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July 31, 2019 Docket No. 52-048

U.S. Nuclear Regulatory Commission
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SUBJECT: NuScale Power, LLC Submittal of “Pipe Rupture Hazards Analysis Technical Report,” TR-0818-61384, Revision 2

REFERENCE: Letter from NuScale Power LLC, to Nuclear Regulatory Commission, “NuScale Power, LLC Submittal of ‘Pipe Rupture Hazards Analysis,’ TR-0818-61384, Revision 1,” dated December 20, 2019 (ML18354B400)

NuScale Power, LLC (NuScale) hereby submits Revision 2 of the “Pipe Rupture Hazards Analysis Technical Report” (TR-0818-61384).

Enclosure 1 contains the proprietary version of the report titled “Pipe Rupture Hazards Analysis Technical Report.” NuScale requests that the proprietary version be withheld from public disclosure in accordance with the requirements of 10 CFR § 2.390. The enclosed affidavit (Enclosure 3) supports this request. Enclosure 1 has also been determined to contain Export Controlled Information. Enclosure 2 contains the nonproprietary version of the report.

This letter makes no regulatory commitments and no revisions to any existing regulatory commitments.

If you have any questions, please contact Marty Bryan at 541-452-7172 or at mbryan@nuscalepower.com.

Sincerely,

Zackary W. Rad
Director, Regulatory Affairs
NuScale Power, LLC

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Enclosure 1: Pipe Rupture Hazards Analysis Technical Report, TR-0818-61384-P, Revision 2, proprietary version
Enclosure 2: Pipe Rupture Hazards Analysis Technical Report, TR-0818-61384-NP, Revision 2, nonproprietary version
Enclosure 3: Affidavit of Zackary W. Rad, AF-0719-66191

Enclosure 1:

Pipe Rupture Hazards Analysis Technical Report, TR-0818-61384-P, Revision 2, proprietary version

Enclosure 2:

Pipe Rupture Hazards Analysis Technical Report, TR-0818-61384-NP, Revision 2, nonproprietary version

Licensing Technical Report

Pipe Rupture Hazards Analysis

July 2019

Revision 2

Docket No.: 52-048

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Abstract

The NuScale Power, LLC (NuScale) Pipe Rupture Hazards Analysis (PRHA) describes the methodology applicable to the identification and assessment of pipe rupture hazards, and the effects of pipe ruptures and leakage cracks on the ability to achieve safe shutdown and cooldown. Specifically, the following are addressed:

- compliance with NRC regulations and guidance
- identification of postulated rupture locations
- characteristics of ruptures, including break types and size
- determination of potential effects of high- and moderate-energy line breaks
- criteria for showing the acceptability of structures, systems, and components exposed to those effects
- mitigation strategies to accommodate pipe rupture hazards, where applicable

The evaluation addresses external effects of high-energy line breaks, moderate-energy line breaks, and leakage cracks in piping in the NuScale Power Module (NPM) and NuScale Reactor Building (RXB). The Pipe Rupture Hazards Analysis (PRHA) evaluation of the piping beyond the NPM disconnect flange in the RXB and through the balance of plant is the responsibility of the COL applicant.

The PRHA is required to support the Design Certification per NRC Standard Review Plan Branch Technical Position 3-4, “Postulated Rupture Locations in Fluid System Piping Inside and Outside Containment.”

The PRHA can be summarized in the Design Certification, Part 2, Tier 2 Final Safety Analysis Report Section 3.6, “Evaluation of Postulated Rupture of Piping,” or submitted as a separate technical report.

This NuScale technical report provides the PRHA results for high- and moderate-energy piping ruptures in the NPM and RXB.

Executive Summary

The NuScale Power, LLC (NuScale) Pipe Rupture Hazards Analysis (PRHA) methodology evaluates the postulated rupture of high- and moderate-energy piping systems and their effects on the surrounding environment. The design approach demonstrates that postulated piping ruptures in fluid systems do not cause loss of function of essential systems and that the NuScale plant is able to withstand postulated failures of fluid system piping, taking into account the direct results of such a failure and further failure of a single active component, with acceptable consequences.

The NuScale design is a compact, integral reactor that relies on passive safety features to ensure safe shutdown and cooldown for design basis events. The absence of large diameter reactor coolant system piping and active safety systems results in a minimal number of safety-related and essential structures, systems, or components (SSC) susceptible to postulated pipe rupture hazards. Examples of key NuScale design features include:

- no operator actions or electrical power are required for safe shutdown and cooldown for design basis accidents.
- a limited number of essential SSC outside the NPM itself.
- a small-volume, metal containment operated at a vacuum and with sensitive leak-detection capability.
- no potential for dislodged piping insulation blocking core cooling.
- reduced energy of blast, pipe whip, and jet impingement effects due to smaller plant size and lower energy system conditions.
- stainless steel primary and secondary piping within containment and areas where break exclusion is applied.
- ready access for inspection.

Application of the criteria for break exclusion and leak-before-break results in a small number of locations in the containment vessel (CNV) and under the bioshield in the NuScale Power Module (NPM) bay requiring evaluation of dynamic effects (i.e., blast waves, pipe whip, jet impingement). Consideration of nonmechanistic breaks of MSS and FWS piping in the containment penetration area under the bioshield involves evaluation of subcompartment pressurization and flooding. Mitigation protection is demonstrated through separation and by the robustness and qualification of safety-related and essential SSC.

For the RXB, evaluation of bounding high-energy line breaks (HELBs) and moderate-energy line breaks (MELBs) and cracks was performed to demonstrate that final piping design is capable of meeting acceptance criteria for evaluation of line breaks.

External effects of HELBs and MELBs in the NuScale Power Plant do not adversely affect the ability to shut down and maintain core cooling of an NPM.

1.0 Introduction

1.1 Purpose

This document describes the NuScale methodology applicable to identification and assessment of pipe rupture hazards and the effects of pipe ruptures and leakage cracks on the ability to achieve safe shutdown and cooldown. Specifically, the following are addressed:

- compliance with NRC regulations and guidance
- identification of postulated rupture locations
- characteristics of ruptures, including break types and sizes
- determination of potential effects of high and moderate-energy line breaks (MELBs)
- criteria for showing acceptability of structures, systems, and components (SSC) exposed to those effects

This evaluation addresses the external effects of high-energy line breaks (HELBs), MELBs, and leakage cracks in piping in the NuScale Power Module (NPM) and NuScale Reactor Building (RXB). The final Pipe Rupture Hazards Analysis (PRHA) is the responsibility of the Combined License (COL) applicant. COL Items 3.6-1 and 3.6-3 identify the requirements to complete the PRHA for lines outside the reactor pool bay:

- Perform final piping design, including stress analysis and design and qualification of associated piping supports
- Evaluate multi-module impacts
- Show that the analysis of RXB piping HELB (as described in this report) bounds the final design or perform a pipe rupture hazards analysis

This report addresses the requirements for the as-designed PRHA Report as described in NRC Inspection Procedure 65001.21 (Reference 1.4.2.8):

> “The as-designed pipe rupture hazards analysis report ITAAC is a set of methodology and criteria pertaining to protection of essential systems or components inside and outside containment from the adverse effects of postulated failures in high and moderate energy piping (HELB and MELB)....”

Reference 1.4.2.8 provides for three options:

1. Resolve during the design certification or amendment to the design certification
2. Resolve as part of the combined license (COL) review
3. Resolve after COL is issued

For piping located inside the NuScale containment vessel (CNV) and in the NPM pool bay under the bioshield, this report satisfies option 1. For piping elsewhere in the RXB and through the balance of plant, this report establishes the methodology and criteria to be applied and the bounding results to be confirmed for balance of plant arrangements as part of the COL review (option 2). The NuScale Final Safety Analysis Report (FSAR)

(Reference 1.4.2.16) Table 2.1-4 Inspections, Tests, Analyses, and Acceptance Criteria (ITAAC) item 4, specifies that the as-built Pipe Break Hazard Analysis Report identifies protective features and qualification of safety-related SSC to withstand the dynamic and environmental effects of piping failures.

1.2 Scope

Pipe ruptures are addressed for each of the distinct regions of the NuScale plant where high- or moderate-energy piping layouts exist.

- inside the CNV
- outside the CNV (under the bioshield)
- in the RXB (outside the bioshield)
- in the Control Building (CRB)
- in the Radioactive Waste Building (RWB)
- onsite (outside the RXB, CRB, and RWB buildings)

Although the final pipe routing and analysis in the RXB beyond the NPM bay is the responsibility of the COL applicant, generic break postulations and mitigation evaluations are provided in this report. There are no high-energy systems in the CRB or RWB, or onsite (outside the buildings). There are however, moderate-energy systems.

Pipe ruptures in other areas onsite, outside the RXB, control building, and radioactive waste building (i.e., turbine buildings), are not within the scope of this report. The final PRHA is the responsibility of the COL applicant and will address postulated ruptures based on final design of high- and moderate-energy systems in the RXB and moderate-energy systems in the control building, radioactive waste building, and onsite (outside the buildings).

1.3 Abbreviations and Definitions

Table 1-1 Abbreviations

Term	Definition
ACRS	Advisory Committee on Reactor Safeguards
ADC	augmented design circuit
ANS	American Nuclear Society
ANSI	American National Standards Institute
ASME	American Society of Mechanical Engineers
BTP	Branch Technical Position
CFD	computational fluid dynamics
CFR	Code of Federal Regulations
CIV	containment isolation valve
CNTS	containment system
CNV	containment vessel
COL	combined license
CRDM	control rod drive mechanism
CRDS	control rod drive system
CVCS	chemical and volume control system
DAC	design acceptance criteria
DC	design-capacity [ratio]
DHRS	decay heat removal system
DLF	dynamic load factor
DSRS	Design-Specific Review Standard
ECCS	emergency core cooling system
EDSS	highly reliable DC power system
ESF	engineered safety feature
FSAR	Final Safety Analysis Report
FWS	feedwater system
GDC	General Design Criteria
HELB	high-energy line break
HPU	hydraulic power unit
HVAC	heating, ventilation, and air conditioning
IAB	inadvertent actuation block

Term	Definition
ITAAC	Inspections, Tests, Analyses, and Acceptance Criteria
LBB	leak-before-break
LOCA	loss-of-coolant accident
LWR	light water reactor
M&E	mass and energy
MELB	moderate-energy line break
MHS	module heatup system
MPS	module protection system
MS	main steam
MSS	main steam system
NMS	neutron monitoring system
NPM	NuScale Power Module
NPS	nominal pipe size
PAM	post-accident monitoring
PWR	pressurized water reactor
PZR	pressurizer
RCPB	reactor coolant pressure boundary
RCS	reactor coolant system
RH	relative humidity
RP	reactor pool
RPV	reactor pressure vessel
RRV	reactor recirculation valve
RSV	reactor safety valve
RVI	reactor vessel internals
RVV	reactor vent valve
RXB	reactor building
SBO	station blackout
SFPCS	spent fuel pool cooling system
SG	steam generator
SRP	Standard Review Plan (NUREG-0800)
SSC	structures, systems, and components
SSE	safe shutdown earthquake

Term	Definition
TOM	top of module
UHS	ultimate heat sink
ZOI	zone of influence

Table 1-2 Definitions

Term	Definition
Active component	Any component that must perform a mechanical motion or change of state during the course of accomplishing a primary safety function.
Associated-ADC	Non-Class 1E circuits that are not physically separated or are not isolated from augmented design circuits (ADC) by acceptable separation distance, structures, barriers, or isolation devices. Circuits include the interconnecting cabling and the connected loads.
Augmented design circuit	A non-Class 1E circuit that supports functionality considered important to safety and is subject to augmented requirements.
Blast wave	A shock wave; viz. a high-pressure, high-density region that initiates due to the rapid opening of a pipe rupture and propagates away from the rupture location at supersonic speed.
Class 1E	Safety classification of the electric equipment and systems that are essential to emergency reactor shutdown, containment isolation, reactor core cooling, and containment and reactor heat removal, or are otherwise essential in preventing a significant release of radioactive material to the environment. The NuScale design does not have Class 1E electrical power.
Essential systems	As defined by BTP 3-4 (Reference 1.4.2.5), those systems "necessary to shut down the reactor and mitigate the consequences of a postulated pipe rupture without off-site power."
External effect	Any consequence of a high- or moderate-energy line break or leakage crack affecting SSC outside the leaking system. External effects include both dynamic (i.e., pipe whip) and environmental (i.e., increased ambient pressure) effects.
High-energy fluid system	Fluid systems that, during normal plant conditions, have either or both: (a) maximum operating temperature exceeding 200°F, (b) maximum operating pressure exceeding 275 psig.
Highly Reliable DC Power System (EDSS)	The EDSS provides a continuous, failure-tolerant source of 125V DC power to assigned plant loads during normal plant operation and for a specified minimum duty cycle (mission time) following a loss of AC power. The EDSS provides electrical system reliability substantially similar to that of a Class 1E DC power system. For that purpose, EDSS functional requirements have been defined based on requirements, regulatory guidance, and standards which would typically be applied to a Class 1E system.
Integral reactor	A design with the entire RCS circulation path contained within a single pressure vessel (i.e., there is no loop piping).
Jet core	The region immediately downstream of a break within which fluid striking a target would experience full recovery of the fluid stagnation pressure. The jet core is shown as Region 1 in Reference 1.4.3.1.
Jet impingement force	The force imparted to an object due to its intersection with the fluid issuing from a ruptured pipe. The magnitude of this force depends on such parameters as the thermodynamic conditions of the fluid in the pipe, distance of the pipe rupture from the target, area of intersection of the jet with the target surface, and the shape of the target.

Term	**Definition**
Moderate-energy fluid system	Fluid systems that, during normal plant conditions, have: (a) maximum operating temperature is 200°F or less, (b) maximum operating pressure is 275 psig or less, or (c) high-energy conditions that exist less than one percent of the plant life or less than two percent of the time period required for the system to accomplish its function.
NuScale Power Module (NPM)	The assembly including the reactor pressure vessel, CNV, and directly-attached components out to the outboard flange connecting module systems to those in the RXB.
Outboard	Identifies location of a component as farther outside the CNV boundary, regardless of flow direction inside the component.
Pipe failure hazard area	An area containing piping normally operating at high or moderate energies.
Pipe whip	Movement of a pipe caused by jet thrust resulting from a pipe failure. Pipe whip is assumed to occur in the plane defined by piping geometry and configuration unless limited by structural members, pipe restraints, or pipe stiffness.
Single active failure	The failure of an active component to complete its intended function upon demand. Per BTP 3-3 (Reference 1.4.2.4), Appendix A, failure of an active component of a fluid system is loss of component function as a result of mechanical, hydraulic, pneumatic, or electrical malfunction, but not the loss of structural integrity. The direct consequences of a single active failure are evaluated. A single active failure is postulated to occur simultaneously with the pipe failure; passive failures are not postulated.
Single failure criterion	As defined in 10 CFR 50 Appendix A, “A single-failure means an occurrence that results in the loss of capability of a component to perform its intended safety functions. Multiple failures resulting from a single occurrence are considered to be a single-failure. Fluid and electric systems are considered to be designed against an assumed single-failure if neither (1) a single-failure of any active component (assuming passive components function properly) nor (2) a single-failure of a passive component (assuming active components function properly), results in a loss of the capability of the system to perform its safety functions.” This definition is accompanied by a footnote: “Single failures of passive components in electric systems should be assumed in designing against a single failure. The conditions under which a single failure of a passive component in a fluid system should be considered in designing the system against a single failure are under development.”
Subcompartment	A fully- or partially-enclosed volume within the NuScale plant that houses or adjoins piping systems and restricts the flow of fluid to other areas of the plant in the event of a postulated pipe rupture.
Terminal end	The extremity of a piping run that connects to structures, components (e.g., vessels, pumps, valves), or pipe anchors that act as rigid constraints to piping motion and thermal expansion. A branch connection on a main piping run is a terminal end for the branch run, except where the branch run is classified as part of a main run in the stress analysis or is shown to have a significant effect on the main run behavior. In piping runs that are maintained pressurized during normal plant conditions for a portion of the run (i.e., up to the first normally closed valve), a terminal end of such a run is the piping connection to this closed valve.

Term	Definition
Zone of influence (ZOI)	The maximum physical range of the direct effects of pipe whip, jet impingement, and the environmental effects resulting from a pipe rupture. The size of ZOI depends on the direct effect being evaluated (e.g., within physical reach of a whipping pipe of a given length or entire compartment for pressurization).

1.4 References

1.4.1 Source Documents

1.4.1.1 American Society of Mechanical Engineers, *Quality Assurance Requirements for Nuclear Facility Applications*, NQA-1-2008, NQA-1a-2009 Addenda, New York, NY.

1.4.1.2 *U.S. Code of Federal Regulations*, "Quality Assurance Criteria for Nuclear Power Plants and Fuel Reprocessing Facilities," Appendix B, Part 50, Chapter 1, Title 10, "Energy," (10 CFR 50 Appendix B).

1.4.2 Referenced Documents

1.4.2.1 *U.S. Code of Federal Regulations*, "General Design Criteria for Nuclear Power Plants," Appendix A, Part 50, Chapter 1, Title 10, "Energy," (10 CFR 50 Appendix A).

1.4.2.2 U.S. Nuclear Regulatory Commission, "Standard Review Plan, Determination of Rupture Locations and Dynamic Effects Associated with the Postulated Rupture of Piping," NUREG-0800, Chapter 3, Section 3.6.2, Rev. 2, March 2007, or Rev. 3, December 2016 (as noted).

1.4.2.3 U.S. Nuclear Regulatory Commission, *Standard Review Plan*, "Leak-before-break Evaluation Procedures," NUREG-0800, Chapter 3, Section 3.6.3, Rev. 1, March 2007.

1.4.2.4 U.S. Nuclear Regulatory Commission, *Standard Review Plan*, "Protection against Postulated Piping Failures in Fluid Systems outside Containment," NUREG-0800, Chapter 3, BTP 3-3, Rev. 3, March 2007.

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1.4.2.6 U.S. Nuclear Regulatory Commission, "Criteria for Accident Monitoring Instrumentation for Nuclear Power Plants," Regulatory Guide 1.97, Rev. 4, June 2006 (June 2013).

1.4.2.7 U.S. Nuclear Regulatory Commission, *NRC Inspection Manual,* "Definition of Leak-Before-Break Analysis and its Application to Plant Piping Systems," EMCB Part 9900: 10 CFR Guidance, LBBGUIDE.CFR.

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1.4.2.9 U.S. Nuclear Regulatory Commission, “Two Phase Jet Loads,” NUREG/CR-2913, January 1983.

1.4.2.10 U.S. Nuclear Regulatory Commission, “Boiling Water Reactor ECCS Suction Strainer Performance Issue No. 7 - ZOI Adjustment for Air Jet Testing,” BWROG Meeting, July 20, 2011, Agencywide Document Access and Management System (ADAMS) Accession No. ML11203A432.

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1.4.2.12 U.S. Nuclear Regulatory Commission, GSI-191 SER, Appendix I, ANSI/ANS Jet Model.

1.4.2.13 Corradini, Michael, Advisory Committee on Reactor Safeguards, letter to Victor McCree, U.S. Nuclear Regulatory Commission, April 12, 2018, ADAMS Access No. ML18102A074.

1.4.2.14 U.S. Nuclear Regulatory Commission, “Damping Values for Seismic Design of Nuclear Power Plants,” Regulatory Guide 1.61, Rev. 1, March 2007 (R April 2005).

1.4.2.15 Advisory Committee on Reactor Safeguards, “Transcript: U.S. EPR Subcommittee Meeting,” February 21, 2012, ADAMS Accession No. ML 120760106

1.4.2.16 *NuScale Final Safety Analysis Report*, NuScale Standard Plant Design Certification Application, Rev. 1.

1.4.3 Other References

1.4.3.1 American Nuclear Society, “Design Basis for Protection of Light Water Nuclear Power Plants Against the Effects of Postulated Pipe Rupture,” ANSI/ANS-58.2-1988, LaGrange Park, IL. (Withdrawn 1998). (Note: Although withdrawn, 58.2 is still referenced by NRC documentation.)

1.4.3.2 American Society of Mechanical Engineers, Boiler and Pressure Vessel Code, 2013 Edition, Section III, Division 1, “Rules for Construction of Nuclear Facility Components,” New York, NY.

1.4.3.3 American Society of Mechanical Engineers, Boiler and Pressure Vessel Code, 2013 Edition, Section XI Division 1, “Rules for In-service Inspection of Nuclear Power Plant Components,” New York, NY.

1.4.3.4 American Society of Mechanical Engineers, “Power Piping,” B31.1, 2013, New York, NY.

1.4.3.5 Westinghouse Electric Corporation, AP1000 Design Control Document, Rev. 19, June 21, 2011.

1.4.3.6 Kinney, G.F. and K.J. Graham, *Explosive Shocks in Air*, 2nd Edition, 1985.

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1.4.3.9 Nuclear Energy Agency, "Knowledge Base for Emergency Core Cooling System Recirculation Reliability," NEA Report NEA/CSNI/R (95)11, February 1996.

1.4.3.10 Shapiro, Ascher H., The Dynamics and Thermodynamics of Compressible Fluid Flow, The Ronald Press, New York, 1953.

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1.4.3.15 Department of Defense, "Structures to Resist the Effects of Accidental Explosions, with Change 2," UFC 3-340-02, December 2008.

1.4.3.16 American Institute of Steel Construction, "Specification for Safety-Related Steel Structures for Nuclear Facilities," ANSI/AISC N690-12, Chicago, Illinois.

1.4.3.17 American Concrete Institute, "Code Requirements for Nuclear Safety-Related Concrete Structures," ACI 349-06.

2.0 Background

Design requirements for piping, such as the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code (Reference 1.4.3.3), ensure that the probability of a pipe rupture is low. However, breaks are postulated conservatively to occur in various plant locations. To ensure protection from postulated breaks, the NRC has provided guidance and criteria for postulating break locations and assumptions to be used in assessing the break consequences.

The consequences of line breaks depend on the thermodynamic conditions in the piping system at the break location and interaction with the break surroundings. Failure of high- and moderate-energy systems have the potential for a range of external effects, as identified in SRP 3.6.2:

- pipe whip impact*
- blast effects*
- jet reaction loads*
- jet impingement*
- potential feedback amplification and resonance effects of jet impingement*
- subcompartment pressurization
- flooding (flooding analysis is addressed in Section 3.4 of the FSAR)

* Applicable to high-energy systems only. Moderate-energy line breaks are considered only for moderate-energy systems not designed to seismic category requirements.

When a pipe rupture initiates, a sudden release of energy and fluid occurs. If the system upstream conditions support continued blowdown (i.e., there is a large amount of fluid), the discharge from the break cannot expand until exiting the pipe. In this scenario, the jet that forms is under-expanded. This means that the jet expands and accelerates once released from the confines of the pipe. Its speed, expansion, and thermodynamic conditions are a function of the fluid conditions in the pipe and the conditions of the ambient environment.

NuScale ambient pressure inside the CNV is maintained at less than 1 psia.

2.1 NuScale Design Features Relevant to Pipe Rupture Hazards Analysis

The NuScale design is an integral, multi-unit, small modular reactor for which safety is provided by passive features without the need for safety-related electrical power. Because NRC regulatory guidance is premised on the existing fleet of large light water reactors (LWRs) with reactor coolant loops and active safety features, instances exist where the current NRC pipe rupture guidance is not a direct fit. In many cases, the NRC has not issued a Design-Specific Review Standard (DSRS) to address what is directly applicable for the NuScale design. Specific examples of NuScale relevant design differences are:

- The response to pipe ruptures requires neither electric power nor injection of additional cooling water.

- The NPMs are mostly submerged in a large pool of water that serves as the ultimate heat sink for the NPMs and does not require replenishment.
- Design basis accidents do not require operator actions or the re-establishment of electric power for long-term cooling.
- Piping is small compared to the large reactors for which regulatory guidance was initially developed.
- Active, safety-related components [i.e., emergency core cooling system (ECCS) valves, decay heat removal system (DHRS) actuation valves, and containment isolation valves (CIVs)] are shown to operate during refueling. As part of the start-up sequence for an NPM, each of the safety-related ECCS, DHRS, and containment isolation valves is repositioned. These periodic system line-up activities ensure that the safety-related valves remain operable.
- The NPM containment is a pressure vessel designed and fabricated to ASME Code Section III Class 1 requirements versus a building in conventional LWRs.
- Piping of the NPM, including secondary system piping, is made of corrosion-resistant stainless steel.
- Main steam system (MSS) and feedwater system (FWS) piping inside the containment boundary is designed to RCS design pressure and temperature.
- MSS and FWS piping inside the CNV meets LBB criteria.
- HELBs inside the CNV are limited to NPS 2 piping.
- The length of piping in which breaks must be postulated is minimal and the size of high-energy piping is small compared to current design reactors.
- The NPM containment is operated at a vacuum.
- Equipment and piping inside the NPM containment are not covered with insulation, which is important for multiple reasons:
    - Jet impingement does not dislodge piping insulation that could lead to blockage of long-term cooling recirculation.
    - Detection of small leakage cracks is not impeded by retention of moisture in insulation.
    - The bare piping is readily inspectable during refueling, because insulation does not need to be removed to note deposits, discoloration, or other signs of degradation.
    - Corrosive substances (e.g., chlorides) cannot be trapped and held in contact with the piping surface.
- Safety-related and essential components inside the NPM containment are qualified to be functional after exposure to saturated steam at containment design pressure of at least 1000 psia, requiring designs that are robust.
- The small containment results in congestion that makes difficult the addition of traditional pipe whip restraints and the physical separation of essential components

from break locations, but whipping pipes in turn, have a limited range of motion before encountering an obstacle.

- The CIVs are installed outside of containment. Where two valves in series are required (i.e., for containment penetrations governed by GDC 55 and 56), both are in a single-piece valve body (i.e., no piping or welds between the CIVs, which precludes breaks in between). Also, the lines directly connected to the primary system or the containment have only a single weld in the area between the containment wall and the CIV.
- Containment pressure suppression is not required and there are no sprays that introduce chemical additives.
- During refueling, the NPM is disconnected from supporting systems by removal of piping spools, transported by crane to a refueling location, and disassembled. This provides access for inspection to portions of the plant not normally accessible.
- Up to 12 NPMs are operating at the same time and in proximity, so the potential for a rupture in a system of one module to affect others is considered.
- The plant main control room is in a separate building that does not contain high-energy piping systems.
- Effects of postulated ruptures on multiple modules are evaluated, and protection for post-accident monitoring (PAM) capability and the highly reliable DC power system (EDSS) is provided by separating them in different compartments within the RXB.

In the NuScale design, postulated HELBs are evaluated in three discrete areas of the plant because of differences of both the potential piping hazard and the surrounding environment:[1]

1. inside the containment of the NPM
2. in the pool bay area above each NPM and under the bioshield
3. in the RXB

The NuScale methodology for evaluating pipe ruptures across the three plant areas accounts for the break hazard and the surrounding environment for that break area. The design approach demonstrates that postulated ruptures in fluid systems do not cause loss of function of essential systems and that the NuScale plant is able to withstand postulated failures of any fluid system piping, taking into account the direct results of such a failure and subsequent failure of a single active component, with acceptable consequences.

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[1] Moderate-energy systems are not in use in areas 1 or 2, with the exception of the reactor component cooling water system (RCCWS) lines for the control rod drive mechanisms (CRDMs), the rupture effects of which are bounded by HELBs. The containment flooding and drain system is moderate energy when in use, but is isolated whenever the reactor is operating. Evaluation of line breaks in other plant areas (i.e., turbine buildings) is outside the scope of this report.

Long-term core cooling for the NuScale plant following an HELB (or MELB) is, therefore, dependent only upon the following:

- The safe state for safety-related actuation devices is defined as de-energized. With no power, the reactor trip and engineered safety feature (ESF) components go to their safe state. The module protection system (MPS) trip signal equipment interface module outputs de-energize to actuate reactor trip and ESF components. Reactor trip occurs upon an automatic or manual MPS trip signal, loss of two or more MPS channels, or loss of electric power.
- Isolation of the CNV by shutting CIVs, for which no ac or dc electric power is required.
- Opening ECCS valves, for which no ac or dc electric power is required.
- Opening DHRS actuation valves, for which no ac or dc electric power is required.

As such, pipe ruptures have limited potential to adversely affect essential functions. Although the mitigation objective is consistent with that of other large LWRs, as described in the NRC guidance, the unique features and passive safety attributes of the NuScale design justify other considerations as part of this PRHA and mitigation, as described in following sections.

2.2 Regulations and Guidance

In this section, regulatory criteria relevant to line breaks are summarized, followed by a brief discussion of the NuScale approach. In subsequent sections, each of the aspects of assessing line breaks is discussed, along with their likelihood of occurring, their applicability to the NuScale design, the detailed methodology for addressing them, and the results of evaluations.

“Environmental and Dynamic Effects Design Bases,” General Design Criterion (GDC) 4, of Appendix A to 10 CFR 50, (Reference 1.4.2.1) requires SSC important to safety “be designed to accommodate the effects of and to be compatible with the environmental conditions associated with normal operation, maintenance, testing, and postulated accidents, including loss-of-coolant accidents.”

2.2.1 History of HELB Effects Analysis Methodology

The nuclear industry has traditionally used ANSI/ANS Standard 58.2-1988 (Reference 1.4.3.1) for estimating jet plume geometries and impingement loads, based on fluid conditions internal and external to the piping, even though it was officially withdrawn in 1988. In 2004, following interactions with the Advisory Committee on Reactor Safeguards (ACRS) on the jet models described in ANSI/ANS 58.2, the staff determined that there were potential nonconservatisms in these models with respect to the strength, Zone of Influence (ZOI), and space and time-varying nature of the loading effects of postulated pipe ruptures on neighboring SSC.

In the time since, the NRC has not developed detailed acceptance criteria for these complex phenomena. The NRC concerns are based on experimental data and are intended to ensure that modeling of HELB effects includes margin to compensate for possible deficiencies in the available data and its interpretation. The lack of acceptance criteria founded on physical phenomena has led to iterative interactions between the industry and the NRC regarding acceptability not just of results, but also of methodologies. The approach discussed herein considers NRC guidance, past precedent, and NuScale specific design features.

2.2.2 NRC Guidance

The following is a description of the relevant guidance, but is not intended to be all-inclusive or to imply that the NuScale implementation of the guidance does not address criteria that are not explicitly discussed. Also, note that this guidance was developed on the premise of application to LWRs with large containments and active safety systems dependent on electrical power availability.

2.2.2.1 Branch Technical Position 3-4

Branch Technical Position 3-4[2] notes that the NRC staff's observation of actual piping failures has indicated that they generally occur at high stress and fatigue locations, such as at the terminal ends of a piping system and at its connection to the nozzles of a component. The BTP 3-4 criteria use the available piping design information by postulating pipe ruptures at locations having higher potential for failure, such that an adequate and practical level of protection is achieved. Branch Technical Position 3-4 also points out that, subject to certain limitations, GDC 4 allows that dynamic effects associated with postulated pipe ruptures be excluded from the design basis when analyses reviewed and approved by the NRC demonstrate that the probability of fluid system piping rupture is extremely low under design-basis conditions. An example of these analyses is LBB analyses, which are reviewed in accordance with SRP Section 3.6.3.

2.2.2.1.1 High-Energy Breaks

For the purpose of assessing separation from high-energy piping, the effects of postulated piping breaks should be physically remote from essential systems and components. A footnote defines essential systems and components as those "necessary to shut down the reactor and mitigate the consequences of a postulated pipe rupture without off-site power."

Containment penetration areas

For piping in containment penetration areas, breaks and cracks need not be postulated (break exclusion) in sections between the containment wall to and including the inboard or outboard CIVs, provided:

- They have at least a specified margin to design criteria of the ASME Boiler and Pressure Vessel Code (Code), Section III, and do not exceed fatigue limits specific to the piping code class. For example, at a high level, Class 1 piping should not exceed

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[2] SRP 3.6.2 states that BTP 3-4 should be used to determine rupture locations both inside and outside containment.

a maximum stress range between any two load sets (including the zero load set) of 2.4 S_m and should be calculated using Equation (10) of ASME Code Section III Subarticle NB-3653, a cumulative usage factor of 0.1, and a maximum stress of 2.25 S_m and 1.8 S_y. Class 2 provisions are similar.

- The length of such piping should be as short as practical.
- The number of fittings and welds are minimized.
- Welded restraints are avoided.
- Piping welds in the zone are 100 percent volumetrically inspected every interval.

Other than containment penetration areas

For Class 1 piping not in containment penetration areas, breaks should be postulated at:

- terminal ends
- intermediate locations where the maximum stress range exceeds 2.4 S_m
- intermediate locations where the cumulative usage factor exceeds 0.1 (0.4 if environmental fatigue considered)

Branch Technical Position 3-4 acknowledges that reanalysis may cause the highest stress locations to shift, but allows the initially determined intermediate break locations be retained, provided the mitigation by original pipe whip restraints and jet shields is still satisfactory and the pipe size, wall thickness, and routing remain similar.

For Class 2 and 3 piping, postulated breaks should be assumed at:

- terminal ends
- intermediate locations selected by one of the following criteria:
    - Each fitting or at the extreme ends of a piping run if there are no fittings
    - Locations where stresses are calculated to exceed 0.8 times the sum of the limits in Subarticles NC/ND-3653 ("/" indicates the applicable article should be used).

Breaks in seismically analyzed non-ASME class piping are postulated according to the same criteria as for ASME Class 2 and 3 piping.

If a structure separates a high-energy line from an essential component, that separating structure should be designed to withstand the consequences of a pipe rupture in the high-energy line that produces the greatest effect at the structure, irrespective of the fact that the above criteria might not need such a break location to be postulated.

Safety-related equipment is environmentally qualified in accordance with SRP Section 3.11. Appropriate pipe ruptures and leakage cracks (whichever controls) should be included in the design bases for environmental qualification of electrical and mechanical equipment both inside and outside containment.

With the exception of locations meeting the break exclusion criteria for piping in containment penetration areas, leakage cracks in piping should be postulated for

- Class 1 piping where the calculated stress range per Subarticle NB-3653 exceeds 1.2 S_m at axial locations.
- Class 2, 3, and nonsafety piping where calculated stress exceeds 0.4 times the sum of the stress limits of Subarticles NC/ND-3653.
- Nonsafety-class piping not evaluated to obtain stress information at axial locations that produce the most severe environmental effects.

NuScale Approach: NuScale follows the guidance of BTP 3-4 with exceptions as described below.

- Inside containment –
    - The CIVs are outside the containment. A break inside the CNV does not lead to containment bypass. Therefore, there is no containment penetration area inside the CNV, and BTP 3-4 Rev. 2 Paragraph B.A.(ii) does not apply.
    - The congestion associated with an integrated small modular reactor design limits the ability to separate fluid systems from essential SSC. Those SSC (e.g., ECCS valves, instrumentation) are designed to function in the severe environment resulting from ECCS initiation, which bounds the HELB effects.
    - The RCS-connected and DHRS piping inside containment, all of which are NPS 2, are assessed for compliance with BTP 3-4 Rev. 2 B.A.(iii):
        - Breaks are postulated at terminal ends, where the piping attaches to RPV or CNV safe ends.
        - Breaks at intermediate locations are precluded by designing for compliance with BTP 3-4 Rev. 2 Paragraph B.A.(iii)(1) and (2). If those criteria are not met at certain locations, then breaks are considered.
    - Large-diameter secondary piping (i.e., MSS and FWS) is analyzed for LBB and shown to meet the criteria, as described below in the Section 2.2.5 discussion of SRP 3.6.3.
    - Postulated break locations are assessed for the effects of a break.
- NuScale Power Module bay under the bioshield –
    - The containment penetration area is defined as the segment from the CNV safe end to and including the weld connecting pipe to the outboard nozzle of the CIV or check valve in a line. The only physical piping in the containment penetration area is the DHRS. The design of piping and valves, nozzles, and fittings within the containment penetration area complies with break exclusion criteria of BTP 3-4 Rev. 2 Paragraph B.A.(ii):
        - Stress and cumulative usage factor criteria are met.
        - Welded attachments and restraints are not used.
        - The number of welds and length of piping is minimized.

        - Guard pipes are not used.
        - A 100-percent volumetric and surface examination is performed for the NPS 2 piping welds in addition to larger piping.
    - Remaining piping, including the refueling pipe spools, complies with BTP 3-4 Rev. 2 Paragraph B.A.(iii).
    - Based on designing to meet the criteria from BTP 3-4, no breaks in the NPM bay outside the CNV (under the bioshield) are postulated. However, nonmechanistic breaks and leakage cracks are considered.
- Reactor Building – The effects on the RXB of a rupture of high-energy piping in any location are bounded and shown to be acceptable for HELB effects.

2.2.2.1.2 Moderate-Energy Piping

Separation adequate to isolate the effects of through-wall cracks should be provided from essential systems and components. However, leakage cracks need not be considered in the containment penetration area provided 1) they meet the criteria of the ASME Code, Section III, NE-1120, and 2) the stresses calculated by the sum of Eqs. (9) and (10) in ASME Code, Section III, NC-3653 do not exceed 0.4 times the sum of the stress limits given in NC-3653.

Outside the containment penetration areas, leakage cracks should be considered where stress criteria are not met, except where exempted (i.e., evaluate cracks except where the criteria of BTP 3-4 2 B.B.(iii) are met). Leakage cracks in moderate-energy piping do not need to be evaluated if environmental conditions resulting from an HELB in the vicinity are more limiting.

NuScale Approach: Consequences of leakage cracks in piping in the moderate-energy piping systems are either bounded by HELB effects or are evaluated and shown to be acceptable. Because piping arrangements in the RXB have not been finalized, precluding demonstrating that stress criteria are met, leakage cracks are evaluated for the limiting systems in areas not containing high-energy piping.

2.2.2.2 Types of Breaks and Cracks

Circumferential breaks should be postulated in high-energy piping as follows:

- For piping over NPS 1, except where specific stress criteria are met.
- For unanalyzed piping, at each weld to a fitting, valve, or attachment.
- Pipe separation of at least one-diameter laterally occurs unless physically constrained.
- Dynamic force of jet discharge should be based on effective flow area of pipe and fluid pressure modified by a thrust coefficient. Limited pipe displacement at the break location, line restrictions, flow limiters, positive pump-controlled flow, and the absence of energy reservoirs may be taken into account, as applicable, in the reduction of jet discharge.

- Pipe whip should be assumed to occur in the plane defined by the piping geometry and configuration and to initiate pipe movement in the direction of the jet reaction.

Longitudinal breaks should be postulated in high-energy piping as follows:

- For piping NPS 4 and larger where circumferential breaks are considered, except where specific stress criteria are met and excluding terminal ends.
- The opening is an axial split without severance, oriented at either of two diametrically opposed points that result in out of plane bending (or in the highest tensile stress location).
- Dynamic force is based on a circular (or elliptical 2D by ½D) area equal to the effective pipe cross-sectional area, modified by a thrust coefficient and considering line restrictions, flow limiters, etc.
- Piping movement occurs in opposite direction of the jet reaction unless physically constrained.

Leakage cracks should be postulated, as follows:

- In piping larger than NPS 1.
- At circumferential (and axial for moderate-energy systems) locations resulting in the most severe environmental consequences.
- Need not be postulated in moderate-energy piping in an area where a HELB is postulated, provided such leakage cracks would not result in more limiting environmental conditions than the HELB.
- Flow is based on circular opening of area equal to that of a rectangle of one half of the diameter by one half of the wall thickness.
- Flow wets unprotected components within the compartment and communicating compartments.

NuScale Approach: NuScale follows this guidance, including as appropriate for piping shown to meet break exclusion (i.e., no breaks or cracks) or LBB (no breaks assumed for purposes of assessing dynamic effects), where essential systems and components could be affected.

2.2.3 Branch Technical Position 3-3

Branch Technical Position 3-3, Rev. 3, describes the approaches acceptable for the “design, including the arrangement, of fluid systems located outside of containment to ensure that the plant can be safely shut down in the event of piping failures outside containment.” The intent is to show that postulated piping failures combined with the failure of any single active component do not cause the loss of function of essential systems. The BTP is also intended to provide clear guidance on acceptable means of protecting against MSS and FWS breaks.

The BTP identifies that protection of essential systems and components against postulated piping failures in high- or moderate-energy fluid systems that operate during normal plant conditions and that are located outside of containment should be provided by (in order of preference):

- Plant arrangements that separate fluid system piping from essential systems and components. Separation should be achieved by plant physical layouts that provide sufficient distances between essential systems and components and fluid system piping, such that the environmental effects of any postulated piping failure therein cannot impair the integrity or operability of essential systems and components.
- Separation of MSS and FWS lines should be implemented even if the criteria of BTP 3-4 are met for break exclusion. A nonmechanistic longitudinal break should have a cross sectional area of at least one square foot[3] and be postulated to occur at a location that has the greatest effect on essential equipment.
- Fluid system piping or portions thereof not satisfying the separation provisions above should be enclosed within structures or compartments designed to protect nearby essential systems and components. Alternatively, essential systems and components may be enclosed within structures or compartments designed to withstand the effects of postulated piping failures in nearby fluid systems.
- If the above cannot be satisfied, then redundant design features that are separated or otherwise protected from postulated piping failures, or additional protection, should be provided so that the effects of postulated piping failures are shown to be acceptable. Additional protection may be provided by designing or testing essential systems and components to withstand the environmental effects associated with postulated piping failures.

The BTP states that protective structures should be designed to withstand the effects of a postulated piping failure (i.e., pipe whip, jet impingement, pressurization of compartments, water spray, and flooding, as appropriate) in combination with loadings associated with the design basis earthquake, within the respective design load limits for structures. Fluid system piping in containment penetration areas should be designed to meet the break exclusion provisions of BTP 3-4.

Piping failures should be postulated in accordance with BTP 3-4 and include full circumferential ruptures of non-seismic moderate-energy piping (because BTP 3-4 only applies during normal conditions, not seismic events). Each longitudinal or circumferential break or leakage crack should be considered separately as a single postulated initial event occurring during normal plant conditions. An analysis should be made of the effects of each such event, taking into account the provisions BTP 3-4 and of the system and component operability considerations.

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[3] The area of 1.0 foot^2 is based on the assumption that the piping in which the longitudinal rupture occurs has a diameter such that the flow area out of a complete circumferential break is at least as large. For the largest high-energy piping in the NuScale plant, which is NPS 12 in the MSS, the circumferential break area is only 0.63 foot^2 (91 inches^2). See Section 3.5.2.5.

In analyzing the effects of postulated piping failures, the following assumptions should be made with regard to the operability of systems and components:

1. Off-site power should be assumed to be unavailable if a trip of the turbine-generator system or reactor protection system is a direct consequence of the postulated piping failure. Also, off-site power should be assumed unavailable following seismic events.
2. A single active component failure should be assumed in systems used to mitigate consequences of the postulated piping failure and to shut down the reactor, except as noted in item 3 below. The single active component failure is in addition to the postulated piping failure and any direct consequences of the piping failure.
3. Where the postulated piping failure is assumed to occur in one of two or more redundant trains of a dual-purpose moderate-energy essential system (i.e., one required to operate during normal plant conditions as well as to shut down the reactor and mitigate consequences of postulated piping failure), single active failures of components in the other train or trains of that system or other systems necessary to mitigate the consequences of the piping failure and shut down the reactor, need not be assumed provided the systems are designed to seismic Category I standards, are powered from both off-site and on-site sources, and are constructed, operated, and inspected to quality assurance, testing, and in-service inspection standards appropriate for nuclear safety systems. Examples of systems that may, in some plant designs, qualify as dual-purpose essential systems are service water systems, component cooling systems, and residual heat removal systems.
4. Available systems, including those actuated by operator actions, may be employed to mitigate the consequences of a postulated piping failure. In judging the availability of systems, account should be taken of the postulated failure and its direct consequences such as unit trip and loss of off-site power, and of the assumed single active component failure and its direct consequences. The feasibility of carrying out operator actions should be judged on the basis of ample time and adequate access to equipment being available for the proposed actions. For breaks in non-seismic piping systems, only seismically-qualified systems should be assumed to be available to mitigate the consequences of the failure because a seismic event may have caused the pipe break.

Environmental effects of a postulated piping failure should not preclude habitability of the control room or access to areas important to safe control of reactor operation needed to cope with the consequences of the piping failure. The functional capability of essential systems and components should be maintained after a failure of piping not designed to seismic Category I standards, assuming a concurrent single active failure.

The considerations related to the LBB approach should conform with the provisions of SRP Section 3.6.3.

<u>NuScale Approach</u>: LBB is applied inside the CNV to steam generator system large-bore (i.e., MSS and FWS) piping. The containment penetration area extends from the CNV safe end to pipe weld to the outermost nozzle weld of a CIV or check valve in a line. Moderate-energy piping leakage cracks are non-limiting in the CNV and NPM bay (under the bioshield), and are considered where not bounded by HELBs in other parts of the RXB. Where breaks can occur, the impact of external effects such as pipe whip is evaluated.

NuScale conforms to the provisions of regulatory guidance, but has slightly extended applicability of the containment penetration area. Nonmechanistic breaks of MSS and FWS piping in the containment penetration area are evaluated.

2.2.4 Standard Review Plan Section 3.6.2

NuScale is working to SRP 3.6.2, Rev. 2, based upon approved guidance existing six months before submittal of the design certification application (DCA). Paragraph III.3 identifies a concern with the guidance in ANSI/ANS Standard 58.2-1988 and notes that reviews of the technical adequacy of jet modeling are being done on a case-by-case basis while the NRC assesses the issue. Revision 3 of SRP 3.6.2, dated December 2016, still does not contain definitive guidance to resolve the concerns with ANSI/ANS Standard 58.2-1988, and states that alternate standards are not yet available to address the problems identified with ANSI/ANS 58.2. It also states that each new reactor design certification application's dynamic jet load modeling is assessed on a case-by-case basis. The following sections outline the NRC's position on the three classes of HELB jet impingement effects. In order to address the NRC concerns regarding HELB effects, this report considers the information in SRP 3.6.2 Rev. 3, despite being not applicable to the NuScale DCA.

Standard Review Plan 3.6.2 states that BTP 3-4 should be used to determine rupture locations both inside and outside containment.

2.2.4.1 Jet Thrust Loads

<u>Static Analysis Model</u>: The jet thrust force is represented by an amplified static loading, and the ruptured system is analyzed statically. An amplification factor can be used to establish the magnitude of the forcing function. However, the factor should be based on a conservative value obtained by comparison with factors derived from detailed dynamic analyses performed on comparable systems.

<u>Dynamic Analysis Models</u>:

1. The time-dependent function representing the thrust force caused by jet flow from a postulated pipe break or crack should include the combined effects of the following: the thrust pulse resulting from the sudden pressure drop at the initial moment of pipe rupture; the thrust transient resulting from wave propagation and reflection; and the blowdown thrust resulting from buildup of the discharge flow rate, which may reach steady state if there is a fluid energy reservoir having sufficient capacity to develop a steady jet for a significant interval. Alternatively, a steady state jet thrust function may be used.
2. A rise time not exceeding one millisecond should be used for the initial pulse, unless a combined crack propagation time and break opening time greater than one millisecond can be substantiated by experimental data or analytical theory based on dynamic structural response.
3. The time variation of the jet thrust forcing function should be related to the pressure, enthalpy, and volume of fluid in the upstream reservoir and the capability of the reservoir to supply a high-energy flow stream to the break area for a significant interval.

The shape of the transient function may be modified by considering the break area and the system flow conditions, piping friction losses, flow directional changes, and application of flow-limiting devices.

4. The jet thrust force may be represented by a steady state function if the energy balance model or the static model is used in the subsequent pipe motion analysis. In either case, a step function amplified as indicated above, is acceptable. The function should have a magnitude not less than T = KPA where P = system pressure before pipe break, A = pipe break area, and K = thrust coefficient[4]. To be acceptable, K values should not be less than 1.26 for steam, saturated water, or steam-water mixtures, or 2.0 for subcooled, nonflashing water.

<u>NuScale Approach</u>: NuScale has applied the approach noted in item 4 above and uses a steady state function of the form jet thrust force T = KPA. For other analyses, such as subcompartment pressurization, a non-steady discharge based on the characteristics of the upstream reservoir is applied.

2.2.4.2 Jet Plume Expansion and Zone of Influence

Although ANSI/ANS Standard 58.2-1998 has been accepted by the NRC, the ACRS (Reference 1.4.2.14) noted the potential for nonconservative assessments of jet impingement loads of postulated pipe breaks on neighboring SSC. The NRC staff has been assessing the technical adequacy of information pertaining to dynamic analyses models for jet thrust force and jet impingement load. Pending completion of this effort, the NRC staff reviews analyses of jet impingement forces on a case by case basis. These analyses should show that jet impingement loadings on nearby safety-related SSC do not impair or preclude their essential functions. The assumptions are as follows:

1. The jet area expands uniformly at a half angle, not exceeding 10 degrees.
2. The impinging jet proceeds along a straight path.
3. The total impingement force acting on any cross-sectional area of the jet is time and distance invariant, with a total magnitude equivalent to the jet thrust force as defined above.
4. The impingement force is uniformly distributed across the cross-sectional area of the jet, and only the portion intercepted by the target is considered.
5. The break opening may be assumed to be a circular orifice of cross-sectional flow area equal to the effective flow area of the break.
6. Jet expansion within a zone of five pipe diameters from the break location is acceptable if substantiated by a valid analysis or testing (i.e., Moody's expansion model). However, jet expansion is applicable to steam or water-steam mixtures only and should not be applied to cases of saturated water or subcooled water blowdown.

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[4] Elsewhere in this report, the thrust coefficient symbol is C_T, consistent with more common usage.

As a result of the ACRS questions, the NRC concluded that some physically incorrect assumptions form the basis for portions of the ANSI/ANS 58.2 methodology.

The standard assumes that it is conservative to model a jet issuing from an HELB as expanding at a constant 45-degree half-angle out to the asymptotic plane and then at a 10-degree half-angle. The asymptotic plane is described as the point at which the jet begins to interact with the surrounding environment, or the point where the jet conditions (e.g., pressure, temperature, flow rate) at the break mix with the surrounding environment. In particular, expansion angle at given distance downstream depends on the relative conditions at the periphery of the jet in relation to the ambient conditions.

Supersonic jet behavior can persist over distances from the break that are longer than those estimated by the standard, extending the ZOI of the jet and the number of SSC that could be impacted by a supersonic jet.

NuScale approach: NuScale has applied assumptions 2 through 6 above. Blowdown from HELBs inside the NuScale CNV differs because of the initially lower surrounding air pressure. The NuScale approach for jet expansion from postulated breaks inside the CNV therefore differs, as described in Section 3.9.5.2 and Appendix E. Jet expansion for postulated HELBs beyond the CNV in the RXB bounds the methodology accepted by the NRC, as also as described in Section 3.9.5.2 and Appendix E.

2.2.4.3 Distribution of Pressure within the Jet Plume

Appendices C and D of ANSI/ANS Standard 58.2-1988 discuss how to determine spatial pressure distribution across different types of jets. For an expanding jet, the Standard assumes variable (not uniform) pressure with a maximum at the jet centerline. The NRC considers that, while this is reasonable in the vicinity of the break, the pressure profile can vary farther away, with peaking near the jet's outer envelope. To ensure impingement loading is conservatively calculated, applicants must justify the pressure distribution as a function of downstream and radial distance.

NuScale approach: Inside the CNV, where jet expansion is constrained only by momentum, impingement effects are {{

}}$^{2(a),(c)}$

See Section 3.9.7 and Appendix E for detailed discussion.

2.2.4.4 Dynamic Loading and Potential Amplification due to Fluid-Structure Interaction

The NRC has identified that unsteadiness in free jets, especially supersonic jets, tends to propagate in the shear layer (i.e., the region with a large velocity gradient near the boundary of the jet) and induce time-varying oscillatory loads on obstacles in the flow path.

The NRC concern is that pressures and densities vary nonmonotonically with distance along the axis of a typical supersonic jet, feeding and interacting with shear layer unsteadiness. In addition, for a typical supersonic jet, interaction with obstructions could lead to backward-propagating transient shock and expansion waves that cause further unsteadiness in downstream shear layers.

Synchronization of the transient waves with the shear layer vortices emanating from the jet break can lead to significant amplification of the jet pressures and forces (a form of resonance) that is not considered in ANSI/ANS 58.2. Should the dynamic response of the neighboring structure also synchronize with the jet loading time scales, further amplification of the loading can occur, including that at the source of the jet. General observations by Ho and Nosseir are that strong discrete frequency loads occur when the impingement surface is within 10 diameters of the jet opening, and that when resonance within the jet does occur, amplification of impingement loads can result (Reference 1.4.3.8).

NuScale approach: This phenomenon is not applicable to pipe breaks in the NuScale plant, as discussed in Section 3.9.7.1 and Appendix B.

2.2.4.5 Blast Waves

In the event of a high-pressure pipe rupture, the first significant fluid load on nearby SSC is induced by a blast wave in the surrounding air. A spherically expanding blast wave is approximated to be a short duration transient and analyzed independently of any subsequent jet formation. However, the expansion of blast waves in an enclosed space is not purely spherical, and reflections and amplifications need to be addressed. Blast waves are not considered in ANSI/ANS 58.2 for evaluating the dynamic effects associated with the postulated pipe rupture.

NuScale approach: {{

}}2(a),(c)

2.2.4.6 Pipe Whip

Standard Review Plan 3.6.2 establishes that pipe whip analyses should show that pipe motions do not result in unacceptable impact upon, or overstress of, any SSC:

> “to the extent that essential functions would be impaired or precluded . . . The analysis methods used should be adequate to determine the resulting loadings in terms of the kinetic energy or momentum induced by the impact of the whipping pipe, if unrestrained, upon a protective barrier or a component important to safety and to determine the dynamic response of the restraints induced by the impact and rebound, if any, of the ruptured pipe.”

The SRP acknowledges that a determination can be made for pipe-on-pipe impact:

> “An unrestrained whipping pipe should be considered capable of causing circumferential and longitudinal breaks, individually, in impacted pipes of smaller nominal pipe size, and of developing through-wall cracks in equal or larger nominal pipe sizes with thinner wall thickness, except where analytical or experimental, or both, data for the expected range of impact energies demonstrate the capability to withstand the impact without rupture.”
>
> “In case of a circumferential rupture, the need for a pipe-whip dynamic analysis may be governed by considerations of the available driving energy.”
>
> “Dynamic analysis methods used for calculating piping and restraint system responses to the jet thrust developed after the postulated rupture should adequately account for the following effects: (a) mass inertia and stiffness properties of the system, (b) impact and rebound, (c) elastic and inelastic deformation of piping and restraints, and (d) support boundary conditions.”

The SRP states that acceptable models for high-energy piping systems include:

- Lumped parameter analysis that accounts for inertia and stiffness properties of the system and maximum initial clearances at restraints.
- Energy balance in which kinetic energy from the first quarter cycle of movement of the ruptured pipe is converted to equivalent strain energy. Deformations should be compatible with the level of absorbed energy, and energy absorbed by pipe deformation may be subtracted from that available. Where rebound may occur, an amplification factor of 1.1 should be used unless another value is justified by detailed analysis.
- Static analysis where the jet thrust force is represented by a conservatively amplified static loading. An amplification factor can be used to establish the magnitude of the forcing function. However, the factor should be based on a conservative value obtained by comparison with factors derived from detailed dynamic analyses performed on comparable systems.
- Other attributes if justified.

<u>_NuScale approach_</u>: Inside the CNV, each of the postulated locations is shown to be acceptable on at least one of the following bases, in order of preference:

1. The piping has insufficient energy to whip (see Appendix C.4.1).

2. The length of whipping pipe is insufficient to reach essential SSC.
3. The whipping pipe is blocked by a barrier, which is a robust component (e.g., RPV, CNV) or wall, from reaching an essential SSC.
4. The essential structure, system or conponent is justified as being sufficiently robust to withstand the impact without loss of function.
5. The number of redundant components is such that the damage caused by pipe whip combined with a single active failure does not cause a loss of an essential function.
6. Dynamic structural analysis of the impact force on a given essential structure, system, or component.

Unless impact effects are clear (e.g., breaking a power cable de-energizes a component), damage caused by an HELB is assumed to fail a component in a way that does not allow the essential function to occur.

Any safety-related or essential components within reach of a whipping pipe are evaluated for need for a pipe whip restraint, pipe whip barrier, or qualification for pipe whip impact. Because piping arrangements within the RXB are not finalized, protection of components for pipe whip will be addressed by the COL applicant in accordance with COL items 3.6-1 and 3.6-3.

For the NPM bay area, because break exclusion eliminates the need to postulate HELBs, pipe whip is not relevant.

For integrity of the RXB concrete structure, an estimate is made of the kinetic energy of the whipping pipe, to be applied over a limited contact area using the methodology described for missile impact in Appendix C.

Regarding multimodule effects, only the impact of {{

}}$^{2(a),(c)}$ Pipe whip and jet reaction loads must be considered in load combinations in accordance with FSAR Section 3.9 and Section 3.12.

2.2.5 Standard Review Plan Section 3.6.3

Standard Review Plan 3.6.3, Rev. 1 (Reference 1.4.2.3) provides guidance on performing an LBB analysis acceptable to the NRC staff. If approved, the LBB analysis precludes the need to postulate HELBs, and the consequent pipe whip restraints and jet impingement barriers (and analysis of dynamic effects), but LBB still requires consideration of cracking.

The adequacy of detection of RCS leakage must be shown, in addition to consideration of the specifications of selecting reactor coolant leakage detection systems in Regulatory Guide 1.45, Rev. 1. In order to demonstrate reliability, redundancy, and sensitivity of the detection system, a margin of 10 on detection of a precursor leak rate is required (i.e., must be able to withstand a leak rate through a precursor crack that is 10 times that detectable).

Leak-before-break may only be applied to high-energy, ASME Code Class 1 or 2 piping, although other applications can be considered. Leak-before-break is applied on a system or system segment basis (i.e., not to individual locations). A deterministic fracture mechanics and leak rate evaluation must be performed to demonstrate that “the probability of pipe rupture is extremely low under conditions consistent with the design basis for the piping.” Using fracture mechanics stability analysis or limit load analysis, the critical crack size for the postulated through-wall crack using loads from the normal plus safe shutdown earthquake (SSE) must be shown to have a margin of two between the critical crack size and the leakage crack size (after application of the factor of 10 on leak rate). Also, a crack stability analysis is performed to demonstrate that leakage cracks do not become unstable if 1.4 times the normal plus SSE loads are applied or if the sum of the absolute values of the deadweight, thermal expansion, pressure, SSE (inertial), and seismic anchor motion loads is satisfactory. Limit load analysis requirements are identified for specific weld types.

Confirmation of LBB acceptability is per ITAAC because as-built, not as-designed, configuration of pipe, supports, gaps, and etc. must be addressed. Pipe integrity degradation must consider water hammer, creep damage, erosion, corrosion, fatigue, and environmental conditions.

Standard Review Plan 3.6.3 identifies material specifications and property testing.

NuScale approach: NuScale has applied LBB only for MSS and FWS piping inside the CNV. Leak-before-break is not applied to RCS-connected piping due to its small size (i.e., NPS 2). Small piping LBB would involve such low leak rates that, after applying the factor of 10, make discerning leakage cracks subject to a threshold so low that it would likely be masked by normal, non-RCPB leakage. Section 3.6.3 in the FSAR provides a detailed description of the LBB analysis.

3.0 Methodology

In Section 2.2.2, the NuScale approach for addressing regulatory expectations is briefly identified in relation to specific NRC regulations and guidance. This section discusses the methodology for demonstrating compliance with GDC 4 and addressing the related regulatory guidance. Details of how the analyses are performed and a summary of results are provided in Appendices A through F.

3.1 General Approach

This PRHA report is prepared to supplement the information contained in the NuScale FSAR relative to the occurrence of postulated pipe ruptures inside the NPM and in the NuScale RXB.

Figure 3-1 is a flowchart depicting the process for evaluation of potential line breaks. The NuScale methodology applicable to identification and assessment of pipe rupture hazards addresses:

- design features of the NuScale plant.
- compliance with NRC regulations and guidance.
- identification of postulated rupture locations
- characteristics of ruptures including break types and size.
- determination of potential effects of HELBs and MELBs.
- criteria for showing acceptability of essential SSC exposed to those effects.

External effects of HELBs and MELBs in the NPM and NuScale RXB do not prevent the ability to shut down and maintain core cooling.

An integral, passive, multi-module, small modular reactor has different line break risks than the larger-scale, single-unit, loop LWR for which regulatory guidance was developed and refined. In particular, the arrangements, number, and mechanism of operation of high and moderate energy piping and of essential systems differs from that assumed by regulatory guidance.

NuScale specific differences are discussed in Section 2.1.

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Figure 3-1 Flowchart of methodology for evaluation of line breaks

3.1.1 Essential Functions

NuScale shutdown and core cooling functions rely on natural forces (i.e., buoyancy driven natural circulation) or local energy storage (i.e., nitrogen accumulator to close CIVs). The functions initiate without human interaction.

In accordance with the footnote in BTP 3-3 that defines essential systems and components as those "necessary to shut down the reactor and mitigate the consequences of a postulated pipe rupture without off-site power," the essential systems in the NuScale design are identified below and discussed in the following sections:

- RCS
- module protection system (MPS)
- neutron monitoring system (NMS)
- chemical and volume control system (CVCS)
- control rod assembly (CRA) and the control rod drive system (CRDS)
- containment system (CNTS)
- DHRS (including portions of the steam generator system (SGS) required for DHRS operation)
- ECCS
- ultimate heat sink (UHS) / reactor pool

In addition, the NuScale design is evaluated for the capability to maintain long-term PAM and plant DC electrical power in order to limit simultaneous multimodule effects due to a loss of AC power. The NuScale design does not rely on any Class 1E power or safety-related and essential systems or components external to the modules to perform any active safety function.

Where a line break is postulated to occur, the appropriate dynamic and environmental effects are considered, with the additional assumptions of a loss of all ac power and a single active failure. Because of the passive safety design, loss of ac power is not a threat to the core cooling of any module, and the EDSS, backed up by the ECCS valve inadvertent actuation block (IAB), ensures that multiple modules do not blow down simultaneously from de-energization of the ECCS valve solenoids. The IAB holds its ECCS valve closed until RCS pressure has decreased to the range of 1200 to 1000 psia, by preventing venting of the control chamber above the main valve disc even if the trip valve opens or the trip/reset actuator line is breached.

3.2 Description of Systems Important to Reactor Shutdown and Core Cooling

Essential SSC are those needed for reactor shutdown and core cooling. The simplicity and passive safety features of the NuScale design result in a small number of SSC being required for reactor shutdown and core cooling. In some cases, only portions of an SSC are essential. Table 3-1 summarizes the safety-related and essential SSC and, in particular, which portions are necessary for shutdown and core cooling.

Table 3-1 Safety-related and essential parts of structures, systems, and components vulnerable to break effects

System	Location	Component
RCS	CNV	All
ECCS	CNV	RRVs & RVVs
	NPM bay	Trip and reset valves*
DHRS	CNV	Piping Feed line thermal relief valves
	NPM bay	Actuation valves
		Valve position indicators
		Passive condenser*
UHS	RXB	NPM pool Spent fuel pool
SGS	CNV	Piping
MPS	Various	Separation Groups
CNTS	NPM bay	CNV CIVs MSS tee fittings between CNV and CIVs Electrical penetration assemblies (EPAs)
	RXB	CIV hydraulic power unit (HPU) skids
CVCS	RXB	CVCS demineralized water make-up valves
CRDS	CNV	CRDM pressure boundary, control rod drive shafts, and latch mechanisms**

* Submerged in pool

** CRDS cooling, power, and instrumentation are not safety related.

Structures, systems, and components are classified as A1, A2, B1, and B2 in accordance with their safety and risk categories:

- A1 – both safety-related and risk-significant
- A2 – safety-related but not risk-significant
- B1 – risk-significant but not safety-related
- B2 – neither safety-related nor risk-significant

3.2.1 Reactor Coolant System

A breach of an RCS line releases reactor coolant into the CNV, which is bounded by and leads to ECCS initiation.

Chemical and volume control system lines inside the CNV are part of the RCS. Reactor coolant system circulation is entirely contained within the RPV (i.e., there is no RCS loop piping). Hot coolant exiting the top of the core moves up through a riser by buoyancy-driven natural circulation, turns at the pressurizer baffle plate, passes downward around the tubes of the steam generators (SGs) where it is cooled, and then passes outside the core to reach the bottom of the RPV to rise again through the core. Pilot-actuated reactor safety valves (RSVs) are mounted on the RPV. RCS lines that carry fluid from and to the CVCS are NPS 2 Sch 160.

3.2.2 Module Protection System

The MPS monitors conditions in the NPM and connected systems, and automatically executes safety-related functions when required. Each NPM has its own dedicated MPS that is not shared with other NPMs. The MPS maintains components in an energized, or nonactuated, state during normal operation.

Plant design criteria require that Class 1E circuits in the CNV and in the NPM bay outside the CNV (under the bioshield) are qualified for environmental conditions, and also be evaluated for pipe whip and jet impingement. Class 1E circuits in the RXB are separated from areas containing high-energy piping. Class 1E circuits are routed or protected so that failure of the mechanical equipment of one division cannot disable Class 1E circuits or equipment essential to the performance of the safety-related function by the systems of the redundant division(s). The effects of failure or misoperation of a mechanical system on its own division is considered when the Class 1E circuits or equipment are required to mitigate the consequences of such failure or misoperation. The effects of pipe whip, jet impingement, water spray, flooding, radiation, pressurization, elevated temperature, or humidity on redundant electrical systems caused by failure, misoperation, or operation of mechanical systems are considered. The potential hazard of missiles resulting from failure of rotating equipment or high-energy systems are considered.

Protection of nonhazard and limited hazard areas from pipe failure hazard areas is accomplished by the use of barriers, restraints, separation distance, or an appropriate combination thereof. The routing of Class 1E and associated circuits in pipe failure hazard areas conforms to the following requirements, unless it can be demonstrated that pipe failure cannot prevent the Class 1E circuits and equipment from performing their safety-related function.

- Where the piping involved is qualified for design-basis events is not assignable to a single division and the pipe failure requires no protective action, Class 1E equipment, associated circuits, or raceways routed through the area are limited to a single division.
- Where the pipe failure requires protective action, Class 1E equipment, associated circuits, or raceways are not routed through the area, except those cables that must terminate at devices or loads within the area.

- Where the piping involved is qualified for design-basis events, it is assignable to a single division, and the pipe failure requires no protective action, Class 1E equipment, associated circuits, or raceways routed through the area are limited to the same division as the piping.
- Where the piping involved is not qualified for design-basis events, Class 1E equipment, associated circuits, or raceways are not located in the area, except for those cables that must terminate at devices or loads within the area.

The location of RPV head penetrations used for instrumentation is shown in Figure 3-2.

No electric power is required to accomplish a reactor trip or initiate engineered safety features, but power is needed to maintain PAM indication.

3.2.3 Neutron Monitoring System

The NMS provides neutron flux data for reactor trip, operating bypasses, and actuation of the MPS and information signals for PAM. A failure (e. g., broken signal cable) that causes an off-scale indication is registered as a fault by the MPS and does not adversely affect trip capability. Such a failure could remove one channel of PAM indication, therefore cables in areas of postulated breaks are routed out of range of HELB effects.

3.2.4 Chemical and Volume Control System

The CVCS maintains RCS inventory during normal operation, provides purification and chemical injection to the RCS, provides pressurizer spray, and supplies heated water to warm up the RCS during start-up. None of these functions are essential or safety-related for HELB scenarios. However, a pair of in-series, fail closed, isolation valves must close to ensure a boron dilution event does not occur. These valves close on an MPS trip. The dilution scenario is highly unlikely: both valves must fail open, power must be maintained to the CVCS make-up pumps, and both CVCS injection CIVs must fail to shut in order for unborated water to flow into the RCS. Dilution of water in the pool is not relevant as HELBs under bioshield are excluded and cracks under the bioshield need not be assumed coincident with a HELB in the RXB that could affect the valves. On this basis, the possibility of a HELB in the RXB adversely affecting these make-up isolation valves is judged an acceptable interaction that requires no additional mitigation.

3.2.5 Control Rod Assembly and Control Rod Drive System

The CRA includes neutron absorber control rods that are mechanically raised and lowered by control rod drive mechanisms (CRDMs) located on top of the RPV. The principal safety function is to achieve an immediate shutdown of the fission process when required by plant conditions. During normal plant operation, an electric coil in the CRDM is maintained energized to hold the control rods withdrawn from the core in a static position. Interruption of electric power de-energizes the CRDM electric coils causing the control rods to be unlatched and fall into the core (i.e., trip) via gravity. This passive insertion of negative reactivity results in the core becoming subcritical, and remaining subcritical during RCS cooldown to 70-degrees Fahrenheit with all rods inserted.

The CRAs are located inside the RPV and, therefore, protected from the external effects of an HELB. Internal effects such a differential pressure forces induced by blowdown are not within the scope of this report.

No electric power is required to accomplish the trip. The control cabinets and wiring for the CRDS are not safety-related and do not need to be protected from HELBs.

3.2.6 Containment System

The CNV is an ASME Class MC (steel) containment that is designed, analyzed, fabricated, inspected, tested, and stamped as an ASME Code Class 1 pressure vessel with a design pressure of at least 1000 psia. The CNV wholly contains the RPV and is mostly immersed in the reactor pool. The containment system (CNTS) is comprised of valves, fittings, and piping connecting systems inside and outside of the CNV (i.e., connecting the RCS lines inside containment to the CVCS piping outside). The CNTS boundary ends at the flange where a pipe spool can be removed so that the NPM can be moved. The containment evacuation system line is open to the CNV to allow the operating vacuum pump to maintain the low internal pressure, and the flooding and drain line is normally isolated and exposed to CNV vacuum. These lines are not discussed in this report because they are not high- or moderate-energy.

Each line connected to the RCS or open-ended to containment has two series CIVs in accordance with 10 CFR 50 Appendix A, GDC 55 and 56, except that both CIVs are located outside the containment within a single piece valve body that is welded directly to the safe end. Each CIV {{

}}2(a),(c)

The following considerations apply to safety-related CNTS SSC that are potential targets:

- In the CNV: The CNV itself is subject to pipe whip and jet impingement but pipe whip and jet impingement loads are low compared to its structural capacity.
- Under the bioshield: The CIV (and DHRS) actuators are potentially exposed to only non-mechanistic breaks and cracks. The actuators are qualified for exposure to the pressure-temperature profile from nonmechanistic breaks.
- In the RXB: The only CNTS target SSCs are the CIV HPU skids. There are two CIV HPU skids for each NPM, one located on the elevation above the pipe gallery and one located in the pipe gallery underneath a CES vacuum pump which is under one of the MSS lines. For all of CNTS lines with dual CIVs, one CIV is actuated by one skid while the other is actuated by the other skid. The CIV HPU skid supplies a constant pressure (minimum 1025 psig) via small diameter hydraulic tubing to keep the CIVs open and the DHRS actuation valves shut. Should the hydraulic lines be breached, the fluid

would vent and the associated valves would be put into their safe position (e.g., CIVs shut) by the pressurized accumulator attached to each valve or remain in the safe position if already there. Similarly, if electric power was lost or wires to the CIV skid solenoid valves were dislodged, the hydraulic fluid would vent when control solenoids de-energized, and the valves would move to their safe position.

The hydraulic lines and electric cables are the portions of the skid most vulnerable to damage by pipe whip or jet impingement (blast wave loading is low and of such short duration that it has less damage potential) and, therefore, would cause valves to go to their safe position (and an associated reactor trip) should they be struck and breached during a HELB. Complete crimping of the hydraulic lines by HELB impact is considered unrealistic because of their high internal pressure which would cause them to breach rather than crimp if struck. Partial crimping could slow CIV closure.

The presence of one of the CIV skids near postulated HELB locations is deemed an acceptable interaction: while there is potential for damage to the skid, that damage would result in the valves being put into their safe position by remote equipment not exposed to HELB effects. The arrangements of MSS and FWS lines are to be finalized by the COL applicant, but it is expected that motion of a whipping MSS or FWS piping would not result in a CIV skid being struck. In accordance with COL action items 3.6.2-1, 2, and 3, the final PRHA report will evaluate CIV HPU skid vulnerability once piping arrangements in the RXB are finalized.

The MSS, FWS, DHRS, and reactor component cooling water system (RCCWS) lines are closed-loop systems inside containment (i.e., GDC 57). The MSS and FWS lines each have a single CIV of the same design as described above. Because of the need for DHRS hot leg connections, the main steam system CIVs are separated from the CNV nozzles by two tee fittings. A bypass line around each main steam system CIV is used to pass steam for secondary system start-up before opening the MSIVs. The bypass valve is closed whenever the plant is operating. With the MSS and FWS systems isolated, secondary side water inventory is maintained for decay heat removal.

The RCCWS lines are small diameter and use the same dual valve design as used for open-ended lines.

Piping lines except those for the MSS and DHRS have only one weld between the CNV head nozzle and the CIVs. In addition to the CIVs, each normally open line directly connected to the RCS has a check or excess flow check valve directly welded to the outboard nozzle of the CIV body. Each feedwater system CIV body also contains an integral check valve that shuts upon flow reversal caused by a FWS line break outside the NPM.

No electric power is required to close the CIVs.

3.2.7 Decay Heat Removal System

The DHRS passively removes decay heat by natural circulation, to establish safe shutdown conditions following a reactor trip, without need for operator action or on-site or off-site power. The DHRS consists of two independent and redundant trains, and each train alone has 100 percent capacity to provide heat removal. During normal plant operation, the DHRS is in standby mode with flow blocked by closed DHRS actuation valves in the inlet line. These valves are maintained closed by energized actuator solenoids on the CIV HPU skids. When power to the solenoids is interrupted, the valves (which are the same design as the CIVs, except that they fail open) open through the force of the nitrogen pressurized accumulator. Opening either of two DHRS actuation valves on one of the two redundant trains provides sufficient cooling. The actuation valves are subject to the same acceptable interaction as the CIVs (Section 3.2.6).

The DHRS is comprised of two closed loop flow paths, each consisting of an SG, a DHRS passive condenser, and associated piping that provides natural circulation of secondary water flow from the SGs to the passive condensers, where heat is rejected to the UHS, the reactor pool.

No electric power is required to open the DHRS actuation valves.

3.2.8 Emergency Core Cooling System

The ECCS ensures core cooling by maintaining the core covered with water during design-basis events in which the system is actuated. Unlike other larger LWR designs, the NuScale ECCS does not require a source of water for injection or the availability of electric power. Decay heat removal occurs by releasing coolant to the CNV, which is cooled by condensation and conduction through the CNV wall to the reactor pool. Water in the CNV flows back into the RPV by natural circulation. Similar to the DHRS, the ECCS is started by interrupting power to the ECCS valves.

The system has five main valves and associated hydraulic lines and actuator assemblies, including control solenoids. The main valves are bolted to the RPV. Three reactor vent valves (RVVs) and two reactor recirculation valves (RRVs) provide sufficient flow area even if one valve fails to open. Each main valve has two associated pilot valves: the trip valve and the reset valve. The pilot valves have solenoids that are used to reposition the pilot valves and subsequently reposition the associated main valves. The trip valve solenoids are kept energized to prevent the ECCS main valves from opening. The reset valve solenoids are only energized to allow the ECCS main valves to close while the plant is being started. The trip and reset valves are part of a single manifold located on the exterior of the CNV, submerged in the pool.

With the trip valve solenoid energized, a vent path for the control chamber above the main valve disc is blocked, and the control chamber is maintained pressurized. With the control chamber pressurized, the main valve is held shut. De-energizing the trip valve solenoid repositions the trip valve removing it from the control chamber vent path.

The ECCS contains an inadvertent actuation block (IAB) feature to prevent opening the main valves at normal operating pressure. The IAB valve, bolted to the main valve body, is installed in the hydraulic path between the control chamber and the trip valve. When the IAB valve is closed and RCS pressure is near normal, the control chamber cannot be vented, regardless of trip valve position or integrity of the trip/reset line.

During normal power operation, the five ECCS main valves are closed, their IAB valves are open, and their trip valves are energized and closed. If electric power to them is interrupted, the trip valves de-energize and open, depressurizing the trip line. The IAB valves are forced closed by the differential pressure between the RCS and CNV. As a result, the ECCS valves remain closed. Should the RCS be completely depressurized before main valve control chamber pressure is vented, springs open the valve.

The ECCS valves open in the following scenarios:

- Because the decay heat removal capacity of the DHRS exceeds decay heat levels, it results in lowering RCS temperature and pressure. If the trip valve is de-energized, then reduction in RCS pressure and the resultant reduction in differential pressure across the actuation valve clears the IAB feature, so that RCS pressure (even though declining) opens each ECCS valve.
- For a reactor coolant system HELB inside the CNV, the RCS depressurization and CNV pressurization clear the IAB, permitting the ECCS main valve disc to open as soon as the trip valve power is interrupted.

No electric power is required to open the ECCS valves because they are opened by RCS pressure (or springs).

3.2.9 Ultimate Heat Sink

The UHS consists of a large pool complex where the NPMs and spent fuel are housed. The combined volume of water is in the associated water-retaining structures and components of the reactor pool, refueling pool, and spent fuel pool (SFP). The water volume in the reactor pool and refueling pool portions of the UHS is connected with the water volume in the SFP through the space above the top of the UHS weir wall. Water level is maintained during normal operation via interface with the spent fuel pool cooling system, and temperature is controlled using the reactor pool cooling system and the spent fuel pool cooling system. If ac power is lost, these nonsafety-related systems are unavailable.

The UHS has capacity for decay heat from up to 12 NPMs operating at full power and a full SFP. Lowering of UHS level due to evaporation and pool boil-off during a loss of ac power event is gradual enough to ensure the DHRS passive condensers remain submerged for greater than 30 days without operator action, electric power, or addition of water. By the time the condensers uncover, decay heat is low enough that heat loss to ambient air is sufficient. Passive venting from the area of the RXB above the pools transfers the energy to the environment.

No electric power is required to fulfill the UHS function of the NuScale plant.

3.2.10 Steam Generator System

The SGS is comprised of NPS 4 and larger piping carrying feedwater and main steam. The piping is not adversely affected by the effects of NPS 2 CVCS line HELBs. However, the feed lines have two thermal relief valves at about the 459 inch elevation that are evaluated for vulnerability to damage, particularly pipe whip.

3.2.11 Post-Accident Monitoring

Post-accident monitoring is a nonsafety-related function that uses other systems' components. Although no operator action is required for a design basis event to ensure core cooling for an unlimited duration, monitoring of the status of the NPMs is desirable and is necessary to meet regulatory guidance. Post-accident monitoring information is displayed on the safety display and indication system. Post-accident monitoring does not have a capability to control any equipment.

Post-accident monitoring uses available instrumentation to monitor Type A, B, C, D, and E variables, as defined in Regulatory Guide 1.97, Rev. 4 (Reference 1.4.2.6). NuScale has no Type A variables. Type B, C, and D variables inside containment are listed in Table 3-2. The location of RPV head penetrations for instrumentation is shown in Figure 3-2. Separation groups B and C are preferred for PAM purposes because they are provided with highly reliable DC power via the EDSS for 72 hours, whereas groups A and D have DC power available for only 24 hours, assuming no operator action during a loss of off-site power or station blackout (SBO). For the purpose of satisfying PAM requirements for an HELB, only separation groups B and C are considered.[5] A single failure of one of these is also assumed, although single failures for an SBO are not considered. Post-accident monitoring indication by at least one channel must still be available after an HELB, which requires both separation groups B and C to be protected for HELB effects. For protection against pipe whip and jet impingement, cables are routed at least 6.75 inches from the path of a whipping pipe from an RCS line terminal end break in the CNV. The cable is qualified by testing for CNV design pressure and temperature, and for jet impingement effects, which bounds RCS line break conditions.

Figure 3-3 shows the exterior, topside view of the break locations at the interior, underside of the CNV head.

The functionality of PAM is neither safety-related nor essential, but is addressed in this report consistent with regulatory guidance. Power from the highly reliable DC power system (EDSS) is required for PAM indication.

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[5] The definition of station blackout in 10 CFR 50 states, in part: "Station blackout does not include the loss of available AC power to buses fed by station batteries through inverters or by alternate AC sources as defined in this section, nor does it assume a concurrent single failure or design basis accident." NuScale does not rely on off-site or alternate source AC power for any safety-related or essential function. The ECCS initiation occurs within two hours for reactor coolant system HELBs inside the CNV, removing the ECCS trip valve load. Removal of the ECCS solenoid load within two hours results in separation group A & D battery power being available for at least 48 hours. If a loss of all AC power occurred, operator action to provide alternate power to battery chargers within 48 hours sustains PAM but is not assumed.

Table 3-2 Separation group B and C post-accident monitoring Type B & C instruments inside containment

Variable	Number of Sensors*	RPV Nozzle Numbers	CNV Nozzle Numbers
Wide Range RCS Hot	2	60, 63	18, 19
Core Inlet Temperature	12	40, 41	17, 18, 19, 20
Core Exit Temperature	12	40, 41	17, 18, 19, 20
Narrow Range CNT Pressure	2	N/A	18, 19
Wide Range RCS Pressure	2	40, 41	18, 19
Wide Range CNT Pressure	2**	N/A	18, 19
RPV Riser Water Level	2	40, 41	18, 19
CNT Water Level	2	N/A	18, 19

* Separation groups B & C are PAM channels with 72-hour DC power; Groups A & D monitor the same Type B & C variables (except for wide range CNT pressure) but have 24-hour DC power. Therefore, only Separation group B & C instrument information is shown.

**No separation group A & D sensors

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}}$^{2(a),(c),ECI}$

Figure 3-2 Reactor pressure vessel head penetrations and break locations

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}}$^{2(a),(c),ECI}$

Figure 3-3 Containment vessel head penetrations and break locations (breaks on underside)

3.3 Systems with Potential for High- or Moderate-Energy Line Ruptures

The following sections provide a description of the high- and moderate-energy systems that could experience a pipe rupture. These systems are summarized in Table 3-3. The table identifies the line operating and design conditions, size, piping design code, and HELB status (i.e., the approach taken to demonstrate essential SSC are protected).

The final design for piping systems beyond the NPM bay is the responsibility of the COL applicant, as stated in the NuScale FSAR 1.4.2.15 COL Items 3.6-1, 3.6-2, and 3.6-3. This includes final equipment location, pipe routing, support placement and design, piping stress evaluation, pipe break mitigation, and evaluation of subcompartment pressurization and multimodule effects. This report documents analyses of bounding scenarios that were performed to ensure the design, when finalized, can comply with NRC regulations and guidance.

3.3.1 Reactor Coolant System

The RCS is wholly contained within the CNV and has no loop or other large piping to rupture. The RCS lines run between the RPV nozzles and the CNV safe ends for pressurizer spray (two lines from the RPV tee into one exiting the CNV), RPV high point degasification (hereafter, just “degasification” or “degas”), discharge, and injection. The RCS lines are NPS 2 Schedule 160. The degasification line is isolated with its CIVs closed during normal operation. Welds and fittings are minimized through use of pipe bends.

3.3.2 Containment System

With the exception of the two reducing tees in each of the two MS lines discussed in Section 3.2.6 and below, the CIVs are welded directly to the CNV safe ends. The CNTS extends from a CNV nozzle on the inside of the CNV to a single (MSS or FWS) or dual CIV in a single body, and two tees in each of the MSS lines outside the CIV. Also, a check valve is incorporated into the body of the feedwater system CIVs.

3.3.3 Chemical Volume and Control System

The CVCS includes the RCS-connected lines off the CNV. The CVCS lines in the RXB are NPS 2, 2½, and 3. The lines to the NPM consist of the following major segments: pressurizer spray, injection, degas, and discharge (each of which has a check or excess flow check valve welded to the CIV outboard nozzle). The piping is stainless steel.

In the NPM bay, lines run between the inboard disconnect flanges and the pool wall. Dual, single-body CIVs are directly welded to the CNV safe ends and are part of CNTS. Outboard of the valves and check or excess flow check valves, NPS 2 flanged piping spool pieces provide the capability to disconnect the NPM from system piping in preparation for movement for refueling.

In the Reactor Building, CVCS lines connect to the balance of the system (i.e., nonregenerative heat exchanger, ion exchangers). The RXB portions of the CVCS have many different state points, including some with high pressure/low temperature.

3.3.4 Emergency Core Cooling System

As described in Section 3.2.8, the ECCS has no physical piping, other than the trip and reset lines, which are small diameter (i.e., less than one-inch diameter). The design basis blowdown for the RCS and CNV is inadvertent opening of an ECCS valve. As described in Section 3.2.8, the IAB is provided to avoid an inadvertent actuation while an NPM is near normal operating pressure. Discharge from the RRVs is directed downward away from essential SSC and discharge from the RVVs is directed toward the CNV walls through diffusers. The ECCS main valves are bolted directly onto the RPV.

3.3.5 Steam Generating System

The steam generator system (SGS) is the in-containment main steam and feedwater piping. In the CNV, four NPS 8 Schedule 120 SGS steam lines from the SG outlet plena connections on the RPV merge into two NPS 12 Schedule 120 steam lines to the CNV safe ends. The piping has a design pressure equal to that of the RCS.

The two NPS 5 feed lines from the CNV nozzles split into two NPS 4 lines (total of four) that supply feedwater to the SG plena. Just upstream of the split, the DHRS return line tees in.

The SGS lines are Schedule 120 with a design pressure and temperature equivalent to that of the RCS.

3.3.6 Main Steam System

In the NPM bay outside the CNV (under the bioshield), two main steam lines consist of NPS 12 flanged piping spools that provide the capability to disconnect the NPM in preparation for movement for refueling, and a fixed section of pipe that projects through the pool bay wall into the pipe galleries on each side. The spools include ball joints to allow for small variations in NPM position. The lines are made from stainless steel.

In the RXB, the NPS 12 lines include an isolation valve with a NPS 4 bypass line. Pipe routing, weld locations, and placement of hangers have not yet been finalized. To ensure that the RXB and its essential SSC are adequately protected, NuScale has evaluated bounding HELBs and established design requirements for separation. Main steam piping designed to ASME B31.1.

3.3.7 Feedwater System

In the NPM bay, two flanged NPS 6 piping spools incorporating ball joints provide the capability to disconnect the NPM in preparation for movement for refueling. The lines are NPS 4 stainless in the containment penetration area. Beyond that, the removable piping spool and the piping from the outboard flange into the pipe gallery are SA-335 PA11.

In the RXB, the NPS 6 lines include a check valve. Pipe routing, weld locations, and placement of hangers have not been finalized. To ensure that the RXB and its essential SSC are adequately protected, NuScale has evaluated bounding HELBs and established design requirements for separation. The FSW piping is designed to ASME B31.1.

3.3.8 Decay Heat Removal System

Cool water from the passive condenser is returned to the FWS piping by a NPS 2 Schedule 160 line located both inside the CNV and inside the bay submerged in the pool.

In the NPM bay, a NPS 8 Schedule 160 line (four lines total) runs from each MSS reducing tee inboard of the main steam CIV through a normally closed, fail open, 6-inch DHRS actuation valve to the passive condenser.

3.3.9 Reactor Component Cooling Water System

The RCCWS is a moderate-energy system supplying cooling water to the CRDMs. Inside the CNV, supply and return lines that are part of the CRDS consist of curved headers connected to which are attached flexible cooling hoses to each CRDM.

The effects of any RCCWS rupture are bounded by those of HELBs.

3.3.10 Auxiliary Boiler System

The auxiliary boiler system (ABS) is a nonsafety, nonseismic system designed to supply steam to systems where main steam is not available or is not preferred. It is a COL applicant-provided system.

The ABS consists of two separate subsystems, neither of which is present in the CNV or NPM bay. The high-pressure system is dedicated to supplying steam to the module heatup system (MHS) heat exchangers during start-up and has two separate headers, with a limited amount of piping in the RXB. The low-pressure portion is outside the RXB and is not discussed further in this report. The high-pressure portion provides up to 18,000 lbm/hr of 575-degree steam at 1100 psig. The two high-pressure boilers can each supply heat for one module on one side of the plant and are equipped with a pressure relief valve. The routing of auxiliary boiler lines is not final.

Based upon an estimated NPM heatup time of 24 hours, no need for ABS steam for NPMs going into a refueling outage, a two-year refueling cycle, and a full 12 NPM plant, each header of the ABS has steam in RXB piping for about 72 hours/year (i.e., one module start-up per header every four months). Branch Technical Position 3-4 paragraph B.2.(v) states that leakage cracks instead of breaks may be postulated in those fluid systems that qualify as high energy for only a short operational period. NuScale FSAR Section 3.6.1.1 defines a short period to include being at “high-energy pressures or temperatures for less than 1 percent of the plant operation time.” The high-energy portion of the ABS in the RXB is expected to operate less than one percent of the year (i.e., 86.4 hours), so the only external effect needing evaluation is from leakage cracks.

3.3.11 Module Heatup System

The MHS conveys heat from the ABS to the CVCS to heat reactor coolant for an NPM during start-up until nuclear heat is available. The MHS heating combined with simultaneous heat removal in the SGs drives RCS flow during the heatup. The two MHS subsystems each contain two heat exchangers, with each subsystem serving six modules on one of two sides of the plant. The CVCS recirculation pumps are used to supply reactor coolant through the MHS and then to the respective NPM. Each MHS subsystem provides heat to only one NPM at a time. Although unlikely, the MHS may also be used during shutdown to maintain RCS flow if decay heat is insufficient.

Consistent with the ABS, the MHS is expected to operate less than one percent of the year and is, therefore, evaluated as a moderate-energy system for effects of leakage cracks.

3.4 Break Characteristics

Where postulated breaks might occur, the characteristics of those breaks (i.e., thermodynamic conditions) are identified as inputs to an evaluation of external effects. In general, “bounding” conditions are used in analysis of breaks. For example, the CVCS piping has considerable variation of fluid temperature and pressure with location in the RXB and with plant initial conditions. Rather than evaluating many specific conditions, initial intact system temperature and pressure values are selected to maximize the mass and energy release from the HELB in the affected area of the plant and are, therefore, conservative for evaluating multiple break locations.

Postulated breaks are circumferential. Longitudinal cracks are not applicable in the CNV, because piping NPS 4 and larger meets LBB criteria. Also, longitudinal breaks need not be considered in the NPM bay outside the CNV (under the bioshield), based on meeting criteria for not considering circumferential breaks. In the rest of the RXB, effects of longitudinal breaks (with break flow areas equal to the piping flow area) are bounded by circumferential breaks. Table 3-4 summarizes potential break locations and characteristics in the NuScale plant.

The initial conditions are selected to bound system conditions for any power level, 102% thermal power or hot standby operation, for which the NuScale equivalent is referred to as hot shutdown. During hot shutdown, MSS pressure and temperature are approximately 300 psia and 420°F, and primary pressure and temperature are approximately 1850 psia and 420°F.

- For MSS HELBs, full power operating conditions produce higher calculated thrust loads that bound those at hot shutdown.
- For CVCS and RCS HELBs, full power operating temperature and pressure produces the most severe blowdown. However, calculated thrust loads are not based solely on system pressure, because the jet thrust load is also dependent on the thrust coefficient, which is 2.0 for nonflashing blowdown vs. 1.26 for steam. To be nonflashing, the coolant temperature would need to be less than about 300°F (saturation pressure 70 psi). During start-up, when RCS temperature approaches 340°F, RCS pressure is limited to only 200 psia. Therefore, even with the higher thrust coefficient, nonflashing hot shutdown conditions would be less limiting than normal operating conditions. For CVCS HELBs in the RXB, the most limiting (maximum pressure and temperature) system conditions are considered, as identified in Table 4-4.

COL items 3.6.2-1 and 3.6.2-3 require that the COL applicant update the HELB analysis for final pipe arrangements by performing stress analyses, design and qualification of piping supports, evaluation of subcompartment pressurization effects, and completion of the balance of plant pipe rupture hazards analysis, including the design and evaluation of pipe whip/jet impingement mitigation as required.

Table 3-3 High-energy and moderate-energy system piping characteristics

System	Location[a]	Line Purpose	Max. Operating		Design		Largest Piping	Piping Code	PRHA Status[b]	Remarks
			Press. (psia)	Temp. (ºF)	Press. (psia)	Temp. (ºF)				
RCS	CNV	Degas	1850	625	2100	650	2” Sch 160	ASME III, Cl 1	BE(iii)/evaluated	Normally isolated
		PZR Spray (2)	1870	455	2100	650	2” Sch 160	ASME III, Cl 1	BE(iii)/evaluated	
		Injection	1870	455	2100	650	2” Sch 160	ASME III, Cl 1	BE(iii)/evaluated	
		Discharge	1850	500	2100	650	2” Sch 160	ASME III, Cl 1	BE(iii)/evaluated	
CVCS	NPM bay	Degas	1850	500	2100	650	2” Sch 160	ASME III Cl 3	BE(ii)(iii)	
		PZR Spray	1850	543	2250	650	2” Sch 160	ASME III Cl 3	BE(ii)(iii)	
		Injection	1875	543	2250	650	2.5” Sch 160	ASME III Cl 3	BE(ii)(iii)	
		Discharge	1850	500	2250	650	2.5” Sch 160	ASME III Cl 3	BE(ii)(iii)	
	RXB	Various	1875	543	2250	650	4” Sch 160	B31.1, seismic Cat II or III	Evaluated	
ECCS	CNV	N/A	1850	543	2100	650	N/A	N/A	N/A	Piping ≤1” [c]
SGS	CNV	FWS (2)	550	300	2100	650	5” Sch 120	ASME III Cl 2	LBB	
		FWS (4)	550	300	2100	650	4” Sch 120	ASME III Cl 2	LBB	
		MSS (4)	500	585	2100	650	8” Sch 120	ASME III Cl 2	LBB	
		MSS (2)	500	585	2100	650	12” Sch 120	ASME III Cl 2	LBB	
MSS	NPM bay	MSS (2)	500	585	2100	650	12” Sch 120	ASME III Cl 2	BE(ii)(iii)	
		MSS CIV bypass (2)	500	585	2100	650	2.5” Sch 160	ASME III Cl 2	BE(ii)(iii)	Open for heat-up
MSS	NPM bay	MSS (2)	500	585	2100	650	12” Sch 120	B31.1; seismic Cat I	BE(ii)(iii)	

System	Location[a]	Line Purpose	Max. Operating Press. (psia)	Max. Operating Temp. (ºF)	Design Press. (psia)	Design Temp. (ºF)	Largest Piping	Piping Code	PRHA Status[b]	Remarks
	RXB	MSS (2)	500	575	1000	650	12”	B31.1; seismic Cat I	Evaluated	Bounding analysis
FWS	NPM bay	FWS (2)	583	300	2100	650	4” Sch 120	ASME III Cl 2	BE(ii)(iii)	
		FWS (2)	583	300	2100	650	6”	B31.1; seismic Cat I	BE(ii)(iii)	
	RXB	FWS (2)	583	300	1000	650	6”	B31.1; seismic Cat I	Evaluated	Bounding analysis
DHRS	NPM bay	Hot leg (4)	1400	635	2100	650	8” Sch 160 6” Sch 160	ASME III Cl 2	BE(ii)(iii)	4 lines tee to 2
		Condensate return	1400	310	2100	650	2” Sch. 160	ASME III Cl 2	BE(ii)(iii)	2 lines
RCCW	NPM bay	CRDM supply/return	80	121	165	200	2”	B31.1	Bounded by HELBs	Moderate energy
ABS	RXB	Steam to MHS	1100	575	1250	650	4”	B31.1	Operates <1%	Moderate energy
MHS	RXB	Hot water for NPM heat-up	1850	555	2250	650	3”	B31.1	Operates <1%	Moderate energy

[a] Systems in more than one region of plant are listed in multiple places.

[b] BE indicates piping is analyzed against break exclusion criteria with (ii) and/or (ii) referring to the applicable criteria of BTP 3-4 B.A. used to determine location of postulated breaks (i.e., BE(iii) means terminal end breaks are assumed but intermediate locations are evaluated against B.A.(iii)). Evaluated means HELB external effects are considered where break are postulated to occur.

[c] Only piping is actuator (trip) line which is normally isolated by IAB while operating.

Table 3-4 Characteristics of blowdown at postulated break locations

System	Plant Location[a]	Line Purpose	Break Location[b]	Flow Direction[c]	Fluid State[d]	Remarks
RCS	CNV	Injection	RPV wall	From RPV[e]	Flashing	Break at mid-height on RPV side: no nearby targets
			RPV wall	From pipe	Flashing	Break at mid-height on RPV side: no nearby targets
			CNV head	From pipe	Flashing	
			CNV head	From safe end[e]	Flashing	
		Discharge	RPV wall	From RPV[e]	Flashing	Break at mid-height on RPV side: no nearby targets
			RPV wall	From pipe	Flashing	Break at mid-height on RPV side: no nearby targets
			CNV head	From pipe	Flashing	
			CNV head	From safe end[e]	Flashing	
		Degas	RPV head	From RPV[e]	Steam	
			RPV head	From pipe	Steam	Little steam in pipe between break and closed CIV
			CNV head	From pipe	Steam	
			CNV head	From safe end[e]	Steam	Little steam in pipe between break and closed CIV
		PZR spray	RPV head	From RPV[e]	Flashing	Blowdown turns to steam after liquid blows from line
			RPV head	From pipe	Flashing	
			CNV head	From pipe	Flashing	Blowdown turns to steam after liquid blows from line
			CNV head	From safe end[e]	Flashing	
CVCS	RXB	RCS injection	High T pipe	To NPM	Flashing	Bounding analysis applicable to any break location
				From NPM	Flashing	Blowdown terminated by check valve adjacent to CIV, so system side blowdown is limiting
			Low T pipe	N/A	Liquid	Bounding analysis applicable to any break location

System	Plant Location[a]	Line Purpose	Break Location[b]	Flow Direction[c]	Fluid State[d]	Remarks
		Discharge	High T pipe	From RCS	Flashing	Blowdown terminated by excess flow check valve adjacent to CIV, so system side blowdown is limiting
				From system	Flashing	Bounding analysis applicable to any break location
DHRS	CNV	Return	CNV wall	From DHRS	Flashing	
				From FWS[e]	Flashing	
			Anywhere	From NPM	Steam	Bounding analysis applicable to any break location
			Anywhere	To NPM	Steam	Return flow bounded by forward flow analysis
MSS	RXB	To turbines	Anywhere	From NPM	Flashing	Backflow from SG limited by FW check valve closure
			Anywhere	To NPM	Flashing	Bounding analysis applicable to any break location
FWS	RXB	From turbines	Anywhere	From upstream	Liquid	Moderate energy; effects bounded by other analyses
			Anywhere	From upstream	Liquid	Moderate energy; evaluated
RCCWS	CNV	CRDM	Not applicable	From boilers	Steam	Leakage cracks only (high energy conditions exist less than one percent of plant life)
	NPM bay	CRDM	Anywhere	From upstream	Liquid	Moderate energy; evaluated
Aux. Boiler	RXB	Steam to MHS	Anywhere	From boilers	Flashing	Leakage cracks only (high energy conditions exist less than one percent of plant life)

[a] The evaluation considers three areas of plant, which are inside the CNV, in the NPM bay outside the CNV (under the bioshield), and throughout the RXB.

[b] May be specific location or "Anywhere," which means evaluation applies to all potential break locations in that area of the plant; locations satisfying break exclusion or LBB criteria are not included as they are excluded from external effects evaluation (except leakage cracks for LBB and for MSS and FWS piping meeting break exclusion and located in the NPM bay outside the CNV (under the bioshield)).

[c] For the given break location, which end of pipe break is considered.

[d] Flashing is from system having liquid with low enough subcooling to cause two-phase blowdown.

[e] Nozzle does not whip.

3.5 Restraints, Barriers, and Shields

Pipe whip restraints may be used to limit the motion of a broken pipe to prevent it from hitting an essential structure, system, or component. Protection for pipe whip and jet impingement is also available through barriers afforded by walls, floors, and other structures. Sufficiently large and robust SSC can also function as a pipe whip barrier or jet impingement shield.

3.5.1 Pipe Whip Restraints

Pipe whip restraints constrain movement of a broken pipe for purposes of preventing or limiting the severity of contact with essential SSC. Restraints installed only for purposes of controlled pipe whip are not ASME Code components; restraints that also serve a support function under normal or seismic conditions are designed to ASME criteria. The design criteria for pipe whip restraints are:

- Pipe whip restraints do not adversely affect structural margin of piping for other conditions.
    - Restraint design does not restrict thermal expansion and contraction.
    - The restraint design either: a) does not carry loads during normal operation or seismic events or b) the structural analysis includes a conservative load combination.
- Pipe whip restraints are located as close to the axis of the reaction thrust force as practicable. Pipe whip restraints are generally located so that a plastic hinge does not form in the pipe using the methodology of Section C.4.1. If, due to of physical limitations, pipe whip restraints are located so that a plastic hinge can form, the consequences of the whipping pipe and the jet impingement effect are further investigated, as discussed in Appendix C. Lateral guides are provided where necessary to predict and control pipe motion.
- Generally, pipe whip restraints are designed and located with sufficient clearances between the pipe and the restraint, such that they do not interact and cause additional piping stresses. A design hot position gap is provided that allows maximum predicted thermal, seismic, and seismic anchor movement displacements to occur without interaction.
    - Exception to this general criterion may occur when a pipe support and restraint are incorporated into the same structural steel frame, or when a zero design gap is required. In these cases, the pipe whip restraint is included in the piping analysis and designed to the requirements of pipe support structures for all loads except pipe break, and designed to the requirements of pipe whip restraints when pipe break loads are included.
- In general, the pipe whip restraints do not prevent access required to conduct in-service inspection examination of piping welds. When the location of the restraint makes the piping welds inaccessible for in-service inspection, a portion of the restraint is designed to be removable to provide accessibility.

- Analysis of pipe whip restraints
    - Is either dynamic or conservative static.
    - Static analysis includes
        - a dynamic load factor of 2.0 to account for the initial pulse thrust force, unless a lower value is analytically justified.
        - potential increase by a factor of 1.1 in loading due to rebound.
    - Whip only restraints are analyzed for:
        - Jet thrust / pipe whip reaction force to confirm whip is restrained.
        - Seismic Category 1 loading to confirm the restraint does not fail and cause damage.
    - The criteria for analysis and design of pipe whip restraints for postulated pipe break effects are consistent with the guidelines in ANSI/ANS 58.2-1988.
    - Design is based on energy absorption principles by considering the elastic-plastic, strain-hardening behavior of the materials used.
    - Non-energy absorbing portions of the pipe whip restraints are designed to the requirements of AISC N690 Code.
    - Except in cases where calculations are performed to determine if a plastic hinge is formed, the energy absorbed by the ruptured pipe is assumed to be zero. That is, the thrust force developed goes directly into moving the broken pipe and is not reduced by the force required to bend the pipe.
    - In that a HELB is an accident (i.e., infrequent) event, pipe whip restraints are single use: allowed to deform provided the whipping pipe is fully restrained throughout the blowdown.
    - Allowable strain in a pipe whip restraint is dependent on the type of restraint.
        - Stainless steel U-bar – this one-dimensional restraint consists of one or more U-shaped, upset-threaded rods or strips of stainless steel looped around the pipe but not in contact with the pipe. This allows unimpeded pipe motion during seismic and thermal movement of the pipe. At rupture, the pipe moves against the U-bars, absorbing the kinetic energy of pipe motion by yielding plastically.
        - Structural steel – this two-dimensional restraint is a stainless steel frame encircling the pipe that does not restrict pipe motion for normal operation or earthquakes. Should a rupture occur, the pipe motion brings it into contact with the frame, absorbing the kinetic energy of the pipe by deforming plastically.
        - Crushable material – if used, the allowable energy absorption of the material is 80 percent of its capacity based on dynamic testing performed at equivalent

temperatures and at loading rates of ±50 percent of that determined by analysis.

Note that a wall penetration may also serve as a two-dimensional pipe whip restraint, provided the wall has sufficient strength to resist the pipe load.

- Material properties are consistent with applicable code values, with strain-rate stress limits 10 percent above code or specification values, consistent with NRC guidance (SRP 3.6.2).

3.5.1.1 Pipe Whip Barriers

Standard Review Plan 3.6.2 identifies that an unrestrained, whipping pipe need not be assumed to cause ruptures or through-wall cracks in pipes of equal or larger NPS with equal or greater wall thickness. By extrapolation, a structure, system, or component made of metal of equivalent or better yield strength, equal or larger diameter, and equal or greater wall thickness does not only not leak or crack but also obstructs further travel of the whipping pipe, protecting SSC farther away from being struck.

Table 3-5 provides a comparison of potential whipping pipes and the SSC credited to act as barriers. The numbers in { } brackets are the factor by which the barrier diameter (“pipe size”) and wall thickness exceed that of the whipping pipe, where a minimum value of 1.0 for both satisfies the SRP 3.6.2 guidance for pipe-on-pipe impact not causing a crack or rupture. Therefore, the SSC listed in Table 3-5 are considered to serve as pipe whip barriers without further evaluation. The pipe whip load must be considered for inclusion in SSC load combinations to verify that the barrier is not displaced by pipe whip impact. For any structures added to serve as a barrier (or jet impingement shield), Seismic Category 1 loading is analyzed to confirm the structure does not fail and cause damage.

Concrete floors, walls, and ceilings can also serve as pipe whip barriers but require a more quantitative approach as described in Section 3.9.5 and Appendix C.

3.5.1.2 Jet Impingement Shields

NRC guidance does not have specific criteria for judging suitability of a structure, system, or component as a jet shield. Regarding impingement effects, if the following criteria are met, then the structure, system, or component is judged capable of serving as a shield:

- The diameter and wall thickness of the shield meet the criteria for a pipe whip barrier with a size equal or greater than that of the broken pipe.
- The barrier is of sufficient area and positioned to subtend a solid angle from the pipe break opening (considering potential pipe whip) that covers the structure, system, or component to be protected.
- The barrier is solid (without openings) to the extent that no direct line of sight exists from the break opening to the structure, system, or component. This criterion allows for some indirect passage of spray through an opening, but environmental qualification for pressurization and flooding demonstrates functionality. The possibility of pipe whip affecting the location of the pipe break exit must be considered.

Table 3-5 Comparison of sizes of whipping pipe to potential barriers for high-energy line breaks in the containtment vessel

Component	**Pipe Size**	**Outer Diameter (in.)**	**Wall Thickness (in.)**
RCS lines	NPS 2 Schedule 160	{{	
CNV	N/A		
RPV	N/A		
CRDM latch housing lower section[d]	N/A		
RXB walls	N/A		}}2(a),(c)

[a] without cladding

[b] varies with vertical location; minimum value in range of pipe break locations

[c] minimum in RXB areas containing high energy piping within range of a whipping pipe

[d] along most of its length, the housing is surrounded by magnetic coils that are about 2 inches thick

3.5.1.3 Pipe Whip Shields and Jet Impingement Barriers in NuScale Design

The RPV and CNV are thick-walled components that serve as barriers and shields to isolate effects of HELBs.

The NuScale RXB includes a functional requirement to accommodate the effects of environmental conditions associated with normal operations, maintenance, testing, and postulated accidents, including loss-of-coolant accidents. Specifically the RXB is to be appropriately protected against dynamic effects, including those of missiles, pipe whipping, and discharging fluids. The design of the RXB considers protection of on-site electric power against water damage, flooding, jet impingement, and pipe whip resulting from failure of nearby piping.

In the RXB, concrete walls, floors, and ceilings serve as barriers separating the effects of HELBs from areas containing EDSS components and cables used for PAM. They also maintain structural integrity of the RXB. This requires that the RXB concrete structures be capable of resisting pipe whip impact and jet impingement.

Analysis of pipe whip impact consistent with established methods for missile impact (i.e., tornado missiles) on concrete is provided in Appendix C. No pipe whip impact need be considered in the NPM bay under the bioshield because piping in that area is designed to satisfy break exclusion criteria.

For jet impingement, the potential for a jet to breach a wall is less than for the pipe whip impact force because the jet expansion distributes the force over a wider area.

3.5.2 Susceptibility of Essential Structures, Systems, and Components by Plant Location

The potential for and consequence of line breaks depends on the location of the rupture being postulated. Three areas of the NuScale plant are considered separately in the following subsections.

3.5.2.1 Inside the Containment Vessel

- Essential components are the RCS, MPS, EPAs, CNV, DHRS, ECCS valves, SGS thermal relief valves, and CRDMs
  - If more than one MPS indication of a type loses its signal because its cable is severed by pipe whip or jet impingement, a reactor trip and/or safety component actuation occurs. For example, breaking signal lines for two or more RCS hot temperature or pressurizer level indications causes a reactor trip.
  - The electrical penetration assemblies (EPAs) form part of the containment boundary.
  - Although not essential to ensure long term shutdown and core cooling, NuScale has evaluated the availability of PAM indication following a pipe rupture in order to satisfy NRC guidance.
  - The reactor safety valves are not needed if a HELB depressurizes the RPV (MSS and FWS ruptures are excluded by LBB).
  - Essential components inside the CNV are qualified to CNV design pressure for exposure to 1000 psia saturated steam caused by ECCS initiation and are isolated from the outside environment by the walls of the CNV.
  - Essential components fail to the safe condition upon loss of power or control signal (i.e., CRDS and ECCS).
- A precursor crack can be detected by an increase in CNV pressure or CES liquid accumulation.
- Potential for an inadvertent ECCS valve opening due to loss of power to the trip valve (i.e., wire breaks) or breach of the trip/reset line is averted by the IAB.
- Piping is not insulated.
- The NPM piping, including MSS and FWS, is stainless steel.
- Piping runs are short.
- The areas at the top of the RPV head and the underside of the CNV head are congested.

3.5.2.2 In the NuScale Power Module Bay

- Essential components are the MPS temperature sensor under the bioshield, CNV, CIVs, EPAs, DHRS actuation valves, NMS (submerged), DHRS condenser (submerged), and ECCS trip/reset valves (submerged)

- Essential components fail to the safe condition upon loss of power or signal (i.e., CIVs and DHRS actuation valves).
- Post-accident monitoring indication is also evaluated.
- Piping in the containment penetration area is stainless steel.[6]
- MSS and FWS piping has a design pressure and temperature of 2100 psia and 650 degrees, similar to the RCS.
- High-energy line breaks are excluded by satisfying break exclusion criteria. Nonmechanistic breaks in an MSS or FWS pipe in accordance with BTP 3-3 are evaluated as discussed in Section 3.5.2.5, and effects of leakage cracks are evaluated.
- The NPM bay under the bioshield is vented to the RXB to limit peak pressure and temperature.

3.5.2.3 In the Reactor Building (pipe routing in the RXB is not finalized[7])

- The safety-related CIV HPU skids are located in the pipe gallery and on the floor above (one in each location for each NPM).
- Structural damage to the RXB that could affect pool integrity has been evaluated.
- Functionality of PAM indications and the EDSS is ensured by separation from areas where high-energy piping is present.
- Adverse effects of postulated HELBs on the CVCS make-up valves are judged acceptable (Section 3.2.4).
- No pipe ruptures in the RXB affect the control room, which is located in a separate building
- Multi-module effects such as pipe-whip induced ruptures are considered. Three interactions are evaluated to determine if an MSS or FWS HELB in one module could:
    - Structurally damage the RXB due to pipe whip impact or subcompartment overpressurization, potentially affecting other NPMs.
    - Cause a pipe whip to impact an adjoining NPM piping. Fluid release occurs too late to reinforce the initial HELB blast wave, and any secondary rupture blast wave is less severe because the piping is smaller. Ability for unaffected NPMs to be safely shut down and to provide long-term core cooling is not affected by the occurrence of an HELB in one or more other NPMs. Although piping arrangements are not finalized (COL Items 3.6-1, 3.6-2, 3.6-3), Figure 3-4 shows the potential

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[6] Feedwater system piping passing through the NPM bay wall is chrome-moly alloy SA-335 P11.

[7] The final design for piping systems beyond the NPM bay is the responsibility of the COL applicant, as stated in the NuScale FSAR (Reference 1.4.2.16 COL Items 3.6-1, 3.6-2, and 3.6-3). This includes final equipment location, pipe routing, support placement and design, piping stress evaluation, pipe break mitigation, and evaluation of subcompartment pressurization and multi-module effects. However, this report documents analysis of bounding scenarios that were performed to ensure the design, when finalized, can comply with NRC regulations and guidance. The COL applicant may perform more detailed (e.g., dynamic structural) analysis based on final design information.

overlap in the pipe galleries of MSS (bright green) and FWS (pale green) piping from adjacent NPMs (light blue):

  - An MSS line impacting an equivalent size and schedule MS line does not cause a rupture or leakage crack per SRP 3.6.2, paragraph III.2.
  - A main steam system HELB could impact the bypass line, causing up to a 4-inch diameter rupture in an adjoining NuScale Power Module MSS. This rupture represents a potential to increase NPM steam mass and energy release, and has been bounded by the overpressurization analysis performed for the pipe gallery.
  - An MSS line impacting another NuScale Power Module FWS line could cause it to break. However, the second module's FWS line break cannot cause additional major ruptures because the other lines are equivalent or larger size and schedule.[8] Because of the lower enthalpy compared to MSS lines and the double-ended discharge (in an FWS break, the FWS check valve quickly shuts off flow from the SG), an MSS bypass line rupture causes higher pressures. Therefore, a collateral break of a feedwater line is not limiting.

- Environmental conditions such as high pressure and temperature or flooding that adversely affect another NPM's essential equipment are evaluated.

Because avoiding a collateral accident in another module is a design objective, the COL applicant needs to assess the final piping arrangements for the possibility of interaction. Where a rupture in an adjacent module cannot be ruled out through use of more detailed analysis, pipe whip restraints or barriers should be included.

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[8] Damage to small diameter (i.e., instrument) lines could occur but does not affect the ability to shut down and maintain cooling in other NPMs and does not increase compartment pressure.

{{

}}$^{2(a),(c)}$

Figure 3-4 Adjacent NuScale Power Module overlap of main steam system and feedwater system piping in the Reactor Building pipe gallery

3.5.2.4 Applicable Dynamic and Environmental Effects

Dynamic and environmental effects are evaluated based on the postulated rupture location, thermodynamic conditions, and the break mechanism:

- Where break exclusion criteria are satisfied, no rupture or leakage cracks are postulated but nonmechanistic breaks of MSS & FWS piping in the containment penetration area are considered (see Section 3.5.2.5).
- Where LBB applies, no dynamic effects (i.e., pipe whip, blast, jet impingement, pressurization) are required to be considered, and the leakage effects are negligible because the allowable crack size is small.
- Remaining postulated rupture locations are evaluated for pipe whip, blast, jet reaction loads, jet impingement loads, pressurization, and flooding effects.

– The magnitude of the jet reaction load and the piping configuration determines if a pipe whips and, if so, its motion and impact force depend on the relative geometry of the pipe, its restraints and barriers, and potential target SSC.

– The ZOI and pressure force of jet impingement are conservatively evaluated.

– Inside the CNV, subcompartment pressurization for postulated breaks is bounded by analysis for ECCS. Outside the CNV, pressurization caused by postulated breaks is limited by venting to a differential pressure within the capability of the RXB structure.

Dynamic amplification and resonance do not occur as a result of HELBs in the NuScale plant, as discussed in Appendix B.

3.5.2.5 Non-mechanistic Secondary Line Breaks in Containment Penetration Area

Branch Technical Position 3-3 B.1.(a)(1) specifies:

> "Even though portions of the main steam and feedwater lines meet the break exclusion requirements of item 2.A(ii) of BTP 3-4, they should be separated from essential equipment. Designers are cautioned to avoid concentrating essential equipment in the break exclusion zone. Essential equipment must be protected from the environmental effects of an assumed nonmechanistic longitudinal break of the main steam and feedwater lines. Each assumed nonmechanistic longitudinal break should have a cross sectional area of at least one square foot and should be postulated to occur at a location that has the greatest effect on essential equipment."

The following considerations form the basis for this guidance:

- The MSS and FWS piping are generally the largest, high-energy piping near the containment boundary.
- The lines have a single CIV outside containment, in accordance with GDC 57 for lines closed inside containment.
- Piping is usually made of less-corrosion-resistant material than that used for the NuScale design: MSS and FWS piping in many pressurized water reactors is carbon or low-alloy steel, which have greater susceptibility to degradation than stainless steel.

Analyzing for nonmechanistic ruptures ensures that multiple essential SSC are capable of withstanding the effects of a limited piping failure should one occur. In the NuScale plant, CIVs are located outside the containment and exposed to the same environmental conditions, making protection against unexpected ruptures particularly important. However, the NuScale design has the following characteristics that make nonmechanistic ruptures low risk:

- The essential SSC in the vicinity of the MSS and FWS piping in the containment penetration area are CIVs, DHRS actuation valves, and instrumentation cables and sensors.
- Unlike safety-related valves in other plant designs that use motor-operators, the NuScale CIVs are {{ }}$^{2(a),(c)}$.

  The DHRS actuation valves similarly fail open.
- Failure of the NuScale MSS and FWS piping is unlikely because
  - Piping in the containment penetration area is made of stainless steel.

- The physical length of MSS and FWS piping in the containment penetration area is zero (i.e., there are only valves and fittings).[9]
- MSS and FWS piping has a design pressure and temperature of 2100 psia and 625-degrees Fahrenheit, respectively, equivalent to RCS piping.

Table 3-6 shows a comparison of new design PWR MSS and FWS piping in the containment penetration area.

Table 3-6 Comparison of main steam system and feedwater system piping in containment penetration area

Plant	MSS Piping				FWS Piping	
	Material	Size	Pressure	Temp.	Material	Size
EPR	SA-106 Grade C	NPS 30	1111 psig	558F	SA-106 Grade B	NPS 20
AP1000	SA-335 Gr. P11	NPS 38	836 psia	523F	SA-335 Gr. P11	NPS 20
APR1400	SA-106 Grade C	NPS 32	992 psia	544F	SA-335 Gr. P22	NPS 24
APWR	SA-106 Grade B	NPS 32	931 psia	536F	SA-335 Gr. P22	NPS 18 & 16
NuScale	**SA-312 304/304L**	NPS 12	500 psia	585F	**SA-312 304/304L[6]**	NPS 4 & 5

The flow area of 1 ft^2 specified in BTP 3-3 for a nonmechanistic, longitudinal break is disproportionately large for a small modular reactor with small pipe sizes. NuScale MSS piping is NPS 12 Schedule 120 and FWS piping is NPS 4 and NPS 5 Schedule 120 in the containment penetration area. For those piping sizes, a 1 ft^2 flow area would be about 142 percent for MSS (1397 percent for FWS) of the area for a full circumferential rupture, which is physically unrealistic. Nonmechanistic breaks of MSS and FWS piping in the containment penetration area are still evaluated even though there is no piping (only valves and fittings). Comparing the large PWR pipe MSS flow area to that of NuScale yields a ratio of one-eighth to one twelfth. On this basis, NuScale analyzes for environmental effects of an MSS nonmechanistic break with an area of 12 in^2, vice 144

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[9] There is an approximately one foot long NPS 2 bypass around each MSS CIV, ending in the normally closed MSS bypass valve.

in^2 (1 ft^2). The comparison is shown pictorially in Figure 3-5. The nonmechanistic FWS break size applied is 5.87 in^2.

Also shown on Figure 3-5 (lower right) is a comparison of the equivalent area for leakage cracks. NuScale MSS leakage cracks are about 60% of the flow area of a large PWR. BTP 3-4 B.C.(iii)(3) defines the area of leakage cracks in terms of one-half the piping inner diameter times one-half the wall thickness. Although the NuScale MSS piping diameter is smaller, its greater wall thickness results in a lesser reduction in the leakage crack size to be evaluated.

The volume under the bioshield is small; roughly a cube 20 feet on a side. Therefore, even though only leakage cracks need to be considered outside the containment penetration area, analysis is performed for the 12 in^2 MSS break at the highest point of the pipe run because that results in a more conservative pressure and temperature profile over time for environmental qualification purposes and bounds breaks occurring in any section of the piping under the bioshield.

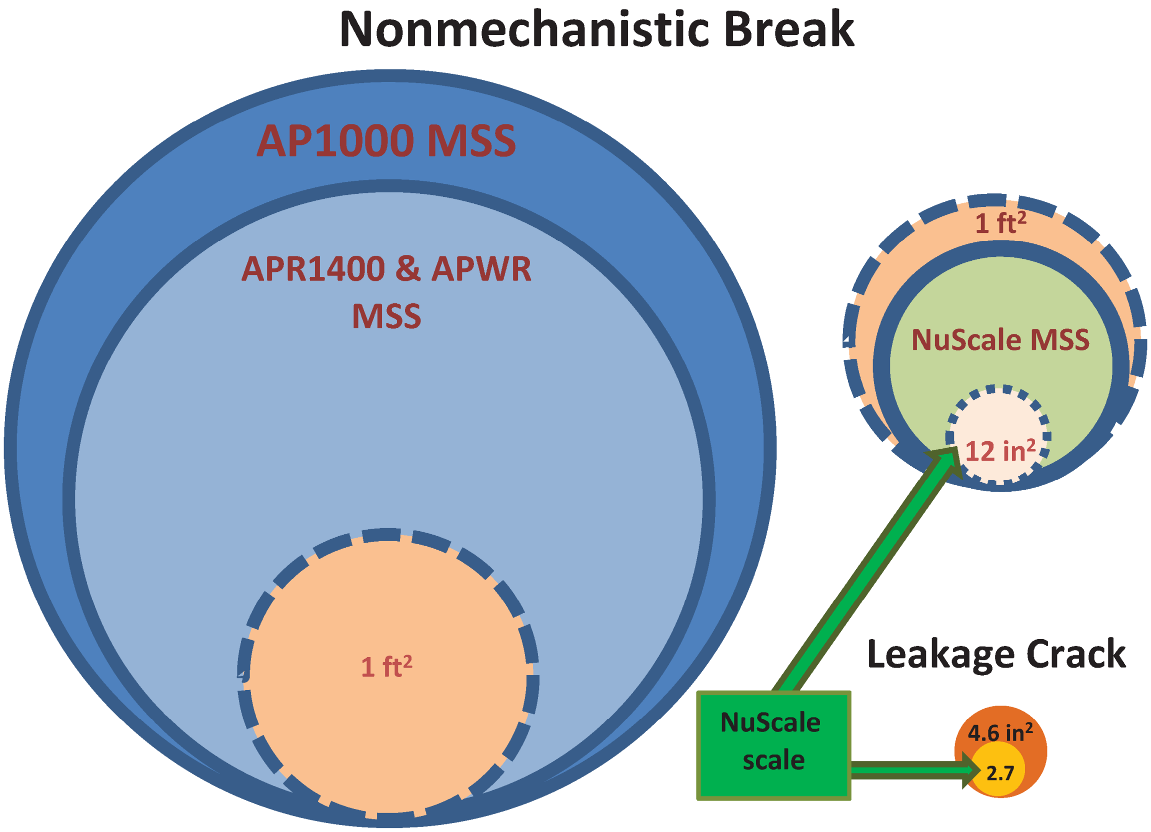

Figure 3-5 Visual Comparison of Large Reactor to NuScale Nonmechanistic Break Size

3.6 Break Exclusion

Branch Technical Position 3-4 Paragraph B.A.(ii) identifies specific criteria for which ruptures need not be considered in piping from the containment wall to and including the inboard or outboard isolation valves (usually referred to as the containment penetration area "break exclusion zone"). This is necessary due to constraints on the ability to cope with breaks between CIVs. Should a break occur between the CIVs, followed by a single failure of one of the CIVs, then containment bypass could occur. To preclude bypass, criteria are developed to ensure that the probability of a piping failure was sufficiently low to make it unlikely.

The NuScale plant has its dual CIVs in a single valve body located directly outside of containment. Therefore, there are no break locations between the valves. However, the weld between the valve body and the CNV safe end is equivalent to those to which break exclusion applies. Therefore, interpretation of the allowable extent of break exclusion would limit it to only a few welds in the NuScale design. NuScale has extended this break exclusion boundary outside the CNV slightly to include:

- The weld at the outboard CIV nozzle.
- The weld at the outboard check or excess flow check valve nozzle in RSC-connected lines.
- DHRS piping welds outside the CNV.

Thus, the guidance of BTP 3-4 Paragraph B.A.(ii) is used in piping design to ensure that breaks and leakage cracks can be excluded in the containment penetration area. The BTP 3-3 nonmechanistic breaks of main steam and feedwater piping are also addressed. The remaining high-energy piping design under the bioshield applies BTP 3-4 Paragraph B.A.(iii) for ruptures and (v) for leakage cracks.

Figure 3-6 is a representation (not all lines are shown) of application of the NRC guidance on break location and size, as applied in the NPM bay and the RXB.

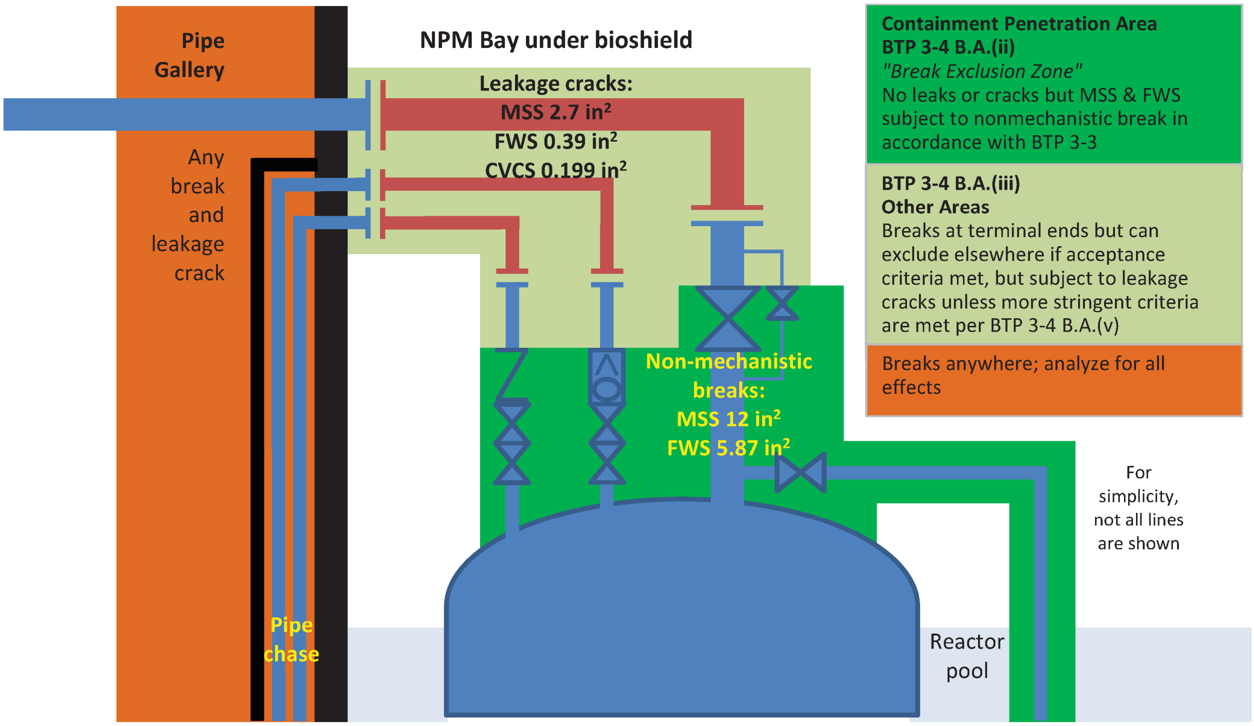

Figure 3-6 Application of NRC break location guidance under the Bioshield and in the RXB

The NuScale design has notable differences from the larger LWRs for which BTP 3-4 was developed.

- The length of piping and number of welds inside the NuScale CNV is limited and is less than for large LWR break exclusion zones. For the NuScale design, no primary or secondary piping, other than about 160 feet of DHRS piping, is within the break exclusion zone outside containment, compared to approximately 1500 feet of primary and secondary break exclusion zone piping in the AP1000.
- The design pressure and temperature of MSS, FWS, and DHRS piping in the break exclusion zone is the same as for the RCS.

Break exclusion is not applied to the piping in the RXB.

3.6.1 Leakage Cracks

Leakage cracks are excluded in containment penetration areas where the criteria of BTP 3-4 Paragraph B.A.(ii) are satisfied.

Per BTP 3-4 Paragraph B.A.(v), leakage cracks are postulated unless specific criteria are met. For Class 2 piping, the acceptance criterion is for the calculated stress to not exceed 0.4 times the sum of stress limits given in Subarticles NC/ND-3635. BTP 3.4 B.C.(iii) specifies postulating leakage cracks with a flow area of one-half of a pipe diameter by one half pipe wall thickness in piping in the vicinity of essential SSCs, regardless of system.

This would be equivalent to a flow area of 2.7 in^2 for MSS piping, 0.439 in^2 for FWS, and 0.2199 in^2 for CVCS.

3.7 Leak-Before-Break

General Design Criterion 4 includes a provision that the dynamic effects associated with postulated pipe ruptures may be excluded from the design basis when analyses, reviewed and approved by the Commission, demonstrate that the probability of fluid system piping rupture is extremely low under conditions consistent with the design basis for the piping. This analysis is called LBB. The LBB concept is based on the ability to detect a leak in the piping components well before the onset of unstable crack growth.

3.7.1 Inside the Containment Vessel

For the NuScale plant, the application of LBB is limited to the large bore ASME Class 2 SGS (i.e., MSS and FWS) piping inside the CNV. The piping analysis addresses cyclic transients and produces bounding loads for ASME Class 2 piping with respect to LBB.

Methods and criteria to evaluate LBB are consistent with the guidance in SRP 3.6.3 and NUREG-1061, Volume 3 (Reference 1.4.2.11). Potential degradation mechanisms are limited. The piping is stainless steel, uninsulated, and in a hot, dry, evacuated environment, precluding external corrosion during normal operation. LBB analysis methodology and results for MS and FWS piping is provided in FSAR Section 3.6.3.

Application of LBB permits elimination of the dynamic external effects of postulated ruptures in high-energy piping; specifically (Reference 1.4.2.7):

- blast effects
- pipe whip
- pipe break reaction forces
- jet impingement forces
- dynamic or non-static pressurization of cavities, compartments, or subcompartments (not performing a containment function)

Therefore, lines qualifying for LBB are evaluated only for leakage cracks and flooding effects. Because essential components inside the CNV are qualified for the containment design pressure conditions with exposure to saturated steam, flooding in an ECCS transient, and flooding during refueling, the effects of leakage from lines meeting LBB criteria are bounded and do not need to be explicitly analyzed.

The methodology, criteria, and results of applying LBB are discussed in detail in NuScale FSAR Section 3.6.3.

3.7.2 In the NuScale Power Module Bay

Leak-before-break is not applied to the piping in the NPM bay.

3.7.3 In the Reactor Building

Leak-before-break is not applied to the piping in the RXB.

3.8 Separation

Separation is a means of protecting essential SSC from the effects of HELBs and MELBs. The four degrees of separation applied are:

- Isolation of essential SSC from high- and moderate-energy piping by placement in different compartments of the plant. An example of this is that components outside the CNV are isolated from rupture effects inside the CNV.
- Separation by distance: if essential SSC are distant from the rupture location, it may be shown that there are no effects of blast, pipe whip, and jet impingement. However, pipe break reaction forces and environmental effects such as pressurization and flooding must be evaluated.
- Separation through redundancy: multiple, distributed components exist such that a HELB can only affect a number such that, after postulation of a single active failure, necessary functionality remains available.
- Separation by intervening obstacle: depending on the obstacle, missiles, blast, pipe whip, jet impingement, or flooding may be mitigated, but not pressurization.
    - Pipe restraint: a restraint may limit the movement of a whipping pipe, keeping the pipe or jet from affecting essential SSC.
    - Plant structure or component: the plant design may include SSC that are large and robust enough to serve as a barrier to HELB effects (see Section 3.5).
    - Pipe whip barrier or jet shield: these are structural features added for the purpose of intercepting a whipping pipe or jet at specific rupture locations from striking an essential SSC. The NPM and RXB evaluated in this PRHA do not require any features the sole purpose of which is to serve as a pipe whip barrier or jet shield.

3.8.1 Inside the Containment Vessel

Three degrees of separation are considered: compartmentalization, distance, and the presence of an intervening obstacle.

- The CNV isolates essential components inside from HELB effects outside.
- The CNV is a tall, narrow vessel. A pipe break at any given location has a limited “reach” for pipe whip and jet effects. For example, a whipping pipe or jet caused by a break at the inner CNV head does not affect an RRV about 50 feet below. An NPS 2

Schedule 160 pipe has an inner diameter of 1.687 inches. For steam discharge, the jet ZOI is limited to about 2.2 diameters, or less than 4 inches (see Appendix E).

- For some pipe break locations inside the CNV, large structures limit the range and direction of a whipping pipe or jet. Examples are the RPV, CNV, and SGS piping.

3.8.1.1 In the NuScale Power Module Bay

With the exception of nonmechanistic breaks, no HELBs occur in the NPM bay area based on high-energy lines satisfying criteria of BTP 3.4 for excluding breaks. Thus, only environmental qualification effects need evaluation.

3.8.1.2 In the Reactor Building

Separation by placement in different subcompartments and redundancy are the degrees of separation considered. Although not essential components, PAM and DC power cables are routed in areas separated from high-energy lines by structural or shield walls.

3.9 Analysis Methodology

Figure 3-1 is a flow chart of the process for identifying postulated rupture locations and vulnerable essential and safety-related targets through assessing the relevance and consequences of possible external effects.

- Essential targets are identified (see Section 3.2).
- High- and moderate-energy systems are identified.
- Each of the three regions of the plant (the CNV, the NPM bay under the bioshield, and the RXB) is considered separately.
- If potential HELB locations satisfy break exclusion (in CNV or NPM bay) or LBB (MSS and FWS piping in CNV) acceptance criteria, then consideration of HELB dynamic effects is avoided.
- For postulated breaks of piping containing steam, the potential for creation of a blast wave is assessed (see Section 3.9.3).
- Availability of energy sufficient to cause pipe whip is evaluated (see Appendix C).
- If pipe whip is possible, then the vulnerability of essential SSC to being hit is determined based on direction of pipe whip and distance.
- If pipe whip impact is possible, the consequences of the impact are assessed. Pipe whip load is included in load combinations in accordance with FSAR Section 3.9 and Section 3.12. Note that pipe whip load does not coexist with peak pressurization load.
- Jet ZOI is defined to determine if any essential SSC are within it (see Appendix E).
- For essential SSC within the ZOI, the jet impingement effects are assessed (see Appendix E).
- Jet reaction load and, if within the ZOI, potential jet impingement load, is included in load combinations in accordance with FSAR Section 3.9 and Section 3.12.

- The pressurization effect of the postulated HELB is quantified (see Appendix D).
- The consequences of flooding are determined FSAR Section 3.4.

3.9.1 Determining Break Locations

As described in Section 3.6 above and FSAR Section 3.6.3, potential break locations are evaluated for ability to satisfy BTP 3-4 or LBB criteria. If one of those sets of criteria is met, then HELB effects need not be further evaluated.

As a result of break exclusion and LBB evaluations in accordance with regulatory guidance, breaks are postulated only at terminal ends of NPS 2 piping inside the CNV. Other than nonmechanistic breaks of MSS & FWS piping, there are no locations in the NPM bay under the bioshield based on designing to satisfy break exclusion criteria of BTP 3-4. In the RXB, ruptures are assumed to occur anywhere that high-energy piping is present.

3.9.2 Parameters Affecting Severity of High-Energy Line Break Effects

The parameters that determine the severity of HELB and MELB effects are:

- Thermodynamic conditions of the system before the break occurs (see Table 3-3) – higher energy fluid generally causes larger magnitude effects. The initial fluid condition in the pipe before rupture bounds that for normal full power (102 percent thermal) operating conditions for that pipe segment. This fluid energy in the blowdown is consumed by several phenomena: failing of the material in order to create the rupture opening, accelerating the fluid out the break, irreversible losses, counteracting spray in opposite directions, bending the pipe at its plastic hinge, and accelerating the end of the pipe in a circumferential offset break. None of these are credited in removing energy from the blowdown, except for pipe whip screening.
- Size of the pipe that breaks – NuScale piping serving a given function (i.e., feedwater) is smaller than traditional LWRs. This reduces the severity and the range of effects. For example, a main steam system NPS 38 line in the AP1000 has approximately 27 times the energy per foot of pipe than the NuScale NPS12 line.[10]
- Location of the break (i.e., proximity to essential SSC, ambient conditions) –
  - If the break is sufficiently remote or separated from essential SSC, the effects are negligible.
  - The flow issues from a straight pipe section downstream of either a long pipe run or a nozzle connected to a reservoir (i.e., the RPV), involving flow resistance and entrance losses.
- Break configuration – in accordance with regulatory guidance, assumptions are made (e.g., discharge coefficient of 1.0). The acceleration of a whipping pipe segment

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[10] AP1000 volume per pipe foot of 7.47 vs. 0.63 ft^3; steam density in AP1000 of 1.84 versus 0.73 lbm/ft^3; and specific enthalpy in AP1000 of 1198 versus 1290 BTU/lbm yields factor of 27.6.

depends on the fluid jet thrust force. The blowdown from postulated ruptures provides a bound on dynamic effects.

  - No credit is taken for the reality that the end of an actual break is ragged, likely with rough and bent edges that provide flow resistance.
  - The break opens instantaneously, which is physically impossible but conservative. Regulatory guidance sets a maximum break opening time of one millisecond unless otherwise justified.

- Duration of blowdown – in accordance with regulatory guidance, credit for reduction in upstream (source) pressure is only considered where justified (e.g., closure of FWS check valve). For estimating jet reaction and pipe whip, the blowdown is from an infinite reservoir at intact system normal operating conditions. This is assumed unless a check valve or normally closed isolation valve is available within a short distance to terminate flow. For subcompartment pressurization, blowdown can be terminated by valve closure after a single active failure or by depletion of the reservoir. For flooding from cracks, discharge may be terminated by operator action as identified in FSAR Section 3.4.
- The thrust load acting on the pipe due to a blowdown jet is equal and opposite to the jet. The pipe may pivot at the nearest surface contact point or pipe restraint. In the case of a circumferential break, the force of the jet is directed along the axis. A nozzle/safe end does not deflect because of its rigidity, straightness, and short length. Jet thrust load is determined as described in Section 3.9.4.
- Occurrence of pipe whip is screened by assessing if the jet thrust load is sufficient to form a plastic hinge, as described in Section 3.9.5 and Appendix C. Because most NuScale high-energy pipe is small diameter but heavy wall (i.e., schedule 160 or 120), available energy compared to bending moment is less than for large LWRs.
- The kinetic energy of a whipping pipe is determined by the distance through which the jet thrust can cause it to move. The smaller scale of the NuScale design reduces the pipe size (hence, thrust) and distance of the whipping pipe.

3.9.3 Blast Effects

As previously noted, the potential for a blast wave to occur depends on the surrounding environment. The timing of opening of the break and the initial, intact system thermodynamic conditions are also key. Although pipe rupture times of less than a millisecond are unlikely, break opening time is assumed to be instantaneous. Appendix F provides a detailed discussion of blast effects based on three-dimensional CFD modeling that reflects the postulated break characteristics and NuScale plant geometry:

- A blast wave is weakly formed if the surrounding environment is at low pressure (less than 1 psia), as is the case inside the CNV. Buildup of pressure as blowdown progresses is not relevant because the blast wave is a prompt and short-lived phenomenon.
- The severity of a blast depends on the amount of fluid that can escape within one millisecond of onset of the break because the blast wave forms within that time.

  - The NuScale high-energy, steam-filled lines are relatively small, which limits the severity of the blast pressure. As previously noted, the energy available to form the blast is about 27 times less than that of AP1000 (see prior Footnote 10).

- Blast waves are not significant for subcooled discharge because liquid flashing occurs on timescales exceeding that of formation of a blast wave according to J. Liu's "Investigation on Energetics" (Reference 1.4.3.7).

- A blast wave has well-defined and interrelated characteristics. For example, its peak pressure and speed decrease with distance proportionately from its origin.

- The pressure load applied by a blast wave is of short duration (i.e., an impulse load as shown in Figure 3-7) and does not apply uniformly across a large SSC at a given instant. Therefore, assuming the peak blast pressure is applied across the entire projected area of a component is inappropriate. The CFD analysis explicitly accounts for the time-varying pressure of the rapidly propagating blast wave. In addition, the load has dissipated before the other loads (e.g., pipe whip, pressurization) can occur.

- Reflection off surfaces can reinforce the pressure load, requiring consideration of plant specific geometry. Angled or curved surfaces are loaded differently than a flat surface perpendicular to a line between the blast origin and surface. The pressures applied to surfaces by reflection can substantially exceed the incoming wave pressure. For this reason, use of representative plant geometry is necessary. The CFD analysis includes the interaction of incident and reflected waves with each other and nearby surfaces, including how the shape and orientation of surfaces affect reflection.

- A small target has a lower peak pressure due to "clearing," which is a phenomenon where some of the blast overpressure is relieved by bleeding off around the edge of the target. From Equation 2-8 of UFC 3-340-02 (Reference 1.4.3.15), clearing distance is equal to the height or half the width, whichever is the smallest, of the side of an object facing a blast wave. Because of both this pressure-relieving clearing and the short load duration as a supersonic blast wave moves over them, small structures are not limiting. The only SSC in the CNV or RXB that are large are the structures (e.g., CNV, RPV, and RXB walls and floors). The CFD analysis models clearing.

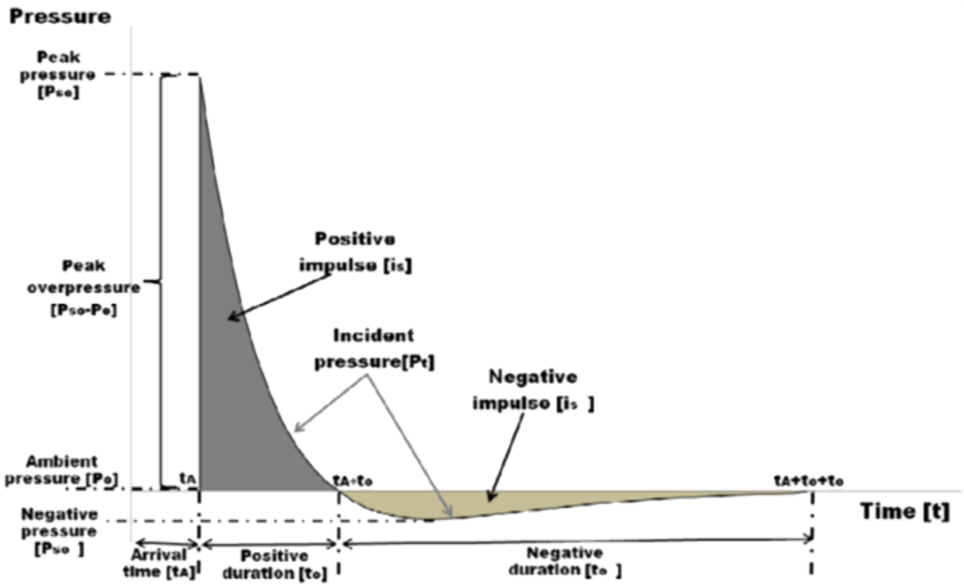

Figure 3-7 Characteristics of a blast wave (Reference 1.4.3.13)

3.9.4 Blowdown Thrust Loads

If the energy in the pipe is insufficient to deform the piping, no whip occurs. If the line is isolated, no sustained jet occurs.

3.9.4.1 Thrust Coefficient

The thrust coefficient is defined as the exit plane thrust force divided by the product of source pressure and exit plane flow area. In Reference 1.4.2.12, the NRC states the "thrust force may be computed by calculating the force that must be exerted to hold in static equilibrium a plate positioned normal to the flow directly at the break point." The exit plane thrust force for a given break represents the maximum jet impingement force that can be delivered to target SSC.

The time dependent thrust force includes the combined effects of the initial pulse, wave propagation and reflection, and the blowdown thrust from buildup of the discharge flow rate. ANSI/ANS 58.2 Appendix B discusses initial behavior of the jet before reaching steady-state. During the initiation of the jet, the peak of a decaying pressure oscillation exceeds the steady-state level that occurs once the blowdown stabilizes. Shock wave pressures in the low-pressure ambient in the CNV are low and their duration is about a millisecond (see Figure F-7 for an example), so this initial pulse is not significant. In the RXB, the jet is not assumed to expand with distance and a conservatively short distance between break exit and target SSC is assumed, eliminating the need to separately model an initial pulse.

Therefore, just the total, steady state jet thrust force F_T as given by SRP Section 3.6.2 needs to be evaluated:

$$F_T = C_T * P_o * A_E \qquad \text{Eq. 3-1}$$

where,

P_o = initial intact system pressure (psia); in most formulations for F_T. P_o is given in terms of the difference between system and surrounding pressure, P_A,

A_E = the pipe break exit area (inches^2) (subscript $_E$ refers to break exit), and

C_T = the thrust coefficient (unitless).

Values for C_T depend on fluid conditions but otherwise are largely independent of plant design. Standard Review Plan Section 3.6.2 specifies that values should not be less than 1.26 for steam, saturated water, and steam-water mixtures and should be 2.0 for subcooled, nonflashing water. ANSI/ANS 58.2 identifies values of 1.26 to 1.30 for saturated and superheated steam. NuScale uses 1.26 for steam and two-phase jets, which meets the acceptance criteria of NRC guidance. No breaks in the CNV cause high pressure, liquid jets.

During operation, CNV pressure is below 1 psia. For pipe ruptures in the CNV, P_A varies with time, starting at less than 1 psia and rising for large leak rates (i.e., RRV opening). Because F_T is maximized when P_A is a minimum, CNV pressure is set to be 0 psia initially.

Eq. 3-1 assumes that there is no substantial flow resistance to the discharge and that the upstream reservoir pressure is constant. The latter is generally true for periods of seconds or minutes, except for isolated lines (i.e., a break of the high point vent degasification line at the RPV head) for which the time span for depressurization is equivalent to that for opening of the break, thereby removing the jet thrust before the pipe can move.

3.9.4.2 Damage Potential

Single-phase steam jets with upstream pressures of 1200 psia were found to cause damage to pipe insulation at a distance of up to 25 times the pipe exit diameter (i.e., L/D = 25). However, insulation is fragile as evident from Reference 1.4.2.10, which reports types of insulation suffering damage for impingement pressures as low as 4 psig.

NUREG/CR-6808 (Reference 1.4.3.14) Table 3-1 provides the impingement pressures found in testing that cause damage to various types of piping insulation used in US PWRs. The damage pressures range from 4 to 40 psi for fibrous insulation to a high of 190 psi for two types of reflective metal insulation. Insulation is more fragile than the solid metal surfaces of SSC inside the CNV, such as ECCS valve bodies and the CNV steel wall. Impingement loads are only meaningful for hard or relatively hard targets such as ECCS valve bodies, the CNV steel wall, and RXB concrete structure. Thus, impingement pressures must be substantial (above 190 psia) rather than the less than 4 psia needed to protect against dislodging insulation. As such, fewer uncertainties exist in predicting jet impingement effects on piping, and the relevant penetration distance is much shorter than 25 L/D.

Jet impingement testing was performed on electrical cable in support of the AP1000 assessment of debris generation. The conclusion was that cables at ≥ 4 L/D from a jet simulating an AP1000 loss of coolant are not damaged. The results are given in terms of distance due to the difficulty in accurately measuring impingement pressure. The NRC staff agreed with the conclusion. In Reference 1.4.2.13, the ACRS also agreed, stating

> "The recommended distance of four break diameters from a loss-of-coolant accident jet, at which unprotected cables would not be damaged, has been shown by testing to be sufficiently conservative to bound plant conditions with high likelihood."

Although the focus of this testing did not include cable functionality, inspection of test target cables showed no damage at ≥ 4 L/D (with exception of one cable). The results are applicable only to the type of cables actually tested, but an AP1000 RCS break jet is considerably larger and higher energy than a NuScale NPS 2 HELB. Therefore, it is likely that even unprotected cable inside the CNV would survive jet impingement from an NPS 2 HELB provided its separation from the break exit exceeded 4 L/D, or 6.75 inches. NuScale cable to be used in the CNV is tested for survival under jet impingement.

An overview of the NuScale vulnerability to jet impingement is:

- Based on plant operating conditions and smaller size of piping, thrust loads for NuScale line breaks are a fraction of those normally encountered in large LWRs (i.e., a NuScale 12-inch MSS line has about five percent of the total thrust force of an AP1000 38-inch MSS line break[11]).
- Main steam system HELB occurrence is limited to the RXB, because MSS breaks inside the CNV and in the NPM bay are eliminated by LBB and break exclusion, respectively. The NuScale full power steam pressure is 500 psia (AP1000 is 836 psia), which is actually a higher enthalpy per pound mass. However, the NuScale MSS steam density is about half, the flow rate driven by the system to ambient differential pressure is about 80 percent, and the full break single-ended flow area is about 11 percent of those of AP1000. The combination of these differences would put NuScale main steam system HELB mass and energy transfer at about 1/27th of AP1000 values.
- Damage to insulation on piping in the RXB is not a concern, so only a few specific essential SSCs need to be evaluated. Allowable impingement pressure on SSC is considerably higher (at least 190 psia) than that in large PWRs where insulation stripping is relevant.

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[11] AP1000 MSS is NPS 38 versus NuScale NPS 12 and AP1000 MSS pressure is 836 vs, 500 psia, yielding a relative thrust of 20 to 1.

- With a lower system pressure and more jet resistant target, a main steam system HELB penetration distance of 25 pipe diameters is an overestimate. In the RXB, NPS 12 (inner diameter of 10.75 in.) MSS line breaks are postulated: 25 L/D corresponds to 22.4 feet. Based upon postulated RXB arrangements (not yet being finalized) and possible break locations (not yet defined), jet impingement anywhere within the subcompartments was considered.

- For HELBs inside the CNV, only piping of NPS 2 size (inner diameter of 1.687 in.) is susceptible. Presuming 25 L/D, the steam jet range would then be about 43 inches. However, as shown in Appendix E, the jet pressure drops off rapidly with distance, even with a conservatively low spreading half-angle, such that the effective range of concern is less than 2.2 L/D (4 inches). For unprotected cable, 4 L/D (6.75 inches) is used.

- Similarly, although NuScale SSC are packed more closely together, the lower CVCS and MSS pressure, smaller pipe size, lesser distance through which a whipping pipe can travel, and presence of robust structures that serve as pipe whip barriers make the damage potential of pipe whip impact considerably less than other LWRs.

3.9.5 Pipe Whip Loads

In the CNV, pipe whip loads are limited because:

- Only the NPS 2 locations that do not satisfy break exclusion are considered. These locations are limited to terminal ends. The opposite end of the break is a safe end, which does not whip.
- The hinge point must be more than 14 inches (or more if the end of the break includes a piping length parallel to whipping motion; see C.4.1) lateral distance from the break to have sufficient energy to form a plastic hinge allowing whip to occur.
- The congested arrangement and short piping lengths limit the whip distance and, thereby, limit the energy at impact.

The occurrence and consequences of pipe whip are determined as follows.

- For piping meeting the criteria of break exclusion or LBB, pipe whip is not considered because dynamic effects of ruptures are excluded.
- If the other end of a terminal end is a RPV or CNV safe end, it does not whip because the nozzle/safe end is short, stiff, straight, and restrained by the component. Similarly, breaks are not postulated to occur in pump and valve bodies because the wall thickness exceeds that of connecting pipe.
- The calculation of thrust and jet impingement forces considers no line restrictions (that is, a flow limiter) between the pressure source and break location, but does consider the absence of energy reservoirs, as applicable (e.g., the degasification pipe in the CNV is normally isolated).
- If the jet thrust is insufficient to yield the pipe, then pipe whip at that break location is eliminated from further consideration.

- Where pipe ruptures are postulated to occur, the distance is determined from the break location to the nearest restraint that limits range or direction of pipe whip.
- Pipe whip is considered to result in unrestrained motion of the pipe along a path governed by the hinge mechanism and the direction of the vector thrust of the break force. A maximum of a 90-degree rotation may take place about any hinge. Pipe whip occurs in the plane defined by the piping geometry and configuration and to initiate pipe movement in the direction of the jet reaction, as identified in BTP 3-3.

For postulated break locations remaining:

- The “reach” of the whipping pipe is compared to the distance from the restraint to the nearest essential SSC and other high-energy lines (the line is not assumed to straighten out because the jet load is trying to compress the piping). If no target of concern is within reach, then pipe whip mitigation at that break location is not needed. Even if a target is within range, pipe whip impact may be prevented by presence of an intervening SSC that is sufficiently robust to serve as a barrier in accordance with Section 3.5.1.
    - If the direction of the initial pipe movement caused by the thrust force is such that the whipping pipe impacts an essentially flat surface normal to its direction of travel, it is assumed that the pipe comes to rest against that surface, with no pipe whip in other directions. However, to account of the potential rebound upon impact, a rebound force of 10 percent is added to the impact load.
- The loading that results from a break in piping is determined as described in Appendix C.

3.9.5.1 Screening for Occurrence of Pipe Whip

The method to determine if pipe whip occurs is based on calculation of the minimum internal forces necessary to form a plastic hinge in the pipe, which depends on the thrust at the break exit plane, the strength of the pipe to resist bending, and the distance to the nearest pipe whip restraint.

Note that a target cannot be subjected to both a pipe whip and a jet impingement load because the whip direction and jet vector are opposite. In other words, for a whipping pipe to strike a target, the jet driving the whip must be pointed away from that target. The jet from the other end of the break would be intercepted by a whipping pipe.

Jet thrust loads are calculated for applicable breaks using Eq. 3-1 (above) with a C_T of 1.26, consistent with SRP 3.6.2. Piping force is estimated by determining the projected length L_h from the pipe break to the nearest pipe whip restraint in the plane perpendicular to the plane of motion. The HELB jet loads applied on the end of the L_h long moment arm are assessed against the plastic moment for the pipe. The methodology assumes the thrust force remains constant, except for an isolated line with a limited length of pressurized piping such as the degasification line, which has insufficient energy to whip for a break postulated at the RPV head.

3.9.5.2 Impingement Pressure

The maximum force applied to an impingement target is determined using Eq. 3-1.

The only breaks inside the CNV are NPS 2 CVCS and DHRS lines. The limiting break in the RXB is an MSS line. The pressures for these two breaks at the break exit plane are as shown in Table 3-7 and include a factor of 1.26 for the thrust coefficient C_T. These values are upper limits for the downstream pressures for real breaks where pressure across the jet drops off as the jet expands and velocity of the jet is reduced by occurrence of turbulence leading to irreversible conversion of kinetic energy to heat. The isentropic expansion of steam jets is discussed in Appendix E.

Table 3-7 Break exit plane parameters

	CVCS Break*	**MSS Break**
Inner diameter (inches)	{{	
Intact system pressure (psia)		
Intact system temperature (degrees F)		
Break exit plane pressure (includes C_T of 1.26)(psia)		
Break exit plane area (inches^2)		
Maximum impingement force (lbf)		}}$^{2(a),(c),ECI}$

* DHRS breaks are assumed equivalent although internal pressure is only about 500 psia

3.9.6 Jet Zone of Influence

Two types of breaks are considered per regulatory guidance: circumferential breaks with full axial or sideways separation of pipe ends and longitudinal breaks. NuScale assumes circumferential breaks are full separation because of the absence of rigid restraints near postulated break locations. In addition, there are three thermodynamic blowdown conditions: 1) liquid, 2) two-phase, and 3) steam that have different behavior, as described in Appendix E.

High-energy line breaks are under-expanded when they issue from the end of the break, because the pipe section immediately upstream confines the flow radially. High-energy line breaks expand rapidly into the surrounding medium, with the expansion limited by jet momentum and increasing pressure at the boundary of the jet with the surrounding medium. In the limit, for a slow leak, the discharged fluid disperses uniformly in all directions. The expansion has the effect of reducing the jet pressure at a target below that at the break exit. ANSI/ANS 58.2 provides guidance on this expansion, but the NRC has expressed concern that this guidance is not generally applicable (see SRP Section 3.6.2).

Considerable effort has gone into evaluating the jet plume appropriate for HELBs. ANSI/ANS 58.2 presents the modified Moody model in which the conical jet expands at a 45-degree half-angle for a downstream distance of 5 L/D_E and at 10 degrees from there on. Some evaluations recommend a hemispherical or even a spherical ZOI. If the wider ZOI is considered in analysis, the drop off of pressure with distance is faster.

The NuScale approach is to overestimate the extent of the ZOI while underestimating the effect of jet expansion on reducing the pressure on downstream SSC, although these are mutually exclusive.

For NuScale, the acceptability of jet impingement pressures is insensitive to the analytical approach. Because piping inside the NuScale CNV is not insulated, the use of non-metallic material inside the CNV is minimized. Most cable is protected by being routed out of range. The RRV intake is directed downward and submerged during ECCS recirculation. Therefore, jet impingement does not present a risk of generating debris capable of blocking ECCS recirculation. Although piping outside the CNV is insulated, insulation stripping presents no hazard to safety-related functions.

3.9.6.1 Inside the Containment Vessel

For breaks inside the CNV, expansion of the jet into the low-pressure surroundings results in different behavior than is usually experienced for HELBs. Wider jet spreading occurs because the initially low air density of a CNV pressure below 1 psia removes most of the resistance to jet expansion. The wider jet expands the ZOI but reduces the pressure and the penetration length, because the mass and energy of the jet is more widely dispersed. Although pressure within the CNV increases with time, the pre-existing wide expansion of the jet persists as the jet is already established. The CFD blast modeling discussed in Appendix F shows that a steam jet initially develops a spreading half-angle greater than 60 degrees.

Appendix E provides a detailed discussion of the jet modeling applied in the CNV. {{

}}$^{2(a),(c)}$

For two-phase jets, the methodology of NUREG/CR-2913 is applied to determine the jet pressure distribution versus distance from the break exit. This is discussed in Appendix E.

Based on the preceding discussion that pressures of at least 190 psi are acceptable for hard components and on the pressure vs. distance behavior for steam and two-phase jets, a distance of slightly more than four inches (2.2 L/D) is sufficient to provide acceptable protection of metal SSC. This distance is sufficiently short that few SSC are within the ZOI. For unprotected cable, 6.75 inches (4 L/D) is sufficient. In summary, any SSC in the CNV more than four inches axially or radially (6.75 inches for unprotected cable) requires no evaluation for damage from jet impingement.

3.9.6.2 In the Reactor Building

In the RXB, normal atmospheric pressure surrounds any postulated break location, and the venting available limits the buildup of backpressure. Except for nonmechanistic breaks in MSS of FWS piping, no breaks are postulated in the NPM bay under the bioshield because piping is designed to satisfy break exclusion criteria of BTP 3-4.

Because piping arrangements are not yet finalized in the RXB except under the bioshield (COL Items 3.6-1, 3.6-2, and 3.6-3), specifying a particular ZOI is not meaningful. The RXB walls, floors, and ceilings are assumed to be two pipe internal diameters from a break exit. This is judged to be closest practical distance from a wall at which to make a field weld (e.g., 22.5 inches for an NPS 12 MSS pipe, 3.5 inches for NPS 2 CVCS pipe). It is also reasonable as the minimum separation necessary to clear the other end of the broken pipe to impinge on an RXB structural surface or another component.

Because the evaluation is performed assuming a distance of only 2 L/D, penetration length is not relevant. To focus the impingement pressure, no expansion is considered. For an MSS break, which imposes the highest load of postulated HELBs in the RXB, the design-capacity ratio (DC) of the wall for jet impingement and reaction loading is 0.02. Because pipe rupture loads are localized, they have no effect on the overall structural integrity of the wall.

Portions of the CVCS RCS injection lines in the RXB contain cold, high pressure water (see Table 3-4). A liquid water jet is assumed to not expand or droop (i.e., sag with distance as specified in SRP Section 3.6.2) and extends until intercepted by SSCs. Because these cold CVCS lines are located in subcompartments that do not contain essential SSCs (except the demineralized water make-up valves for which a HELB-induced failure is acceptable) and the force applied to structural concrete is bounded by an MSS jet, HELB jet impingement is not a concern.

3.9.7 Jet Impingement Loads

The load on an object exposed to a jet depends on the pressure of the jet upon the object's surface, on the intersection of the jet with the object, and on the shape of the object.

Jet pressure at the nearest target surface is determined, including the thrust coefficient C_T (1.26 for steam and two phase jets). If less than 190 psia (or beyond 4 L/D for unprotected cable)[12], the impingement pressure is low enough to be non-damaging, but a load is determined in accordance with Eqn. E-7 for use in load combinations.

3.9.7.1 Dynamic Amplification and Resonance

Experiments simulating HELBs routinely evince oscillations but not resonance. For dynamic amplification and resonance to occur, a number of criteria must be met, as

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[12] No additional factors need be applied because these criteria are based on testing.

discussed in Appendix B. These criteria are based on the research referenced in SRP Section 3.6.2 and similar work that identified the physical phenomena leading to resonance. The processes at work during a HELB have fundamental differences from those that occur in a jet with dry, noncondensable gas issuing from a smooth, fixed nozzle. These physical differences involve instability of the discharge, irregular discharge geometry, phase changes that suppress pressure changes, misalignment of jet and impingement target surfaces preventing establishment of a feedback loop, lack of an appropriately flat surface within a sufficiently close distance, and etc. If any one of these criteria is not met, a resonance is unlikely. In an HELB, none of the criteria is satisfied, precluding formation of a resonance.

3.9.8 Pressurization Caused by High-Energy Line Breaks

Appendix D provides the detailed discussion of evaluation of subcompartment pressurization of portions of the NuScale plant caused by HELBs. In locations where HELB dynamic effects are not obviated by satisfying break exclusion or LBB criteria, the pressurization transient resulting from the mass and energy (M&E) release to the surrounding volume(s) has been analyzed using a GOTHIC computer model of affected portions of the RXB. As additional M&E is introduced into the surroundings, it increases pressure and temperature. Pressure continues to rise until cooling of the enclosed volume (i.e., the CNV) or venting (e.g., RXB) of the volume is sufficient to offset the blowdown.

3.9.8.1 Inside the CNV

Postulated HELB locations involve blowdown from an RCS- or DHRS-connected NPS 2 pipe. The M&E release for these HELBs is less than 10 percent of that from an ECCS initiation that serves as the design basis for the CNV and for environmental qualification of safety-related and essential equipment in the CNV. Therefore, a separate environmental evaluation of HELBs inside the CNV is not performed.

3.9.8.2 In the NPM bay under the Bioshield

No postulated HELB locations require evaluation because piping is designed to break exclusion criteria. However, nonmechanistic breaks of MSS and FWS piping must be evaluated (as discussed in Section 3.5.2.5). In addition, leakage cracks are assessed. The purpose of this evaluation is: 1) to show that the structural limit of 1 psi differential pressure across the bioshield is not exceeded and 2) to determine the enveloping pressure and temperature profile for purposes of EQ of essential and safety-related components under the bioshield.

Nonmechanistic breaks of MSS and FWS piping and leakage cracks in MSS, FWS, and CVCS piping were analyzed with input conditions selected to maximize pressure and temperature, as discussed in Appendix D. A passive vent path out the side of the bioshield provides a means to vent M&E to the pool room to limit pressure and temperature under the bioshield.

3.9.8.3 In the RXB

The concern is room pressurization that challenges the structural integrity of the building, due to the combination of the pressure load with other loads (e.g., seismic, deadweight) or releases steam into areas of the RXB designated as mild environment to protect essential or safety-related equipment. Based on an assessment of RXB structural capability that considers combination with other loads (i.e., deadweight, structural, etc.), a pressure load that can be sustained on walls, floors, and ceiling of rooms housing high-energy piping is at least 3 psid.

Detailed design of RXB piping arrangements is a COL applicant item. To ensure that RXB design is satisfactory for any allowable arrangements, the pressurization and temperature effects of HELBs and leakage cracks must be isolated from areas containing essential or safety-related equipment. This is accomplished by providing paths to vent the M&E release for postulated breaks and leakage cracks between designated pipe failure hazard areas and then to outside the RXB. These vent paths are either always open or are equipped with safety-related pressure relieving devices (e.g., blowout panels, rupture disks). Also, RXB design criteria and MPS specifications provide that:

- The areas through which Class 1E, associated circuits, augmented design circuits and associated-ADC circuits are routed and in which equipment is located are reviewed for potential hazards such as high-energy piping. Separation commensurate with the damage potential of the hazard is provided through the use of features such as separate rooms.
- Pipe failure hazard areas contain piping normally operating at high or moderate energies. For moderate-energy piping, pipe whip and jet impingement need not be considered; however, the wetting and environmental effects must be considered. Protection of nonhazard and limited hazard areas from pipe failure hazard areas are accomplished by the use of barriers, restraints, separation distance, or appropriate combination thereof.
- The routing of Class 1E, associated circuits, augmented design circuits, associated-ADC circuits, or raceways in pipe failure hazard areas conforms to specific requirements, unless it can be demonstrated that pipe failure cannot prevent the Class 1E circuits and equipment from performing their safety-related function, and it can be demonstrated that pipe failure cannot prevent the applicable augmented design circuits and equipment from performing their important-to-safety function. Separation criteria depend on the qualification of piping for design basis events, the division(s) it is in and co-located with, and the need for protective action.
- Class 1E circuits are routed or protected so that failure of the mechanical equipment of one division cannot disable Class 1E circuits or equipment essential to the performance of the safety-related function of the redundant division(s). The effects of pipe whip, jet impingement, water spray, flooding, radiation, pressurization, elevated temperature, or humidity on redundant electrical systems caused by failure, misoperation, or operation of mechanical systems are considered.
- The MPS fails into a safe state or into a state demonstrated to be acceptable on some other defined basis, if conditions such as disconnection of the system, loss of energy

(e.g., electric power, instrument air), or postulated adverse environments (e.g., extreme heat or cold, fire, pressure, steam, water, and radiation) are experienced.

For practical purposes, the above require that instrument cables used for the MPS or PAM and dc power systems and cables not be located in the same rooms as high-energy piping or through which venting occurs, with the exception of the NPM bay where HELBs are excluded.

To bound postulated HELBs anywhere in the RXB, the following scenarios are evaluated, using a GOTHIC model of relevant parts of the building.

- A full shear of a NPS 12 MSS pipe of one NPM is postulated to occur in the pipe gallery. Blowdown occurs from both ends of the pipe. Whip of the MSS pipe fails either a NPS 4 MSS bypass line or an NPS 8 FWS pipe (pipe whip of an MS pipe into another MS pipe does not cause a second rupture, in accordance with regulatory guidance), adding to the M&E release. Although COL Item 3.6-1 requires that the COL applicant assess and mitigate multi-module effects, this approach ensures that the RXB structure is adequate for beyond design basis interactions between adjoining modules.
- A double-ended shear of a high temperature and pressure section of the CVCS discharge line is postulated to occur in the smallest room through which it passes or in the pipe chase from the NPM bay to the 50 foot elevation. The highest energy lines in the CVCS system in the RXB are the hot side inlet (i.e., discharge) and outlet of the non-regenerative heat exchanger, at maximums of 1840 psia and 500-degrees Fahrenheit and of 1960 psia and 453-degrees Fahrenheit, respectively. The higher temperature of the discharge line results in a greater room pressurization.
- A leakage crack in the ABS piping is evaluated.

For locations in the RXB with postulated HELB locations, GOTHIC analysis is used to determine the vent opening area necessary to limit pressurization to less than the RXB structural limit (Appendix D). Where a room vents into another room, the downstream room also needs its own vent area until venting into the pipe gallery or pool area occurs, and these two areas are vented directly to outside the RXB via piping protected against physical security threats. The vent paths are not dependent on the RXB ventilation system.

3.9.9 Effects of Leakage Cracks

Leakage cracks are considered in high-energy systems not satisfying break exclusion criteria and in moderate-energy systems. Consequences of leakage cracks in piping in the moderate energy systems are either bounded by HELB effects or are evaluated and shown acceptable. Leakage cracks in high-energy systems could release small quantities of steam.

3.9.9.1 Inside the Containment Vessel

The effects of leakage cracks are bounded by evaluations of HELBs and ECCS initiation. The SGS lines are shown to meet LBB based on the ability to detect leakage cracks. Very small leak rates can be detected by monitoring CNV pressure and containment evacuation system (CES) sample vessel level. Operation of the CES vacuum pump prevents a continued accumulation of water or steam in the CNV.

3.9.9.2 In the NPM Bay under the Bioshield

High-energy piping in the containment penetration area is designed to satisfy break exclusion criteria out to and including the welds attaching the outermost valve body nozzle to the piping section that ends in the spool flange, eliminating the need to evaluate effects of ruptures or leakage cracks, except for those of nonmechanistic breaks of MSS and FWS lines (as discussed in Section 3.5.4.2). Beyond that point and to the first weld on the pipe gallery side of the pool wall (including the piping spools), the piping satisfies the BTP 3-4 paragraph B.A.(iii)(2)(b)(ii) criteria for no breaks at intermediate locations. Leakage crack environmental effects are bounded by those of nonmechanistic breaks of MSS piping in the vicinity. Safety-related and essential SSC (e.g., CIVs, I&C) are qualified for pressure and temperature conditions resulting from leakage cracks.

The one moderate-energy system is RCCWS (the CFDS is normally isolated). With an operating temperature below boiling, no pressure or temperature increase in the NPM bay occurs. Continued leakage is detected by a loss of expansion tank level before dilution of borated pool water could occur.

3.9.9.3 In the Reactor Building

The effect of leakage cracks in high- and moderate-energy systems is bounded by the HELB pressurization analyses and RXB flooding analysis, except for areas housing ABS piping, which are explicitly analyzed as noted in Appendix D.

4.0 Results

This section discusses postulated HELBs and MELBs and their external effects in the NuScale plant. The effects are based on the methodology discussed in Section 3.0. Because of the different conditions and systems in the CNV, the NPM bay under the bioshield, and the RXB, results are subdivided accordingly.

4.1 Postulated Break Locations

4.1.1 In the Containment Vessel

MSS and FWS piping satisfy LBB criteria. Breaks are postulated at terminal ends of RCS-connected pipes and DHRS pipes, as identified in Table 3-4. Intermediate locations satisfy BTP 3-4 paragraph B.A.(iii) criteria or are evaluated for external effects. Longitudinal breaks are not considered because this piping is NPS 2. Leakage crack effects are bounded by those of ECCS initiation and ruptures, and leakage detection in the CNV (i.e., CNV pressure and CES sample tank level) is capable of identifying very small leaks.

Appendix A provides details of piping evaluation against BTP 3-4 criteria.

4.1.2 In the NPM Bay under the Bioshield

No breaks or cracks occur in the containment penetration area (other than nonmechanistic breaks in the MSS and FWS), based on designing to satisfy the break exclusion criteria of BTP 3-4. The containment penetration area extends from the CNV safe end-to-pipe weld to the outermost CIV or check valve-to-pipe weld, allowing application of the criteria of BTP 3-4 Paragraph B.A.(ii) to exclude breaks at terminal ends. Ruptures at intermediate locations are excluded because the design satisfies BTP 3-4 Paragraph B.A.(iii). Appendix A provides details of piping evaluation against BTP 3-4 criteria. Piping under the bioshield beyond the containment penetration area is not subject to rupture as it is designed to meet BTP 3-4 Paragraph B.A.(iii) criteria, and effects of leakage cracks are bounded by nonmechanistic breaks of MSS and FWS piping considered in the contiguous containment penetration area.

4.1.3 In the Reactor Building

Breaks are postulated in any location where high- or moderate-energy MSS, FWS, or CVCS piping is located because piping arrangements are not finalized. Therefore, no piping stress calculations are needed. Effects of longitudinal breaks in MSS and FWS piping are bounded by this approach. COL Items 3.6.2-1 and 3.6.2-3 require that the COL applicant update the HELB analysis for final pipe arrangements by performing stress analyses, design and qualification of piping supports, evaluation of subcompartment pressurization effects, and completion of the balance of plant pipe rupture hazards analysis, including the design and evaluation of pipe whip/jet impingement mitigation as required.

4.2 Blast Effects

Blast effects results are based on three-dimensional CFD analysis discussed in Appendix F.

4.2.1 In the Containment Vessel

Because only NPS 2 lines are postulated to break, the mass and energy release feeding the blast formation is small. Only the degasification line has the potential for forming a blast, because the other CVCS lines contain subcooled liquid. The magnitude of the blast wave pressures is low, and the maximum force imposed on any component is limited to 6,000 lbf. In addition, the load is of very short duration (a few milliseconds). Because the blast load is small, its effect on load combinations is inconsequential, and its exclusion does not affect compliance with the ASME allowable limits.

4.2.2 In the NPM Bay under the Bioshield

Not applicable.

4.2.3 In the Reactor Building

Breaks are postulated in MSS lines at three locations in a pipe gallery. Only MSS lines have a potential for forming a blast, because the other high-energy lines contain subcooled liquid. The maximum force on any component is less than 10,000 lbf. Although a force of 103,000 lbf on the pool wall was calculated, it is distributed over a surface area with a radius of about 100 inches, yielding a momentary overpressure of less than 15 psig and no damage to the structure. In addition, the load is of very short duration (a few milliseconds). Because the blast load is small, its effect on load combinations is inconsequential, and its exclusion does not affect compliance with the ACI 349 allowable limits.

4.3 Pipe Whip

Results of pipe whip evaluations are detailed in Appendix C.

4.3.1 In the Containment Vessel

Pipe whip for breaks at the RPV and CNV terminals ends has been evaluated. The nozzle/safe end end does not whip. For the piping end, the motion of the pipe is such that no safety-related or essential SSC are impacted. Even if an impact did occur, the SSC are of heavy wall construction so that they neither leak nor crack. There is one exception: the ECCS trip/reset line. If a whipping pipe strikes a trip/reset line, the line is severed, causing it to vent. This has the same effect as opening the trip valve and allows the ECCS main valve to open once the IAB clears. As the response to the HELB is ECCS initiation, the severance of a trip/reset line has no effect on response to the event.

4.3.2 In the NPM Bay under the Bioshield

Not applicable.

4.3.3 In the Reactor Building

Because of their higher internal energy and longer whip arc possible in the pipe gallery, MSS breaks are limiting. To bound future piping arrangements, a large pipe whip arc was evaluated. Penetration of the concrete was minor, and the pool and main structural walls are sufficiently thick to avoid spalling.

4.4 Jet Impingement

The small diameter piping in the NuScale plant yields small impingement forces. Testing previously performed as part of GSI-191 research showed reflective metal insulation could withstand at least an impingement pressure of 190 psi. Because stripping of insulation is not a concern in the NuScale design, safety-related and essential components are considered acceptable for jet impingement pressures of 190 psi. Impingement loads must still be considered in load combinations. Based on industry available cable insulation testing, but to be confirmed by testing NuScale specific cable, unprotected cables are considered acceptable if at least 4 L/D from an HELB exit, which is confirmed by testing of NuScale cable.

4.4.1 In the Containment Vessel

Only NPS 2 CVCS and DHRS breaks at terminal ends are considered. Pressure of the RCS jet is below 190 psi within 2.2 L/D, or 4 inches for CVCS and within 1 L/D for DHRS. Damage to cables for separation group B & C is a concern, because MPS functionality is satisfactory for loss of signal from one channel (see Section 3.2.2) but PAM functionality requires that neither group B & C signals be lost to HELB effects. The cable separation distance of 4 L/D corresponds to about 6.75 inches. No damage from jet impingement occurs because cables are routed more than 6.75 inches away from postulated breaks.

4.4.2 In the NPM Bay under the Bioshield

Not applicable.

4.4.3 In the Reactor Building

Potential impact on a CIV HPU skid is acceptable because it causes the hydraulic lines or electrical wiring to break, venting off pressure, and allowing the CIVs and DHRS actuation valves to go to their safe position. The consequences of HELB-induced failure of the CVCS demineralized water make-up valves are acceptable.

For effects on concrete, MSS breaks are limiting and are assumed to occur within 2 L/D of a wall, with no reduction in jet pressure with distance from the break. For an MSS break, which imposes the highest load of postulated HELBs in the RXB, the DC ratio of the wall for jet impingement and reaction loading is 0.02. Because pipe rupture loads are localized, they have no effect on the overall structural integrity of the wall.

In addition, the effect of erosion is negligible.

4.5 Subcompartment pressurization

4.5.1 In the Containment Vessel

Structures, systems, and components within the CNV are designed and qualified for ECCS initiation. Therefore, the effects of the NPS 2 high-energy line breaks are bounded and do not require further evaluation.

4.5.2 In the NPM Bay under the Bioshield

The pressure limiting MSS nonmechanistic break provides the maximum pressure transient for both comparison to the bioshield structural acceptance criterion of 1.0 psid and the EQ profile. For the EQ temperature profile, temperature results from the analyzed cases are overlaid to develop bounding temperature profile in the area under the bioshield.

4.5.3 In the Reactor Building

For purposes of pressurization in the pipe gallery, the double-ended MSS line rupture with MSS bypass line split results in the most severe pressure transient, which is shown to be within the 3 psid differential pressure criterion to maintain an acceptable DC ratio of the RXB. CVCS breaks in the pipe chase and heat exchanger rooms and ABS leakage cracks have also been demonstrated to meet the 3 psid acceptance criterion.

5.0 Conclusions

This report documents the methodology and results of evaluations performed to determine postulated break locations and the effects of those breaks. The NRC guidance on relevant effects is identified and how differences in the NuScale design affect application of that guidance.

The NuScale design is a compact, integral reactor than relies on passive safety features to ensure safe shutdown and cooldown for design basis events. The absence of large diameter RCS piping and active safety systems leads to a minimal number of safety-related and essential SSC. Examples of key features include

- No operator action or electric power is required for safe shutdown and cooldown for design basis accidents.
- Absence of essential and safety-related SSC in the RXB in areas containing high- or moderate-energy piping.
- Small-volume metal containment operated a low pressure and with sensitive leak detection capability.
- No insulation used inside the CNV, therefore there is no concern for dislodged piping insulation blocking core cooling.
- Greatly reduced energy of blast, pipe whip, and jet impingement effects due to smaller plant size and lower energy system conditions.
- Stainless steel primary and secondary piping within the containment and containment penetration area.
- Ready access for inspection.

Application of the criteria for break exclusion and LBB leaves few locations in the CNV and none in the NPM bay requiring evaluation of external effects of blast waves, pipe whip, jet impingement, subcompartment pressurization, and flooding. Protection is demonstrated through separation and by virtue of the robustness and qualification of safety-related and essential SSC.

Evaluation of bounding HELBs and MELBs demonstrates the essential components in the RXB and the RXB structure are capable of withstanding the external effects of HELBs and providing separation from PAM instrument lines and DC electric power.

External effects of HELBs and MELBs in the NuScale plant do not adversely affect the ability to shut down and maintain core cooling of the NPM.

The following table summarizes the evaluations and results of this report.

Table 5-1 Summary of approach and result for line break assessment by plant area

	Inside Containment	**NPM Bay under Bioshield**	**Reactor Building**
Limits on occurrence of breaks	RCS: Break exclusion at intermediate locations satisfy BTP 3-4 B.A.(iii) MSS & FWS: LBB	Containment penetration area (all lines out to and including outboard valve body to pipe weld): BTP 3-4 B.A.(ii) Rest of high-energy lines satisfy BTP 3-4 B.A.(iii)(2)	None
Postulated break locations	RCS terminal ends	Nonmechanistic breaks of MSS & FWS in containment penetration area	Any high- or moderate-energy part of MSS, FWS, or CVCS
Blast effects	Negligible as confirmed by 3D CFD	Not applicable	Low, as confirmed by evaluating bounding MSS cases with 3D CFD
Pipe whip	Insufficient energy to whip, separation, separation sufficient to avoid impact, or acceptable consequences	Not applicable	Protection by showing separation or acceptable consequences
Jet impingement	*Pressure of jet:* Steam: NUREG-2913 2-phase: 30˚to 5 L/D & 10˚ *Hemispherical ZOI:* 2.1 L/D for pipe 4 L/D for unprotected cable	Not applicable	Analysis of jet impingement effects on essential components is acceptable assuming no pressure reduction.
Dynamic amplification	Does not occur		
Pressurization	Bounded by ECCS initiation	Evaluated nonmechanistic breaks and leakage cracks in MSS and FWS piping	Evaluated bounding HELBs and leakage cracks
Flooding	Bounded by ECCS initiation	Not applicable (discharge goes into pool)	Bounded by existing analyses in FSAR Section 3.4.
Leakage cracks	Bounded by ECCS initiation	Environmental effects determined and used in equipment qualification	Bounded by HELBs

Appendix A. Break Exclusion – Compliance with Regulatory Acceptance Criteria

A.1 Application of BTP 3-4 Criteria for the Determination of Postulated Break Locations

The criteria used to determine the location of postulated HELBs and to exclude the need to postulate HELBs are provided in BTP 3-4. BTP 3-4 contains two sets of criteria for determining break locations; one for piping located within containment penetration areas and the other for areas outside containment penetration areas. Both are described in Section 2.2.2.1. NuScale's application of the guidance of BTP 3-4 with respect to postulated HELB locations is described below. Separate discussions are provided for three distinct regions of the NuScale plant.

A.2 Inside the CNV

SGS (i.e., MSS and FWS) lines are qualified to LBB criteria (see FSAR Section 3.6.3). Other high energy piping located inside the CNV is designed to the break criteria of BTP 3-4 B.A.(iii). Also, the five bolted-flange connections for the RVV and RRV are designed to break exclusion criteria (see FSAR Section 3.6.2.7).

Per the criteria in BTP 3-4 B.A.(iii)(1), breaks are postulated at piping system terminal ends and at intermediate locations. Additional intermediate break locations may be selected by one of two criteria: (i) at every fitting, weld, and valve and additionally at the extremities of protective structures, or (ii) through application of conservative stress criteria based on ASME code equation stresses. For the NuScale design the second option was used, and stress analysis performed to determine the location of postulated break locations. The break locations determined using this approach are listed in FSAR Table 3.6-2.

A.3 Outside the CNV under the Bioshield

The region outside the CNV under the bioshield contains high-energy piping both within and outside the containment penetration area. High-energy piping within the containment penetration area is identified in Figure 1 for the CNTS and Figure 2 for the DHRS and is presented in red. Where the portion of piping being identified is limited to a single weld, a red dot is shown rather than a line. The remainder of the high-energy piping, beginning immediately outboard of the containment penetration area welds (indicated with red dots) and continuing beyond the reactor pool wall, is outside the containment penetration area. Where piping connects to a containment vessel safe-end, only the weld between the piping and the safe-end is considered to be within the containment penetration area, while the weld between the safe-end and the containment vessel is considered part of the vessel (i.e., not piping), and therefore not within the scope of BTP 3-4. Although the welds between the safe-ends and the vessel are not within the containment penetration area, these welds do comply with the ISI requirements of BTP 3-4 B.A.(ii)(7) in order to ensure a low probability of rupture. These ISI requirements are included in FSAR Section 6.6, Inservice Inspection and Testing of Class 2 and 3 Systems and Components and in FSAR Section 6.2, Containment Systems.

For high-energy piping outside the containment penetration area, postulated pipe break locations are selected per the criteria in BTP 3-4 B.A.(iii)(2). Terminal end breaks in this region have been eliminated by including the terminal ends at the connection to the CIVs, check valves, and nozzles in the containment penetration area. Other terminal ends for these piping systems are located at anchors beyond the reactor pool walls. Intermediate break locations are eliminated by meeting the stress criteria from BTP 3-4 B.A.(iii)(2). This methodology results in the elimination of all postulated pipe breaks in this region, except for the non-mechanistic breaks described in Section 3.5.2.5 of this report.

High-energy piping within the containment penetration area (highlighted red in Figure A-1 and Figure A-2) is required to satisfy the criteria in BTP 3-4 B.A.(ii). These criteria are summarized below and apply to all high-energy main run and branch piping within the containment penetration area.

1. Design stress and fatigue limits must meet conservative acceptance criteria.
2. Welded attachments should be avoided, except where detailed stress analysis is performed.
3. The number of welds should be minimized and configured to permit volumetric examination.
4. The length of piping within the containment penetration area should be reduced to the minimum length practical.
5. Pipe supports and anchors should not be welded directly to the piping, unless the welds are 100 percent examinable and detailed stress analysis is performed.
6. Where guard pipes are used, conservative design criteria are satisfied.
7. A 100 percent volumetric inservice examination of pipe welds should be conducted during each inspection interval as defined in the ASME Code.

NuScale FSAR Section 3.6.2.1.2 discusses how the FWS and CVCS lines in the containment penetration area satisfy the above criteria. For these lines, the containment penetration area is limited to single welds, and the criteria are inherently satisfied as there is no physical piping. A FWS line is shown in Figure A-3, while the CVCS discharge line, representative of all of the CVCS lines, is shown in Figure A-4.

The DHRS lines and the portions of the MSS lines that are in the containment penetration area are discussed in FSAR Section 3.6.2.7. The MS piping is shown in Figure A-5 and the DHRS piping is shown in Figure A-6. The application of BTP 3-4 B.A.(ii) criteria to this piping is discussed below.

1. The MSS and DHRS piping within the containment penetration area is designed to satisfy the BTP 3-4 B.A.(ii) stress limits as described in FSAR Section 3.6.2.1.2 for the FW lines.
2. Welded attachments to this piping are limited only to instrument connections. These instrument connections can be seen on the MSS line in Figure A-5 and on the DHRS lines in Detail A and Detail B of Figure A-6. These instruments are attached to the piping using weld-on (e.g., sockolet) fittings. The

attachments are evaluated in the detailed piping stress analysis by inclusion of the appropriate stress indices and stress intensification factors at the location of the attachments.

3. The number of welds has been minimized through the use of piping bends instead of welded fittings, where practical. Access has been provided for volumetric inspections by providing a clearance (unobstructed pipe) on either side of the weld of approximately four wall thicknesses (4t) based on skip distance = 2t*tan(60°). Where necessary, custom fittings have been specified to achieve this unobstructed distance requirement. Figure A-7 shows examples of where custom fitting have been specified for the DHRS piping. Additionally, the welds are located away from surrounding structures such as pipe supports that would interfere with inspections.
4. The piping in these areas is kept as short as practical:
    a. CNTS-MS – The length of the MSS tees within the containment penetration area is limited to that required to fit two DHRS connections between the CNV nozzle and the MSS CIV.
    b. DHRS – Sixty feet per train of piping is needed to route the lines from their connection at the MSS tees to their connection at the DHRS condenser inlets. Other than an expansion loop used to reduced thermal stress in the system, the piping is routed as directly to the condenser inlets as possible. The NPS 2 piping that runs from the DHRS condenser outlet to the CNV nozzles also utilizes an expansion loop to accommodate thermal growth of the condenser, which is allowed to expand downward.
5. No pipe supports or anchors are welded directly to piping within the containment penetration area.
6. No guard pipes are used for piping within the containment penetration area.
7. A 100 percent volumetric inservice examination of pipe welds is to be conducted during each inspection interval as defined in the ASME Code.

The CIVs are within the containment penetration area. Design criteria ensure their functional capability and operability under service load conditions resulting from postulated events, including HELBs. The CIVs are designed to not be damaged under normal or operating conditions and are required to be able to close under conditions associated with a break in the line. The loading combinations for these valves are shown in FSAR Table 3.9-12 for the secondary system CIVs and Table 3.9-13 for the primary system CIVs.

A.4 Piping in the remainder of the RXB

BTP 3-4 criteria regarding the location of postulated breaks is not used because the effects of a rupture of high-energy piping at any location is bounded and shown to be acceptable.

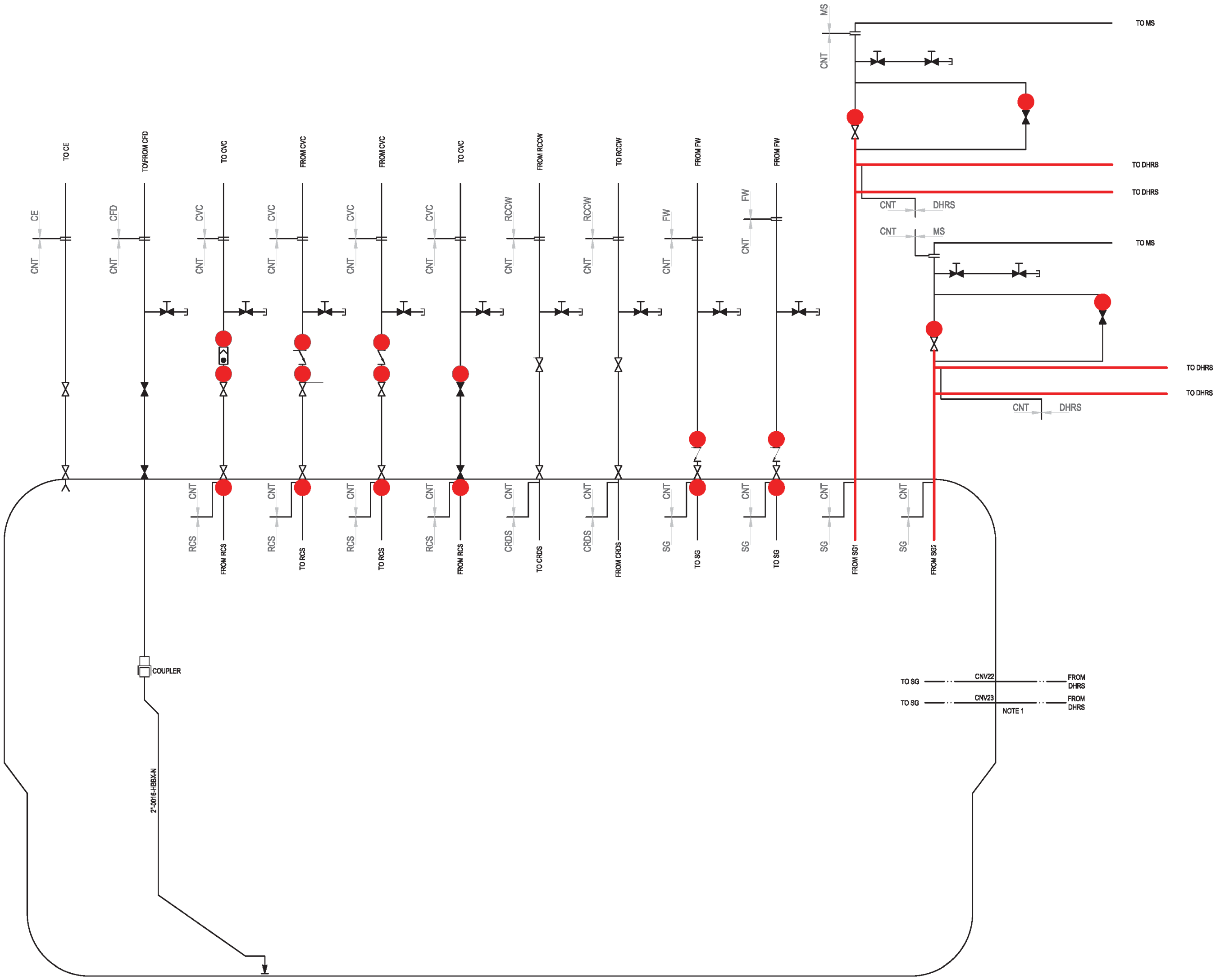


Figure A-1 Containment Penetration Areas – Containment System (CNTS)

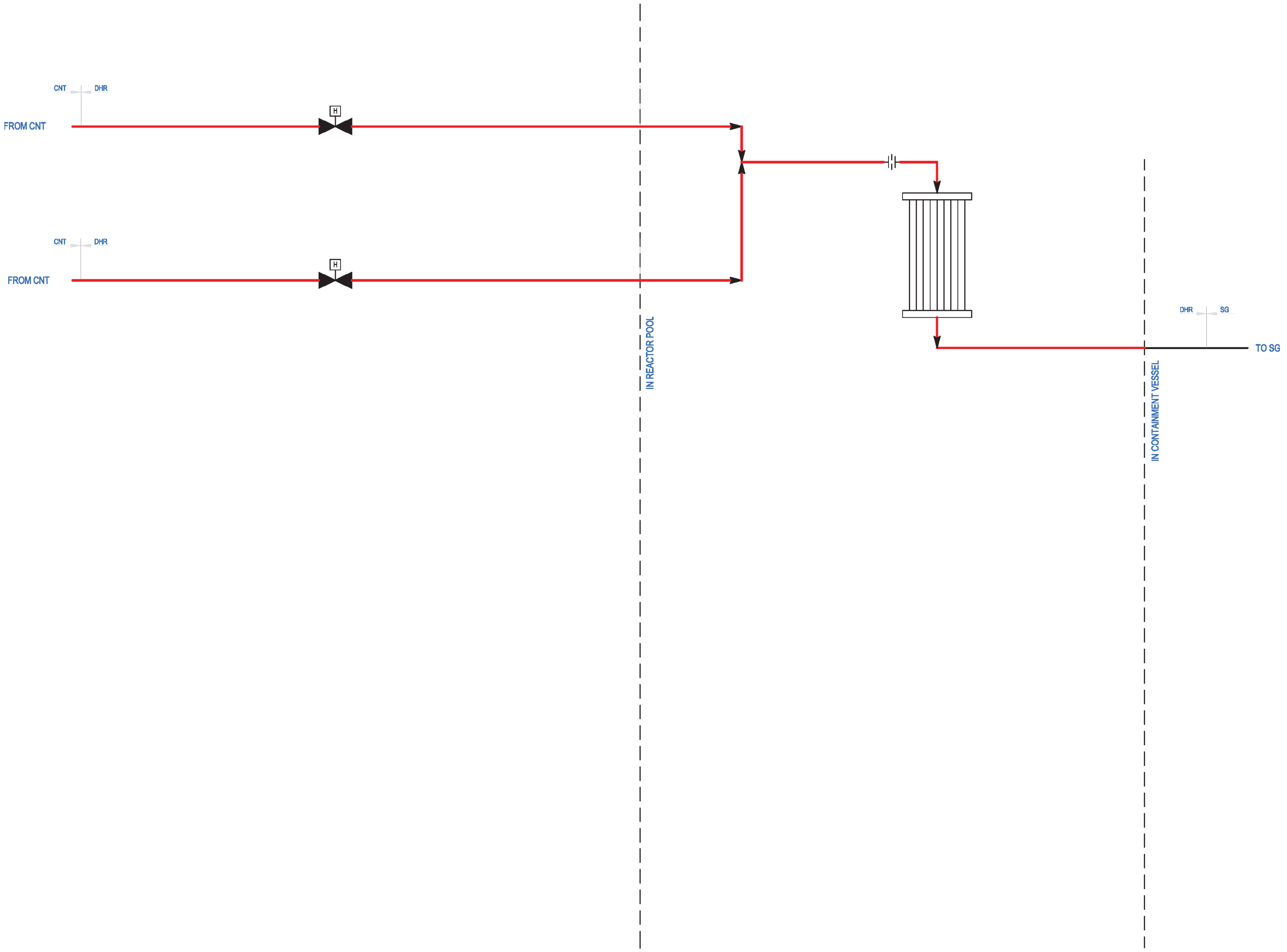
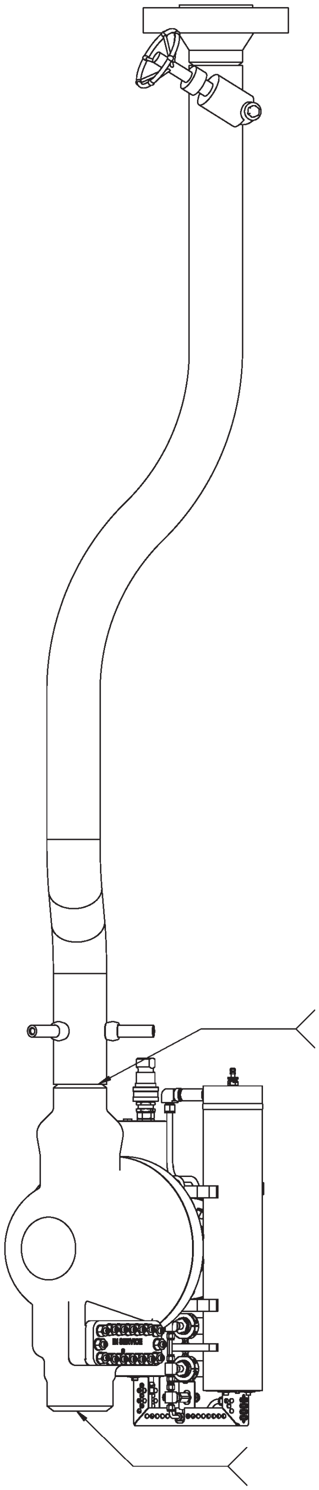
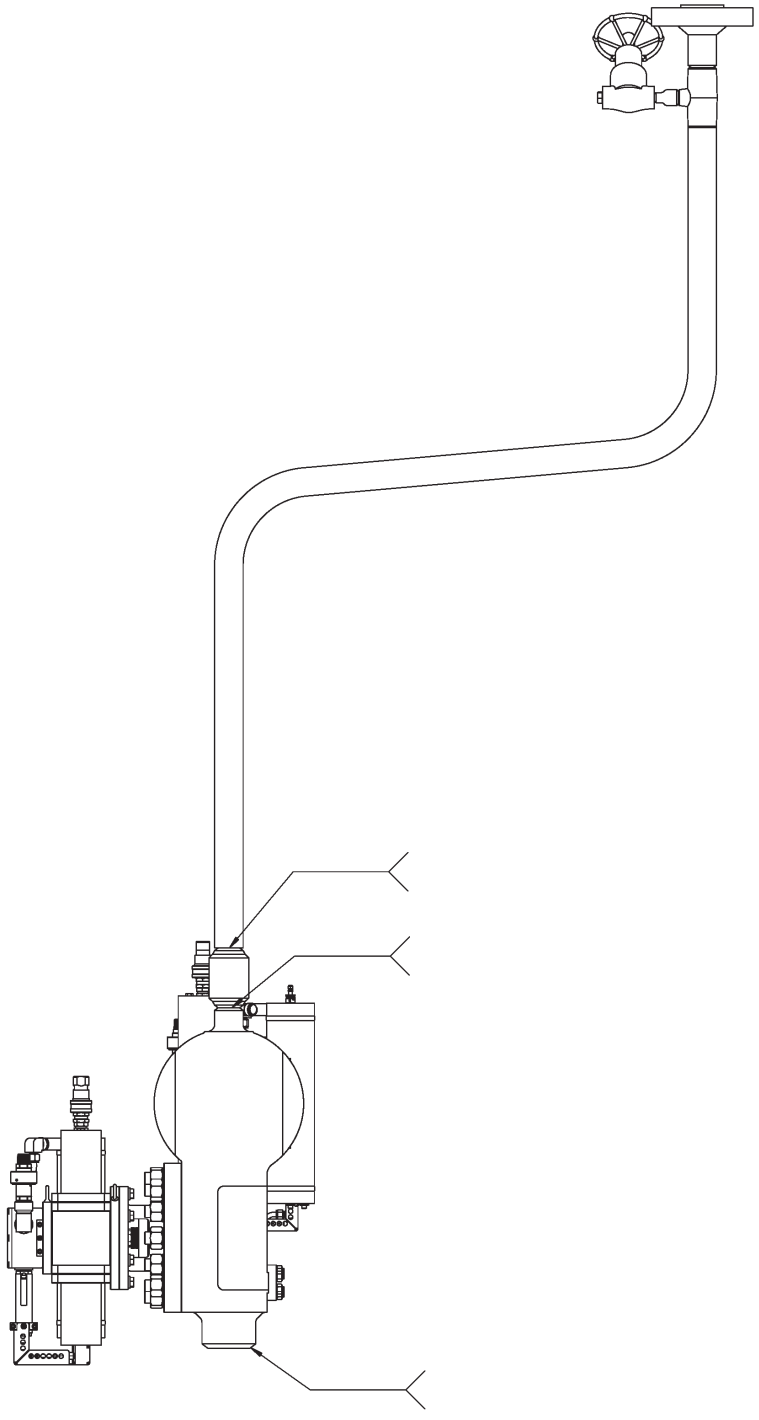


Figure A-2 Containment Penetration Areas – Decay Heat Removal System (DHRS)



CNTS FEEDWATER

Figure A-3 Feedwater line with containment penetration area welds indicated



CNTS DISCHARGE LINE

Figure A-4 Discharge line with containment penetration area welds indicated

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}}2(a),(c),ECI

Figure A-5 MS line with containment penetration area welds indicated (Approximate length NPS 12 tee fittings = 4 feet)

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}}$^{2(a),(c),ECI}$

Figure A-6 DHRS lines with containment penetration area welds indicated (Approximate length per train: NPS 8 = 2 feet, NPS 6 = 60 feet, NPS 2 = 12 feet)

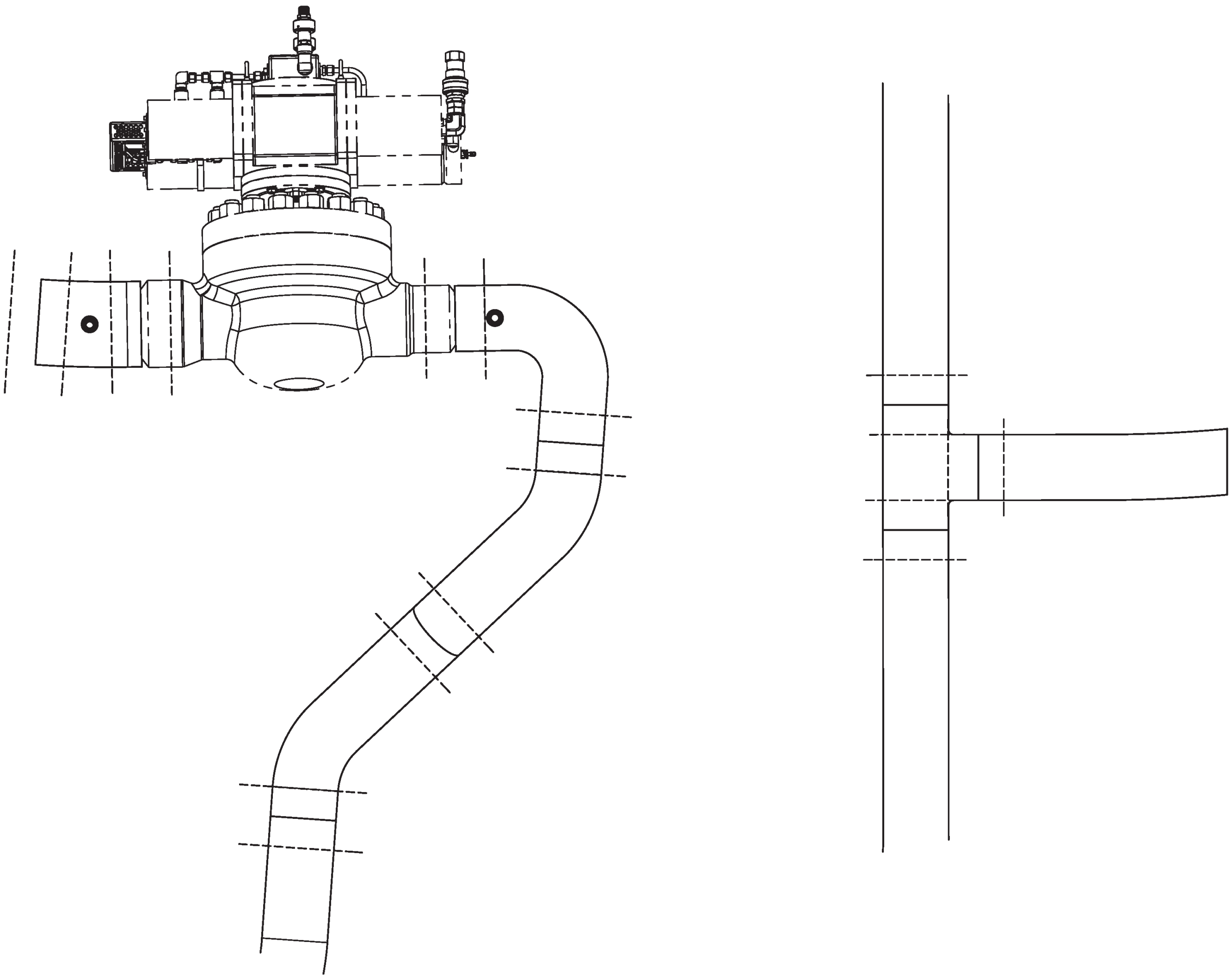

Figure A-7 Custom fittings to allow for volumetric examinations – Left: custom elbows, Right: custom tee – dashed lines represent a distance of 4t from the weld

Appendix B. Dynamic Amplification and Potential for Resonance

B.1 Background

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[13] {{

}}$^{2(a),(c)}$

B.2 Necessary Conditions for Resonance

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}}$^{2(a),(c)}$

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}}$^{2(a),(c)}$

B.3 Susceptibility to Dynamic Amplification and Resonance

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B.3.1.1 Flat surface within 7.5 diameters

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Table B-2 Range of potential resonance region

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}}$^{2(a),(c)}$

B.3.1.2 Mach Number > 0.7

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}}$^{2(a),(c)}$

B.3.1.3 Phase Difference Integer Multiple of 2π

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}}$^{2(a),(c)}$

Table B-3 Wavelengths of downstream propagating waves

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B.3.1.4 Speed of Upstream Propagating Waves

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}}$^{2(a),(c)}$

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[14] {{ }}$^{2(a),(c)}$

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}}$^{2(a),(c)}$

B.3.1.5 Period Set by Wave Speed and Distance between Nozzle and Plate

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}}$^{2(a),(c)}$

B.3.1.6 Thin Shear Layer Near the Nozzle Lip

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}}2(a),(c)

B.3.1.7 Large Coherent Structures Play Main Role in Feedback

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B.3.1.8 Dynamic Loading As Much As 50 Percent Higher Than Non-resonant Jet

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}}2(a),(c)

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}}2(a),(c)

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B.3.1.9 Jet Must Be Axisymmetric

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B.3.1.10 Jet Axis Normal to Impingement Surface

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B.3.1.11 Addition of Moisture

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B.4 Summary

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B.5 References

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Appendix C. Pipe Whip

This appendix provides the detailed methodology for pipe whip evaluation and results of the evaluations of pipe whip in the CNV and RXB. The methodology includes determination of whether a pipe has sufficient energy to whip, whether a whipping pipe can actually contact a safety-significant target, whether the target is sufficiently robust to withstand the impact, and the consequences of an impact should the previous steps not obviate the possibility of damage.

The thrust force caused by the release of fluid from a circumferential break of a high-energy piping system may result in pipe whip, causing the piping to rotate about a plastic hinge point (e.g., pipe restraint, pipe anchor point) and possibly impact nearby SSC.

Inside the CNV, the largest pipe size subject to HELB conditions is NPS 2, and target SSC are robust (i.e., RVVs). Other pipe sizes above NPS 2 have been qualified for LBB inside the CNV.

Within the NPM bay, piping is designed to satisfy the criteria of BTP 3-4 to conclude that no breaks occur and does not need to be evaluated for whip. In the RXB outside the bioshield, MSS, FWS, and CVCS lines are subject to a postulated HELB.

C.1 Considerations for Evaluating Pipe Whip

As noted in Section 3.9.5, the following considerations apply to evaluation of pipe whip:

- For piping meeting the criteria of break exclusion or LBB, pipe whip is not considered because dynamic effects of ruptures are excluded.
- If the end is a RPV or CNV safe end, it does not whip because the nozzle/safe end is short, stiff, straight, and restrained by the component.
- In accordance with SRP Section 3.6.2, a pipe struck by another pipe of equal or smaller diameter and schedule (i.e., wall thickness) does not break or crack. In the CNV where HELBs are limited to NPS 2 Schedule 160 pipe, the RPV, CNV, ECCS valve bodies, and CRDMs are equivalent to larger, thicker walled pipe and, therefore, do not crack or break. This is discussed further in Section C.2.
- Where pipe ruptures are postulated to occur, the distance is determined from the break location to the nearest restraint that limits range or direction of pipe whip.
- The jet thrust necessary to cause pipe whip is determined. The calculation of thrust and jet impingement forces consider no line restrictions (e.g., a flow limiter) between the pressure source and break location, but does consider the absence of energy reservoirs, as applicable (e.g., the degasification pipe in the CNV is normally isolated).
- If the jet thrust is insufficient to damage/deform the pipe, then pipe whip at that break location is eliminated from further consideration, although jet impingement is still evaluated.

- Pipe whip is considered to result in unrestrained motion of the pipe along a path governed by the hinge mechanism and the direction of the vector thrust of the break force. A maximum of a 90-degree rotation may take place about any hinge. Pipe whip occurs in the plane defined by the piping geometry and configuration and in the direction of the jet reaction, as identified in BTP 3-3.

C.2 Pipe Whip Impact Inside the Containment Vessel

Section 3.5.1.1 discusses the barriers presented by the RPV, CNV, and CRDMs. These, in addition to the ECCS main valve bodies, are robust structures with equivalent wall thicknesses considerably in excess of the NPS 2 Schedule 160 pipe that may whip inside the CNV. Similar to Table 3-5, Table C-1 provides a comparison of the safety-related and essential SSC size and wall thickness to those of the potentially whipping pipe. Figure C-1 is a visual representation of the information provided in the table.

Table C-1 Comparison of sizes of whipping pipe to potential targets for high-energy line breaks in the containment vessel

Component	Pipe Size	Outer Diameter (in.)	Wall Thickness (in.)
Whipping pipe			
RCS lines	NPS 2 Schedule 160	{{	
SSC			
CNV	N/A		
RPV	N/A		
CRDM latch housing lower section	N/A		
ECCS main valve body	N/A		}}2(a),(c)

[a] without cladding
[b] varies with vertical location; minimum value in range of pipe break locations shown
[c] minimum in RXB areas containing high-energy piping within range of a whipping pipe
[d] scaled from drawing

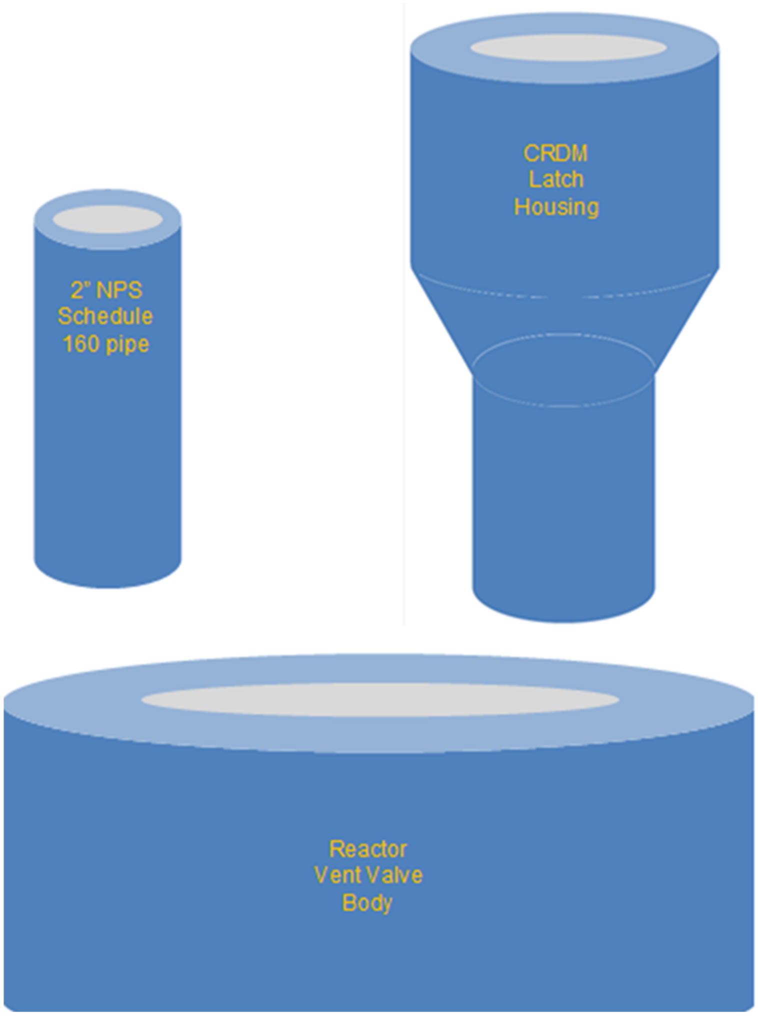

Figure C-1 Visual scale comparison of NPS 2 Sch. 160 pipe to SSC wall thickness

In view of the SRP 3.6.2 provision for impact of a pipe on like-size or larger pipe, the RPV, CNV, CRDMs, and ECCS valve bodies experience neither rupture nor crack if struck by a whipping NPS 2 Schedule 160 pipe in the CNV. Because of the large disparity in the thickness of the walls, much of the whipping pipe kinetic energy would be absorbed in crushing of the pipe itself. Regardless, functionality of components with moving parts (i.e., CRDMs and ECCS valves) following impact must still be addressed.

Postulated break locations are at the RPV (head for spray and degasification lines and side wall for injection and discharge lines), the CNV wall (for the DHRS condensate return lines) and the CNV head (spray, degas, injection, and discharge lines).

C.2.1 Breaks at Reactor Pressure Vessel

Only terminal end breaks for the NPS 2 RCS piping are postulated. The degasification line does not whip for a break at the RPV head because the isolated line is filled with steam that immediately depressurizes as the break begins to open. For the spray line breaks at the RPV head:

- Reactor vent valves – pressurizer spray line breaks at the RPV head do not result in pipe impact on an RVV because of the direction of pipe motion and intervening barriers. The two branches of the spray line are close to symmetrical. The image on the left side (a) of Figure C-2 shows the arrangement on one side with the spray line shaded grey. If a break were to occur at the safe end-to-pipe weld, the jet thrust force pushes the pipe up and away from the only nearby RVV (dashed blue box). Further, breaks at the other safe-end to piping welds are blocked by the barrier presented by the CRDMs. Even should an RVV be within range of pipe whip, the RVV functionality is not impaired:

    - The center-to-center spacing of RPV head penetrations for RVVs to potentially whipping pipes is at most 19 inches, but the RVVs are about 12 inches in diameter and the pipe is 2.375 inches outer diameter, reducing the separation to less than 12 inches. In this short distance, the whipping pipe gains only a small amount of kinetic energy.

    - Reactor vent valves in the closed position are held shut by primary pressure, with discs not free to move. The valves are qualified to be functional following seismic accelerations.

    - Less sturdy components on the outside of the RVV are the IAB and the position indicator housing. The IAB is out of reach of an RCS line whip because it is underneath the main valve body. If the position indicator housing were to be dislodged, the indicator stem might be broken off. This would eliminate indication (not a safety-related function) and might slightly increase frictional resistance to opening if the stem stub rubbed when the disc opened, but ECCS performance is not dependent on the speed of valve opening.

    - The trip/reset line runs from the IAB to the CNV wall. If in range, a whipping pipe could pass through the trip/reset line, which is small diameter tubing. If the line is severed, it is equivalent to opening the trip valve: the RVV opens once RCS pressure drops below the IAB setpoint. The only concern is if the trip/reset line crimped completely shut on the valve side, preventing depressurization of the main valve control chamber. Crimping could only occur if the whipping pipe uniformly slammed the trip/reset line against a smooth surface, and is unlikely even then. Given the direction of motion of pipe whip at the RPV head, the tubing would break apart rather than crimp.

  Therefore, pipe whip on the RVVs does not impair RVV functionality.

  - Reactor recirculation valves – the RRVs are located out of range of the injection and discharge line terminal ends. The image (b) on the right side of Figure C-2 shows the separation of the discharge line (light blue rectangle) from the closest RRV (dashed blue square). The injection line to RRV separation is similar. As discussed for the RVVs, if the whipping pipe impacts a trip/reset line, it is equivalent to opening the trip valve which is acceptable as the RRV would still perform its safety function. Thus, an injection or discharge line break does not impact an RRV.

- Control rod drive mechanisms – Referring to the left side (a) of Figure C-2, the pressurizer spray lines have an insufficient L_h (refer to Figure C-4) to whip towards the CRDMs. Even if the pipe were to move through the nearest support (yellow dashed circle), the motion of the spray line (green arrow) is almost parallel to the CRDMs and if contact were to occur the impact is limited to a glancing blow. Also, the whipping pipe gains only a small amount of kinetic energy. If any impact were to occur, it would be on the coil assembly surrounding the upper latch housing, so that negligible energy is transmitted into the CRDM internals. In view that the CRDMs are qualified to function after exposure to seismic accelerations, scram functionality is not impaired by pipe whip impact.

C.2.1.1 Breaks at Containment Vessel

Pipe whip for postulated breaks at the RCS-connected line safe ends on the inner CNV head also does not result in impact on essential or safety-related SSC, other than the CNV. The only target SSC to be evaluated are I&C cables passing through CNV head penetrations and the tops of the CRDMs. Figure C-3 shows three of the break locations (yellow boxes) on the interior of the CNV head in two cross-section views: the injection line in Figure C-3(a), and the pressurizer spray (left) and degasification line (right) in Figure C-3(b). Again, the nearest pipe whip restraint locations are shown in dashed yellow circles.

In Figure C-3(a), the injection line could move downward and pivot either toward or away from the CNV wall, depending on which bend(s) yields. The separation between the centerlines of the break and the nearest I&C penetration is 20 inches. However, per Section C.4.1, the pipe does not whip, because the long straight length extending downward from the break location (i.e., L = 37.9 inches[16]) results in the need for an L_h of 38.2 inches, compared to an actual L_h of less than 30.8 inches.

Figure C-3(b) shows the pressurizer spray and degasification lines. Neither line is expected to whip as they both have an insufficiently long L_h when their nearest restraints are taken into account. Therefore, neither of these postulated breaks result in contact with cabling or the rod travel housings atop the CRDMs.

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[16] The lengths noted for the end segments exclude the 4.5 inches for the previous location of the RCS check and excess flow check valves, so that they are conservative after relocation of the valves to outside the CNV. Also, the determination of whether a pipe whips was done at a consistent temperature and pressure (543-degrees Fahrenheit and 1893 psia); variations in temperature and pressure with break location would have small effects on material properties and on thrust force, but conclusions would not change.

The remaining postulated break is the discharge line. Like the injection line, the pipe end moves downward and pivots either toward or away from the CNV wall. The (L = 19.59 inch) piece at the end results in the need for an L_h of at least 29.7 inches. This is an underestimate because there are two pipe bends, both of which absorb energy between the break and support. Whether or not the pipe whips, the 19.59 inch long end piece is too short to impact the nearest I&C cable.

As for the DHRS end breaks, the pipe segments are in the annulus between the CNV and RPV and are at an elevation separated from the RRVs so as to be out of range of the main valve bodies, although they could sever a trip/reset line, which is acceptable as discussed in Section 4.3.1. The separation is also sufficient to preclude DHRS pipe whip from reaching the SGS thermal relief valves.

For the locations discussed, pipe whip impact due to potential HELBs in the CNV does not adversely affect the integrity or functionality of safety-related and essential SSC, and further evaluation of pipe whip impact loads at those locations is not needed.

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}}$^{2(a),(c),ECI}$

Figure C-2 Separation of Reactor Coolant system line terminal ends from emergency core cooling system valves

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}}$^{2(a),(c),ECI}$

Figure C-3 Reactor Coolant system breaks on underside of containment vessel head

C.3 Pipe Whip Impact in the Reactor Building

Ruptures in the NPM bay are excluded. The RXB structural integrity and, in particular, the integrity of the pool wall must be assessed, so pipe whip impact force on concrete surfaces is determined.

The safety-related or essential components potentially within whip range elsewhere in the RXB are the CIV HPU skids, CVCS demineralized water make-up valves, and the building structure itself. As noted in Section 3.2.6, impact on a skid causes CIVs and DHRS actuation valves to move (or stay) in the safe position, and impact on the make-up valves is acceptable. However, the RXB structural integrity and, in particular, the integrity of the pool wall must be assessed, so pipe whip impact force on concrete surfaces is determined.

C.4 Simplified Solution of Pipe Whip Impact Velocity

Figure C-4 shows a piping system of two mass segments, m_1 and m_2 (lower case used to differentiate from moment), and a thrust load applied at the break location immediately after rupture, depicted by position “A.” The thrust load causes a bending moment over the length of piping, where a plastic hinge forms allowing the pipe segment to rotate at an angular velocity, ω (rad/sec) and traverse a path, δ, as depicted by position “B.”

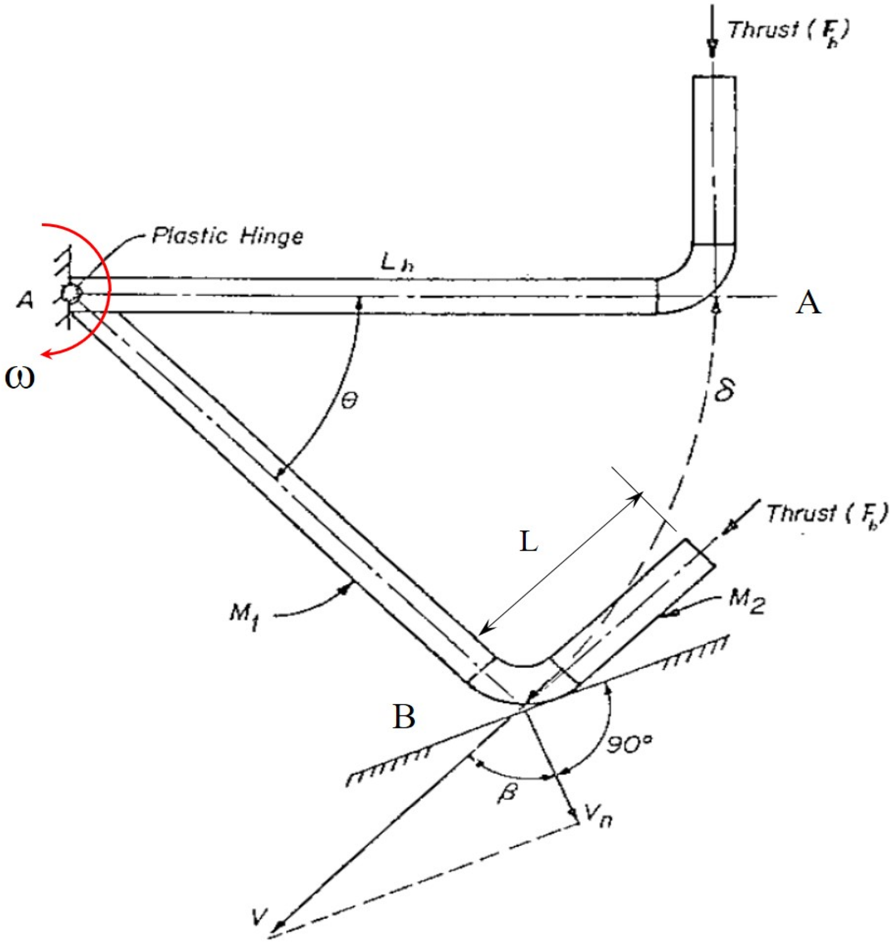

Figure C-4 Pipe whip example

After break-opening, the steady-state jet thrust force, F_b, is (see Section 3.9.4):

$$F_b = C_T P_o A_e \qquad \text{Eq. C-1}$$

where,

F_b = Steady state thrust force at the break (lbf),
C_T = Thrust coefficient (unitless),
P_o = Internal system pressure (psia)[17], and
A_e = Pipe flow area (inches^2).

As identified in Section 3.9.4.1, the thrust coefficients are:

$$C_T = 1.26 \text{ (Saturated or superheated steam)}$$

$$C_T = 2.0 \text{ (Non-flashing water jets)}$$

The hinge is formed at a distance, L_h ,from the break, resulting in a plastic moment defined by:

$$L_h = \frac{M_p}{F_b} \qquad \text{Eq. C-2}$$

where,

L_h = Distance from hinge point to pipe as shown in Figure C-4, and
M_p = Bending moment.

The above form is commonly used in static analyses, yet neglects any influence of pipe length from the break to the first elbow, as well as restraint effects. It allows for an estimation of the minimum unrestrained length of pipe that causes the formation of a plastic hinge but leads to short hinge lengths. A more accurate formulation for the hinge length often used in restraint design, based on energy balance (Reference C.7.1) assumes the possibility of an additional length of piping, L, located perpendicular to rotational motion (Figure C-4, portion of piping labeled m_2):

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[17] SRP 3.6.2 stipulates that the initial condition used should be the one with the greater of the contained energy at hot standby or at 102% power. For the NuScale design, "hot shutdown" is the equivalent of hot standby and is a lower energy state. See Section 3.4.

$$L_h = \frac{3M_p}{2F_b}\left(1 + \sqrt{1 + \frac{8LF_b}{3M_p}}\right) \qquad \text{Eq. C-3}$$

Nonetheless, if there is no additional length of piping, i.e., setting *L* = 0, the hinge length equation reduces to:

$$L_h = \frac{3M_p}{F_b} \qquad \text{Eq. C-4}$$

Here, the plastic bending moment, assuming small deformations, are taken as:

$$M_p = S_y Z_p \qquad \text{Eq. C-5}$$

where

S_y = Yield strength of pipe, and

Z_p = Plastic bending section modulus, which is given by

$$Z_p = \frac{4}{3}\left(r_o^3 - r_i^3\right) \qquad \text{Eq. C-6}$$

where

r_o = pipe outer radius, and

r_i = pipe inner radius.

If large deformation is assumed, which includes strain hardening behavior of the material, an approximation to the plastic bending moment capacity is given as:

$$M_p = S_y Z_p + \left(S_u - S_y\right) Z_e \qquad \text{Eq. C-7}$$

where

$S_u =$ Ultimate strength of pipe, and

$Z_e =$ Elastic bending section modulus, which is given by

$$Z_e = \frac{\pi}{4r_o}\left(r_o^4 - r_i^4\right) \qquad \text{Eq. C-8}$$

In solving the pipe whip problem, work-energy principles are applied to the model of Figure C-4, while noting that position “A” depicts the piping system immediately after rupture and just before any motion takes place, and position “B” depicts when impact occurs with a target. Therefore, the kinetic energy at position A plus the work done in going from A to B, is equal to the kinetic energy at position B.

The effective mass of the system and associated kinetic energy are generally derived from dynamic principles (References C.7.1 and C.7.4) as:

$$m_{eff} = \frac{m_1}{3} + m_2 \qquad \text{Eq. C-9}$$

$$\left(KE\right)_A + W_{A-B} = \left(KE\right)_B \qquad \text{Eq. C-10}$$

Where the work is defined as the thrust force over the distance traversed minus the plastic moment resistance:

$$W_{A-B} = F_b\delta - M_p\theta \qquad \text{Eq. C-11}$$

where

θ = the angle through which the pipe whips.

The kinetic energy of the whipping pipe about the hinge point is based on rotational kinematics (see Figure C-5 and Figure C-6):

$$\left(KE\right)_B = \frac{1}{2} I_h \omega^2 \qquad \text{Eq. C-12}$$

where

$\omega =$ Angular velocity, and
$I_h =$ Mass moment of inertia about hinge-point.

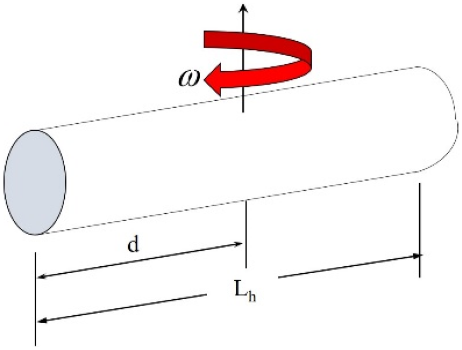

Figure C-5 Mass moment of inertia about centroidal axis

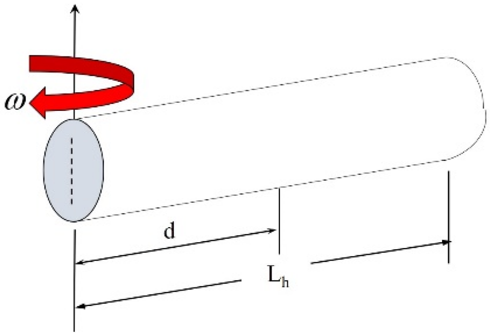

Figure C-6 Mass moment of inertia about hinge location.

The rotational mass moment of inertia, I_h, of a tubular pipe section about the hinge-point is found from the parallel-axis theorem. At the centroidal axis of the pipe, the mass moment of inertia is:

$$I_h = I_o + m_{eff} d^2 \qquad \text{Eq. C-13}$$

where

$$I_o = m_{eff}\left(\frac{1}{4}R^2 + \frac{1}{12}L_h^2\right) \qquad \text{Eq. C-14}$$

$$d = \frac{L_h}{2} \qquad \text{Eq. C-15}$$

Then, substituting

$$I_h = m_{eff}\left(\frac{1}{4}R^2 + \frac{1}{3}L_h^2\right) \qquad \text{Eq. C-16}$$

The work-energy equation can be re-written and solved for the tangential linear velocity at the point of impact:

$$F_b\delta - M_p\theta = \frac{1}{2} I_h \omega^2 \qquad \text{Eq. C-17}$$

$$F_b\delta - M_p\theta = \frac{1}{2} I_h \left(\frac{V_t}{L_h}\right)^2 \qquad \text{Eq. C-18}$$

Solving for the pipe velocity at impact:

$$V_t = L_h \left[\frac{2}{I_h}\left(F_b\delta - M_p\theta\right)\right]^{1/2} \qquad \text{Eq. C-19}$$

C.4.1 Screening for Onset of Pipe Whip

The ability to cause a pipe whip is dependent on the thrust and distance to the plastic hinge point. Like a lever, a smaller force is needed when applied at a longer distance. Because the thrust force F_b is specific to the system pressure and break flow area, each break type (e.g., chemical and volume control system, main steam system) has a minimum L_h that is necessary to initiate pipe whip.

From Eq. C-4, the minimum distance L_h for the thrust force to overcome the pipe resistance to bending can be determined. Alternatively, if there is a substantial length of pipe at the end of the whipping segment, then Eq. C-3 applies. Resulting values for 304 stainless steel at operating temperature are shown in the table below:

Table C-2 Maximum hinge length L_h to avoid pipe whip

System	L_h (feet) from Eq. C-4	L_h (feet) from Eq. C-3 for L = 5*OD[18]
CVCS	1.1	2.1
MSS	9.2	21.4

Thus, if the distance from the break exit axis to the plastic hinge axis in the plane of rotation is less than the values shown in the table above, then the pipe does not whip. For the MSS pipe in the RXB, this information cannot be used for screening at this time because

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[18] Reference 1.4.3.2 Subarticle NC-3642.1 identifies requirements for bend radius from three to six piping diameters. Five piping diameters (5D) are used as an example for an area such as the pipe gallery where tight radius bends are not needed to provide a compact layout. Because a pipe restraint is usually not placed on a curved piping segment, the bend radius is a likely minimum segment L on the end of the pipe.

pipe arrangements are not finalized, but it could be used to inform the placement of pipe whip restraints in the future.

C.4.2 Maximum Impact Force

The maximum dynamic impact force on a potential structure, system, or component target is estimated from the tangential pipe velocity by equating the kinetic energy at impact with the potential energy of the target in compression, such that:

$$\frac{1}{2} m_{eff} V_t^2 = \frac{1}{2} K_{SCC} x_{\max}^2 \qquad \text{Eq. C-20}$$

where,

$x_{\max}$ = Maximum compression of impacted spring, and
K_{SSC} = Stiffness of structure, system, or component.

Solving for $x_{\max}$:

$$x_{\max} = V_t \sqrt{\frac{m_{eff}}{K_{SCC}}} \qquad \text{Eq. C-21}$$

Therefore, the maximum spring force is merely

$$F_i = K_{SCC} x_{\max} \qquad \text{Eq. C-22}$$

Simplifying terms, results in a maximum impact force of:

$$F_i = V_t \sqrt{m_{eff} K_{SSC}} \qquad \text{Eq. C-23}$$

The above estimation is conservative because it does not consider the material's plastic deformation, crushing, gaps or strain-rate effects. Additionally, the stiffness estimation is based purely on elastic motion, which tends to overpredict the impact force.

C.4.3 Impact on Concrete Wall

A steam line pipe whip event within the pipe gallery is capable of applying a large impact force to the concrete wall. Treating the reinforced concrete wall as a spring in compression, as described in the prior section, is not an acceptable method for evaluating concrete and overpredicts impact loads generated. Concrete penetration equations developed via empirical relationships provide a means of estimating damage based on an impact velocity.

The Sandia formula developed by Young in SAND 97-2426 (Reference C.7.5) is an empirical representation taking the form for the depth of penetration, *D* as:

$$D = 0.00178 K_h S N \left(\frac{W}{A} \right)^{0.7} (V - 100) \text{ for } \quad V \geq 200 \text{ ft/s} \qquad \text{Eq. C-24}$$

where,

$K_h =$ Mass scaling term for hard targets (use 1.0) (unitless),
$S =$ Penetrability index (unitless),
$N =$ Nose performance coefficient (unitless),
$W =$ Weight of penetrator (lbm),
$A =$ Cross-sectional area (inches^2), and
$V =$ Impact velocity (ft/sec).

The nose performance coefficient and penetrability index are:

$$N = 0.18 \frac{L_n}{d} + 0.56 \quad \text{for tangent ogives} \qquad \text{Eq. C-25}$$

$$N = 0.25 \frac{L_n}{d} + 0.56 \quad \text{for conic shapes} \qquad \text{Eq. C-26}$$

where,

$L_N =$ Length of penetrator nose (in.), and
$d =$ Penetrator diameter (in.)

$$S = 0.085 K_e (11 - P)(t_c T_c)^{-0.06} \left(\frac{5000}{f_c^{'}} \right)^{0.3} \qquad \text{Eq. C-27}$$

where,

$P =$ Volumetric percent rebar in concrete (~2 percent),
$t_c =$ Cure time of concrete (if greater than one year, use 1.0),
$T_c =$ Target thickness in penetrator diameters or caliber, and
$f_c^{'} =$ Unconfined compressive strength at 28 days (psi).

$$K_e = \left(\frac{F}{W_1} \right)^{0.3} \qquad \text{Eq. C-28}$$

where,

$W_1 =$ Target width in penetrator calibers (unitless), and
$F = 20$ for reinforced concrete (unitless).

A concern with a high-energy impact on a concrete wall is spalling, which is the dislodgement of concrete on the far side. Spalling occurs when the impact generates a compression wave that, in turn, causes a tension wave that exceeds the compressive strength of the concrete. According to Reference C.7.8, the spalling depth typically does not exceed the reinforcement depth. The National Defense Research Council formula (Reference C.7.8) for spalling is:

$$h_s = 2.12 * d + 1.36 * D \qquad \text{Eq. C-29}$$

where

h_s = Necessary concrete thickness to prevent spalling.

Work has been performed over the years to characterize damage to nuclear plant and other reinforced concrete structures. McLean, et al. in NBSIR 86-338 (Reference C.7.6) state:

> “The investigations found that the high velocity impact of a missile on a reinforced concrete slab or shell was a localized phenomenon as large deformations and damage occurred only in the immediate zone of the impact.”

Based on this observation, localized penetration and spalling do not adversely affect the structural capability of the RXB. Penetration and spalling should be avoided in regard to the pool walls.

Section C.6 provides an example problem of pipe whip for an NPS 12 piping system within the pipe gallery. The target is a reinforced concrete wall, and the maximum depth of penetration is determined.

C.5 Reactor Building Piping Arrangements

The piping arrangements in the RXB outside the bioshield are not yet finalized, and the final piping analysis is a COL item. Figure C-7 shows a notional layout for MSS (bright green) and FWS (pale green) piping and some surrounding systems. Two major structural walls are shown running the full width of the figure (slightly transparent lavender): the pool wall is 5 feet thick, the RXB outer wall is 5 feet thick, and the floor is 3 feet thick.

The gallery is congested and much of the MSS piping is in the same plane. It is likely that a main steam system HELB pipe whip impacts another pipe, but indeterminate if it has sufficient length to strike either of the walls.

As noted previously, SRP Section 3.6.2 states that a whipping pipe does not cause a break or crack if it hits a pipe of equal or larger diameter and thickness. On this basis, an MSS pipe whip can be assumed to rupture a NPS 4 bypass or NPS 8 FWS line in the pipe gallery. The combination of an MSS rupture with a resultant bypass rupture has the bounding M&E release.

{{

}}$^{2(a),(c)}$

Figure C-7 Potential high-energy line break locations in pipe gallery

C.6 Bounding Main Steam System Pipe Whip

This section shows the calculational steps necessary to determine the dynamic impact force of pipe whip on a reinforced concrete wall. Assume that a NPS 12 main steam line ruptures creating a HELB in a pipe gallery near the NPM bay wall. The MSS piping in this area is schedule 80 made of SA-335 P11 material. The hinge length L_h of 20 feet is selected to bound expected arrangements, based on the available space in the pipe gallery. The jet thrust reaction force is sufficient to create a plastic hinge, allowing the pipe to whip. The assumed rotation of the pipe extends over a 30-degree sector, i.e., $\theta = 30$ degrees (refer to Figure C-4).

Table C-3 shows how the information in this appendix is used to determine the speed of the whipping MSS pipe section. In turn, this speed is used to find the depth of penetration into an RXB concrete wall. Finally, the necessary thickness of the concrete wall to avoid spalling is determined. Even if spalling did occur, the loss of concrete would be limited in area and in depth, having a minor effect on the structural capability of the structure.

Table C-3 Example of simplified pipe whip analysis

SIMPLIFIED PIPE WHIP ANALYSIS

	Hinge Length	Whip Angle	Impact Velocity	Penetration tion Depth	Spall Limit
	L_h	θ	V_t	D	h_s
MSS Pipe HELB *NPS 12 Schedule 80 in RXB*	(in)	(deg)	(ft/sec)	(in)	(in)
	240	30	377	6.7	36.1

Pipe Dimensions and Properties

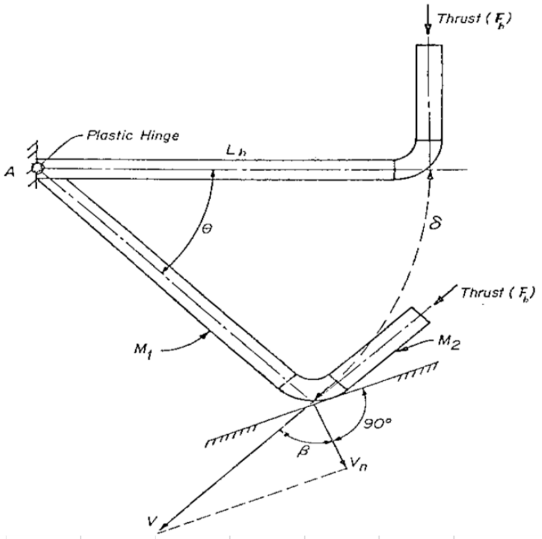
NPS	Sch	OD	ID	Z_p	Z_e	A	I_o	I_h	S_y	S_u	γ	g
		(in)	(in)	(in^3)	(in^3)	(in^2)	($lb\text{-}in^2\text{-}sec^2/in$)	($lb\text{-}in^2\text{-}sec^2/in$)	(ksi)	(ksi)	(lb/in^3)	(in/sec^2)
12	80	12.75	11.376	100.1	74.5	26.04	7,577	30,260	23.635	60	0.29	386.09
	t_w	r_o	r_i			Note c						
	(in)	(in)	(in)									
	0.687	6.375	5.688									

Material strength from 2013 ASME B&PVC Section II, Vol. D:
Pp 496-497, Table U, Row 22: $S_u(500)$ = 60.0 ksi $S_u(600)$ = 60.0 ksi
Pg 598-601, Table Y-1, Row 31: $S_y(500)$= 24.4 ksi $S_y(600)$ = 23.5 ksi
Properties used interpolated.

Pipe and Water Weight			**System Initial Conditions**			**Plastic Bending Moment**	
Metal	Steam	Total	P	T	Steam Density	M_{p1}	M_{p2}
(lbm)	(lbm)	(lbm)	psi	°F	(lb/ft^3)	(in-kip)	(in-kip)
1812	12	1824	500	585	0.8806	2,365	5,075
					Note b		

Thrust Force	**Hinge Length**	**Effective Weight**	**Effective Mass**		**Bending Moment from Thrust**
F_b	L_h		m_{eff}		M_T
(kip)	(in)	(lb)	($lb\text{-}sec^2/in$)	($kip\text{-}sec^2/in$)	(in-kip)
64.03	240	608.16	1.575	0.00158	15,368
	Note a				

Distance Traversed by Pipe		**Work Accomplished**	**Impact Velocity**	
θ	$\delta = \theta L_h$	($F_b\delta$-$M_p\theta$)	V_t	
(deg)	(in)	(in-kip)	(in/sec)	(ft/sec)
30	125.66	5,389	4530	**377.5**
Note e				



NOTES:
Tan shaded cells are input.
Green shaded cells are results.
a) Piping arrangements in RXB are not finalized. Based on NP12-00-F010-1697, the pipe gallery width is less than 30 feet. Given that there are components and bends, 20 feet is judged to bound the length between restraints
b) From steam tables
c) Metal cross-section area (i.e., A_o - A_i)
d) Based on NP12-00-F010-1697, the pool walls are 60 in. thick, the outer building wall of the pipe gallery is 60 inches thick, and the floor and ceiling are 36 in. thick.
e) 90° is upper limit because most pipes are perpendicular to any RXB structural surface that they might strike if not stopped sooner by intervening pipe.

The results show an impact velocity of ~377 ft/sec for the 12-inch MS line. The impact velocity is applied to a reinforced concrete target through an elbow geometry that is similar to an ogive shape. Again, this result is conservative yet provides a simple way to bound the potential penetration depth, which is calculated to be 6.7 inches in the example.

Results show that the NPS 12 main steam line does not penetrate the reinforced concrete wall, as summarized in Table C-4. For the 60-inch thick concrete pool wall, the maximum depth (20 foot pipe length whip through an angle of 90 degrees) represents approximately 22 percent of the overall wall thickness (37 percent for a 36-inch thick floor or ceiling). No spalling occurs for the 60-inch thick structural walls.

Table C-4 Reactor building wall penetration depth (inches) for main steam system pipe whip impact

Length of Pipe Segment	Angle through which Segment Whips		
L (ft)	θ = 30˚	θ = 60˚	θ = 90˚
10	2.5	4.2	5.4
15	4.8	7.7	9.8
20	6.7	10.5	13.4

C.7 References

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Appendix D. Subcompartment Pressurization

NRC regulations and guidance identify the need to evaluate the effects of subcompartment pressurization caused by the mass and energy release from HELBs. The pressurization effects of interest are the pressure and temperature conditions needed for environmental qualification (EQ) to demonstrate functionality of safety-related components and the pressure loads on safety-related SSCs.

A HELB suddenly releases a large amount of mass and energy into its surroundings. As noted in Section 3.9.2, the small scale of the NuScale plant involves about $^1/_{27}{}^{th}$ the energy release of a large PWR for a main steam line rupture. Even so, the mass and energy release can cause a substantial increase in pressure and temperature in a surrounding subcompartment.

As discussed in Section 2.1, postulated HELBs are evaluated in three discrete areas of the plant because of differences of the potential piping hazard and the surrounding environment.

- In the CNV – as identified in Section 3.4, HELBs are limited to circumferential breaks of NPS 2 lines. Even for a double-ended blowdown, CNV pressurization is less limiting than for initiation of the ECCS, which is a design condition. Therefore, further analysis is not required.
- In the NPM Bay under the Bioshield – as identified in Section 3.5.2.5, only nonmechanistic breaks of MSS and FWS piping and leakage cracks of CVCS, MSS, and FWS piping need be evaluated. Because of the larger mass and energy release, MSS nonmechanistic breaks are limiting. These are equivalent to a 12 in^2 opening, as described in Section 3.5.2.5.
- In the RXB – different high energy systems are present in different areas of the RXB.
    - In the pipe galleries, where MSS and FWS piping is routed, a MSS break is limiting. To account for the possibility of a MSS pipe whip impacting and breaking the smaller NPS 4 bypass line in another header, the blowdown is based on a double-ended MSS break and a single ended bypass break. Note that COL Item 3.6-1 requires evaluation of multi-module effects, but that this subcompartment pressurization analysis ensures that the RXB is structurally adequate even if a neighboring module bypass line were breached in a beyond design basis scenario.
    - The CVCS piping is enclosed in a pipe chase from the NPM Bay (100 foot elevation) down to the ceiling of the 62 foot elevation. A rupture of a CVCS line in the pipe chase is enclosed in a small volume. CVCS piping is also present on the 50 and 24 foot elevations.
    - The ABS high pressure lines are evaluated only for leakage cracks, based on limited time of use (see Section 3.3.10).

D.1 Severity Factors

The subcompartment pressurization transient is basically a mass and energy balance between what is discharged from the HELB and what is vented and condensed from the subcompartment. Factors affecting the severity of subcompartment pressurization are:

- Break flow rate – this is a function of the size of the break, the pressure differential between the intact system and the ambient, and the discharge coefficient. Break flow rate is maximized by conservative assumptions on discharge coefficient, initial system pressure, etc. In some cases, a lower break flow is more limiting because it extends the duration of the pressure and temperature transient even though at a somewhat lower peak.
- Energy release – in addition to break flow, energy release depends on the temperature of the fluid blowdown and its phase.
- Break flow duration – if the flow rate is assumed to persist (e.g., a large upstream reservoir is present), subcompartment pressure rises to a higher value and is sustained there.
- Surrounding subcompartment characteristics – these include:
    - Ambient temperature – has competing effects that must be evaluated.
    - Ambient pressure – a large contributor to heating is compression of the ambient atmosphere, such that higher ambient pressure generally results in higher peak pressure even though the smaller pressure differential slightly slows break flow.
    - Humidity – lower humidity results in higher peak pressure because the heat capacity of the water vapor absorbs energy that would otherwise increase pressure.
    - Volume – larger volume can absorb a given amount of mass and energy with a lower rise in pressure.
    - Surface area – a large surface area (e.g., walls, equipment) with an initially cool temperature serves to lessen the rate of pressure rise by initially condensing some of the released vapor.
    - Heat capacity – if there is a heat sink with substantial capacity and a good heat transfer coefficient, considerable vapor may be condensed, suppressing the pressure rise. This is what the CNV is designed to do. For other regions of the plant, heat transfer is not fast enough to be effective in reducing pressure.
- Venting – if the blowdown from the break has an escape path, mass and energy loss out the vent will equilibrate with the break flow. This is the NuScale design feature that is used to limit the pressurization transient. Venting is through dedicated normally open or blowout paths and does not rely on the reactor building ventilation system.

  - Flow resistance: higher vent flow lowers the subcompartment pressure and temperature. Flow resistance can be reduced with a larger flow area and shorter vent path.

  - Vent initiation pressure: if the vent path is normally closed off by a safety-related blowout panel or similar device until some differential pressure is reached, the delay in initiating venting will result in a higher peak pressure.

- Protective trips – if there is a condition that is monitored to respond to indications of a HELB by closing valves, break parameters that avoid initiating the trip may be most limiting.

D.2 Acceptance Criteria

D.2.1 Under the bioshield

The bioshield consists of multiple pieces. The horizontal bioshield section is a large concrete block almost two feet thick that rests on top of the walls enclosing three sides of an NPM bay. On the side without a wall, there is a hanging vertical steel cover made of a square stainless steel tube frame which supports radiation panels. The panels are arranged to provide a zig-zag vent path for shielding against radiation streaming while still providing a passive vent path that continually vents the area under the bioshield. Therefore, in the event of a HELB, the mass and energy are vented into the large pool room volume, which in turn has a vent path to the outside of the reactor building.

The HELB has two effects requiring consideration:

- Environmental qualification – the peak pressure and temperature and their duration define the EQ envelope for essential and safety-related equipment.
- Structural – the bioshield is designed based on the weight of the horizontal and vertical components, live load during maintenance, sloshing and pressure loads, and maximum seismic based on soil-structure interaction analysis of the RXB. Peak pressure must be limited to less than 1 psi (differential from atmospheric) to maintain the bioshield components within their demonstrated capacity.

D.2.2 In the RXB

A structural limit of 3 psid applies.[19] The RXB was evaluated for load combinations involving static loads, dynamic (seismic) loads, equivalent static loads from hydrodynamic pressure inside the pool, and effects of operating thermal loads (T_0), accident thermal loads (T_a), and accident pressure loads (P_a). These loads are parts of Load Combinations 9-6 and 9-9 as defined in Section 9.2.1 of ACI 349-06 (Reference 1.4.3.17).

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[19] At 3 psid, there is margin to the structural limits, but 3 psid was selected as the limit to avoid additional analysis.

D.3 Methodology

The basic approach involved the following steps.

1. Identify postulated break locations and sizes
    a. Under the bioshield, breaks are as described in Section 3.5.2.5, with the limiting case being a 12 in^2 MSS nonmechanistic break.
    b. In the RXB, break size and location was selected to bound the effects of the final Pipe Rupture Analysis performed for the finalized piping designs.
2. Obtain conservative (high) mass and energy release from a plant NRELAP5 model
3. Develop a GOTHIC model of the affected area of the plant
4. Determine venting options to relieve pressure build up
5. Analyze pressure transient to determine peak pressure
6. If peak pressure exceeded design limit, adjust vent design and re-analyze

D.4 Vent Paths

D.4.1 Under the bioshield

Venting from under the bioshield is through the passive vent path described in Section D.2.1. The mass and energy are thereby vented into the large pool room volume, which in turn has a vent path to the outside of the building via a rupture disk that relieves building pressure at a predetermined setpoint.

D.4.2 In the RXB

The following vent paths are provided within the RXB:

- The pipe galleries vent through the wall at the 100 foot elevation to outside the RXB through blow-off panels designed to open at 0.5 psid. The external building exhaust of this path is under the protective shroud that provides protection against security threats.
- The CVCS pipes are routed from the RXB 50 foot elevation to the NPM bay via a rectangular concrete pipe chase. To prevent damage to the pipe chase and pool wall for CVCS HELBs within it, a vent with blow-out panels set at 0.5 psid is provided to the pipe galleries at the 100 foot elevation. The pipe chase is also open at the ceiling of the CVCS heat exchanger rooms on the 50 foot elevation.
- Always open paths between CVCS heat exchanger rooms distribute pressure through a larger volume. Although there are knockout panels from the heat exchanger rooms to the hallways, they do not open and are not credited for limiting room pressure.
- Although the ABS is treated as a moderate energy system based on limited operating time, pressurization caused by leakage cracks requires use of a guard pipe from the 100 foot to the 62 foot elevation to prevent steam from entering the 75 foot and 86 foot

elevations (designated as mild environments). The guard pipe has a 0.5 psid blowout panel to relieve steam from an ABS pipe leakage crack to the pipe gallery.

D.5 GOTHIC model

GOTHIC Version 8.1(QA) thermal-hydraulic analysis software package is used to evaluate subcompartment pressurization. GOTHIC (Generation of Thermal-Hydraulic Information for Containments) is an integrated, general purpose thermal-hydraulics software package for design, licensing, safety, and operating analysis of nuclear power plant containments and other confinement buildings. GOTHIC Version 8.1 is pre-verified for use.

The GOTHIC model included major RXB volumes and vent paths relevant to HELB blowdown. Each room/area of the relevant part of the RXB was modeled with separate nodes in the GOTHIC model so that environment profiles for the desired areas could be developed. The free volume of each room was calculated external to GOTHIC and entered into the “control volume parameters” table. By the nature of the large subdivided model, the specific geometry of each room (length, width and height) is not preserved, but is maintained as close to the actual as practically possible. The free volume of each room is preserved by use of blockages and porosities that are specified in the sub-volumes menu.

Flow paths were used to represent the physical connections associated with the detailed rooms and piping systems. These connections can include doors, hatches, drains, piping systems, and various ductwork. Friction in flow paths representing structural interconnections between spaces is accounted for using the forward and reverse loss coefficients for flow paths. The flow path inputs include inertia lengths, loss coefficients, compressibility options, and critical flow models. GOTHIC was set to use one of three critical flow models, depending on the thermodynamic quality of the fluid flowing through the junction: 1) subcooled – the Henry subcooled model, 2) saturated but the vapor mass fraction is less than 0.98 – Moody model, and 3) vapor mass fraction greater than 0.999 – isentropic ideal gas model (for vapor fractions between 0.98 and 0.999, the flow model results are linearly interpolated).

Conductors were included for walls, floors, and ceilings of specific rooms and vertical volumes in the areas of interest. GOTHIC computes the convective heat transfer coefficient depending on the orientation, type, and configuration of thermal conductors. To ensure a conservative HELB analysis, forced convection was turned off and the phase option was changed from vapor to split.

Components were used to model the operation of specialized equipment (e.g., blowout panels) located within a control volume or in a flow path. These components may be turned on and off, or opened and closed, by input referred to as trips. Trips may be actuated by time or by calculated parameters such as a temperature or differential pressure. Blowout panels and rupture disks were modeled as quick (1 ms) open valves with the appropriate flow areas.

Boundary conditions are used to model fluid mass and energy sources, such as HELBs. They are connected to control volumes via flow paths. Initial fluid conditions specified for each control volume include temperature, humidity, gas composition, and pressure.

Transient run parameters are specified in the time domain section (time step size, edit interval, graphics edit interval, etc.)

D.5.1 Protective trip, other mitigations, and single failures

The under the bioshield (UTB) sensor initiates reactor trip on high temperature, causing the reactor to scram and initiation of containment isolation. This is effective in detecting a nonmechanistic break under the bioshield that might not be sufficiently large to reach a system trip point. As there are two sensors, a single failure does not prevent a trip.

The MPS system senses several conditions (e.g., decreasing MSS pressure) that not only cause a reactor scram but also containment isolation. Upon containment isolation, CIVs should close within seven seconds, shutting off flow from the NPM to the break.

The MSS lines each have a single CIV (as allowed by GDC 57), which is assumed to have the single active component failure. For purposes of the MSS nonmechanistic breaks and leakage cracks under the bioshield, no isolation is assumed. For MSS HELBs in the RXB, blowdown should still be terminated by the MSS isolation valve, which is non-safety related but qualified for the HELB environment in the pipe gallery. The other end of the broken pipe would discharge reverse flow from the lines to the turbines. For conservatism, the subcompartment pressurization analysis assumes continuing steam flow from both ends of the break.

For FWS ruptures, even though there is a single FWS CIV, the in line check valve promptly shuts off reverse flow from the NPM. Forward flow would be terminated by either or both of a feedwater pump trip and a FWS regulating valve (FRV) closure. One case under the bioshield is analyzed assuming the FRV fails to shut, and another assumes neither the CIV nor the check valve stop reverse flow.

For CVCS breaks and leakage cracks, the dual series CIVs should close and/or the in-series (excess flow) check valves would terminate flow from the NPM.

Design of the ABS is COL applicant responsibility and no protective trip or isolation is assumed. Although the ABS is expected to be shut down within 30 minutes by operators, the limiting pressure and temperature conditions in RXB rooms would be reached within a few seconds without the guard pipe described in Section D.4.2.

D.6 Analysis

D.6.1 HELBs evaluated

Mass and energy inputs for each HELB were based on NRELAP5 analyses. Where the GOTHIC transient extends into a timeframe in which NRELAP5 showed negative pressure or reverse flow (due to condensation in the ruptured system), the input was conservatively set to zero.

D.6.1.1 In the CNV

SSCs within the CNV are designed and qualified for ECCS initiation (saturated steam at CNV design pressure). MSS and FWS ruptures are excluded by LBB. Therefore, only the effects of the NPS 2 HELBs need to be considered, and they are bounded and do not require further evaluation.

D.6.1.2 In the NPM bay under the bioshield

Ruptures and leakage cracks are excluded in the containment penetration area by designing to meet the acceptance criteria of BTP 3-4 paragraph B.A.(ii). However, BTP 3-3 specifies the need to evaluate non-mechanistic breaks in MSS and FWS piping in the containment penetration area. Nonmechanistic break area is 12 in^2, as discussed in Section 3.5.2.2. The remaining piping is designed to BTP 3-4 paragraph B.A.(iii), leaving only leakage cracks to be considered. The largest leakage crack would be 2.7 in^2 in a MSS line, the peak pressure and temperature of which are bounded by the non-mechanistic break because all piping under the bioshield is in close proximity in a small space. Therefore, the 12 in^2 MSS non-mechanistic break sets the mass and energy release to be considered, but other nonmechanistic break and leakage crack cases were evaluated to verify that judgment and to establish the long duration temperature profile.

The following HELB breaks under the bioshield were evaluated:

- MSS non-mechanistic break (12 in^2)
- MSS leakage crack (2.7 in^2)
- FWS non-mechanistic break (5.87 in^2)
- FWS leakage crack (0.0932 in^2)
- CVCS leakage crack (0.199 in^2)

In addition, other sensitivity cases were performed, as identified in Table D-1. The bias column indicates that initial conditions were selected to maximize the value of the listed parameter. This process is to ensure that the limiting pressure and temperature transient is identified.

GOTHIC analysis was performed to confirm that the passive flow area of the bioshield vertical section is sufficient to vent to the RXB pool room and limit the pressure differential to less than or equal to 1 psid. The pressure and temperature transient is applicable to EQ for essential and safety-related components under the bioshield such as the CIVs.

Table D-1 Under the Bioshield HELB case definitions

System	Break Type	Bias	Case ID
MSS (failed CIV)	Non-Mechanistic Break	UTB Trip Time	MS1TT
MSS (failed CIV)	Leakage Crack	UTB Trip Time	MS2TT
MSS (failed CIV)	Non-Mechanistic Break	Peak Pressure	MS1PP
MSS (failed CIV)	Leakage Crack	Peak Pressure	MS2PP
MSS (failed CIV)	Non-Mechanistic Break	Peak Temperature	MS1PT
MSS (failed CIV)	Leakage Crack	Peak Temperature	MS2PT
FWS (failed CIV)	Non-Mechanistic Break	Peak Pressure	FW1PP
FWS (failed FWS regulating valve (FRV))	Non-Mechanistic Break	Peak Pressure	FW2PP
FWS	Leakage Crack	Peak Pressure	FW3PP
CVCS	Leakage Crack	Peak Pressure	CV1PP
CVCS	Leakage Crack	Peak Pressure	CV2PP

The elevation of the MSS line break is assumed to be the highest location under the bioshield at which MSS piping is located. Breaks located at upper elevations in the bioshield benefit less from mixing with cooler air from below, which ensures bounding temperature results. For evaluating peak temperature, the break is positioned as far back from the vented bioshield panel as possible without positioning the break in a cell that is adjacent to the back NPM bay back wall. For evaluating peak pressure, the break is placed close to and directed toward the nearest impinging vertical surface (the bioshield), originating from the top of the vertical portion of MSS piping. Locating the break as far as possible from the bioshield vent limits beneficial mixing with air from the pool room. For peak pressure cases, the maximum pressure occurs where the jet is obstructed by the bioshield in the cell immediately downstream of the break jet. For this reason, this break location is also suitable for evaluating peak bioshield differential pressure.

The location of the high temperature trip sensor beneath the bioshield has not been determined. Therefore, the minimum cell temperature of any of the cells in the upper region of the NPM bay is used, because the lower region above the pool surface does not have an appropriate location at which to place the sensor.

D.6.1.3 In the RXB

As discussed in Section 3.9.8.3, a bounding approach is taken for HELBs occurring in the RXB. Although piping arrangements are not finalized, the subcompartments (i.e., rooms) containing high energy piping are defined. For rooms with a limiting combination of postulated HELBs (i.e., large mass & energy release for a small room volume), the pressure and temperature transient was determined.

D.6.2 Initial conditions

Initial RXB conditions are summarized in Table D-2. Conditions are selected to bound system design and operating conditions to ensure a conservative HELB analysis. The following conservatisms are applied:

1. Cases requiring a low-biased initial pressure assumed a mountainous elevation with a pressure of 12 psia. Cases requiring a high-biased initial pressure assume sea level pressure of 14.7 psia.

2. Pool room temperature is biased either 10 degrees F below the heating, ventilation, and air conditioning system (HVAC) design minimum temperature or 15 degrees F above the HVAC design maximum temperature: 50 degrees F and 100 degrees F.

3. For cases with initially high temperatures, the NPM bay was assumed to be 35 degrees F above the design HVAC maximum temperature: 120 degrees F.

4. Initial pool room relative humidity (RH) is biased 10 percent below the HVAC design minimum humidity for initially dry conditions, and 10 percent RH above the HVAC design maximum humidity for initially moist conditions: 20 and 70 percent. For initially moist conditions in the NPM bays, which are partially isolated from the remainder of the pool room, 100 percent humidity is selected as the maximum RH.

Table D-3 Initial condition minimum and maximum values

Sensitivity Parameter	Minimum	Maximum
Pressure	12 psia	14.7 psia*
Liquid Pool Temperature	40°F (100°F)*	140°F*
Pool Room Temperature	50°F	100°F
NPM Bay Temperature	50°F	120°F
RXB Room Temperature	50°F*	-
Pool Room Humidity	20%	70%

Sensitivity Parameter	Minimum	Maximum
RXB Bay Humidity	20%	100%
RXB Room Humidity	20%*	-

* Used for RXB cases

Table D-4 Initial condition biasing for NPM bay under the bioshield

Case Bias	Pressure Bias	Temperature Bias	Humidity Bias
Peak Pressure (Superheated Break)	Max Pressure	Max Temperature	Min Humidity
Peak Temperature (Superheated Break)	Min Pressure	Max Temperature	Min Humidity
Peak Pressure (Saturated Break)	Max Pressure	Min Temperature	Min Humidity

D.7 Results

D.7.1 In the CNV

Postulated HELB pressurization effects are bounded by ECCS initiation.

D.7.2 In the NPM Bay under the Bioshield

The limiting MSS nonmechanistic break pressure and temperature profiles are shown in Figure D-1 and Figure D-2, respectively, for both the top of the module (TOM) under the bioshield and the pool room to which it vents. Differential pressure between the area under the bioshield and the pool room to which it is venting does not exceed 1 psid for the MSS nonmechanistic break. Note that the initial conditions differ for the pressure and temperature limiting cases. as noted in Table D-4.

In Figure D-3 and Figure D-4, pressure and temperature results from the analyzed cases are overlaid (case identifiers are listed in Table D-1), to develop bounding pressure and temperature profiles for EQ in the area under the bioshield. Figure D-4 shows the bounding temperature envelope for EQ (dashed line). The time span of the figures is limited for clarity, but the bounding temperature profiles are assumed to continue indefinitely. Temperatures may continue to approach 212 degrees F for scenarios that do not result in automatic break isolation. Because the break fluid for these cases is subcooled liquid or saturated steam/liquid, the ambient temperature does not exceed 212 degrees F, and an EQ curve extended at 220 degrees F provides a bounding result indefinitely. Figure D-5 shows the pressure transient for the pool room as mass and energy from under the bioshield are vented into it before being subsequently relieved to outside the building.

These results demonstrate that the 1 psid differential pressure limit for the bioshield is satisfied and provide the EQ envelope for essential and safety-related equipment under the bioshield.

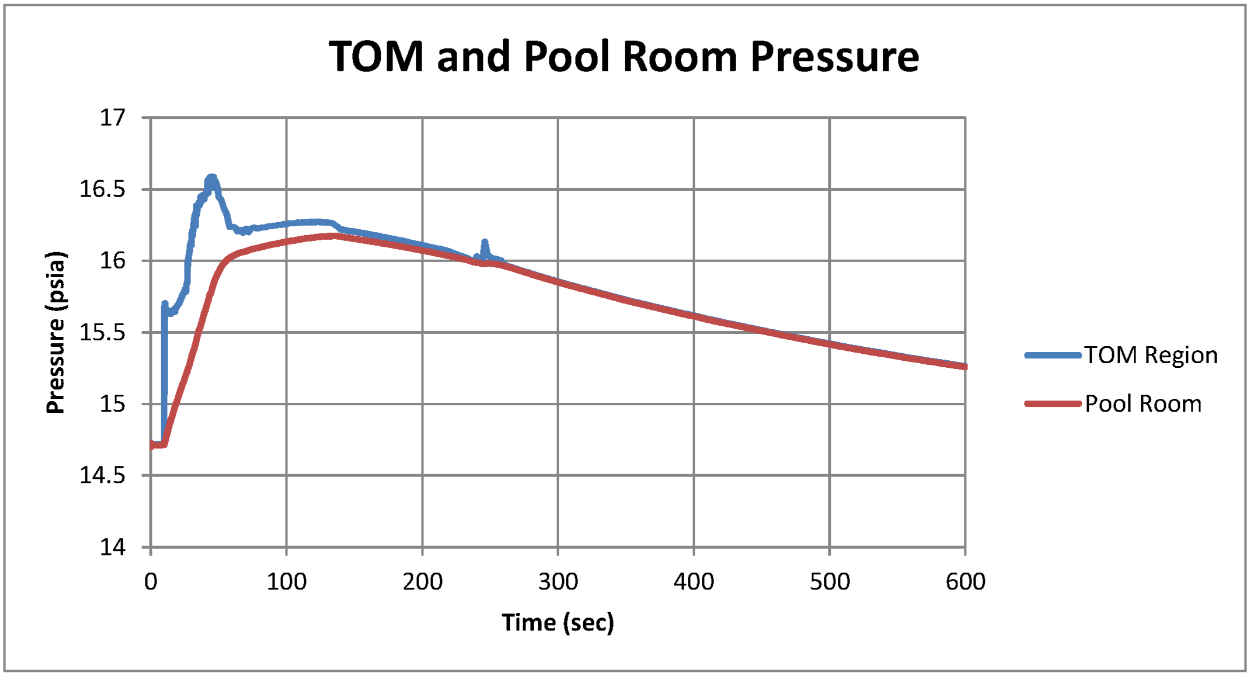


Figure D-1 Pressure under Bioshield and in Pool Room for MSS Nonmechanistic Break

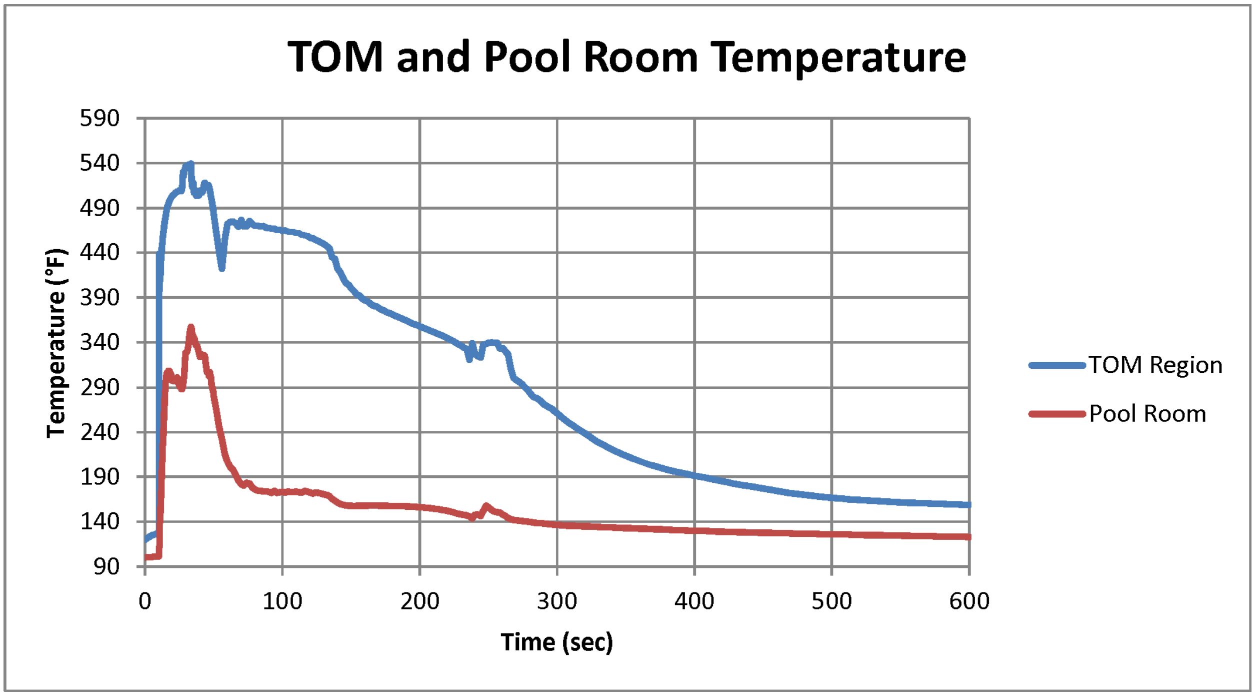


Figure D-2 Temperature under Bioshield and in Pool Room for MSS Nonmechanistic Break

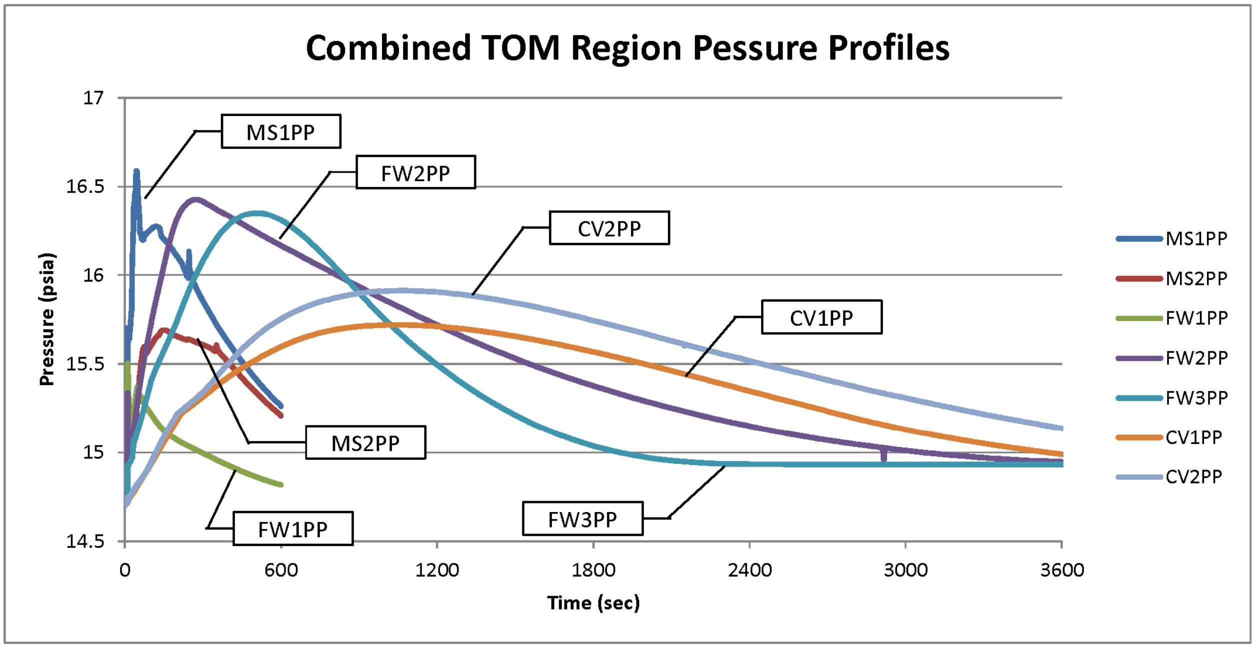


Figure D-3 Composite NuScale EQ Pressure Curve under Bioshield

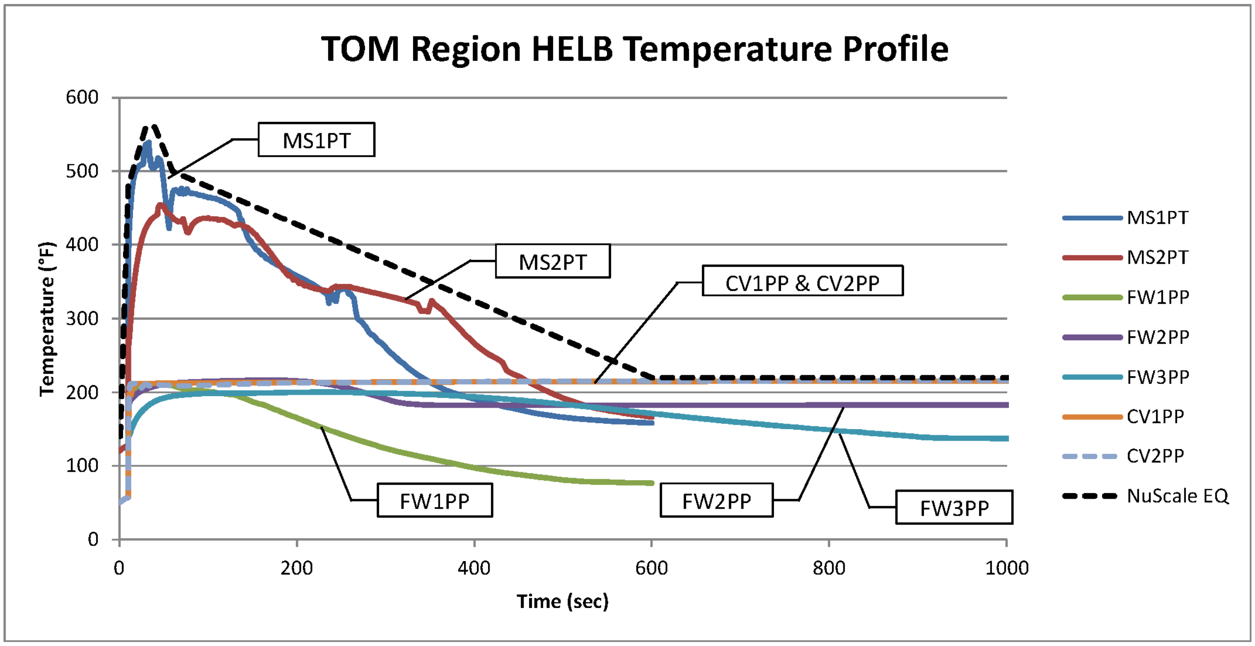


Figure D-4   Composite NuScale EQ Temperature Curve under Bioshield

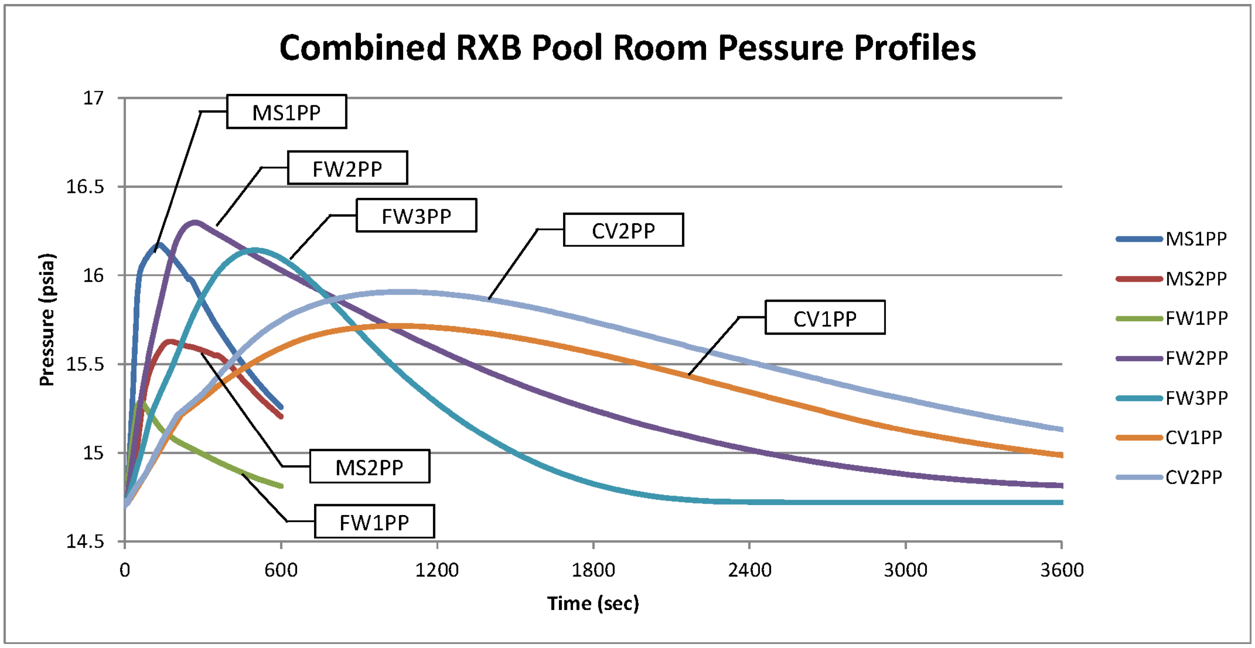


Figure D-5 RXB Pool Room Pressure for Nonmechanistic Breaks under the Bioshield

D.7.3 In the RXB

For purposes of pressurization in the pipe gallery, the double-ended MSS line rupture with MSS bypass line split results in the most severe pressure transient. Figure D-6 shows MSS rupture transient, which serves as the basis for sizing the blowout area and setting the blowout pressure of the vent path.

CVCS breaks in the pipe chase and heat exchanger rooms and ABS leakage cracks have also been demonstrated to meet the 3 psid acceptance criterion.

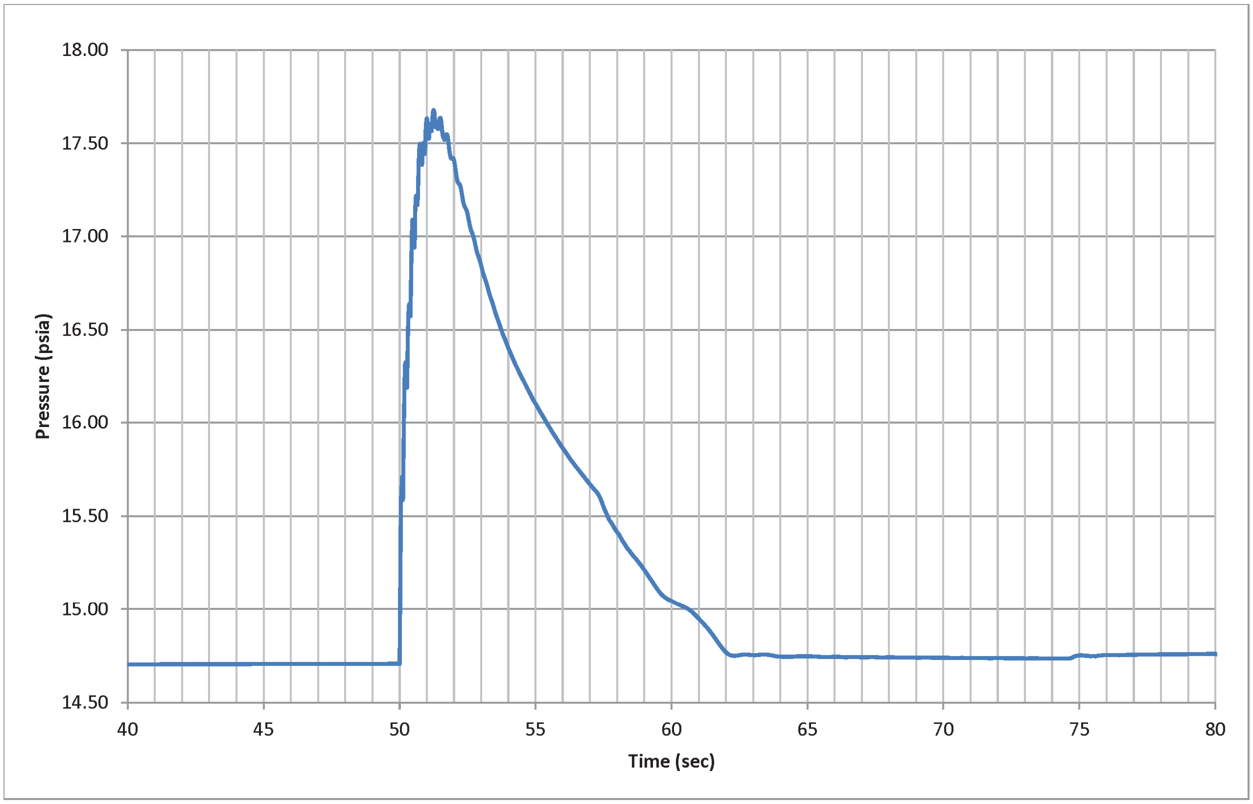


Figure D-6 RXB Pipe Gallery Pressure for MSS Rupture

D.8 Conclusion

GOTHIC analysis performed for postulated HELBs in the NPM bay under the bioshield and in areas of the RXB demonstrates that RXB structural acceptance criteria are satisfied and provides the EQ pressure and temperature profile for components.

Appendix E. Jet Impingement

As discussed in Appendix B, jets issuing from pipe breaks in the NuScale plant are not susceptible to dynamic amplification or resonance. However, target SSC potentially in the path of postulated breaks must be assessed for the load imparted by the jet. Three categories of jets are considered:

1. liquid jets
2. two-phase jets
3. steam jets

As for other effects, jet behavior and effects differ for the three areas of the plant:

- Inside the CNV: breaks are limited to NPS 2 RCS-connected and DHRS piping because SGS piping meets LBB. Only a degasification line break is initially steam, but spray line break reverse flow almost immediately turns to steam. Other breaks such as injection line or spray line forward flow are two-phase.

- In the NPM bay under the bioshield: no postulated breaks occur (nonmechanistic breaks do not involve pipe whip) because piping is designed to satisfy break exclusion criteria of BTP 3-4 Paragraph B.A.(ii) and (iii).

- In the RXB: piping arrangements are not finalized, so break locations and jet directions must be assumed to be anywhere in the rooms containing high-energy piping. The piping is limited to NPS 12 and 4 main steam system, NPS 6 feedwater system, and NPS 2 to 3 chemical volume and control system piping at various pressures and temperatures. Main steam system jets are steam only, whereas FWS and CVCS breaks are two-phase jets, and sections of CVCS could be susceptible to breaks leading to liquid jets.

The concern for jet impingement that underlies regulatory guidance is the stripping of insulation with subsequent sump blockage (GSI-191). In the NuScale plant, there is no piping insulation inside the CNV and stripping of insulation outside the CNV has no deleterious safety effects. This raises the impingement damage threshold from four psig to more than 190 psig (NUREG/CR-6808), based on the impingement pressures for which metal insulation sheathing has been found to not be damaged during testing.

E.1.1 Total Force

The total force by the jet (adjusted for thrust coefficient) cannot exceed that at the break exit plane, which is {{ }}$^{2(a),(c)}$ for CVCS and MSS, respectively (Table 3-7).

E.1.2 Liquid jets

Liquid jets are assumed to not expand (i.e., the cross section of the pipe rupture is maintained) and to not droop with distance (i.e., travels straight until impeded). The only areas subject to liquid jets are in the RXB where CVCS low temperature, high pressure piping is present. The essential SSCs in this area are the CVCS demineralized water makeup valves and RXB structure (for which liquid jets are considered to have less potential to damage concrete structure than steam jets, which are shown to be acceptable).

E.1.3 Two-phase jets

Two-phase jets are assessed using the methodology of NUREG/CR-2913. A bounding approach is taken by applying conservative criteria for jet formation in order to avoid the need to analyze individual break locations in the CNV and RXB.

E.1.3.1 In the Containment Vessel

Although the low operating pressure of the CNV is a deviation from the experimental and analytical basis of NUREG/CR-2913, the low ambient pressure results in faster expansion of the jet, which is conservative when estimating loading. This is supported by the CFD analysis of blast waves described in Appendix F. Although that analysis is terminated while the jet is still forming, Figure F-8 and Figure F-9 show the half-angle of the 10 percent steam region (grey) already exceeds 60 degrees within the first millisecond.

Only RCS-connected NPS 2 pipe breaks need to be evaluated because the NPS 2 DHRS breaks have a substantially lower system pressure and are not close to any essential SSCs except the RPV and CNV walls. The inputs needed for the NUREG/CR-2913 (hereafter referred to as just “2913”) methodology are the system static thermodynamic conditions, which are shown in Table 3-3.

a. Static temperature and pressure determine the entropy from Figure D.1 of 2913.

b. Entropy and break flow rate are used to obtain the stagnation temperature T_0 from either Figure D.4 or D.5 of 2913.

c. Given the stagnation temperature and flow rate Ge, Figure D.6 provides the stagnation pressure P_0. However, Figure D.7 is used to find the stagnation quality X_0 if blowdown is initially two phase.

d. Given the stagnation pressure P_0 determined above, the corresponding saturation temperature at stagnation conditions $T_{sat,0}$ is found, which allows the degree of subcooling of the system at the break to be determined from the equation:

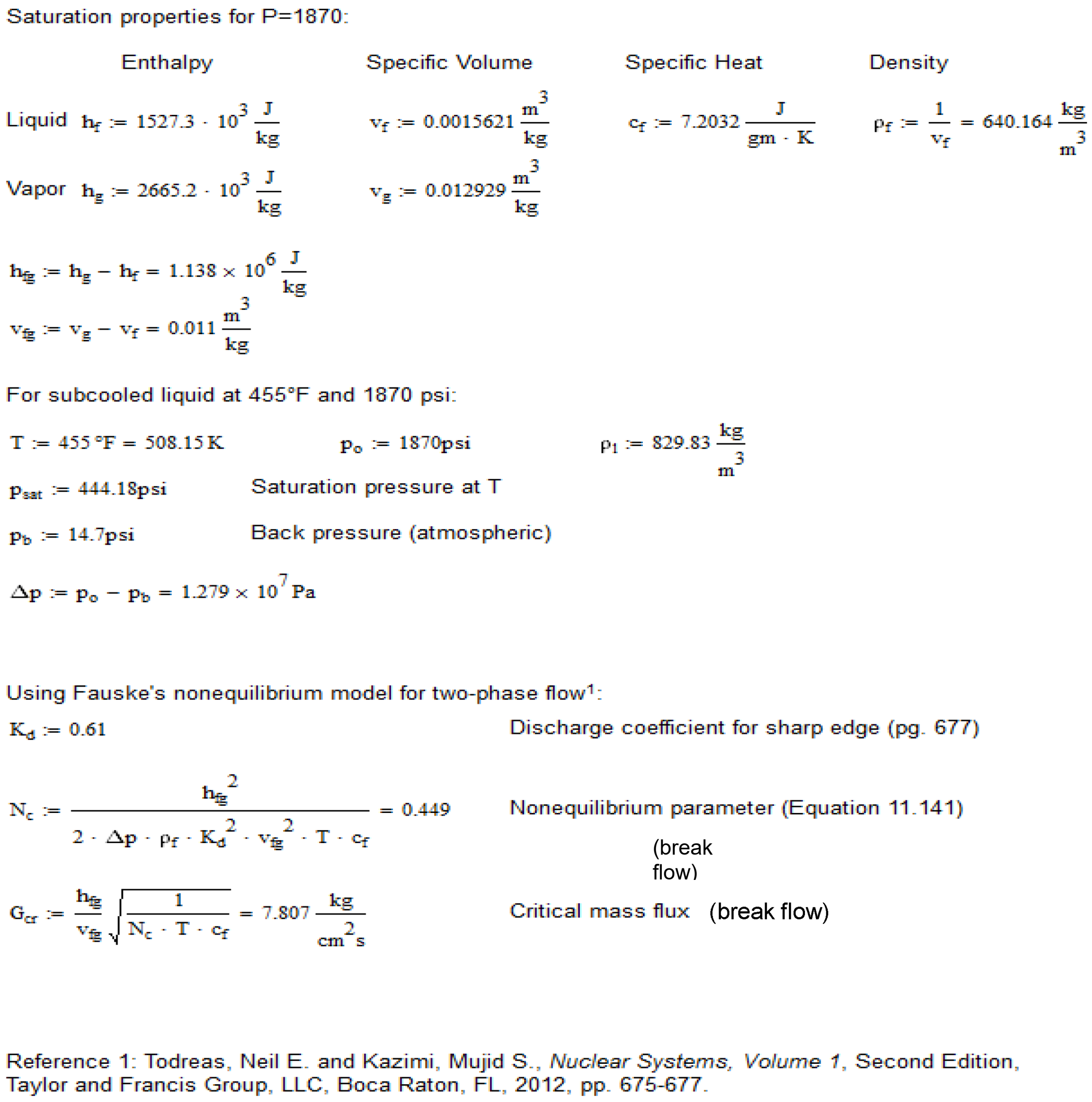
$$\Delta T_0 = T_{sat,0} - T_0 \qquad \text{Eq. E-1}$$

The relevant graph of Appendix A of 2913 is selected to obtain target pressure and total force on the target for appropriate values of P_0, ΔT_0, or X_0, and distance to the target in L/D.

Although the graphs can be used to determine the ZOI, the ZOI in the CNV is assumed to be anywhere in the forward facing hemisphere because of the greater spreading angle in the low-pressure CNV and possible pipe whip. Similarly, in the RXB, the generic approach of a ZOI that includes everywhere allows for breaks at any locations determined once pipe routing is finalized and for pipe whip.

E.1.3.2 Example 2913 Calculation of Two-Phase Jet Behavior

Find break mass flux for a CVCS break:



Saturation properties for P=1870:

	Enthalpy	Specific Volume	Specific Heat	Density
Liquid	$h_f := 1527.3 \cdot 10^3 \frac{J}{kg}$	$v_f := 0.0015621 \frac{m^3}{kg}$	$c_f := 7.2032 \frac{J}{gm \cdot K}$	$\rho_f := \frac{1}{v_f} = 640.164 \frac{kg}{m^3}$
Vapor	$h_g := 2665.2 \cdot 10^3 \frac{J}{kg}$	$v_g := 0.012929 \frac{m^3}{kg}$		

$$h_{fg} := h_g - h_f = 1.138 \times 10^6 \frac{J}{kg}$$

$$v_{fg} := v_g - v_f = 0.011 \frac{m^3}{kg}$$

For subcooled liquid at 455°F and 1870 psi:

$T := 455\,°F = 508.15\,K$ $\qquad p_o := 1870 psi$ $\qquad \rho_1 := 829.83 \frac{kg}{m^3}$

$p_{sat} := 444.18 psi$ Saturation pressure at T

$p_b := 14.7 psi$ Back pressure (atmospheric)

$$\Delta p := p_o - p_b = 1.279 \times 10^7\,Pa$$

Using Fauske's nonequilibrium model for two-phase flow[1]:

$K_d := 0.61$ Discharge coefficient for sharp edge (pg. 677)

$$N_c := \frac{h_{fg}^2}{2 \cdot \Delta p \cdot \rho_f \cdot K_d^2 \cdot v_{fg}^2 \cdot T \cdot c_f} = 0.449$$

Nonequilibrium parameter (Equation 11.141)

(break flow)

$$G_{cr} := \frac{h_{fg}}{v_{fg}} \sqrt{\frac{1}{N_c \cdot T \cdot c_f}} = 7.807 \frac{kg}{cm^2 s}$$

Critical mass flux (break flow)

Reference 1: Todreas, Neil E. and Kazimi, Mujid S., *Nuclear Systems, Volume 1*, Second Edition, Taylor and Francis Group, LLC, Boca Raton, FL, 2012, pp. 675-677.

Find break entropy:

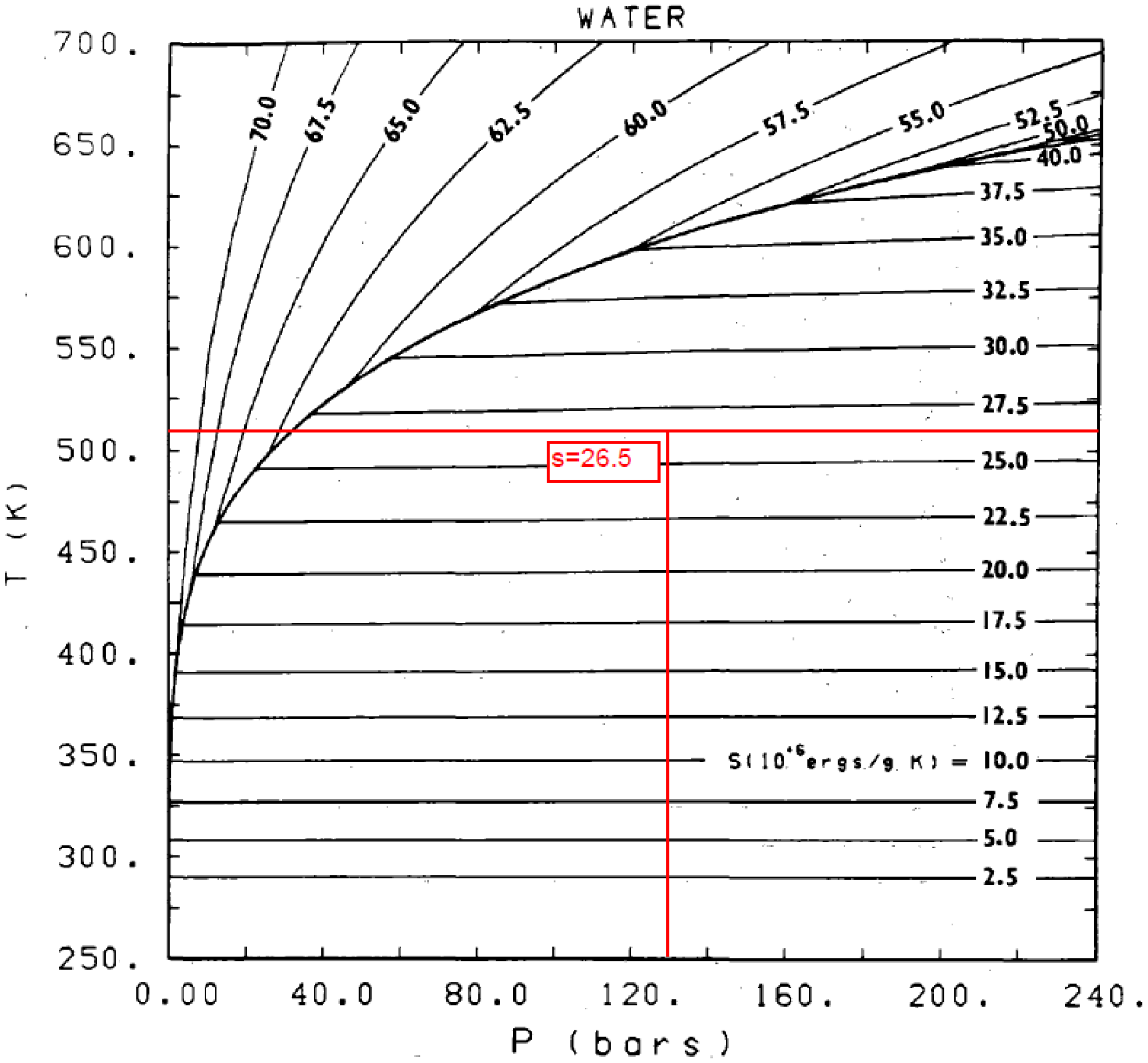


Figure D.1 Thermodynamic properties of water. Temperature as a function of pressure and entropy for a range of pressure and entropy that emphasizes subcooled conditions.

Find stagnation temperature:

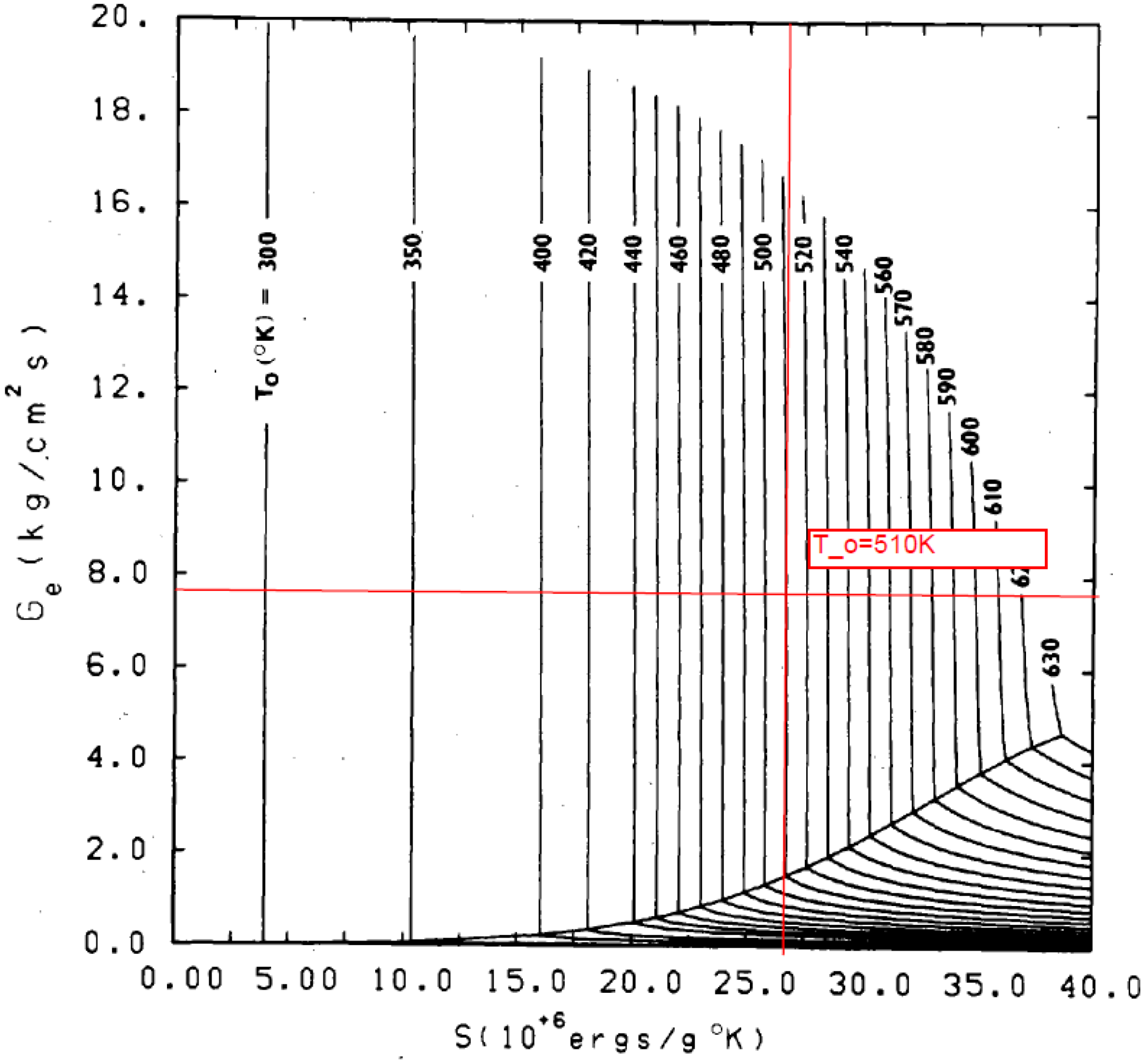


Figure D.4 HEM mass flux as a function of entropy and stagnation temperature for a range of entropy which emphasizes subcooled stagnation conditions.

Find stagnation pressure:

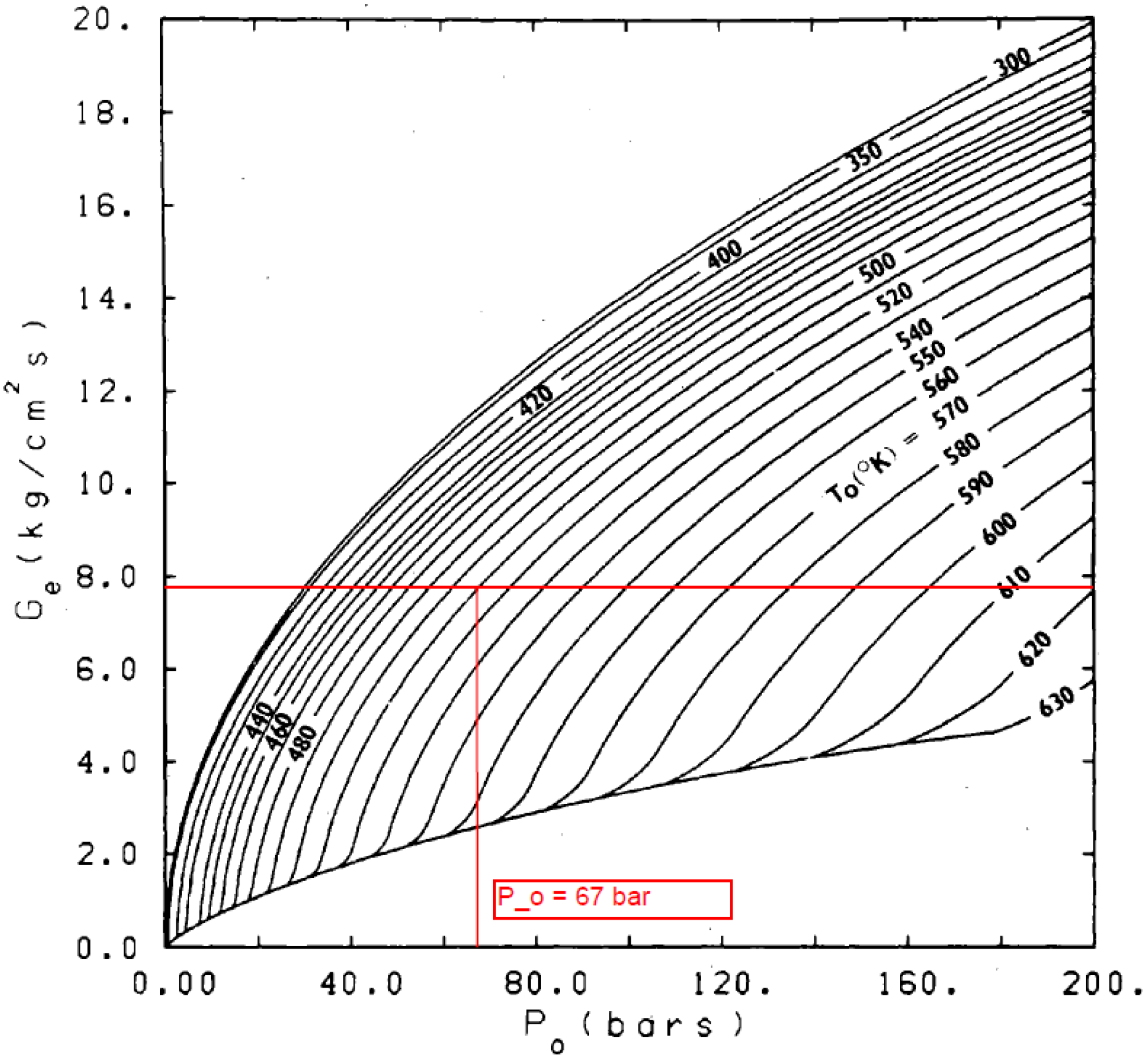


Figure D.6 HEM mass flux as a function of stagnation pressure and stagnation temperature.

Find saturation temperature at stagnation conditions:

$$T_{sat,0}(P_0 = 67\ bar) = 556\ K$$

Calculate degree of subcooling:

$$\Delta T_0 = T_{sat,0} - T_0 = 556\,K - 508\,K = 48\,K$$

Use plot for $\Delta T_0 = 50\ K$ and $P_0 = 80\ bar$ to bound actual subcooling/pressure.

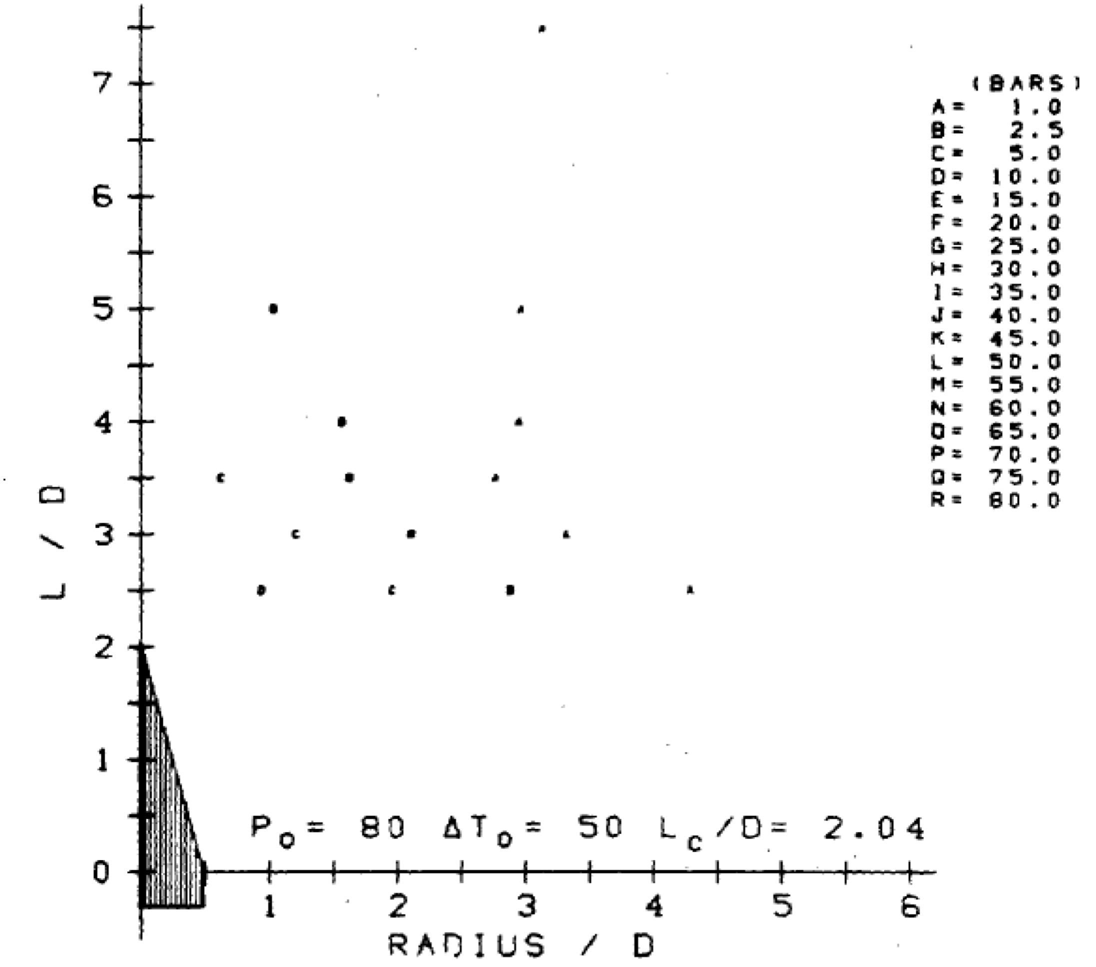


FIGURE A.39 COMPOSITE TARGET PRESSURE CONTOURS

The final step involves selecting the correct figure representing the pressure contours of a jet most closely matching the thermodynamic conditions of 48-degrees Kelvin subcooling and 67 bar. This is Figure A.39 from 2913. The figure shows pressures at specific points downstream in L/D and radially from the jet centerline in r/D. The origin of the plot is the jet centerline at the break exit plane, and the shaded area at the lower left is the jet core (the region that has not yet begun to interact with the environment). The letters A through D refer to the key for pressure (letters beyond D for pressures above 10 bar are not plotted). For example, a letter B indicates pressure was 2.5 bar at 4 L/D and 1.5 r/D.

The jet core is the region immediately downstream of a break in which the target pressure is the full stagnation pressure. Reference 1.4.3.14, Section 3.3.1.1 states that this region is significant only for jets involving subcooled stagnation conditions. Figure A.39 shows that the jet core dissipates within 2 L/D or about 3.4 inches for a thermodynamic condition similar to a CVCS HELB. This is viewed as conservative. Reference B.5.4, Section 3.5.3.B notes that Sandia (Reference 1.4.2.9) emphasizes the pipe exit core. The persistence of the core is attributed by Sandia to the time it takes for external pressure to penetrate the jet, and that the core length is always longer than 0.5D for subcooled and saturated water jets. Reference 4 notes, however, that test data is not consistent with the Sandia model, with only one or two test data sets exhibiting something like a liquid core while most data contradict the presence of a liquid core. Reference B.5.4 concludes “If a liquid core exists, it seems to be much smaller than indicated by Sandia.” At 2.5 L/D and 1 r/D, the single D point is a pressure of 10 bar (145 psig), which is already below the conservative NuScale damage threshold of 190 psig. Within 4 L/D or about 6.8 inches, the jet peak pressure has dropped to below 5.0 bar (72.5 psig). The A points representing 1.0 bar correspond to the edge of the jet. The jet persists beyond 7.5 L/D, which is indicative of the concern for fibrous insulation damage at pressures of 4 psig out to a 10 L/D penetration distance. For NuScale’s design, pressures at about 2 L/D are low enough to cause no damage to the hard components.

E.1.4 Steam Jets

E.1.4.1 In the Containment Vessel

For breaks inside the CNV, expansion of the jet into the low-pressure surroundings results in different behavior than usually experienced for HELBs. Wider jet spreading is expected to occur because the initially low air density of a CNV pressure below 1 psia removes most of the resistance to jet expansion, as seen in the initial jet formation calculated by the blast effects CFD analysis (see Figure F-8 and Figure F-9 which show a half-angle exceeding 60 degrees). The wider jet expands the ZOI but substantially reduces the pressure and the penetration length, because the mass and energy of the jet are more widely dispersed. Although pressure within the CNV increases with time, the pre-existing wide expansion of the jet persists because the jet is already established.

Deleted Eq. E-2

Deleted Eq. E-3

Figure E-1 Deleted

For simplicity and because there are no rigid restraints at postulated break locations to constrain separation, circumferential breaks are assumed to be full separation. For circumferential breaks with full separation, it is assumed that any essential system or component is within the ZOI if it is located within the forward-facing hemisphere (see right image of Figure E-2) based on the original pipe orientation and subsequent pipe whip path.

Applying the break exit pressure over a large ZOI would be a large overestimation of the possible jet impingement loading. {{

}}$^{2(a), (c)}$

As noted, the jet core is only significant for subcooled jets. Reference 1.4.2.9 Section 3.6 discusses the core length L_c as ½D, one half of the pipe diameter for saturated stagnation conditions. It also notes that the length L_c depends on the time it takes a pressure wave to travel from the outer edge of the nozzle (i.e., break) to the jet center. Figure 4.3 of Reference 1.4.2.9 shows that for zero degrees subcooling L_c=½D. Thus, even if a jet core existed for a steam jet, its influence would be dissipated within ½D, which is too close for a jet impingement force to be of concern compared to pipe whip impact.

{{

}}$^{2(a), (c)}$

Figure E-2 Jet ZOI and expansion for circumferential break with full separation in CNV

Table E-1 Deleted

{{ }}2(a),(c) Eq. E-4

$$A_j = D_j^2 * \frac{\pi}{4} \quad \text{Eq. E-5}$$

$$P_j = C_T * P_o * \frac{A_E}{A_j} \quad \text{Eq. E-6}$$

where,

D_j = Jet diameter at distance L/D_E (inches),

L/D_E = Distance of nearest point on impingement surface in L/D (unitless),

D_E = Inside diameter of break exit (inches),

A_j = Total cross-sectional area of the jet at the target SSC (inches^2),

P_j = Applied jet pressure at nearest target surface,

C_T = Thrust coefficient (unitless),

P_o = Internal system pressure (psia)[20], and

A_E = Pipe flow area (inches^2).

Applying Eq. E-4 and Eq. E-5, the jet pressure variation with distance is given in Table E-2. {{

}}2(a),(c)

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[20] In accordance with SRP 3.6.2, jet thrust load is based on operating pressure and temperature.

{{

}}$^{2(a),(c)}$

There are no subcooled, nonflashing jets for HELBs inside the CNV.

Table E-2 CVCS steam jet impingement pressure versus distance

Distance L (in.)	L/D_E	A_{j30} / A_E	Total P_{30} (psia)▲	Total P_{30}/Total P_{60}
0	0	{{		
1	0.6			
2	1.2			
3	1.8			
4	2.4			
5	3.0			
6	3.6			
7	4.1			
8	4.7			
9	5.3			
10	5.9			
15	8.9			
20	11.9			
25	14.8			
30	17.8			
35	20.7			
40	23.7			}}$^{2(a),(c)}$

▲Includes 1.26 thrust coefficient C_T

E.1.4.2 In the Reactor Building

Jet core length is not relevant for RXB breaks because full exit plane pressure is assumed. In the RXB, the distance between a break and a target structure, system, or component is not defined because RXB piping arrangements have not been finalized. To verify suitability of the design of the RXB, bounding HELB scenarios have been identified.

The MSS lines are much larger and contain more energy than any other potential sources in the RXB. Demonstrating passing performance for MSS breaks provides confidence that final HELB analysis results are satisfactory. Therefore, a conservative approach is taken in which the jet impingement pressure is assumed to be the same as that at the break exit (i.e., no reduction for spreading with distance). For an MSS HELB, the break exit pressure is 500 to which the thrust coefficient CT of 1.26 is applied. For an MSS break, which imposes the highest load of postulated HELBs in the RXB, the design-capacity ratio (DC) of the wall for jet impingement and reaction loading is 0.02. Because pipe rupture loads are localized, they have no effect on the overall structural integrity of the wall.

E.2 Jet Impingement Force

The force delivered by an impinging jet is highly dependent on geometry:

- Intersection of the area of the jet with the projected area of the target perpendicular to the jet.
- Angle of the jet to the surface.
- Shape of the surface.

This dependency is usually represented by:

$$Y_j = P_I * A_I * S_F * D_{LF} \cos \varphi \qquad \text{Eq. E-7}$$

where,

P_I = Impingement pressure (psia),

A_I = Area of intersection of the jet and the projected target surface area perpendicular to jet axis (inches^2),

Y_j = Normal load applied to a target by the jet (lbf),

S_F = Shape factor for target SSC (unitless)(see Table E-3),

D_{LF} = Dynamic load factor (unitless), and

φ = Angle made by jet axis and line perpendicular to predominant target surface.

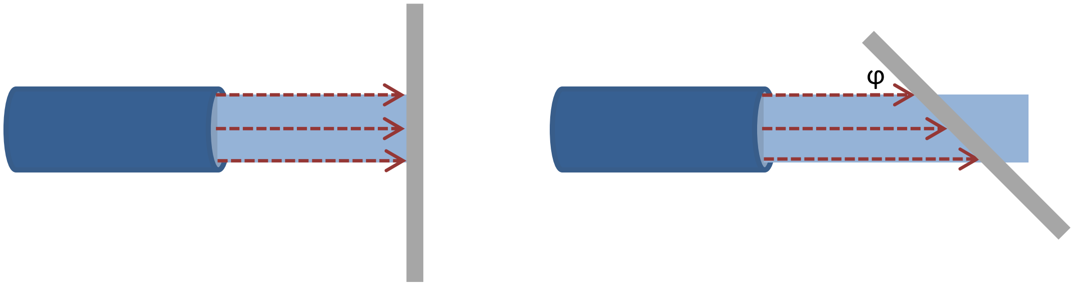
Table E-3 Shape factors for jet impingement

Target Shape	Shape Factor	Reference
Jet impinging on flat surface	1.0	N/A
Circular jet on pipe with jet diameter > pipe diameter	0.576	ANSI/ANS 58.2
Elliptical cylinder 2:1 major:minor axis ratio (C_D = 0.6)	0.3	ANSI/ANS 58.2
Square cylinder (C_D = 2.0)	1.0	ANSI/ANS 58.2

Eq. E-7 is based on the assumption that the jet is not spreading, as shown in Figure E-3. The left side of the figure shows a non-spreading jet impinging on a flat surface normal to the jet. This scenario results in a maximum impingement force. If, however, the jet is not normal to the surface, then the jet force is reduced as the cosine of the angle φ from normal, as shown in Figure E-3(b). In the extreme, for an angle of φ = 90 degrees, the jet is parallel to the surface and imparts no force.

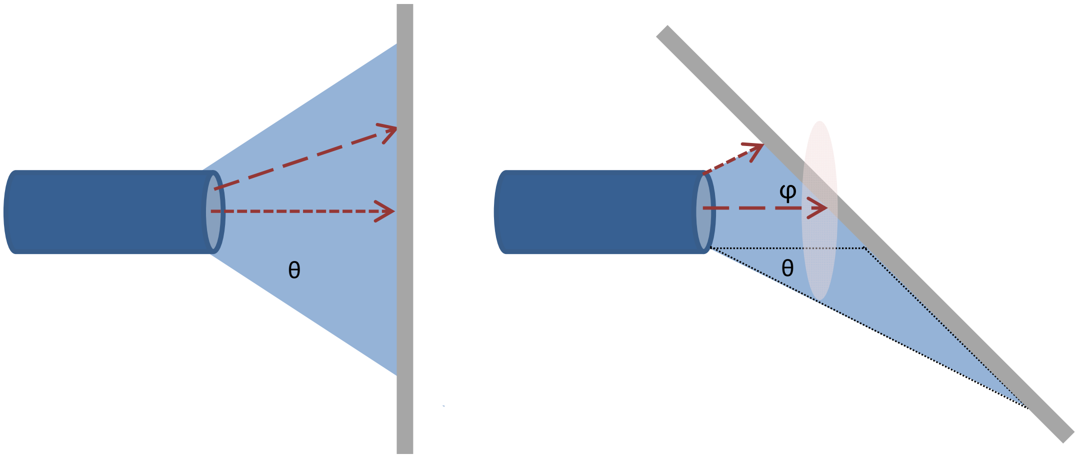
However, the situation is more complicated for an expanding jet, as shown in Figure E-3. If the jet is spreading with a half-angle θ, then all flow lines except the jet's axis (short dash arrow in Figure E-4 (b)) interact with the surface at angles that increase with distance from the axis. This is just like having all off-axis portions of the jet impinging a surface at increasing angles.

If the jet to surface angle is not normal, then there may be no flow line that is normal to the surface (short dash arrow in Figure E-4(b) such that the force is farther reduced. In addition, the angled surface points are at different distances from the jet exit, such that the jet has spread more widely by the time it encounters the surface, thereby again reducing the pressure. If the target surface is large and intersects the entire jet, then this has no effect. Where the intersection is not complete, the distance at which the jet pressure is determined is important, at least within 5 L/D where the jet is expanding at the greatest half-angle.



(a) (b)

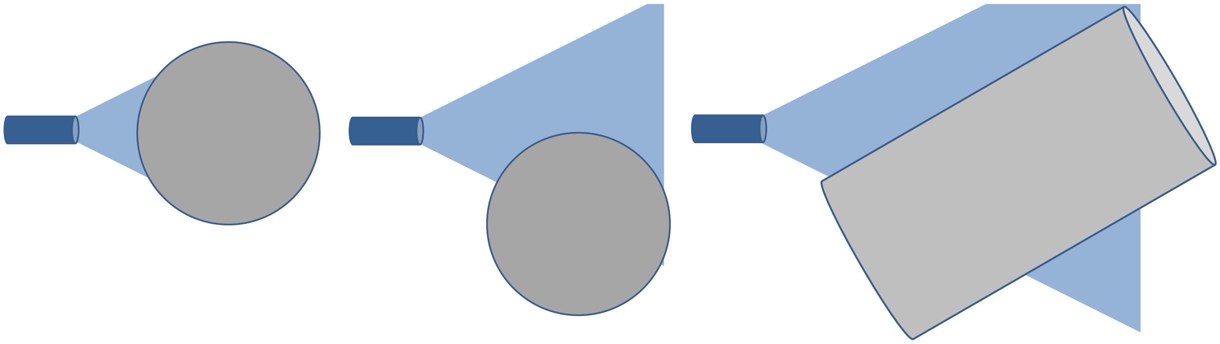
Figure E-3 Jet Impingement on flat plate



(a) (b)

Figure E-4 Expanding jet impingement on a flat plate

Introducing the complication of an angled, spreading jet off-center to an angled, limited size, non-flat surface results in an overestimate of the impingement force. This is shown graphically by comparing Figure E-5(a) to (b) and (c). In each part, the jet spreading, the target size, and the break-target minimum separation are the same, but (b) and (c) show that much of the jet misses the target, even if the cross-sectional areas of the jet and target are similar.



(a) Side on (b) Offset side on (c) Offset, end on, inclined

Figure E-5 Expanding jet impingement on a cylinder

As noted in the previous section, the RVV impingement pressure would be no more than 43.6 psia. The RVV is about 12 inches in diameter and 20 inches long, and the jet diameter is also about 12 inches. Even assuming optimum alignment for maximum interaction of the jet with the valve, the valve is angled downward at about {{ }}$^{2(a),(c)}$ from horizontal. Assuming the areas of the jet and valve cross-section subject it to the full CVCS exit plane force of {{ }}$^{2(a),(c)}$ (Table 3-7) applied at {{ }}$^{2(a),(c)}$ with and a cylindrical shape factor (Table E-3) of 0.576, the total force is only about {{ }}$^{2(a),(c)}$ times its dead weight.

But this force is transitory, because there is no obstacle to stop the pipe whip with the jet pointed at the valve. Impingement effects testing fixes the jet exit pointed at the target. In in postulated HELB, the speed of the end of the whipping pipe increases with the angle through which it moves. Although the speed depends on the exact pipe configuration, within 10 degrees of starting its whip it should be moving more than 100 ft/sec, with the jet cross-section sweeping even faster as distance from the break lengthens. For 100 ft/sec, a 12-inch diameter jet sweeping across a 12-inch diameter target exposes the target to a load for a maximum of 1/100th of a second, with most of that time being at a partial load. With its compact size and heavy metal walls, an RVV is a very stiff component. Because of the sinusoidal application of the jet force and its rapid passing, the jet impingement is an impulse with a duration short in comparison with other loads and need not be combined with them. Further, the dynamic load factor D_{LF} in Eq. E-7 can be set to 1.

E.3 Jet Impingement Summary

Jet impingement is of low significance in the NuScale design:

- The total impingement force is small because of the small size of CVCS and MSS piping.
- A conservatively wide ZOI is applied.
- In the CNV:
  - The trajectory of postulated whipping pipes does not result in a jet pointed directly at an essential target structure, system, or component, except possibly the CNV, which is capable of withstanding the much higher pipe whip impact load.
  - Insulation stripping concerns do not apply, so the threshold for essential SSC damage is set at 190 psi, based on testing showing that metal reflective insulation is not damaged.
  - A conservatively shallow jet expansion half-angle is assumed for steam jets, and NUREG/CR-2913 is used for two-phase jets. Considering the decrease of jet pressure with distance from the break exit, impingement pressure has dropped below the component damage threshold of 190 psi within four inches. At closest expected approach to an RVV of about 10 inches, the impingement pressure would be less than 45 psia.
  - The maximum total load is {{ }}$^{2(a),(c)}$. For an RVV, the impingement force would be further reduced by the target shape factor and angle to below {{ }}$^{2(a),(c)}$.
  - The rapid movement of the whipping pipe limits the imposition of this small load to less than 1/100th of a second.
- In the RXB, no credit is taken for reduction in pressure with distance. Impingement pressures and total force are small compared to the load capacity and erosion would be negligible.

Appendix F. Blast Effects

F.1 Background

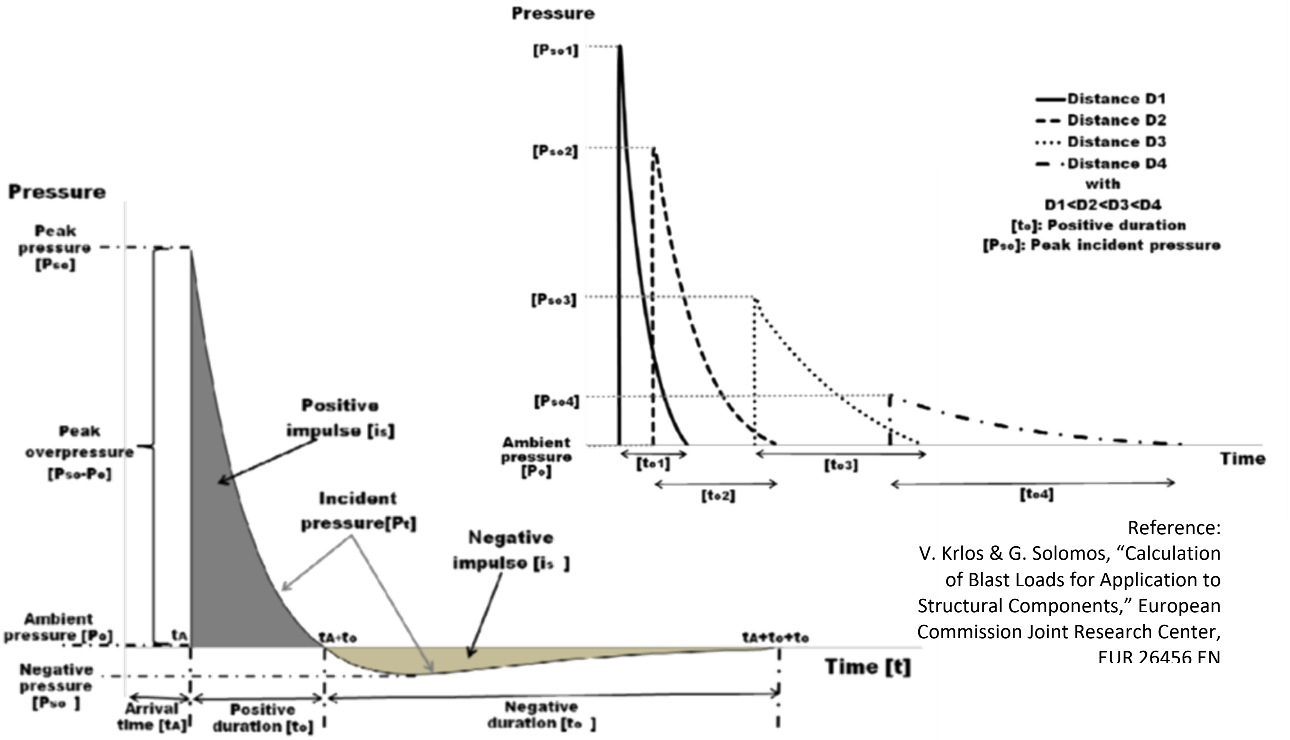
F.1.1 Blast Wave Behavior

Standard Review Plan 3.6.2 requires assuming a maximum break opening time (i.e., the duration that it takes for an HELB to fully open) of one millisecond, unless a combined crack propagation time and break opening time greater than one millisecond can be substantiated. A very rapid break opening time for a HELB can cause a blast (i.e., shock) wave to form, driven by a rapid release of mass and energy. If the rupture opens over a period of more than a few milliseconds, the mass and energy release rate is too slow to create a blast wave.

A blast wave could occur as a HELB injects mass and energy rapidly into the surroundings, creating a region of high density. The pressure differential accelerates material (fluid from the HELB and air in the immediate vicinity) to spread outward at the speed of sound. This material continually interacts with the undisturbed atmosphere impeding its expansion, creating higher pressure, temperature, and density at the interface. A sharp peak of pressure, temperature, and density is formed that travels at the speed of sound for the high density region, which is faster than the speed of sound (i.e., supersonic) of the surrounding atmosphere. The compression created by the blast leaves behind it a low density region into which the continuing HELB blowdown is injected.

A HELB does not cause a large blast. Once the wave forms, it is moving at supersonic speed, which keeps it out ahead of the on-going blowdown, preventing additional fluid from contributing to the blast. Break initiation creates a depressurization that can move upstream in the pipe no faster than the speed of sound of the fluid in the pipe. This fluid upstream in the pipe farther than the distance traveled at the speed of sound at intact system conditions (i.e., pressure and temperature) cannot contribute to the initial blast. Therefore, defining the initial energy and mass contributing to the formation of the blast wave involves conservatively estimating the volume of fluid in the pipe that can physically escape before the blast wave initiates.

Figure F-1 shows the characteristic features of a blast wave. The region of blast wave pressure above the surrounding ambient pressure P_O is the positive specific impulse. It has a peak side-on pressure P_{SO} at its leading edge and a time duration (t_o or t_d). The product (area under the curve) of peak pressure and pulse duration is the positive specific impulse. Blast wave spatial extent grows and its speed decreases away from the source, causing the pulse duration to lengthen and the peak incident pressure to decrease. The speed of the blast front depends on the pressure and density, and peak pressure can be determined from the speed of travel and vice versa, using the Rankine-Hugoniot relationship. The area of the positive specific impulse is the energy carried by the wave.



Reference:
V. Krlos & G. Solomos, “Calculation of Blast Loads for Application to Structural Components,” European Commission Joint Research Center, EUR 26456 EN

Figure F-1 Characteristic shape of a blast wave and decay with time

Predicting the behavior of a blast wave is further complicated if the wave reflects off of objects, as would occur during an HELB event. Reflection can influence the loads caused by a shock wave in two ways:

- The presence of condensable vapor can lead to shock-induced condensation that has been found to reduce peak pressure. Reference 1.4.3.7 states “Vapor condensation at the shock front causes the coolant to be in single phase (liquid). As a result, the pressure shock is retarded and energy conversion ratio is reduced.”

- The damage potential of a blast wave depends on the magnitude of the overpressure upon reflection and its duration, and also on the responsiveness and projected surface area presented by the target.

F.1.1.1 Effects of Wave Reflection

Reflection of an incoming wave exerts more force than blast overpressure due to the change in momentum of the gas in the blast wave. In reflection of normal sound waves (like jet impingement), the imposed load is up to twice the incoming sound pressure. For a blast wave, the accumulation of mass and energy in the vicinity of the surface is reinforced by the higher speed (i.e., momentum) of the incoming wave compared to normal sound waves. Blast wave reflection off of a surface amplifies the pressure, which is a function of both incoming blast wave speed and angle. This is shown in the Figure F-2 graph (Reference F.6.2) of the reflection coefficient C_r, which is the ratio of the reflected (outgoing) pressure to that of the incident (incoming) wave pressure. For example, an incident wave of 100 psi encountering a surface at 30 degrees would have a C_r of about 4.5, so the reflected wave pressure imposed on the surface would be about 450 psi. A HELB is a relatively slow release of energy (compared to chemical explosions) with peak incident pressures of less than 100 psi that result in mild amplification of five or less for a wave perpendicular to the surface. Because separation distances are short within a plant, the spherically expanding blast wave is never perpendicular to an SSC surface at more than one point, so the SSC encounters a range of amplifications.

An incident wave may be reinforced by overlapping of waves that have previously reflected off other surfaces. This is a complex interaction in congested areas, but is less significant where SSC are more widely spaced.

Normal intersection of a shock wave with a SSC is the exception: (a) most SSC have curved surfaces, and (b) flat surfaces are rarely normal to the blast wave. Oblique reflection is when the blast wave arrives at other than normal to the surface. If the surface is not smooth, flat, and large, then the blast wave is distorted. For example, a blast wave striking a cylindrical surface encounters that surface at a different angle at each point around the circumference, with a different reflected pressure being the result (this is similar to the shape effect for jet impingement).

The wave pressure drops below the ambient pressure P_{S0}, in which the high density region is followed by a depleted zone: the negative specific impulse that can be considered similar to the troughs of ocean waves. Therefore, as a blast wave washes over a surface, the initial peak pressure at a point drops off rapidly and goes subatmospheric, while other portions of the surface farther from the blast origin are still being subjected to the high pressure portion of the wave. The net effect is that the component is not loaded at the full pressure implied by the wave peak. Blast positive impulse durations are short, usually on the order of a few milliseconds. The loading imposed is short-lived and therefore not treated as a static load. Finally, if the blast wave is created in an enclosed space, the waves reflected from different locations constructively and destructively combine, arriving at subsequent surfaces from a variety of angles and at different points in the wave transient.

These interactions make the pressure loading on a surface very geometry dependent, which requires knowledge of the blast wave formation initial pressure, the distance to the reflection surface, and the angle between the incoming blast wave and the surface.

Because of these interactions, the best method to determine the pressures created by a HELB blast is to perform a three-dimensional CFD analysis. However, a three-dimensional CFD is time-consuming, making it impractical to use for every possible HELB location and orientation. In view of this, NuScale defined bounding cases in the CNV and RXB and conservative inputs for each to be analyzed.

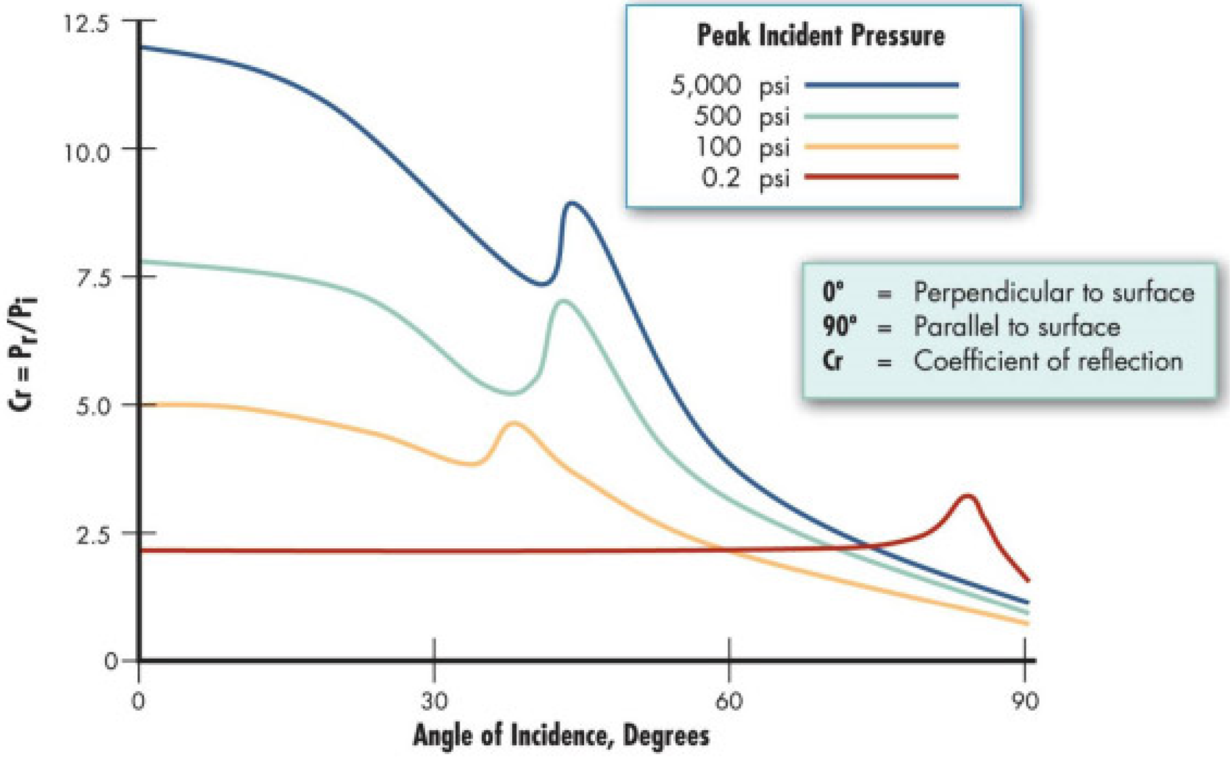


Figure F-2 Blast wave reflection coefficient

F.1.2 Inside the Containment Vessel

The NuScale plant has a unique feature of operating the CNV at very low pressure. The low air density removes most of the medium (air molecules) necessary for a shock wave to have any substantial pressure.

Postulated HELBs are limited to an NPS 2 (1.687 inch inner diameter) pipe break in the degasification line at two locations. Larger piping inside the CNV (i.e., MSS and FWS) meets LBB criteria and is excluded from need to consider a sudden rupture causing a blast wave. Other NPS 2 piping initially contains subcooled fluid with negligible blast potential (Reference 1.4.3.7).

The potential for blast effects in the CNV is limited for three reasons:

a. The low atmospheric pressure means few air molecules are present to support formation of the blast wave. In other words, there is no medium to support propagation of the blast wave. By the time sufficient mass has been deposited in the CNV, the opportunity to form the blast wave has passed.

b. The only piping not excluded from pipe rupture is NPS 2, with a small mass and energy input. Also, the piping except for the degas line contains subcooled liquid; the presence of liquid in blowdown takes energy away from the blast (Reference 1.4.3.7).

c. Although safety-related components (e.g., ECCS valves) and instrumentation cables are nearby, they are hardened to withstand the CNV design pressure (1000 psia) and temperature of the CNV resulting from ECCS initiation, and the cables are enclosed in conduit in the vicinity of the RPV head.

Table F-3 shows maximum force results for an HELB inside the CNV from an NPS 2 degas line rupture. Blast effects are deemed negligible and not evaluated further.

F.1.3 In the NuScale Power Module Bay under the Bioshield

Piping in this portion of the plant is excluded from need of consideration of dynamic effects through satisfying BTP 3-4 break exclusion criteria.

F.1.4 In the Reactor Building

Ruptures of piping containing only steam can form a blast wave, limiting the potential impact to essential SSCs in the pipe galleries. Separation of essential components in compartments not containing high-energy piping eliminates most potential for negative effects, leaving the RXB structure, the CIV HPU skids, and multi-module effects to assess. Piping routing in the RXB is subject to change, which could affect the postulated HELB locations. In any case, there would be a considerable number of potential locations, so NuScale has taken the approach of identifying a bounding scenario:

- NPS 12 pipe break in the MSS – This is the largest diameter steam line in the RXB. Feedwater system and CVCS pipes are smaller than MSS piping and contain subcooled liquid at intact system conditions, which moderates formation of the blast wave.

- Break surroundings – Because routing of piping within the RXB has not been finalized, a conservative but hypothetical arrangement is used in which the break is postulated to occur close to another similar pipe at three different locations within a pipe gallery. This allows for developing a conservative loading on building structure and on a pipe representing a nearby line for another NPM.

F.2 Computational Fluid Dynamics Model

F.2.1 Computational Fluid Dynamics Code

This analysis was performed with the ANSYS CFD program CFX Version 18.0 on the servers running the RHEL Release 6.5 operating system. Correct program function was verified by the ANSYS Certificate of Conformance stored in the ANSYS user's controlled software file. Installation verification was documented and validation of the applicability of CFX for the analysis of HELB blast effects was performed as described in the next section.

F.2.2 Verification and Validation

Reference F.6.16 provides the verification and validation (V&V) of the CFX code for blast effects. Eight test cases were analyzed to validate the CFD methodology for analysis of supersonic flows and shock waves. The CFD methodology is applicable to the analysis of the effects of blast waves generated from sudden pipe ruptures as postulated for the NuScale reactor module design.

In each test case, comparison between the simulation results obtained on three levels of grid refinement and either experimental data or theoretical predictions was performed. The methodology of ASME V&V 20 (Reference F.6.8) was used to estimate the model error ($\delta model$) in each case. Typical model error, which is expressed as the average ratio of comparison difference and uncertainty to simulation results, is presented for each case in Table F-1.

Table F-1 Summary of average error from validation analysis

Case	Quantities Compared	Average Error (δ_{model}/S)
1) Shock reflection	Pressure, heat flux	21%
2) Oblique shock	Density, Mach number, temperature, pressure	1%
3) Transient shock wave	Mach disc location	5%
4) Steam-air shock tube	Mach number, pressure, temperature, density, contact surface	1%
5) Supersonic steam nozzle	Pressure	13%
6) Jet impingement – single phase	Force	16%
7) Jet impingement – multiphase	Force	8%
8) Blast into low pressure	Pressure	8%

F.2.2.1 Phenomena Identification

The formation of a blast wave and its propagation in a nuclear plant HELB features complex, interactive phenomena with limited data available to characterize the shock loads. The important aspects of modeling are the transfer of fluid mass and energy into the surrounding air, the formation and propagation of the shock wave, reflection and amplification in the crowded confines within the plant, and loading of SSC within range.

Based on the fundamental physics involved in the flow, the following characteristics are relevant to be present in a validation test suite:

1. supersonic compressible flow
2. shock behavior
3. transient shock propagation
4. multi-component gas behavior
5. real gas effects
6. shock reflection
7. phase change (minor effect)
8. environment initial pressure

The eight physical processes listed above guide the selection of the test cases. A test case may entail the modeling of more than a single process. Phase change due to rapid temperature and pressure fluctuations is not included in a test case because non-equilibrium condensation in supersonic jets downstream of the nozzle throat has been shown to increase total pressure loss in the jet (Reference F.6.9). Therefore, neglecting condensation effects is conservative for the analysis of loads due to HELB blast.

F.2.2.2 Test Case Selection

Validation of the CFD method and CFX code for modeling blast effects is achieved by running test problems and comparing the results to either theoretical or experimental results. Agreement between the CFX results and the reference values provides validation and confidence that the numerical approach and mesh adequately model the associated phenomena. This process validates the ability of CFX to predict the behavior of supersonic flows of both air and steam which are possible mechanisms that would govern fluid behavior following a pipe rupture in the NuScale plant.

To this end, the following eight cases were evaluated:

1. {{

}}$^{2(a),(c)}$

{{

}}2(a),(c)

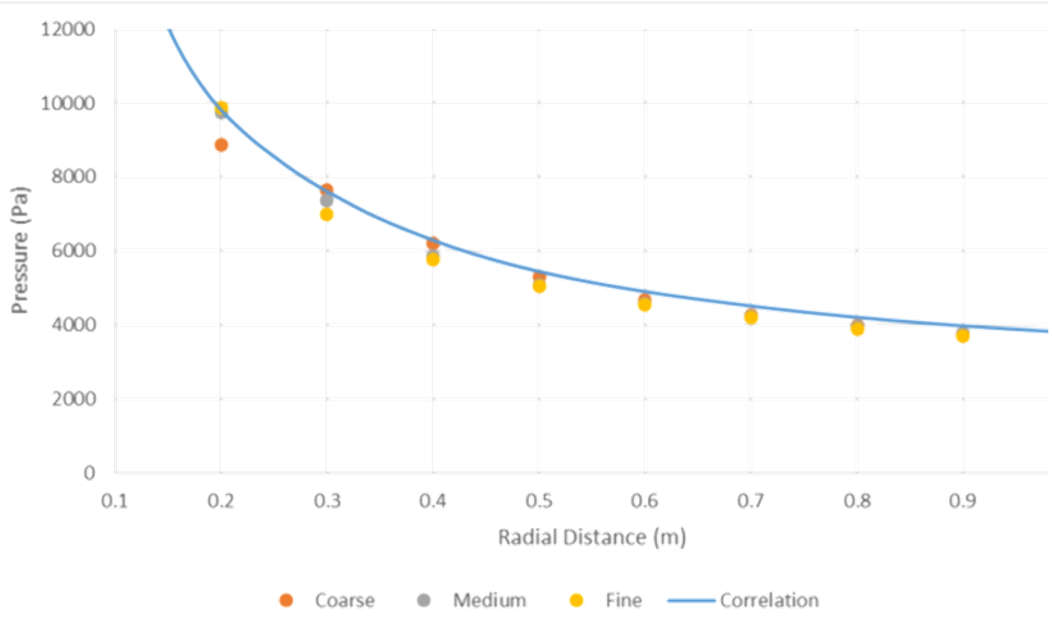


Figure F-3 Verification and validation case 8 results

F.3 Methodology

Each break scenario is analyzed in two parts: a steady-state simulation and a transient simulation. The steady-state represents the conditions before the pipe breaks. The transient simulation starts from the steady-state results and models an instantaneous, open-ended break of the pipe. The transient CFD results are then used to generate transient load profiles on several nearby SSC of interest.

Meshing is performed using the ANSYS Workbench Meshing module. The mesh is built with sufficient density to capture the relevant physics of the blast. Refinement is added around the postulated break using the “Sphere of Influence” method. Multiple concentric spheres are used to transition from the finest mesh directly around the break to the coarser mesh further away from the break location. Inflation layers are added to key surfaces to improve the flow resolution near surfaces. As part of the V&V of CFX for use in evaluating blast waves, the effects of mesh density were investigated. The mesh size in the vicinity of the pipe break is chosen to match the typical element size relative to the characteristic length scale of the meshes used in the V&V simulation.

F.4 Results of Blast Effects Modeling

F.4.1 In the Containment Vessel

F.4.1.1 Containment Vessel Break Scenarios

Three scenarios were selected to provide loads that bound the potential HELBs within the CNV. High point degasification line breaks were analyzed to bound any CVCS breaks in the CNV because lines filled with subcooled liquid do not cause a significant blast. Although blast effects are geometry dependent, the degasification line break locations are representative of the geometry of any of the CVCS lines at the RPV head or CNV head. Table F-2 summarizes the key modeling parameters.

Three different breaks of the degas line are considered as shown in :

Case 1: upward-oriented break at the RPV nozzle.
Case 2: downward-oriented break close to the RPV nozzle.
Case 3: upward-oriented break immediately inside the CNV head.

Table F-2 Overview of blast CFD modeling inside the CNV

Parameter	Selection	Discussion
Dimensionality	3D	Model is too complex for reduced dimensionality
Turbulence model	SST	SST model was validated as appropriate for blast waves
Energy model	Total energy	Total energy is required for modeling supersonic flows
Equation of state	Ideal gas	Appropriate per Section 1.4.3.1.2 of Reference F.6.15
Wall roughness	Smooth	Solid surfaces modeled smooth (zero sand grain roughness)
Buoyancy	None	Buoyancy effects not considered due to short timescales
Time discretization	Second order backward Euler	Recommended setting for accuracy
Space discretization	High resolution	Primarily a 2nd order accurate discretization that blends 1st order terms to ensure boundedness
Solver precision	Double	Reduces truncation error
Time step	Adaptive $10^{-7} – 10^{-5}$ s	Time step adjusted by solver to increase performance
RMS residuals	$< 10^{-5}$	Convergence criteria for RMS residual of all equations $<10^{-5}$
Compressibility control	High speed numerics	Improved performance and stability for high speed flows (transient portion only)
Topology estimate factor	1.05	Increases internal memory estimate (expert parameter)

The ambient pressure in the CNV is assumed to be 0.95 psia, although normal CNV pressure is below 0.1 psia. This is a reasonable upper limit for plant operation, because it corresponds to a saturation temperature of 100-degrees Fahrenheit, a likely maximum CNV wall temperature. A higher pressure is conservative because a higher density medium transmits the blast energy more effectively.

F.4.1.2 Containment Vessel Computational Fluid Dynamics Model

The simulation domain is generated from an NPM computer model of the CNV and RPV, and is simplified to remove unnecessary detail and to improve runtime of the simulations. The simplifications include removal of small components and reduction of detail for select larger components. Removed features include bolts, cables, and small pipes. These simplifications do not significantly affect the behavior of the blast wave. The SGS steam and feedwater pipes, for which loading is determined, and the degas line, which is postulated to break, are retained in the model. The overall geometry shown in is tailored to the different break locations by trimming the geometry.

To simulate the blast propagation through the air space, the solid model is inverted to produce a model of the fluid domain. This process uses the simplified model as a mold from which the air space is created. Figure F-5 and Figure F-6 show a visual representation of the computational mesh for Case 1.

{{

}}2(a),(c)

Figure F-4 Simplified containment vessel model showing break locations and key structures, systems, and components

{{

}}$^{2(a),(c)}$

Figure F-5   Cutaway view of the mesh in the center of the model (case 1)

{{

}}$^{2(a),(c)}$

Figure F-6 Detailed view of the mesh around the pipe break (case 1)

Immediately following the break, a blast wave is formed when high pressure steam is released from the pipe. The steam quickly accelerates to supersonic velocities and propagates a supersonic pressure wave that takes the form of a blast in air. The blast expands radially outward from the break location. In each case, the blast is biased in the direction along the pipe axis. Targets in the immediate vicinity of the break are subject to the highest pressure loads. The blast loads for close targets are quickly surpassed by the jet that imparts higher loads on the targets. The opposite end of the ruptured pipe receives a significant load due to both the blast and jet.

The blast is reflected by solid surfaces and may reach areas that are shielded from the initial blast. The reflecting surface is loaded by a pressure greater than the incident pressure. However, the pressure magnitudes are small because the vacuum conditions inside the CNV do not propagate the blast wave well.

The effects of the HELB on the surrounding structures and components can be divided into two separate physical phenomena: blast and jet. The blast is created when high pressure steam expands into the lower pressure surroundings. It is characterized by a supersonic shock front that causes a sudden pressure increase as it propagates through the surrounding medium. The blast is not associated with bulk mass transport. Conversely, the jet is characterized by bulk mass transport and forms a continuous region that is connected to the break location. Because the medium inside and outside of the pipe are different, mass fractions provide a convenient way to distinguish the blast and jet. Based on post-processing of the results, a cutoff of 10 percent steam is reasonable to distinguish between blast and jet. This distinction is used to visually separate the blast and jet effects in the contour plots provided below, where grey shading is indicative of steam from the jet.

The forces on selected components are monitored continuously during the simulated transient. The calculated forces are plotted in Figure F-7 for Case 1. The traces for most loads show three distinct regions: 1) a distinct spike indicative of the sudden arrival of the blast wave and the associated load, 2) a decrease of loading as the blast wave clears the component, and 3) a sustained rise in load which eventually reaches a steady state that is caused by the impingement.

Figure F-8 provides pressure contour plots at four time steps for Case 1. The results show blast pressures are low, dissipate quickly, and have a short range. Figure F-9 provides pressure contours at one time step for Cases 2 and 3, showing similar behavior. Because of the weak blast front in the low-pressure surroundings, the peak blast loads from the three CNV cases are low (Table F-3) and are bounded by the jet impingement loads.

{{

}}$^{2(a),(c)}$

Figure F-7 Time history of total forces on key SSC for CNV Case 1

{{

}}$^{2(a),(c)}$

Figure F-8 Absolute pressure contours at four time steps for CNV blast Case 1

{{

}}$^{2(a),(c)}$

Figure F-9 Absolute pressure contours for CNV Cases 2 & 3

Table F-3 Maximum total forces on selected components for blasts in the containment vessel

Component	CNV Head	RPV Head	MS Piping (Upper/Lower)	Support Beam	ECCS Valve	Bounding CRDM Tube	FWS Pipe
Force (lbf)	{{						}}$^{2(a),(c)}$

F.4.2 In the Reactor Building

F.4.2.1 Reactor Building Blast Scenarios

Given that the design of the NuScale RXB and pipe layout is not final, the following three different breaks of the main steam line are considered to generate a diverse set of break conditions with bias towards maximizing blast wave reflection and dynamic loads on representative components (e.g., valve bodies, MSS line, FWS line):

Case 1: break at a MS line in the mid-gallery with the blast traveling horizontally from the turbine side towards the pool wall.
Case 2: break at a MS line in the mid-gallery with the blast traveling horizontally from the reactor side towards the RXB wall.
Case 3: break at a MS line in the gallery corner with the blast traveling horizontally from the turbine side towards the pool wall.

F.4.2.2 Reactor Building Blast Model

Table F-4 summarizes key modeling parameters for the RXB blast analysis. Geometry of the modeled region of the RXB is shown in Figure F-10. The three break locations are shown in Figure F-11. Breaks in MSS lines are analyzed because of their large diameter and high-energy content. Figure F-12 identifies SSC of interest in the modeled region, and Table F-5 is the key identified which SSC correspond to each number. Figure F-13 depicts the mesh used for RXB Case 1.

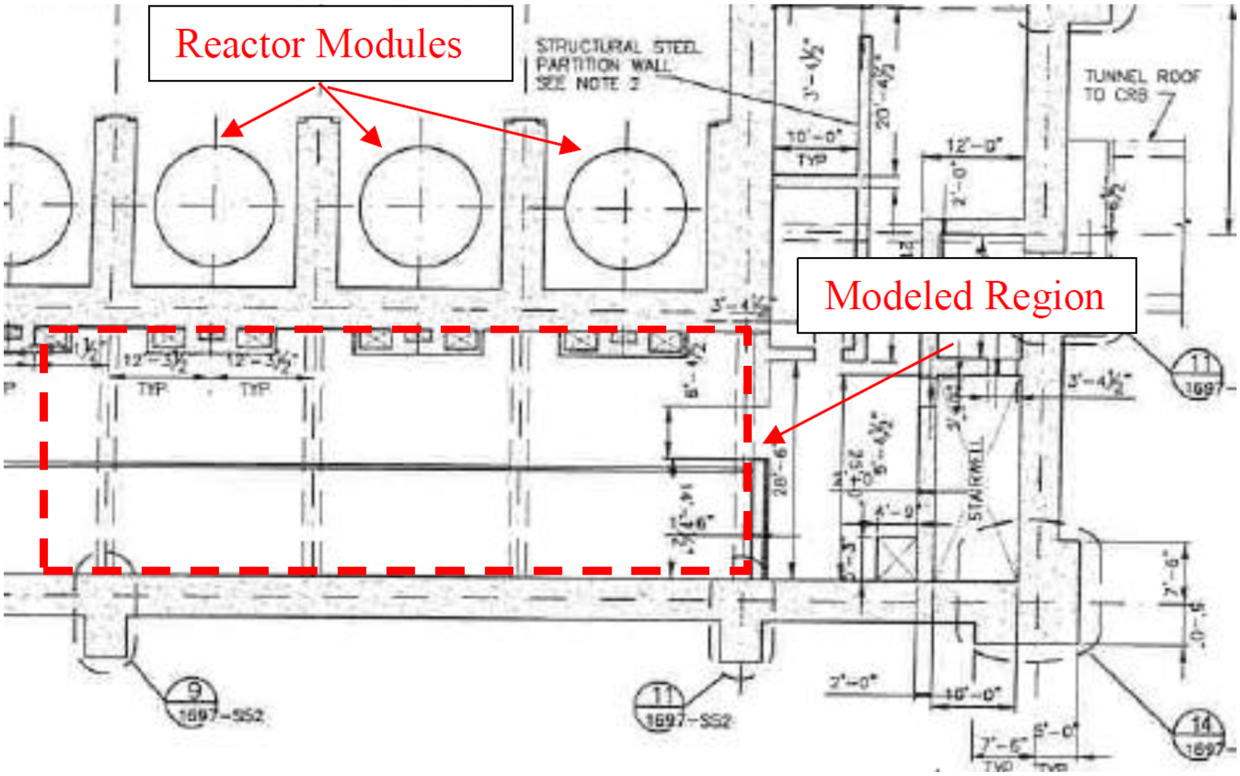


Figure F-10 Modeled region of reactor building

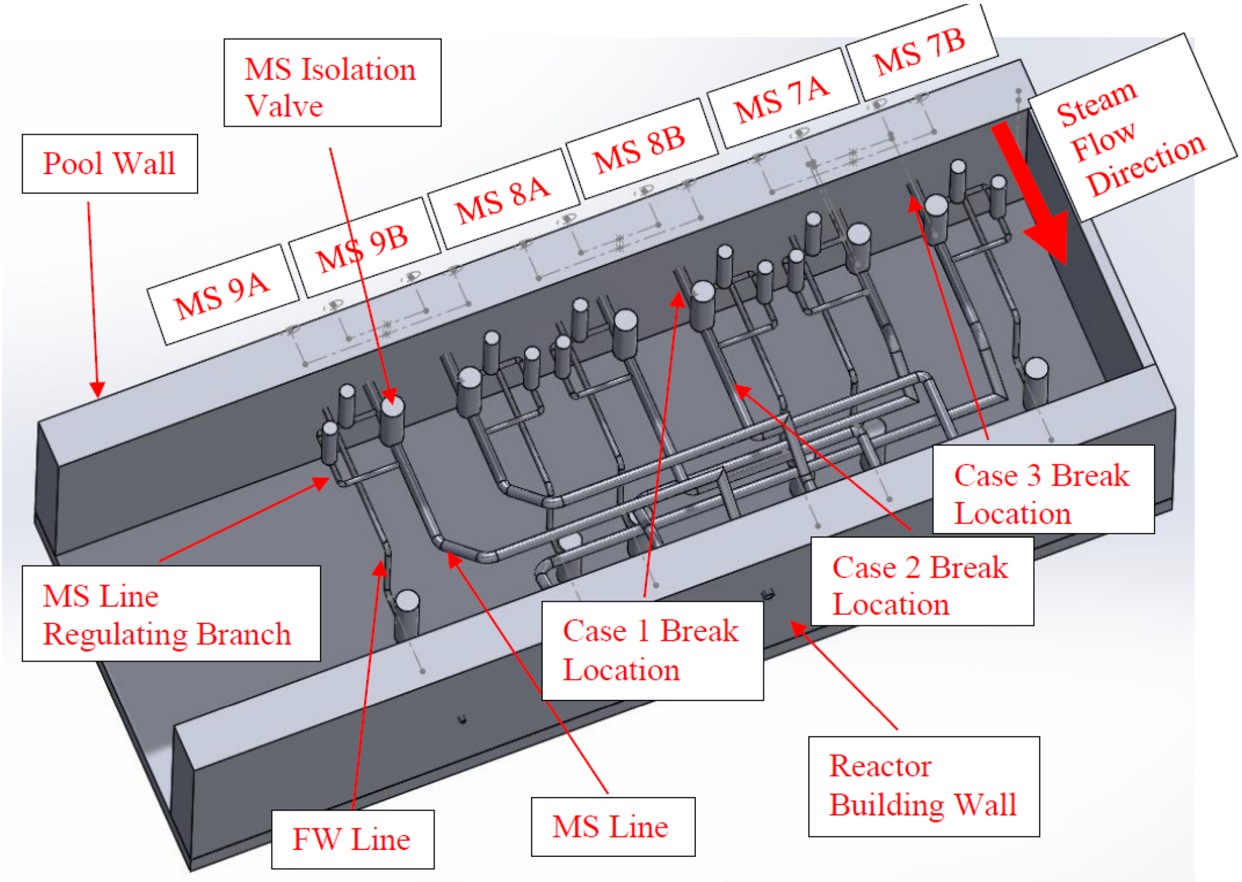


Figure F-11 Geometry of part of one pipe gallery in reactor building showing break locations

Table F-4 Overview of modeling scheme for blast analysis in reactor building

Parameter	Selection	Discussion
Turbulence Model	Shear Stress Transport (SST)	SST model was validated as appropriate for blast wave simulation
Energy Model	Total Energy	Total energy is required for modeling supersonic flow
Buoyancy	None	Buoyancy effects not considered due to short timescales
Time Discretization	High Resolution	Primarily a 2nd order accurate discretization that blends 1st order terms to ensure boundedness
Space Discretization	High Resolution	Blend of 1st and 2nd order terms to ensure robustness and accuracy. Blend factor is based on solution values.
Solver Precision	Double	Reduces the truncation error
Time Step	Adaptive $10^{-6} – 10^{-5}$ s	Time step adjusted by solver to achieve appropriate Courant number.
RMS Residuals	$< 10^{-5}$	Convergence criteria for RMS residual of all equations less than 10^{-5} per Section 15.10.1.1.1 of Appendix F of Reference 9.
Solver Control	High Speed	Improved performance and stability for high speed flows

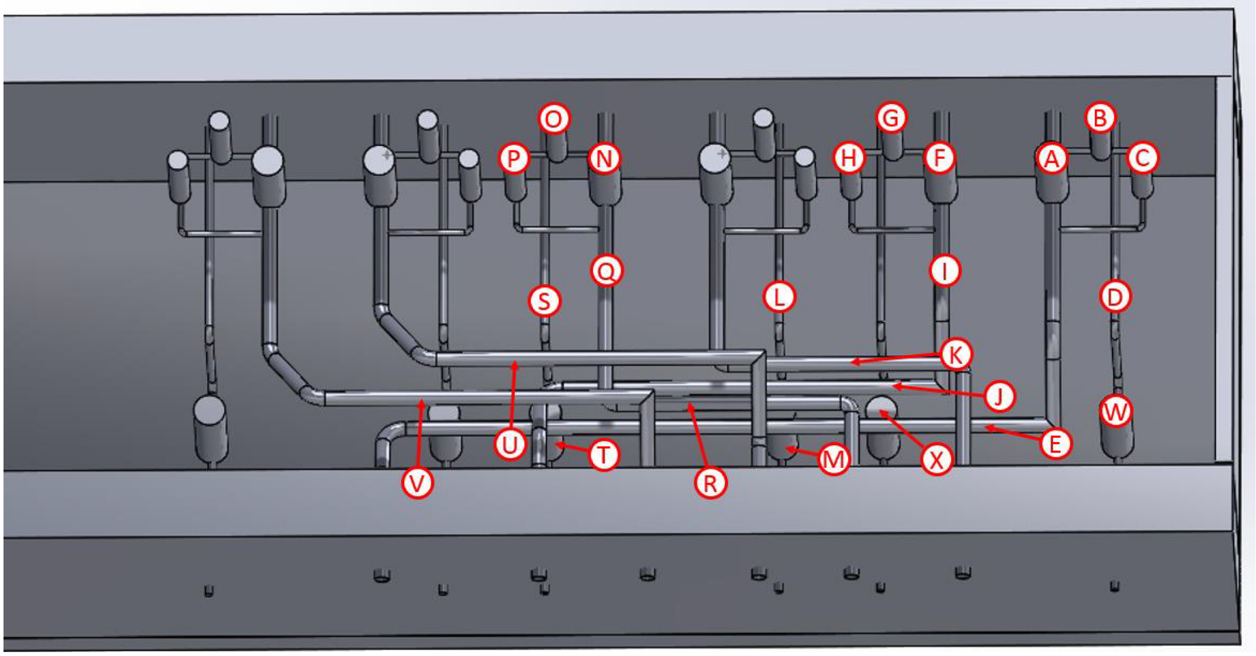


Figure F-12 Identification of components in reactor building

Table F-5 Key to reactor building SSC of interest for blast effects

Component Label in Figure F-12	Component Name	Description
A	MS7B Valve	MS line 7B isolation valve
B	MS7B BPV#1	MS line 7B bypass valve #1
C	MS7B BPV#2	MS line 7B bypass valve #2
D	FW Line 7B	Feedwater line 7B
E	MS Line 7B EW	MS line 7B east-west section
F	MS7A Valve	MS line 7A isolation valve
G	MS7A BPV#1	MS line 7A bypass valve #1
H	MS7A BPV#2	MS line 7A bypass valve #2
I	MS Line 7A NS	MS line 7A north-south section
J	MS Line 7A EW	MS line 7A east-west section
K	MS Line 8B EW	MS line 8B east-west section
L	FW Line 8B	Feedwater line 8B
M	FW8B Valve	Feedwater line 8B isolation valve
N	MS8A Valve	MS line 8A isolation valve
O	MS8A BPV#1	MS line 8A bypass valve #1
P	MS8A BPV#2	MS line 8A bypass valve #2
Q	MS Line 8A NS	MS line 8A north-south section
R	MS Line 8A EW	MS line 8A east-west section
S	FW Line 8A	Feedwater line 8A
T	FW8A Valve	Feedwater line 8A isolation valve
U	MS Line 9B EW	MS line 9B east-west section
V	MS Line 9A	EW MS line 9A east-west section
W	FW7B Valve	Feedwater line 7B isolation valve
X	FW7A Valve	Feedwater line 7A isolation valve

{{

}}$^{2(a),(c)}$

Figure F-13 Cross-section view and close-up view of the mesh in case 1

F.4.2.3 Reactor Building Blast Results

The blast wave propagation from the MS8B break for Case 1 is provided in Figure F-14. Regions with steam content higher than 10 percent are colored white to distinguish between regions with blast effects and jet effects.

Figure F-15 provide the force-time histories for SSC. The curves show an initial peak when the leading blast wave impacts the object. The duration of this largest, initial peak is in general about one millisecond, characteristic of an impulse load that is applied and gone too quickly for the SSC to be damaged.

The subsequent peaks are associated with reflected waves that arrive after the leading wave. MS Line 8A and MS8A Valve are the two components that experienced the highest forces due to blast waves during the transient. The maximum forces on MS Line 8A NS section and MS8A Valve, which are parallel to the broken pipe, are {{ }}$^{2(a),(c)}$, respectively. The maximum force exerted on the pool wall is {{ }}$^{2(a),(c)}$, which is induced by the combination of the jet and blast shock front.

{{

}}$^{2(a),(c)}$

Figure F-14 Pressure contours for three time steps for reactor building blast Case 1

{{

}}$^{2(a),(c)}$

Figure F-15 Force time history for various SSC for reactor building blast Case 1

Table F-6 Peak blast wave forces on selected SSC

Case	Component[1]	Peak Force (lbf)
Case 1 MS8B break towards Pool Wall	MS Line 8A Isolation Valve	{{
	MS Line 8A (north-south section)	
	Pool Wall	
Case 2 MS8B break towards Reactor Building Wall	MS Line 9B (east-west section)	
	MS Line 8A (north-south section)	
	MS Line 7B Bypass Valve #1	
Case 3 MS7B break towards Pool Wall	MS Line 7A Isolation Valve	
	Pool Wall	}}$^{2(a),(c)}$

1. See Figure F-12 and Table F-5 for components locations.
2. The force is induced by the combination of the jet and blast shock front over the surface on the pool wall that is centered at the break point with a radius of 100 inches. This radius corresponds to the spherical propagation of the shock front at approximately 2.3 ms.

F.5 Conclusions

Three-dimensional CFD analysis of blast wave formation in the CNV and RXB has been performed using conservative modeling assumptions that bound the pressurization effects that may occur for any HELBs in the plant. Blast wave force time histories were calculated for nearby SSC of interest. The results show:

- Peak forces are low and bounded by the jet thrust forces that subsequently develop. The low values are because NuScale HELBs are relatively small diameter and deposit a small amount of mass and energy in the less than one millisecond that it takes for a blast wave to form. The forces inside the CNV are particularly low because the initial low ambient pressure does not support formation of a significant blast wave.
- The forces of the passing shock wave are of very short duration.

Therefore, detrimental effects of HELB-induced blast waves anywhere in the NuScale plant can be ignored.

F.6 References

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Enclosure 3:

Affidavit of Zackary W. Rad, AF-0719-66191

NuScale Power, LLC

AFFIDAVIT of Zackary W. Rad

I, Zackary W. Rad, state as follows:

(1) I am the Director of Regulatory Affairs of NuScale Power, LLC (NuScale), and as such, I have been specifically delegated the function of reviewing the information described in this Affidavit that NuScale seeks to have withheld from public disclosure, and am authorized to apply for its withholding on behalf of NuScale

(2) I am knowledgeable of the criteria and procedures used by NuScale in designating information as a trade secret, privileged, or as confidential commercial or financial information. This request to withhold information from public disclosure is driven by one or more of the following:

(a) The information requested to be withheld reveals distinguishing aspects of a process (or component, structure, tool, method, etc.) whose use by NuScale competitors, without a license from NuScale, would constitute a competitive economic disadvantage to NuScale.

(b) The information requested to be withheld consists of supporting data, including test data, relative to a process (or component, structure, tool, method, etc.), and the application of the data secures a competitive economic advantage, as described more fully in paragraph 3 of this Affidavit.

(c) Use by a competitor of the information requested to be withheld would reduce the competitor's expenditure of resources, or improve its competitive position, in the design, manufacture, shipment, installation, assurance of quality, or licensing of a similar product.

(d) The information requested to be withheld reveals cost or price information, production capabilities, budget levels, or commercial strategies of NuScale.

(e) The information requested to be withheld consists of patentable ideas.

(3) Public disclosure of the information sought to be withheld is likely to cause substantial harm to NuScale's competitive position and foreclose or reduce the availability of profit-making opportunities. The accompanying technical report reveals distinguishing aspects about the methodology and process by which NuScale develops its pipe rupture hazards analysis (PRHA).

NuScale has performed significant research and evaluation to develop a basis for this PRHA methodology and has invested significant resources, including the expenditure of a considerable sum of money.

The precise financial value of the information is difficult to quantify, but it is a key element of the design basis for a NuScale plant and, therefore, has substantial value to NuScale.

If the information were disclosed to the public, NuScale's competitors would have access to the information without purchasing the right to use it or having been required to undertake a similar expenditure of resources. Such disclosure would constitute a misappropriation of NuScale's intellectual property, and would deprive NuScale of the opportunity to exercise its competitive advantage to seek an adequate return on its investment.

(4) The information sought to be withheld is in the enclosed technical report titled "Pipe Rupture Hazards Analysis Technical Report." The enclosure contains the designation "Proprietary" at the top of each page containing proprietary information. The information considered by NuScale to be proprietary is identified within double braces, "{{ }}" in the document.

(5) The basis for proposing that the information be withheld is that NuScale treats the information as a trade secret, privileged, or as confidential commercial or financial information. NuScale relies upon

the exemption from disclosure set forth in the Freedom of Information Act ("FOIA"), 5 USC § 552(b)(4), as well as exemptions applicable to the NRC under 10 CFR §§ 2.390(a)(4) and 9.17(a)(4).

(6) Pursuant to the provisions set forth in 10 CFR § 2.390(b)(4), the following is provided for consideration by the Commission in determining whether the information sought to be withheld from public disclosure should be withheld:

(a) The information sought to be withheld is owned and has been held in confidence by NuScale.

(b) The information is of a sort customarily held in confidence by NuScale and, to the best of my knowledge and belief, consistently has been held in confidence by NuScale. The procedure for approval of external release of such information typically requires review by the staff manager, project manager, chief technology officer or other equivalent authority, or the manager of the cognizant marketing function (or his delegate), for technical content, competitive effect, and determination of the accuracy of the proprietary designation. Disclosures outside NuScale are limited to regulatory bodies, customers and potential customers and their agents, suppliers, licensees, and others with a legitimate need for the information, and then only in accordance with appropriate regulatory provisions or contractual agreements to maintain confidentiality.

(c) The information is being transmitted to and received by the NRC in confidence.

(d) No public disclosure of the information has been made, and it is not available in public sources. All disclosures to third parties, including any required transmittals to NRC, have been made, or must be made, pursuant to regulatory provisions or contractual agreements that provide for maintenance of the information in confidence.

(e) Public disclosure of the information is likely to cause substantial harm to the competitive position of NuScale, taking into account the value of the information to NuScale, the amount of effort and money expended by NuScale in developing the information, and the difficulty others would have in acquiring or duplicating the information. The information sought to be withheld is part of NuScale's technology that provides NuScale with a competitive advantage over other firms in the industry. NuScale has invested significant human and financial capital in developing this technology and NuScale believes it would be difficult for others to duplicate the technology without access to the information sought to be withheld.

I declare under penalty of perjury that the foregoing is true and correct. Executed on July 31, 2019.

Zackary W. Rad