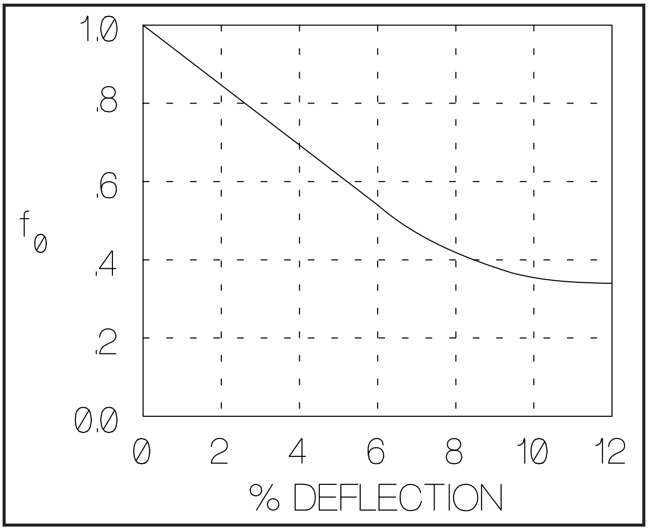


Figure 3 Ovality Compensation Factor=f_o

For a detailed discussion of buckling see the section in Chapter 6 titled "Unconstrained Pipe Wall Buckling (Hydrostatic Buckling). Note that the apparent modulus of elasticity is a function of the duration of the anticipated load. When selecting a modulus to use in Equation 11 consideration should be given to internal pressurization of the line. When the pressure in the pipe exceeds the external pressure due to earth and live load, groundwater and/or slurry, the stress in the pipe wall reverses from compressive to tensile stress and collapse will not occur. For determining the pipe's resistance to buckling during pullback, an additional reduction for tensile stresses is required, which is discussed in a later section of this chapter.

Wall Compressive Stress

The compressive stress in the wall of a directionally drilled PE pipe rarely controls design and it is normally not checked. However, it is included here because in some special cases such as directional drilling at very deep depths such as in landfills it may control design.

The earth pressure applied to a buried pipe creates a compressive thrust stress in the pipe wall. When the pipe is pressurized, the stress is reduced due to the internal pressure creating tensile thrust stresses. The net stress can be positive or negative depending on the depth of cover. Buried pressure lines may be subject to net compressive stress when shut down or when experiencing vacuum. These are usually short-term conditions and are not typically considered significant for design, since the short-term design stress of polyolefins is considerably higher than the long-term design stress. Pipes with large depths of cover and operating at low pressures may have net compressive stresses in the pipe wall. The following equation can be used to determine the net compressive stress:

(12)

$$S_c = \frac{P_S D_O}{288t} - \frac{PD}{2t}$$

WHERE

S_C **= Compressive wall stress, psi**

P_S **= Earth load pressures, psf**

D_O **= Pipe outside diameter, in**

t **= Wall thickness, in**

P **= (Positive) internal pressure, psi**

D **= Mean diameter,** D_O**-t, in**

The compressive wall stress should be kept less than the allowable compressive stress of the material. For PE4710 PE pipe grade resins, 1150 psi is a safe allowable stress. For other materials see the Appendix of Chapter 3.

EXAMPLE CALCULATIONS An example calculation for selecting the DR for an HDD pipe is given in Appendix A.

Installation Design Considerations

After determining the DR required for long-term service, the designer must determine if this DR is sufficient for installation. Since installation forces are so significant, a lower DR (stronger pipe) may be required.

During pullback the pipe is subjected to axial tensile forces caused by the frictional drag between the pipe and the borehole or slurry, the frictional drag on the ground surface, the capstan effect around drill-path bends, and hydrokinetic drag. In addition, the pipe may be subjected to external hoop pressures due to net external fluid head and bending stresses. The pipe's collapse resistance to external pressure given in Equation 2 is reduced by the axial pulling force. Furthermore, the drill path curvature may be limited by the pipe's bending radius. (Torsional forces occur but are usually negligible when back-reamer swivels are properly designed.) Considerable judgment is required to predict the pullback force because of the complex interaction between pipe and soil. Sources for information include experienced drillers and engineers, programs such as DRILLPATH(14) and publications such as ASTM F1962 and ASCE MOP 108, "Pipeline Design for Installation by Horizontal Directional Drilling". Typically, pullback force calculations are approximations that depend on considerable experience and judgment.

The pullback formulas given herein and in DRILLPATH and ASTM F1962 are based on essentially an "ideal" borehole. The ideal borehole behaves like a rigid tunnel with gradual curvature, smooth alignment (no dog-legs), no borehole collapses, nearly complete cuttings removal, and good slurry circulation. The ideal borehole may be approached with proper drilling techniques that achieve a clean bore fully reamed to its final size before pullback. The closer the bore is to ideal; the more likely the calculated pullback force will match the actual.

Because of the large number of variables involved and the sensitivity of pullback forces to installation techniques, the formulas presented in this document are for guidelines only and are given only to familiarize the designer with the interaction that occurs during pullback. Pullback values obtained should be considered only as qualitative values and used only for preliminary estimates. The designer is advised to consult with an experienced driller or with an engineer familiar with calculating these forces. The following discussion assumes that the entry and exit pits of the bore are on the same, or close to the same, elevation. For an overview, see Svetlik(15).

Pullback Force

Large HDD rigs can exert between 100,000 lbs. to 500,000 lbs. pull force. The majority of this power is applied to the cutting face of the reamer device/tool, which precedes the pipeline segment into the borehole. It is difficult to predict what portion of the total pullback force is actually transmitted to the pipeline being inserted.

The pulling force which overcomes the combined frictional drag, capstan effect, and hydrokinetic drag, is applied to the pull-head and first joint of PE pipe. The axial tensile stress grows in intensity over the length of the pull. The duration of the pullload is longest at the pull-nose. The tail end of the pipe segment has zero applied tensile stress for zero time. The incremental time duration of stress intensity along the length of the pipeline from nose to tail causes a varying degree of recoverable elastic strain and viscoelastic stretch per foot of length along the pipe.

The DR must be selected so that the tensile stress in the pipe wall due to the pullback force, does not exceed the permitted tensile stress for the pipe material. Increasing the pipe wall thickness will allow for a greater total pull-force. Even though the thicker wall increases the weight per foot of the pipe, the pullback force within the bore itself is not significantly affected by the increased weight. Hence, thicker wall pipe generally reduces stress. The designer should carefully check all proposed DR's.

Frictional Drag Resistance

Pipe resistance to pullback in the borehole depends primarily on the frictional force created between the pipe and the borehole or the pipe and the ground surface in the entry area, the frictional drag between pipe and drilling slurry, the capstan effect at bends, and the weight of the pipe. Equation 13 gives the frictional resistance or required pulling force for pipe pulled in straight, level bores or across level ground. Equation 13, gives the frictional resistance or required pulling force for pipe pulled in straight, level bores or across level ground. (See Kirby et al. (16)).

(13) $$F_P = mW_B L$$

WHERE

F_P **= pulling force, lbs**

m **= coefficient of friction between pipe and slurry (typically 0.25) or between pipe and ground (typically 0.40)**

w_B **= net downward (or upward) force on pipe, lb/ft**

L **= length, ft**

When a slurry is present, W_B equals the buoyant force on the pipe minus the weight of the pipe and its contents, if any. Filling the pipe with fluid significantly reduces the buoyancy force and thus the pulling force. PE pipe has a density near that of water. If the pipe is installed "dry" (empty) using a closed nose-pull head, the pipe will want to "float" on the crown of the borehole leading to the sidewall loading and frictional drag through the buoyancy-per-foot force and the wetted soil to pipe coefficient of friction. Most major pullbacks are done "wet". That is, the pipeline is filled with water as it starts to descend into the bore (past the breakover point). Water is added through a hose or small pipe inserted into the pullback pipe. (See the calculation examples.)

Note: The buoyant force pushing the empty pipe to the borehole crown will cause the PE pipe to "rub" the borehole crown. During pullback, the moving drill mud lubricates the contact zone. If the drilling stops, the pipe stops, or the mud flow stops, the pipe - slightly ring deflected by the buoyant force - can push up and squeeze out the lubricating mud. The resultant "start-up" friction is measurably increased. The pulling load to loosen the PE pipe from being "stuck" in the now decanted (moist) mud can be very high. This situation is best avoided by using thicker (lower DR) pipes, doing "wet" pulls, and stopping the pull only when removing drill rods.

Capstan Force

For curves in the borehole, the force can be factored into horizontal and vertical components. Huey et al.(17) shows an additional frictional force that occurs in steel pipe due to the pressure required by the borehole to keep the steel pipe curved. For bores with a radius of curvature similar to that used for steel pipe, these forces are insignificant for PE pipe. For very tight bends, it may be prudent to consider them. In addition to this force, the capstan effect increases frictional resistance when pulling along a curved path. As the pipe is pulled around a curve or bend creating an angle q, there is a compounding of the forces due to the direction of the pulling vectors. The pulling force, F_C, due to the capstan effect is given in Eq. 14. Equations 13 and 14 are applied recursively to the pipe for each section along the pullback distance as shown in Figure 4. This method is credited to Larry Slavin, Outside Plant Consulting Services, Inc. Rockaway, N.J.

$$\text{(14)} \quad F_c = e^{mq}(mW_B L)$$

WHERE

e = **Natural logarithm base (e=2.71828)**

m = **coefficient of friction**

q = **angle of bend in pipe, radians**

w_B = **weight of pipe or buoyant force on pipe, lbs/ft**

L = **Length of pull, ft**

$$F_1 = \exp(m_g a)(m_g W_p (L_1 + L_2 + L_3 + L_4))$$

$$F_2 = \exp(m_b a)(F_1 + m_b W_b L_2 + W_b H - m_g W_p L_2 \exp(m_g a))$$

$$F_3 = F_2 + m_b W_b L_3 - \exp(m_b a)(m_g W_p L_3 \exp(m_g a))$$

$$F_4 = \exp(m_b b)(F_3 + m_b W_b L_4 - W_b H - \exp(m_b a)(m_g W_p L_4 \exp(m_g a)))$$

WHERE
H **= Depth of bore (ft)**
Fi **= Pull Force on pipe at Point i (lb)**
Li **= Horizontal distance of Pull from point to point (ft)**
m **= Coeff. of friction (ground (g) and borehole (b))**
W_p **= Weight of pipe (lb/ft)**
W_b **= Buoyant force on pipe minus weight of pipe and contents (lb/ft)**
a, b **= Entry and Exit angles (radians)**

Figure 4 Estimated Pullback Force Calculation

Hydrokinetic Force

During pulling, pipe movement is resisted by the drag force of the drilling fluid. This hydrokinetic force is difficult to estimate and depends on the drilling slurry, slurry flow rate pipe pullback rate, and borehole and pipe sizes. Typically, the hydrokinetic pressure is estimated to be in the 30 to 60 kPa (4 to 8 psi) range.

(15)
$$F_{HK} = p\frac{\pi}{8}(D_H{}^2 - OD^2)$$

WHERE
F_{HK} **= hydrokinetic force, lbs**
p **= hydrokinetic pressure, psi**
D_H **= borehole diameter, in**
OD **= pipe outside diameter, in**

ASCE MOP 108 suggests a different method for calculating the hydrokinetic drag force. It suggests multiplying the external surface area of the pipe by a fluid drag coefficient of 0.025 lb/in^2 after Puckett (18). The total pull back force, F_T, then is the combined pullback force, F_P, plus the hydrokinetic force, F_{HK}. For the example shown in Figure 4, F_P equals F_4.

Tensile Stress During Pullback

The maximum outer fiber tensile stress should not exceed the safe pull stress. The maximum outer fiber tensile stress is obtained by taking the sum of the tensile stress in the pipe due to the pullback force, the hydrokinetic pulling force, and the tensile bending stress due to pipe curvature. During pullback it is advisable to monitor the pulling force and to use a “weak link” (such as a pipe of higher DR) mechanical break- away connector or other failsafe method to prevent over-stressing the pipe.

The tensile stress occurring in the pipe wall during pullback is given by Eq. 16.

(16)

$$s_t = \frac{F_T}{\pi t\,(D_{OD} - t)} + \frac{E_T D_{OD}}{2R}$$

WHERE

s_T = **Axial tensile stress, psi**

F_T = **Total pulling force, lbs**

t = **Minimum wall thickness, in**

D_{OD} = **Outer diameter of pipe, in**

E_T = **Time-dependent apparent modulus, psi (Refer to Appendix, Chapter 3, Engineering Properties, for the appropriate value for the Material Designation Code of the PE pipe being used and the applicable service conditions**

R = **Minimum radius of curvature in bore path, in**

The axial tensile stress due to the pulling force should not exceed the pipe’s safe pull load. As discussed in a previous section, the tensile strength of PE pipe is load-rate sensitive. Time under load is an important consideration in selecting the appropriate tensile strength to use in calculating the safe pull load. During pullback, the pulling force is not continually applied to the pipe, as the driller must stop pulling after extracting each drill rod in order to remove the rod from the drill string. The net result is that the pipe moves the length of the drill rod and then stops until the extracted rod is removed. Pullback is an incremental (discrete) process rather than a continuous process. The pipe is not subjected to a constant tensile force and thus may relax some between pulls. A one-hour apparent modulus value might be safe for design, however, a 12-hour value will normally minimize “stretching” of the pipeline. Tables 3 through 6 give safe pull loads for PE pipes based on a 12-hour value. The safe pull force also referred to as the allowable tensile load in the Tables 3 through 6 is based on the minimum pipe wall thickness and may be found using Equation 17. (The safe pull load may also be found using the average wall thickness. Check with the manufacture for the average wall values.) Allowable safe pullback values for gas pipe are given in ASTM F-1807, “Practice for Determining Allowable Tensile Load for Polyehtylene (PE) Gas Pipe during Pull-In Installation”.

(17)
$$F_S = (T_{ALLOW})\pi D_{OD}^2 \left(\frac{1}{DR} - \frac{1}{DR^2}\right)$$

WHERE

F_S **= Safe Pull Force (lbs)**

T_{ALLOW} **= Safe Pull Stress (psi)**

D_{OD} **= Outside Diameter (in)**

DR **= Dimension Ratio**

After pullback, pipe may take several hours (typically equal to the duration of the pull) to recover from the axial strain. When pulled from the reamed borehole, the pull-nose should be pulled out about 3% longer than the total length of the pull. The elastic strain will recover immediately and the viscoelastic stretch will “remember” its original length and recover overnight. One does not want to come back in the morning to discover the pull-nose sucked back below the borehole exit level due to stretch recovery and thermal-contraction to an equilibrium temperature. In the worst case, the driller may want to pull out about 4% extra length (40 feet per 1000 feet) to insure the pull-nose remains extended beyond the borehole exit.

TABLE 3

PE 3xxx 12 hour Pull IPS Size

		Safe Pull Force, lbs			
Size	**Nom. OD**	**9**	**11**	**13.5**	**17**
1.25	1.660	940	787	653	527
1.5	1.900	1232	1030	855	690
2	2.375	1924	1610	1336	1079
3	3.500	4179	3497	2902	2343
4	4.500	6908	5780	4797	3872
6	6.625	14973	12529	10398	8393
8	8.625	25377	21235	17623	14225
10	10.750	39423	32988	27377	22098
12	12.750	55456	46404	38511	31086
14	14.000	66863	55949	46432	37480
16	16.000	87331	73076	60646	48954
18	18.000	110528	92487	76756	61957
20	20.000	136454	114182	94760	76490
22	22.000	165110	138160	114660	92553
24	24.000	196494	164422	136454	110146
26	26.000	230608	192967	160144	129268
28	28.000	267450	223796	185729	149920
30	30.000	307022	256909	213210	172102
32	32.000	N.A.	292305	242585	195814
34	34.000	N.A.	329985	273856	221056
36	36.000	N.A.	369949	307022	247827
42	42.000	N.A.	N.A.	417891	337321
48	48.000	N.A.	N.A.	N.A.	440582
54	54.000	N.A.	N.A.	N.A.	N.A.

*Tables are based on the Minimum Wall Thickness of Pipe

TABLE 4
PE 3xxx 12 hour Pull DIPS Size

		Safe Pull Force, lbs			
Size	**Nom. OD**	**9**	**11**	**13.5**	**17**
4	4.800	7860	6577	5458	4406
6	6.900	16241	13590	11279	9104
8	9.050	27940	23379	19403	15662
10	11.100	42031	35171	29188	23561
12	13.200	59440	49738	41277	33319
14	15.300	79856	66822	55456	44764
16	17.400	103282	86424	71724	57895
18	19.500	129717	108544	90081	72713
20	21.600	159160	133182	110528	89218
24	25.800	227074	190010	157690	127287
30	32.000	349323	292305	242585	195814
36	38.300	N.A.	418730	347506	280506
42	44.500	N.A.	N.A.	469121	378673
48	50.800	N.A.	N.A.	N.A.	493483

*Tables are based on the Minimum Wall Thickness of Pipe

TABLE 5
PE 4xxx 12 hour Pull IPS Size

		Safe Pull Force, lbs			
Size	**Nom. OD**	**9**	**11**	**13.5**	**17**
1.25	1.660	983	822	682	551
1.5	1.900	1287	1077	894	722
2	2.375	2012	1683	1397	1128
3	3.500	4369	3656	3034	2449
4	4.500	7222	6043	5015	4048
6	6.625	15653	13098	10870	8774
8	8.625	26531	22200	18424	14872
10	10.750	41214	34487	28621	23103
12	12.750	57977	48513	40262	32499
14	14.000	69902	58492	48543	39184
16	16.000	91300	76398	63403	51179
18	18.000	115552	96691	80244	64773
20	20.000	142657	119372	99067	79967
22	22.000	172615	144440	119871	96760
24	24.000	205426	171896	142657	115152
26	26.000	241090	201739	167424	135144
28	28.000	279607	233969	194172	156735
30	30.000	320978	268587	222901	179925
32	32.000	N.A.	305592	253612	204715
34	34.000	N.A.	344985	286304	231104
36	36.000	N.A.	386765	320978	259092
42	42.000	N.A.	N.A.	436886	352654
48	48.000	N.A.	N.A.	N.A.	460609
54	54.000	N.A.	N.A.	N.A.	N.A.

*Tables are based on the Minimum Wall Thickness of Pipe

TABLE 6
PE 4xxx 12 hour Pull DIPS Size

		Safe Pull Force, lbs			
Size	**Nom. OD**	**9**	**11**	**13.5**	**17**
4	4.800	8217	6876	5706	4606
6	6.900	16980	14208	11791	9518
8	9.050	29210	24442	20285	16374
10	11.100	43942	36770	30515	24632
12	13.200	62141	51998	43154	34834
14	15.300	83486	69859	57977	46799
16	17.400	107977	90353	74984	60527
18	19.500	135613	113478	94176	76018
20	21.600	166395	139235	115552	93273
24	25.800	237395	198647	164858	133073
30	32.000	365201	305592	253612	204715
36	38.300	N.A.	437764	363302	293256
42	44.500	N.A.	N.A.	490445	395886
48	50.800	N.A.	N.A.	N.A.	515914

*Tables are based on the Minimum Wall Thickness of Pipe

External Pressure During Installation

During pullback it is reasonable to assume that the borehole remains stable and open and that the borehole is full of drilling slurry. The net external pressure due to fluid in the borehole, then, is the slurry head, P_{MUD}. This head can be offset by pulling the pipe with an open nose or filling the pipe with water for the pullback. However, this may not always be possible, for instance when installing electrical conduit. In addition to the fluid head in the borehole, there are also dynamic sources of external pressure:

1. If the pulling end of the pipe is capped, a plunger action occurs during pulling which creates a mild surge pressure. The pressure is difficult to calculate. The pipe will resist such an instantaneous pressure with its relatively high short-term modulus. If care is taken to pull the pipe smoothly at a constant speed, this calculation can be ignored. If the pipe nose is left open, this surge is eliminated.

2. External pressure will also be produced by the frictional resistance of the drilling mud flow. Some pressure is needed to pump drilling mud from the reamer tool into the borehole, then into the pipe annulus, and along the pipe length while conveying reamed soil debris to the mud recovery pit. An estimate of this short term hydrokinetic pressure may be calculated using annular flow pressure loss formulas borrowed from the oil well drilling industry. This external pressure is dependent upon specific drilling mud properties, flow rates, annular opening, and hole configuration. This is a short-term installation condition. Thus, PE pipe's short-term external differential pressure capabilities are compared to the actual

short-term total external pressure during this installation condition. Under normal conditions, the annular-flow back pressure component is less than 4-8 psi.

In consideration of the dynamic or hydrokinetic pressure, P_{HK}, the designer will add additional external pressure to the slurry head:

(18) $$P_N = P_{MUD} + P_{HK} - P_I$$

Where the terms have been defined previously.

Resistance to External Collapse Pressure During Pullback Installation

The allowable external buckling pressure equation, Eq.11, with the appropriate apparent modulus (see chapter 3- Appendix) value can be used to calculate the pipe's resistance to the external pressure, P_N, given by Eq.18 during pullback. The following reductions in strength should be taken:

The tensile pulling force reduces the buckling resistance. This can be accounted for by an additional reduction factor, F_R. The pulling load in the pipe creates a hoop strain as described by Poisson's ratio. The hoop strain reduces the buckling resistance. Multiply Eq.11 by the reduction factor, F_R to obtain the allowable external buckling pressure during pullback.

(19) $$F_R = \sqrt{(5.57 - (r + 1.09)^2)} - 1.09$$

(20) $$r = \frac{s_T}{2S}$$

WHERE

s_T **= calculated tensile stress during pullback (psi)**

S **= safe pull stress (psi)**

r **= tensile stress ratio**

Since the pullback time is typically several hours, a modulus value consistent with the pullback time can be selected from Appendix, Chapter 3.

Bending Stress

HDD river crossings incorporate radii-of-curvature, which allow the PE pipe to cold bend within its elastic limit. These bends are so long in radius as to be well within the flexural bending capability of SDR 11 PE pipe which can be cold bent to 25 times its nominal OD (example: for a 12" SDR 11 PE pipe, the radius of curvature could be from infinity down to the minimum of 25 feet, i.e., a 50-foot diameter circle). Because the drill stem and reaming rod are less flexible, normally PE can bend easily to whatever radius the borehole steel drilling and reaming shafts can bend because these radii are many times the pipe OD. However, in order to minimize the effect of ovaling some manufacturers limit the radius of curvature to a minimum of 40 to 50 times the pipe diameter. As in a previous section, the tensile stress due to bending is included in the calculations.

Thermal Stresses and Strains

HDD pipeline crossings generally become fully restrained in the axial direction as progressive sedimentation and soil consolidation occur within the borehole. The rate at which restraint occurs depends on the soil and drilling techniques and can take from a few hours to months. This assumption is valid for the vast majority of soil conditions, although it may not be completely true for each and every project. During pipe installation, the moving pipeline is not axially restrained by the oversize borehole. However, the native soil tends to sediment and embed the pipeline when installation velocity and mud flow are stopped, thus allowing the soil to grip the pipeline and prevent forward progress or removal. Under such unfortunate stoppage conditions, many pipelines may become stuck within minutes to only a few hours.

The degree to which the pipeline will be restrained after completed installation is in large part a function of the sub-surface soil conditions and behavior, and the soil pressure at the depth of installation. Although the longitudinal displacement due to thermal expansion or contraction is minimal, the possibility of its displacement should be recognized. The PE pipe should be cut to length only after it is in thermal equilibrium with the surrounding soil (usually overnight). In this way the "installed" versus "operating" temperature difference is dropped to nearly zero, and the pipe will have assumed its natural length at the existing soil/water temperature. Additionally, the thermal inertia of the pipe and soil will oppose any brief temperature changes from the flow stream. Seasonal temperature changes happen so slowly that actual thermally induced stresses are usually insignificant within PE for design purposes.

Torsion Stress

A typical value for torsional shear stress is 50% of the tensile strength. Divide the transmitted torque by the wall area to get the torsional shear stress intensity. During the pullback and reaming procedure, a swivel is typically used to separate the rotating cutting head assembly from the pipeline pull segment. Swivels are not 100% efficient and some minor percent of torsion will be transmitted to the pipeline. For thick wall PE pipes of SDR 17, 15.5, 11, 9 and 7, this torsion is not significant and usually does not merit a detailed engineering analysis.

EXAMPLE CALCULATIONS Example Calculations are given in Appendix A and B.

References

1. Sener, E.M. & Stein, R. (1995). *Mini-Horizontal Directional Drilling Manual*, North American Society for Trenchless Technology (NASTT), Reston, Virginia.
2. *Horizontal Directional Drilling Good Practices Guidelines*, North American Society for Trenchless Technology (NASTT), Reston, Virginia.
3. *Safety Manual: Directional Drilling Tracking Equipment*, Equipment Manufacturer's Institute (EMI).
4. ASTM F1962, Guide for Use of Maxi-Horizontal Directional Drilling for Placement of Polyethylene Pipe or Conduit Under Obstacles, Including River Crossings, ASTM, West Conshohocken, PA.
5. ASCE Manuals and Reports on Engineering Practice No. 108, "Pipeline Design for Installation by Horizontal Directional Drilling", ASCE, Reston, Virginia (2005).
6. Petroff, L.J. (2006). *Designing Polyethylene Water Pipe for Directional Drilling Applications Using ASTM F1962*, NASTT No-Dig Conference, Nashville, TN.
7. O'Rourke, T.D., El-Gharbawy, S.L. & Stewart, H.E. (1991). Soil Loads at Pipeline Crossings, ASCE Specialty Conference on Pipeline Crossings, Denver, CO..
8. Stein, D., Mollers, K. & Bielecki, R (1989) Microtunnelling, Ernest & Sohn, Berlin..
9. Petroff, L.J. (1999). *Guidelines for Design of Directionally-Drilled Polyethylene Pipe*, International Plastic Pipe Fuel Gas Symposium, PPI, AGA, & GTI, New Orleans, LA.
10. Spangler, M. G. & Handy, R. L. (1973). *Soil Engineering*, Intext, Harper and Row, New York, NY.
11. Knight, M.A., Duyvestyn, G., & Gelinas, M. (2001, Sept). Excavation of surface installed pipeline, J. *Infrastructural Systems*, Vol. 7, no 3, ASCE.
12. Ariaratnam, S.T. (2001). *Evaluation of the Annular Space Region in Horizontal Directional Drilling Installations*, Arizona State University.
13. Watkins, R.K. & Anderson, L.R. (1995). Structural Mechanics of Buried Pipes, Dept. of Civil and Environmental Engineering, Utah State University, Logan, UT.
14. DRILLPATH (1996). Infrasoft L.L.C., Maurer Technology.
15. Svetlik, H. (1995, March). Design Considerations for PE Pipe Used in Directional Drilling, *No-Dig Engineering*, Vol.2, No.3.
16. Kirby, M.J., Kramer, S.R., Pittard, G.T., & Mamoun, M. (1996). Design Guidelines and Procedures for Guided Horizontal Drilling, Proceedings of the International No-Dig '96 Conf., New Orleans, LA.
17. Huey, D.P., Hair, J.D., & McLeod, K.B. (1996). Installation Loading and Stress Analysis Involved with Pipelines Installed by Horizontal Directional Drilling, No-Dig '96 Conf., New Orleans, LA.
18. Puckett, J.S. (2003). *Analysis of Theoretical versus Actual HDD Pulling Loads*, ASCE International Conference on Pipeline Engineering and Construction, Baltimore, MD.

Appendix A

Design Calculation Example for Service Loads (Post-Installation)

Example 1

A 6″ IPS DR 11 PE4710 pipe is being pulled under a railroad track. The minimum depth under the track is 10 ft. Determine the safety factor against buckling.

GIVEN PARAMETERS

OD **= 6.625 in**
Nominal Pipe OD

DR **= 11 Pipe**
Dimension Ratio

H **= 10 ft.**
Max. Borehole Depth

g_s **= 120 lbf/ft^3**
Unit Weight of Soil

P_{Live} **= 1,100 lbf/ft^2**
E-80 Live Load

PE Material Parameters

Wheel loading from train will be applied for several minutes without relaxation. Repetitive trains crossing may accumulate. A conservative choice for the apparent modulus is the 1000-hour modulus. See Appendix of Chapter 3 Table B.1.1.

$E_{mid} = 46{,}000$ psi

μ = Poisson's Ratio = 0.45 for all PE pipe materials

Soil and Live Load Pressure on Pipe (Assuming that the earth load equals the prism load is perhaps too conservative except for a calculation involving dynamic surface loading.)

$P = (g_s H + P_{Live})\ 1/144$

P **= 16.0 psi**

Ring Deflection resulting from soil and live load pressures assuming no side support is given by equation 10.

$$\frac{\Delta y}{D} = \frac{0.0125P}{\dfrac{E_{mid}}{12(DR-1)^3}}$$

$\% \Delta y/D$ **= 5.1 Percent deflection from soil loads**

Determine critical unconstrained buckling pressure based on deflection from loading and safety factor using Eq. 11

f_o **= 0.58 Ovality compensation factor for 5.1% ovality from Figure 3**

$$P_{UC} = \frac{2E_{mid}}{(1-\mu^2)}\left(\frac{1}{DR-1}\right)^3 f_O$$

P_{UC} **= 68.4 psi**

Critical unconstrained buckling pressure (no safety factor)

$$SF_{cr} = \frac{P_{UC}}{P}$$

SF_{cr} **= 4.3 Safety factor against buckling**

Example 2

A 6″ IPS DR 13.5 PE4710 pipe is being pulled under a small river for use as an electrical duct. At its lowest point, the pipe will be 18 feet below the river surface. Assume the slurry weight is equal to 75 Ib/cu.ft. The duct is empty during the pull. Calculate a) the maximum pulling force and b) the safety factor against buckling for the pipe. Assume that the pipe's ovality is 3% and that the pulling time will not exceed 10 hours.

Solution

Calculate the safe pull strength or allowable tensile load.

OD **= 6.625in. - Pipe outside diameter**

DR **= 13.5 - Pipe dimension ratio**

T_{allow} **= 1150 psi - Typical safe pull stress for PE4710 for 12-hour pull duration. See Table 1.**

$$F_s = \pi T_{allow}\ OD^2\ \left(\frac{1}{DR} - \frac{1}{DR^2}\right)$$

F_s **= 1.088 x 10^4 lbf**

Safe pull force for 6" IPS DR 13.5 PE pipe assuming 12-hour maximum pull duration.
Also see Table 5 for safe pull force.

Step 1

Determine the critical buckling pressure during Installation for the pipe (include tensile reduction factor assuming the frictional drag during pull results in 1000 psi longitudinal pipe stress)

E **= 63,000 psi - Apparent modulus of elasticity (for 12 hours at 73 degrees F)**

μ **= Poisson's Ratio = 0.45 for all PE materials**

f_o **= 0.76 - Ovality compensation factor (for 3% ovality)**

$$f_R = \sqrt{5.57 - (r + 1.09)^2} - 1.09$$

R **= 0.435 - Tensile ratio (based on assumed 1000 psi pull stress calculation)**

f_R **= 0.71**

$$Pcr = \frac{2E}{(1 - \mu^2)}\left(\frac{1}{DR - 1}\right)^3 \cdot f_O \cdot f_R$$

Tensile Reduction Factor

P_{CR} **= 43.71**

Critical unconstrained buckling pressure for DR 13.5 pipe without safety factor

Step 2

Determine expected loads on pipe (assume only static drilling fluid head acting on pipe, and borehole intact with no soil loading)

gslurry **= 75 lbf/ft^3, drilling fluid weight**

H **= 18 ft, Maximum bore depth**

$$P_{slurry} = Hg_{slurry}\left(\frac{1}{144}\right)$$

P_{slurry} **= 9.36 psi**

Total static drilling fluid head pressure if drilled from surface

Step 3

Determine the resulting safety factor against critical buckling during installation

$$SF_{CR} = \frac{P_{CR}}{P_{slurry}}$$

SF_{CR} **= 4.67**

Safety factor against critical buckling during pull

Example 3

Determine the safety factor for long-term performance for the communication duct in Example 2. Assume there are 10 feet of riverbed deposits above the borehole having a saturated unit weight of 110 lb/ft^3. (18 feet deep, 3% initial ovality)

Solution

Step 1

Determine the pipe soil load (Warning: Requires input of ovality compensation in step 4.

E long **= 29,000 psi - Long-term apparent modulus**

gw **= 62.4 lbf/ft.^{3} - Unit weight of water**

H **= 18 ft Max. - Borehole depth**

g_S **= 110 lbf/ft.^{3} - Saturated unit weight of sediments**

GW **= 18 ft - Groundwater height**

C **= 10ft. - Height of soil cover**

OD **= 6.625 in - Nominal pipe OD**

DR **= 13.5 - Pipe dimension ratio**

μ **= Poisson's Ratio = 0.45 for all PE materials**

$$P_{soil} = (g_S - g_W)\,C\,\left(\frac{1}{144}\right)$$

Psoil **= 3.30 psi**

Prism load on pipe from 10' of saturated cover (including buoyant force on submerged soil)

Step 2

Calculate the ring deflection resulting from soil loads assuming no side support.

$$\% \ (\Delta y/D) = \frac{0.0125 \ \times P_{soil}}{\left[\frac{E_{long}}{12 \ (DR \ -1)^3}\right]} \times 100$$

$\% \ (\Delta y/D)$ **= 3.33 Percent deflection from soil loads**

t **= OD/DR t =0.491 in**

Step 3

Determine the long-term hydrostatic loads on the pipe

$$P_W = \left(\frac{GW}{2.31 \ \text{ft/psi}}\right) + \ P_{soil}$$

P_W **= 11.09**

External pressure due to groundwater head

$$g_{slurry} = 75 \ \text{lb/cu.ft.}^3$$

Unit weight of drilling fluid

$$P_{slurry} = g_{slurry} \ H \ \left(\frac{1}{144}\right)$$

P_{slurry} **= 9.37 psi**

External pressure due to slurry head

$$P_W > P_{slurry}$$

Therefor use PW for buckling load

Step 4

Determine critical unconstrained buckling pressure based on deflection from loading

f_o **= 0. 64 Five percent Ovality Compensation based on 3.3% deflection with an additional factor for conservatism.**

$$P_{UC} = \frac{2E_{long}}{(1-\mu^2)} \ \left(\frac{1}{DR \ -1}\right)^3 \ f_O$$

P_{UC} **= 23.83 psi**

Critical unconstrained buckling pressure (no safety factor)

SF_{CR} **= 2.14**

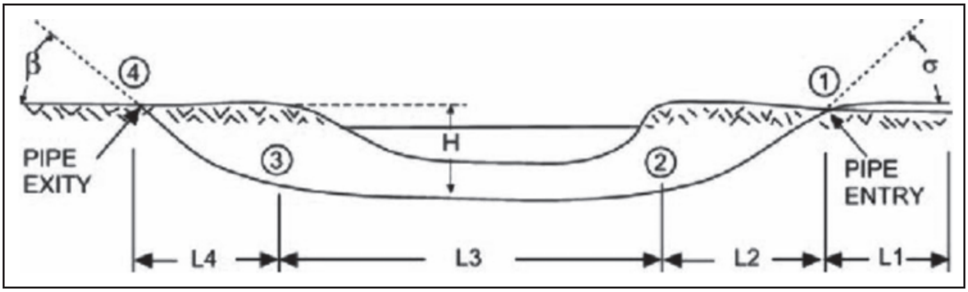
$$SF_{CR} = \frac{P_{UC}}{P_W} \qquad SF_{CR} = 2.14$$

Safety Factor against buckling pressure of highest load groundwater head (11.09 psi)

APPENDIX B

Design Calculations Example for Pullback Force

Example 1



Find the estimated force required to pull back pipe for the above theoretical river crossing using Slavin's Method. Determine the safety factor against collapse. Assume the PE pipe is 35 ft deep and approximately 870 ft long with a 10 deg. entry angle and a 15 deg. exit angle. Actual pullback force will vary depending on backreamer size, selection, and use; bore hole staying open; soil conditions; lubrication with bentonite; driller expertise; and other application circumstances.

PIPE PROPERTIES

Outside Diameter

OD = 24 in - Long-term Modulus - E_{long} = 29,000 psi, PE4710 Material

Standard Dimension Ratio

DR = 12 - 12 hr Modulus - E_{24hr} =63,000 psi

Minimum wall thickness

t = 2.182 in - Poisson's ratio (long term) - μ = 0.45 - Safe Pull Stress (12 hr) - s_{pb} = 1,150 psi

PATH PROFILE

H **= 35 ft Depth of bore**

g_{in} **= 10 deg Pipe entry angle**

g_{ex} **= 15 deg Pipe exit angle**

L_1 **= 100 ft Pipe drag on surface (This value starts at total length of pull, approximately 870 ft. then decreases with time. Assume 100 ft remaining at end of pull)**

L_{cross} **= 870 ft**

PATH LENGTH (DETERMINE L_2 AND L_4)

Average Radius of Curvature for Path at Pipe Entry g_{in} is given in radians

$$R_{avg\ in} = 2H/g_{in}^{\ 2}$$

$R_{avg\ in}$ **= 2.298 x 10^3 ft**

Average Radius of Curvature for Path at Pipe Exit

$$R_{avg\ ex} = 2H/g_{ex}^{\ 2}$$

$R_{avg\ ex}$ **= 1.021 x 10^3 ft**

Horizontal Distance Required to Achieve Depth or Rise to the Surface at Pipe Entry

$$L_2 = 2H/g_{in}$$

L_2 **= 401.07 ft**

Horizontal Distance Required to Achieve Depth or Rise to the Surface at Pipe Exit

WHERE

L_2 & L_4 **= horizontal transition distance at bore exit & entry respectively.**

DETERMINE AXIAL BENDING STRESS

R **= $R_{avg\ ex}$ - Min. Radius for Drill path**

R **= 1.021 x 10^3 ft**

OD **= 24 in**

Radius of curvature should exceed 40 times the pipe outside diameter to prevent ring collapse.

r **= 40 OD**

r **= 80 ft Okay**

$R > r$

Bending strain

$e_a = OD/2R$

$e_a = 9.79 \times 10^{-4}$ in/in

WHERE

e_a **= bending strain, in/in**

OD **= outside diameter of pipe, in**

R **= minimum radius of curvature, ft**

Bending stress

$S_a = E_{12hr}e_a$

Sa **= 61.68 psi**

WHERE

S_a **= bending stress, psi**

FIND PULLING FORCE

Weight of Empty Pipe

$P_w = 3.61 \times 10^{-2}$ lbf/in^3

$g_a = 0.95$

$g_b = 1.5$

$w_a = \pi OD^2 (DR-1/DR^2) r_w \, g_a$ 12 in/ft

$w_a = 61.54$ lbf/ft

Net Upward Buoyant Force on Empty Pipe Surrounded by Mud Slurry

$W_b = \pi(OD^2/4)\, r_w \, g_b$ 12 in/ft - w_a

$w_b = 232.41$ lbf/ft

WHERE

r_w **= density of water, lb/in3**

g_a **= specific gravity of the pipe material**

g_b **= specific gravity of the mud slurry**

w_a **= weight of empty pipe, lbf/ft**

$w_b = \pi(OD^2/4) rwgb$ **12in/ft - wa**

DETERMINE PULLBACK FORCE ACTING ON PIPE

See figure:

L_1 **= 100 ft -** $v_a = 0.4$

L_2 **= 401.07ft -** $v_b = 0.25$

L_3 **= 200ft -** $\sigma = g_{in} - \sigma = 10$ **deg = 0.175 radians**

L_4 **= 267.38 -** $\beta = g_{ex} - \beta = 15$ **deg = 0.262 radians**

$L_3 = L_{cross} - L_2 - L_4 - L_3 = 201.549$**ft**

$T_A = \exp(v_a \sigma)\, [v_a w_a (L_1 + L_2 + L_3 + L_4)]$

$T_A = 2.561 \times 10^4$ **lbf**

$T_B = \exp(v_b \sigma)\, (T_A + v_b [w_b] L2 + w_b H - v_a w_a L_2 \exp(v_b \sigma))$

$T_B = 4.853 \times 10^4$ **lbf**

$T_C = TB + v_b [wb] L_3 - \exp(v_b \sigma)\, (v_a w_a L_3 . \exp(v_a \sigma))$

$T_C = 5.468 \times 10^4$ **lbf**

$T_D = \exp(v_b \sigma)\, [T_C + v_b [w_b] L_4 - w_b H - \exp(v_b \sigma)\, (v_a w_a L_4 \exp(v_b \sigma))]$

$T_D = 5.841 \times 10^4$ **lbf**

WHERE

T_A **= pull force on pipe at point A, lbf**

T_B **= pull force on pipe at point B. lbf**

T_C **= pull force on pipe at point C, lbf**

T_D **= pull force on pipe at point D, lbf**

L_1 **= pipe on surface, ft**

L_2 **= horizontal distance to achieve desired depth, ft**

L_3 **= additional distance traversed at desired depth, ft**

L_4 **= horizontal distance to rise to surface, ft**

v_a **= coefficient of friction applicable at the surface before the pipe enters bore hole**

v_b **= coefficient of friction applicable within the lubricated bore hole or after the (wet) pipe exits**

σ **= bore hole angle at pipe entry, radians**

β **= bore hole angle at pipe exit, radians**

(refer to figure at start of this appendix)

HYDROKINETIC PRESSURE

ΔP **= 10 psi**

Dh **= 1.5 OD**

Dh **= 36in**

$\Delta T = \Delta P\ (\pi/8)\ (Dh^2 - OD^2)$

$\Delta T = 2.82 \times 10^3 \text{lbf}$

WHERE:

ΔT **= pulling force increment, lbf**

ΔP **= hydrokinetic pressure, psi**

Dh **= back reamed hole diameter, in**

Compare Axial Tensile Stress with Allowable Tensile Stress During Pullback of 1,150 psi: (Assume the pull takes several hours and use 12 hours safe pull stress.)

Average Axial Stress Acting on Pipe Cross-section at Points A, B. C, D

s_1 **= 190.13 psi <1,150 psi OK**

s_2 **= 343.40 psi <1,150 psi OK**

s_3 **= 384.55 psi <1,150 psi OK**

s_4 **= 409.48 psi <1,150 psi OK**

$$s_1 = \left(Ti + \Delta T\right) \quad \left(\frac{1}{\pi OD^2}\right)\ \left(\frac{DR^2}{DR-1}\right)$$

WHERE

Ti **=** T_A, T_B, T_C, T_D **(lbf)**

si **= corresponding stress, psi**

Breakaway links should be set so that pullback force applied to pipe does not exceed 1,150 psi stress.

$ID = OD - 2t$

$Fb = s_{pb}\ (\pi/4)(OD^2 - ID^2)$

$Fb = 1.64 \times 10^5 \text{ lbf}$

DETERMINE SAFETY FACTOR AGAINST RING COLLAPSE DURING PULLBACK

External Hydraulic Load

External static head pressure

$P_{ha} = (1.5)\ (62.4\ \text{lbf/ft}^3)\ (H)$

$Pha = 22.75$ psi

Combine static head with hydrokinetic pressure

$P_{effa} = P_{ha} + \Delta P$

$P_{effa} = 32.75$ psi

CRITICAL COLLAPSE PRESSURE

Resistance to external hydraulic load during pullback

$f_o = 0.76$ Ovality compensation factor (for 3% ovality)

$r = S_4/2S_{Pb}$

$r = 0.178$

Tensile ratio (based on 1,150 psi pull stress calculation)

Tensile reduction factor

$P_{CR} = 108$ psi

SAFETY FACTOR AGAINST COLLAPSE

SF = Pcr/Pha

F = 4.75

WHERE

P_{ha} = applied efflective pressure due to head of water of drilling

P_{cr} = calculated critical buckling pressure found by solving Equation 11 multiplied by Equation 19 for 24” DR11, psi

SF = Safety Factor

Chapter 13

HVAC Applications for PE Pipe

Introduction

The performance and use characteristics of polyethylene pipe make it an ideal choice for use in certain HVAC – Heating, Ventilation, and Air Conditioning – applications. Typically, HVAC is thought of as flexible vent pipes, steam pipes, etc. However, since the 1980's polyethylene pipe's flexibility, strength, and ease of use has had a major impact on HVAC applications such as geothermal heat pumps and radiant heating systems.

This chapter presents information and general design criteria for the use of polyethylene pipe in applications such as:

Ground Source Heat Pumps – basic use and standards, configuration, joining methods and installation considerations.

Solar Applications – use of PE pipe for solar water heating applications.

Vacuum Systems – use and design limitations.

Ground Source Heat Pump Systems

Due to polyethylene pipe's versatility, flexibility, durability, leakproof fusion joints, and ease of use, it has become a key component in the success of Ground Source Heat Pumps systems.

There are two basic types of heat pumps – air source and ground source. An air source system utilizes temperature variations in the air to gain operating efficiency. A ground source, or Geothermal Heat Pump (GHP) system uses an electric pump to circulate fluid from the heat pump cycle through a series of polyethylene pipes buried in the ground to take advantage of the relatively constant ground temperatures. These pipes are known as Ground Heat Exchangers. In simple terms, in the summer the heat pump's refrigerant cycle transfers heat from the building into the circulating fluid. The fluid is then circulated through the ground heat exchanger where the ground acts as a heat sink, cooling the fluid before it returns to the building. In the winter, the system works in reverse. The heat pump uses the earth to warm the circulating fluid, which is then transferred back to the inside heat exchanger. In addition to heating and cooling the air, a desuperheater can be added to this cycle that can provide most, if not all, hot water for use in the building as well.

The properties that control this process are based on the ability of the PE pipe to transfer heat either out of, or into, the system. The heat transfer by conduction mechanism that governs this system is the same as any heat exchanger. It is assumed that the ground is at a steady state condition. This type of heat transfer mechanism is governed by the basic equation:

$$q = (k\,A/x)\,(T_1 - T_2)$$

WHERE

q = **Heat loss, BTU/hr**

k = **Thermal conductivity, BTU/in/ft ^{2}/hr/°F**

A = **Heat transfer area, ft ^{2}**

x = **Wall thickness, inches**

T_1 = **Outside temperature, °F**

T_2 = **Inside pipe temperature, °F**

Note: The above equation only addresses the question of heat transfer through the PE pipe. Depending on the application (ground source heat exchange systems, snow melting, radiant heating, etc.) there are other factors that may have a significant influence on the accuracy of the heat transfer calculation including the thermal conductivity of the surrounding embedment material, the inside and outside film coefficients of the pipe and perhaps others. Therefore it is recommended that such calculations should be referred to engineers who are expert in this field.

Polyethylene itself is typically considered an insulator and holds heat rather well. However, in this application, the benefits of the polyethylene pipe far outweigh this performance characteristic. There are many other variables that need consideration when designing a GHP system. Most manufacturers have software available to aid in the determination of the size of the unit and the footage of pipe needed for the geothermal heat exchanger.

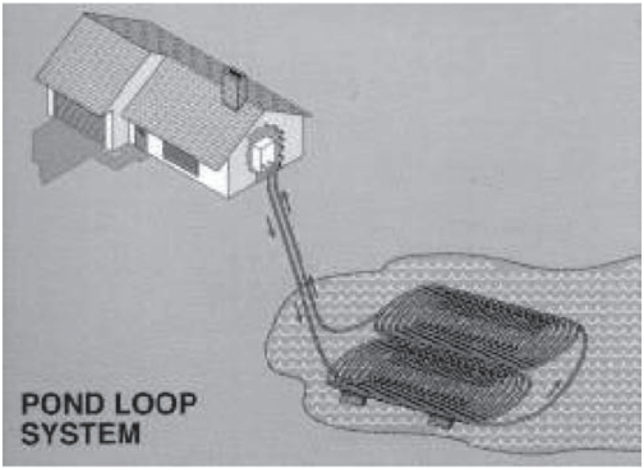
Geothermal heat pumps are very economical to operate and can save a substantial amount of money in operating costs over the life of the system. It has been reported(1) that a traditional furnace uses one unit of energy but returns less than one unit back as heat. A ground source heat pump uses one unit of energy but returns as much as three units back as heat. The polyethylene pipe acting as the heat transfer medium in the ground helps make this possible.

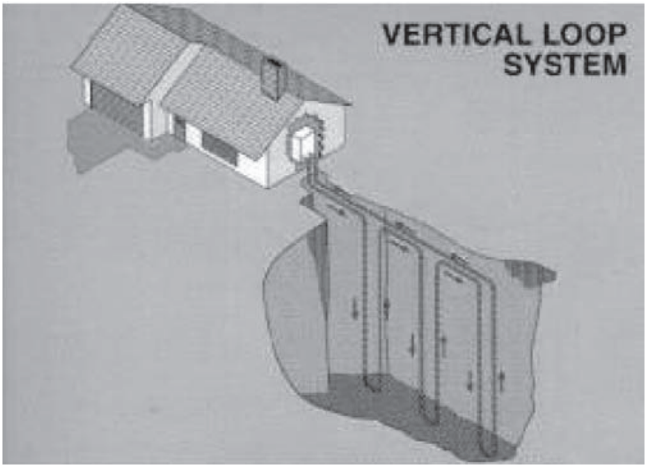
Types of Ground Heat Exchangers

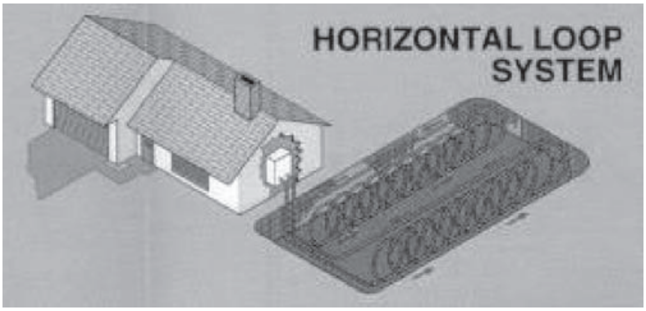
There are two basic types of heat exchangers: open and closed loop systems. Both can be configured several different ways depending on the size of the system, surrounding land, or availability of a large open water source.

Open systems require a suitable supply of water where open discharge is possible. This type of system uses the HDPE pipe to bring fresh water to the heat pump, and then discharges the water back into the water supply. Only fresh water is used, and there is no need for a special heat transfer or antifreeze solution. A key PE pipe design consideration for an open system is the fact that the system will have a suction and discharge loop. This means the pipe may need to be designed to handle negative vacuum pressures and positive pumping pressures.

The more common type of GHP installation is a closed loop system. A closed system is just that — a "closed loop" recirculating system where the HDPE pipe circulates an "antifreeze" solution continuously. This type of system can be installed several different ways such as: a pond loop system, a vertical loop system, or a horizontal (slinky) loop system. Each of these types of installation utilizes the basic performance benefits and versatility of HDPE pipe to get the most beneficial type installation for the surrounding conditions.







Pipe Specifications and Requirements

PE is the material of choice for the pipe in the heat exchanger for ground source heat pump system. The International Ground Source Heat Pump Association (IGSHPA) has developed some design and installation standards for the HDPE pipe that is required for a geothermal heat exchanger. For further details, refer to the latest edition of the IGSHPA publication "Closed Loop/Geothermal Heat Pump Design and Installation Standards.

The recommended specification takes into account the optimum performance based on the need to make sure the pipe and fittings can handle the pressures and stresses involved in the application, as well as the heat transfer requirements for the heat exchanger itself. Heavier wall pipe may be able to handle higher pressures and stresses, but the thicker wall lowers the heat transfer efficiency with the ground. All of these parameters must be balanced. When designing the PE pipe heat exchanger, maximum operating pressures and temperatures, as well as head and surge pressures must be taken into account.

For closed-loop geothermal heat exchangers, even though a high stress crack-resistant PE material is required, it is appropriate to make sure the antifreeze solution used in the heat exchanger does not adversely affect the stress crack performance of the pipe and fittings. The antifreeze solution manufacturer should be able to supply this information.

More information on the design of PE pipe systems for pressure, surges, flow capacities, etc. can be found in the Design of PE Piping Systems chapter of this Handbook.

Pipe Joining Methods

PE pipe can be joined by several different methods. One of the outstanding features of PE pipe is its ability to be heat-fused, producing a 100% leakproof joint that is as strong, or stronger, than the pipe itself.

IGSHPA recommends acceptable methods for joining as 1) a heat fusion process, or 2) stab-type mechanical fittings to provide a leak-free union between the pipe ends that is stronger than the pipe itself. This type of mechanical joint is also known as a Category 1 mechanical joint according to ASTM D 2513, Standard Specification for Thermoplastic Gas Pressure Pipe, Tubing and Fittings.

In addition, it is recommended that fusion transition fittings with threads must be used to adapt to copper pipe or fittings. Fusion transition fittings with threads or barbs must be used to adapt to high strength hose. Barbed fittings are not permitted to be connected directly to the PE pipe, with the exception of stab-type fittings as described above. All mechanical connections must be accessible.

Since mechanical connections must remain accessible, fusion joints are preferred wherever possible. Butt, socket or electro-fusion is used to join individual sections of pipe. "U-bend" fusion fittings are used for creating the return line in vertical bores. In fact, it is common for polyethylene pipe made for geothermal heat exchangers to be double wrapped on a coil and the "u-bend" fitting fused on at the factory. This makes insertion into a vertical bore very quick and easy. Sidewall fusion can be used to join parallel pipe loops to a header. All fittings must be pressure rated for the expected operating and surge pressures, and joined according to the manufacturer's recommended procedures. This is a critical feature since this joint will be at the bottom of a well and grouted into place. Repair of a leaky joint in this location would be very difficult. However, this is a rare problem due to the nature of the fusion procedure and the dependability of the joints made using this process. Extensive information on joining PE pipe can be found in the PE Joining Procedures chapter of this handbook.

Pipe Installation

As discussed previously, there are several types of installation choices for ground source heat pumps. It is important to follow the GHP manufacturer's requirements for the type of unit being used. This will define the amount of pipe needed for the particular installation and environment. However, there are some general guidelines for polyethylene pipe that will help assure a successful installation.

Generally, it is desired to keep the diameter of the HDPE pipe as small as possible, but not so small that pumping power to circulate the antifreeze solution becomes too great, thus losing the operating efficiency of the GHP. The smaller the diameter, the higher the surface to volume ratio will be, and the better chance for turbulent flow inside the pipe. Both of these conditions promote more efficient heat transfer. Most ground heat exchangers are constructed from ¾″ to 2″ diameter pipe. The headers will be 1 ¼″ to 2″, and the individual loops will be ¾″, 1″ or 1 ¼″. The amount of pipe utilized varies depending on environmental conditions and how much heating or cooling capacity is needed. As an example, a typical 3-ton ground heat exchanger may use 200 feet of headers and 400 feet for each parallel loop.

If trenching for a horizontal installation or header system, avoid sharp bends around corners. Pipe manufacturers have a minimum bend radius that will assure that the pipe is not overstressed. If a sharp corner is needed, utilize an elbow fitting. Remove any sharp rocks from backfill material. Long-term contact between the polyethylene pipe and a sharp object could lead to premature failure of the pipe. Even though PE pipe has very high stress-crack resistance, it is a good idea to minimize this kind of contact. The addition of sand in the bottom of the trench and preferably all around the pipe will help minimize incidental contact with sharp objects. It is also possible to plow the pipe directly into the ground using a vibratory plow. This works well up to 3-4 feet depth in areas with loose or unstable soils, and where there is not an excessive amount of rocks that could impinge on the pipe over time.

Vertical bores for ground heat exchangers are typically much simpler than drilling a water well. Generally casing is not needed if the borehole is sufficiently stable long enough to get the pipe loop installed. It is sometimes more economical to have several shallow bores rather than one deep bore. However, the bores need to be more than 50 ft. to be assured of reaching depths where ground temperatures are cooler and constant. Vertical bores must be backfilled appropriately to be sure the pipe loops have intimate contact with the soil or grout. If there are air gaps around the pipe, the heat transfer by conduction will be negatively affected.

For both types of installations leave a significant portion (3-5% of total length) of pipe extending from the bores or trenches to compensate for any relaxation from stretching, or contraction from temperature changes. Final connections to the header can be made after the system comes to steady state, usually within 24 hours. More detailed information on the installation and burial of PE pipe can be found in the Chapter entitled Underground Installation of PE Piping.

Pressure Testing Ground Heat Exchanger

After installation of pipe is completed, but prior to backfilling and/or grouting, it is necessary to flush, purge and pressure test the system. Flushing any dirt or foreign matter that entered the piping during construction is necessary in order to minimize excessive wear on pumps and seals. Purging of any air pockets will make sure that all loops are flowing as intended and heat transfer will be optimized. Flushing and purging can be done at the same time.

Before charging the system with antifreeze, it is necessary to pressure test the system with water (not air) to make sure all of the joints and connections were done correctly. Testing with air is not recommended due to safety considerations. Failure of any part of the system can be very dangerous due to the explosive nature of air under high pressure. It could result in serious injury to personnel in the area. Therefore, testing with air is discouraged. IGSHPA recommends that the heat exchanger be isolated and tested to 150% of the pipe design pressure, or 300% of the system operating pressure, whichever is less, when measured from the lowest point in the loop being tested. No leaks shall occur within a 30-minute test period. At this time flow rates and pressure drops can be compared to calculated design values. A minimum flow velocity of 2 ft/min. must be maintained for a minimum of 15 minutes to remove all air from the heat exchanger.

Since the PE pipe can expand slightly during this high level of pressurization, a certain amount of make-up water may be required. This is normal and does not indicate a leak in the system. If the pressure does not stabilize, then this may be an indication of a leak. Follow the pipe manufacturer's guidelines for pressure testing the system.

For additional information of Ground Source Heat Pump design and installation contact:
International Ground Source Heat Pump Association (IGSHPA) www.igshpa.okstate.edu.
American Society of Heating, Refrigeration, and Air-Conditioning Engineers (ASHRAE) www.ashrae.org.

Solar Applications

The use of solar energy was virtually nonexistent 25 years ago, but has grown to become a significant industry in the United States. Most solar applications are geographically concentrated in the states with a high percentage of sunshine - California, Arizona, New Mexico, Colorado, and Florida.

Solar heating systems vary in size. The very simplest consist of nothing more than a black pipe lying in the sun connected to a swimming pool circulating pump. The more complex systems utilize collectors with 1, 2, or 3 layers of glazing plus piping and pumps. In addition, the latter systems may include heat transfer fluids, heat storage tanks, heat exchangers, and temperature and pressure controls. PE piping can play a major role in this application. Its combination of flexibility, high temperature properties, and resistance to freeze damage and corrosion are major advantages to this end-use. There are, however, precautions that should be taken to prevent misuse.

Check with the pipe manufacturer for recommendations on using PE pipe in solar applications.

Features and Benefits

The performance benefits of polyethylene pipe in solar heating are:

Ease of Installation – Minimizing the overall cost of solar heating is important to make them viable alternatives and to expand customer acceptance. Polyethylene pipe and tubing is available in many sizes and lengths. Its versatility and flexibility allows installations to be made with the most cost-effective design.

Freeze Tolerant – Frozen lines can be a major problem. Although collectors are protected, supply lines need to be protected from freezing or they should be made of materials that are resistant to damage if water freezes. Polyethylene pipe can normally handle a full-freeze situation without cracking or splitting.

High Temperature Resistance – For continuous use, polyethylene pipe must be suitable for high temperature environments. Polyethylene materials for use at elevated temperatures are listed in PPI's TR-4. Currently, the maximum rated temperature for PE pipe designed for pressure applications is 140°F (60°C). For use at higher temperatures contact the manufacturer for recommendations.

Collector Technologies

The most significant use of solar heating has been for swimming pool and space heating. Solar collectors are classified according to their water discharge temperatures: low temperature, medium temperature, and high temperature.
Low temperature systems generally operate at a temperature of 110ºF and have a maximum stagnation temperature of 180ºF. Medium temperature collectors typically have discharge temperatures of 180-200ºF, but can generate stagnation temperatures of 280ºF, or more, for several hours. High temperature collectors routinely operate at temperatures of at least 210ºF and can generate stagnation temperatures of more than 400ºF. Pipe or tubing made of PPI listed pressure rated PE materials can be used directly with low temperature collectors with no special precautions. In addition, PE piping is being used extensively inside unglazed collectors where temperatures rarely exceed 110ºF on a frequent basis.

To protect against ultraviolet exposure damage and to increase efficiency, plastic piping for use in collector panels should contain a minimum of 2% carbon black of proper particle size and with good dispersion. The carbon black has a two-fold benefit. One, the right kind of carbon black in the proper levels and adequately dispersed protects the PE from UV degradation. Two, the carbon black aids in the absorption and retention of solar radiation, making the pipe more efficient in the collection of solar energy. Check with the pipe manufacturer for recommendations on long-term UV exposure resistance.

Plastic piping should not be used in conjunction with high temperature collectors such as the evacuated tube or concentrating types because of their extreme temperatures. In between these two extremes are the systems with medium temperature collectors that constitute the bulk of the market. These glazed collectors are used for domestic hot water and space heating systems. Depending on the type of collector and system design, some special precautions should be taken. The major types of medium temperature systems are described in the following paragraphs along with appropriate precautions. Medium temperature systems are either passive or active types.

Passive systems use no pumps or mechanical equipment to transport the heated water. The breadbox (passive) design uses a tank placed under a glazing material. The tank is painted flat black or coated with a selective absorber to increase the solar energy absorption. The collector may be the primary storage tank or the storage tank may be in the house. In the later case, when a preset temperature is reached, water flows by gravity to the storage tank in the home and fresh water from the main is added to bring the system up to volume. In the thermosyphon passive design, a storage tank is mounted above a collector and cold water flows down into the collector. As the water is heated in the collector, it rises through thermosyphon action back up to the storage tank. Because of the large volume of water in the collector, passive solar systems are not subject to high stagnation temperatures. Thus, polyethylene piping can be used throughout, including a hook-up directly to the collector system.

Active solar systems utilize a pump to move heat transfer fluids through the collector. Some utilize potable water as the heat transfer fluid (open systems) while others use solutions such as ethylene glycol, propylene glycol, silicone oils, or hydrocarbon oils (closed systems). Hydrocarbon oil or silicone oils are generally not recommended with polyethylene pipe. In closed systems, heat is transferred from the heat transfer fluid to potable water by means of a heat exchanger in the hot water storage tank. There are many types of heat transfer fluids, and it is necessary to verify that the fluid being used is compatible and will not negatively affect the long-term performance of the pipe or other system components; refer to PPI TR-33 for further assistance.

Precautions

The extreme conditions encountered during stagnation can be a problem in active medium temperature collectors. As mentioned earlier, stagnation temperatures can exceed 280ºF in most active medium temperature collectors. Under no circumstances should any PE piping be used inside the collector, or in the system where it will be exposed to such temperatures.

Installation

In general, solar collector manufacturers do not provide piping for the system.

The installer most likely will purchase the piping from the local plumbing supply wholesaler or solar supply house. Installers are usually plumbers, but in some areas like California, solar specialists also do installations. A qualified plumbing supply house may also perform installations. The installation requires knowledge of carpentry to provide roof support or mounting, electricity to install the control system, and plumbing to install the piping system and to tie it in to the storage tank and the existing domestic water supply. Always be sure the installation meets the requirements of the local building, plumbing and mechanical codes.

References

1. Ground Source Heat Pump. (1996, February). *Popular Science*, p.73, Times Mirror Magazines, Inc.
2. *Do It Naturally!* Brochure, International Ground Source Heat Pump Association, Oklahoma State University.
3. Closed-Loop/Geothermal Heat Pump Systems, Design and Installation Standards latest edition. P. Albertson, International Ground Source Heat Pump Association, Oklahoma State University.
4. *Geothermal Heat Pumps*, Introductory Guide, Rural Electric Research (RER) Project 86-1A, Oklahoma State University Division of Engineering Technology, Stillwater, OK.
5. *ASTM Annual Book*, Volume 8.04, Plastic Pipe and Building Products, American Society for Testing and Materials, Philadelphia, PA.
6. Plastics Pipe Institute: Various Technical Reports, Technical Notes, Model Specifications, Irving, TX.

Chapter 14

Duct and Conduit

Introduction

The general purpose of conduit, or duct, is to provide a clear, protected pathway for a cable, or for smaller conduits, sometimes called innerducts. Advances in cable technologies, as well as the expense of repairing sensitive cable materials like fiber optic cable, have driven preferences for protective conduit over that of direct burial. Polyethylene (PE) conduit provides mechanical protection to fragile cable materials like fiber optic and coaxial cables, as well as protection from moisture or chemicals and even, in some cases, animals. Furthermore, the permanent pathway provided by conduit also facilitates replacement projects or future installations of additional cable or duct.

Buried conduit evolved from terracotta tile, cast concrete and Transite to plastics in the 1960s. Originally, PVC was utilized, but ultimately, PE has emerged as the material of choice due to its distinct advantages in installation options, versatility and toughness.

PE conduit can be installed below ground by a variety of methods, including open trench, plowing, continuous trenching and directional drilling. Also, its flexibility and availability in continuous coiled lengths facilitates installation into existing conduits or ducts as innerduct. In addition PE conduit provides many above ground or aerial options.

Conduit Specifications

The following specifications are utilized by the industry for the production of Conduit and Raceways:

- **Telecommunication Conduits** – ASTM F2160 Standard Specification for Solid-Wall High Density Polyethylene (HDPE) Conduit Based on Controlled Outside Diameter (OD)

- **Power Conduits** – ASTM F2160 Standard Specification for Solid-Wall High Density Polyethylene (PE) Conduit Based on Controlled Outside Diameter (OD)
- **NEMA TC7 Smooth-wall Coilable Polyethylene Electric Plastic Conduit**
- **Electrical Conduits** – UL 651A Type EB and A Rigid PVC Conduit and PE Conduit – UL 651B Continuous Length PE Conduit
- **Premise Raceways** – UL 2024 Optical Fiber Cable Raceway

Applications

PE conduit serves two primary industries: communications (telephone, CATV, data transmission) and electrical (power transmission).

In the communications industry, the advent of fiber optic cable has had a tremendous impact due to its significantly higher data-carrying capacity, particularly due to the explosion of the Internet. In telecommunications service (phone, data transmission), fiber optic cable is used, along with traditional copper cable. In cable television service (CATV), fiber optic is also growing rapidly in addition to (or replacing) coaxial cable. This progression toward fiber optic cable has made the need for protection more critical, since these materials are highly sensitive to moisture and mechanical stress. Damage can be very expensive in terms of interrupted service and replacement costs. Also, these cables are installed in very long, continuous runs which require a clear, protected pathway, as well as a leak-free system for air-assisted ("blow-in") installations. In addition to fiber optic, coaxial cables have seen improvements to increase bandwidth, making these materials more mechanically sensitive.

In the electrical industry, a critical requirement is on maintaining uninterrupted service, as consumers and businesses are even less tolerant of power outages than they are of phone or CATV service interruptions. Although many direct-buried power cable systems are designed for 30- or 40-year lifetimes, they are susceptible to external influences like rock impingement and often require frequent repairs. Conduit is finding favor over direct burial in these applications due to improved protection, but it must be continuous and facilitate quick repair operations. PE conduit is used to carry both primary (substation to transformer) and secondary (transformer to end-user) cables. Some of these installations also contain fiber optic cables placed alongside the power cables to connect with load-monitoring sensors located throughout the network.

Advantages of PE Conduit

High Density Polyethylene (PE) is the most commonly used PE material for conduit. PE conduit delivers significant physical property advantages over other conduit materials:

- **Ductility** - tough, PE conduit will better resist brittleness with age or cold weather.
- **Low temperature impact resistance** – PE withstands low temperature impact better than any other material. This is illustrated by impact testing on PE conduit conditioned at 4ºF as compared to other materials conditioned at 73ºF.
- **Permanent flexibility** – PE conduit bends and flexes without breakage, even with ground heaves or shifts, over a wide range of temperatures.
- **Temperature versatility** – PE conduit can be installed over an ambient temperature range of -30ºF to 180ºF. Power conductors rated at 90ºC and medium voltage cable rated at 105ºC are permitted for use with PE Conduit.

Installation

Flexible PE conduit can be wound onto reels several thousand feet long, does not require manufactured bends, and can be easily navigated around unexpected obstructions (in the ground or within existing ducts), simplifying installation. The few joints that are required can be made reliably through a number of options.

PE conduit is suitable for all methods of duct and cable installation, including trenching, direct plow and installation into existing main pathways (conduit pulling, sliplining and pipe bursting). Also, the flexible nature of PE conduit facilitates directional bore installations to breach obstacles like rivers or highways. Cable can consistently be pulled or blown into PE duct in great distances and at fast rates due to its low coefficient of friction. Special PE products and accessories are also available for above ground or aerial applications.

Features

A variety of PE conduit products are available for special applications.

- **Multiple ducts** of different color/stripe combinations and sizes can be delivered on one common reel, for a more efficient installation.
- Pre-installed **Cable-in-Conduit (CIC)** saves time and labor by allowing one-step placement of both cable and duct. The integrity of the cable is protected during the installation process by the PE duct. Testing prior to and after the duct has been extruded around cable is performed to ensure no performance loss. Cable-in-Conduit can be provided with fiber, coaxial, twisted pair and electrical cables.
- **Corrugated** innerduct is flexible, lightweight with a low coefficient of friction.
- **Ribbed conduit** (longitudinally or spiral) provides friction reduction in cable installation.
- **Self-supporting duct** includes a suspension strand already built into the duct for greater dimensional stability and ease of installation in the aerial plant.

Deployment of ducts aerially allows for enhanced protection for the cable and allows for less costly cable repairs and capacity upgrade options.

Material Selection

The primary physical property advantages of PE conduit are flexibility, ductility and chemical resistance. Other physical attributes critical to the performance of PE conduit are tensile strength and stress crack resistance. However, the designing or specifying engineer should be aware that not all PE materials deliver the same level of performance in these areas, and it is critical to ensure that the material meets all the demands of the installation and service conditions. This section will briefly discuss these material considerations, but a more thorough discussion of PE technology is provided in the chapter on engineering properties of polyethylene in this Handbook.

Physical Properties

Cell Classification

The Cell Classification (ASTM D 3350) is a 6-digit numeric "code" which describes an PE conduit material's performance level in six key physical characteristics. This 6-digit classification often includes a single letter suffix representing a color or UV stabilizer category. This cell classification is used in specifications such as ASTM F2160 Standard Specification for Solid Wall High Density Polyethylene (PE) Conduit Based on Controlled Outside Diameter (OD). Each property is broken into 4-6 specific performance ranges.

Density – PE density generally has the greatest effect on many physical properties. For example, higher densities favor increased tensile strength and stiffness, while lower densities generally favor impact resistance, and flexibility and stress crack resistance. Density also affects coefficient of friction (COF – see Section 7), with higher density typically related to lower COF. Therefore, some degree of compromise may be necessary to balance properties required for a particular application.

Melt Index – Melt Index (MI), a measurement of a polymer's molten flow properties (ASTM D 1238), is related to molecular weight, or the length of the individual polymer chains. Generally, lower melt indices represent higher molecular weights while higher values indicate lower molecular weights. For any given PE resin, a lower melt index (higher molecular weight) will normally have superior physical properties.

Flexural Modulus – Flexural modulus is a measure of a plastic's stiffness, or its resistance to bending or deflection under applied load. In PE conduit, these stiffness characteristics generally affect load-bearing capability, bending radius, and tendency to ovalize (when coiled or bent). Flexural modulus should be taken into account when determining the appropriate wall thickness for an installation.

Tensile Strength/Yield Strength – Tensile yield strength, or the point at which a stress causes a material to deform beyond its elastic region (irreversible deformation), is a critical property for many conduit installation methods involving pulling (e.g., directional drilling). Yield strength can limit the rates or lengths of such installations (see page 7 Design Considerations), and it is an important consideration in determining allowable pull loads. It is important to note that both flexural modulus and tensile strength are affected by temperature (both decrease with increasing temperature).

Slow Crack Growth – ASTM D1693 Environmental Stress Cracking Resistance (ESCR) or ASTM F1473 Polyethylene Notched Tensile (PENT) can measure properties of slow crack growth. For PE conduit applications, ESCR is utilized. As one of the most important properties affecting the service life of PE conduit, stresses due to bends and rock impingement can cause inferior conduit materials to crack and fail, particularly at higher temperatures. ESCR is a laboratory test which measures a material's ability to resist cracking under these conditions. As mentioned above, higher densities generally have a negative effect on ESCR, and, as a general practice, base resins with densities below 0.950 have ESCR properties suitable for conduit applications.

Hydrostatic Strength Classification – The hydrostatic strength classification describes the material's resistance to failure under internal pressure; this property is primarily used for pressure piping applications and is not required for conduit. PE conduit materials are represented by a "0" (not pressure rated) in this category.

Other Important Physical Properties

Chemical Resistance – PE is highly resistant to a wide range of chemical agents even at elevated temperatures. However, when installing in potentially aggressive environments, the user should refer to PPI Technical Report TR-19, *Thermoplastic Piping for the Transport of Chemicals,* which provides chemical resistance data for PE with a wide range of chemicals.

Impact Resistance – Impact resistance is related to the pipe's ability to absorb impact and resist cracking during handling and installation, particularly in cold weather. An advantage of PE over many other materials is its ductility at low temperatures. For example, PE's glass transition temperature (the temperature below which it is more brittle and glassy) is well below 0°F, at approximately -166°F (~-110°C), while for PVC it is well above room temperature, at about 176°F (~80°C). Like ESCR, impact resistance is strongly influenced by density, with lower densities generally favoring greater impact resistance.

There are a number of impact tests for materials, like Izod or Charpy (see the chapter on engineering properties in this Handbook), but generally finished pipe and fittings are tested by a falling weight (tup) impact test (for example, ASTM D2444) at low temperature — typically -4°F (-20°C). This test, commonly used in Quality Assurance, is a pass/fail test, in which any cracking or breaking is considered a failure.

Stabilization

Unprotected PE, like virtually all other polymers, is vulnerable to degradation due to prolonged exposure to heat, oxygen or ultraviolet (UV) radiation, resulting in embrittlement and reduced service life. To prevent these damaging effects, PE conduit materials are typically formulated with a variety of stabilizing additives, ranging from antioxidants to UV stabilizers, to maintain required long-term performance. For a more in-depth discussion on both antioxidants and UV protection, see the chapter on engineering properties in this Handbook. Regardless of the type of UV protection used, the conduit must be adequately protected from UV attack to withstand normal storage conditions and special use intervals. Adequate protection for conduit destined for underground installation is to provide for at least one year's protection from outdoor storage. If longer storage times are possible or anticipated, the user may specify additional stabilization, or, preferably, should provide for a covered storage environment. Otherwise, if the conduit exceeds one year of UV exposure, it should be tested to ensure it meets all physical property requirements (cell classification, impact resistance) prior to installation.

The most common means for UV protection is to employ carbon black at a minimum loading of 2%. For long-term aerial exposure in self-supporting Figure-8 duct designs, due to the heightened mechanical stress level, the carbon black should be more finely divided and dispersed, having an average particle size of less than or equal to 20 nanometers, in accordance with ASTM F 2160.

PE non-black materials, however, require special stabilizers in addition to their normal pigments, generally UV blockers or Hindered Amine Light Stabilizers (HALS).

Colorants for Conduit

PE conduit is produced in a variety of solid and striped colors, which serve to help identify the duct for either its end use application (e.g., fiber optic cable, power, etc.) or owner. In determining the color of the conduit, its striping or the marking of the conduit or a combination thereof, it is recommended for safety reasons that the color yellow not be utilized since this is the uniform color code for natural gas applications.

Design Considerations

Conduit vs. Pipe

In general, plastic conduits and plastic pipes are very similar in structure and composition, but deployment is where they differ.

- Conduits do not have long-term internal pressure.

  External forces are unchecked; if ovalized during installation, it may not recover during service.

  Long-term stress rupture is not a factor. (Hydrostatic Design Basis is not required in material selection.)
- Conduit ID is chosen by cable occupancy, where internal clearances are critical; whereas, for piping applications, ID is based on volumetric flow requirements.
- Path of installation for conduit is very important – radius of curvature, vertical and horizontal path deviations (undulations) and elevation changes all significantly affect cable placement.

Cable Dimension Considerations

Determination of a conduit's dimensions begins with the largest cable, or group of cables or innerducts, intended for occupancy. From a functional viewpoint, selection of diameter can be broken down into the following general considerations:

1. The inside diameter of the conduit is determined by the cable diameter and placement method (pulling or air-assisted pushing).

2. Pulling cables into underground conduits requires sufficient free clearance and is typically further distinguished by classifying the cables into two groups: power and coax (short lengths) and fiber (long lengths). Additionally, electrical cable fill is controlled by the National Electric Code (Chapter 9), whereas, dielectric, or fiber optic cables, are not.

3. Long pulling lengths require low volume fill, i.e. 36% max.

4 Short pulling lengths may be filled up to 53%, or up to the latest NEC limitations for groups of cables.

5. Push-blow installation methods for long length fiber cables utilize higher volume fills, i.e. up to 70% max.

6. Innerducts are smaller diameter conduits, intended for placement into larger

conduits or casings. Their purpose is to subdivide the larger conduit space into discrete continuous pathways for incorporation of fiber optic cables. Diameters of conduits and innerducts are often specially designed to maximize the conduit fill.

Using these guidelines, one can determine the minimum ID of the conduit or innerduct. When over-sizing a conduit for power, coaxial or multi-pair telecom cables, the more room the better. This rule does not necessarily apply for push-blow methods of installation. Here, it is found to be more difficult to push a cable with additional clearance since a cable tends to form a helix, which transfers some of the axial load laterally into the wall causing friction. The air velocity moving over the cable can also be maximized with a minimum volume of air when the free volume is low. Higher air velocities result in improved drag forces on the cable, thus aiding with its placement.

Conduit Wall Determination

Conduit and duct products come in a wide range of sizes, spanning 1/4-inch (5mm) to 24-inch (610mm) bore casings. The standard dimension ratio, SDR, of a conduit is defined as the ratio of the average conduit diameter divided by the minimum wall thickness. Wall thickness typically ranges between SDR 9 to SDR 17. (Larger SDR numbers indicate a thinner wall thickness.)

Conventions exist that work off of either the average outside diameter (SDR) or the average inside diameter (SIDR). Internally sized (SIDR) are usually chosen when the inside diameter clearance must be very carefully controlled. This usually does not apply to most duct installations because, as noted above, the free clearance between the cable and the inner wall of the conduit is not usually that close. Bore casings, on the other hand, offer situations that can benefit from close ID control because many times several innerducts are tightly fit into a casing. In this latter case, the conduit wall can be increased or decreased relative to service conditions without jeopardizing the inside clearance fit. Internally sized dimension tables tend to preserve the minimum ID above the nominal conduit size, whereas, externally sized conduits often fall below the nominal ID as the wall thickness increases.

For most conduit installations, SDR sizing is utilized because the OD control lends itself to better joint formation using external couplers. This becomes very important when air-assisted placement methods are used for placing the cable. On the other hand, large diameter conduits (4 and above) typically undergo butt fusion as a means of joining.

Determination of the wall thickness becomes a function of either the method by which the conduit is placed, or the nature of environmental stresses that it will be exposed to over the service life. ASTM F 2160, *"Standards Specification for Solid Wall*

High Density Polyethylene (PE) Conduit Based on Controlled Outside Diameter (OD)", explains the conduit sizing systems fully.

Installation Method vs. Short-Term and Long-Term Stress

The viscoelastic nature of PE results in differences in the observed mechanical properties as a function of time (and/or temperature). The apparent stress/strain behavior of the material is time dependent under the influence of a sustained load. This is referred to as "creep" properties. In this regard, we can distinguish between "short-term" properties, such as those exhibited during a laboratory tensile test at a strain (stretching) rate of two inches per minute, as compared with "long-term" properties typical of conduit placement and sustained service loads.

Knowledge of the load-bearing capability of PE as a function of loading rate allows one to select appropriate strength values to substitute into design equations. Loads are applied to conduits both by the environment that they are placed into and by the placement means under which they are installed; the chief difference being the duration over which the load is applied. For example, a common means to install multiple conduits is to directly plow them into the ground using either a railroad plow or tractor-drawn plow. During this installation process, a certain amount of bending and tensile stress is encountered over a rather short period of time (only seconds to minutes). Whereas, after the plow cavity collapses about the conduit, the ground continues to settle upon stones that may be pressing directly against the conduit, thus setting up a long-term compressive load. For this application, we see that we would require both long-term and short-term moduli to assess the deflection resistance. Initially the conduit may offer resistance to ovalization, but in time, the resin may yield under the sustained load, resulting in a reduced pathway for the cable.

Numerous approaches to placing conduits have evolved over the years. Each method presents its own unique set of challenges with respect to the potential for conduit damage, or installation related predicaments. Perhaps one way to compare the potential sensitivity to damage of the various methods is the following table. Here the potential for damage is depicted by a numerical scale ranging from 0 to 5, where 5 is the most severe condition, resulting in yielding and permanent deformation of the conduit; 4 is the potential for loads greater than 75% of yield stress; 3 represents loads greater than 50%; 2 representing greater than 25%; 1 less than 25%, and 0 representing no significant load at all. The shaded areas depict the most severe condition.

TABLE 1
Relative Damage Sensitivity vs. Installation Method

Installation Method	Short-Term Loading				Long-Term Loading		Recommended SDR Range
	Tensile	Bending	Crushing	Impact	Crushing	Tensile	
Conduit*	3 - 5	3	2	1	1	1 - 2	9.0 – 13.5
Horizontal Bore	4 - 5	2	3 - 4	0	3 - 5	1	9.0 – 11.0
Direct Plow	2	3	4 - 5	1 - 2	4 - 5	1	9.0 –11.0
Continuous Trench	2	2	3 - 4	1 - 2	3 - 4	1	9.0 – 11.0
Open Trench	0	0	1 - 3	1	1 - 3	1	11.0 – 17.0
Aerial	1 - 2	3 - 5	2 - 3	1	1	2	11.0 – 13.5

* The term "conduit" in this chart refers to the placement of PE innerducts into a buried 4" to 6" PVC conduit typical of the underground telecom plant. The SDR recommendation range attempts to select safe SDR's based upon the potential for stressful conditions.

It should be noted that the above table is not intended to be representative of all conduits installed by these methods, but is indicative of what can happen when the wrong diameter, wall or material is used. Check with supplier for specific design recommendations.

Perhaps the most serious and least controlled problem for cable placement is that of ovalization or kinking of the conduit. This condition can be brought about through tensile yielding, severe bending, excessive sidewall loading, or probably more frequently, the crushing action of rocks in the underground environment. In direct plow or bore applications, one gets little feedback from the process to indicate that a potential problem is developing. For these applications, the most robust conduit design should be considered.

Below Ground Installations

Open Trench / Continuous Trenching

Conduits intended for buried applications are commonly differentiated into two classes, rigid and flexible, depending on their capacity to deform in service without cracking, or otherwise failing. PE conduit can safely withstand considerable deformation and is, therefore, classified as a flexible conduit.

Flexible conduits deform vertically under load and expand laterally into the surrounding soil. The lateral movement mobilizes the soil's passive resistance forces, which limit deformation of the conduit. The accompanying vertical deflection permits soil-arching action to create a more uniform and reduced soil pressure acting on the conduit. PE stress relaxes over time to decrease the bending moment in the conduit wall and accommodates local deformation (strain) due to imperfections in the embedment material, both in the ring and longitudinal directions.

The relationship between pipe stiffness, soil modulus (stiffness), compaction and vertical loading is documented by the work of Spangler and others. The pipe stiffness, as measured in ASTM D2412 and Spangler's Iowa formula provide a basis for prediction of conduit deflection as related to dimension ratio and resin modulus. It should be noted, however, that creep affects the pipe stiffness, so the long-term modulus should be used. Additional information pertaining to soil embedment materials, trench construction and installation procedures can be found in the chapter on "Underground Installation of Polyethylene Piping" in this Handbook.

Flexible conduit can occasionally fail due to stress cracking when localized forces (for example, from a large sharp rock) exceed the material's ability to relax and relieve stress. However, PE resins suitable for conduit applications should have adequate stress relieving properties to avoid these failures. Therefore, the design process should include consideration of the conduit resin's stress crack resistance, as well as the selection of appropriate embedment material and compaction.

Direct Plow

Flexible conduit materials need adequate compressive strength to safely resist the compressive stresses generated by external loading. However, the usual design constraint is not material failure due to overstraining, but, rather, excessive deflection or buckling under anticipated earth and ground water pressures. Deflection or buckling is more probable when the embedment material does not provide adequate side support. For example, pipe installed by directional drilling and plowing typically does not receive side support equivalent to that provided by the embedment material used in trench installations where bed and backfill can be "engineered" to provide a specific level of lateral support.

Plowing installations often encounter rocky soils, which would induce significant crush loads for conduits 2-inch diameter and smaller. In these cases, SDR 11 is the minimum wall thickness that should be used, and if rocky conditions were likely, SDR 9 would be more appropriate.

Pipe stiffness, as calculated per ASTM D2412, gives a measure of flexural stiffness of the pipe. Pipe stiffness equals the ratio of the applied load in units of lbs/lineal inch to the corresponding deflection in units of inches at 5% deflection. It should be understood, however, that although two conduits, 6-inch and 1.25-inch diameter, may possess the same pipe stiffness, the amount of soil load required to induce a 5% deflection in each is considerably different. As a result, the sensitivity of smaller diameter conduits to underground obstructions is that much greater. Another physical parameter for smaller conduits, crush strength, is often employed to establish limits of crush resistance. Unfortunately, there is no universally agreed upon criterion or test method for crush testing. Typically, the conduits are subjected to an increasing load, similarly applied as in ASTM D2412, but to a far greater deflection—on the order of 25 to 50% of the inside diameter. This deflection-limiting load is then reported on a per-foot basis.

Table 2 illustrates the difference in the load required to induce a 5% deflection in conduits having different diameters but common pipe stiffness values. These values were generated assuming a flexural modulus of 150,000 psi for the resin. Units for pipe stiffness are in pounds/inch of length/inch of deflection, whereas those for the crush are presented as pounds per foot. It is apparent that a fixed external load more easily deflects smaller diameter conduits. It is also important to remember that, in long-term loading, the resin will maintain only about 22 to 25% of its original modulus; thus, smaller thin-wall conduits can be quite susceptible to localized loads brought about by buried obstructions.

Conduit Network Pulling

In the telephone and electrical utility industries, the underground plant is often comprised of a network of 3", 4", and 6" conduit banks. These "rigid" conduits are composed of clay tile, cement conduit, or more recently, PVC constructions. They are usually separated by manhole vaults or buried pull-boxes. Distances between, and placement of manholes and pull-boxes is largely a function of the following constraints:

1. Location of branch circuit intersections
2. Lengths of cables (or innerducts) available on reels
3. Access to, or limited by physical obstructions
4. Path difficulty for placement of cable or innerducts
5. Surface environment
6. Method of cable placement (mid-assist access)

In addition, Department of Transportation (DOT) regulations often require additional protection and support structure for buried conduits in road bores and traffic areas. Although steel casings have been used in the past, it is becoming more prevalent to horizontally bore under roadways (or waterways) and pull back an PE casing into which PE innerducts are installed.

Pull placement of innerducts has obvious similarity to traditional cable placement methods. Several good references on this subject exist, including *Guide For Installation of Extruded Dielectric Insulated Power Cable Systems Rated 69KV Through 138KV,* *Underground Extruded Power Cable Pulling Guide, AEIC Task Group 28 and IEEE Guide Distribution Cable Installation Methods In Duct Systems.*

There are a number of variables that influence loading and selection of innerducts when pulling into conduit structures:

- Diameter of conduit and innerduct, and number of innerducts to be installed – clearance fit
- Length and direction changes of conduit run, sweeps
- Composition of conduit and coefficient of friction
- Jam combinations
- Pull speed and temperature
- Elevation and innerduct weight

Horizontal Directional Bore

For directional drilling the design process should include consideration of tensile forces and bend radii created during these processes. Flexible conduits installed in continuous lengths are susceptible to potential tensile failures when pulled into place, so allowable tensile forces should be determined to avoid neck-down from tensile yield. The engineer should also account for the conduit's allowable bend radius, especially on bends with no additional support given to the conduit, to prevent ovalization and kinking from installation. For additional information, please refer to the chapter on horizontal directional drilling in this Handbook.

TABLE 2
Pipe Stiffness (PS) vs. Crush Strength

		SDR 9			SDR 11			SDR 13.5			SDR 15.5			SDR 17		
Conduit Size	OD In.	Wall In.	PS Lb/in. in.	Crush Lb./6 in.	Wall In.	PS Lb/in. in.	Crush Lb./6 in.	Wall In.	PS Lb/in. in.	Crush Lb./6 in.	Wall In.	PS Lb/in. in.	Crush Lb./6 in.	Wall In.	PS Lb/in. in.	Crush Lb./6 in.
1	1.315	.146	1310	804	.120	671	433	.097	344	231	.085	220	151	.077	164	114
1.25	1.660	.184	1310	1020	.151	671	547	.123	344	292	.107	220	190	.098	164	144
1.5	1.900	211	1310	1160	.173	671	626	.141	344	33	.123	220	218	.112	164	165
2	2.375	.264	1310	1450	.216	671	782	.176	344	417	.153	220	272	.140	164	206
2.5	2.875	.319	1310	1760	.261	671	947	.213	344	50	.185	220	330	.169	164	249
3	3.5	.389	1310	2140	.318	671	1150	.259	344	615	.226	220	402	.206	164	304
4	4.5	.500	1310	2750	.409	671	1480	.333	344	790	.290	220	516	.265	164	390
6	6.625	.736	1310	4050	.602	671	2180	.491	344	1160	.427	220	760	.390	164	575

Table 2 is for comparative purposes only. Pipe stiffness values are based on 150,000-psi flexural modulus. Crush values are estimated from empirical data for 6″ long conduit samples compression tested in accordance with ASTM D2412 to 50% deflection.

Installation Methods

This section discusses various conduit installation options in general terms and should not be interpreted as a step-by-step guide or "operations manual." The user should contact the equipment manufacturer for more detailed instruction, as operating procedures will vary with equipment.

NOTE: The consequences of striking gas or power lines (above and below ground) during installation can be dangerous, possibly deadly. Before digging, it is critical to ensure that all existing underground service lines (gas, water, power, etc.) in the vicinity are located and marked. It is recommended to contact the local "Call Before You Dig" agency to ensure these provisions are made. Furthermore, prior to installation, consult NEC, NFPA and NESC codes, as well as any applicable local codes.

General Considerations

Mechanical Stress

Regardless of the installation method, mechanical stress is of great concern during conduit placement. Exceeding the maximum allowable pulling tension or the minimum allowable bending radii can damage conduit. Consult the conduit supplier for allowable pulling tensions.

Pulling Tension

During conduit pulling placement, attention should be given to the number of sweeps, bends or offsets and their distribution over the pull.

Tail loading is the tension in the cable caused by the mass of the conduit on the reel and reel brakes. Tail loading is controlled by two methods. Using minimal braking during the pay-off of the conduit from the reel at times can minimize tension; no braking is preferred. Rotating the reel in the direction of pay-off can also minimize tail loading.

Breakaway swivels should be placed on the conduit to ensure that the maximum allowable tension for that specific conduit type is not exceeded. The swivel is placed between the winch line and pulling grip. A breakaway swivel is required for each conduit.

Bending Radii

Conduit is often routed around corners during placement, and pulling tension must be increased to complete the pull. It is important to determine the minimum radius to which the conduit can be bent without mechanically degrading the performance of the conduit. See Table 3.

TABLE 3
Minimum Bend Radius as a function of Diameter and Standard Dimension Ratio

		SDR 9		SDR 11		SDR 13.5		SDR 15.5		SDR 17	
Size	OD In.	Wall In.	Min. Radius In.	Wall In.	Min. Radius In.	Wall In.	Min. Radius In.	Wall In.	Min. Radius In.	Wall In.	Min. Radius In.
1	1.315	.146	15.4	.120	20.1	.097	25.9	.085	30.6	.077	34.1
1.25	1.660	.184	17.1	.151	22.3	.123	28.9	107	34.2	.098	38.1
1.5	1.900	.211	18.2	.173	23.8	.141	30.8	.123	36.4	.112	40.6
2	2.375	.264	20.0	.216	26.3	.176	34.2	.153	40.5	.140	45.2
2.5	2.875	.319	21.8	.261	28.0	.213	37.3	.180	44.3	169	49.5
3	3.500	.389	23.8	.318	31.4	.259	40.9	.226	48.5	.206	54.2
4	4.500	.500	26.4	.409	35.0	.333	45.8	.290	54.5	.265	61.0
6	6.625	.736	30.9	.602	41.3	.491	54.4	.427	64.9	.390	72.8

Ovalization is independent of tensile strength or modulus, but is controlled by diameter, wall thickness and bending radius. The radii listed above are estimated, as the minimum unsupported bending radius required producing a 5% ovalization. The values in the above table are calculated based on minimum wall thickness and are a first approximation to ovality in the bending conduit (actual bending radius may be slightly smaller). Ovality is calculated as: Ovality = [(Max. OD – Min. OD)/Avg. OD] x 100.

Underground Installation

Generally, the three primary underground installation (or “underground plant”) methods are trenching, plowing and boring, described in general terms below.

Trenching Methods

As with all methods, there are many variations on trenching installations, but generally the two main variations are the traditional “open trench” method and “continuous” trenching.

Open Trench/Continuous Trench

As the name implies, open trench installations involve digging an open trench and laying the conduit directly into the trench, often along with embedment material to protect the conduit from damage due to the surrounding soil. This installation is accomplished with specialized trenching machines that cut the trench and remove the soil in a single action and can be used to place multiple conduits over long or short distances. This technique, more common in pressure pipe or PVC installations, is described in more detail in the chapter on underground installation in this Handbook.

In Continuous trenching, conduit payoff moves along with the trenching process.

Digging the Trench

The trench should be dug as straight, level and rock free as possible. Avoid curves smaller than the conduit's allowable bend radius. Undercut inside corners to increase the radius of the bend. Should there be a rapid grade change, use back-fill to support the conduit.

Excavate the trench to the desired depth, and remove all rocks and large stones from the bottom of the trench to prevent damage to the conduit. Push some clean fill (fine material, without stones) into the trench to cushion the conduit as it is installed in the trench.

Supplemental trenches should be made to all offset enclosure locations. Trench intersections should be excavated to provide adequate space to make sweeping bends in the conduit.

Fill the trench and compact as required. Tamp the trench to provide compaction that will prevent the trench backfill from settling.

Placing the conduit

An important consideration for open-trench installations of PE conduit is that conduit should be straightened to remove any residual "coil memory," which can create a tortuous path for the cable and create significant challenges to cable installation. Conduit pay off can be accomplished by pulling the conduit into the trench from a stationary reel or by laying the conduit into the trench from a moving reel, usually attached to a trailer.

Spacers should be used when placing multiple ducts in a trench. Spacers prevent the ducts from twisting over and around each other. By keeping the ducts in straight alignment, cable-pulling tensions are reduced. When water is present in the trench, or when using extremely wet concrete slurry, floating of the conduit can be restricted through the use of the spacers.

Backfilling

It is best to place the best quality soil directly on and around the conduit. DO NOT place large rocks directly on the conduit. Allow at least 2 – 4 inches (5 – 10 cm) of clean, uniform soil to cushion the conduit.

A good practice to insure long-term protection of underground facilities is to utilize sand for padding the conduit. It provides a more stable environment for the conduit, prohibiting damage from rocks and allowing water to drain away from conduit easily. More importantly is the protection it can provide during future excavation near your facilities. The apparent change in soil condition provides warning that there is a utility buried there. This should not replace the practice of placing warning tape, but rather should serve as a supplement.

During backfill, warning tape should be placed typically 1 to 3 feet above the conduit.

Plowing

Plowing is the preferred installation for long continuous runs where space permits, for example, in rural areas. Plowing installations use a plow blade (pulled by a tractor or mounted to a railroad car) to split the earth and place the cable at the required depth through a feed tube located directly on the plow blade. The key distinction between plowing and continuous trenching is that trenching involves the actual removal of soil from the trench, whereas plowing only displaces soil while laying in the conduit.

Consult the equipment manufacturer for specific recommendations on plow blade and feed tube designs. It is strongly recommend to have a professionally engineered single or double feed tube plow blade with a tube at least 0.5 inch (1.25 cm) larger than the largest conduit size and a radius no smaller than the minimum bend radius of the largest conduit size. It is recommended that DR 11 or DR 9 be used, depending on conditions and conduit diameter.

Local regulation may require that warning tape be plowed in with the cable. Most plow manufacturers make plow blades that bury cable and tape at the same time.

Plowing Variations

There are several variations of plowing installations. A few are described briefly below:

- **Vibratory Plowing** – This method uses a vibrating blade and may allow use of a smaller tractor than that used for static plowing.
- **Rip and Plow** – This method may be required when significant obstructions (for example, roots) are anticipated and uses an additional lead plow (without conduit) to rip the ground and clear obstructions several hundred yards ahead of the primary plow with conduit.
- **Pull Plows Method** – Instead of installing from a reel traveling with the plow, conduit is pulled from a stationery reel behind the plow through the plowed trench.

Directional Bores

Directional boring allows the installation of conduit under obstacles that do not allow convenient plowing or trenching installations, for example rivers or highways. This unique installation method, which capitalizes on a primary strength of PE conduit — its flexibility, can be accomplished over very long distances.

Directional boring is accomplished using a steerable drill stem to create a pathway for the conduit. The equipment operator can control the depth and direction of the boring. A detailed discussion of this installation method is presented in the chapter on "Polyethylene Pipe for Horizontal Directional Drilling" in this Handbook. Also, consult the equipment supplier for detailed operating procedures and safety precautions.

It is recommended that DR 11 or DR 9 be used, depending on conditions and conduit diameter.

Installation into Existing Conduit

Conduit (or multiple conduits) is often pulled into existing conduit systems as innerduct.

NOTE: ALWAYS test and ventilate manholes prior to entering into them and follow OSHA confined space requirements.

Proofing

An important step that should be taken prior to this type of installation is "proofing" the existing conduit to ensure that all obstructions are cleared and that conduit continuity and alignment is good. It is recommended that a rigid mandrel roughly 90% of the inner diameter of the conduit be used to perform the proof. Proofing conduit is typically performed by pushing a fiberglass fish with a rigid mandrel attached to the end of it through the conduit. Any problem areas should be felt by the person pushing the fiberglass fish and should then be marked on the fish so that the distance to the problem is recorded and if necessary can be located for repair with greater ease. If the fiberglass fish makes its way through the conduit without any difficulties experienced, then the conduit has "proofed out," and no repairs should be necessary.

Before placement of the innerduct inside the conduit can be started, it is important to have all of the necessary equipment to protect the innerduct. The use of sheaves, bending shoes, rolling blocks (45 and 90 degrees) and straight pulleys are required for protection of the innerduct during installation. It is important that they all meet the proper radius for the innerduct size. The use of a pulling lubricant will greatly reduce the tension and stress on the innerduct when pulling innerduct into an existing conduit. Ball bearing swivels are needed for attaching the winch line to the innerduct harness system.

Mid-Assists

On long routes and routes with many turns in them it is important to consider the selection of mid-assist locations. There are different ways of providing mid-assist for innerduct pulls. Typically the use of a winch is required such as a capstan or vehicle drum winch. The introduction of mid-assist capstan winches has made innerduct pulling an easier task, requiring less manpower and communication than traditional drum winching involves. More importantly it provides greater production capabilities.

After Pulling

The stress of pulling innerduct through existing conduit will vary with the length of the route and the number of turns it has to make, as well as the condition of the conduit it is being pulled into and the amount of lubrication used. The effects of the stress will cause the innerduct to elongate (or stretch) in proportion to the amount of stress, but should be less than 2% of the total length placed. Due to this effect, it is important to pull past the conduit system slightly to compensate for recovery to the original length. An allowance of at least one hour needs to be given for the innerduct to "relax" before cutting and trimming it.

Above Ground/Aerial

There are many applications for aerial conduit, which include but are not limited to road crossings, rail crossings, trolley line crossings, and water crossings. They provide for efficient means of supporting cable that can easily be replaced and/or allow for the addition of cables without requiring encroachment in often hazardous or difficult to access spaces.

A critical consideration for aerial applications is UV protection. For this reason, only conduit materials with special carbon black pigments can be used, since constant direct exposure to UV radiation significantly shortens the lifetime of unprotected PE conduit (see Material Selection in this chapter).

Installation

The two preferred methods for aerial installation of conduit are the back-pull/stationary reel method and the drive-off/moving reel method. Circumstances at the construction site and equipment/manpower availability will dictate which placement method will be used.

Design consideration must be given to the expansion/contraction potential of PE conduit. This consideration is more important when lashing conduit than with the use of self-supporting conduit.

Installation – Back-Pull/Stationary Reel Method

The back-pull/stationary reel method is the usual method of aerial conduit placement. This method is also best suited for locations where the strand changes from the field side of the pole to the street side of the pole and where there are excessive obstacles to work around. The conduit is run from the reel up to the strand, pulled back by an over lash cable puller that only travels forward and is held aloft by the cable blocks and rollers. Once the section of conduit is pulled into place it is lashed and then cut.

Installation – Drive-Off/Moving Reel Method

The drive-off/moving reel method may realize some manpower and timesaving in aerial conduit placement and lash-up. This method is used where there is existing strand and is on one side of the poles, typically roadside. In it, the conduit is attached to the strand and payed off a reel moving away from it. The conduit is being lashed as it is pulled.

Self-Supporting Conduit

Installation of self-supporting conduit can be accomplished by both of the above methods, the difference being that the support strand is an integral part of the conduit. This product approach not only simplifies installation by eliminating the step of independently installing a support strand, but it improves the controllability of the expansion-contraction properties of the conduit.

Installation – Over-lashing Existing Cable

Over-lashing conduit onto existing cable plant is similar to installing conduit onto new strand. However, there are some unique aspects.

A sag and tension analysis should be performed to see if the new cable load will overwhelm the strand. Also, over-lashing conduit on top of sensitive coaxial cables may influence the cables signal carrying capability due to rising lashing wire tensions that may result from contraction-induced movement of the conduit. It is best to seek the help of engineering services in planning an aerial plant.

Joining Methods

Introduction

Conduit can be joined by a variety of thermal and mechanical methods. Since conduit does not experience any long-term internal pressure and acts only as a pathway for power or other cables, the owner of the system may be tempted to neglect the importance of specifying effective couplings. However, an integral part of any conduit system is the type and quality of joining method used. Proper engineering design of a system will consider the type and effectiveness of these joining techniques.

The owner of the conduit system should be aware that there are joint performance considerations that affect the system's reliability well beyond initial installation. Some of those might include:

- **Pull out resistance**, both at installation and over time due to thermal contraction/ expansion, must be considered. This is critical for "blow-in" cable installations, which will exert an outward force at joints, less so for pulling installations, which will tend to exert the opposite force.
- **Pressure leak rates**, for "blow-in" installations at pressures of 125 to 150 psig. Consideration must be given to how much leakage can be tolerated without reducing the distance the cable can consistently be moved through the conduit.
- **Infiltration leakage**, allowing water and/or silt to enter the conduit over time, can create obstacles for cable installation and repair or cause water freeze compression of fiber optic cables.
- **Corrosion resistance** is important as conduit systems are often buried in soils exposed to and containing alkali, fertilizers, and ice-thawing chemicals, insecticides, herbicides and acids.
- **Cold temperature brittleness resistance** is required to avoid problems with installation and long-term performance in colder climates.

General Provisions

PE-to-PE joints may be made using heat fusion, electrofusion or mechanical fittings. However, mechanical couplings are often preferred over fusion joints, due to the internal bead of a butt fusion joint, which can interfere with cable installation. PE conduit may be joined to other materials in junction boxes or other hardware utilized by communication and electrical industries, by using mechanical fittings, flanges, or other types of qualified transition fittings. The user may choose from many available types and styles of joining methods, each with its own particular advantages and limitations for any joining situation encountered. Contact with the various manufacturers is advisable for guidance in proper applications and styles available for joining as described in this section.

Mechanical Fittings

PE conduit can be joined by a variety of available styles of mechanical fittings, each with its own particular advantages and limitations in any given application. This section will not address these advantages or limitations but will only offer general descriptions of many of these fitting types and how they might be utilized. ASTM F 2176, *"Standard Specification for Mechanical Couplings Used on Polyethylene Conduit, Duct and Innerduct,"* establishes performance requirements for material, workmanship, and testing of 2-inch and smaller mechanical fittings for PE conduit. PPI recommends that the user be well informed about the manufacturer's recommended joining procedure, as well as any performance limitations, for the particular mechanical connector being used.

Barbed Mechanical Fittings

Barbed fittings are available in various materials and configurations for joining conduit sizes 2-inch and smaller. None of these fittings are offered with sealing capabilities. Installation involves pressing the fitting over ends of the conduit to be joined using a special tool. The inside of these fittings contain sharp, inward-facing barbs which allow the conduit to be pressed in, yet dig into the conduit and resist removal when pulled.

Threaded Mechanical Fittings

Threaded mechanical fittings are available in various materials and configurations for conduit sizes 2-inches and smaller. Some are designed with sealing capabilities while others are not. Internal thread designs of these fittings are typically tapered similar to pipe threads, with a left-hand thread on one end and a right-hand thread on the other to cut thread paths on the conduit's outer surface. This thread design allows the operator to thread the fitting onto the ends of both conduit sections simultaneously. Some variations of threaded fittings may also be pressed on the conduit ends and used as barbed fittings. The user should consult the fitting manufacturer to determine if this alternate installation method is recommended.

Compression Fittings

As with the other mechanical fittings, compression fittings are also available in numerous designs – some designs for conduit as large as 8-inch and others for only 2-inch and below. While compression fittings used in PE pressure piping industries, such as water or gas, require internal stiffeners, conduit systems typically do not, because stiffeners may create obstacles for cable being blown through the conduit. For any fitting style being considered, consult the fitting manufacturer for available sizes and written instructions for use.

Expansion Joints

Expansion joints are designed primarily for aerial conduit installations. The primary purpose of this fitting design is to absorb thermal expansion and contraction in the conduit system created by ambient temperature changes, which can be extreme in these above ground installations. System designers should determine the number of expansion joints required based on the expansion length provided by the fitting and a calculation of the pipe's overall thermal expansion factor for the overall length of above ground installation.

Heat Fusion

The principle of heat fusion is to heat two surfaces to a designated temperature and fuse them together by application of a force sufficient to cause the materials to flow together and mix. When fused in accordance with the manufacturer's recommended procedure and allowed to cool to nearly ambient temperatures, the joint becomes as strong or stronger than the conduit itself in both tensile and pressure properties.

Three primary heat fusion methods used in joining PE conduit are butt, socket and electrofusion. Butt and socket fusion joints are made using "hot irons" designed specifically for PE joining, and electrofusion supplies heat internally by electric current applied to a special fitting containing a wire coil. More specific information on heat fusion joining practices can be found in the chapter on "Joining" in this Handbook, as well as in ASTM F 2620 for the hot iron methods (butt and socket fusion) and in ASTM F 1290 for electrofusion.

PPI recommends that the user precisely follow the qualified fusion procedures established by the manufacturer of the particular heat fusion and joining equipment being used.

Butt Fusion Joining

Butt fusion joints are produced without need of special fittings, using specially developed butt fusion machines, that secure, face and precisely align the conduit for the flat face hot iron (not shown) fusion process. It should be noted that the butt fusion process produces an internal bead of equal or larger size than the visible outer bead. If internal restrictions are a concern for the cable installation, alternative-joining methods may be more appropriate.

Socket Fusion Joining

This technique requires the use of specially designed hot irons to simultaneously heat both the external surface of the pipe and the internal surface of the socket coupling. Specially designed hand tools are available to maintain alignment and stab depth of the hot irons until the materials reach fusion temperature. These tools also help secure the heated conduit end and coupling as the joint is made. Design requirements for socket fusion can be found in ASTM D 2683 for fittings and in ASTM F 1056 for socket fusion tools. As with butt fusion, socket-fused joints may have an internal bead that can interfere with cable placement.

Electrofusion Joining

Electrofusion is somewhat different from the hot iron fusion method described previously, the main difference being the method by which heat is applied. Electrofusion involves the use of a special electrofusion fitting with an embedded wire coil. Electrical current supplied to the wire coil by an electrofusion control box generates the heat for fusion. Special training in equipment use and maintenance may be needed. For additional information consult the chapter on "Joining" in this Handbook.

Repair Operations

Repair joints, as the name implies, are often designed specifically for use in repair situations. The nature of the damage will often dictate what types of joints are needed for repairs. For example, one type of design, a clamp-on style may be preferred when damage is limited and removal of the cable for repair is not necessary. However, in more severe damage situations, where new cable and conduit sections must be installed, many of the joining methods described earlier in this section may be suitable. Ultimately, the type of repair fitting or joint installed should maintain the integrity of the conduit system, prevent infiltration and provide sufficient resistance to thermal expansion/contraction.

Cable Installation

Installing cable-in-conduit or innerduct can be accomplished in a number of ways. These include:

1. Pulling cable into the conduit using a pull line or rope
2. Blowing cable into the conduit using specialized equipment that installs the cable in conjunction with a high volume jet of air
3. Pre-installed in the conduit by the conduit manufacturer (cable-in-conduit)

Pulling Cable into Conduit

The traditional method of installing cable-in-conduit has been to attach a pull line (or rope) to the cable and pull the cable into the conduit. This placement method requires equipment to do the actual pulling, to apply lubricants to reduce friction, and devices that measure the amount of tension being applied to the cable.

Conduit may be supplied with a preinstalled pull line. This line is either a twisted rope or a woven tape. These pull lines come in a wide variety of tensile strengths that range from 500 - 6000 pounds-force. Pull lines are also available pre-lubricated to reduce friction.

Pull tapes are available with sequential footage marks. This type of tape is useful in determining the progress of the cable pull.

Empty conduit would require a pull line to be installed. Blowing a pull line directly or blowing a lightweight line through the conduit using compressed air accomplishes this. This line is then used to pull a pull line or a winch line into the conduit to pull the cable.

A winch mechanism with a take-up reel is used to pull the pull line with the cable attached. The winch should have a tension meter to monitor the amount of tension being placed on the cable during the pull. This monitor will reduce the risk of damaging a sensitive fiber optic cable during the pull. Check with the cable manufacturer to determine the amount of tension a cable can safely withstand.

The use of cable lubricants is strongly recommended. Cable lubricants reduce the amount of friction during a pull and therefore allow longer cable pulls and reduce the risk of damage to a cable during the pull.

When the cable is attached to the pull line, it is recommended that a swivel be used between the two. This swivel will allow the cable and pull line to move independently in the conduit during the pull and prevent unnecessary twisting of the cable or pull line.

On very long pulls the use of mid-assists is common. Mid-assist equipment can be as simple as a person pulling on the cable midway or it can be a capstan type device that provides a controlled amount of pulling tension to the cable to reduce the tension on the cable and increase the possible length of the pull.

If the conduit is in a manhole, protective devices are needed to guide the cable into the manhole and then into the conduit. These guides protect the cable from scraping on metal or concrete surfaces that could damage the cable sheath.

Cable Blowing or Jetting

In recent years the practice of pulling cable has frequently been replaced with a newer method that uses compressed air to blow the cable into the conduit. Cable blowing requires specialized equipment produced by a number of manufacturers that utilize high volume air compressors. There are two categories of air-assisted cable placement: Low Volume/High Pressure, and High Volume/Low Pressure.
In the first case a dart seal is attached to the end of the cable and compressed air is introduced into the duct building pressure behind the seal, thus forcing the dart forward and creating a tensile pull on the end of the cable. At the same time, the cable is pushed into the conduit through a manifold seal using a tractor pusher. The cable then experiences simultaneous push and pull forces. In the second case, the cable is tractor fed into the conduit, again through a manifold seal, but this time has no dart seal. Instead, cable progress is based on the viscous drag of high volume air alone. In these methods of cable installation, much longer lengths of cable can be placed than traditional cable pulling methods, and the tension applied to the cable is significantly reduced.

When blowing cables into conduit, the use of corrugated conduit is not recommended. Corrugated conduit causes turbulence of the air that disrupts the flow of air in the conduit and thus reduces the distance a cable can be blown.

The conduit should also be capable of withstanding the pressure of the air being introduced. Generally the maximum pressure used is in the range of 125 psi.

Caution should be exercised when using compressed air to pressurize the conduit as a loose joint can lead to injury due to the conduit/joint exploding.

Cable Installed by the Conduit Manufacturer (Cable-in-Conduit)

Some producers of conduit have the capability of installing cable while the conduit is being extruded. Each conduit producer has specific size and length limits, and it is necessary to discuss with the producer the type of cable you desire to be installed: its size, type of material and lengths.

Most producers can lubricate the conduit during this process to allow easy movement of the cable in the conduit for future removal and replacement.

Cable can be tested prior to and following installation to guarantee the integrity of the cable. Check with the conduit producer for specific information on testing the cable.

Friction in Conduit Systems

Friction is a critical limiting factor in determining the type and length of cable installation. Although very little information on cable installation is provided in this guide, this section has been made available as a background reference on frictional properties.

Definitions

Friction: the nature of interaction occurring between two surfaces. The basis of friction has its roots in the mechanical and physical-chemical makeup of the interface created by bringing together two surfaces.

Coefficient of friction, COF: the ratio of the force required to move a body relative to the normal, or clamping force, acting to keep the bodies together.

Static COF: the ratio of forces required to bring about the onset of motion between two bodies at rest with each other.

Kinetic COF: the ratio of forces acting on a body already in motion. It is essentially a measure of the effort required to keep the body in motion.

Friction Reduction

Friction reduction can be promoted by reducing mechanical interactions, grounding electrostatic charges, reducing polar interactions, selecting dissimilar polymers, and employing methods and mechanisms which act to dissipate heat. Although many times little can be done to control the composition of cable jacket materials, choices can be made to select friction-reducing conduit designs and lubricating mechanisms.

The use of lubricants is strongly recommended during the placement of the conduit or cable, or may be included in the manufacturing process of the conduit. Typical lubrication methods would include:

Water-soluble lubricants are available in many different forms including low viscosity free-flowing petuitous liquids, creamy consistencies, and stiff gels. Low viscosity liquids are best suited for placement of long lengths of lightweight cables, such as fiber cables. Heavier, cream-like consistencies are useful on lightweight power conductors. Stiff gels are used in vertical applications in buildings, or where high sidewall loads are expected in placement of heavy power cables or innerducts.

Polymeric water-soluble lubricants are commonly used in the field to lubricate the placement of cable, or of the conduits themselves. In this case the lubricant is applied either ahead of, or in conjunction with, the advancing cable. Water-soluble polymer chemistries include a number of different enhancements including surface wetting and cling, modification via fatty acids or their derivatives, or by inclusion of various friction-reducing oils, including silicones.

Conduits may be **pre-lubricated** during the manufacturing process by incorporation of lubricants directly onto the conduit inner wall, or via a lubricant-modified coextruded layer. The most common type of lubricant used for this type of application is silicone polymer, although other agents such as mineral oils, fatty acid derivatives and glycols have also found use.

Prelubrication finds particular value with fiber cable push-blow systems. Because the sidewall loads with these techniques are quite low compared with pulling, and the distances so great, the viscous drag contributed by water-soluble lubes can be detrimental. The ultra-light amount of lubricants employed by factory pre-lubrication methods can be a real advantage.

Geometry of the inner surface of the conduit can also play a role in friction reduction. As the normal load increases, the COF is found to decrease, unless the surface is damaged in such a way so as to increase the contact area, or heat is allowed to build up at a rate faster than it can be conducted away. Ribs formed on the inner conduit wall are a common design feature to reduce friction.

Longitudinal ribbing results in a reduction of the contact surface between the cable and the conduit wall from an area to a line of contact. Decreasing the area of contact under the same sidewall load results in a higher localized normal force. Within a limited range of sidewall loads, the COF is found to go down – at least until the loading causes localized damage to the jacket sheath.

Spiral ribbing further reduces the contact area from a line to a series of points. In addition, because the advancing cable is alternately on and off the ribbing, there is an opportunity for cooling and re-lubrication. Constantly changing the direction of the spiral eliminates the tendency to accumulate spiral-induced torque in the cable.

Transverse ribbing, or corrugated profiles, results in similar friction reducing geometries. However, there is a tendency for field-added lubrication to be scraped off the cable by the corrugations. In addition, the high degree of flexibility requires careful placement of the duct to reduce the buildup of friction due to path curvature.

Field Effects of Friction

Burn-through results when the winch line or cable develops so much frictional heat that it melts its way through the conduit wall. There are a number of factors that exacerbate this condition including: sidewall load, pull speed, conduit and pull-line materials of construction.

Aside from lubrication, sidewall loading may not be easily reduced; however, speed of pulling is controllable by the operator. Because PE and other thermoplastics are such good insulators, frictional heat build-up can go unchecked. Slower pull speeds combined with water-based lubricants can help reduce the rate of heat accumulation.

PVC elbows are commonly used for transitions out of the underground plant. Unfortunately, PVC not only has a higher COF than PE conduit (due largely to hydrogen bonding to the fillers), but also tends to soften with the onset of heating at a much faster rate (due to plasticizers). PE conduit on the other hand, has lower inherent COF (about 0.35 vs. >0.40 for PVC), as well as higher heat capacity due to its semi-crystalline nature.

Pull-line construction also plays a significant role in burn-through. Polypropylene ropes or even PE pull-lines exhibit low COF at low sidewall loads, but rapidly cut through both PVC conduit and PE conduit when the load increases. The tendency for these materials to soften, combined with high structural similarity (to PE), limit the pull load range over which they may be used. Polyester and polyaramid pull lines, particularly in tape form, offer greater protection from burn through.

Sidewall loading results any time a cable or pull-line is pulled about a sweep or bend. Dividing the tension in the pull-line by the radius of the bend may approximate the magnitude of the load. Obviously, the smaller the radius is, the greater the magnitude of load.

Speed, as noted above, is a critical variable in the operator's hands that can often spell the difference between success and failure. Speeds, which are too low, can result in a lot of mechanical interaction, whereas an excessively high speed results in heat build-up.

Compatibility, in conjunction with high sidewall loading, can be a problem – not only for higher relative friction, but also is a key determinant in burn-through.

Contamination with inorganic soils roughens the surfaces of both conduit and cable jacket, thus increasing the mechanical interaction between them. In addition, the embedment of small particles increases hydrogen bonding with water that may be in the conduit, further enhancing the interaction of jacket with conduit.

Placement Planning

Curvature in the conduit run is the greatest deterrent to long pulls. Some curvature is unavoidable due to path layout, e.g. elevation changes, direction changes, etc. On the other hand, sloppy installation techniques can introduce more curvature than would otherwise be planned. For example, open trench work without proper tensioning and bedding can lead to installations that severely limit cable placement.

Equations for calculation of accumulated frictional drag have been derived and can be found in Appendix A. These are combinations of straight section and exponential sweeps. If the cable has appreciable weight, the transition to sweep up or sweep down results in significant differences. In addition, for multiple conductor power cables, certain combinations of cable multiples and free volume result in locking configurations.

Push-blow techniques are also greatly affected by friction. As noted above, pre-lubricated ducts, or very light applications of silicone emulsions, produce the best results. Techniques that rely on air predominantly to accelerate the cable work best with lightweight cables. As cable weight increases, systems with greater pushing power and piston seals provide improved performance.

Insert sizing is different for pulling vs. push-blow installations. In pulling cables, the greater the free volume in the conduit, the better, and maximum fill ratios based on cable and duct diameters are around 60 percent. On the other hand, maximum fill ratios in push-blow installations are closer to 85 percent fill. The reason for this is that if the cable is not allowed to deflect laterally, it can assume a greater axial load. The more free volume existing in the conduit during pushing, the easier it is to deflect, and having done so, the greater the curvature, and the greater the accompanying sidewall loads.

Placement planning for fiber cable installation is critical because the cable lengths are so long. Typically, one would locate a point along the route possessing similar accumulated frictional drag in either direction. Part of the cable is then installed to one end of the run, then the cable is figure-eighted to recover the opposite free end. The free end is then installed into the other end of the run. It is not uncommon to place 3,000 to 6,000 feet over any given span, and to gang placement equipment at mid-assist intervals along the path to deliver over 20,000 feet continuously in one direction. Using proper combinations of conduit design, installation method, lubrication and placing equipment, it is possible for crews to install over 40,000 feet of cable per day.

Special Applications

Corrugated Duct

Corrugated conduit has properties that generally make it easier to work with in difficult and confined environments. Primarily, this is a result of the lack of memory with corrugated and greater flexibility vs. smooth wall conduit. The lack of memory also provides a corrugated conduit that, when installed as an innerduct (inside of another larger conduit), does not spiral and therefore has lower friction when cables are pulled through it.

The greater degree of flexibility makes corrugated conduit easier to handle when used in confined spaces and other restricted environments.

Corrugated conduit is not appropriate for use in direct buried applications because of its limited crush resistance and the difficulty of laying it in a straight path. Corrugated conduit is also not appropriate for use when cables are to be installed using air-assisted placement. Corrugated conduit is relatively thin-walled and may not be able to handle the air pressure of air-assisted placement. The corrugations create air turbulence that is counterproductive to the air-assisted placement systems and significantly reduce the distance cables can be blown through it.

Corrugated conduit should not be installed using directional drilling equipment due to limited tensile strength and the fact that the corrugations will create significant friction during the pullback that will likely cause the conduit to separate.

The ASTM standards that cover SIDR and SDR designs do not apply to corrugated duct. Corrugation equipment varies from producer to producer, and inside and outside diameter may vary from each source of supply. All corrugated conduit specifications are per the producer only. Generally a minimum ID is specified and a maximum OD.

Corrugation design (or profile) greatly affects the properties of the conduit such as crush resistance and tensile strength. Tooling used to produce corrugated conduit does not allow the producer to change the profile or dimensions without costly retooling.

Check with the source of supply for detailed dimensional and performance specifications.

Bridge Structures

Bridge structures can range from a simple conduit placed in the bridge structure when the bridge is built to a major retrofit of an existing bridge that does not contain a conduit or structure in place to secure a single conduit or conduits. Bridge structures, new or old, require specially designed support systems to ensure structural integrity and meet all federal, state and local requirements.

When installing conduit on bridges, it is important to incorporate into the design the expansion and contraction of the bridge. Expansion joints must be installed in the conduit to prevent the conduit from either separating or bending and kinking due to bridge movement. As an alternative to expansion joints, use of a serpentine path have been proven effective in reducing expansion/contraction issues.

Underwater

The term underwater is also referred to as marine, or submarine, applications. The three basic methods of placing a structure conduit are laying the conduit on the bottom, plowing and jetting the conduit into the sub-aqueous terrain, or drilling under the waterway. Each method has it's own unique requirements based on the type of waterway, length, environmental issues, and federal, state and local requirements. There may be instances when all three types of application will be required on the same installation.

Conduit placed on the bottom of waterways should be black to prevent UV damage. For a complete discussion of underwater installations, see the chapter on marine installations in this Handbook.

Premise (Flame Retardant)

In addition to using conduit for installing fiber optic/communication cables in the underground, there are a few other very specialized applications for conduit type products.

With the growing market for data communications systems within buildings, there has been a concurrent growth in the use of fiber optic/communication cables in buildings as well. These installations typically place fiber optic/communication cables in the same cable trays and vertical risers as other communications cables and electrical cables.

Designers and installers have been concerned about identifying and protecting these fiber optic/communication cables. Manufacturers have responded with the development of several types of conduit for building use, or as it is known in the industry, premise wiring.

Premise wiring generally uses plenum air spaces, vertical riser shafts and general-purpose areas to run cables throughout buildings. The types of conduit developed were specifically for these environments. Because fiber optic/communication premise wiring falls into areas generally thought of as electrical, the National Electric Code and Underwriters Laboratories have addressed the characteristics needed by conduits to be safely used in building wiring.

Initial development produced the Plenum Raceway, a specialized conduit that meets stringent Underwriters Laboratories (UL 2024) requirements for minimum flame spread and smoke generation. Plenum Raceway is a corrugated conduit made from plastic materials that do not support flame and produces almost no smoke. At this time PVDF is the material of choice for Plenum Raceway. Products for plenum air spaces are required to carry a Listing Mark to verify that the product has been tested and meets the requirements for installation in the plenum environment.

A riser raceway was developed for premise wiring applications in riser shafts. Riser Raceway meets the Underwriters Laboratories (UL 2024) requirements for vertical flame spread. Riser Raceway is also a corrugated conduit, which is currently produced from either PVC or Nylon materials. Products for riser locations are required to carry a Listing Mark to verify that the product has been tested and meets the requirements for installation in the riser environment. Plenum Raceways are permitted to be placed in a riser application.

A general-purpose raceway was developed for premise wiring applications in general purpose applications. General Purpose Raceway meets the Underwriters Laboratories (UL 2024) requirements for flame spread. General Purpose Raceway is typically a corrugated conduit, which is currently produced from either PVC or Nylon materials. Products for general-purpose locations are required to carry a Listing Mark to verify that the product has been tested and meets the requirements for installation in the riser environment. Plenum and Riser Raceways are permitted to be placed in a general-purpose application.

The uses of Plenum or Riser Raceways do not eliminate the use of a Plenum or Riser rated cable.

As the use of fiber optic/communication cables in premise wiring increases there will likely be other specific needs that may generate other types of conduit for use in building wiring systems.

Electrical/Building Code (Conduit Entry Issues)

Electrical/Building Code regulations vary greatly regarding the placement of conduit into a building. Codes require the use of conduit constructed of a material that is listed for use in specific building areas, and these codes prohibit the use of PE conduit beyond a specific distance after entry through an exterior wall. The greatest variation in local code is the location of the transition from PE conduit to a conduit that meets the code requirement (distance from the exterior of the wall). Check your local codes for local amendments.

Armored (Rodent and Mechanical Protection)

When placing cables in the underground there is occasionally concern about the ability of the conduit to protect the cable(s) inside. Concerns usually are for crush resistance and resistance to cutting and gnawing by animals.

This need led to the development of armored conduit. Armored Conduit is standard PE conduit that has been wrapped with a second layer of metal and jacketed to provide a barrier to the problem of gnawing by animals. Armored Conduit also protects against cuts and abrasions from accidental strikes by persons digging nearby.

Multi-Cell Conduit

Multi-cell conduits are designed to meet special needs and unique job situations. There are a number of designs available to meet most of these special needs. Multi-cell conduit can be a product that is installed as an innerduct inside of existing conduits designed to maximize the available space in a vacant or occupied conduit, or it can be a fully assembled conduit with internal conduits that when installed provides a multi-channel conduit without the need to install any other innerducts. Some multi-cell designs can be direct buried like PE conduit using standard installation methods (plowing or open trenching).

Summary

The information contained in this chapter should help the reader to understand the fundamental properties of polyethylene (PE) conduit. A basic understanding of these properties will aid the engineer or designer in the use of PE conduit and serve to maximize the utility of the service into which it is ultimately installed.

While every effort has been made to present the fundamental properties as thoroughly as possible, it is obvious that this discussion is not all-inclusive. For further information concerning PE conduit, the reader is referred to a variety of sources including the pipe manufacturers' literature, additional publications of the Plastics Pipe Institute and the references at the end of this chapter.

References

ASTM International, D 1238, Standard Test Method for Flow Rates of Thermoplastics by Extrusion Plastometer.

ASTM International, D 1693, Standard Test Method for Environmental Stress-Cracking of Ethylene Plastics.

ASTM International, D 2444, Standard Test Method for Determination of the Impact Resistance of Thermoplastic Pipe and Fittings by Means of a Tup (Falling Weight).

ASTM International, D 2683, Standard Specification for Socket-Type Polyethylene Fittings for Outside Diameter-Controlled Polyethylene Pipe and Tubing.

ASTM International, D 3350, Standard Specification for Polyethylene Plastics Pipe and Fittings Materials.

ASTM International, D 3485, Standard Specification for Smooth-Wall Coilable Polyethylene (PE) Conduit (Duct) for Preassembled Wire and Cable.

ASTM International, F 1056, Standard Specification for Socket Fusion Tools for Use in Socket Fusion Joining Polyethylene Pipe or Tubing and Fittings.

ASTM International, F 1290, Standard Practice for Electrofusion Joining Polyolefin Pipe and Fittings.

ASTM International, F 1473, Standard Test Method for Notch Tensile Test to Measure the Resistance to Slow Crack Growth of Polyethylene Pipes and Resins.

ASTM International, F 2160, Standard Specification for Solid Wall High Density Polyethylene (PE) Conduit Based on Controlled Outside Diameter (OD).

ASTM International, F 2176, Standard Specification for Mechanical Couplings Used on Polyethylene Conduit, Duct and Innerduct.

ASTM International, F 2620, Standard Practice for Heat Fusion Joining of Polyethylene Pipe and Fittings.

AEIC Task Group 38.

Guide for Installation of Extruded Dielectric Insulated Power Cable Systems Rated 69KV -138KV.

IEEE Guide Distribution Cable Installation Methods in Duct Systems.

National Electrical Code (NEC), Chapter 9.

National Electrical Manufacturers Association, NEMA TC 7, Smooth-Wall Coilable Polyethylene Electrical Plastic Conduit.

Plastics Pipe Institute, Inc., *Handbook of Polyethylene Pipe.*

Plastics Pipe Institute, Inc., TR19, Thermoplastic Piping for the Transport of Chemicals.

Underground Extruded Power Cable Pulling Guide.

Underwriters Laboratories, Inc. UL 651A.

Underwriters Laboratories, Inc., UL 651B, Continuous Length PE Conduit.

Underwriters Laboratories, Inc., UL 2024, Optical Fiber Cable Raceway.

Appendix A

Calculation of Frictional Forces

Reference – *Maximum Safe Pulling Lengths for Solid Dielectric Insulated Cables – vol. 2: Cable User's Guide,* EPRI EL=3333-CCM, Volume 2, Research Project 1519-1, Electric Power Research Institute.

Calculations of Pulling Tensions

The following formulae can be employed to determine pulling tensions for a cable installation. Each equation applies to a specific conduit configuration. In order to use the formulae, the cable pull should be subdivided into specific sections. The configuration of each section should be identifiable with one of the graphical depictions accompanying the equations.

The mathematical expression associated with each of the accompanying sketches will yield the cumulative tension (T_2) on the leading end of the cable(s) as it exits from a specified section when T_1 is the tension in the cable entering that section.

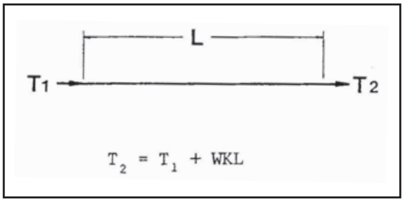
The maximum tension obtained when pulling in one direction often differs from that obtained when pulling in the opposite direction due to the location of the bends and the slope of the pull. Therefore, the required tension should be calculated for both directions.

A listing of the symbols employed and their definitions are as follows:

DEFINITIONS OF SYMBOLS

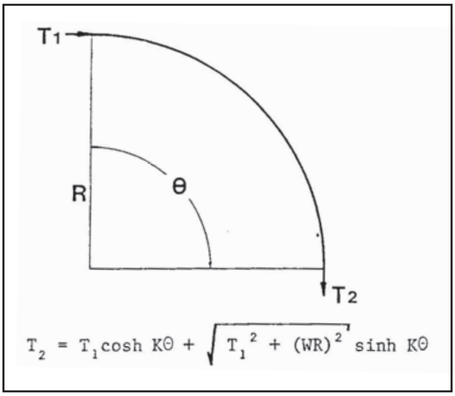
Symbols	Definition	Units
T_1	Section incoming cable tension	Pounds
T_2	Section outgoing cable tension	Pounds
R	Inside radius of conduit bend	Feet
W	Total weight of cables in conduit	Pounds/foot
Θ	Angle subtended by bend for curved sections or angle of slope measured from horizontal for inclined planes	Radians
Θ_a	Offset angle from vertical axis	Radians
Θ_b	Total angle from vertical axis	Radians
K	Effective coefficient of friction	—
L	Actual length of cable in section	Feet
D’	Depth of dip from horizontal axis	Feet
2s	Horizontal length of dip section	Feet

FIGURE 1 PULLING TENSION FORMULAE FOR CABLE IN CONDUIT



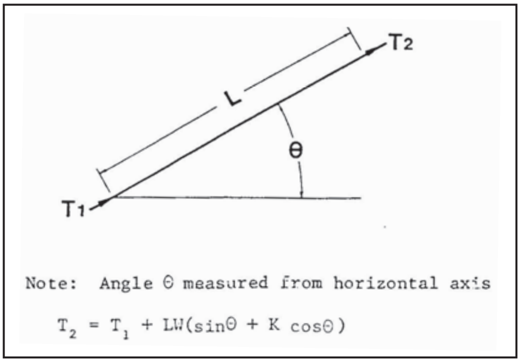
$$T_2 = T_1 + WKL$$

Figure 1.1 Straight Pull



$$T_2 = T_1 \cosh K\Theta + \sqrt{T_1^{\,2} + (WR)^2}\,\sinh K\Theta$$

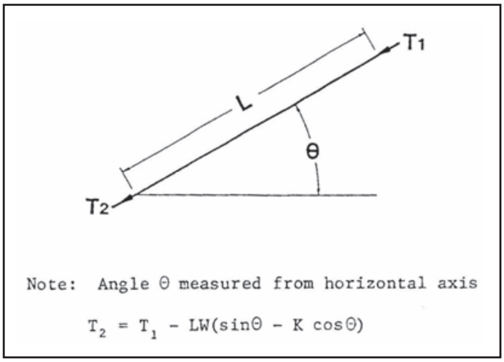
Figure 1.2 Horizontal Bend Pull



Note: Angle Θ measured from horizontal axis

$$T_2 = T_1 + LW(\sin\Theta + K\cos\Theta)$$

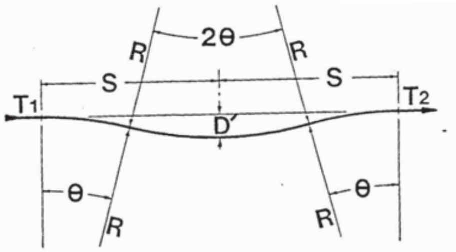
Figure 1.3 Slope - Upward Pull



Note: Angle Θ measured from horizontal axis

$$T_2 = T_1 - LW(\sin\Theta - K\cos\Theta)$$

Figure 1.4 Slope - Downward Pull



$$\Theta = \frac{2D'}{S}$$

$$R = \frac{S^2}{4D'}$$

$$T = T_1\varepsilon^{K\Theta} + RW(\varepsilon^{K\Theta} - 1)$$

(Use coefficient of friction corresponding to SWBP < 150 lbs/ft in the equation above.)

Where D' is small compared to S (i.e. $\tan \Theta/2 = \sin \Theta/2 = D'/S$)

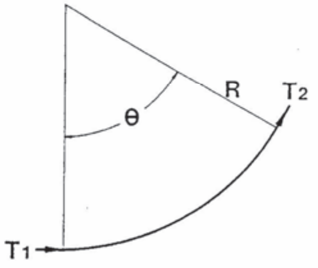
For $T > RW$

$$T_2 = T_1\varepsilon^{4K\Theta} + RW[\varepsilon^{4K\Theta} - 2\varepsilon^{3K\Theta} + 2\varepsilon^{K\Theta} - 1]$$

For $T \leq RW$

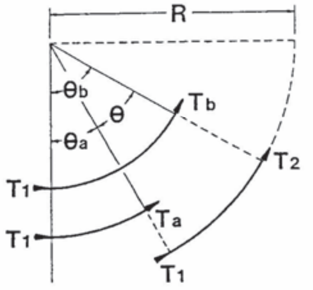
$$T_2 = T_1 + WK2S$$

Figure 1.5 Vertical Dip Pull (Small Angle)



$$T_2 = T_1\varepsilon^{K\Theta} - \frac{WR}{1+K^2}\left[2K \sin\Theta - (1-K^2)(\varepsilon^{k\Theta} - \cos\Theta)\right]$$

Figure 1.6a Concave Bend - Upward Pull, for Angle Θ Measured from Vertical Axis



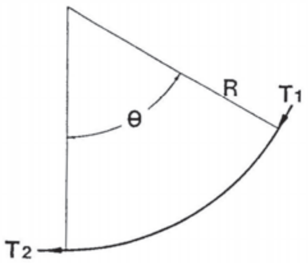
$$\Theta = \Theta_b - \Theta_a$$

$$T_a = T_1\varepsilon^{K\Theta_a} - \frac{WR}{1+K^2}\,[2K\sin\Theta_a - (1-K^2)(\varepsilon^{K\Theta_a} - \cos\Theta_a)]$$

$$T_b = T_1\varepsilon^{K\Theta_b} - \frac{WR}{1+K^2}\,[2K\sin\Theta_b - (1-K^2)(\varepsilon^{K\Theta_b} - \cos\Theta_b)]$$

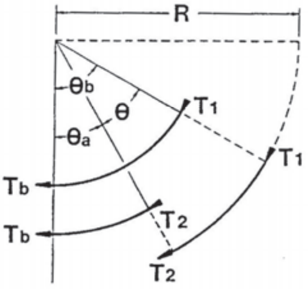
$$T_2 = T_b - T_a + T_1$$

Figure 1.6b Concave Bend - Upward Pull, for Angle Θ Offset from Vertical Axis by Angle Θa (Derived from Figure 1.6a, above)



$$T_2 = T_1\varepsilon^{K\Theta} - \frac{WR}{1+K^2}\,[2K\varepsilon^{K\Theta}\sin\Theta + (1-K^2)(1-\varepsilon^{K\Theta}\cos\Theta).$$

Figure 1.7a Concave Bend - Downward Pull, for Angle Θ Measured from Vertical Axis

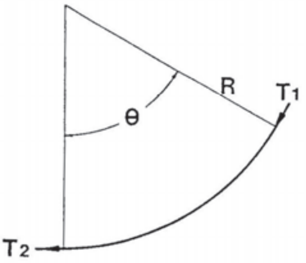


$$\Theta = \Theta_b - \Theta_a$$

$$T_b = T_1 \varepsilon^{K\Theta_b} - \frac{WR}{1+K^2}\left[2K\varepsilon^{K\Theta_b} \sin\Theta_b + (1-K^2)(1-\varepsilon^{K\Theta_b} \cos\Theta_b)\right.$$

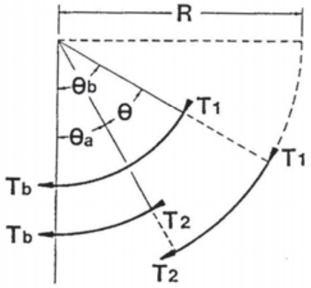
$$T_2 = \left(\frac{T_b + \frac{WR}{1+K^2}\left[2K\varepsilon^{K\Theta_a} \sin\Theta_a + (1-K^2)(1-\varepsilon^{K\Theta_a} \cos\Theta_a)\right]}{\varepsilon^{K\Theta_a}}\right)$$

Figure 1.7b Concave Bend - Downward Pull, for Angle Θ Offset from Vertical Axis by Angle Θa (Derived from Figure 1.7a, above)



$$T_2 = T_1 \varepsilon^{K\Theta} - \frac{WR}{1+K^2}\left[2K\varepsilon^{K\Theta} \sin\Theta + (1-K^2)(1-\varepsilon^{K\Theta} \cos\Theta)\right]$$

Figure 1.8a Concave Bend - Downward Pull, for angle Θ Measured from Vertical Axis

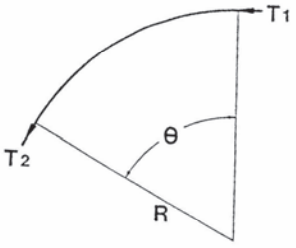


$$\Theta = \Theta_b - \Theta_a$$

$$T_b = T_1 \varepsilon^{K\Theta_b} - \frac{WR}{1+K^2}\left[2K\varepsilon^{K\Theta_b}\sin\Theta_b + (1-K^2)(1-\varepsilon^{K\Theta_b}\cos\Theta_b)\right]$$

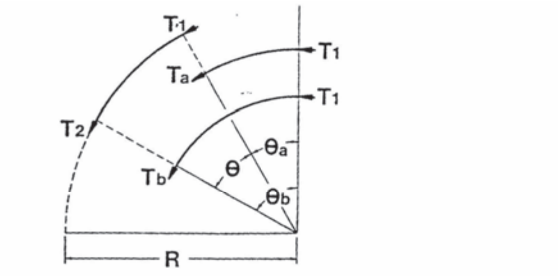
$$T_2 = \left(\frac{T_b + \frac{WR}{1+K^2}\left[2K\varepsilon^{K\Theta_a}\sin\Theta_a + (1-K^2)(1-\varepsilon^{K\Theta_a}\cos\Theta_a)\right]}{\varepsilon^{K\Theta_a}}\right)$$

Figure 1.8b Concave Bend - Downward Pull, for angle Θ Offset from Vertical Axis by Angle Θ_a (Derived from Figure 1.8a, above)



$$T_2 = T_1 \varepsilon^{K\Theta} + \frac{WR}{1+K^2}\left[2K\sin\Theta - (1-K^2)(\varepsilon^{K\Theta} - \cos\Theta)\right]$$

Figure 1.9a Convex Bend - Downward Pull, for Angle Θ Measured from Vertical Axis



$$\Theta = \Theta_b - \Theta_a$$

$$T_a = T_1 \varepsilon^{K\Theta_a} + \frac{WR}{1+K^2}\,[2K \sin\Theta_a - (1-K^2)(\varepsilon^{K\Theta_a} - \cos\Theta_a)]$$

$$T_b = T_1 \varepsilon^{K\Theta_b} + \frac{WR}{1+K^2}\,[2K \sin\Theta_b - (1-K^2)(\varepsilon^{K\Theta_b} - \cos\Theta_b)]$$

$$T_2 = T_b - T_a + T_1$$

Figure 1.9b Convex Bend - Downward Pull, for Angle Θ Offset from Vertical Axis by Angle Θ_a (Derived from Figure 1.8a, above)

Chapter 15

General Guidelines for Repairing Buried PE Potable Water Pressure Pipes

Introduction

Traditional piping systems have gasket-sealed bell and spigot joints every 20 feet, which can be a potential maintenance and repair point at each connection. Metallic pipes are subject to corrosion which can require constant maintenance over the life of the pipes. A heat fused high density polyethylene (PE) pipeline is not only corrosion and chemical resistant but the leak free joints at 40 to 50 foot intervals are as strong as the pipe itself which provides a maintenance free system except for infrequent unforeseen third party damage. If PE is damaged by a third party, repair methods may be required to bring the piping system back into service as soon as possible. This document will provide general guidelines for repairing PE. They should be useful in establishing procedures and/or specifications for various repair methods to PE piping systems.

For above ground repairs, when the pipe can be moved, the damage can be cut out and replacement pipe can be butt fused or electrofused into the system.

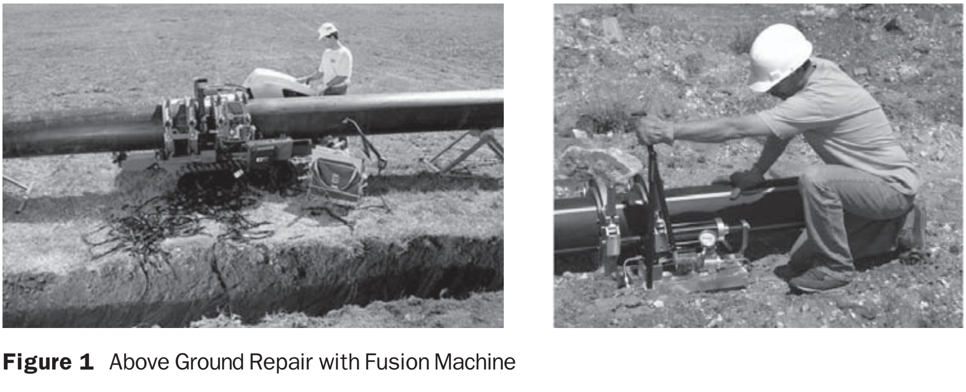


Figure 1 Above Ground Repair with Fusion Machine

However constrained installations, such as buried pipes, may not allow such movement. Permanent repairs of constrained pipes may require techniques and fittings that do not require longitudinal movement such as spool or flanged assemblies, mechanical or electrofusion couplings, etc.

Caution: Be sure to follow OSHA safety guidelines when uncovering and repairing buried pipelines.

Natural Gas Polyethylene Piping Systems

In this application, only those persons qualified pursuant to a gas company's Operator Qualification program shall make repairs.

Plastic piping systems may be damaged during installation or through third party damage by others once in service. The repair or replacement must be made in accordance with requirements of DOT 49 CFR 192.311. All imperfections or damaged sites that would impair the serviceability of the plastic pipe (significant scratches, gouges or flaws) must be removed or repaired.

Mechanical or electrofusion couplings appropriate for plastic gas piping systems are frequently used for economical and convenient replacement of damaged plastic pipe segments. The gas flow is stopped; the damaged section cut out and replaced with a mechanical repair fitting or a new segment using either two couplings or a fusion joint and a coupling. Joints fabricated from mechanical fittings used in replacement must be designed to restrain the pipe against pullout forces and, if metallic fittings are utilized, be protected against corrosion.

Full encirclement type band clamps have been successfully used with plastic pipe to make repairs. ASTM F 1025 "Standard Guide for Selection and Use of Full Encirclement Type band clamps for Reinforcement or Repairs of Punctures or Holes in Polyethylene Gas Pressure Pipe" provides guidance regarding use of this fitting for repair and reinforcement of polyethylene pipe. The important consideration is that the clamp permanently exerts limited unit-bearing pressure on the plastic pipe since it is not possible to install metal stiffeners inside the plastic pipe in this application. A soft gasket formulation with waffle-type inner surface would generally be preferred for this application. In all cases, the method used should follow procedures that have been established and qualified by test.

Full encirclement type band clamps in compliance with the guidelines of ASTM F 1025 are acceptable for temporary repairs of polyethylene pipe.

Before placing in service, test segments of plastic pipe that are installed to replace damaged sections of mains and services according to the operator's procedures. Leak test all tie-in joints and the squeeze-off areas at system pressure after the repair is complete. If recommended by the manufacturer, any anti-static fluid should be rinsed from the piping using water. If, in a dig-in situation or a plastic service other than a low pressure service, it appears that the pipe or casing was pulled or moved, and that damage could have occurred at locations along the service other than those inspected or repaired, leak-test the entire service at 100 psig for a minimum of 5 minutes per the operator's procedures. Leak- test low –pressure services at 10 psig for a minimum of 5 minutes per the operator's procedures. If additional damage is found, replace the service.

Municipal and Other Polyethylene Piping Systems

Temporary Field Repairs with Full Circle Band Clamp

Many system operators will have full circle band clamps in their specifications as a repair option. In general these types of repair clamps have proven to be a great method of temporary repair, especially in emergency situations.

Some general design considerations for the successful use of full circle band clamps are as follows:

- Full Circle Band Clamps are recommended for repairs only where the pipe is able to maintain its structural integrity. Consider repairs only to a clean-cut round hole or deep scratches or gouges of maximum dimension, less than the nominal diameter of the pipe divided by three. Do not use band clamps when the pipe has cracks, jagged punctures, long tears, or deep scratches or gouges which could propagate outside the clamp under anticipated field loads.
- Do not exceed the manufacturer's recommended maximum operating parameters such as temperature and pressure.
- The installer should always follow the clamp manufacturer's recommend installation guidelines. Whenever possible, use a product that has been specifically designed for use with polyethylene pipe.
- The manufacturer should always be consulted on the use of their product on polyethylene pipe if the clamp was not manufactured specifically for use with polyethylene pipe.
- Pipe movement due to thermal expansion, thermal contraction and creep, as well as, surge events must be considered when repairing polyethylene pipe with a full circle band clamp.
- Generally, full circle band clamps are intended for use in underground applications. If your application is of a different nature, contact the manufacturer of the band clamp.

If the band clamp is to be used as a permanent repair, contact the fitting manufacturer for the suitability of use as a permanent repair.

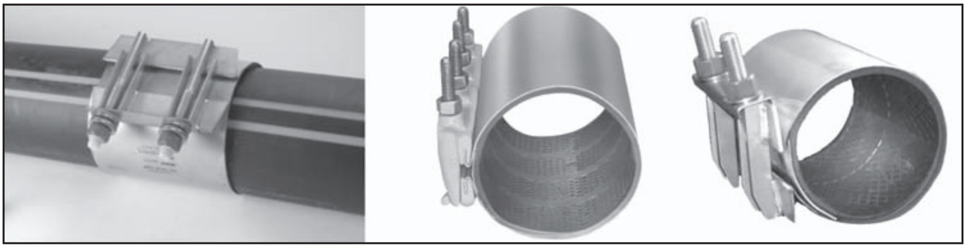


Figure 2 Full Circle Band Clamps

Permanent Field Repairs

Small Field Repairs

Saddle Fusion Repair

If the size of the puncture damage is very small (1inch or smaller puncture on one pipe wall), a capped off Tapping Tee or High Volume Tapping Tee or patch can be saddle fused to the main over the damaged area, provided the water flow can be stopped and the repair area kept dry during the repair process. Before adding the patch or fitting, drill a small hole at each end of the damage to prevent the crack from propagating further.

Then, butt fuse a cap on the service outlet of the Tapping Tee selected for the repair. Turn off the water and prepare the surface area around the damage for the saddle fusion process (see PPI Generic Saddle Fusion Procedure TR-41). Saddle fuse the fitting over the damaged area using the Generic Procedure and allow the joint to cool. Wait 30 minutes, turn the water back on.

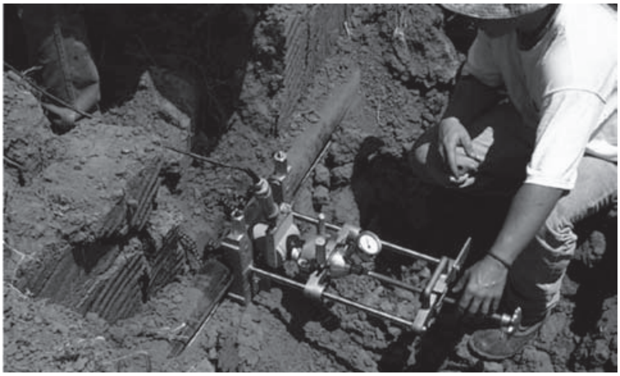


Figure 3 Saddle Fusion Repair

Electrofusion Patch Repair

An electrofusion patch can also be used to repair small puncture damage in the pipe (3 inches or smaller puncture in one wall of the pipe) as long as the water flow can be stopped and the repair area kept dry during the repair process. Use the manufacturer's recommended electrofusion procedure and equipment for saddle fusion.

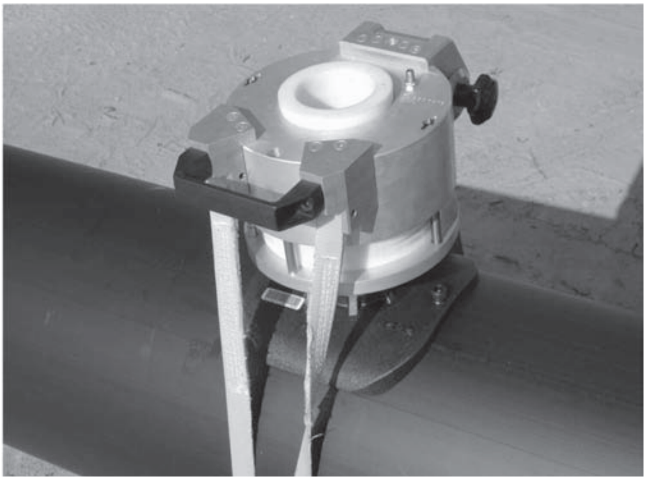


Figure 4 Electrofusion Patch Repair

Mechanical Fitting Repair

In some cases where the damage is slight but has severed the pipe, the line can be shut off and a small section of the pipe cut out to install a mechanical coupling in the damaged area (see Figures 5, 6, & 7). Contact the coupling manufacturer for the size of damage that can be repaired. A certain amount of the piping system will need to be exposed to allow the pipe to be bent for the installation of the coupling.

Some couplings are self restrained and others are not. Some require a stainless steel stiffener inside the PE pipe and some do not.

For damage to small diameter water service lines (2 inches and smaller), mechanical compression fittings appropriate for PE pipe or tubing are commonly used for the repair. Water flow is stopped, generally using a pinch off tool, and the damaged area evaluated. If it is a small cut or hole, the pipe can be cut in the damaged area and a compression fitting installed between the pipe ends. As required for larger pipe sizes, this method may require a certain amount of the piping system be exposed to allow the pipe to be bent for the installation of the coupling. If the damage is more extensive, a section of pipe is cut out and replaced with a replacement piece of pipe and two compression fittings.

It is recommended that all couplings used with PE should have a stiffener installed to increase the sealing capability of the coupling by minimizing the effects of creep and dimensional changes due to temperature variations (see “Stiffener Installation Guidelines” section in this chapter). It is also recommended that, if the coupling does not provide its own restraint, then external restraints should be utilized on each side of the fitting to prevent pullout due to the thermal expansion or the Poisson effect of the pipe (see “Restraint Methods” section in this chapter). Mechanical fittings have different design advantages and accommodate different sizes. Contact the mechanical fitting manufacturer for more information. Several manufacturers make mechanical fittings specifically for use with PE, including Mueller, Elster Perfection, Victaulic, Dresser, JCM, Ford, Romac, Cascade Water Works and Smith-Blair.

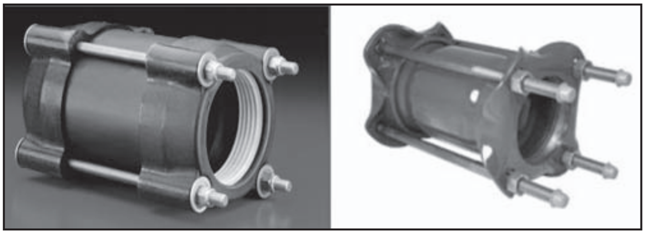


Figure 5 Mechanical Couplings

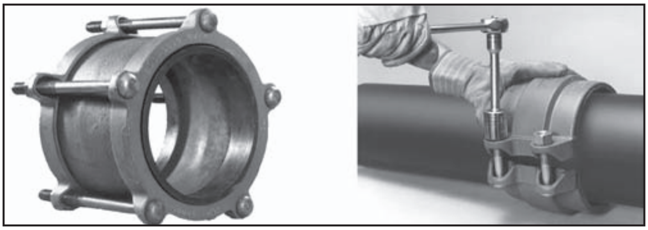


Figure 6 Mechanical Couplings

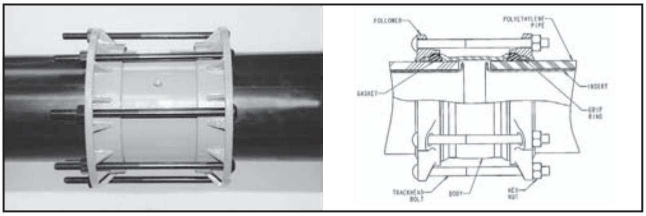


Figure 7 Mechanical Couplings

Large Field Repairs

Mechanical Fitting Repair

If the damage to the pipeline cannot be repaired with a single mechanical coupling as described above, two mechanical fittings can be used by cutting out the damaged pipe (Figure 8 & 9) and making up an assembly with two mechanical fittings and a properly sized and length of polyethylene pipe in the middle. Again, install per the fitting manufacturer's instructions. (Figure 10) A repair to larger pipes requires joining devices for the size of pipe being repaired. However, the various types of joining devices discussed in this section may not be available for all pipe sizes. Contact the joining device manufacturer or supplier for availability and applicability with polyethylene pipe.

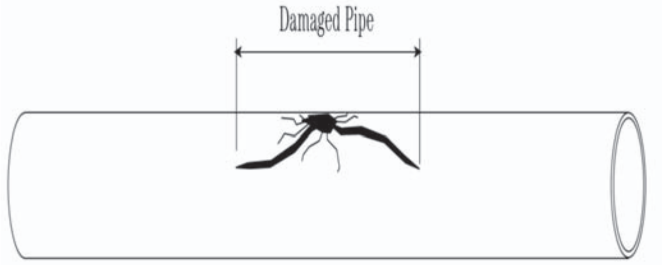


Figure 8 Damaged Pipe

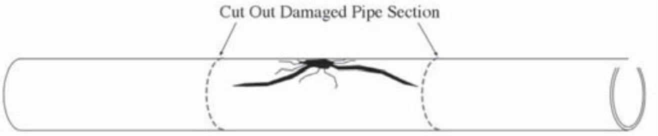


Figure 9 Cut out Damaged Section of Pipe

A saw is needed to cut out the damaged pipe and to cut the replacement section between the cut ends. A wrench is also needed to tighten the bolts. After the damaged section is examined, it can be removed. Damaged PE pipe is usually cut using a dry chain saw. Measure the distance between the cut pipe ends and cut an PE replacement section approximately ½-inch shorter than that length. Install the insert stiffeners in both ends of the existing PE pipes and in both ends of the replacement section.

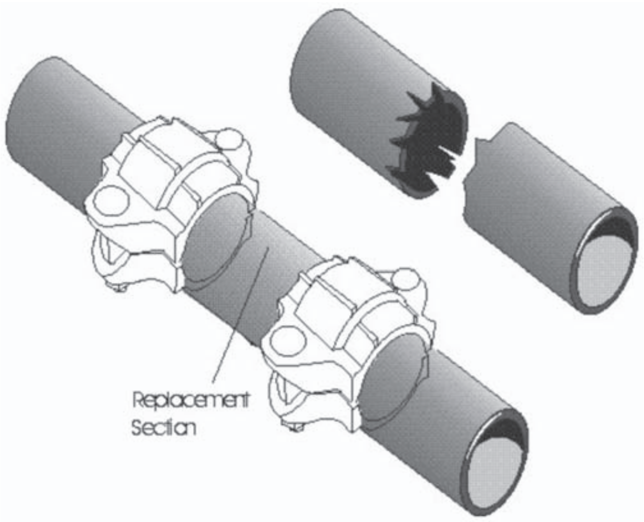


Figure 10 Mechanical Coupling Repair Assembly

Slide the couplings over the replacement section of the pipe and drop the assembly between two cut ends. Then slide the couplings between the replacement section and the cut ends and tighten the bolts using the manufacturer's procedures.

Caution: Make sure to provide restraints or anchors for the PE pipe if the mechanical couplings are not self restrained. Failure to follow this procedure could result in the pipe pulling out of the coupling (see "Mechanical Restraint" section in this chapter).

As noted above, it is recommended that all PE pipe ends used with mechanical couplings have a stiffener installed to increase the sealing capability of the coupling by minimizing the effects of creep and dimensional changes due to temperature variations (see "Stiffener Installation Guidelines" section in this chapter).

Repairs with Solid Sleeves

Repairs can be made using a mechanical joint (MJ) solid sleeve along with insert stiffeners, restraint device, gasket and tee bolts. A saw is needed to cut out the damaged pipe and to cut the replacement section of PE pipe. A wrench is also needed to tighten bolts. The pipe, gasket and solid sleeve must be cleaned before final tightening of the bolts.

The benefit of this repair method is that it can be made in a wet environment with no special equipment. This is basically the same repair method used for PVC and ductile iron pipe with the addition of insert stiffeners used with PE pipe. The parts are MJ sleeve or sleeves, glands, restraint ring, gasket, extra pipe if large area is damaged, gaskets and tee bolts.

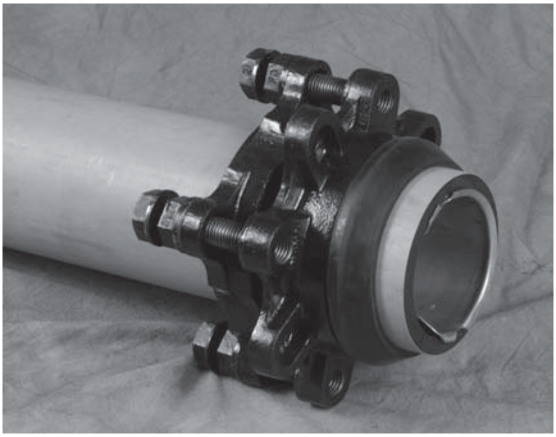
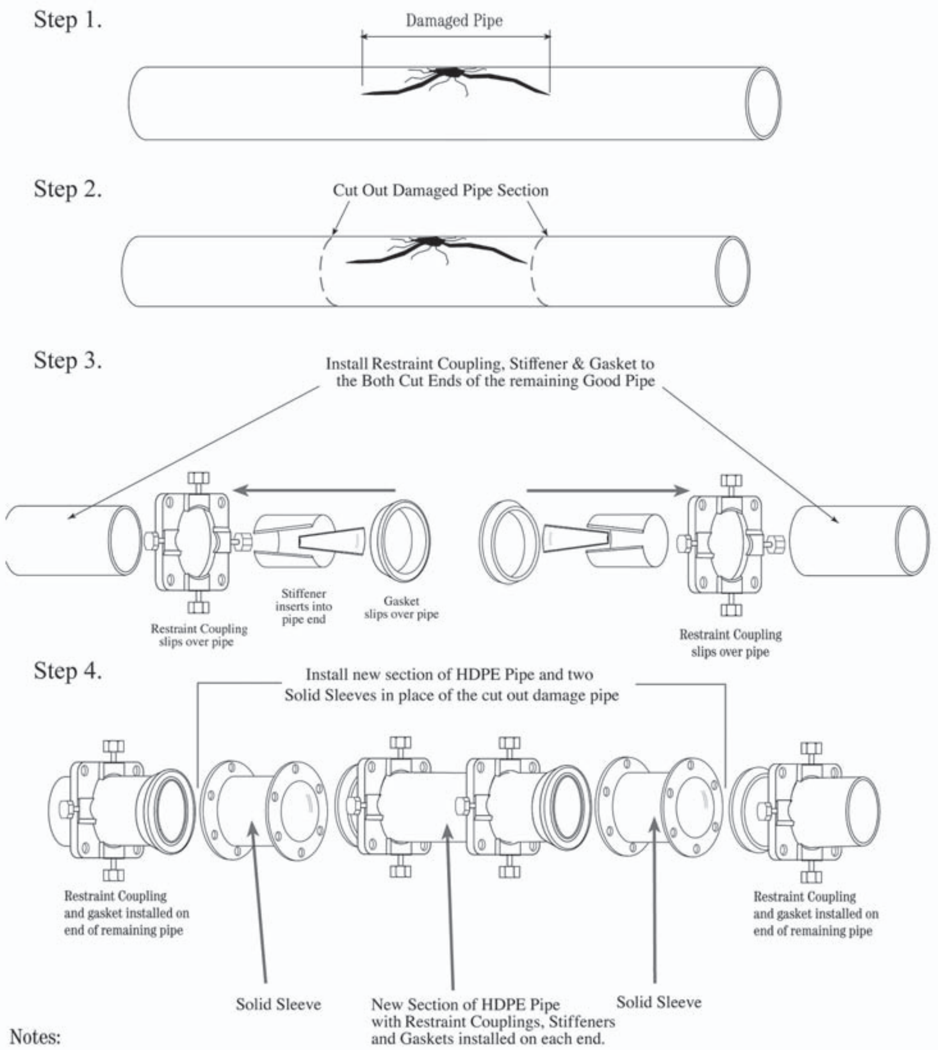


Figure 11 Restraint fitting placed on PE pipe

After cleaning the contact surfaces, and installing a stiffener in existing PE pipe ends and in the ends of the replacement HPDE pipe section, slide the restraint ring and gland over pipe followed by a gasket as shown above. The drawing below shows a typical layout of parts needed to make a repair.

In a repair situation, the MJ sleeve is connected on both ends to PE pipe. The solid sleeve can make up small sections of pipe. If the damaged pipe is longer than the span of a single sleeve, two solid sleeves are used to replace damaged pipe.



Notes:

Notes: 1. This method of repair is acceptable when area is wet or fusion equipment not available.

2. All steps must be followed.

Figure 12 Solid Sleeve Repair Assembly

Flange Adapter Spool Repair

Once pipeline damage has been reported, the size of the pipeline and the DR needs to be established. The correct flange adapter and backup ring size is selected and (4) are required for the repair (see Table 1). The water valve is then shut off and the area excavated and planking installed.

Cut the damaged pipe from the piping system. Make sure that the length removed is long enough for the flange adapter spool assembly to be installed. (See Table 1)

Caution: Butt or Electro-fusion joints cannot be made with water flowing through the pipes. Make sure the water valve shuts-off the water flow 100% and make sure no water is flowing. If a small amount of water is flowing, a towel or pneumatic bladder can be inserted in the valve end to dam up the water long enough to make the butt fusion joint. Be sure to remove this item before making the final connection.

A butt-fusion machine capable of fusing the pipe size is installed in the ditch on planking and clamped to the main pipe. A proper sized flange adapter/back-up ring assembly is installed in the movable jaw. Face the pipe and the flange adapter end to mechanical stops. Remove the pipe chips from the area and align the pipe ends. Using the pipe manufacturer's recommended butt fusion procedures, fuse the pipe to the flange adapter/back-up ring assembly and allow the joint to cool under pressure.

When this joint is cool, remove the fusion machine from the pipe and install the fusion machine's fixed end on the other end of the pipe. Install the proper sized flange adapter/back-up ring assembly in the movable jaw. Face the pipe and the flange adapter end to mechanical stops. Remove the pipe chips from the area and align the pipe ends. Using the pipe manufacturer's recommended butt- fusion procedures, fuse the pipe to the flange adapter/back-up ring assembly and allow the joint to cool under pressure. Also, refer to PPI TR-33.

Once the flange adapters have been fused to the existing pipe ends, measure the inside distance between the flanges. Using the pipe manufacturer's recommended butt fusion procedures, fuse the other two flange adapter/back-up ring assemblies to a piece of pipe with the same OD, DR and specification as the existing pipe to produce an assembly that matches the inside distance between the flanges on the existing pipe. Install the spool piece between the two flanged pipe ends. Bolt the assembly together using the manufacturer's recommended guide for alignment and bolt torque. This will result in a fully restrained joint that does not require thrust blocks or thrust restraints (see Figure 13).

TABLE 1
Minimum Recommended Length of Pipe to Remove for Repair Spool

Pipe Size	Minimum Length of Pipe to be Cut Out for Repair
4” IPS/DIPS	4-5’
6” IPS/DIPS	4-5’
8” IPS/DIPS	5’
10” IPS/DIPS	5’
12” IPS/DIPS	5’
14” IPS/DIPS	5’
16” IPS/DIPS	5’
18” IPS/DIPS	5’
20” IPS/DIPS	5’
22” IPS/DIPS	5’
24” IPS/DIPS	6’

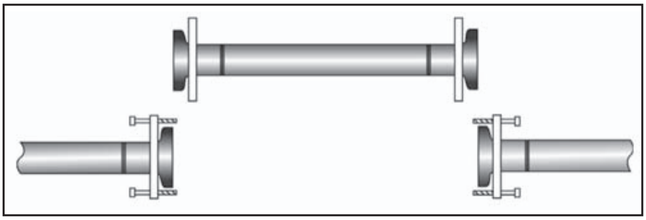


Figure 13 Flange Adapter Repair Spool

Electrofusion Spool Repair

This method is very similar to the Flange Adapter Spool Assembly method, but uses different fusion technology to produce a permanent leak free connection. Instead of butt fusing the pipe ends to flange adaptors, electrofusion couplings are used to connect the replacement spool of pipe to the existing undamaged pipe. Consult the electrofusion manufacturer for the detailed joining procedure to follow in making this joint. Here are some general guidelines for follow.

Resistance wires are imbedded into the inside diameter of the electro-fusion couplings to facilitate the fusion joining of the pipe. Fusion is accomplished by energizing the coupling using a processor attached to the fitting. The processor provides the proper amount of energy required to achieve a proper fusion joint.

When damage has been detected, isolate the damaged area by closing valves or utilizing squeeze off tooling. Excavate the damage and determine the extent of the damage. Confirm the size and DR of the pipe to be repaired. The water valve is then shut off and the area excavated and planking installed.

Caution: Make sure the water valve shuts the water flow off 100% with no water flowing. Butt or Electrofusion joints cannot be made with water flowing through the pipes.

Caution: Pipe diameter and surface condition – Before making electrofusion coupling joints, the user must first determine that the pipe diameter and OD surface condition are suitable for electrofusion joining. Consult the electrofusion coupling manufacturer's instructions for diameter and surface damage limits.

Caution: Joining by qualified persons – Large diameter electrofusion joining is performed only by persons that have personally received training in large diameter electrofusion from the electrofusion coupling manufacturer.

Remove the damaged section of pipe, cutting the ends as square as possible. Cut a spool of the repair pipe to the same length as the removed section of pipe.

On pipe sizes larger than 8″ or if the pipe is out of round, it is recommended that a re-rounding tool be installed beyond the area to be scraped. This will help in the scraping process and in the installation of the electro-fusion coupling.

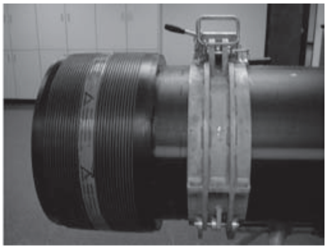


Figure 14 Hydraulic Re-Rounding Clamp Installed

Figure 15 Mechanical Re-Rounding Clamp Installed

Prepare the ends of the spool piece by removing all of the oxidized material from the outside diameter, using a scraper tool. Do not use grinders, emery cloth or other abrasive materials or tools, as they do not completely remove the oxidation.

Prepare each end for the full length of the electrofusion coupling.

Install the couplings completely on each end of the spool piece. Prepare the existing pipe ends in the same manner. Position the spool and move the couplings over the existing pipe ends to be repaired. Provide support for the couplings and the pipe and eliminate any misalignment and stress from the repair area. Using the Electrofusion manufacturers recommended procedures, attach the control box to the fittings and fuse the couplings to both ends of the spool and pipe. This will result in a fully restrained joint that does not require thrust blocks or thrust restraints.

Always follow the manufacturer's installation instructions when installing electrofusion fittings. When making a large diameter pipe repair, refer to the Plastics Pipe Institute Technical Note TN-34.

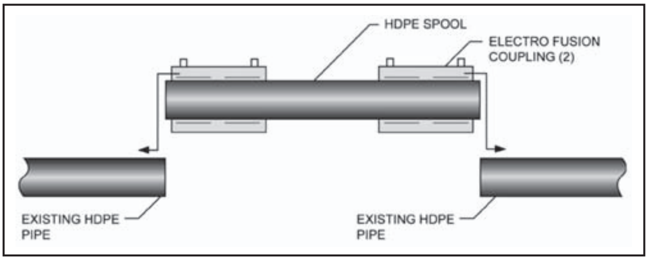


Figure 16 Electrofusion Repair Spool

Stiffener Installation Guidelines

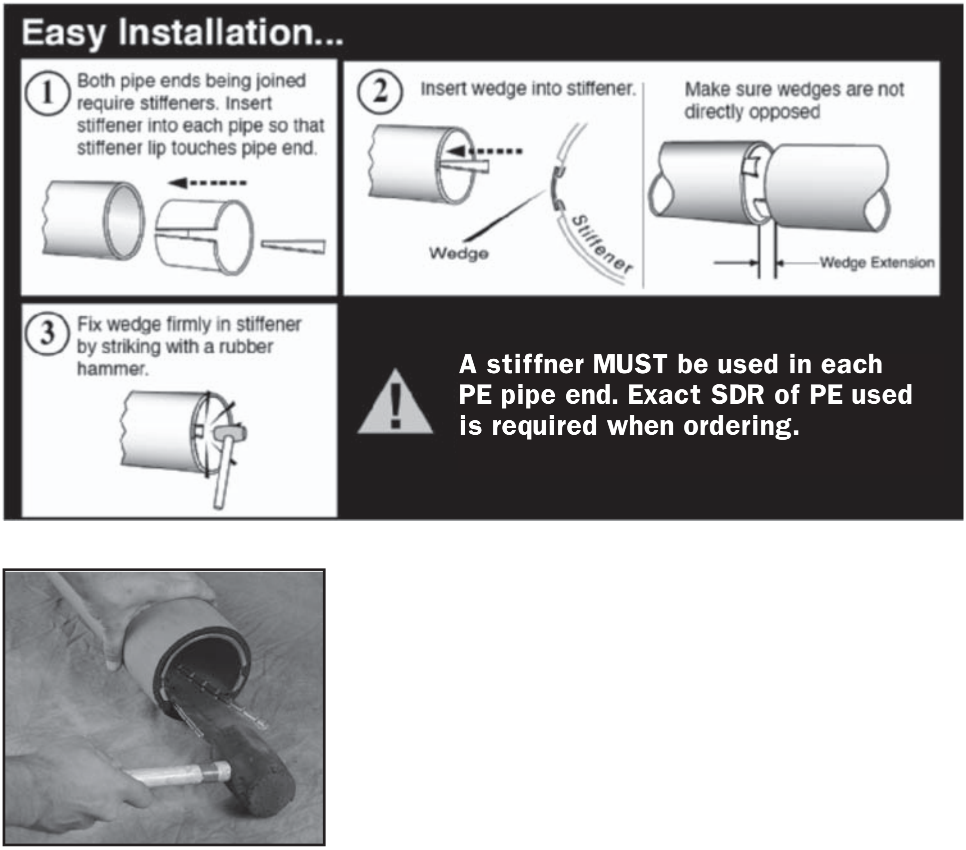
When using a mechanical connection for repair that grips on the OD of the PE pipe, it is recommended that a stiffener be added to the ID of the pipe to insure a good connection between the coupling and the pipe. Check the pipe for toe in, which is an inward curvature of the pipe ends due to residual stress. If it is severe, cut the pipe back to remove it. If possible, have some means to press the stiffener into place. Lubricant will minimize the insertion effort required. A detergent or silicone grease is recommended.

There are two types of stiffeners available on the market. One type is a fixed diameter stiffener that matches the ID of the pipe being repaired (see Figure 17). Caution should be used when using fixed diameter stiffeners to be sure they are sized properly to obtain the proper press fit in the PE pipe. These are mainly used with smaller diameter service lines.

Figure 17 Fixed Diameter Stiffener for PE pipe

The other type of stiffener is a split ring stiffener (see Figure 18). These are normally made of stainless steel and provide a thin yet strong pipe wall reinforcement without disturbing the flow characteristic of the pipe. The easy installation instructions are shown below.

Figure 18 Split Ring Stiffener for PE pipe



Easy Installation...

① Both pipe ends being joined require stiffeners. Insert stiffener into each pipe so that stiffener lip touches pipe end.

② Insert wedge into stiffener.

Make sure wedges are not directly opposed

③ Fix wedge firmly in stiffener by striking with a rubber hammer.

A stiffner MUST be used in each PE pipe end. Exact SDR of PE used is required when ordering.

Figure 19 Install Split Ring Stiffener in PE pipe

Restraint Methods

Mechanical Repair Fitting Restraint

The most common method of restraining a mechanical repair fitting is to add a back-up flange to each pipe and electro-fuse the appropriate number of Flex Restraints to each end of the mechanical fitting. The number of Flex Restraints fused to each end depends on the pipe diameter (contact the fitting manufacturer for proper assembly instructions). Once the Flex Restraints have been cooled properly, the mechanical components such as the sleeve, glands, gaskets and bolts can be installed per the manufacturer’s procedures to complete the restraining process.

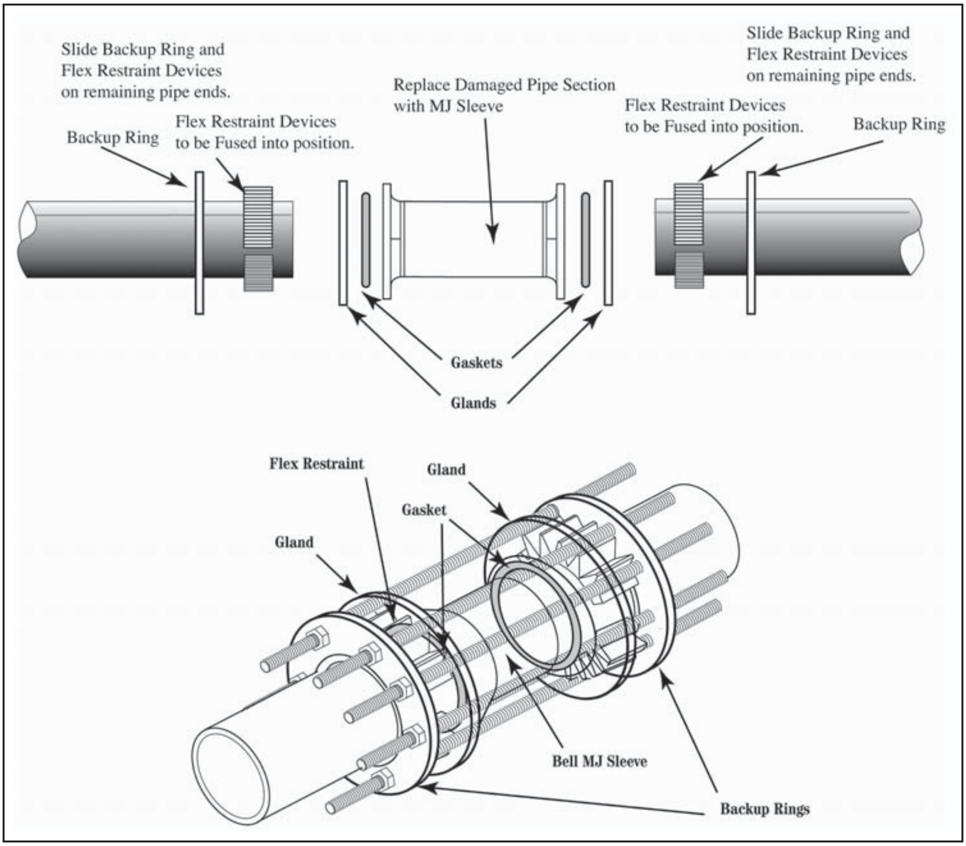


Figure 20 Mechanical Repair Fitting Restraint

Mechanical Coupling Restraint

When the damage is small and a mechanical coupling will satisfy the repair, it may need to be restrained. This is accomplished by using flex restraints (or mechanical restraints) and back up rings on both sides of the coupling. In this situation, the proper quantity of flex restraint couplings are electro-fused to the PE pipe on each side of the coupling (contact the fitting manufacturer for proper assembly instructions). Two backup rings are used with all-thread rods to restrain the connection. Consult the restraint harness manufacturer for the proper assembly procedure.

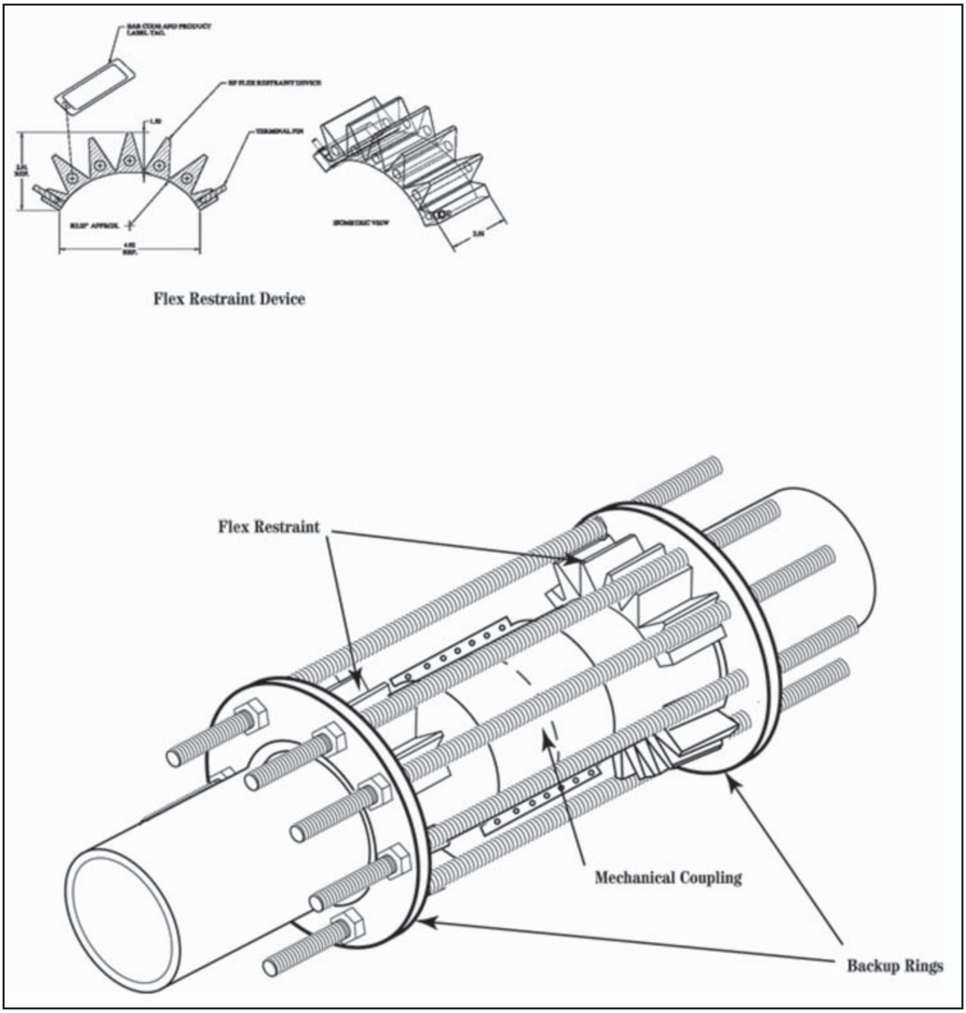


Figure 21 Mechanical Coupling Restraint

Repair Clamps

Third party damage to PE or any pipe material is always a possibility. Repairs can be made by cutting out the damaged section of pipe and replacing the section by use of heat fusion or mechanical fitting technology discussed earlier. Within limits, repairs can also be made with clamp-on repair saddles as depicted in Figure 22. Such devices do have limitations for use. They are intended only to repair locally damaged pipe such as gouges or even punctures of the pipe wall. A clamp length of not less than 1½″ times the nominal pipe diameter is recommended. The procedure is basically to clean the pipe area where the clamp will be placed, and bolt the clamp in place according to the fitting manufacturer's instructions. As with all fittings, limitations on use should be verified with the fitting manufacturer.

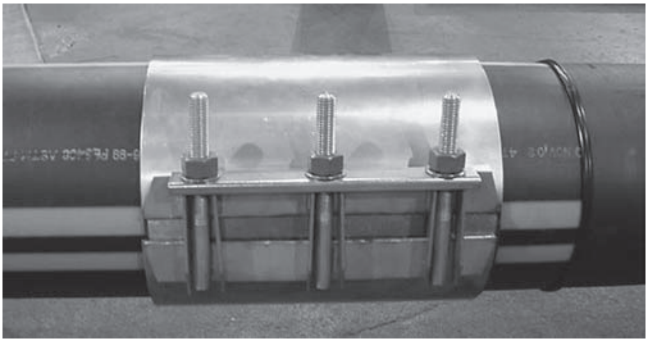


Figure 22 Mechancial Clamp-on Repair Saddle

Squeeze-off

Regardless of the joining method applied in the installation of PE pipe, it may become necessary to shut off the flow in the system. With PE pipe materials, squeeze-off of the pipe with specially-designed tools is a common practice for gas applications. Use squeeze-off tools per ASTM F 1563 and follow the squeeze-off procedures in ASTM F 1041.

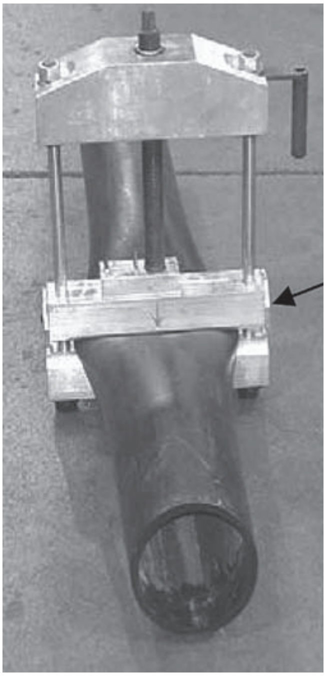


Figure 23 Squeeze-Off Tool

Chapter 16

Pipe Bursting

Introduction

Underground service utilities in many American cities have been in place for over 100 years. While existing systems have functioned well beyond reasonably anticipated service life, underground systems are mostly deteriorated and need costly maintenance and repair. Common problems involve corrosion and deterioration of pipe materials, failure or leakage of pipe joints, and reduction of flow due to mineral deposits and debris build up inside the pipe. Damage to existing pipes can also occur by ground movements due to adjacent construction activity, uneven settlement or other ground instability. This leads to infiltration and inflow (I&I) increase in sewer systems. In water systems, it leads to flow and pressure reductions, persistent leakage (up to 30 percent of water provided in some systems), pipe bursts, and poor water quality. These problems tend to increase with the age of the network where maintaining this large network of underground sewer, water, and gas pipelines is difficult and costly. The above problems are compounded by the significant negative impacts (of open cut repair or replacement projects) on the daily life, traffic, and commerce of the area served by and along the pipeline in question.

Pipe bursting is a well-established trenchless method that is widely used for the replacement of deteriorated pipes with a new pipe of the same or larger diameter. Pipe bursting is an economic pipe replacement alternative that reduces disturbance to business and residents when it is compared to the open cut technique. Pipe bursting is especially cost-effective if the existing pipe is out of capacity, deep, and/or below the ground water table (GWT). Replacing an old pipe with a larger one is termed upsizing. One-size upsizing is replacing the old pipe with a pipe one standard size larger, for example replacing 8” pipe with 10” one. Similarly, two-size upsizing is replacing the old pipe with a pipe two standard sizes larger, e.g. replacing 8” pipe with 12” one.

Pipe bursting conventionally involves the insertion of a cone shaped bursting head into an old pipe. The base of the cone is larger than the inside diameter of the old pipe and slightly larger than the outside diameter of the new pipe to reduce friction and to provide space for maneuvering the pipe. The back end of the bursting head is connected to the new Polyethylene (PE) pipe and the front end is attached to a cable or pulling rod. The new pipe and bursting head are launched from the insertion shaft and the cable or pulling rod is pulled from the pulling shaft, as shown in Figure 1. The bursting head receives energy to break the old pipe from one of the following sources: a pulling cable or rod, a hydraulic source, or an air compressor. The energy breaks the old pipe into pieces and expands the diameter of the cavity. As the bursting head is pulled through the old pipe debris, it creates a bigger cavity through which the new pipe is simultaneously pulled from the insertion shaft. There are many variations to this conventional layout that are presented later in the chapter.

History

Pipe bursting was first developed in the UK in the late 1970s by D. J. Ryan & Sons in conjunction with British Gas, for the replacement of small-diameter, 3- and 4-inch cast iron gas mains (Howell 1995). The process involved a pneumatically driven, cone-shaped bursting head operated by a reciprocating impact process. This method was patented in the UK in 1981 and in the United States in 1986; these patents expired in April, 2005. When it was first introduced, this method was used only in replacing cast iron gas distribution lines; it was later employed to replace water and sewer lines. By 1985, the process was further developed to install up to 16-inch outer diameter (OD) medium-density polyethylene (MDPE) sewer pipe. Replacement of sewers in the UK using sectional pipes as opposed to continuously welded PE pipe was described in a paper by Boot et al. (1987). Up to 2006, approximately 9,000 miles of PE pipe has been installed by bursting (Najafi, 2006). Currently, pipe bursting is used to replace water lines, gas lines, and sewer lines throughout the world.

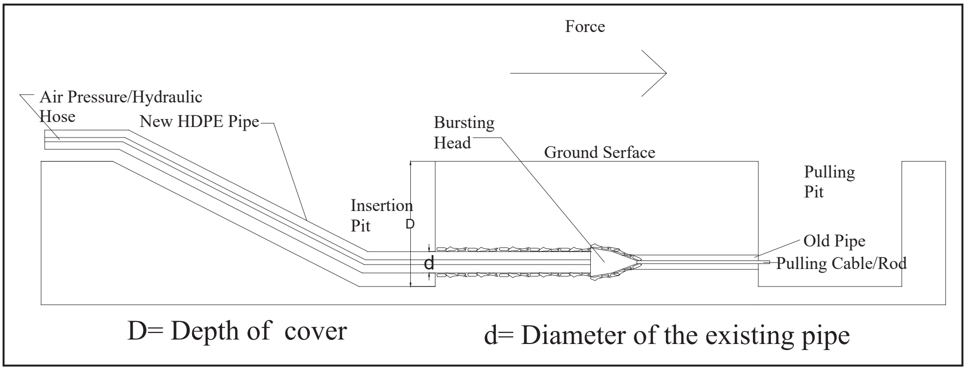


Figure 1 The Pipe Bursting Operation Layout

Pipe Bursting and Trenchless Pipe Replacement Systems

Existing old pipes can be replaced by one of several trenchless techniques developed up to date. There are three basic methods of pipe bursting: pneumatic, hydraulic, and static pull. In addition, there are proprietary trenchless pipe replacement systems that incorporate significant modifications to the basic pipe bursting technique. The basic difference among these systems is in the source of energy and the method of breaking the old pipe and some consequent differences in operation that are briefly described in the following paragraphs. The selection of a specific replacement method depends on soil conditions, groundwater conditions, degree of upsizing required, type of new pipe, construction of the existing pipeline, depth of the pipeline, availability of experienced contractors, and so on.

Pneumatic Bursting Systems

The most common pipe bursting method is the pneumatic system. In the pneumatic system, the bursting tool is a soil displacement hammer driven by compressed air and operated at a rate of 180 to 580 blows per minute. It is similar to a pile-driving operation going horizontally. The percussive action of the hammering cone-shaped head is also similar to hammering a nail into the wall; each hammer pushes the nail a short distance as shown in Figure 2. With each stroke, the bursting tool cracks and breaks the old pipe, the expander on the head - combined with the percussive action of the bursting tool, push the fragments and the surrounding soil providing space to pull in the new PE pipe. The expander can be frontend (attached to the frontend of the hammer) for pipes smaller than 12” or back-end (attached to the backend of the hammer) for pipes larger than 12”. The frontend expander allows withdrawing the hammer through the PE pipe after removing the expander from the existing manhole at the pulling shaft without damaging the manhole. The tension applied to the cable keeps the bursting head aligned with the old pipe, keeps the bursting tool pressed against the existing pipe wall, and pulls the new PE pipe behind the head. An air pressure supply hose is inserted through the PE pipe and connected to the bursting tool. The bursting starts once (1) the head is attached to the new pipe, (2) the winch cable is inserted through the old pipe and attached to the head, (3) the air compressor and the winch are set at a constant pressure and tension values. The process continues with little operator intervention until the head reaches the pulling shaft at which point it is separated from the PE Pipe.

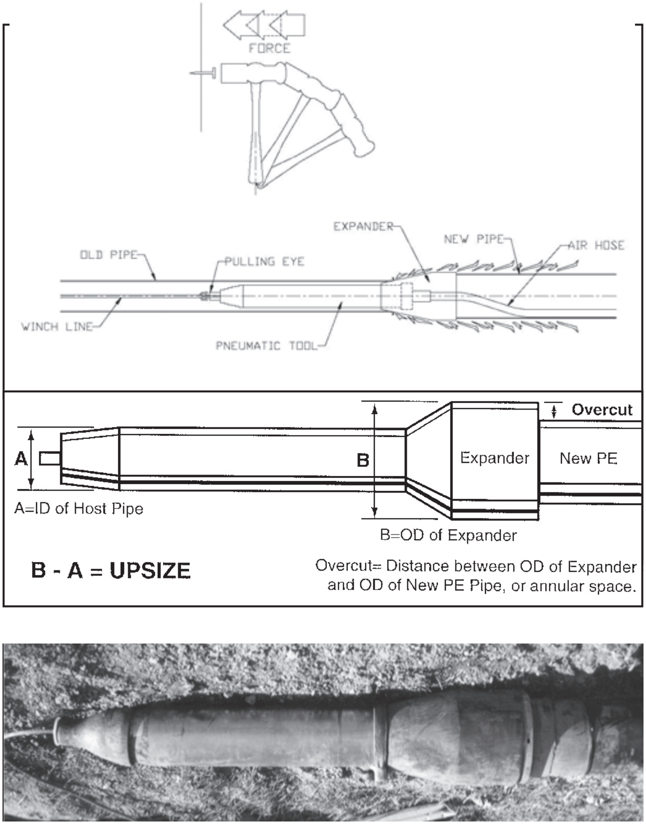


Figure 2 The Bursting Head of the Pneumatic System

Static Bursting Systems

The second common method of pipe bursting is the static pull system. In the static pull system, a larger tensile force is applied to the cone-shaped expansion head through a pulling rod assembly or cable inserted through the existing pipe. The cone transfers the horizontal pulling force into a radial force -- breaking the old pipe and expanding the cavity providing space for the PE pipe as shown in Figure 3. The steel rods, each is about four feet long, are inserted into the old pipe from the pulling shaft. The rods are connected together using different types of connections. When the rods reach the insertion shaft, the bursting head is connected to the rods and the PE pipe is connected to the rear of the head. A hydraulic unit in the pulling shaft pulls the rods one rod at a time, and the rod sections are removed. The process continues until the bursting head reaches the pulling shaft, where it is separated from the PE pipe. If cable is used instead of rod, the pulling process continues with minimum interruption, but the tensile force of a cable compared to a rod section is limited.

Pipe Splitting

The North American Society for Trenchless Technology (NASTT) defines *pipe splitting* as a replacement method for breaking an existing pipe by longitudinal slitting. At the same time a new pipe of the same or larger diameter may be drawn in behind the splitting tool (NASTT 2008). Pipe splitting is used to replace ductile material pipes, which does not fracture using the above-cited bursting techniques. The system has a splitting wheel or cutting knives that slit the pipe longitudinally at two more lines along the side of the pipe. An example of splitting head is shown in Figure 4.

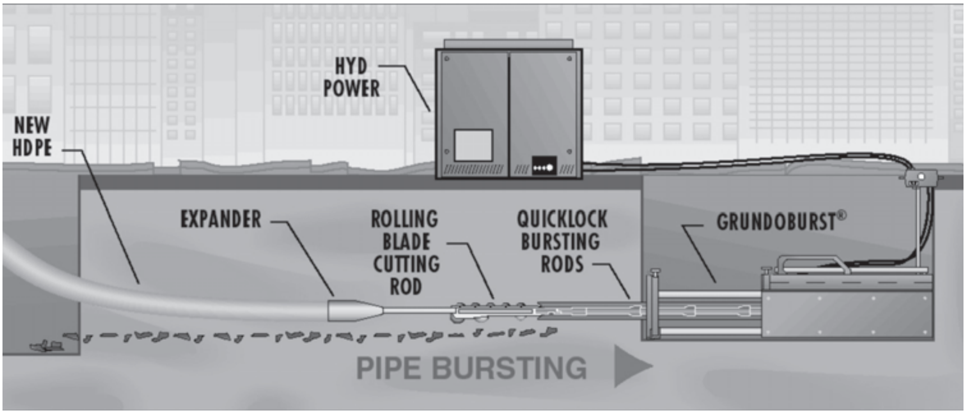


Figure 3 The Static Pull Bursting Head with Accessories to Cut Reinforcing Steel in RCP

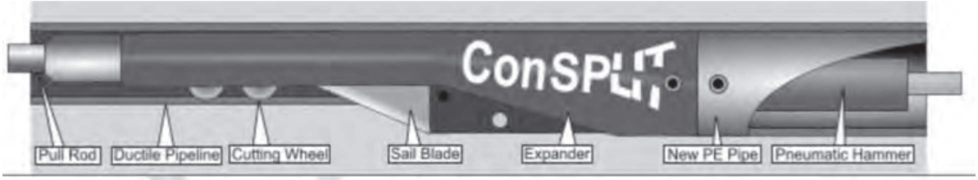


Figure 4 Pipe Splitting Head (PIM Corporation 2007)

Pipe Reaming

Pipe reaming is pipe replacement technique that uses a horizontal directional drilling (HDD) machine with minor modification. After pushing the drill rods through the old pipeline and connecting the rods to a special reamer (see Figure 5), the new PE pipe string is attached to the reamer via a swivel and towing head. As the drill rig rotates and simultaneously pulls back, the old pipe is grinded and replaced by the new PE pipe. Removal of the old pipe is accomplished by mixing the grinded material with the drilling fluid and transferring it to an exit point for removal via a vacuum truck. Directional drilling contractors or utility contractors who use an HDD rig can add inexpensively modified reamers of various types for different pipe materials and ground conditions. Pipe reaming is limited to non-metallic pipeline replacement. According to Nowak (Hayward 2002), the surrounding environmental conditions (groundwater, sand, rock, concrete encasement, etc) that prohibit other procedures are not obstacles to successful installations.

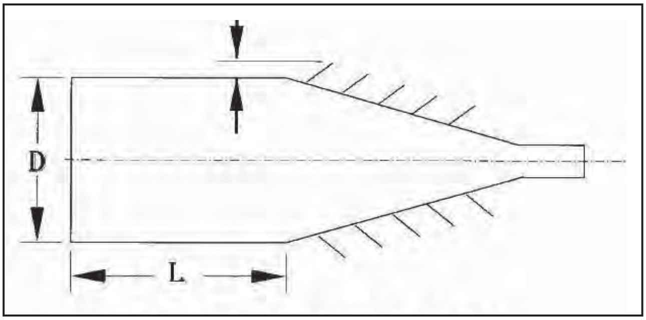


Figure 5 Reaming Head

Impactor Process

The patented Impactor process is another system that combines the HDD with pipe bursting as shown in Figure 6. The bursting head (Impactor) receives air through the HDD stems. The HDD is connected to the air supply and positioned to drill out to an entry manhole. Then the HDD stem is pushed through old pipe to the next manhole and drilled back to the entry manhole. The Impactor device, after it is attached to the drill stem and to the replacement pipe, is pulled into the old pipe. While pulling back, the Impactor system is activated and bursts the old pipe. The combined actions - of pulling using the HDD rig and of hammering of the Impactor device - breaks up the old pipe and replace it with the new pipe. The Impactor system can reduce excavation and overcomes blocked old pipes.

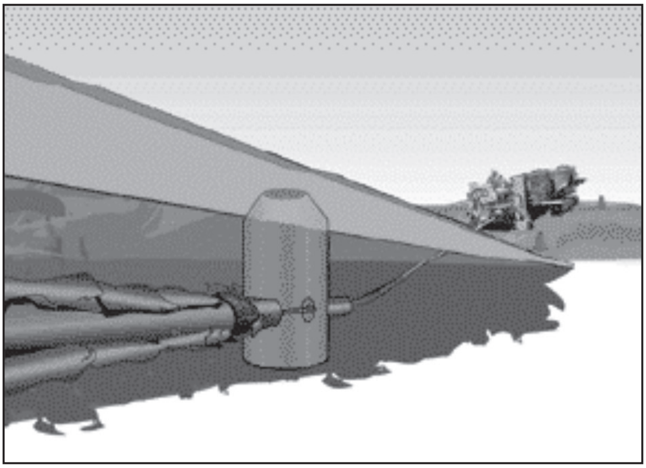


Figure 6 The Impactor Process Combines HDD with Pipe Bursting

Old Pipe Material

In most bursting applications, the old pipe is made of a rigid material such as vitrified clay pipe (VCP), ductile iron, cast iron, plain concrete, asbestos, or some plastics. Reinforced concrete pipe (RCP) was successfully replaced when it was not heavily reinforced or if it was substantially deteriorated. The diameter of the old pipe typically ranges from 2 inches to 30 inches, although the bursting of larger diameters is increasing. A length of 300 to 400 feet is a typical length for bursting; however, much longer runs were completed with bursting systems that are more powerful. In addition, some point repairs on the old pipe, especially repairs made with ductile materials, can make the process more difficult.

New Pipe Material

High-and medium-density polyethylene (HDPE and MDPE) have been the most-used replacement pipes for pipe bursting applications. The main advantages of PE pipe are its continuity, flexibility, and versatility. The continuity, which is obtained by butt fusing together long segments in the field, reduces the possibility of stopping the process. The flexibility allows bending the pipe for angled insertion in the field. In addition, it is a versatile material that meets all the other requirements for gas, water, and wastewater lines. The smoother interior surface (relative to other pipe material) reduces the friction between the flow and the pipe wall, which allow higher flow speed and increased flow capacity. The PE pipe does not erode, rotten, corrode, or rust; it also does not support bacteriological growth. The relatively higher thermal expansion coefficients are the main issue with PE pipes, but when the PE pipe is installed and restrained appropriately, the pipe expands and contracts without any damage. When used in pipe bursting applications, the friction between the soil and the pipe is reduced.

The internal surface of the PE pipe is smoother than those of the concrete or clay pipes. For gravity applications, after some algebraic manipulation to the following Chezy-Manning equation, it is can be demonstrated that the flow capacity of the PE is 44% more than those of the concrete or clay pipes considering the internal diameter for the old clay or concrete pipe equals that of the replacement PE pipe.

$$Q = \frac{1.49}{n} A(r_H)^{2/3} \sqrt{S}$$

WHERE

Q = the flow quantity

n = Manning roughness coefficient

A = the area of the pipe

r_H = hydraulic radius

S = the slope of the energy line, which is parallel to the water surface and pipe invert if the flow is uniform.

The n value ranges for clay or concrete pipes between 0.012 and 0.015 (on average about 0.013), and it is about 0.009 for PE (Lindeburg 1992).

In addition to PE, other new pipe materials can be ductile iron, VCP, or RCP. However, these pipes cannot be assembled into a single pipe string prior to bursting operation; but they can be jacked into position behind the bursting head or kept compressed by towing them via a cap connected to the cable or rod that passes through the pipes. Therefore, the static pull system is the only bursting system that can be used with these pipes. The joints of these pipes must be designed for trenchless installations.

When is Pipe Bursting a Preferred Solution?

For repair and replacement, conventional techniques have involved open cut excavation to expose and replace the pipe. Alternatively, the pipeline can be rehabilitated by inserting a new lining or replaced by pipe bursting. There are several pipe lining technologies available such as cured in place pipe, deform and reform, and slip lining. The main advantage of the lining methods over pipe bursting is the need for small or no access excavation to the pipeline. In contrast, pipe bursting has the advantage of increasing the pipe capacity by more than 100%.

The unique advantage of pipe bursting over pipe lining techniques is the ability to upsize the service lines. A 15% and 41% upsizing doubles the capacity of the sewer and water lines respectively. The technique is most cost advantageous compared to the lining techniques when (1) there are few lateral connections to be reconnected within a replacement section, (2) the old pipe is structurally deteriorated, and (3) additional capacity is needed.

For pressure applications, 41% increase in the inside pipe diameter double the cross sectional area of the pipe and consequently double the flow capacity of the pipe. For gravity applications, after some algebraic manipulation to the above-mentioned Chezy-Manning equation, it shown that a 15% and 32% increase in the inside diameter of the pipe combined with the smoother pipe surface can produce a 100% and 200 % increase in the flow capacity, respectively.

Pipe bursting has substantial advantages over open cut replacements; it is much faster, more efficient, and often less expensive than open cut especially in sewer applications due to high depths that usually gravity sewer pipes are installed. The increased sewer depth requires extra excavation, shoring, and dewatering which substantially increases the cost of open cut replacement. The increased depth has a minimal effect on the cost per foot for pipe bursting as shown in Figure 7 (Poole et al 1985). Specific studies carried out in the US have shown that pipe bursting cost savings are as high as 44% with an average savings of 25% compared to open cut (Fraser et al 1992). This cost saving could be much more if the soil is hard rock because rock excavation is extremely expensive compared to pipe bursting. Additionally, open cut can cause significant damage to nearby buildings and structures (Atalah 2004).

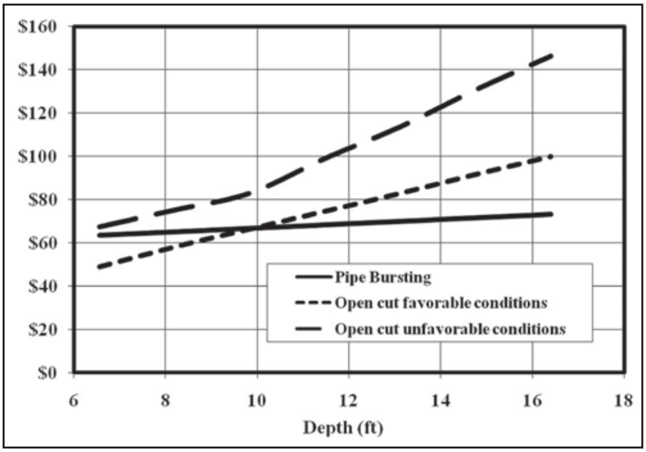


Figure 7 Cost Comparison Between Pipe Bursting and Open Cut Replacements (Poole et al 1985)

In addition to the direct cost advantage of pipe bursting over open cut, pipe bursting, as a trenchless technique, has several indirect cost savings. Less traffic disturbance, road or lane closing, time for replacement, business interruption, and environmental intrusion are some examples of these indirect cost savings. Pipe bursting has minimal interference with other utilities, and less safety hazards (for both operators and the public) due to reduced open excavation.

The unique advantage of pipe bursting over pipe lining techniques; such as cured-in-place pipe (CIPP), sliplining, and deform and reform, etc.; is the ability to upsize the service lines. A 15% and 41% upsizing doubles the capacity of the sewer and water lines respectively. The technique is most cost advantageous compared to the lining techniques when (1) there are few lateral connections to be reconnected within a replacement section, (2) the old pipe is structurally deteriorated, and (3) additional capacity is needed. Pipe bursting has the following additional advantages over open cut: (1) minimal disruption to traffic, (2) minimal interference with other utilities, (3) superior safety (for both operators and the public) due to reduced open excavation, and (4) substantial time savings.

Pipe Bursting Project Classification

National Association of Sewer Service Companies (NASSCO) classified bursting projects into three classifications in terms of difficulty; they are A – routine, B - moderately difficult to challenging, and C – challenging to extremely challenging. The projects are classified as A - routine if the depth is less than 12 feet, the existing pipe is 4-12 inch in diameter, the new pipe is same size as the old pipe or one diameter upsize, the burst length is less than 350 feet, the old trench is significantly wider than the diameter of the new pipe, and the soil is compressible outside trench (soft clay, loose sand). The projects are classified as B - moderately difficult to challenging if the depth is between 12 feet and 18 feet, existing pipe is between 12 to 20 inch, the diameter of the new pipe is two diameter upsize, the burst length is between 350 feet to 450 feet, the trench width less than 4 inch wider than new pipe diameter, or the soil is moderately compressible outside trench such as medium dense to dense sand, medium to stiff clay. The projects are classified as C – Challenging to Extremely Challenging if the depth is more than 18 feet, existing pipe is between 20 and 36 inch, the new pipe diameter is three or more diameter upsize, the length is more than 450 feet, the soil is incompressible outside trench, or the trench width is less than or equal to upsize diameter. Note that the degree of difficulty increases as more than one of the above criteria applies (Najafi 2007).

TABLE 1
Summary of NASSCO Pipe Bursting Classification

Criteria	A – Routine (all of the criteria below apply)	B - Moderately Difficult to Challenging	C – Challenging to Extremely Challenging
Depth	Less than 12 feet	12 ft to 18 ft	More than 18 ft
Existing Pipe	4”-12”	12” to 20”	20”-36”
New Pipe Diameter	Size for size or one diameter upsize	Two diameter upsize	Three or more diameter upsize
Burst Length	Less than 350 feet	350 feet to 450 feet	More than 450 feet
Trench Width	Relatively wide trench compared to upsized diameter	Trench width less than 4” wider than upsize diameter	Incompressible soils (very dense sand, hard clay or rock) outside trench
Soil	Compressible soils outside trench (soft clay, loose sand)	Moderately compressible soils outside trench (medium dense to dense sand, medium to stiff clay)	Constricted trench geometry (width less than or equal to upsize diameter)

Pipe Bursting Applicability and Limitations

Pipe bursting is used to replace water lines, sewer mains, and gas lines, as well as sewer lateral connections. Typical replacement length is between 300 feet and 500 feet; however, in favorable conditions, longer drives have been completed successfully. The size of pipes being burst typically range from 2 to 30”, although pipes of larger sizes can be burst. Pipe bursting is commonly performed size-for-size and one-size upsize above the diameter of the existing pipe. Larger upsize (up to three pipe sizes) have been successful, but the larger the pipe upsizing, the more energy needed and the more ground movement will be experienced. It is important to pay close attention to the project surroundings, depth of installation, and soil conditions when replacing an existing pipe especially in unfavorable conditions such as expansive soils, repairs made with ductile material, collapsed pipe, concrete encasement, sleeves, and adjacent utility lines.

On the other hand, pipe bursting has the following specific limitations: (1) excavation for the lateral connections is needed, (2) expansive soils could cause difficulties for bursting, (3) a collapsed pipe at a certain point along the old pipe may require excavation at that point to allow the insertion of pulling cable or rod and to fix the pipe sag, (4) point repairs with ductile material can also interfere with the replacement process, (5) if the old sewer line is significantly out of line and grade, the new line will also tend to be out of line and grade although some corrections of localized sags are possible, and (6) insertion and pulling shafts are needed specially for larger bursts.

Design Considerations

Pipe-bursting projects can be broken down to three phases: pre-design, design, and construction. The pre-design phase involves collecting information about the problem pipeline, investigating the alternative solutions, and ensuring that pipe bursting is the best solution. The design phase involves investigating the conditions of the old pipe and trench, nearby utilities and structures, determining shaft locations, bypass pumping requirements, and developing detailed drawing and specifications. The construction phase involves selecting the bursting system, lateral connections, submittals, shaft construction and shoring, bypass pumping, and restoration.

Pre-design Phase

At the pre-design and design phases, the ability to influence the cost of the project is the highest, and the cost of project modification is lowest, as shown in Figure 8. This is especially true for small jobs where the contractor’s cost savings (from design modification) is small in magnitude, and the benefits do not justify the risk of being responsible for the redesign and its consequences. Therefore, invested effort in this phase will pay dividends later.

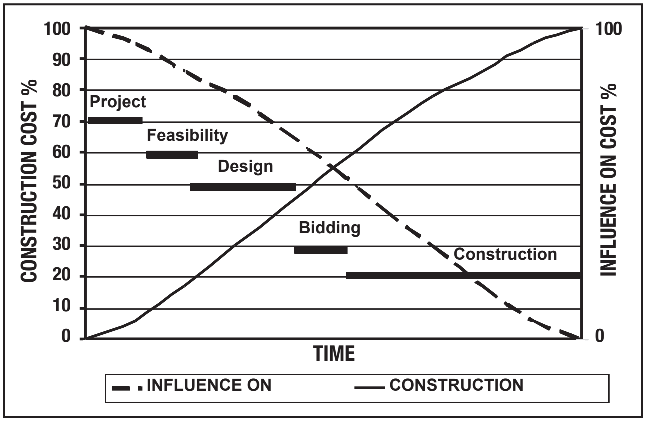


Figure 8 Ability to Influence Construction Cost Over Time (Project Management Institue Inc. 2004)

The pre-design phase involves collecting information about the old and new pipelines. The designer determines the maximum flow requirements for the future design life of the pipeline (considering the future economical developments and population growth trends), and then calculates the diameter of the new pipe. This phase also includes investigating potential solutions for the problem and collecting the relevant information to evaluate the valid solutions. For example, potential solutions may include installing another new line, lining the old pipe, replacing the pipeline via open cut, replacing it by pipe bursting, and so forth. If pipe bursting is the optimal solution, the design team proceeds to the design phase.

Many times open cut is the specified method of construction for most pipeline projects, and the bursting contractors offer pipe bursting as an alternative to open cut. This process may include preparation and submittal of two bids: one is based on open cut and the second is a value-engineering proposal based on pipe bursting. While this arrangement may increase the competition among bidding contractors, it increases the overall project cost (due to risk and contingency factors) for the project because (1) while the presented information in the contract document might be complete for the open cut method, it may be incomplete for estimating the cost of the bursting project and (2) this incomplete bid information increases the risk of problems during construction period that may lead to change orders and possible disputes that are more costly to resolve. It is believed that if the owner and the engineer select the methods of construction (for example open cut and pipe bursting) early during the design phase, the competition is maintained, bidding information is complete, and the risk of changes is reduced as illustrated in Figure 8.

Design Phase

The design phase starts with collecting further information about the old line, such as: the type of soil and backfill, current flow volume for bypass pumping, lateral connections, trench width, backfill compaction levels, and manhole locations. This phase also includes locating nearby utilities, investigating soil and trench backfill material, and developing risk assessment plans. The feasibility of pipe bursting as the optimal solution may need to be re-evaluated in light of the new collected information. The designer completes this phase with developing detailed drawing and specifications and complete bid documents which include listing of the needed submittals. The drawings should provide all relevant information, such as diameter and material type of existing pipe, existing plan view and profile, existing nearby utilities and structures (crossing and parallel), repair clamps, concrete encasement, fittings, and so forth. This information is collect through a CCTV or similar inspection of the old pipe.

Utility Survey

Surrounding utilities have significant impact on the success of the pipe bursting operation, and the design engineer should attempt to identify and locate these existing utilities. However, the *exact* location of these utilities must be identified during the construction phase through visual locating, such as vacuum potholing. The identification of nearby utilities by design engineer is critical for the following reasons:

- The presence of nearby utilities may steer the engineer to eliminate pipe bursting as a construction method.
- The existing utilities may affect the location of insertion and pulling/jacking shafts.
- Reduce or eliminate the risk of causing significant damage to these utilities.
- The contractors need to know the number of utilities that they need to expose to account for them in their bid.
- Consideration for protection of existing utilities from the ground movement of the bursting operation must be made early on to reduce the risk of service interruptions to the customers.
- Reduce the risk of injuries and fatalities to the workers and nearby people if these utilities are accidently damaged during bursting.

Site investigation should indicate the locations of many utilities; for example, sewer manholes indicate the presence of a sewer line and fire hydrants indicate the presence of a water line, etc. The engineer should contact the One-Call center for utilities marking, review the available as-built drawings from the different utility owners, and ideally consider geographic information system (GIS) data (if available), utility maps, and conducts surface and subsurface investigations to superimpose these utilities on plans and profiles.

Investigation of Existing Pipe and Site Conditions

Investigation of the old pipe condition assists in selecting the suitable rehabilitation technique and provides the exact location of the lateral connections. The conditions of the existing pipe may render pipe bursting as an unsuitable method for correcting the problem. The presence of sags in the line may require treatment for the sag prior to bursting. The host pipe (diameter, material, and conditions) and the diameter of the new pipe guide the contractor to select the appropriate bursting system type, size, and accessories during the bidding and construction phase. The site conditions and surface features may affect the locations of the insertion and pulling shafts, staging area for fused pipe, traffic control planes, and foot print for the needed bursting system components.

Insertion and Pulling Shaft Requirements

When planning for shaft locations, the engineer identifies spots where excavation is needed to replace manholes, valves, lateral connections, or fittings. These excavation spots are used as insertion or pulling shafts. However, if excavation at the manhole location is not feasible or needed, shaft excavation at other locations may be considered. In selecting the location of these shafts, the engineer has to consider the following issues:

- Sufficient staging area for the fused replacement pipe to avoid blocking driveways and intersecting roads.
- The shaft length should be long enough to allow alignment of the bursting head with old line and for the PE pipe to bend safely from the entry point to the ground surface.
- Space for the construction equipments such as backhoe, loader, crane, etc.
- Nearby flow bypass discharge spot or space to lay by pass lines without blocking driveways and intersecting roads.
- Traffic control around shafts.
- Soil borings close to these shafts.
- Discharge spots for dewatering if needed.
- Using the same shaft to insert or pull pipes more than once.

Generally, the engineer recommends locations for the insertion and pulling shaft but leaves the final determination to the contractor (through a submittal process) with the guidelines of minimizing excavation and disturbance to the surrounding environment.

Soil Considerations in Pipe Bursting

The soil and subsurface investigation is collecting the necessary information to properly design the project. It assists the contractor in submitting a proper bid by selecting the appropriate bursting system (type and size), shoring of the pulling and insertion shafts, dewatering system, compacting backfill material, etc. This proper decisions and biding increase the chances of success during the construction phase of the project.

The soil investigation activities include soil borings, standard penetration tests, groundwater level determinations, trench geometry investigation, and native soil and trench backfill material classifications. If the presence of washouts or voids around the existing pipe is suspected, Ground Penetrating Radar (GPR) survey may assist in determining locations and magnitude of these voids. Special attention should be given to the presence of major difficulties that may render pipe bursting not feasible such as the presence of rock, hard cemented dense soils, very soft or loose soils, reinforced concrete encasement, very narrow trench in hard soils or rock, or ductile point repairs. If contaminated soil is suspected, the type and extent of contamination should be identified and indicated in the contract documents. The contractor should be requested to take the necessary measures to handle and dispose of this contaminated soil.

The soil around the pipe (backfill and native soil) has to be compressible to absorb the diameter expansion. Compressible soils are the ideal soils for pipe bursting because the outward ground displacements will be limited to an area surrounding the pipe alignment as shown in Figure 9. Original backfill is the most suitable soil for bursting followed by (increasing difficulty) compressible clay, loose cobble, beach and running sand, densely compacted clay, then sandstone. Soils with long standup time allow the overcut (created by the expanded hole) to remain open for most of the bursting operation, thus reducing the friction force between the soil and the pipe. The overcut lowers the needed pulling forces and consequently the axial stress on the new pipe during installation. Somewhat less favorable ground conditions for pipe bursting involve densely compacted soils and backfills, soils below the water table and expandable soils. Special soils such as highly expansive soils or collapsible soils will also cause problems.

Pipe bursting below the groundwater table increases the difficulty of the bursting operations because the groundwater flows towards the insertion shaft requiring dewatering of the shaft. Also, in very soft or loose soils, significant ground movements may take place causing significant sags in the new line and damage to nearby structures. In sever situations, the soils particles migrate to the old pipe converting the bursting operation into a piercing operation. If the groundwater is lowered via any dewatering technique such as deep wells, well point system, or open sumps in the pulling and receiving shafts, the effective soil pressure will increase.

This will increase the vertical loads on the pipe causing increased friction, bursting and pulling force, and tensile stresses in the PE pipe. On the other hand, the presence of water reduces the coefficient of friction between the pipe and the soil, reducing the applied pulling force.

If the original soil borings (during the old pipe installation) are available, they should be reviewed and made part of the supplemental information available to the bidders. The determination of the trench geometry and backfill material and compaction is important for the designer and contractor.

Maximum Allowable Operating Pressure (MAOP)

For pressure applications such as water, gas, and force mains, the maximum allowable pressure should be determined based on the maximum surge pressure that pipe will be subject to and the maximum operating pressure for the pipe. The PE pipe should be designed to withstand the maximum allowable operating and surge pressures according to the design procedure shown in Chapter 6 in this Handbook. DR 17 is typically used for bursting pressure or gravity pipe unless a higher pressure rating is required. In short bursting runs where high tensile forces are not expected DR 21 can be used.

Risk Assessment Plan

Most underground and pipeline construction projects generally have some risks associated with the unknown subsurface conditions. The risks associated with pipe bursting include damage to nearby utilities and structures, failure to complete the project using pipe bursting, and time and/or budget overrun. There is risk of damage to nearby utilities, buried structures, and pavement if there are adverse soil conditions, improper construction techniques, design mistakes, inappropriate toning of utilities, etc. There are also many risks associated with flow bypass, dewatering, shoring, etc if the appropriate procedures were compromised. A list of additional risks that may stop the bursting operation and/or create problems include:

- Settlement at insertion/pulling pits if the density of the backfill exceeds that of native soil.
- Bursting through sharp curves.
- Concrete encasement or steel point repair inside existing pipe.
- Excessive bursting lengths.
- Damage to new pipe from sharp edge or fragments of existing pipe being burst/split.
- Damage to laterals from bursting of main line.

- The presence of rock under the existing pipe may create a 'bump' in the replacement pipe.
- Collapsed pipe.

Projects with class C classification-challenging to extremely challenging as indicated in Table 1- must be carefully examined in terms of required forces and ground displacements. Additionally, the depth of the old pipe affects the expansion of surrounding soil and consequently the extent of ground displacement around the pipe. If the pipe is shallow, damage to the pavement may take place. Saw cutting the pavement prior to bursting might be advisable. If the existing pipe is below the GWT, the difficulties increase. Insertion and pulling shafts grow larger and more complex as the depth increases.

If there are unacceptable sags in the existing sewer line, these sags need to be corrected before bursting. The sags can be corrected by local excavation, surface grouting, or grouting from within the pipe. Some reduction of sag magnitude may be expected (without corrective measures) from the bursting operation, but the extent to which the problem is corrected depends on the relative stiffness of the soil below the sagging section.

If there is erosion of the soil around the pipe, the bursting head and the following PE pipe will tend to deviate toward the void or lower density region. If there is a hard soil layer or rock close to the pipe, the bursting head will tend to displace towards the softer soil. In shallow conditions, the bursting head will deviate mostly upwards towards the ground surface. If the conditions change substantially along the length of the burst, this may cause some change in the grade and/or alignment of the pipe. When the grade is critical, these possibilities should be considered.

Most pipe bursting operations can be done safely if site and project conditions are known before bursting and appropriate measure are taken to address these conditions. There are well known solutions to all of the above mentioned risks and problems, and successful project engineers or construction managers identify these risks and develop a risk management plan to address these specific risks for this project. This plan includes quantification of the occurrence probability of the identified events and their associated impact or damage; it also includes measures to eliminate, mitigate, transfer, or undertake these risks. One of the general measures to mitigate the project risks is building and maintaining cooperative relationships among owners, engineers, contractors, equipment manufacturers, and pipe suppliers. Identifying and developing a realistic plan to manage and share risks appropriately is an important part of effectively communicating responsibilities, defining roles, and building a strong team. It is important to pay close attention to the project surroundings (surface and subsurface conditions) for unfavorable conditions and risks. These conditions require extra attention in order to ensure the safety of all involved people as well as surrounding facilities and infrastructure.

Ground Movement Associated with Pipe Bursting

The pipe bursting process creates a cavity in the soil around the pipe where the new pipe is pulled through. This cavity creates a compression plastic zone around the new pipe outlined by an elastic zone as shown in Figure 9.

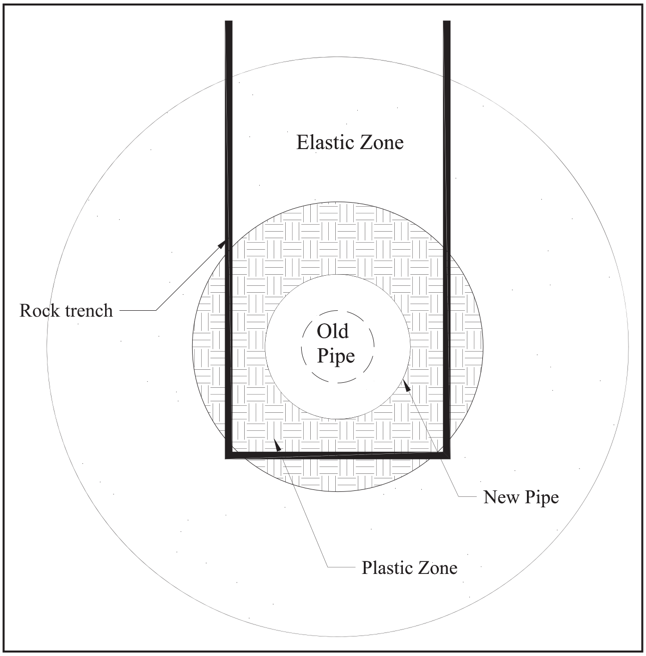


Figure 9 Cavity Expansion and the Plastic and Elastic Zones

The magnitude of the compression and the dimensions of these zones correlate with the amount of upsizing, the diameter of the pipe, and the type of soil (Atalah 1998). The author investigated the ground movements and vibrations associated with bursting small diameter pipes in soft soils (Atalah 1998) and with large diameter pipes in rock conditions (Atalah 2004) and developed guidelines for safe distance from existing nearby utilities, structures, and pavement. Large diameter bursting in rock conditions is applicable for upsizing 24″ in diameter reinforced RCP pipes with upsize percentage less than 50%. Small diameter bursting in soft soils refers to upsizing 8″ and 10″ in diameter VCP with upsize percentage less than 30%. The findings of these reports are summarized in Figure 10.

Figure 10 compares the peak particle velocity (PPS) of the soil versus the distance from the source of the vibration for different types of construction equipment and small diameter pipe bursting in soft soils and large diameter bursting in rock conditions. The PPS is the velocity of soil particles as they vibrate due to these construction activities. There is a strong correlation between the distance from the bursting head and the level of vibration for pneumatic bursting. As shown in Figure 10, the bursting vibration levels quickly fall to levels that do not cause damage to buildings. For structurally sound residential buildings, a safe distance (away from these structures) of eleven feet and eight feet are recommended for large diameter bursting in rock conditions and small diameter bursting in soft soils respectively. Safe distances of eight feet and four feet from nearby structurally sound commercial structures are recommended for bursting large diameter bursting in rock conditions and small diameter bursting in soft soils respectively. In addition, the statistical analysis indicates that the safe distance should be more than 7.5 feet from the buried structures. These pipes are mostly deep main lines installed in the right of way, which are usually far from the residential or commercial buildings.

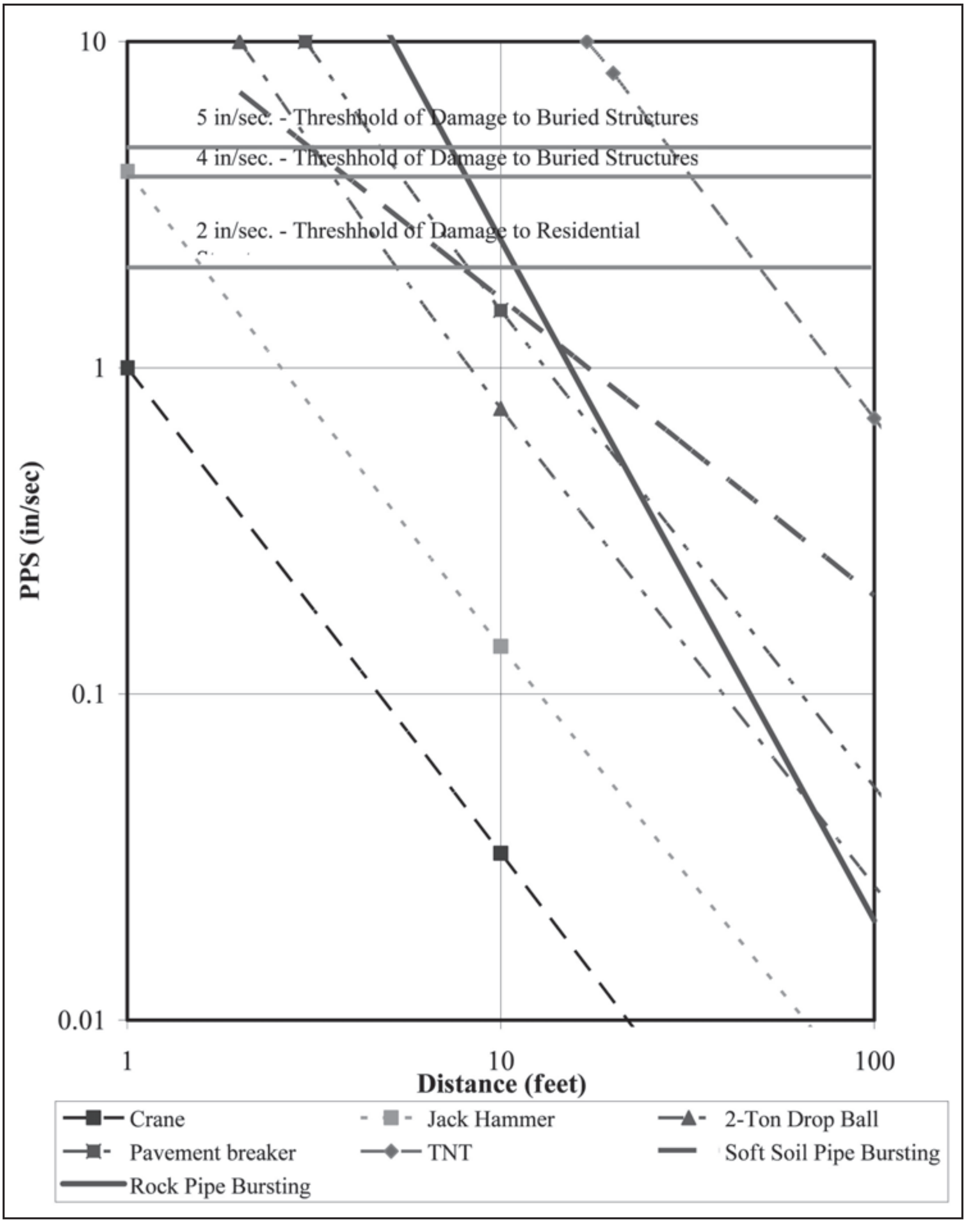


Figure 10 The Attenuation Lines of the PPS Versus Distance from the Source for Different Construction Pieces of Equipment (Wiss 1980) and the Attenuations of the 90% PI Upper Limit lines for the Pneumatic Bursting in Soft Soils (Atalah 1998) and Hard Soils (Atalah 2004).

Plans and Specifications

The contract documents typically include the contract agreement, general conditions, special conditions, project plans, specifications, geotechnical report, and CCTV records. The plans and specifications for pipe bursting projects should have all the required information for typical open cut water or wastewater pipeline projects plus the information listed in this section. The drawings should provide information about the existing site conditions and the required construction work. Description of site constraints (i.e., work hours, noise, etc.) and the procedures to review the CCTV data should be listed in the notes section in the drawings. The plans may also include information to show erosion and sediment control requirements, flow bypassing plans, and service connection and reinstatement details. Generally the plans should include:

- Limits of work; horizontal and vertical control references.
- Topography and survey points of existing structures.
- Boundaries, easements, and rights-of-way.
- Existing utilities, sizes, locations, and pipe materials.
- The verification requirements for existing utilities.
- Plan and profile of the design alignment.
- Existing point repairs, encasement, sleeves, etc.
- Construction easement and the allowable work areas around the insertion and pulling pits.
- Details for lateral connections and connections to the rest of the network.
- Restoration plans.
- Traffic control plans.
- Existing flow measurements for bypass pumping (Najafi 2007).

The technical specifications supplement the drawings in communicating the project requirements. Information to be included in the technical specifications should include:

General

- Minimum contractor qualifications.
- Permit matrix and responsibilities.
- Safety requirements with focus on confined space entry, flow bypass, and shoring.
- Scheduling requirements and construction sequence.
- Submittals.

Pipe and Manhole Materials

- Standards and tolerances for materials, wall thickness and class, testing and certification requirements.
- Construction installation instructions for pipe joining and handling.
- Fittings, appurtenances, and connection-adaptors.
- Acceptable material performance criteria and tests.

Construction Considerations

- Flow bypassing, downtime limits, and service reinstatement requirements.
- Spill and emergency response plans.
- Traffic control requirements.
- Erosion and sediment control requirements.
- Existing conditions documentation (e.g., photographs, videos, interviews).
- Protection plan for existing structure and utility (ground movement monitoring).
- Accuracy requirements of the installed pipe.
- Daily construction monitoring reports.
- Field testing and follow-up requirements for pipe joining, pipe leakage, disinfection, backfill, etc.
- Site restoration and spoil material disposal requirements (Najafi, 2007).

Submittals

In addition to the submittals needed for a traditional open cut projects, the submittals for pipe bursting projects usually include the following submittals: site layout plans, sequence of bursting, shoring design for all the excavations, bypass pumping plan, manufacturers' specifications of the selected bursting system and its components, dewatering plan, new pipe material, lateral connections material and plans, site layout plans, and so forth. The site layout plans would show the location of the insertion and pulling shafts, dimensions of shafts, traffic flow, safety and communication plan, storage space to store and lay the new pipe, and so forth. Lastly, the site restoration and clean-up plans should be included in the submittals

Quality Control/Quality Assurance Issues

The project specifications should state the quality control and assurance measures required to ensure that the project is executed according to the contract specifications. In addition to the quality control and quality assurance measures usually specified for a traditional open cut projects, there are a few measures that are specific to the pipe bursting operations. The project specifications should state the quality control and assurance measures required to ensure that the project is executed according to the contract specifications. These measures can take the form of tests, certifications, inspection procedures, etc. Extensive listing of the relevant required submittals, careful preparation of the submittals, and alert review and approval of the submittal are significant steps in the QC/QA program. The QC/QA program states the performance criteria for the product line and the acceptable tolerance from these criteria. For example, the invert of the new pipe should not deviate from the invert of the old pipe by more than a certain number of inches, the depth of sags in the line should not exceed one inch, and the difference in the vertical and horizontal dimensions of the new pipe diameter should not exceed 2%. The QC program should state how these performance criteria will be measured, tested, and checked. Some of these performance criteria that can be specified are post bursting CCTV inspection, pressure tests, and mandrel test. The surface and subsurface displacement-monitoring program should be outlined in the specifications along with the acceptable amount of ground movements. Certifications from the manufacturers of the bursting system, replacement pipe, and other material that these products meet the contract specifications based on tests conducted by the manufacturer or a third party may be required. For challenging projects, the presence of bursting system manufacturer representative at the jobsite may be required. The owner's quality assurance program should ensure that the field and management team of the contractor have the knowledge and the experience needed to complete the project successfully and able to respond appropriately to unforeseen problems.

Dispute Resolution Mechanisms

The contract should include different site conditions and unforeseen conditions clauses that allow contract time and amount adjustment if the conditions at site *materially* differ from the conditions expected and indicated in the bid documents. These clauses facilitate resolving disputes efficiently and quickly without negative impact on the project. If site conditions are significantly different than those described in the contract documents and the contractor or owner can show that the different conditions impacted the work, the contract value and duration should be adjusted accordingly. Conducting the proper surface and subsurface investigations, outlined earlier in this chapter, should minimize the occurrence of project disputes and possibility of work stoppage during the pipe bursting operations.

Maximum Allowable Tensile Pull

After the bursting head breaks the old pipe and creates a cavity in the ground, the winch pulls the new pipe through this cavity. For the pipe to be pulled, the pulling force has to exceed the friction between the outside surface of the pipe and the surrounding soils. When the coefficient of friction between soil and the pipe is high and the outside surface area of the pipe is large, high pulling forces are needed to overcome this high friction resistance. The high pulling force generates high tensile stresses on the replacement pipe. If the allowable tensile strength of the pipe is less than the anticipated tensile stresses on the pipe, actions to reduce friction must be adopted to avoid excessive strains in the pipe. Examples of these actions are increasing the diameter of the bursting head by about an inch to create about half an inch of overcut around the pipe, and injecting bentonite and/or polymer lubrication into the annular space behind the bursting head to reduce the frictional forces. If these actions are not sufficient to rectify the problem, shorter bursting run and relocation of the insertion or pulling shafts must be considered. Friction force calculations need to be conducted before bursting operation starts to avoid over stressing the pipe. It is much easier and less costly to incorporate the above-mentioned corrective actions before bursting than during bursting.

Typical safe pull tensile stress values for MDPE and HDPE are given in Table 2. Consult the manufacturer for specific applications. The values are given as a function of the duration of continuous loading. For pipe temperatures (not outside air temperatures) other than 73ºF, multiply the value in Table 2 by the temperature compensating multipliers found in Table B.1.2 of the Appendix to Chapter 3. The Safe Pull Load at 12 hours is given for many pipe sizes and DR's in Chapter 12, Tables 4 and 5 (3xxx material) and Tables 6 and 7 (4xxx material).

TABLE 2
Safe Pull Tensile Stress @ 73ºF

	Typical Safe Pull Stress (psi) @ 73ºF		
Duration (Hours)	**PE2xxx (PE2406)**	**PE3xxx (PE3408)**	**PE4xxx**
0.5	1100	1400	1500
1	1050	1350	1400
12	850	1100	1150
24	800	1050	1100

Note: The safe pull stress is the stress at 3% strain. For strains less than 3% the pipe will essentially have complete strain recovery after pullback. The stress values in Table 2 were determined by multiplying 3% times the apparent tensile modulus from the Appendix to Chapter 3 adjusted by a 0.60 factor to account for the high stress level during pullback.

Estimating the pulling force to break the old pipe and overcome friction resistance between the new PE and the surrounding soil is very difficult and currently there is no accurate method to calculate it. Many site and project factors interact to make developing an accurate and reliable model very difficult; among these factors: the strength of the old pipe, the type of backfill material, the type of native material, degree of upsize, bursting system, the amount of overcut, the presence of sags along the line, etc. Comparisons between the actual pulling forces and the calculated forces using the Terzaghi's Silo Theory that is used in calculating the jacking force in pipe jacking operations is presented later in this chapter.

Atalah et al (1998) instrumented two PE pipe with strain gauges and measured the strain in the pipe due to the pipe bursting process. They also calculated the friction resistance between the pipe and the soil using Terzaghi's silo theory. Figure 11 presents a comparison between the maximum stresses recorded in the pipe against calculated pipe stresses. The stress was calculated on the basis that the soil collapsed around the pipe and exerted a normal pressure on the pipe related to its depth below the ground surface similar to the frictional drag on jacking pipe. The assumptions for ground pressure and frictional resistance followed the typical assumptions for pipe jacking calculation presented in Atalah 1994 and Atalah 1996.

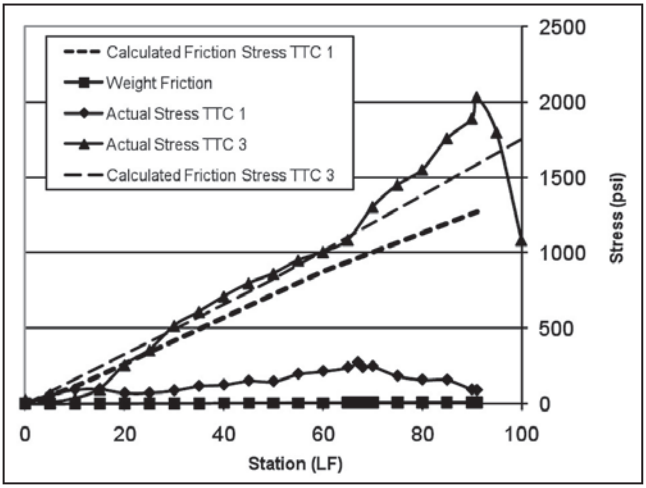


Figure 11 Actual Stress vs. Calculated Stress for TTC Test Site #1 and 3

As shown in the Figure 11 in TTC test site 1, there was substantially less frictional drag on the pipe than would be expected from a fully collapsed soil around the pipe. This indicated that the hole remained at least partially open during the replacement process. The cavity around the pipe stayed open during and possibly after the bursting because the nominal overcut was about 0.7 inch and the hammering action of the head compressed the surrounding soil. For the TTC test site 3, the measured data correlated well with the stresses that were generated from a collapsed soil around the replacement pipe over its full length. It is not clear why the friction on the pipe in this test is so much more than on the pipe in TTC Test Site #1 which had a larger upsizing. The following are the conclusions from these pipe stress measurements:

- Appear to match the range of stresses measured
- Measures to retard the collapse of soil around the replacement pipe will lower stresses in the replacement pipe

- None of the stresses measured exceeded about two-thirds of the yield stress of the PE pipe
- The level of stress in the replacement pipe was actually less for the pipe with larger upsizing percentage so there is not a direct relationship between upsizing percentage and replacement pipe stress
- The magnitude of the stress cycling in the replacement pipe during installation is small compared with the mean stress level

The pulling force must overcome the penetration resistance at the bursting head and the friction resistance along the outside surface of the pipe. The friction equals the outside surface area of the pipe times the soil pressure on the pipe times the friction coefficient between the soil and the pipe surface. A more detailed discussion about estimating the jacking force on jacking pipes is presented in Atalah 1994 and 1996. The frictional resistance, R, is calculated as follows:

$$R = \mu \times V$$

WHERE

μ = coefficient of friction.

V = the force perpendicular to the contact surface calculated using the Terzaghi's Silo Theory

There are two techniques to reduce the pulling force through the pipe: oversize cut and lubrication of the outside surface of the pipe. Oversize cut at the face reduces the puling force if the soil is highly stable. In unstable soil, oversize cut must be made nevertheless to allow lubricating the outside surface of the pipe, but it should be minimized. Lubrication around the whole perimeter of the pipe and along the whole length of the drive significantly reduces the friction resistance.

Permitting Issues

Permits from all the affected parties should be secured before the start of the bursting phase. Some of these permits could be secured by the owner and its representatives, and rest should be secured by the contractor. The permits responsibilities should be outlined in the specifications and stated on the drawings. Permits to burst under the road and to modify the regular traffic flow according to the project traffic control plan should be secured from owner of the affected road if the pipe crosses underneath a road. If the pipe crosses underneath a runway, taxiway, drainage ditch, irrigation channel or canal, and railroad track, permits should be secured from the owners of these facilities. Communications with the affected residents should take place before bursting to inform them about road closures, night or weekend work, service disruptions, driveway blockings and so on.

Typical Bidding Form For a Pipe Bursting Project

In addition to providing the owner with the total price of the project to compare the different bids, the bid form should provide the contractor and the owner with a mechanism for fair pricing and payment system based on the progress during construction. The unit prices in the form can also be used to resolve disputes amicably. It is recommended that the bursting is measured in linear feet and segmented by classification or sections from manhole to manhole or from insertion to pulling shaft. Segmentation by run or bursting class provides the owner and the contractor with fairer pricing mechanism and reduces and resolves disputes. Table 3 shows an example of a typical bid form for a pipe-bursting project (Bennett and Ariaratnam 2005).

TABLE 3
Example of Pipe Bursting Bid Form (Bennett and Ariaratnam 2005)

Item No.	Description	Quantity	Unit	Unit price	Total Price
1	Mobilization/Demobilization		LS		
2	Pipe Cleaning and Pre CCTV Inspection		LF		
3	Pipe Bursting of Exist. 6” VCP with New 9.05” O.D., SDR 17 PE Pipe (4’-8’ Deep) from MH 1 to MH 6		LF		
4	Pipe Bursting of Exist. 12” Class 250 Cast Iron Pipe with New 21.6” O.D. PE Pipe (8’-12’ Deep)		LF		
5	Pipe Bursting of Exist. 24” RCP with New 30” VCP (12’-16’ Deep) from MH 10 to MH 16		LF		
6	Pipe Bursting of Existing 4” Service Lateral with New 4.5” O.D., SDR 17 PE Pipe (4’-8’ Deep)		LF		
7	4” Lateral Connection to 9.05 O.D. SDR 17 PE Pipe (8’-12’ Deep)		EA		
8	6” Lateral Connection to Exist. MH		EA		
9	New PE Pipe Connection at MH		EA		
10	Furnish & Install 48” Dia. MH		EA		
11	Manhole Renewal		VF		
12	Cleaning, Testing and Post CCTV of New Sewer		LS		
13	Replacement of Unsuitable Trench Backfill Material		LS		
14	Bypass Pumping		LS		
15	Traffic Control		LS		
16	Pavement, Sidewalk and Curb Installation		LS		
17	Landscaping and Surface Restoration on Private Property		LS		

Please note that the lateral connections are accounted as a separate bid items and segmented by depth. Cleaning, testing, and post CCTV of the sewer line is a separate bid item. By pass pumping can be priced as a lump sum or measured by each run.

Selection of Pipe SDR

The PE pipes are available with iron pipe sized (IPS) or ductile iron pipe sized (DIPS) outside diameters. PE pipes are extruded with fixed outside diameter with variance in the inside diameter controlled by the Standard Dimensional Ratio (SDR) as shown in following equation:

$$\text{SDR} = \frac{\text{Pipe O.D.}}{\text{Wall Thickness of Pipe}}$$

The PE pipe should withstand the internal pressure requirements of the water or the force main line, overburden dead and live loads, and pulling forces during the bursting phase. The SDR of the PE pipe is a major factor in the ability of the pipe to withstand the installation forces and service pressures. Experience has shown that SDR 17 is sufficient for gravity sewer applications, and thinner wall pipes with SDR of 19 or 21 can be used in shorter and smaller diameter applications. Thinner wall pipes tend to stretch excessively during bursting. For pressure applications, if the maximum allowable design pressure is less than 100 psi, SDR of 17 is sufficient. If the maximum allowable design pressure is more than 100 psi, the allowable pressure governs the needed SDR. If the allowable pressure is 150 psi, PE pipe with SDR 11 meets needed pressure requirements.

In most trenchless applications, but not always, the pipe that withstands the pulling stresses during installation can withstand the vertical overburden and traffic pressures. The pipe stresses caused by construction are higher than those caused by vertical pressures. However, each application is different; it is possible that a specific application can require a different SDR. An engineering analysis is suggested for very deep or very shallow installations. Deep installations may be subject high overburden pressures, and shallow installations may be subject to high concentrated traffic loads that the pipe has to withstand.

Section 2 of Chapter 6 in this Handbook presents how to calculate the live loads on the pipe and stress distribution of live load with depth using the Timoshenko and Boussinesq equations to calculate the live load at the centerline of the pipe. The over burden pressure in trenchless applications can be calculated using the Terzaghi’s Silo Theory.

Terzaghi’s Silo Theory

Terzaghi established a calculation model to estimate the normal pressure acting on the pipe from vertical load and soil arch action. Terzaghi’s theory presents the load on the pipe in a similar form to that of the horizontal earth pressure theory. The following equation gives the normal pressure on the pipe (P) as a function of soil density (w), depth of cover to center-line of the pipe (H), vertical live load at the pipe level (PL) and coefficient of soil load (k).

$$P = k\,(w\text{x}H + P_L)$$

The coefficient of soil load (k)

$$k = \frac{1 - e^{-2K \times \tan\delta \times H / B}}{2K \times \tan\delta \times H / B}$$

WHERE

K **= soil lateral pressure coefficient**

δ **= angle of wall friction between pipe and soil**

B **= the influence width above the pipe.**

According to the German Association for Water Pollution Control (ATVA 161), the values of these variables are: K = 0.5, δ = 0.5F (angle of internal friction of soil) and B= 1.73d (the outside diameter of the pipe). Figure 12 presents the value of k as a function of F and the ratio H/d for K= 0.5. On the other hand, in Japan, K= 1, δ= F and b= δ(0.5+tan(45-F/2) are used in the above equation. Although ground water does not significantly influence the soil friction, the ATVA 161 specifies, for safety reasons, that the full soil load should be applied in case of jacking below the ground water table. If the surrounding soil is swelling soil, additional swelling pressure must be considered (Stein 89).

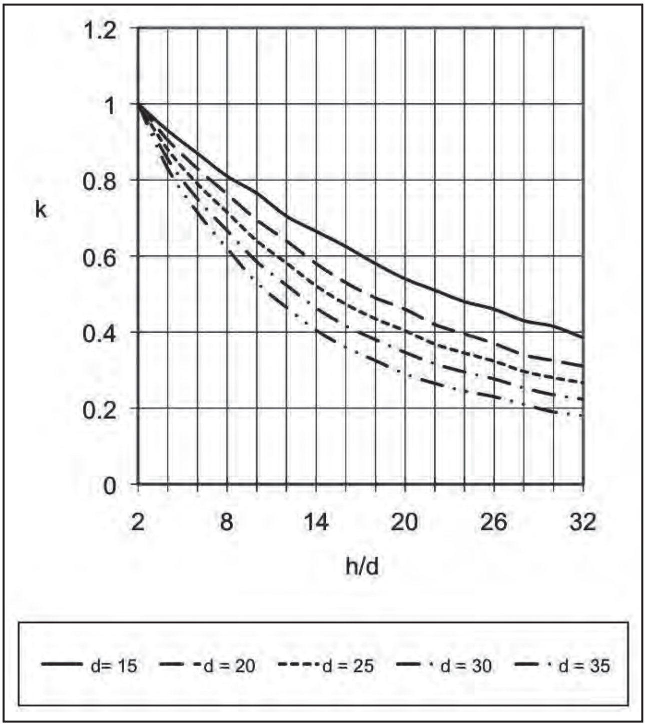


Figure 12 Reduction Factor k According to ATVA 161

Construction Considerations

Once the owner issues the notice to proceed, the contractor prepares the submittals for the project according to bid documents. Typically, the contractor takes the following steps:

- Pre-construction survey
- Cleaning or pigging of line, if needed
- Closed circuit TV inspection, if needed
- Excavations at services for temporary bypass
- Setting up temporary bypass or connections to customers
- Excavation of insertion and pulling shafts
- Fusion of PE
- Setting up the winch or hydraulic pulling unit and insertion of pulling cable or pulling rods inside the old pipe.
- Installation of hoses through the PE pipe to attach to bursting head (air supply hoses or hydraulic hoses for pneumatic or hydraulic systems respectively)

- Connection of bursting head to pulling cable or rod
- Pipe bursting and replacement with new pipe
- Removal of bursting head and hoses from the pipe
- Post installation inspection
- Pipeline chlorination if it is not pre-chlorinated (for water mains)
- Reconnection of services and reinstating manhole connections
- Site restoration

Butt fusion of PE replacement pipe is typically carried out prior to the bursting operation, so that all fused joints can be chlorinated (for water lines), checked, and tested. The pipe should not be dragged over the ground, and rollers, pipe cutouts, or slings should be used for both insertion and transportation of the pipe. The ends of water or gas pipes should be capped to prevent the entry of contaminants into the pipe.

Typical Pipe Bursting Operation Layout

The first step in planning the pipe bursting operation is the optimization of the locations of the insertion and pulling shafts by using the insertion shafts to insert the new pipe into two directions. This optimization reduces the amount of excavation, mobilization, and demobilization efforts. These shafts should be planned at manholes or lateral connections in sewer lines and at fire hydrants or gate valves in water applications. The length of the run between the insertion and pulling shafts should not generate friction forces that exceed the capabilities of the bursting system and the tensile strength of the pipe. The next step is ensuring that the area around every shaft is sufficient for safe operation of the needed pieces of equipment and material staging. The insertion shaft has a flat section and sloped section; the flat portion has to be long enough to allow aligning the centerlines of the bursting head with that of the old pipe. The slopped section has to be long enough to allow the PE pipe to bend without any negative impact on the pipe (i.e. accommodate the bending radius requirements of the pipe). PE pipes can be cold bent to a radius of 25 to 30 times the OD of the pipe depending on its SDR. Because of the pipe's ability to bend, the lay down area of the pipe prior to insertion does not necessarily have to be in line with the existing pipe. For example for an 18" PE pipe with an SDR of 17, the minimum length of the insertion shaft is a horizontal length of 12 times the diameter of the new pipe (18 feet) plus a sloped length of 2.5 times the depth of the shaft as shown in Figure 13 (Bennett and Ariaratnam 2005). The width of the pit depends on the pipe diameter and required working space around the pipe. The pulling pit must be large enough to allow for operation of the winch or pull-back device, along with removal of the bursting head.

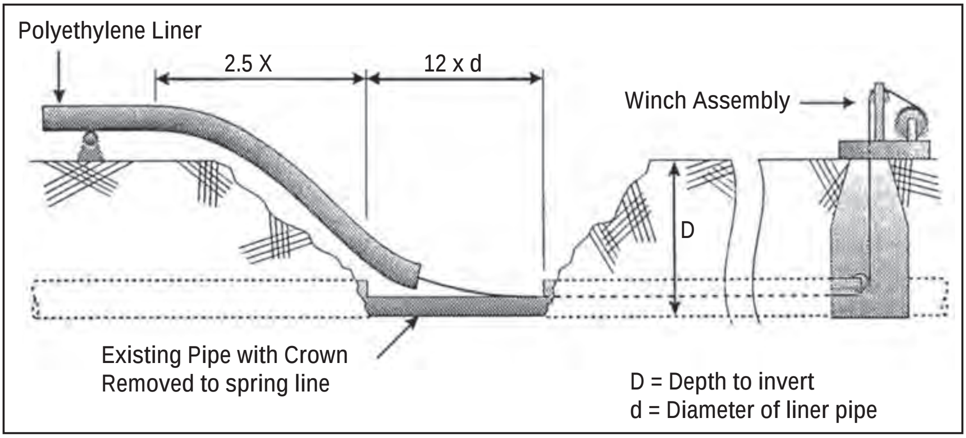


Figure 13 Insertion Shaft Dimensions for PE Pipe with SDR 17 (Bennett and Ariaratnam 2005)

Acceptable arrangements for traffic control, based on DOT and local government regulations, and for stretching the fused PE pipe with minimum inconvenience to nearby residents and businesses must be carefully considered. The flow bypass pumping and pipes layout should be also planned and considered. If dewatering needs arise, safe and proper flow discharge plans are required. The contractor submits the jobsite layout plan that reflects the intended method of construction and addresses the above mentioned considerations. The contractor does not start bursting before the engineer reviews and approves the jobsite layout plan, and the site inspector enforces the adherence to this plan unless there is a reason for the deviation approved by engineer or owner. If contaminated soil is excavated, the contractor should take the necessary measures to handle and dispose of this contaminated soil.

Shoring The Insertion and Pulling Shafts.

Proper shoring of the insertion and pulling shafts is essential for the safety of the workers and the safety of the surrounding environment. The trench shoring or bracing should be constructed to comply with OSHA standards. Some of the available means of shoring these shafts are: trench box, solder pile and lagging, steel sheet piles, corrugated pipes, etc. Also, if space is available, sloping the sides of the shaft to provide stability is an option. The judgment and the supervision of a competent person (as defined by OSHA) or a qualified geotechnical engineer is needed to ensure safe shoring.

In the pulling shafts, the winch will thrust against manhole wall or one side of the pulling shaft. This side has to be able to withstand the pressure coming from the pulling winch. Therefore, a thrust block or structure is needed to distribute the force over a larger area. In the static pull applications, the contractor should construct a thrust block against which the pulling system thrusts during pulling and bursting. The thrust block, shoring, and soil behind the shoring must be able to withstand the stresses from the pulling system. The passive earth pressure of the soil has to exceed the stresses generated by the pulling system with an acceptable factor of safety.

Matching System Components to Reduce Risk of Failure

One of the most critical activities before bursting is to ensure that the bursting system has sufficient power to burst the old run from the insertion shaft to the pulling shaft. The system must be able to overcome the friction between the soil and the outside surface of the new pipe and the soil with reasonable margin of safety to overcome unforeseen repair sleeves, clamps, etc.

The contractor should adhere to the sizing guidelines stated in the operations manual issued by the bursting system manufacturer to match the system with the needs of the job. The bursting system manufacturer should be consulted if there is any doubt regarding the adequacy of the system for that specific run in that particular conditions (soil, depth, type of pipe, etc.). Lubricating the outside surface of the pipe with polymer or bentonite (depending on the type of soil) can dramatically reduce the coefficient of friction between the pipe and the soil, and consequently, reduce the needed pulling force. In addition, the bursting system components should be appropriately matched to the need of the project; for example, the winch capacity is matched with the bursting head size and the conditions of the job.

Toning for Utilities

The contractor should do its due diligent to identify, locate, and verify the nearby underground utilities prior to digging the shafts and bursting. The contractor must contact the one state call center to have representatives of the nearby utilities come to the site and mark the existing utilities on the ground surface. Then the contractor has to verify the exact location and depth of these utilities via careful excavation. Manual excavation may be needed for the last few inches from the existing utilities to avoid damaging this utility. Vacuum excavation is an excellent tool to expose utilities with minimum surface excavation and minimum risk to the existing utility.

The underground utilities that are in moderate condition are unlikely to be damaged by vibrations at distances of greater than 2.5 feet from the bursting head in small (less than 12 inch in diameter) typical pneumatic pipe bursting operations (Atalah 1998). According to Atalah (2006), this safe distance for large diameter bursting (up to 24 inch) is about seven feet. Rogers (1995) reported that ground displacements are unlikely to cause problems at distances greater than 2-3 diameters from the pipe alignment. Utilities that are closer to the bursting head than these distances should be exposed prior to bursting so the vibration from the bursting operation would be isolated or reduced before it reaches the utility in question.

By Pass Pumping Considerations

One of the objectives of the bursting team (owner, engineer, contractor, etc.) is to minimize customers' service interruptions for water and gas applications and continuation of flow for sewer applications. The key for achieving this objective is the bypass pumping system. For water applications, the system should be able to deliver the needed flow volume with the specified pressure to the customers. For gravity applications, the system should be able to adequately pump the upstream flow and discharge it to the manhole downstream of the run being burst. The plan should ensure that the bypass system has adequate pumping capacity to handle the flow with emergency backup pumps to ensure no interruption to existing services. The bypass pipes and fittings should have sufficient strength to withstand the surge water pressures. Contractual arrangements between the owner and contractor should be made regarding third party damage due to the disconnection and reconnection of the water lines without fault of the contractor.

Dewatering Considerations

The pulling and the insertion shafts should be dry during installation to avoid disturbing the sub-grade in the shaft. Therefore, if rain is expected or the pipe invert is slightly below the GWT in clay soil, installation of a dewatering sump pump at one corner of the shaft is needed. Ditches crossing the shaft, sloped towards the sump, lined with filter fabric, and filled with gravel may be needed to direct the water towards the sump. If the pipe invert is significantly below the GWT in sandy or silty soils, more elaborate dewatering system is recommended such as well point system, deep wells, or larger sump and pump system. As the water level is drawn down, soil particles travel with the water towards the dewatering system undermining utilities and structures. As it is the case with every dewatering system, the contractor should take all necessary measure to prevent the migration of the soil particles from underneath nearby buildings and utilities. The discharge flow volume in this case is expected to be large; therefore, a suitable discharge in compliance with the EPA requirements is needed. If sump pump is used, preliminary treatment of flow to reduce the sediments may be needed before discharging into water streams.

Ground Movement Monitoring Program

The safety of nearby buildings and structures is paramount as it is the case in deep open cut installations. The safety of nearby structures can be compromised if the structures are subject more ground movements or vibration than what they can withstand. Referring to extremely challenging pipe bursting operations (class C—see Table 1), preconstruction survey and monitoring of the ground movement is advisable if there are nearby structures. A preconstruction survey of all nearby buildings and structures that documents all existing cracks, cosmetic problems, and structural deficiencies is recommended prior to any work on site. The elevations of carefully planned settlement points (on nearby buildings and on the ground surface) around the insertion and pulling shafts should be surveyed prior to bursting, during bursting, and after bursting. These preconstruction surveys and elevations monitoring can significantly reduce the risk of unmerited law suits to the contractor and the owner.

Pipe Connection to the Manhole

The thermal elasticity of the PE material causes changes in the pipe length; one inch change in length per 100 ft of pipe for each 10°F temperature change. Therefore, in extreme hot or cold weather when there is significant difference between the temperature of the deep soil and the ambient air temperature, it is recommended to allow the pipe to rest for 12 to 24 hours prior to tie-ins. Also when pipe has been pulled to a significant portion of its allowable tensile load, it may be prudent to let the pipe rest as well before connecting to other pipes, fittings, manholes, and lateral connection. This allows the pipe to rebound from any stretch that may have occurred during bursting. Chapter 9 presents in more detail the PE pipe joining procedures.

In most pipe bursting applications, the sewer line is old and deteriorated and so are the manholes along the line. It is economical on the long run in most cases to replace the old deteriorated manholes and use their location as pulling or insertion shafts. When existing manholes are replaced with new ones, connections to PE pipe can be made using flexible rubber manhole connectors called boots. A pipe clamp is used to tighten the boot around the PE pipe as shown in Figure 14.

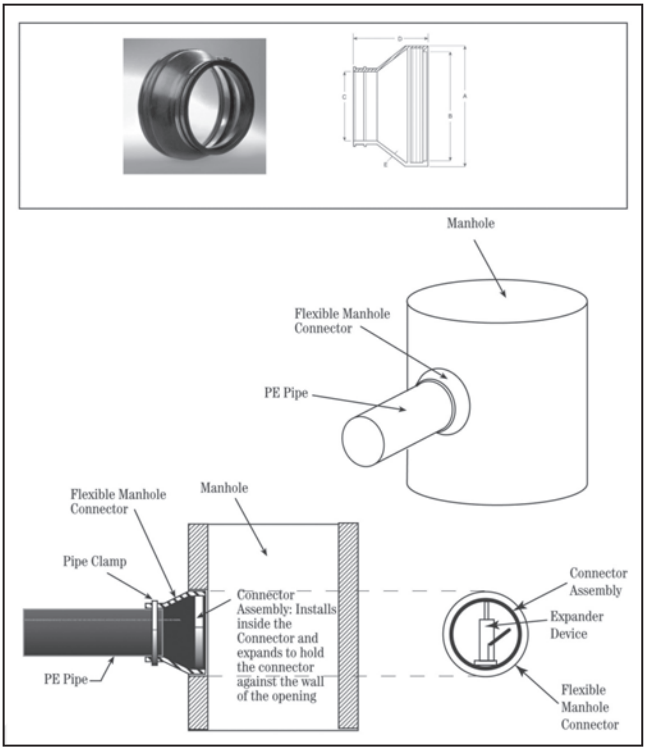


Figure 14 Connecting PE Pipe to New Concrete Manhole

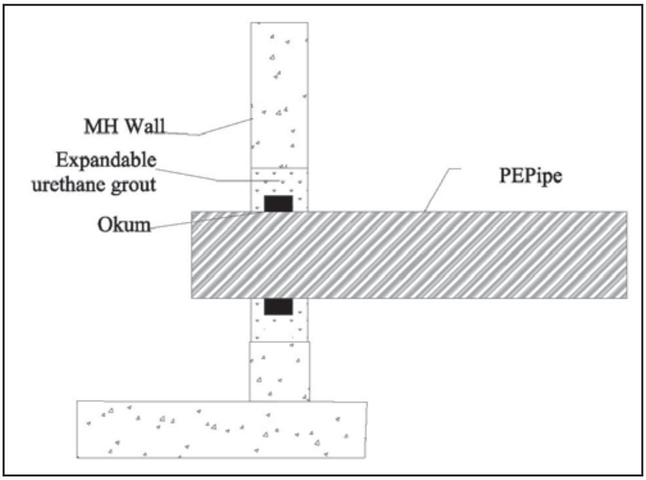


Figure 15 Connecting PE Pipe to Old Manhole

If the old manhole is in reasonable conditions and it is economical to use it after bursting, the manhole benching is removed and the pipe opening is enlarged to allow the passage of the bursting head. Expandable urethane grout and oakum can be used to create a seal between the exiting pipe opening and the PE pipe as shown in Figure 15. The compression allows pipe movement.

Frequently, when pipe bursting the inlets and outlets of the manhole are damaged, the resulting inlet or outlet is no longer round. A low shrink polymer cement grout is used to repair the damage. To get a good seal to the PE pipe, special PVC fitting with bell end and sand adhered to the outer surface (as shown in Figure 16) is used. The grout bonds to the manhole and the rough sandy surface of the PVC fitting giving a good seal. The gasket between the PVC fitting and the PE pipe allows the PE pipe to move if expansion or contraction occurs. The PVC fitting requires PE pipes with SDR of 21 or lower.

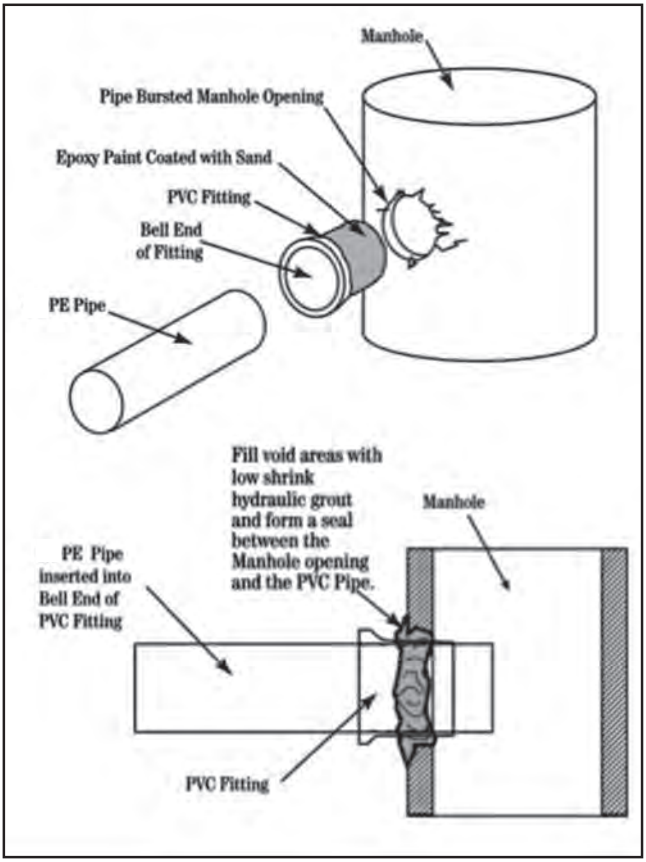


Figure 16 Connecting PE Pipe toOld Manhole with Damaged Inlets/Outlet

Pipe Connection to Other Pipes

PE pipes are joined to other PE fittings by heat fusion or mechanical fittings. They are joined to other material by means of compression fittings, flanges, or other qualified transition fittings (PPI).

Pipe Bursting Water Mains

The most common materials for existing water mains are cast iron, ductile iron, and PVC. All three can be replaced by pipe bursting but each requires a different piping burst approach. Cast iron pipe is a relatively brittle material, and therefore, basic pipe bursting system is sufficient. PVC pipes require multi-blade cutting accessories in front of the bursting head to facilitate cutting the pipe. Ductile iron pipe is not brittle; therefore, pipe splitting is the most suitable bursting system.

Valves are connected to PE pipe using mechanical joint (MJ) adapters, which is butt fused to the PE pipe. A gland ring is then used to make a restrained connection to ductile iron valves. Figure 17 shows connections to PVC or ductile iron pipes can be made using a female MJ connector, which is butt fused to the PE pipe. This connection provides a restrained connection.

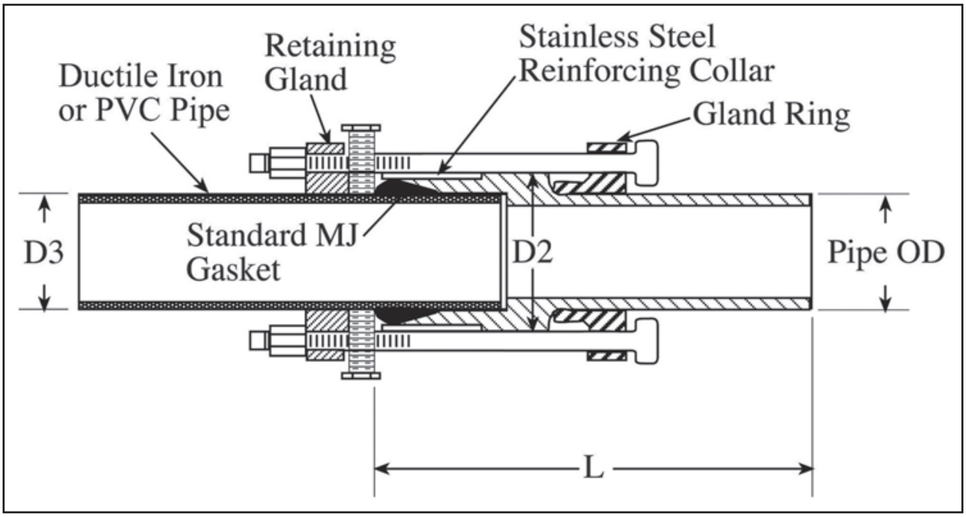


Figure 17 Connection to Existing PVC or DI Pipes Using Female MJ Adapter

Service connections can be attached to PE pipe using mechanical saddle connections or electrofusion saddles. Figure 18 shows an electrofusion saddle with a cutter attached; it is easy to hot tap PE pipe lines.

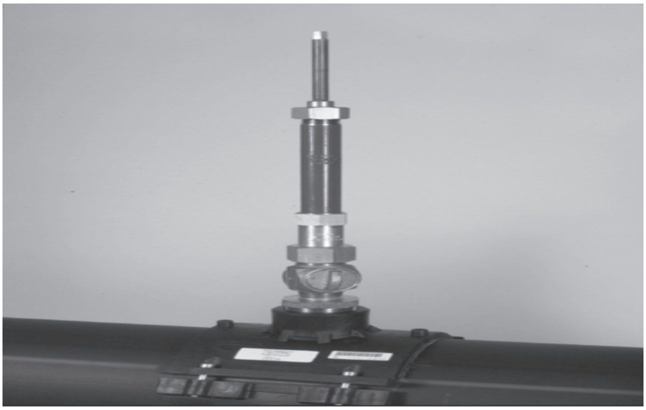


Figure 18 Electrofusion Saddle with a Cutter Attached

During installation, a temporary above ground PE pass is installed to continue to supply water to the home owners while the main line is under construction. Figure 19 shows an example of above ground PE bypass pipe.

The PE pipe can be pre-chlorinated prior to bursting to reduce the overall installation time and inconvenience to the home/business owners.

Figure 19 Example of Above Ground PE Bypass Pipe

Service Connections

The lateral connections and material plan stated in the submittal list should explain the proposed material and connection procedures. Video inspection of the original sewer line normally provides the location of service connections. In replacing water and gas lines, metal detectors can be used. Standard practice is to locate and expose services prior to pipe bursting. Service connections can be made with Inserta Tee®, specially designed fusion fittings, or strap-on saddles.

Figure 20 Inserta Tee® Fittings for Sewer Lateral Connections

For sewer applications, after service connections are excavated, a "window" is cut in the PE pipe wall, and then one of the above fittings connects the new PE pipe to the lateral connection. Inserta Tee® connection is a three piece service connection consisting of a PVC hub, rubber sleeve, and stainless steel band as shown in Figure 20. Inserta Tee® is compression fit into the cored wall of a mainline and requires no special tooling. Inserta Tees® are designed to connect 4 inch through 15 inch services to all known solid wall, profile, closed profile, and corrugated pipe. The PE lateral connection options are fusing a lateral PE pipe to the main line and Electrofusion sewer saddle. Fusing a lateral PE to the main PE line requires curved iron that allows heating the ends of both pipes. This connection require highly skilled fusion worker because it is usually made in small muddy space. Electrofusion saddle is mounted on the opening for fusion with the main line as shown in Figure 21. Careful considerations are needed to ensure that all exposed surfaces are cleaned and maintained in an acceptable condition for the fusion operation. Strap-on saddles use a PE or PVC saddle that are lined with a rubber layer; the saddle is trapped around the main line using a stainless steel strap as shown in Figure 21. After testing and inspecting the line and the connection, the excavation is backfilled and line returns to service. More service connections details for gravity and pressure applications are presented in Chapter 9 in this Handbook.

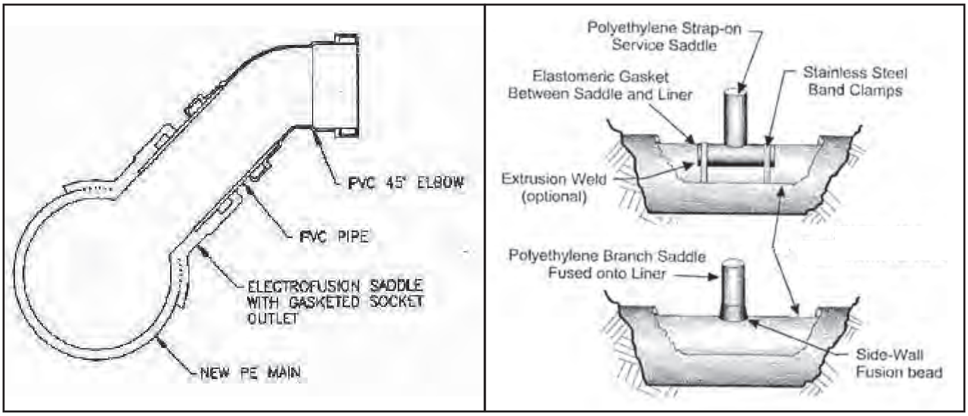


Figure 21 Pipe Fusion and Strap On Saddle Lateral Connections

Groves on the Outside Surface of the Pipe

One common misconception about bursting is that the existing pipe fragments from the old pipe can damage PE pipe during bursting. British Gas conducted study on bursting cast iron pipes and concluded that there was no damage to the PE. The pipe bursting research conducted at Louisiana Tech University and Bowling Green State University indicated the groves are very shallow and narrow when bursting clay, asbestos, and concrete pipes. The widest grove was 0.07 inch and depth of the deepest grove was 0.03 inch with no damage to the PE. CI, clay, concrete, and asbestos pipes generally break off without sharp shards that do not puncture PE (Atalah 1998 and 2004). The exception to this rule occurs when trying to significantly upsize ductile iron (DI) pipe. It is recommended to limit PE pipe to size-on-size bursting or a single upsize when bursting DI pipes. If larger upsize of DI pipe is required, PE pipes with harder outside shell similar to ones shown in Figure 22 can be used. If the PE will be dragged for a long distance over rough pavement, the contractor can reduce the risk of scratching the pipe by placing it on cut-outs of old PE or PVC to keep the pipe higher than the pavement. Sometimes the contractor needs to press on the PE with bucket of the excavator to ensure that the PE pipe is aligned with the old pipe at the entry point in the insertion shaft because the shaft is not long enough. Welding wheels similar to the one shown in Figure 23 reduces the risk of groves or scratches on the PE pipe. When the head end of the pipe reaches the pulling shaft, the pipe should be inspected for surface damage. Surface scratches or defects in excess of 10% of the wall thickness should be rejected.

As-Built Drawing

As built drawings are usually required for any underground utility construction as well as pipe bursting projects. The bursting contractor should mark the new line, manholes, ancillary structure information on a copy of the plans marked as and dedicated to the as-built. On these plans, the contractor should document any changes to the original layout of the underground utilities and structures that took place during the construction phase. For example, rerouting any utility due to the excavation of the shafts, reconfiguration of other utilities needed for bypass pumping, etc. should be marked on the as-built drawings. These changes shown on the as-built drawings should be verified and used to update the as-built electronic files for the locality.

Figure 22 Protecting the PE Pipe from Shards

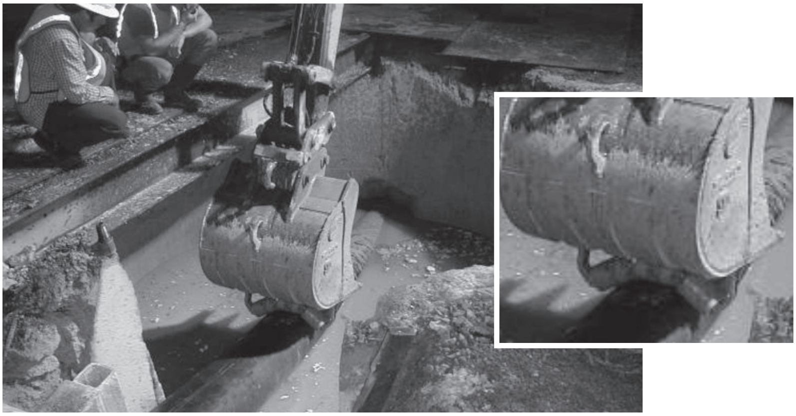


Figure 23 Protecting the PE Pipe from Groves Using Welded Wheels on the Bucket

Contingency Plan

An important submittal is the contractor's contingency plan. Most contractors have contingency plans that include planned corrective actions if certain events take place. Pipe bursting projects require adding a few specific additions to this standard contingency plan. Some of these specific events that are unique to pipe bursting and need to be addressed include:

- There is more than allowable ground movement or vibration
- The bursting progress is slow or the bursting head is stuck
- Problem with the bypass system and with diverting and reconnecting the services to the customers
- Damage to existing waterline, gas line, sewer line, power cable
- Dewatering problem in the insertion or pulling shaft or at lateral connection pits.

Safety Considerations

The standard safety procedures, adhered to in typical open cut construction, should be followed in bursting projects. Additionally, the workers should understand the components of the bursting system and how they work with special attention to the moving parts in the system. The involved workers should be trained on and equipped with the needed tools for confined space entry because the workers work in live sewers during flow bypass and diversion, which takes place mostly inside a manhole. The winch should thrusts against a thrust block that (along with the soil behind it) should withstand the forces of the winch. The stability of the soil behind the thrust block should not be compromised. During the flow bypass, the upstream pipe will be plugged; these plugs should be braced and preferably remotely inflated and deflated. Prior to bursting, the contractor has to ensure that there is no unforeseen gas line or power line close to bursting head.

Cost Estimating

Estimating pipe bursting projects for bidding purposes needs to be detailed, methodical, and systematic as it is the case for open cut installations. For each run, the contractor has to estimate the labor, material, and equipment needed for excavation and shoring of shafts, shaft bottom stabilization (concrete or gravel), bursting system set up, pipe fusion, lateral connection excavation, bypass pumping, bursting, service reconnection, shaft backfill, surface restoration, and potential dewatering.

As shown in Figure 7, the cost per foot of pipe bursting installations are less than that of open cut in unfavorable situations. The figure also shows that that cost is less than that of open cut in favorable conditions if the depth of cut is more than 10 feet.

Bennett and Ariaratnam (2005) presented Table 4 which shows the unit cost from several pipe bursting projects with different sizes and upsize percentages in North America.

TABLE 4
Example Unit Cost from Various Pipe Bursting Projects

Project #	Existing to New Pipe Information	Length	Overall Cost/LF
1	6” VCP to 8” PE	8,500 LF	$80
2	8” conc. to 12” PE	350 LF	$200
3	8” conc. to 14” PE	700LF	$215
4	10” PVC to 16” PE	520 LF	$230
5	12” AC Pipe to 14” PE	2640 LF	$160
6	24” RCP to 24” VCP	521 LF	$380

In 1999, the Trenchless Technology Center surveyed several municipalities and contractors for bidding prices per linear foot. The bid prices ranges for size to size replacement using pipe bursting for different pipe diameters are shown in Figure 24. The bid prices ranges for upsizing less than 20% and upsizing larger than 20% using pipe bursting replacement of different diameters pipes are shown in Figure 25 (Simicevic and Sterling, 2001).

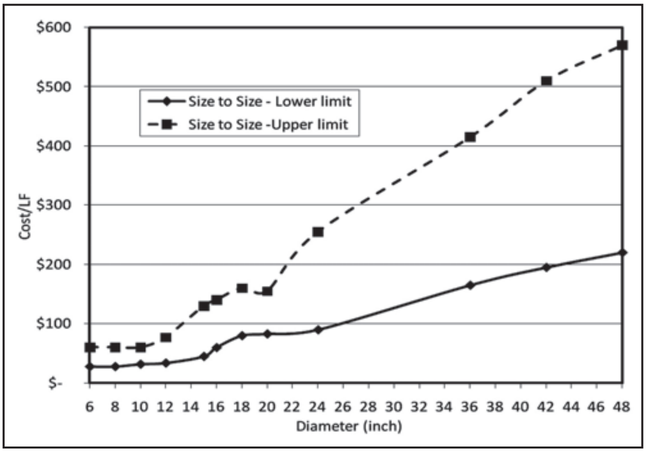


Figure 24 The Bid Prices Ranges for Size to Size Replacement for Different Pipe Diameters

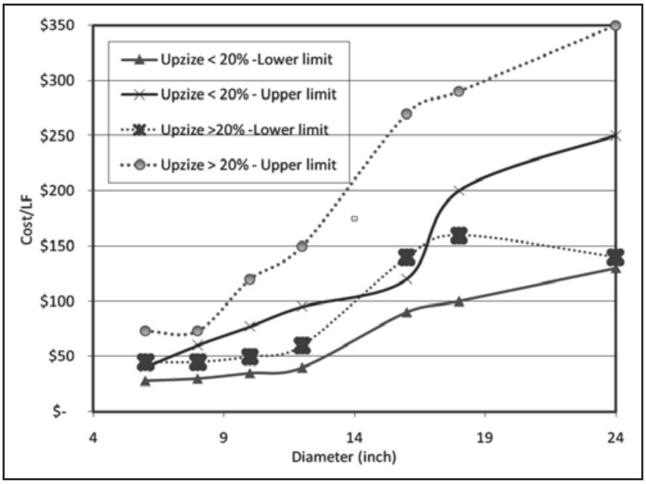


Figure 25 The Bid Price Ranges for Upsizing Less than 20% and Upsizing Larger than 20% Using Pipe Bursting Replacement of Different Diameter Pipes

Potential Problems and their Possible Solutions

The best option for dealing with the pipe bursting problems is avoiding them or reducing the probability of their occurrence by properly following the design and construction precautions mentioned thus far in this chapter. However, if some of these precautions are not followed or unforeseen conditions occur, this section attempts to provide actions that help avoid these troubles or correct them when they occur. Some of the potential problems associated with pipe bursting include sag correction, soil displacement, protecting utilities, bursting system selection problems, unforeseen obstacles, and site restrictions.

If the sewer line has excessive sags in it, these sags have to be repaired prior to bursting using any of the earlier – discussed techniques. However, if they were discovered after bursting, the contractor can fix the sag by digging this spot and improving the soil under the pipe. Replacement of a section of pipe may be needed at this excavation. If the excavation at this spot is not feasible, grouting and stabilizing the soil underneath the pipe can be a solution.

If excessive ground movement is anticipated very close to an existing structure, a ground movements and vibrations monitoring plan should be developed. If dangerous movements are observed, slowing the rate of bursting is mandated. If the movement is still high, bursting should be halted until analysis of the causes and corrective options is studied (including the option of abandoning the pipe bursting method). If there is a gas line, water line, or sewer line that is too close to the bursting head and is at risk of damage, exposing the line reduces this risk significantly. The excavation to expose this utility should be done using means that do not damage the line such as vacuum or manual excavation. If the pipe is shallow and there is a high risk of damaging the surface pavement, saw cutting the pavement prior to bursting prevents the spreading of the damage to the rest of the pavement. Later on, the pavement over the trench can be replaced.

If the bursting is significantly slower than expected, the contractor should investigate the reason and study the available corrective actions. Here some potential reasons for slow bursting:

The bursting system does not have sufficient power relative to the bursting applications (upsize percentage, large diameter, length, etc.). If this problem takes place shortly after the start of the run, the solution is replacing the system with a more powerful one. If it takes place close to the pulling shaft, continue until the bursting head reach the pulling shaft and replace the system before the next run if the reason of the slow down is not a repair ductile clamp or a fitting. Also in this case, consider shorting the length of the runs. If this problem takes place in the middle of the run at location where excavation is feasible, dig shaft on top of the bursting head and replace the system. The new shaft can be an insertion shaft for the remainder of the run.

Certain components or accessories of the system (for example, the winch, air compressor, hydraulic components, cutting accessories in front of bursting head, etc) are under sized or unmatched. Adding accessories in front of the bursting head to cut PVC fitting, ductile clamps or fittings, etc. reduces the potential of stopping or slowing the bursting. Upsizing these components (within the allowable range of that system) is the recommended solution. Matching the system and its components and accessories with the needs of the bursting jobs may solve the problem.

There are obstacles such as ductile repair fittings, concrete encasement, or change in the existing pipe material along the line. If the obstacle is close to the pulling shaft, continue bursting slowly until the head reaches the pulling shaft. If the obstacle is far from the pulling shaft, rescue shaft to remove the obstacle, change the bursting head, or add/change cutting accessories.

The soil around the pipe is flowing or running and is causing excessive friction. Lubrication of outside surface of the pipe with suitable lubricant is an effective way to reduce required pulling force on the PE pipe by reducing the friction between the pipe and the soil. The key to apply this solution is setting a lubrication manifold and lubrication line before bursting start to pump the lubrication during bursting.

Breaking the old pipe in running soil below the GWT fills the pipe with dirt so that the operation turns from bursting to piercing. The first step is to make sure that bursting head did not damage any nearby water line then dewater the site.

It is critical that the contractor ensure that the replacement pipe meets the specification before, during, and after bursting. Adhering to the quality control and quality assurance plans during the manufacturing and shipping to the site along with proper unloading of the pipe reduces risk of pipe failure. It is recommended that the pipe fusion is performed by certified and well trained workers under appropriate supervision to reduce the risk of pipe failure later when repair is difficult and costly. For pressure application, the PE pipe should be inspected and pressure tested before bursting.

References

Atalah A. (2006), "The Safe Distance between Large-Diameter Rock Pipe Bursting and Nearby Buildings and Buried Structures," ASCE Journal of Transportation Engineering. April 2006, Volume 132.

Atalah, A. (2004), "Ground Movement in Hard Rock Conditions Related to Pipe Bursting," ASCE Pipeline Specialty Conference, San Diego, CA; August 2004.

Atalah, A. (2004), "The Ground Vibration Associated with Pipe Bursting in Rock Conditions," North American NO-DIG 04, Annual Conference of the North American Society of Trenchless Technology, New Orleans, LA; March 2004.

Atalah, A. (2003), "The Ground Movement Associated With Pipe Bursting in Rock Conditions and its Impact on Nearby Utilities and Structures," International NO-DIG 03, Annual Conference of the North American Society of Trenchless Technology, Las Vegas, NV; April 2003.

Atalah, A. (2004), "The Ground Movement Associated With Large Diameter Pipe Bursting In Rock Conditions And Its Impact On Nearby Utilities And Structures," Bowling Green State University, Bowling Green, Ohio.

Atalah, A (2001) 'Cost Comparison between Open Cut Construction and Pipe Bursting for the Repair of Tripler Army Medical Center Sewer Line Project', North American NO-DIG 2001, Annual Conference of the North American Society of Trenchless Technology, Nashville, TN.

Atalah, A. (1998). "The Effect of Pipe Bursting on Nearby Utilities Pavement, and Structures." Dissertation in Partial Fulfillment of the Requirement for the Degree Doctor of Engineering, UMI Microform 9829093.

Atalah, A. (1996), "Design of Microtunneling and Jacking Pipe," ASCE Specialty Conference-Pipeline Crossings 1996, Burlington, VT; June 1996.

Atalah, A., T. Iseley, and D. Bennett (1994), "Estimating the Required Jacking Force," NO-DIG 94, Annual Conference of the North American Society of Trenchless Technology, Dallas, TX; April 1994.

Boot J., G. Woods and R. Streatfield, (1987), On –line Replacement of Sewer Using Vitrified Clayware Pipes, Proceedings of No-Dig International '87, ISTT, UK

Bennett R. D. and S. Ariaratnam, S. Khan (2005), "Pipe Bursting Good Practices," North American Society for Trenchless Technology, Arlington, VA.

Fraser, R., N. Howell and R. Torielli (1992) 'Pipe Bursting: The Pipeline Insertion Method', Proceedings of No-Dig International '92, Washington DC, ISTT, UK.

Hayward P. (2002) 'Pipe Replacement Systems', Nodig International, June 2002, page 15

Howell, N. (1995) 'The PE pipe Philosophy for Pipeline Renovation', Proceedings of No-Dig International 95, Dresden, Germany, ISTT, UK

Jadranka Simicevic, Raymond L. Sterling (2001). Guidelines for Pipe Bursting TTC Technical Report #2001.02, pp 47

Lindeburg, M. (1992) *Civil Engineering Reference Manual for the PE Exam*. Professional Publications Inc.

Najafi, M. (2007), "Pipe Bursting Projects - ASCE Manuals and Reports on Engineering Practice No. 112," American Society of Civil Engineers, Reston, VA.

NASTT (2008), Glossary of Terms, URL http://nastt.org/glossary.php?index=P, North American Society for Trenchless Technology, Arlington, VA.

PIM Corporation (2007), "ConSplit ductile pipelines quickly and cost-effectively," URL http://www.pimcorp.com/consplit.html, Piscataway, NJ.

Poole A., R. Rosbrook, and J. Reynolds (1985) 'Replacement of Small-Diameter Pipes by Pipe Bursting', Proc. of 1st Intl. Conf. on Trenchless Construction for Utilities: No-Dig '85, April 16-18, London, UK.

Project Management Institute Inc. (2004), 'A Guide to the Project Management Body of Knowledge', Project Management Institute Inc., Newtown Square, Pennsylvania, USA.

Rogers, C. (1995) Ground Displacements Caused by Trenching and Pipe Bursting, Loughborough University of Technology, UK.

Rogers, C. and D. Chapman (1995). 'Ground Movement Caused by Trenchless Pipe Installation Techniques', Proc. Transportation Research Board, 74th Annual Meeting, Jan. 95, Washington DC.

Stein D., K Mollers, and R. Bielecki, 1989. *Microtunneling: Installation and Renewal of Non-Man-Size Supply and Sewage Lines by the Trenchless Construction Method*, pp. 302-310, Ernst & Sohn, Berlin, Germany.

Wiss, J. F., 1980, "Construction Vibration – State of the Art," *ASCE National Convention*, Portland, Oregon, April 14-18, 1980.

Credit

This chapter was prepared by Dr. Alan Atalah, PE, Associate Professor and Graduate Coordinator, Bowling Green State University, Ohio, USA.

Index

A

AASHTO 213, 217, 218, 219, 220, 234, 235

Above Ground 7, 8, 80, 265, 325, 326, 327, 328, 329, 493, 495, 511, 514, 535, 594

Above Ground Piping Systems 265

Abrasion Resistance 55, 79, 94, 169

Acceptance Deflection 293

Access 329, 418, 429,430, 432, 433, 435, 429, 504, 563

Advantages 7, 9, 43, 44, 159, 319, 347, 420, 435, 489, 493, 494, 496, 513, 540, 561, 563, 564

AGA 141, 171

Aging 210

Air Entrapment 387

Allman 211, 268

American Association of State Highway and Transportation Officials 218

American Society for Testing and Materials (ASTM) 346, 439

American Water Works Association (AWWA) 164

Anchor 26, 266, 312, 321, 332, 337, 338, 339, 340, 372, 373, 374, 413, 414, 427

Anchored 266

Anchoring 336, 345, 346, 385

ANSI 37, 88, 96, 153, 162, 163, 180, 267, 361, 369, 376

Apparent Modulus 12, 13, 57, 62, 63, 100, 101, 231, 232, 233, 250, 253, 281, 327, 328, 330, 333, 419, 422, 450, 454, 455, 457, 458, 464, 470, 473, 475

Apparent Tensile Strength 142

Appearance 37, 86, 141, 329

Applications 5, 6, 7, 10, 11, 12, 13, 15, 16, 25, 34, 39, 41, 43, 44, 48, 63, 65, 69, 71, 72, 73, 75, 79, 80, 85, 86, 87, 90, 95, 98, 99, 127, 145, 146, 149, 161, 162, 163, 164, 165, 166, 169, 170, 171, 172, 175, 177, 179, 180, 181, 195, 197, 203, 207, 212, 214, 215, 217, 238, 241, 246, 247, 252, 258, 262, 265, 266, 285, 288, 291, 294, 297, 300, 319, 325, 347, 363, 368, 376, 379, 381, 390, 401, 402, 403, 406, 422, 424, 426, 436, 445, 447, 451, 452, 455, 457, 483, 489, 483, 489, 494, 522, 537, 553, 561, 562, 563, 571, 579, 583, 586, 587, 589, 590, 595, 601

Arching 214, 216, 217, 230, 233, 240, 246, 247, 248, 249, 251, 283, 288, 293, 319, 449, 451, 452, 502

Armored 214, 525

Army Corps of Engineers 296

ASCE 268, 315, 441, 446, 460, 463, 472, 602, 603

Asphalt Dipped 192

Assembly 15, 141, 265, 302, 309, 349, 350, 355, 364, 365, 367, 368, 382, 392, 432, 436, 471, 541, 542, 545, 550, 551, 559

ASTM 7, 16, 24, 29, 30, 34, 37, 39, 40, 41, 47, 52, 57, 62, 64, 66, 68, 70, 73, 74, 79, 80, 81, 82, 83, 84, 86, 89, 90, 91, 92, 93, 99, 101, 103, 125, 127, 133, 134, 139, 141, 142, 143, 145, 146, 147, 148, 149, 150, 152, 153, 154, 156, 157, 158, 160, 162, 163, 164, 166, 167, 168, 170, 171, 172, 177, 178, 180, 181, 182, 188, 189, 213, 214, 220, 225, 231, 232, 234, 236, 238, 239, 267, 268, 272, 286, 290, 291, 294, 298, 316, 318, 344, 346, 349, 351, 352, 355, 357, 376, 392, 404, 414, 421, 429, 439, 440, 441, 446, 447, 457, 460, 464, 472, 487, 492, 493, 494, 496, 497, 498, 500, 503, 504, 505, 513, 515, 522, 526, 536, 553

ASTM D1248 47

ASTM D2683 515

ASTM D1586 236

ASTM D1598 66

ASTM D2321 213, 346, 439

ASTM D2513 180, 181, 188, 357, 376

ASTM D2774 213

ASTM D2837 68, 70, 82, 178, 346

ASTM D3035 188, 346

ASTM F894 189, 231, 232, 239, 376, 429, 439

Aude 199, 268

Average Inside Diameter 151, 189, 281, 500

AWWA 7, 13, 16, 37, 41, 72, 86, 98, 125, 142, 145, 149, 153, 154, 156, 164, 165, 166, 167, 172, 188, 189, 212, 213, 266, 267, 268, 291, 355, 361, 368, 369, 376, 377, 388, 439

AWWA C901 164, 179, 188, 189, 267, 376

AWWA C906 164, 179, 186, 188, 267

AWWA M55 388

Axial Bending Stress 478

Axial Tensile Stress 61, 460, 464, 480

B

Backfill 25, 30, 31, 211, 236, 237, 285, 286, 287, 288, 290, 293, 295, 296, 297, 299, 301, 303, 306, 307, 309, 310, 311, 312, 313, 315, 319, 364, 386, 392, 400, 442, 488, 503, 508, 509, 568, 570, 571, 577, 579, 598

Ballast 304, 381, 382, 383, 386, 388, 389, 390, 391, 392, 393, 394, 396, 397, 399, 400, 401, 402, 403, 412, 413, 414, 415

Barbed Mechanical Fittings 514

Barrel 128, 129, 130, 135, 136, 143, 309, 314

Bead Removal 349

Beam Analysis 342, 343

Beam Deflection 340, 341, 342

Bedding 231, 282, 287, 289, 290, 295, 303, 304, 305, 307, 309, 310, 319, 380, 382, 392, 521

Bell and Spigot 7, 26, 263, 265, 266, 313, 320, 372, 373, 430, 432, 433, 535

Below Ground Installations 502

Bend Radius 20, 289, 311, 312, 315, 488, 505, 508, 509

Bend-Back Test 142

Bending Radii 399, 506

Bending Strain Development 338

Bending Stress 232, 341, 364, 388, 464, 478

Bent Strap Test 29

Berm 329, 337

Biological Resistance 91

Blowing 516, 517

Bolt Type Mechanical Flange Adapter 365

Bolting 361, 365, 390

Bore 130, 133, 138, 190, 193, 199, 205, 206, 208, 281, 361, 364, 415, 441, 442, 443, 444, 446, 460, 461, 463, 464, 475, 477, 478, 480, , 488, 495, 500, 502, 504

Borehole 443, 444, 446, 448, 449, 450, 451, 452, 455, 456, 459, 460, 461, 462, 463, 465, 469, 471, 475

Bowles 250, 253, 268

Box 306, 354, 355, 515, 548, 587

Bracing 289, 301, 304, 587

Branch Saddles 372, 428, 436

Breaker Plate/Screen Pack 130

Bridge Structures 523

Buckling 182, 183, 211, 212, 213, 214, 215, 216, 230, 239, 240, 241, 242, 243, 244, 246, 247, 252, 253, 254, 258, 259, 260, 282, 383, 386, 398, 399, 419, 420, 421, 437, 454, 456, 457, 458, 470, 472, 473, 474, 475, 476, 477, 481, 503

Building Code 524

Bundling 135

Buoyant Force 254, 255, 281, 383, 384, 385, 404, 461, 462, 475

Burial of Fabricated PE Fittings 313

Buried PE Pipe Design 211

Buried Piping Systems 265

Butt Fusion 5, 26, 27, 28, 29, 35, 36, 37, 159, 321, 348, 349, 377, 379, 392, 402, 403, 430, 432, 500, 513, 515, 545, 586

C

C Factor 10

Cable 38, 133, 403, 433, 434, 435, 446, 493, 494, 495, 496, 498, 499, 500, 501, 502, 504, 506, 508, 509, 511, 512, 513, 514, 515, 516, 517, 518, 519, 520, 521, 522, 523, 524, 525, 526, 527, 556, 557, 558, 559, 562, 566, 585, 586, 598

California Bearing Ratio 319

Canadian Standards Association 145, 166, 172

CANDE 231, 268, 292

Capstan 443, 459, 460, 461, 462, 511, 517

Casing 28, 168, 224, 258, 488, 500, 504, 537

Cast Iron 192, 357, 364, 379, 425, 556, 561, 593, 596

Category 10, 65, 149, 152, 213, 230, 357, 487, 496, 497

Catenary 338

Cell Classification 496

Cement Mortar Relined 192

Cement Stabilized Sand 296

Chemical Resistance 8, 41, 54, 87, 496, 497

CIC 495

Class 45, 67, 74, 95, 98, 165, 177, 181, 182, 186, 294, 295, 296, 297, 299, 300, 304, 307, 309, 310, 316, 323, 361, 368, 572, 577, 582, 589

Class II material 296, 297

Class III 309, 310

Clay 21, 90, 198, 200, 207, 209, 235, 237, 240, 290, 297, 303, 316, 317, 318, 328, 421, 438, 443, 444, 449, 504, 561, 562, 565, 570, 589, 596

Cleaning 27, 38, 210, 237, 430, 445, 543, 582, 585

Coarse Grain Soils 317

Coefficient of Linear Expansion 328

COF 496, 518, 519, 520

Cohesion 317, 318

Cold Weather Handling 25

Collapse 297, 303, 383, 398, 421, 441, 443, 449, 454, 455, 458, 459, 477, 478, 480, 481, 580

Color 82, 84, 127, 128, 141, 148, 495, 496, 498, 499

Colorants 45, 55, 498

Combustion Toxicity 93, 94

Compaction 215, 230, 233, 234, 236, 286, 290, 297, 298, 299, 300, 309, 310, 313, 317, 318, 374, 503, 508, 568, 571

Compressed Air 400, 402, 516, 517, 518, 557

Compressible Gas Flow 188, 202

Compression Fittings 159, 347, 357, 514, 539, 593

Compression Nut 356

Compressive Ring Thrust 239, 247

Compressive Stress 211, 212, 236, 239, 240, 241, 244, 247, 248, 249, 265, 283

Concrete 139, 192, 207, 296, 303, 311, 313, 322, 328, 332, 337, 364, 372, 374, 379, 380, 389, 412, 413, 425, 493, 508, 517, 561, 562, 565, 568, 570, 596, 598, 601

Conduit 2, 168, 172, 214, 356, 441, 446, 447, 457, 472, 493, 494, 495, 496, 498, 499, 500, 501, 502, 504, 505, 506, 508, 510, 512, 513, 516, 518, 523, 524, 525, 526, 527, 533

Conduit Entry Issues 524

Conduit Wall Determination 500

Connection to Rigid Structure 336

Connections 11, 263, 266, 308, 311, 313, 320, 322, 347, 353, 357, 361, 363, 364, 368, 371, 372, 418, 426, 427, 428, 429, 436, 437, 488, 559, 563, 564, 565, 566, 568, 569, 576, 577, 582, 585, 586, 590, 593, 594, 595

Construction of the Land-to-Water Transition 392

Continuous Beam Analysis 342, 343

Continuous Support 335, 345

Contract Documents 25

Contraction 76, 80, 103, 160, 263, 311, 312, 313, 323, 328, 331, 372, 374, 375, 465, 471, 488, 511, 512, 513, 514, 516, 523, 537, 592

Cooling 311, 353, 392, 483, 484, 488, 520

Copper Tubing Sizes 188, 356

Corrugated Duct 522

Cracking 142, 319, 330, 389, 413, 490, 497, 526

Cradle 344, 421

Creep Rupture 94

Critical Velocity 198

Crown 31, 215, 216, 223, 224, 226, 229, 237, 238, 239, 242, 244, 245, 251, 258, 260, 283, 293, 304, 305, 306, 310, 374, 419, 445, 449, 451, 453, 461

Crush 216, 230, 239, 503, 504, 522, 525

CSA 86, 145, 149, 153, 154, 166, 172, 177, 180, 181, 182, 189

CTS 351, 356, 357, 369

Culvert Analysis and Design 231

Cumulative Deflection Effects 342

Currents 380, 384, 389, 391, 397, 399, 400, 403, 406

Curvature 237, 238, 240, 259, 443, 460, 462, 464, 470, 471, 478, 499, 520, 521, 548

D

D3350 147, 149, 150, 156, 157, 429, 439

Damage 11, 19, 20, 21, 22, 25, 27, 28, 38, 44, 56, 75, 76, 79, 87, 92, 170, 172, 181, 210, 286, 293, 309, 310, 329, 330, 335, 391, 393, 396, 401, 403, 417, 418, 441, 442, 445, 489, 490, 494, 502, 535, 536, 537, 538, 539, 541, 544, 546, 547, 551, 553, 555, 571, 598

Deep Fill 319

Deep Fill Installation 214, 217, 230, 240, 246

Definitions of Symbols 527

Deflection 28, 30, 31, 192, 230, 231, 232, 234, 236, 237, 238, 249, 268, 282, 286, 287, 288, 291, 292, 293, 294, 295, 297, 304, 305, 315, 319, 335, 338, 339, 340, 341, 342, 343, 344, 356, 388, 398, 402, 406, 420, 454, 455, 456, 457, 473, 476, 496, 501, 502, 503, 504, 505

Deformation Factor 250, 251

Density 30, 126, 127, 141, 147, 148, 150, 171, 172, 180, 181, 191, 216, 232, 233, 234, 237, 248, 255, 256, 281, 283, 290, 341, 374, 379, 383, 384, 385, 389, 405, 406, 412, 421, 422, 423, 456, 461, 479, 493, 494, 496, 501, 526, 556, 561, 571, 572, 584

Design 6, 10, 11, 12, 13, 15, 16, 28, 33, 35, 36, 40, 43, 44, 45, 46, 56, 57, 63, 64, 65, 67, 69, 74, 79, 80, 83, 88, 95, 97, 99, 101, 128, 129, 130, 132, 141, 145, 147, 148, 149, 150, 151, 154, 155, 156, 158, 160, 161, 164, 165, 175, 177, 178, 179, 180, 188, 192, 196, 211, 212, 213, 214, 230, 231, 238, 254, 262, 263, 265, 266, 267, 268, 281, 282, 325, 326, 327, 330, 331, 332, 334, 336, 341, 343, 344, 346, 347, 353, 356, 357, 365, 366, 368, 369, 371, 376, 380, 381, 382, 383, 387, 388, 389, 390, 392, 395, 399, 400, 401, 402, 403, 406, 407, 408, 411, 413, 418, 426, 439, 440, 441, 442, 443, 444, 446, 447, 448, 450, 451, 454, 456, 458, 459, 464, 471, 483, 485, 486, 489, 490, 491, 501, 502, 503, 505, 512, 514, 516, 519, 522, 523, 537, 540, 566, 568, 602

Design Window 212, 213, 266

DF 65, 67, 88, 95, 155, 156, 158, , 179, 180, 249, 251, 281

Diameters 7, 9, 95, 96, 125, 151, 152, 154, 165, 196, 199, 230, 254, 308, 336, 337, 352, 354, 392, 418, 419, 420, 500, 561, 583, 588, 599

Digging 305, 506, 507, 525, 588, 600

Dimension Ratio 33, 95, 152, 154, 178, 231, 239, 242, 250, 259, 281, 282, 286, 382, 384, 420, 447, 457, 458, 465, 472, 477, 500, 503

Dimensions 31, 76, 77, 86, 132, 136, 142, 154, 162, 164, 165, 176, 188, 189, 226, 228, 283, 331, 335, 352, 412, 413, 431, 434, 499, 573, 577, 578

DIPS 152, 165, 188, 323, 467, 469, 546, 583

Direct Plow 495, 502

Directional Bores 510

Directional Drilling 6, 9, 44, 168, 172, 214, 403, 441, 442, 444, 445, 446, 447, 457, 460, 472, 493, 497, 503, 505, 522, 560

Disinfecting Water Mains 37, 41

Disinfection 169, 577

Dissipation Factor 103

Distributed Loads 225, 228

DR 24, 33, 34, 68, 95, 96, 152, 153, 154, 178, 179, 182, 183, 184, 188, 189, 196, 209, 212, 213, 215, 217, 230, 231, 232, 233, 237, 238, 239, 240, 241, 242, 243, 244, 247, 248, 250, 258, 259, 260, 267, 269, 270, 271, 272, 273, 274, 275, 276, 277, 278, 279, 280, 281, 286, 288, 291, 312, 319, 322, 323, 346, 349, 366, 382, 383, 384, 385, 398, 399, 404, 420, 421, 422, 431, 509, 510, 544, 545, 546, 571, 579

Drag Resistance 461

Drawn Tubing 192

Dredging 94, 381, 392, 402, 403

Drilling Mud 443, 444, 448, 449, 456, 469

Drilling Process 442

Ductile 6, 7, 11, 12, 25, 26, 64, 65, 69, 72, 73, 74, 77, 139, 152, 157, 165, 175, 188, 207, 319, 320, 327, 356, 357, 361, 368, 448, 542, 559

Ductility 8, 11, 12, 39, 47, 51, 73, 79, 84, 149, 380, 495

Duncan 233, 235, 268

E

E′ 212, 213, 215, 230, 231, 233, 234, 235, 236, 237, 242, 243, 246, 249, 267, 268, 281

E′N 235, 236, 237

Earth and Groundwater Pressure 450, 453, 456

Earth Load 215, 216, 231, 232, 237, 239, 240, 247, 282, 288, 459

Earth Pressure 213, 239, 319, 448, 449, 451, 452, 453, 454, 459, 583, 588

Effluent 379, 380, 395, 400, 403

Electrofusion 7, 26, 138, 139, 159, 160, 314, 347, 353, 354, 355, 371, 428, 432, 513, 515, 536, 539, 546, 547, 548, 593

Elevation Changes 194

Elongation 86, 434

Embankment 213, 230, 439

Embedment 20, 30, 31, 60, 212, 215, 217, 230, 232, 233, 234, 235, 236, 237, 241, 243, 245, 246, 248, 252, 253, 258, 262, 286, 287, 288, 290, 291, 292, 293, 294, 295, 296, 297, 298, 299, 300, 301, 302, 303, 304, 305, 306, 307, 309, 310, 311, 314, 315, 316, 317, 318, 319, 371, 456, 484, , 507, 521

End Restrained Thermal Effects 264

Engineering Properties 6, 13, 76, 149, 262, 326, 457, 458, 464, 496, 498

Enveloping Soil 292

Environmental Stress Crack Resistance 126, 168

Equipment 7, 9, 20, 21, 22, 25, 26, 27, 28, 29, 32, 34, 35, 36, 37, 39, 129, 135, 163, 215, 218, 221, 237, 290, 329, 347, 351, 355, 361, 372, 376, 379, 392, 393, 396, 401, 403, 429, 431, 435, 445, 491, 506, 509, 510, 511, 515, 516, 517, 521, 522, 539, 542, 572, 574, 586, 598

Equivalent Length of Pipe 193

ESCR 126, 147, 168, 497, 498

Existing Pipe 208, 418, 419, 421, 423, 424, 427, 429, 430, 432, 433, 435, 436, 438, 545, 548, 555, 558, 559, 564, 565, 568, 569, 570, 571, 572, 586, 596, 601

Expansion Joints 263, 514

Exposure to UV and Weather 24

External Hydraulic Load 480

External load 188, 450, 451, 453, 454, 504

External Pressure 26, 183, 239, 241, 242, 259, 398, 421, 447, 448, 449, 450, 452, 457, 458, 459, 469, 470

Extruded Profile Pipe 31

Extruder 128, 129, 130, 134, 135, 136

Extrusion 26, 28, 30, 47, 52, 83, 126, 127, 128, 129, 143, 430, 432, 436, 526

F

Fabricated Fittings 171

Factory Mutual Research 166

Fat Clays 316

FDA 92

Features 2, 6, 77, 128, 379, 402, 403, 486, 495, 569

Field Effects of Friction 520

Field Fusion Joining 27

Field Handling 20

Field Joining 28, 56

Fine Grain Soil 318

Finish 132

Fire Protection 166, 313, 314

Fittings 7, 8, 13, 15, 16, 18, 22, 43, 44, 45, 55, 65, 79, 92, 125, 135, 136, 137, 138, 139, 140, 142, 145, 152, 155, 159, 160, 161, 162, 163, 164, 166, 188, 193, 197, 311, 313, 314, 315, 320, 321, 347, 348, 355, 356, 357, 365, 368, 369, 371, 372, 376, 379, 395, 400, 402, 403, 436, 437, 486, 487, 498, 513, 514, 515, 536, 539, 540, 541, 548, 553, 568, 569, 589, 590, 593, 595, 601

Flame Retardant 92, 523

Flammability 92

Flange Adapter 321, 360, 362, 363, 365, 544, 546

Flange Assembly 364, 395

Flange Gasket 363

Flanges 26, 159, 314, 320, 347, 361, 363, 364, 368, 395, 402, 437, 513, 545, 593

Flat-bottomed Ballasts 389

Flattening 237

Flexibility 8, 39, 43, 192, 286, 376, 379, 483, 489, 490, 493, 495, 496, 510, 520, 522, 561, 562

Flexible Pavement 220, 221

Flexible Pipe 218, 286, 315, 316, 319, 440

Flexural Modulus 82, 83, 47, 148, 496

Float 254, 297, 303, 381, 385, 386, 391, 392, 395, 397, 400, 401, 403, 461, 212, 214, 230, 254

Flotation 214, 230, 253, 254, 255, 257, 260, 300, 402

Flow Capacity 54, 188, 192, 208, 210, 398, 418, 419, 424, 425, 426, 439, 447, 562, 563

Flows for Slipliners 208, 209

Flushing 488

FM 139, 166

Fold and Form 438

Food and Drug Administration 92

Forklift 21, 22

Foundation 30, 225, 287, 315, 364, 402

Fracture Mechanics 93, 156, 157

Freeze Tolerant 490

Friction 43, 85, 89, 190, 191, 193, 195, 196, 197, 198, 202, 205, 206, 209, 245, 254, 281, 282, 284, 332, 339, 393, 424, 452, 461, 462, 463, 480, 495, 496, 500, 505, 516, 517, 518, 519, 520, 521, 522, 527, 556, 562, 570, 571, 578, 579, 580, 581, 584, 586, 588, 601

Frictional Forces 526, 579

Fuel Oil 87, 179

Fusion 5, 19, 26, 27, 28, 29, 30, 35, 36, 37, 44, 55, 82, 91, 125, 138, 139, 146, 159, 160, 195, 208, 263, 291, 293, 312, 321, 329, 347, 348, 349, 350, 351, 352, 353, 354, 355, 360, 361, 362, 371, 376, 379, 391, 392, 401, 402, 403, 417, 427, 428, 430, 432, 436, 437, 444, 483, 487, 500, 513, 515, 516, 535, 538, 546, 585, 596

G

Galvanized Iron 192

Gas Flow 40, 188, 202, 536

Gas Permeation 89, 204

Gaube 214, 246, 249, 250, 251, 252, 268

General Guidelines 170, 289, 304, 444, 487, 535

Geotechnical 216, 248, 249, 250, 251, 300, 446, 576, 587

Geotextile Separation Fabrics 296

Geothermal Heat Pump Systems 492

Glass Transition Temperature 56, 497

Grade Beam 336

Gravel 200, 237, 290, 294, 316, 408, 410, 589, 598

Gravity 1, 82, 170, 172, 188, 198, 202, 203, 205, 206, 208, 209, 210, 241, 266, 283, 291, 293, 294, 315, 319, 376, 417, 418, 419, 424, 425, 427, 429, 436, 437, 445, 479, 491, 562, 563, 571, 583, 589, 595

Ground Source Heat Pump Systems 483

Ground Water 212, 230, 240, 241, 242, 243, 247, 250, 252, 254, 255, 256, 258, 261, 281, 282, 287, 295, 297, 299, 317, 437, 449, 503, 555, 584

H

H2O 203, 222, 282, 454

Handling 1, 2, 11, 13, 20, 21, 25, 41, 43, 85, 126, 134, 135, 139, 156, 158, 260, 290, 315, 327, 348, 379, 444, 497, 577

Hardness 47, 363

Haunching 287, 295, 298, 309, 310

Hazen-Williams 195, 196, 202, 206, 281, 424, 425

HDB 66, 148, 155, 156, 157, 158, 159, 161, 169, 171, 179, 180, 282

HDD 6, 9, 44, 168, 172, 214, 441, 442, 444, 445, 446, 447, 448, 450, 451, 452, 454, 456, 457, 459, 460, 470, 471, 472, 505, 560, 561

HDPE 6, 68, 94, 170, 171, 172, 179, 181, 395, 402, 403, 407, 408, 410, 413, 455, 484, 485, 486, 487, 493, 561, 579

HDS 177, 178, 179, 180, 181, 265

Head Loss 188, 195, 196, 202

Health Effects 92, 93, 164

Heat Pump Systems 483, 492

High Pressure 38, 46, 130, 135, 202, 327, 364, 489, 517

High Temperature 489, 490, 491

Hoop 66, 70, 71, 150, 155, 211, 239, 247, 249, 312, 322, 457, 459, 470

Horizontal Directional Drilling 44, 214

Howard 230, 233, 234, 236, 267, 268, 292, 315

HSB 158, 161

HVAC 2, 483

Hydrokinetic 459, 460, 463, 464, 469, 470, 480, 481

Hydrostatic Design Basis 66, 67, 93, 95, 98, 143, 147, 149, 151, 155, 156, 499

Hydrostatic Design Stress 33, 57, 65, 67, 69, 74, 95, 97, 177, 178, 179, 265, 330, 382, 419, 420, 421

Hydrostatic Pressure 34, 64, 66, 99, 155, 157, 158, 240, 254, 383, 443, 447, 448, 451

Hydrostatic Strength 57, 65, 66, 67, 74, 75, 86, 87, 147, 497

Hydrostatic Stress Board 127, 158, 161

Hydrostatic Testing 32, 34, 344

I

ICC 165

ID Controlled Pipe 189

IGSHPA 486, 487, 489

IGT Distribution Equation 203

Immersion Test 86

Impact 9, 25, 29, 53, 56, 77, 79, 82, 86, 168, 217, 218, 219, 220, 221, 222, 223, 224, 225, 245, 247, 264, 282, 286, 288, 298, 299, 300, 310, 325, 326, 327, 330, 403, 409, 424, 483, 494, 495, 496, 497, 498, 556, 568, 572, 578, 586

Infiltration 297, 417, 426, 427, 437, 439, 513, 555

Influence Value 225, 226, 228, 282

Infrastructure 417, 439, 442, 573

Injection Molded Fittings 125

Innerducts 493, 499, 500, 502, 504, 505, 519, 525

Inspection 2, 18, 30, 238, 288, 293, 315, 325, 355, 404, 417, 429, 430, 444, 568, 578, 585, 586, 594

Installation 1, 2, 6, 7, 8, 9, 11, 13, 15, 18, 19, 22, 25, 26, 28, 29, 30, 37, 40, 41, 43, 44, 63, 65, 73, 79, 80, 85, 139, 155, 158, 159, 165, 208, 211, 212, 213, 215, 217, 233, 236, 244, 249, 260, 263, 267, 286, 288, 289, 291, 292, 294, 296, 302, 306, 312, 316, 319, 325, 326, 329, 330, 331, 334, 335, 336, 337, 344, 345, 346, 349, 359, 372, 376, 381, 387, 388, 392, 394, 397, 401, 402, 423, 428, 429, 431, 432, 433, 435, 436, 437, 439, 441, 442, 446, 447, 448, 451, 456, 459, 460, 469, 470, 471, 475, 483, 485, 486, 487, 488, 489, 492, 493, 495, 496, 497, 498, 499, 500, 501, 503, 505, 506, 507, 508, 509, 510, 511, 512, 513, 514, 515, 517, 518, 521, 522, 523, 524, 525, 526, 536, 537, 539, 547, 548, 549, 553, 570, 571, 577, 581, 583, 586, 589, 594

Intermittent Support 335

Internal Pressure 32, 39, 149, 155, 160, 179, 188, 195, 196, 204, 206, 238, 239, 241, 282, 312, 322, 326, 382, 383, 423, 448, 449, 457, 459, 497, 499, 512, 583

Internal Pressure 63

International Ground Source Heat Pump Association 486, 489, 492

International Organization for Standardization 93

International Plumbing Code 165

Iowa Formula 213, 231, 232, 236, 456, 503

IPC 165

IPS 39, 139, 141, 152, 165, 188, 196, 273, 347, 356, 357, 367, 410, 412, 413, 466, 468, 472, 474, 546, 583

Iron Pipe Size 165, 347

ISO 147, 151, 152, 162, 163, 165, 166, 177

Izod 77, 78, 79, 498

J

Janson 268, 386, 390, 398, 404, 407, 410

Jetting 300, 517

Joining 5, 16, 19, 26, 27, 28, 56, 82, 138, 141, 146, 156, 159, 160, 302, 329, 347, 352, 355, 356, 358, 376, 381, 391, 393, 402, 403, 417, 430, 442, 445, 486, 487, 500, 512, 513, 514, 515, 516, 541, 546, 547, 553, 577, 590

Joint 26, 28, 29, 32, 35, 36, 37, 90, 138, 139, 159, 160, 208, 263, 311, 312, 314, 320, 321, 322, 325, 345, 379, 401, 402, 432, 436, 442, 460, 486, 487, 500, 513, 515, 516, 518, 536, 538, 542, 545, 546, 548, 593

K

Katona 231, 268

K_{BULK} 184, 282

Kinetic COF 518

Knight 456, 472

L

L/D ratio 130

Lag Factor 231, 236, 282, 297

Land-to-Water Transition 382, 392, 401

Landfill Gas 203

Lateral Connections 429, 436, 563, 564, 565, 566, 568, 569, 576, 577, 582, 586, 594

Lateral Deflection 338

Launching 38, 381, 391, 393, 395, 396

Leak 26, 28, 32, 33, 34, 35, 36, 37, 535, 537, 546

Leak Free 7, 417, 535, 546

Leak Test 32, 33, 34, 35, 36, 37, 536

Load Per Unit Length 341, 342, 343

Loading 11, 12, 13, 43, 44, 60, 61, 63, 64, 66, 73, 75, 77, 84, 99, 135, 158, 160, 181, 213, 216, 217, 218, 219, 220, 221, 222, 224, 230, 241, 242, 243, 262, 290, 291, 292, 297, 301, 308, 310, 326, 344, 380, 386, 388, 396, , 420, 421, 422, 423, 437, 450, 451, 452, 453, 455, 461, 473, 475, 476, 498, 501, 502, 503, 504, 505, 506, 519, 520, 521, 579

Long-Term Hydrostatic Strength 65, 67, 75, 86, 87, 155, 158

Long-Term Loading 243, 455, 502

Longitudinal Force vs. Temperature Change 333

Longitudinal Stress vs. Temperature Change 332

Loose Storage Stacking Height 24

Love's Equation 419, 420, 421

Low Pressure 16, 35, 36, 37, 46, 203, 291, 517, 537

Low Temperature 55, 327, 490, 495

LPG 87, 88, 180

LTHS 57, 65, 66, 67, 68, 69, 70, 71, 72, 74, 75, 155, 158, 170

Lubricants 516, 517, 519, 520

M

Make-Up Water 489

Manhole Placements 427

Manning 206, 207, 424, 425, 562, 563

Manual 39, 72, 98, 141, 142, 143, 165, 208, 291, 441, 442, 445, 472, 506, 588, 601

Marking 134, 162, 498, 568

Marston 247, 268

Material Properties 1, 12, 43, 455

Material Selection 496, 511

Maxwell Model 59

MDPE 7, 179, 181, 455, 556, 561, 579

Measuring Density 318

Mechanical Connections 320, 322, 347, 357, 372, 395, 418, 487

Mechanical Couplings 26, 139, 170, 172, 311, 513, 540

Mechanical Fittings 7, 159, 347, 356, 379, 403, 436, 487, 513, 514, 536, 540, 541, 593

Mechanical Impact 300, 325, 326

Mechanical Properties 44, 50, 501

Mechanical Protection 493

Mechanical Pulling Heads 434

Mechanical Stress 494, 498, 506

Melt Index 52, 82, 83, 126, 147, 148, 496

Mesh 130, 200

Migration 294, 295, 296, 303, 306, 307, 309, 316, 437, 589

Mining 266, 326

MJ Adapter 320, 321, 365, 367, 369, 370, 372, 593

Model Specifications 159

Modulus 50, 57, 58, 61, 62, 63, 64, 75, 80, 82, 83, 99, 101, 147, 148, 184, 215, 231, 232, 233, 235, 241, 242, 243, 247, 248, 249, 250, 251, 252, 253, 259, 260, 261, 262, 263, 264, 265, 281, 282, 327, 328, 330, 333, 334, 342, 343, 419, 422, 450, 454, 455, 457, 458, 464, 469, 470, 473, 474, 475, 496, 579

Modulus of Soil Reaction Values 268

Molded Fittings 16, 125, 135, 138, 139

Moody Diagram 190, 193

Moore-Selig Equation 214, 241, 252, 253

Mounting 138, 382, 393, 492

MRS 143, 158, 159, 161, 169, 177

Ms 247, 248, 282

MS-3 172

Mueller Equation 202, 203

Multi-Cell Conduit 525

N

Native Soil 212, 287, 293, 301, 302, 304, 307, 310, 456, 471, 570, 571

O

Open Trench 289, 300, 309, 493, 507, 521

Organic Silts 256, 304, 316, 317

Original Line 418, 424, 429

Ovality 31, 142, 259, 260, 281, 419, 420, 458, 473, 474, 476, 481, 507

Ovality Compensation Factor 260, 419, 458, 473, 474, 481

Ovality Correction Factor 259, 281, 420

Ovalization 398, 455, 501, 502, 505, 507

P

Packing List 19

Particle Size 197, 198, 290, 296, 316, 392, 490, 498

Particle Size 80

Passive Resistance 211, 291, 502

Path Profile 477

Pavement (Rigid) 219

PC 67, 68, 86, 87, 95, 96, 97, 98, 177, 181, 182, 186, 187, 231, 282

PDB 143, 158, 159, 161, 169, 177

PE 2406 102

PE 3408 186, 244

PE 3710 102, 178

PE 4710 54, 68, 102, 178, 237, 330, 332, 339

PE Pipe to PVC 366

PE Pipe to Steel 370

PE Plastics 45

Performance Limits 211, 213, 216, 239, 246, 355, 454

Permeability 55, 88, 204, 282, 295, 303, 318

Permeation 8, 53, 89, 90, 94, 204,

PEX 1, 158, 161, 170

Physical Properties 2,9, 11, 47, 50, 53, 54, 81, 126, 128, 141, 176, 496, 497

Physical Property Tests 142

Pilot Hole 442, 443, 445

Pipe Bursting 9, 25, 214, 438, 495, 586, 593, 599, 600, 602, 555, 557, 561, 562, 564, 565, 570, 573, 582

Pipe Deflection 28, 30, 192, 268, 291, 293, 295, 388, 398, 422, 456

Pipe Deformation 262, 287, 291

Pipe Directly Beneath a Surcharge Load 225

Pipe Embedment 230, 233, 286, 290, 293

Pipe Extrusion 30, 126, 143

Pipe Hanger 344

Pipe ID for Flow Calculations 188

Pipe Installation 19, 29, 233, 286, 316, 335, 392, 471, 487, 571

Pipe Joining Methods 486

Pipe Length vs. Temperature Change 331

Pipe Liner Diameter 418

Pipe Restraint 356

Pipe Specifications and Requirements 486

Pipe Splitting 438, 559, 560

Pipe Support in Transition 308

Pipe Trench 287

Pipe Wall Buckling 240, 258

Pipe Wall Buckling 458

Pipeline Being Floated Out 396

PL 222, 223, 224, 225, 226, 228, 229, 231, 239, 245, 282

Placement Planning 521

Plastometer 52, 83

Plenum 524

Plow 9, 302, 488, 495, 501, 502, 509

Plowing 302, 493, 503, 507, 509, 510, 523, 525

Plumbing Codes 165

Pneumatic Testing 35

Poisson's Ratio 76, 102, 312, 419, 458, 473, 474, 475

Polymer Characteristics 47

Polymeric Water-Soluble 519

Portable Trench Shield 305, 306

Post-Installation Survey 401

PPI 1, 2, 3, 20, 26, 27, 41, 71, 72, 82, 86, 87, 88, 90, 92, 93, 94, 97, 127, 141, 143, 145, 150, 158, 159, 160, 161, 169, 170, 171, 172, 177, 178, 181, 263, 267, 268, 326, 344, 349, 351, 377, 406, 490, 491, 497, 514, 515, 538, 545

PR 67, 68, 86, 87, 95, 96, 97, 151, 152, 153, 154, 171, 177, 178, 179, 180, 181, 182, 183, 186, 187, 267

Pre-Installation Storage 22

Preparing the Land-to-Water Transition Zone 382

Pressure 1, 5, 8, 10, 11, 16, 26, 28, 32, 33, 34, 35, 36, 37, 38, 39, 41, 43, 44, 46, 47, 48, 53, 54, 55, 62, 63, 64, 65, 66, 67, 69, 70, 71, 72, 74, 75, 76, 79, 84, 86, 88, 95, 98, 99, 101, 102, 127, 129, 130, 131, 132, 133, 134, 135, 136, 138, 139, 142, 145, 149, 150, 151, 152, 153, 154, 155, 157, 158, 159, 160, 161, 164, 165, 170, 173, 175, 177, 178, 180, 181, 182, 183, 185, 186, 187, 195, 197, 202, 203, 212, 215, 220, 221, 225, 226, 231, 239, 248, 267, 268, 282, 283, 288, 289, 290, 291, 293, 297, 300, 303, 312, 315, 319, 320, 321, 322, 323, 326, 327, 330, 344, 348, 355, 356, 357, 361, 363, 364, 369, 375, 377, 382, 383, 392, 398, 400, 415, 417, 419, 420, 421, 423, 428, 429, 436, 437, 438, 440, 443, 447, 448, 449, 450, 451, 452, 453, 454, 455, 456, 457, 458, 459, 462, 463, 469, 470, 471, 473, 474, 475, 476, 477, 480, 481, 486, 487, 488, 489, 490, 492, 497, 499, 502, 507, 512, 514, 515, 517, 518, 522, 536, 554, 555, 558, 563, 570, 571, 578, 580, 581, 583, 584, 587, 588, 589, 595, 602, 603

Pressure Capability 327, 330, 428

Pressure Capacity 175

Pressure Class 67, 74, 95, 98, 177, 181, 182, 186

Pressure Flow 80, 195, 197

Pressure Pipe 26, 39, 64, 69, 71, 72, 75, 127, 150, 151, 155, 158, 164, 165, 175, 238, 241, 262, 289, 290, 297, 319, 320, 363, 392, 456, 487, 507, 536

Pressure Rating 35, 36, 65, 67, 74, 76, 88, 95, 102, 134, 139, 145, 151, 152, 154, 157, 160, 177, 180, 181, 186, 283, 326, 327, 328, 330, 382, 400, 447, 571

Pressure Surge 177, 183, 184, 185, 322

Pressure Test 142

Pressure Testing 321

Primary Initial Backfill 287, 299, 307, 310

Prism 213, 216, 217, 233, 236, 237, 242, 243, 248, 249, 251, 301, 449, 452, 453, 473

Proctor 212, 234, 237, 248, 290, 298, 299, 300, 307, 309, 313, 314, 318, 374

Product Design 447

Profile Pipe 125, 133, 214, 215, 217, 232, 233, 239, 240, 241, 244, 245, 246, 248, 250, 258, 281, 432, 433

Profile Wall 1, 17, 125, 126, 130, 133, 145, 149, 231, 232, 238, 239, 240, 244, 247, 248, 281, 291, 422

Proofing 510

Proper Transition 309

Properties of Gases 205

Properties of Water 196

Protection 22, 25

Pull-line construction 520

Pulling 20, 44, 63, 99, 134, 266, 305, 312, 315, 396, 399, 430, 431, 433, 434, 443, 444, 447, 455, 459, 460, 461, 462, 463, 464, 469, 470, 474, 480, 495, 497, 499, 505, 506, 508, 510, 511, 513, 516, 517, 519, 520, 521, 526, 527, 556, 557, 558, 559, 561, 566, 568, 569, 570, 571, 572, 576, 577, 578, 579, 581, 582, 583, 585, 586, 587, 588, 589, 590, 596, 598, 601

Purchase Order 19

Purging 488

Push 320, 396, 400, 433, 435, 461, 499, 508, 521, 557

Pushing Technique 435

PVC 7, 9, 10, 13, 26, 41, 45, 93, 158, 170, 177, 181, 182, 186, 187, 231, 267, 268, 282, 313, 320, 357, 358, 365, 366, 367, 368, 370, 375, 377, 425, 439, 493, 494, 498, 502, 504, 507, 520, 524, 542, 592, 593, 595, 596, 599, 601

Q

Quality Assurance 28, 141, 143, 430, 498, 577

Quality Control 125, 126, 127, 141, 154, 577

R

Radius of Curvature 259, 443, 462, 464, 470, 471, 478, 499

Railroad Loading 225

Rapid Crack Propagation 56, 77, 79, 327

Rate Process Method 170

Ravine Crossing 335

Raw Materials 127

RCP 79, 327, 559, 561, 562, 573, 582, 599

Reaming 442, 443, 470, 471, 560

Receiving Report 19

Reduction Factor 33, 34, 67, 155, 235, 242, 243, 283, 384, 470, 474, 481, 585

Reel Method 511, 512

Rehabilitation Methods 437

Repair Clamps 537, 568

Repair Operations 494

Repairs 2, 35, 36, 494, 496, 510, 516, 535, 536, 537, 553, 561, 565, 566, 570, 576

Reporting Damage 19

Required Strength 177

Required Weighting 383, 387

Resistance to External Collapse 470

Restrained Joints 7, 313, 320, 372

Restrained Pipelines 336

Restraining 7, 321, 332, 336, 369, 550

Reynolds Numbers 198

Rigid Pavement 219, 220

Rigidity Factor 250, 251

Ring Compression 240

Ring Stiffness 231, 232, 283, 292, 297, 383, 422

Riser Raceways 524

River Crossings 214, 396, 397

Riveted Steel 192, 425

Roadway 218, 329

Rock Trench Bottom 309

Rodent and Mechanical Protection 525

Rolldown 438

S

Saddle Fusion 19, 26, 137, 160, 169, 171, 350, 351, 371, 538

Safe Deflection Limits for Pressurized Pipe 238

Safe Pull Load 455, 579

Safe Pull Stress 455, 465, 477, 579

Safe Pull Tensile Stress 455

Safety 2, 6, 15, 32, 65, 74, 85, 86, 88,135, 143, 154, 155, 163, 183, 211, 212, 224, 234, 238, 242, 245, 246, 253, 259, 260, 282, 289, 290, 293, 300, 304, 306, 312, 347, 376, 380, 381, 382, 383, 400, 421, 422, 431, 488, 499, 510, 536, 564, 573, 577, 584, 587, 588, 589, 598

Safety Factor 65, 211, 212, 234, 238, 242, 245, 246, 253, 259, 260, 282, 293, 380, 382, 383, 421, 422

Sand Stabilized with Cement 313, 314

Saturated and Dry Soil Unit Weight 256

Scale 37, 53, 85, 200, 403, 501

Scrapes 19, 28

Screen Mesh 200

Screen Pack 130

Screw 39, 128, 129, 130, 134, 135, 138

SDB 134, 159, 161, 169, 177

SDR 96, 134, 152, 153, 154, 161, 165, 169, 171, 184, 186, 189, 238, 243, 252, 253, 267, 272, 293, 297, 330, 332, 339, 360, 381, 382, 384, 385, 457, 470, 471, 477, 500, 502, 503, 505, 507, 522, 550, 582, 583, 586, 587, 592

Secondary Initial Backfill 287, 297, 309, 310

Seismic 8, 43

Select a Pipe Liner Diameter 418

Selection of an Appropriate Site for Staging, Joining and Launching The Pipe 381

Service and Lateral Connections 429

Service Connections 427

Service Life 7, 9, 67, 73, 74, 79, 91, 167,197, 328, 39, 40, 448, 497, 498, 500, 555

Service Temperatures 178

Shallow Cover 212, 216, 241, 244, 245, 254, 258, 291, 297, 309

Sheathing 303, 304, 305

Sheeting 303, 304, 305

Shield 25, 27, 305, 306

Shipping Claims 20

SIDR 152, 153, 154, 171, 267, 356, 500, 522

Silo 17, 22, 452

Silt 198, 200, 303, 317, 392, 423, 513

Sizing 126, 132, 133, 134, 152, 188, 443, 500, 501, 521, 588

Slipliners 208, 209

Sliplining 208

Sloping The Trench Wall 289

Slow Crack Growth 53, 54, 57, 64, 66, 69, 70, 71, 73, 74, 76, 87, 126, 147, 148, 157, 168, 497, 526

Slurry 46, 79, 188, 197, 198, 199, 202, 209, 283, 325, 403, 508

Smooth Pipe(S) 10, 192

Soft Pigs 38

Softening 55

Soil Arching 246

Soil Classification 233, 316

Soil Pressure 211, 221, 448, 450, 454, 471, 502, 570, 581

Soil Reaction 215, 233, 235, 242, 249, 281, 299

Soil Support Factor 231, 235, 236, 237, 281

Soil Tests 28, 308

Soil Type 215, 292

Soil Unit Weight 256

Solar 170, 483, 489, 490

Solid Wall 1, 6, 24, 125, 126, 130, 132, 145, 149, 231, 233, 242, 253, 291, 313, 419, 420, 421, 425, 430, 432, 433, 435, 496, 500, 526, 595

Spacing Of Ballasts 388

Span 155, 341, 342, 343, 363, 521, 543

Spangler 230, 231, 232, 233, 236, 238, 246, 268, 292, 456, 472, 503

Special Applications 2, 10, 44, 495

Specific Gravity 82, 198, 202, 203, 283, 479

Specific Heat 81, 103

Specifications 2, 11, 15, 25, 29, 30, 57, 67, 125, 134, 141, 142, 145, 159, 160, 161, 167, 212, 289, 355, 486, 492, 493, 535, 537, 566, 568, 576, 577, 578, 581

Spitzglass Equation 203

Springline 235, 238, 258, 293, 299, 302, 305, 435, 453

Stab Type Fitting 357

Stability 23, 30, 91, 211, 237, 239, 289, 293, 299, 301, 303, 304, 307, 308, 387, 391, 423, 427, 430, 495, 587, 598

Stabilization 24, 384, 91, 03, 392, 437, 498, 598

Stabilizer 84, 90, 91, 92, 496

Stable 91, 212, 249, 289, 301, 302, 303, 304, 306, 307, 319, 326, 364, 400, 402, 403, 421, 450, 451, 488, 508, 581

Stacking Heights 23

Staging 22, 381, 391, 443, 569, 586

Standard Mesh 200

Standard Practice 160, 162, 168, 171, 172, 294, 392, 595

Standard Proctor 212, 237, 248, 290, 298, 299, 307, 309, 313, 314, 318, 374

Standard Specification(S) 57, 67, 145, 159, 232, 267

Standard Test Method 52, 73, 79, 80, 83, 84, 92, 101, 142

Static Charge 40, 85

Static COF 518

Stationary Reel 508, 511, 512

Steel 9, 12, 79, 81, 130, 139, 141,192, 207, 304, 305, 333, 334, 357, 359, 361, 367, 390, 400, 414, 425, 437, 439, 442, 462, 471, 504, 539, 549, 559, 571, 587, 595

Stiffener 320, 356, 357, 358, 359, 360, 361, 365, 366, 367, 371, 375, 539, 540, 542, 543, 548, 549

Stiffness 25, 50, 57, 82, 149, 150, 181, 211, 215, 216, 230, 232, 235, 244, 246, 247, 249, 250, 253, 262, 264, 286, 288, 292, 293, 294, 297, 316, 318, 319, 383, 421, 422, 450, 454, 455, 456, 496, 503, 504, 505, 572

Storage 2, 15, 22, 23, 24, 25, 40, 43, 55, 84, 85, 135, 315, 391, 445, 489, 491, 492, 498, 577

Strain 11, 12, 44, 57, 58, 59, 60, 61, 63, 64, 73, 75, 76, 77, 83, 84, 99, 101, 237, 238, 251, 252, 263, 284, 338, 346, 355, 380, 388, 398, 402, 455, 460, 465, 470, 478, 501, 503, 579, 580

Strength Design Basis 177

Strength of Embedment Soil 294

Stress 10, 11, 12, 32, 33, 41, 44, 57, 58, 59, 60, 61, 62, 63, 64, 65, 66, 67, 68, 69, 70, 71, 72, 73, 74, 75, 77, 80, 83, 84, 85, 95, 97, 99, 101, 102, 126, 139, 149, 150, 151, 154, 155, 156, 157, 158, 160, 161, 173, 177, 178, 179, 240, 248, 262, 265, 268, 293, 312, 320, 322, 328, 330, 332, 333, 335, 336, 338, 339, 341, 364, 377, 382, 388, 390, 394, 415, 448, 449, 451, 455, 457, 458, 459, 460, 461, 464, 470, 471, 474, 478, 480, 481, 486, 488, 494, 496, 497, 498, 499, 501, 502, 503, 506, 510, 511, 548, 570, 579, 580, 581, 583

Stress Distribution 583

Stress Rating 74

Stub Ends 135, 139, 360

Submarine Outfalls 386

Submerged 9, 255, 256, 258, 260, 376, 379, 380, 383, 384, 385, 386, 387, 388, 389, 392, 394, 395, 396, 400, 401, 402, 404, 406, 407, 475

Sudden Velocity Change 184, 281, 284

Sunlight 32, 90, 147, 311, 326, 329, 331

Support 8, 11, 43, 75, 183, 210, 214, 237, 241, 243, 254, 258, 262, 286, 287, 288, 289, 291, 294, 295, 297, 300, 301, 302, 303, 305, 307, 308, 309, 310, 313, 314, 319, 325, 334, 340, 341, 342, 344, 356, 357, 361, 364, 374, 375, 379, 388, 392, 400, 402, 423, 443, 444, 457, 473, 476, 492, 503, 504, 505, 508, 512, 523, 524, 548, 562

Surcharge Load 216, 225, 226, 227, 228

Surface damage 27, 441, 547, 596

Surface Resistivity 103

Surface Roughness 190, 191, 210, 281

Suspended From Rigid Structure 335

Suspended Pipelines 340, 388

Suspension Spacing 340

Sustained Pressure 65, 74, 76,142, 175, 177, 181, 182, 183

Swagelining 438

Swelling 86, 584

Swivels 460, 506, 510

Symbols 173, 234, 294, 317, 527

T

Take-Off Equipment 129

Tamping 290, 298

Temperature 10, 44, 45, 46, 52, 55, 56, 60, 61, 64, 66, 67, 68, 69, 70, 71, 72, 73, 76, 77, 79, 80, 81, 82, 83, 85, 86, 89, 91, 95, 96, 97, 98, 100, 101, 102, 129, 130, 142,157, 158, 175, 177, 178, 180, 182, 183, 184, 195, 204, 232, 240, 242, 259, 262, 263, 264, 265, 266, 282, 283, 284, 325, 326, 327, 328, 330, 331, 332, 333, 334, 335, 337, 338, 339, 340, 341, 342, 343, 344, 348, 350, 351, 352, 355, 36, 382, 392, 393, 422, 455, 465, 471, 483, 484, 488, 489, 490, 491, 492, 495, 497, 498, 501, 505, 513, 514, 515, 579, 590

Temporary Floating Lines 403

Temporary Repair 537

Tensile Creep 63

Tensile Properties 84, 101

Tensile Strength 55, 82, 83, 142, 147, 363, 430, 431, 455, 464, 471, 496, 497, 507, 522, 578, 586

Tensile Stress 12, 59, 63, 264, 265, 284, 320, 455, 458, 460, 464, 470, 471, 481, 501, 579

Terminal Connections 429, 437

Test Duration 33, 34, 35, 36, 147

Test Pressure 32, 35, 88

Test Procedure 35, 53

Testing 10, 15, 25, 30, 32, 34, 35, 36, 37, 40, 41, 47, 71, 93, 94, 101, 127, 142, 157, 158, 160, 161, 162, 165, 166, 231, 247, 248, 249, 250, 290, 344, 346, 488, 492, 495, 504, 514, 518, 577, 582, 595

Thermal Conductivity 81, 103,484

Thermal Expansion 80, 103,169, 263, 313, 323, 334, 336, 342, 372, 374, 471, 514, 516, 537, 540, 562

Thermal Heat Fusion Methods 347

Thermal Properties 80, 103, 331, 332

Thermal Stability 91

Thermoformed Fittings 139

Threaded Mechanical Fittings 514

Thrust Anchor 266

Thrust Block 266, 587, 588, 598

Timoshenko 222, 224, 245, 583

Titeliner 438

TN 36 377

TN 38 361, 377

Torsion Stress 471

Toxicological 92

TR 33 160

TR 41 160

Traffic 213, 217, 221, 230, 297, 301, 329, 391, 392, 396, 397, 399, 403, 418, 439, 441, 442, 452, 504, 555, 564, 569, 577, 581, 583, 587

Transition 56, 83, 190, 191, 308, 313, 321, 336, 347, 369, 372, 373, 382, 392, 401, 415, 418, 437, 478, 487, 497, 513, 521, 525, 593

Transport 16, 79, 85, 86, 87, 197, 205, 325, 327, 330, 402, 403, 443, 491, 497, 526

Trench 9, 20, 29, 175, 214, 230, 235, 237, 246, 249, 285, 286, 287, 289, 290, 293, 295, 297, 299, 300, 301, 302, 303, 304, 305, 306, 307, 308, 309, 310, 311, 312, 314, 315, 319, 386, 392, 400, 401, 402, 428, 451, 456, 488, 493, 503, 507, 508, 509, 521, 564, 565, 566, 568, 570, 571, 587, 601

Trenching 289, 379, 380, 386, 453, 488, 493, 495, 507, 508, 509, 510, 525

Trenchless 7, 214, 438, 442, 472

Truckload 17, 18

Turbulent 190, 191, 197, 198, 199, 209, 210, 487

Typical Electrofusion Joint. 353

Typical Impact Factors For Paved Roads 219

U

Ultraviolet 24, 90, 325, 329, 490, 498

Unconfined Compressive Strength 236, 289, 303

Unconstrained Buckling 243, 258, 457

Unconstrained Pipe Wall Buckling 258, 458

Undercut 307, 508

Underwater Bedding 382

Uniform Particle Size 198

Unloading 19, 20, 21, 22, 135, 139, 454

Unloading 602

Unpaved 219, 220, 221, 222, 245

Unrestrained Thermal Effects 263

USBR 234, 268

V

Vacuum 128, 132, 133, 134, 183, 187, 206, 241, 242, 243, 247, 258, 447, 448, 449, 450, 454, 459, 483, 560, 568, 601

Valve 182, 183, 185, 187, 193, 314, 364, 368, 395, 544, 545, 546, 547

Vehicle Loading 218, 222

Vehicle Loads 219

Vehicles 217, 218, 219, 220, 221, 223, 232, 310, 329, 453

Velocity 38, 40, 79, 80, 177, 181, 182, 184, 185, 186, 187, 190, 191, 197, 199, 206, 207, 209, 210, 281, 283, 284, 407, 409, 411, 424, 444, 471, 489, 500, 574

Vertical Arching Factor 247, 283

Vertical Deflection 30, 211, 237, 251, Deflection 293, 502

Vertical Soil Pressure 215, 216, 219, 220, 222, 223, 225, 226, 232, 239, 252, 282

Vertical Surcharge 227, 229

Viscoelastic 59, 93, 197, 242, 259, 319, 450, 454, 460, 465, 501

Viscoelasticity 247

Voids 136, 309, 312, 570

Volume Resistivity 103

W

Wall Buckling 215, 216, 244, 246, 247, 258, 259, 260, 282, 458

Wall Compressive Stress 239, 240, 244, 283, 458

Wall Determination 500, 533

Wall Thickness 8, 28, 79, 88, 95, 134, 139, 142, 150, 151, 152, 155, 165, 178, 269, 270, 271, 272, 273, 274, 275, 276, 277, 278, 279, 280, 329, , 383, 384, 398, 404, 405, 418, 419, 420, 447, 460, 464, 477, 484, 497, 500, 503, 507, 577, 596

Water Service 164, 172, 177, 376, 539

Water-Base Slurry Specific Gravities 201

Watkins 211, 214, 231, 244, 246, 249, 250, 251, 252, 268, 292, 315, 456, 472

Watkins And Spangler 292

Weatherability 90, 169

Working Pressure Rating 182, 186, 187, 447

Workmanship 513

WPR 182, 183, 186, 187, 283

Y

Yield Strength 50, 244, 283, 319, 356, 357, 431,0455, 497

Z

Zero-Leak-Rate 442