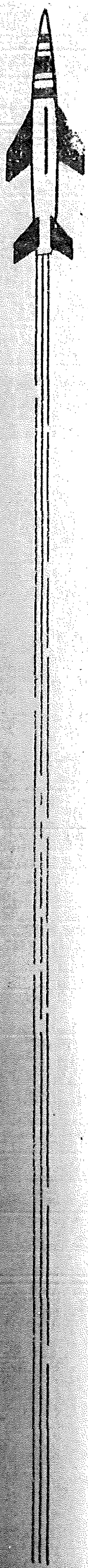

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A STUDY OF ROCKET ENGINE TESTING IN THE ENGINE TEST FACILITY

By

Aerojet-General Corporation
Covina, California

June 1959

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ARNOLD ENGINEERING DEVELOPMENT CENTER

AIR RESEARCH AND DEVELOPMENT COMMAND

U S A F

Approved for public release

Per AF letter dt'd 5 Feb. 7
W.O Cole, STINFO

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A STUDY OF ROCKET ENGINE TESTING IN THE ENGINE TEST FACILITY

ARNOLD ENGINEERING DEVELOPMENT CENTER
Tullahoma, Tennessee

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Aerojet-General Corporation
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W.O. Cole, STINFO

The research reported herein was performed by Aerojet-General Corporation under AEDC sponsorship - Contract No. AF 40(600)-740.

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I. INTRODUCTION

The purpose of this report is to determine the maximum sizes of rocket engines which can be tested in Test Cell T1, T2, T4, J1 and J2 of the Engine Test Facility (ETF) at Arnold Engineering Development Center (AEDC). This determination has been based on the structural ability of the test cells to contain explosions resulting from malfunctions occurring during tests conducted on rocket engines burning several different liquid and solid propellant combinations. The propellants selected for study are those currently in use and those which appear most likely to be used in the near future. It has been assumed in the study that necessary safety precautions will be followed and that the fastest acting control devices presently available will be used.

The test cells under consideration are in close proximity to their control rooms and millions of dollars worth of specialized equipment. This fact dictates the necessity of the test cells being able to contain any explosion resulting from a malfunction. For this reason it is recommended that the engine sizes be so limited that any resulting explosion will not cause more than slight damage to the cells as defined in the Corps of Engineers Manual, "Fundamentals of Protective Design."

Following are Usage Tables which show the maximum sizes of rocket engines which, in the event of the worst possible explosion that can be expected from test malfunctions, will result in no damage and slight damage to the various test cells. The engines are sized by thrust in the case of liquid engines and by total propellant weight for solid engines. It can be seen from these tables that liquid engines, burning propellants presently in use, between the ranges of 10, 000 to 70, 000 lbs thrust and solid engines with total propellant weight up to 1000 lbs can be safely tested in ETF.

USAGE TABLE FOR T1 & T2

			ENGINE THRUST SIZE IN LBS.	
LIQUID PROPELLANTS	TNT EQUIV.	Isp	NO DAMAGE	SLIGHT DAMAGE
LIQ. FLUORINE - LIQ HYDROGEN	2.4	365	4,560	10,000
LIQ. FLUORINE - HYDRAZINE	1.8	316	5,270	11,600
LIQ. FLUORINE - AMMONIA	1.8	312	5,210	11,470
NITROGEN TETROXIDE - HYDRAZINE	1.2	257	6,420	14,180
CHLORINE TRIFLUORIDE - HYDRAZINE	1.1	247	6,750	14,900
LOX - JP - 4	1.8	261	4,350	9,540
LOX - UDMH	1.7	270	4,770	10,500
LOX - HYDROGEN	2.3	379	4,960	10,900
BROMINE PENTAFLUORIDE - 33 % HYDRAZINE - 67 % AMMONIA	0.7	293	12,600	27,000
SOLID PROPELLANTS			WT. OF GRAIN	
AMMONIUM PERCHLORATE POLYSULFIDE	0.3		100 LBS	220 LBS
ALUMINIZED NITROCELLULOSE	0.8		37.5 LBS	82 LBS
ALUMINIZED POLYURETHANE	0.3		100 LBS	220 LBS

N.D. - 15/0.5 = 30 LBS TNT

S.D. - 33/0.5 = 66 LBS TNT

TABLE I

USAGE TABLE FOR T 4

			ENGINE THRUST SIZE IN LBS	
LIQUID PROPELLANTS	TNT EQUIV.	Isp	NO DAMAGE	SLIGHT DAMAGE
LIQ. FLUORINE - LIQ. HYDROGEN	2.4	365	4,560	15,800
LIQ. FLUORINE - HYDRAZINE	1.8	316	5,270	18,300
LIQ. FLUORINE - AMMONIA	1.8	312	5,210	18,100
NITROGEN TETROXIDE - HYDRAZINE	1.2	257	6,420	22,400
CHLORINE TRIFLUORIDE - HYDRAZINE	1.1	247	6,750	23,500
LOX - JP-4	1.8	261	4,350	15,000
LOX - UDMH	1.7	270	4,770	16,600
LOX - HYDROGEN	2.3	379	4,960	17,200
BROMINE PENTAFLUORIDE - 33 % HYDRAZINE 67 % AMMONIA	0.7	293	12,600	42,600
SOLID PROPELLANTS			WT. OF GRAIN	
AMMONIUM PERCHLORATE POLYSULFIDE	0.3		100 LBS	347 LBS
ALUMINIZED NITROCELLULOSE	0.8		375 LBS	130 LBS
ALUMINIZED POLYURETHANE	0.3		100 LBS	347 LBS

N.D. - 15/0.5 = 30 LBS TNT.
S.D. - 52/0.5 = 104 LBS TNT

TABLE 1A

USAGE TABLE FOR J-1

PRESSURE CAPSULE

			ENGINE THRUST SIZE IN LBS.	
LIQUID PROPELLANTS	TNT EQUIV.	Isp	NO DAMAGE	SLIGHT DAMAGE
LIQ. FLUORINE - LIQ. HYDROGEN	2.4	365	7,560	27,400
LIQ. FLUORINE - HYDRAZINE	1.8	316	8,760	31,600
LIQ. FLUORINE - AMMONIA	1.8	312	8,640	31,200
NITROGEN TETROXIDE - HYDRAZINE	1.2	257	10,700	38,400
CHLORINE TRIFLUORIDE - HYDRAZINE	1.1	247	10,750	38,700
LOX - JP-4	1.8	261	7,230	26,100
LOX - UDMH	1.7	270	7,950	28,700
LOX - HYDROGEN	2.3	379	8,250	29,800
BROMINE PENTAFLUORIDE - 33% HYDRAZINE - 67% AMMONIA	0.7	293	20,940	75,600
SOLID PROPELLANTS			WT. OF GRAIN	
AMMONIUM PERCHLORATE POLYSULFIDE	0.3		167 LBS	600 LBS
ALUMINIZED NITROCELLULOSE	0.8		62.5 LBS	225 LBS
ALUMINIZED POLYURETHANE	0.3		167 LBS	600 LBS

N.D. - 25/.5 = 50. LBS TNT

S.D. - 90/.5 = 180 LBS TNT

TABLE 2

USAGE TABLE FOR J-2

PRESSURE CAPSULE

			ENGINE THRUST SIZE IN LBS.	
LIQUID PROPELLANTS	TNT EQUIV.	Isp	NO DAMAGE	SLIGHT DAMAGE
LIQ. FLUORINE - LIQ. HYDROGEN	2.4	365	13,100	47,200
LIQ. FLUORINE - HYDRAZINE	1.8	316	15,140	54,500
LIQ. FLUORINE - AMMONIA	1.8	312	14,900	53,500
NITROGEN TETROXIDE - HYDRAZINE	1.2	257	18,400	66,000
CHLORINE TRIFLUORIDE - HYDRAZINE	1.1	247	19,300	69,000
LOX - JP-4	1.8	261	12,400	44,700
LOX - UDMH	1.7	270	13,700	49,200
LOX - HYDROGEN	2.3	379	14,160	51,000
BROMINE PENTAFLUORIDE - 33% HYDRAZINE - 67% AMMONIA	0.7	293	36,000	129,600
SOLID PROPELLANTS			WT. OF GRAIN	
AMMONIUM PERCHLORATE POLYSULFIDE	0.3		288 LBS	1040 LBS
ALUMINIZED NITROCELLULOSE	0.8		108 LBS	389 LBS
ALUMINIZED POLYURETHANE	0.3		288 LBS	1040 LBS

N.D. - 43/.5 = 85.8 LBS TNT

S.D. - 155/.5 = 310 LBS TNT

TABLE 3

II. GENERAL

The testing of rocket engines in a confined area such as the ETF test cells is affected by the following characteristics of the facility.

A. TEST CELL SIZE

The test cells are large enough to accommodate large rocket engines and it is believed that as larger engines are considered the testing will be limited by considerations other than that of the physical size of the cells.

B. MALFUNCTIONS

1. General

Malfunctions of a rocket engine under test are caused by the improper operation of any one or combination of its electrical, mechanical or chemical parts. The frequency of malfunctions is further dependent upon the degree of development of the engine under test. In a test facility devoted primarily to qualification testing, the frequency of serious mishaps, such as explosions, is relatively low. In development testing the frequency of malfunctions can be expected to vary inversly with the stage of development of the engine under study. In the very early stages of development, a malfunction and explosion is considerably more likely than a successful test. It is expected that rocket engine testing in ETF will be primarily of engines in an advanced state of design.

The occurrence of explosions during rocket engine testing is possible in all stages of development of a particular engine, therefore, every engine firing is, to some extent, a calculated risk. While equipment and material may be subjected to these calculated risks, every effort should be made to minimize or eliminate risk to personnel. The proximity of the control rooms to the test cells in the ETF area will thus limit the size of engines that might be tested on a calculated risk basis.

2. Malfunctions Resulting in Explosions

In the case of solid propellant engines, a rocket motor complete with one or more grains of propellant, would be mounted in the test cell and ignited by means of an electrical circuit, and squibs, black powder or other pyrotechnic devices. The grains of propellant under proper conditions burn at a predetermined rate resulting in high velocity exhaust gases which produce the required thrust.

Should the ignition be improper or the propellant grain not uniform, an explosion could ensue. Control devices to limit the explosion in this case are not presently available or in prospect in the near future. Therefore, no solid propellant engine should be tested in a test cell if the total weight of propellant it contains could cause more than slight damage to the cell in the event of an explosion. The basis for prediction of damage resulting from an explosion is more fully explained in Section IV of this report. Certain solid propellants that will not detonate at ordinary temperatures become highly detonable at low temperatures and this fact should likewise be considered before testing.

The testing of liquid propellant rocket engines can be handled and controlled to some extent more satisfactorily than solid propellant engines. Propellant test tanks should be located outside of the test cells in order to minimize the amount of propellants present in the test cells at any time. In this case, explosions can result from an accumulation of fuel and oxidizer in the test cell, resulting from ruptured propellant lines or an ignition failure. In both cases the possible explosion can be limited by controlling the amount of fuel and oxidizer that could enter the test cell after the line rupture or ignition failure occurred. Control devices to accomplish this would include pressure switches that sense when the pressure build up in the combustion chamber is not according to program, or when the lines lose pressure unexpectedly. The pressure switch then actuates electrical circuits which in turn actuate solenoid valves which finally actuate shut-off valves in the fuel and oxidizer lines. Leak detectors, or temperature switches, can be used in place of or in conjunction with the pressure switches. Shut-off valves that can be actuated in 150 milliseconds including time lags in the sensing device and solenoid valve have been found to be available. Actuation times such as these for valves over 2 inches in size will require a bleed system, surge system or flow diversion system to keep the water hammer effect of quick shut-off within reasonable limits. However, these systems present no unusual design problems.

The amount of propellant that can contribute to a detonation in the test cell would be the sum of the wet weight of propellant in the thrust chamber, turbopump units and lines; plus the amount in the piping from the engine to the sides of the cell (where the fast acting valves will be located); plus the amount entering cell after a malfunction is detected until propellant shut-off valves are fully closed. Thus, even with extremely fast acting valves, an amount of propellant equivalent to approximately a full second's flow could be in the test chamber and could conceivably contribute to the total explosion.

The size of engine that can be safely tested can be determined from the TNT equivalent of the maximum amount of propellant that could contribute to an explosion which would produce slight damage to the cell.

C. PROPELLANT TANKS

The propellant test tanks can be either permanent or mobile units. They will be located on opposite sides of the test cell. A dike or other type of impervious barrier will be necessary to prevent mixing of fuel and oxidizer, should a leak or break occur in one of the test tanks.

In addition, where a fluid such as fluorine may become spilled, it will be necessary to have neutralizing equipment available to accommodate any possible spillage.

D. EXHAUST PRODUCTS

Exhaust gases from rocket engines vary with the type of fuel and oxidizer employed and the degree of combustion which has occurred. Many existing and potential combinations of fuels and oxidizer will produce exhaust products which are highly noxious and/or corrosive. The discharge of these products into the air within a congested area such as the ETF would be highly dangerous and undesirable. It will, therefore, be necessary to have a neutralizing, scrubbing, and collecting system where the exhaust can be made innoxious before discharge into the atmosphere.

III. DESCRIPTION OF EXISTING FACILITY

A. GENERAL

The Engine Test Facility (ETF) referred to herein is defined as the basic ETF plus the Engine Test Facility Addition (ETFA) formerly known as the Ramjet Addition.

B. DESCRIPTION

To properly evaluate the testing of rocket engines in a facility designed for air-breathing engines using low energy fuels, a detail study of existing equipment and structures was conducted. This study was concerned primarily with the test cells and components of the cells that are effected by the presence of rocket engines fired under static conditions.

1. Basic Engine Test Facility

The basic ETF consists of a series of high-altitude test cells connected to a flexible air supply and exhaust system. Four compressor systems, arranged for parallel operation, supply air to the test cells. Equipment for cooling, heating and drying of air provide process air for varied altitudes, temperatures, and speed conditions. Air flows of 165 lbs per second at a temperature of -120°F to 200 lbs per second at a temperature of +200°F are obtained from the basic ETF air supply system. By utilizing the ETFA, flow conditions in the basic test cells can be increased to 500 lbs per second at temperatures up to 650°F.

The basic ETF exhaust system consists of six compressors. These compressors can be used in various configurations to provide exhaust conditions as dictated by the test program.

2. Engine Test Facility Addition

Basically the ETFA is similar to the basic ETF. It contains an air supply system, test sections, and exhaust system. The air supply system consists of two low stage and one high stage compressor. Air from the basic ETF is utilized as the first stage of compression for the high stage compressor and is combined with the discharge from the low stage compressors to provide air flows to 500 lbs per second. Air flows to 1000 lbs per second may be obtained for short periods by utilizing 500 lbs per second from the air storage tank of the adjacent gas dynamics facility. The arrangement of the test cells, or supply system, and exhauster system of ETF and ETFA is shown in Figure 1.

3. Test Cells

a. Test Cell T-1 consists of an entrance section, a variable length test chamber and a water-jacketed flame chamber. The entrance section connects the test chamber to the inlet air ducting. The testing chamber is made up of a fixed section 33'-4" long by 12'-4" in diameter. This length may be increased to 78'-0" by adding section segments. The flame chamber connects the test chamber to the exhaust ducting. The flame chamber may also be extended by inserting section segments.

The test article is mounted in the test chamber on a model support car, which is connected to a thrust stand to provide rigid support. Rails for moving the car into position, and bolting slots in the walls for mounting hardware, are provided in the chamber.

Engine exhaust gases are ducted from the flame chamber through sections of ducting containing spray nozzles, where they are cooled, and either exhausted to atmosphere or routed to the exhaust compressors.

Operations of the ETF plant equipment is controlled from the central control room located in the test building. The instrumentation and data recording equipment is maintained in individual control rooms adjacent to the test cells. Instrumentation lines lead from the control room to disconnect panels at the test cell.

Explosion-relief ports and carbon dioxide fire extinguishing systems provide protection in case of explosion or fire within the test cell.

b. Test Cell T-2 is similar to T-1, except the fixed portion of the test chamber is 30'-5" in length. The variable length is a maximum of 58'-0". The test chamber and flame chamber extension segments are interchangeable with Test Cell T-1.

c. Test Cell T-4 is designed primarily for testing ramjets, and it is a completely water-jacketed cell. The entrance section contains a variable Mach number, variable angle of attack, supersonic nozzle. The cell is 12'-4" in diameter with the test chamber being variable in length from 19 to 78 ft. T-4, as do T-1 and

T-2, has provisions for installing a removable diffuser in the quick lock section between the test chamber and the flame chamber.

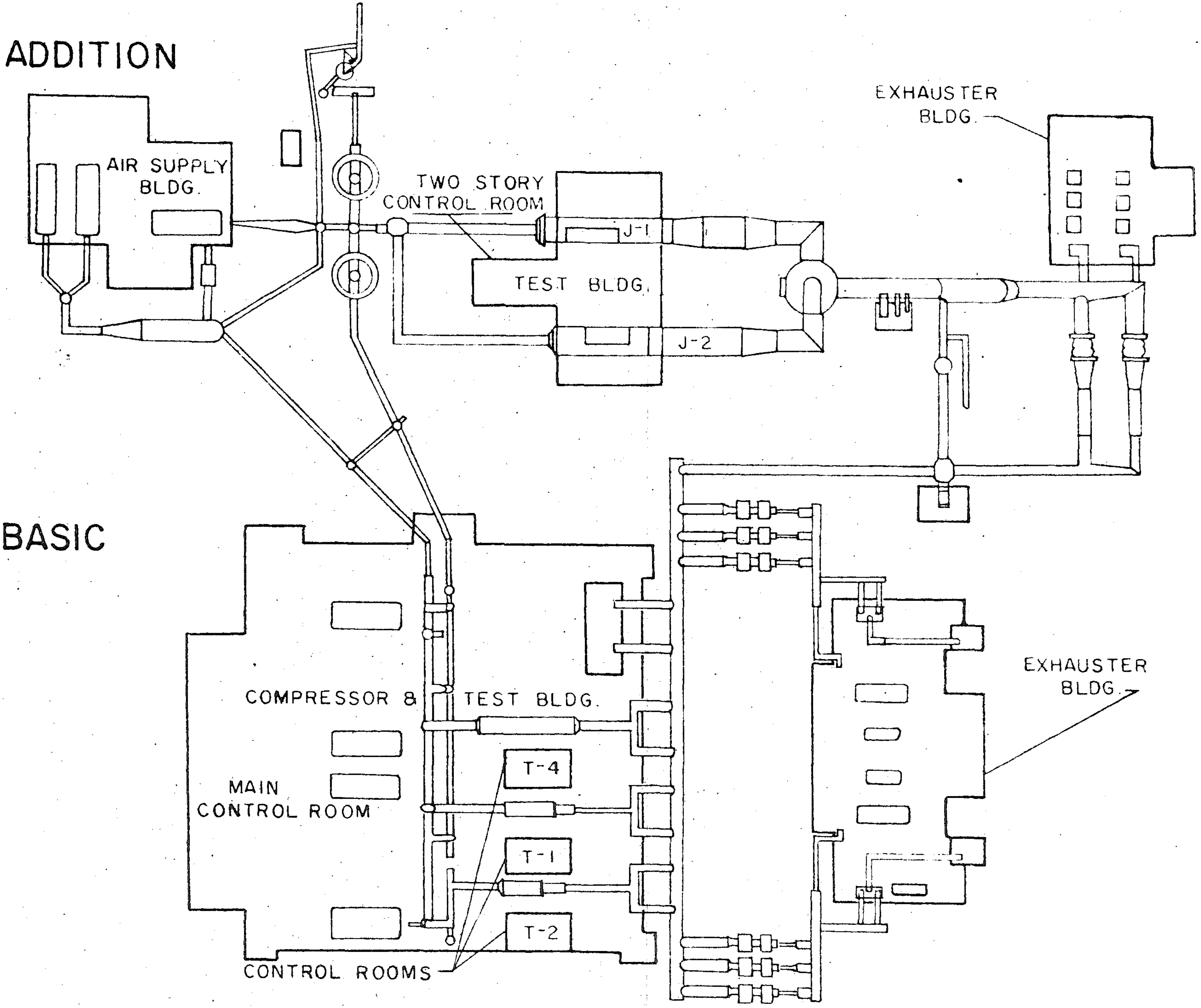
d. Test Cell J-1, located in the ETFA test building, is 16' in diameter with a total length of 92 ft. The upstream portion of the cell consists of a pressure chamber and is separated from the test section by a water-jacketed bulk-head. The pressure chamber is designed to withstand 150 psi and temperatures of 1200°F. The test section is designed for 40 psi to vacuum with a maximum permissible inner-shell wall temperature of 250°F. Access is provided by a 40 ft, 180° hinged hatch. Tapped holes in the inner wall provide for mounting test hardware.

Test Cell J-1 is connected to the ETFA exhaust system which provides control of test section exhaust conditions. Exhaust gases are cooled by spray cooling prior to being exhausted to atmosphere, either direct or through the exhaust machines.

Standard pressure and thermocouple leads along with electrical power connections are provided at the test cell. Instrumentation and data recording equipment is located in the J-1 control room adjacent to the cell. Cooling water, service air, and fuel supply are provided with disconnects at the cell. Carbon dioxide fire extinguishing systems provide protection for fire in the cell.

e. Test Cell J-2, is 20 ft in diameter and 119 ft in overall length. Flow conditions within the cell are controlled by an inlet diffuser and a variable angle of attack, variable Mach number, supersonic nozzle. The inlet diffuser is 14 ft in length and the nozzle section is 35 ft in length. There are facilities for installation of a second throat, with exit ports, for removal of low energy air from the nozzle exit. The test section is 69 ft long.

Standard instrumentation and service leads are provided as required. Other features of Cell J-2 are similar to those of J-1 and an adjacent control room houses the instrumentation and data recording equipment.



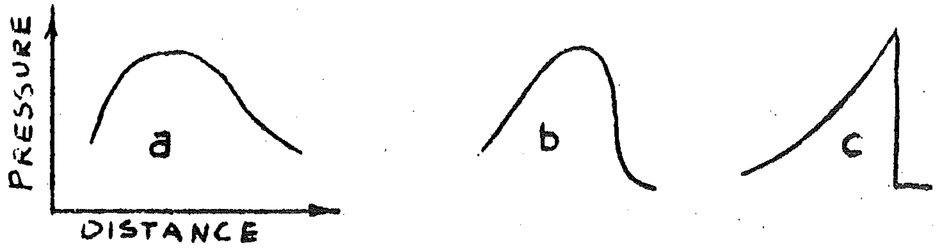
ENGINE TEST FACILITY LAYOUT
FIGURE 1

IV. DISCUSSION

A. EXPLOSIONS

1. General

When an explosion occurs, a large amount of energy is released very suddenly producing a considerable rise in temperature, which in turn, results in the almost complete vaporization or gasification of the products of the explosion. The very hot gases so produced, in a restricted space, are at a very high pressure, and immediately following the explosion they begin to move outward. The great expansion which occurs pushes away the surrounding air. As the wave is propagated away from the center of the explosion, the following (or inner) part of the wave moves through a region which has already been compressed and heated by the leading (or outer) part of the wave. The disturbance moves with the velocity of sound characteristic of the medium, and since this velocity increases with temperature and pressure, the following part of the wave moves more rapidly and catches up to the leading part. The wave front thus gets steeper and steeper, and with a short period becomes mathematically abrupt as shown below.



A Simplified Representation of the Development of a Shock Wave

This represents the destructive shock wave which continues to move forward through the medium with gradually decreasing intensity. When the shock wave strikes a resistant surface it is reflected back and the reflected wave reinforces advancing waves, thus building up the maximum peak pressure experienced by the resisting surface.

2. Effect of Low Pressure Atmosphere

When an explosion occurs in a large space with an atmosphere of low pressure, an attenuation of the maximum peak pressure is experienced. This attenuation is such that the maximum peak pressure is almost directly proportional to the ratio of the ambient pressure in which the explosion occurs, to sea level pressure. As the size of the space or chamber in which the explosion occurs is decreased, the attenuation effect is also decreased until a point is reached where no attenuation effect is experienced. When the volume of the chamber in which the explosion occurs is such that the mass of air at sea level conditions which can be contained in that volume is less than ten times the mass of the explosive, there will be no attenuation of the maximum peak pressure.[1.]

In the case of the ETF test cells, the volume to be considered would be the volume of a sphere with a radius equal to that of the test cells. If the mass of potential explosive with a test cell is greater

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1. "Numerical Solutions of Spherical Blast Waves" by H. L. Brode, June 1955 Issue, Journal of Applied Physics.

than 0.1 of the mass of sea level air in that volume, no attenuation of the maximum peak pressure could be expected in the test chamber itself. Some attenuation would take place in the exhaust ducting. However, this has no effect on the results of this study as the structural strength of the test chambers rather than the exhaust ducting is the limiting factor on the size of explosion that can be contained in the test cells. See Figures 5 through 10.

Following is a tabulation showing the maximum mass of explosives that can be detonated in the test cells with an attenuation effect on the maximum peak pressure. It can be seen that these masses are, in each case, very small and any benefit from attenuation in the ETF test chambers can be virtually ruled out.

Test Chamber	Test Chamber Radius	Maximum Mass of Explosive - Lbs
T1	6' - 2"	8
T2	6' - 2"	8
T4	6' - 2"	8
J1	8' - 0"	17.3
J2	10' - 0"	33.9

B. PROBABILITY OF ROCKET ENGINE MALFUNCTIONS

1. General

The possibility of a malfunction resulting in an explosion always exists in rocket engine testing. However, the probability of such a malfunction appears to be a function of the stage of development of a particular engine. No two engines will have identical histories of malfunctions during their development and qualification stages, but a general trend does exist.

For the purpose of this report, a malfunction is defined as an unsuccessful firing caused by rupture of any mechanical part of the engine. Misfires or erratic field flights caused by anything other than the rocket thrust system are not considered.

Rocket engineers have stated that any new engine under development is tested with the understanding that initially there may be more malfunctions than successful test runs. A new rocket engine is tested by degrees and stages. If it is a liquid engine, the various components are first tested separately. Upon completion of the tests of the individual components, they are assembled and tested as an assembly. A solid motor is developed in much the same way, although, the number of parts are much less. Thus in the development stage, the assembly is constantly being altered and redesigned to decrease the number of malfunctions.

After the development stage, the motor is qualified and used in field test firing where it is installed in a vehicle with other motors or systems for ballistic evaluation. By this time, the motor has attained a high degree of reliability, although, a malfunction possibility is ever present. This is exemplified by the following tests on several new rocket engines.

2. Solid Propellant Engines

During one particular solid engine development program, 83 tests were performed resulting in 26 various malfunctions for an overall reliability of 68.7%. However, the data gathered during the early malfunctions was used to improve the performance of other engines tested later in the same program. For example, one engine tested 16 times resulted in 12 malfunctions (reliability 25%), but another engine, utilizing information contributed by these malfunctions, was tested 18 times with only 3 malfunctions (reliability 83.3%).

The degree of progress, from early stages of development to later stages, is indicated by the increase in reliability percentages. Over the last 34 tests conducted on engines mostly for ballistic evaluation, there were only 7 malfunctions (reliability 76.5%) compared to a reliability of 61% which was obtained during earlier tests.

During the entire program, 10 out of the above malfunctions resulted in explosions, mostly due to case rupture or separation. The initial propellant weight in these engines varied from 7000 lbs to 15,000 lbs. The approximate weight of propellant at the time of the explosions was determined by prorating the total propellant, using the burning rate. The propellant explosion weight varied from 2800 lbs to 12,400 lbs. It was noted that in all cases, the damage was confined to the test equipment and stand. No estimates of TNT equivalents were made.

Another example of malfunction probability is the following small 300 lb solid propellant motor. In development tests in moderate temperature ranges, a reliability of 89.7% was achieved on 49 trials. During qualification, no malfunctions occurred in 64 trials, but in production firings a reliability of 96.5% was obtained. In a summary of field firings totaling 309, there were no malfunctions. Thus it can be briefly stated that this solid rocket motor has a highly successful reliability percentage of proper operation.

3. Liquid Propellant Engines

The reliability factors of liquid propellant engines are not quite as successful as the above mentioned solid engines. In the development stages of two different LOX and JP propellant engines, the reliability of parts in subassembly and assembly test firings averages only 53.3% for one and 64% for the other. Some of the malfunctions were:

LOX pumps rupture, explosion in LOX lines due to contamination, thrust control valve rupture, manifold rupture, and torus rupture. All of these malfunctions resulted in damage to the engine parts and some of the torus failures resulted in complete destruction of the engine. On one model, out of 1773 firings, three were destroyed while only one was destroyed out of 1408 firings of another model. The TNT equivalent of the explosions is not known since no convenient method of determination was available.

4. Conclusions

The primary difference in solid versus liquid rocket motor explosions in ETF test cells is in the amount of propellant available. A solid motor has less equipment to cause trouble, but when the case ruptures, the entire propellant could possibly detonate. In the case of a liquid engine test in one of the ETF test cells the propellants will be supplied from test tanks located outside of the test cells. Liquid engines have more parts to cause possible malfunctions, but the amount of propellants present in the cells can be limited, thus decreasing the potential of a total explosion.

The best way of forcasting the probability of a damaging explosion is to investigate the complete past history of test runs previously conducted on a rocket engine before it is fired in a test cell.

The past performance will generally indicate the degree of damage to be expected and the probable type of malfunction. Any test conducted under these conditions should nevertheless be approached on the calculated risk basis and all precautions should be taken to avoid injury to personnel and extensive damage to equipment.

C. TNT EQUIVALENTS OF PROPELLANT COMBINATIONS

To determine the effect of explosions resulting in malfunctions of rocket engines burning various propellant combinations, the TNT equivalents of the propellants being considered in this study have been determined. TNT equivalent is defined as the relative violence or damage capable by the explosive composition in question in comparison to that produced by the same weight of TNT under identical conditions. Experience has demonstrated that the energy released in the detonation wave is a measure of the violence of the explosive. Hence the ratio of the energy released in the detonation of the explosive composition to that released in the detonation of TNT is by definition the TNT equivalent of the explosive composition.

The computations of the TNT equivalents shown below have involved the use of three assumptions:

1. The TNT equivalents are based on the ratio of the maximum enthalpy release at 298°K and 1 atmosphere of the explosive mixture, to that of TNT under the same conditions.

2. The mixture compositions have been chosen so that the maximum enthalpy is released.

3. The kinetics and mixing problems of the situation have not been considered.

The following table lists the TNT equivalents of the propellant combinations being considered in this study.

Propellants	Type	TNT Equiv.
Liquid Fluorine - Liquid Hydrogen	Liquid	2.4
Liquid Fluorine - Hydrazine	Liquid	1.8
Liquid Fluorine - Ammonia	Liquid	1.8
Nitrogen Tetroxide - Hydrazine	Liquid	1.2
Chlorine Trifluoride - Hydrazine	Liquid	1.1
Liquid Oxygen - JP-4	Liquid	1.8
Liquid Oxygen - UDMH	Liquid	1.7
Liquid Oxygen - Liquid Hydrogen	Liquid	2.3
Bromine Pentafluoride - 33% Hydrazine 67% Ammonia	Liquid	0.7
Ammonia Perchlorate Polysulfide	Solid	0.3
Aluminized Nitrocellulose	Solid	0.8
Aluminized Polyurethane	Solid	0.3

D. AUTOMATIC CONTROL DEVICES

The most effective method of minimizing potential explosions, resulting from malfunctions occurring during the testing of liquid rocket engines in the test cells of ETF, is by keeping the amount of propellants present in the cells to a minimum. This can be accomplished by employing fast acting control devices. There are several such devices currently available among which are pressure switches, leak detectors, and fire detectors. Any one or combination of these devices could be used to detect a malfunction, and in turn initiate a series of event culminating in the rapid closure of shut-off valves in the lines supplying propellants to a test engine. The pressure switch system is the fastest and most positive system presently available, and it is recommended that this system be employed during liquid engine testing.

A typical test installation employing the pressure switch control system is shown in Figure 2. A typical chain of events for such a system would be as follows:

1. The switch senses a loss of chamber or line pressure.
2. The switch operates a relay
3. The relay operates a pilot valve.
4. The pilot valve supplies gas or hydraulic pressure to actuate the propellant shut-off valves.

5. The propellant shut-off valves close.

The above system could also be used to sense feed line flow by having the switch sense a differential pressure across an orifice plate or venturi meter.

It is also recommended that a flow limiting venturi be placed in the propellant feed lines. This would limit the propellant flow to a value slightly above rated flow in case of line rupture in the test cell rather than permitting a marked increase in flow due to the loss of back pressure.[2]

There are many companies that manufacture shut-off and control valves which are suitable for use with rocket engine propellants. Three of these are Annin Corp, Hydromatics, Inc., and Aerojet-General.

Annin has a complete line of valves up to 10" which can handle cryogenic and non-cryogenic materials. The small valves, up to approximately 2", have a very quick response time and can be closed in under 100 milliseconds. The larger valves, however, have much longer response times ranging from 500 milliseconds to one second.

Hydromatics has a complete line of valves up to 12" that can handle liquid propellants with an extremely short shut-off time. These are explosive operated valves and can be closed in approximately 10 milliseconds.

---

2. Rocket Applications of The Cavitating Venturi, by L. N. Randall, January-February 1952, Issue of A.R.S. Journal

Aerojet has a line of valves for handling cryogenic and non-cryogenic propellants up to 7" that have a shut-off time under 100 milliseconds and have excellent characteristics as control valves.

Pressure switches for control equipment are manufactured by Aerojet-General Corp., Square D Company, and Meletron Company.

Square "D" Company and Meletron produce switches that can operate from vacuum up to about 3000 psi with about 10% of the pressure required for actuation. The Aerojet switch has a range of from 20 psi to 1000 psi and will actuate on less than 10% of the line pressure.

Leak detectors for detecting combustible mixtures are manufactured by Davis Instrument Co., Mine Safety Appliances and the Bristol Company.

Fire detectors or temperature switches are made by Consolidated Controls, Control Products, Inc., and Fenwal Company.

Annin Corporation
6570 E. Telegraph Rd.
Los Angeles, California

Hydromatics Inc.
40 Factory St.
Cedar Grove, New Jersey

Aerojet-General Corporation
6352 N. Irwindale Ave.
Azusa, California

Square "D" Company
4041 N. Richards St.
Milwaukee 12, Wisconsin

Meletron Company
950 N. Highland Ave.
Los Angeles 38, Calif.

Davis Instrument Company
47 Halleck St.
Newark 4, New Jersey

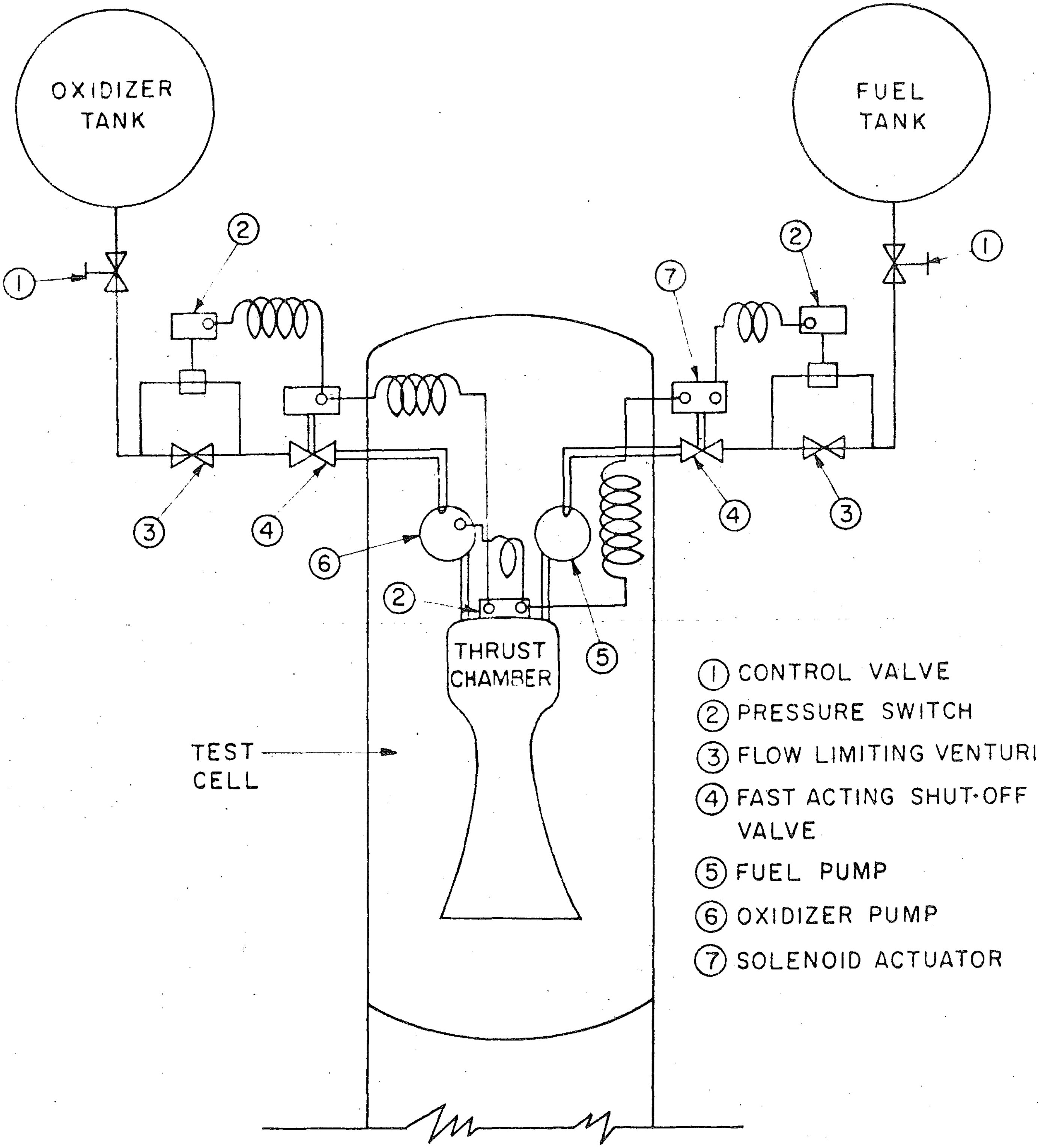
Mine Safety Appliances
201 N. Braddock St.
Pittsburg 8, Pa.

Bristol Company
113 Bristol Rd.
Waterbury 20, Conn.

Consolidated Controls
6 Durant Ave.
Bethel, Conn.

Control Products, Inc.
P. O. Box 8037
Pittsburg 16, Pa.

Fenwal Inc.
Leland St.
Ashland, Mass.



TYPICAL TEST SET UP

FIGURE 2

E. DETERMINATION OF PROBABLE DAMAGE

1. Quantity of Explosives

The first step to be taken in determining the probable damage to the test cells, resulting from explosions occurring during rocket engine tests, is to determine the quantity of explosives that will detonate in the event of the worst possible malfunction.

In the case of solid propellant engines the total weight of propellant will be present in the cell and is subject to detonation. However, experience has shown that the entire grain of propellant does not detonate. This is due to the fact that upon detonation the grain is broken up and scattered, resulting in scattered burning rather than total detonation. It is estimated that from 15 to 40% of the total propellant weight actually detonates.

For the purpose of this report it has been assumed that 50% of the total propellant weight of solid engines could detonate. Therefore, the quantity of explosive considered for solid engines will be the TNT equivalent of one half of the total propellant weight.

In the case of liquid engines the propellants will be stored in test tanks outside of the test cells. Therefore, the quantity of propellants that can be spilled in the test cell at the time of a malfunction will be the wet weight of the engine turbopump and thrust chamber units;

plus the amount of propellants in the feed lines downstream of the shut-off valves located outside of the test cell; plus the amount of propellants which flow in the feed lines prior to shut-off valve closure.

Using the fast-acting control devices described earlier in the report, it has been determined that the total quantity of propellants present in the test cell at the time of a potential explosion can be limited to the equivalent of approximately one second of rated flow.

Liquid propellants are combined in the test chamber at a mixture ratio which is slightly fuel rich with respect to the stoichiometric mixture ratio of the propellants. In addition, the wet weight of an engine consists of approximately 30% excess fuel because the fuel is used to cool the thrust chamber by flowing through the cooling jacket prior to entering the chamber for burning. In view of the above, along with the improbability of the total amount of propellants being physically mixed, it can be seen that only a portion of the spilled propellants will mix in the ratio required for maximum detonation. For the purpose of this report it has been assumed that a maximum of 50% of the spilled propellants will detonate. Therefore, for liquid engines the quantity of explosive considered will be the TNT equivalent of one half second of rated flow.

2. Blast Design Parameters

a. Incident Peak Pressure, Ps.

When an explosion occurs a blast wave is produced which, when it strikes a resisting surface, exerts a pressure called the incident peak pressure (Ps) on the surface. The magnitude of this pressure is found by:

$$Ps = \frac{4120}{Z^3} - \frac{105}{Z^2} + \frac{39.5}{Z} \quad \text{where}$$

$$Z = \frac{r}{W^{1/3}}$$

r = distance from blast in feet

w = weight of TNT in pounds

b. Reflected Peak Pressure, Pf.

When the blast wave strikes a resisting surface a pressure wave is reflected from the surface. This pressure is called the reflected peak pressure, Pf, and is found by:

$$Pf = 2\ Ps \left(\frac{103 + 4\ Ps}{103 + Ps} \right)$$

The intensity of the reflected peak pressure varies from approximately 2 Ps to approximately 8 Ps depending upon the intensity of the incident peak pressure. The reflected peak pressure remains nearly constant when the wave strikes the surface at angles from normal to 45°, however, at angles smaller than 45°, this pressure drops off rapidly.

c. Peak Face-on Pressure, Pm

The reflected peak pressure reinforces the incident peak pressure resulting in a pressure called the peak face-on pressure, Pm which is found by:

$$Pm = Ps + Pf/2.$$

d. Impulse, I

Impulse is a force acting for a short period of time and is measured by average pressure multiplied by time. The units used are pound seconds per square inch or pound milliseconds per square inch.

For bare or uncased charges,

$$I = 0.081 \frac{w^{2/3}}{r}$$

For cased charges

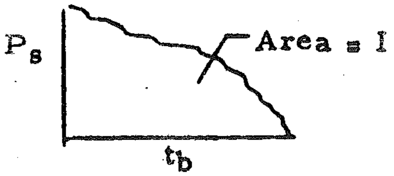
$$I = 0.054 \frac{w^{2/3}}{r}$$

Since a rocket engine skin can be considered a flimsy casing, it has been assumed that the impulse in this case is the average of a cased and uncased charge. Therefore,

$$I = 0.067 \frac{w^{2/3}}{r}$$

e. Duration of Pulse, t_b

The duration of the pulse is the impulse divided by the average incident pressure:



$$t_b = \frac{I}{P_s/2} = \frac{2I}{P_s}$$

f. Period of Resisting Medium, T

The period of resisting medium is dependent upon physical properties only and is expressed by:

$$T = \frac{1}{f}$$

where f = frequency of vibration in cycles per second.

For a circular ring such as the cross section of one of the test cells, there are two types of vibration possible, radial and flexural. The radial vibration frequency is much higher than the flexural frequency, and the actual vibration of the test cells is probably a combination of both radial and flexural. For the purpose of this study the radial frequency is used as it leads to some what more conservative results. The frequency, therefore, is expressed as follows:

$$f = \frac{1}{2\pi}\sqrt{\frac{Eg}{\gamma r^2}}, \text{ where}$$

E = modulus of elasticity
g = acceleration of gravity
γ = unit weight of material
r = radius of ring

g. Dynamic Load Factor, d

The dynamic load factor is the intensification or dampening effect on a vibratory load, such as a blast wave, due to the period of vibration of the load being nearly equal to or greatly different from that of the object being loaded. Values of the dynamic load factor d, for various values of $^{t}b/T$ are given in Figure 3.

h. Design Dynamic Pressure, Pst

Since the shells of the test cells of ETF are not infinitely rigid, the pressure exerted on the test cell shells resulting from explosion must consider the dynamic load factor described above. This pressure is called the design dynamic pressure, Pst. In the case where reflecting pressures exist,

$$Pst = d \times Pm$$

Where there are no reflected pressures,

$$Pst = d \times Ps$$

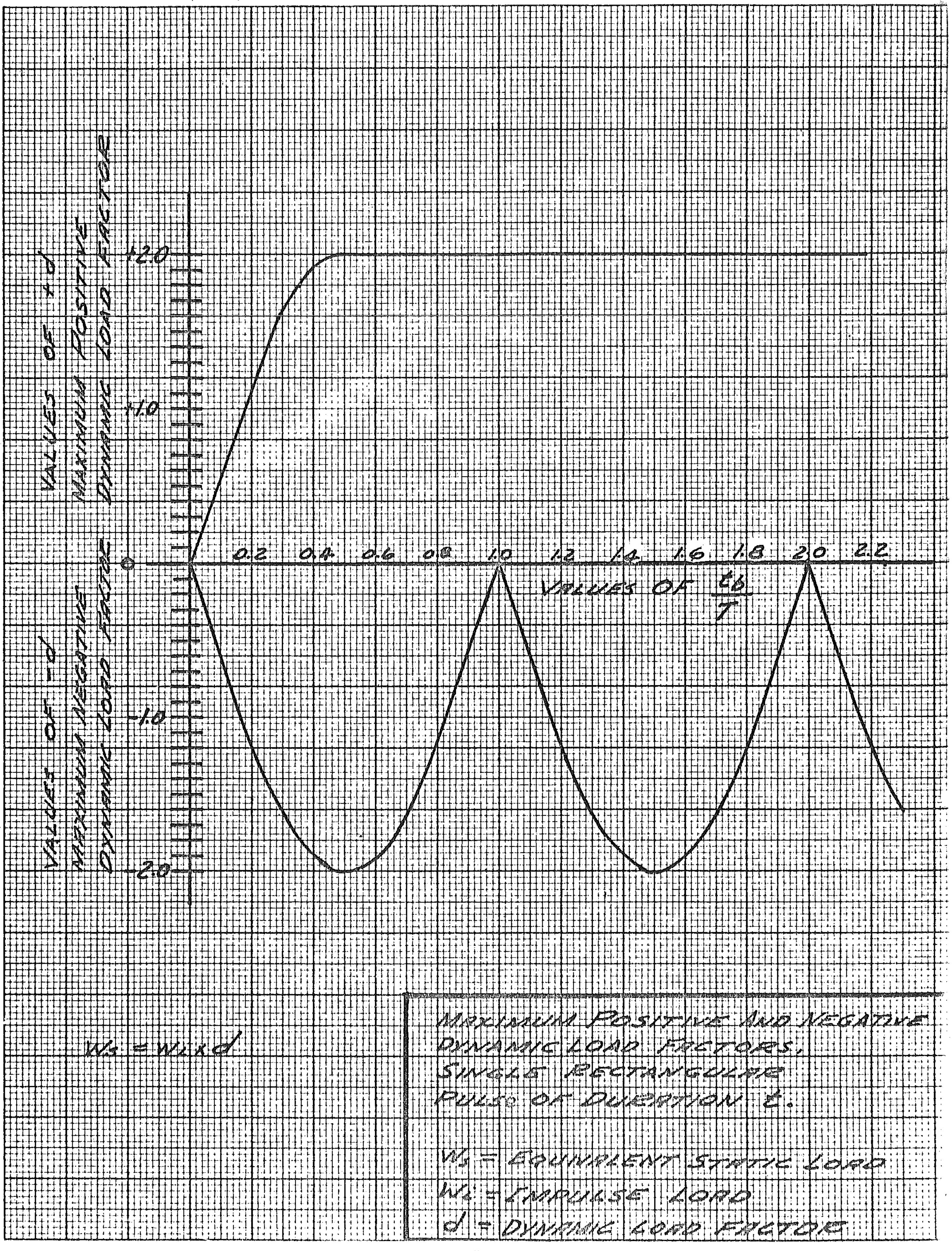
i. Elastic Design Index

Under an extremely fast acting load such as the peak pressure produced from an explosion, there is not enough time for a material, experiencing the pressure, to stretch or deform to its fullest extent. Therefore, the material can absorb the energy equivalent of loads many times greater than that which would be required to rupture the material if applied in a normal slow manner. As an example, the area under the stress-strain curve for mild steel from zero psi to the yield point is less than 0.01 of the total area under the curve to the ultimate stress.

In the Corps of Engineers Manual, "Fundamentals of Protective Design," the allowable stresses produced by explosions has been designated for various degrees of damage. These stresses are called the allowable design elastic stresses, f_s, and are computed as follows:

No Damage - fs = 2.2 x yield stress
Slight Damage - fs = 3.33 x ultimate stress
Moderate Damage - fs = 10 x ultimate stress
Heavy Damage - fs = 13.3 x ultimate stress

Figure 4 is a typical stress-strain curve for mild steel where the various areas equivalent to the above damage criteria are shown



$W_s = W_i \times d$

MAXIMUM POSITIVE AND NEGATIVE DYNAMIC LOAD FACTORS. SINGLE RECTANGULAR PULSE OF DURATION t.

W_s = EQUIVALENT STATIC LOAD
W_i = IMPULSE LOAD
d = DYNAMIC LOAD FACTOR

FIGURE 3

TYPICAL STRESS STRAIN CURVE
FOR
MILD STEEL

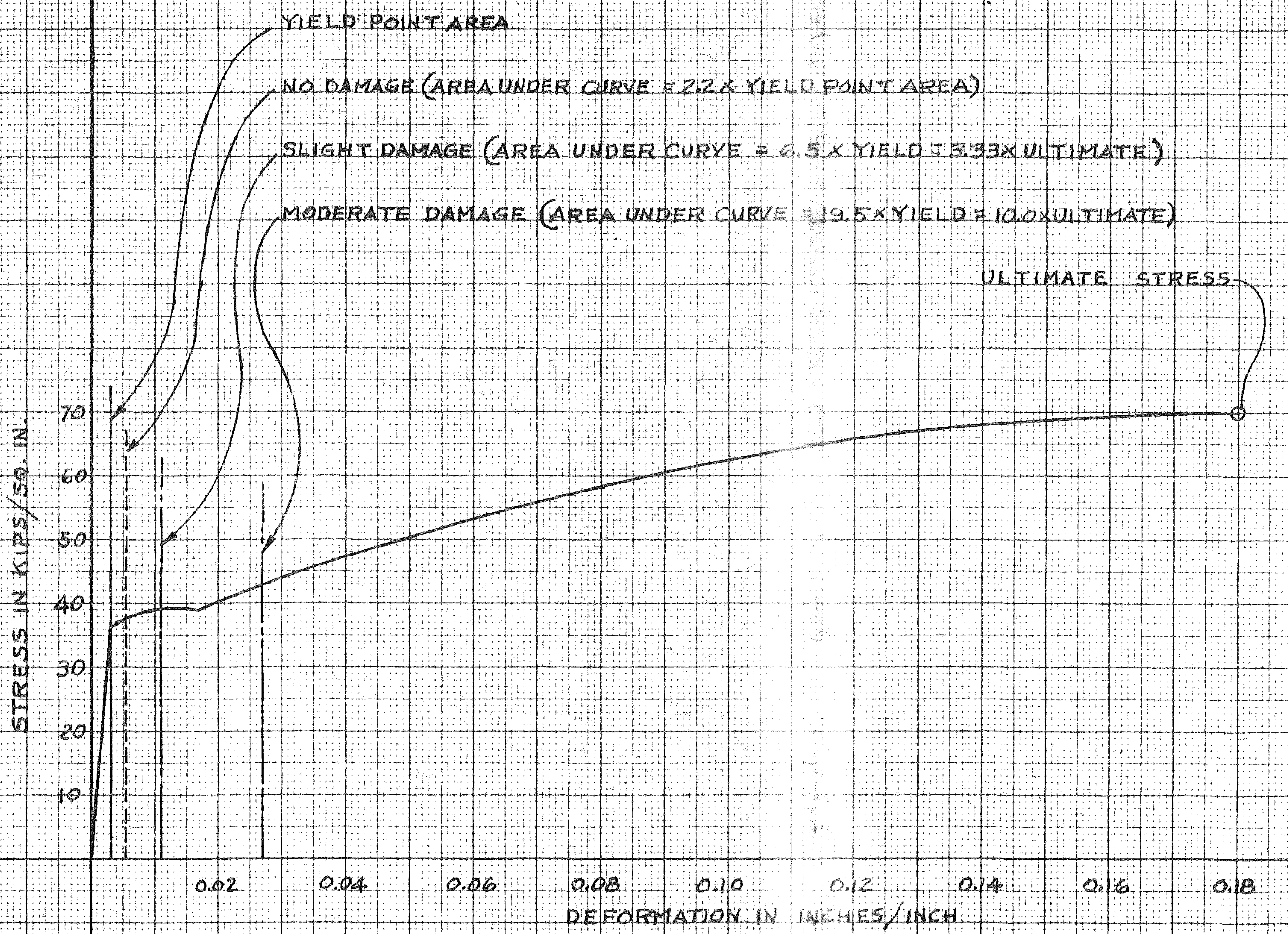


FIGURE 4

F. SUMMARY

Tables 4 through 7 show the values of incident peak pressure, reflected peak pressure, peak face-on pressure, and dynamic design pressure that will be produced in the ETF test chambers and exhaust ducts for various weights of TNT. It was assumed that there would be reflected pressures in the test chamber but not in the exhaust ducts. The value of design dynamic pressure versus TNT weight are plotted in graph form in Figures 5 through 10.

The allowable stresses, as determined by the design elastic index method, are calculated for the test cells and their exhaust ducts for no damage, slight damage, and moderate damage. These allowable stresses are superimposed on Figures 5 through 10 to determine the amounts of TNT to produce the various degrees of damage.

It can be seen from the curves and calculations that the strength of Test Cells T1 and T2 is limited by their hatch bolts, whereas T4 is limited by shell strength. It is also evident that the pressure capsules of Test Cells J1 and J2 are much stronger than the test chambers, and it is recommended that all rocket engine tests be conducted in the pressure capsules of these cells.

In the interest of safety to personnel and nearby equipment, it is recommended that the size of rocket engines to be tested in the ETF test cells be limited; so that an explosion resulting from a malfunction will cause no more than slight damage. With such explosions cell rupture will not occur, but strain hardening can be expected within the material of the cells. Therefore, after an explosion it will be necessary to inspect the cell thoroughly to determine if any strain hardening did occur, and if so to what degree. It may be necessary to repair such locations before another test can be made.

Usage Tables 1 through 3 were prepared from the foregoing information in the following manner. For example, in the case of an engine burning liquid oxygen and JP-4 in Test Cell T1 or T2 it can be seen from Figure 5 that the weight of TNT to produce slight damage is 33 pounds. The TNT equivalent of this propellant combination is 1.8, therefore, the allowable propellant flow is $(33/1.8) \times 2 = 36.6$ pounds per second. Since the specific impulse, Isp, of this combination is 261, the thrust rating of the engine would be 36.6×261 which equals 9540 pounds.

In the case of a solid engine burning ammonia perchloride polysulfide in this cell, the propellant weight for slight damage would be $33/.3 \times 2 = 220$ pounds.

EXPLOSION PRESSURE TABLE FOR TEST CELLS T-1, T-2 & T-4

W	Z	P_s	P_f	P_{MAX}	I	t_b	d	P_{st}
20	2.27	349	2310	1500	.080	.00046	1.20	1810
50	1.68	854	6270	3990	.148	.000347	0.90	3590
100	1.33	1720	13200	8320	.235	.000272	0.72	6000
150	1.16	2600	20100	12600	.308	.000237	0.65	8230
200	1.05	3450	27200	17000	.374	.000217	0.57	9700
250	0.980	4330	34100	21400	.435	.000201	0.53	11300
500	0.776	8710	69200	43300	.685	.000157	0.42	18200
1000	0.619	17300	138000	86300	1.08	.000124	0.33	28500

$Z = \frac{r}{W^{1/3}}$ r=6.17 ft. =RADIUS OF CELL

$P_s = \frac{39.5}{Z} - \frac{105}{Z^2} + \frac{4120}{Z^3}$

$P_f = 2P_s \left(\frac{103+4P_s}{103+P_s}\right)$

$P_{MAX} = \frac{P_f}{2} + P_s$

$I = .067 \frac{W^{2/3}}{r}$

$t_b = \frac{2I}{P_s}$

d = DYNAMIC LOAD FACTOR FROM FIG. 3

FOR PERIOD T = .00228

$T = \frac{1}{f}$

$f = \frac{1}{2\pi}\sqrt{\frac{Eg}{\gamma r^2}}$

$= \frac{1}{2\pi}\sqrt{\frac{29\times10^6\times144\times32.2}{485\times6.17^2}}$

$= .159\sqrt{7.57\times10^6}$

$= .159\times2750 = 440$ C.P.S.

$T = \frac{1}{440} = \underline{\underline{.00228}}$

E = 29 × 10^6 PSI

g = 32.2 ft/Sec^2

γ = 485 lb/ft^3 (steel)

r = RADIUS OF RING = 6.17 FT.

TABLE 4

EXPLOSION PRESSURE TABLE FOR TEST CELL J-1

W	Z	Ps	Pf	PMAX	I	tb	d	Pst
20	2.94	163	925	625	.062	.00076	1.54	960
50	2.17	400	2710	1750	.114	.00057	1.16	2040
150	1.72	796	5880	3720	.181	.000455	0.90	3360
150	1.51	1170	8860	5620	.236	.000402	0.81	4540
200	1.37	1570	12100	7630	.288	.000366	0.74	5640
250	1.27	1980	15200	9580	.335	.000339	0.68	6520
500	1.00	3990	31400	19700	.530	.000265	0.54	10600
1000	.80	7940	63000	38900	.839	.000211	0.42	16400

$Z = \frac{r}{W^{1/3}}$ r = 8'-0" = RADIUS OF CHAMBER

$Ps = \frac{39.5}{Z} - \frac{105}{Z^2} + \frac{4120}{Z^3}$

$Pf = 2\,Ps\left(\frac{103 + 4\,Ps}{103 + Ps}\right)$

$P_{MAX} = \frac{Pf}{Z} + Ps$

$I = .067\,\frac{W^{2/3}}{r}$

$tb = \frac{2I}{Ps}$

d = DYNAMIC LOAD FACTOR FROM FIG. 3

*1 FOR PERIOD T = .00297

$T = \frac{1}{f}$

$f = \frac{1}{2\pi}\sqrt{\frac{E\,g}{\gamma r^2}}$

$= \frac{1}{2\pi}\sqrt{\frac{29\times10^6\times144\times32.2}{485\times8}}$

$= .159\sqrt{4.49\times10^6}$

$= .159 \quad 2120 = 337$ CPS

$T = \frac{1}{337} = \underline{\underline{.00297}}$

$E = 29\times10^6$ PSI

$g = 32.2$ ft/sec^3

$\gamma = 485$ LB/ft^3

(steel)

r = Radius of ring = 8'

TABLE 5

EXPLOSION PRESSURE TABLE FOR TEST CELL J-2

W	Z	Ps	Pf	PMAX	I	tb	d	Pst
20	3.68	85.4	405	287	.0495	.00116	1.8	514
50	2.71	206	1240	826	.091	.000885	1.4	1159
100	2.15	411	2800	1810	.145	.000708	1.13	2050
150	1.89	603	4290	2750	.190	.000630	1.02	2800
200	1.71	812	5960	3790	.230	.000567	0.90	3460
250	1.59	1000	7450	4730	.265	.000532	0.85	4020
500	1.26	2030	15600	9830	.423	.000418	0.67	6590
1000	1.00	4050	31800	19900	.670	.000330	0.52	10400

$$Z = \frac{r}{w^{1/3}}$$

$$Ps = \frac{39.5}{Z} - \frac{105}{Z^2} + \frac{4120}{Z^3}$$

$$Pf = 2Ps\left(\frac{103 + 4Ps}{103 + Ps}\right)$$

$$P_{MAX} = \frac{Pf}{2} + Ps$$

$$I = .067\,\frac{w^{2/3}}{r}$$

$$tb = \frac{2I}{Ps}$$

d = DYNAMIC LOAD FACTOR FROM FIG. 3

$$T = \frac{1}{f}$$

$$f = \frac{1}{2\pi}\sqrt{\frac{Eg}{\gamma r^2}}$$

$$= \frac{1}{2\pi}\sqrt{\frac{29 \times 10^6 \times 144 \times 32.2}{485 \times 10^2}}$$

$$= .159\sqrt{2.86 \times 10^6}$$

$$= .159 \times 1690 = 269 \text{ CPS}$$

$$T = \frac{1}{f} = .00372$$

$E = 29 \times 10^6$ PSI

$g = 32.2$ ft./Sec^2

$\gamma = 485$ lb/ft^3 (steel)

r = RADIUS OF BLAST = 10'

TABLE 6

EXPLOSION PRESSURE TABLE FOR DUCTS

TEST CELLS T-1, T-2, T-4

FOR DUCTS: IT IS ASSUMED THAT INCIDENT PRESSURE Ps AND DURATION OF PULSE tb CONTINUE UNCHANGED THROUGH THE EXHAUST DUCTS. HOWEVER, SINCE THE RADIUS OF THE DUCTS IS ONLY 42" WHICH IS LESS THAN THE TEST CELL RADIUS, THE FREQUENCY OF VIBRATION IS CHANGED, THE RATIO t_b/T IS CHANGED & THE DYNAMIC LOAD FACTOR d IS CHANGED, $P_{ST} = d \times P_s$

$$f = \frac{1}{2\pi}\sqrt{\frac{E g}{\gamma r^2}} = \frac{1}{2\pi}\sqrt{\frac{29 \times 10^6 \times 386}{0.280 \times (42)^2}} = 760 \text{ CPS}$$

$T = 0.0013$

TEST CELLS J-1 & J-2

TEST CELLS AND DUCTS HAVE SAME DIAMETER AND THUS d IS UNCHANGED. THEREFORE $P_{ST} = d \times P_s$

	T-1 T-2 T-4 DUCTS			J-1 DUCTS			J-2 DUCTS		
W	Ps	d	Pst	Ps	d	Pst	Ps	d	Pst
20	349	1.8	630	163	1.54	250	85	1.8	153
50	854	1.5	1280	400	1.16	464	206	1.4	288
100	1725	1.2	2070	796	0.90	715	411	1.13	465
150	2596	1.1	2860	1175	0.81	950	602	1.02	613
200	3452	1.0	3450	1578	0.74	1170	822	0.90	740
250	4350	0.96	4170	1976	0.68	1340	1003	0.85	850
500	8700	0.72	6260	3995	0.54	2160	2025	0.67	1360
1000	17,438	0.54	9400	7945	0.42	3340	4055	0.52	2110

TABLE 7

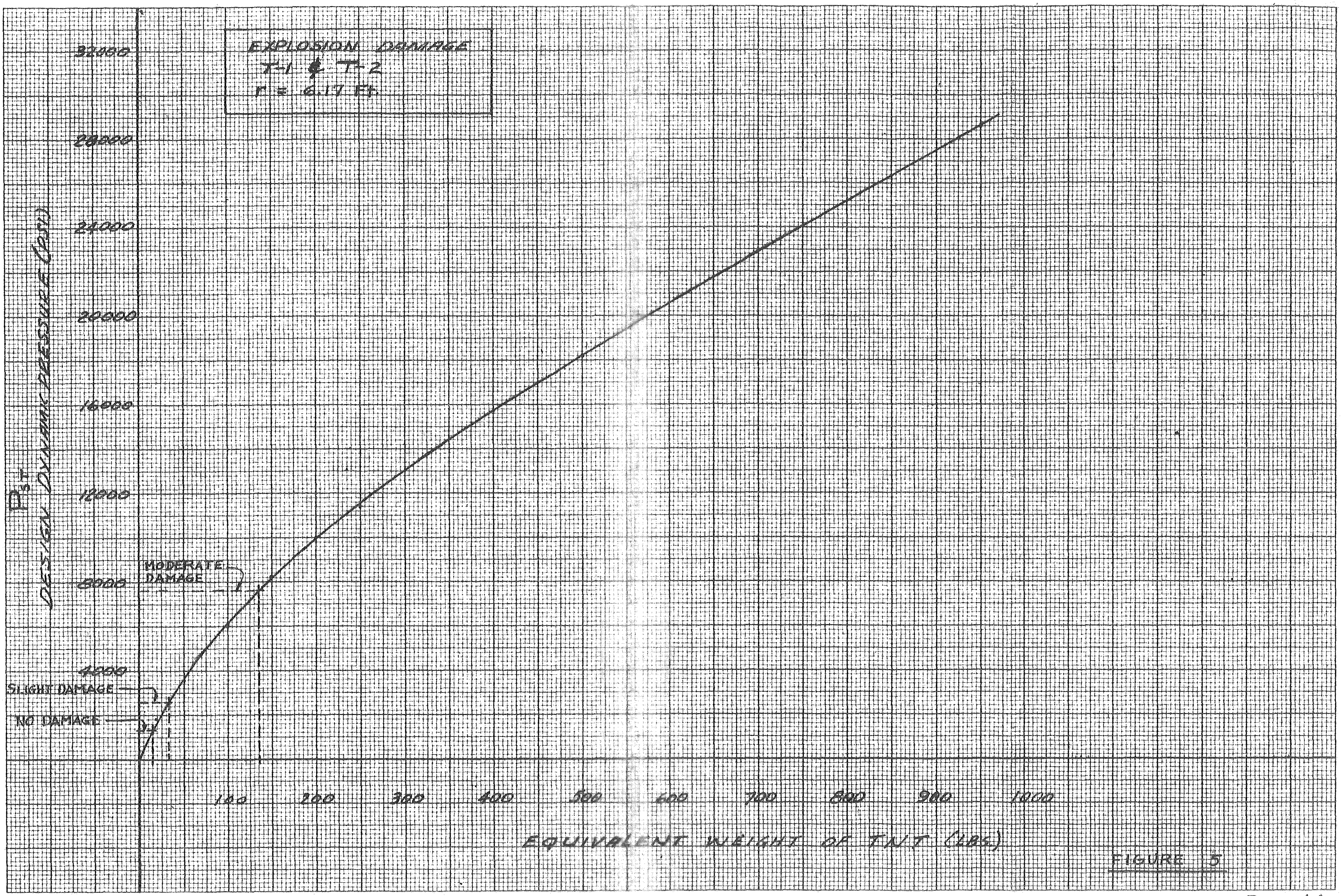

EXPLOSION DAMAGE
T-1 & T-2
r = 6.17 Ft.
32000
28000
24000
20000
16000
12000
8000
4000
P_{ST}
DESIGN DYNAMIC PRESSURE (PSI)
MODERATE DAMAGE
1
SLIGHT DAMAGE
2
NO DAMAGE
3
100
200
300
400
500
600
700
800
900
1000
EQUIVALENT WEIGHT OF T.N.T. (LBS)

FIGURE 5

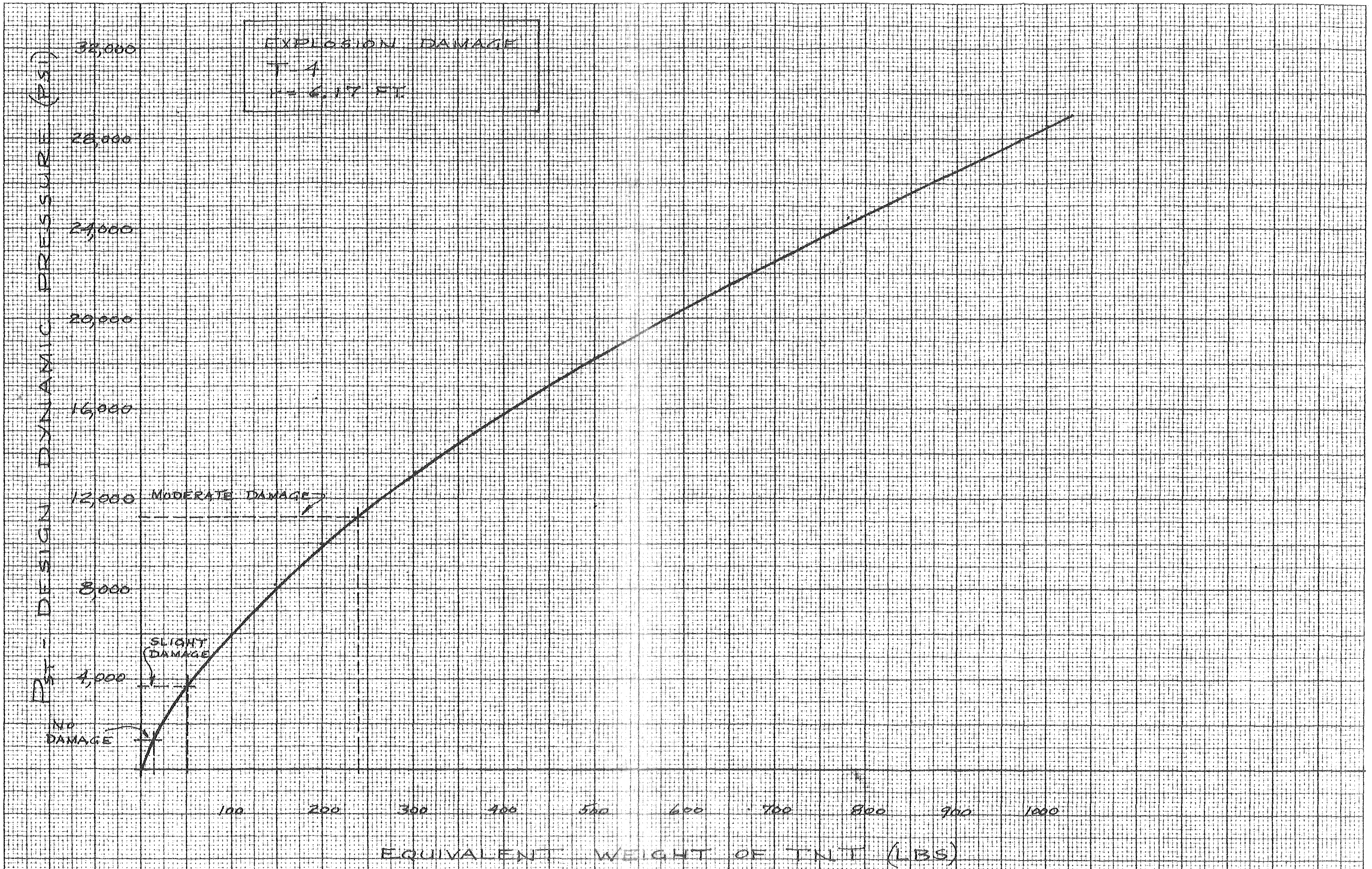

EXPLOSION DAMAGE
T-4
r = 6.17 FT.
P_{ST} - DESIGN DYNAMIC PRESSURE (PSI)
32,000
28,000
24,000
20,000
16,000
12,000
8,000
4,000
MODERATE DAMAGE
SLIGHT DAMAGE
NO DAMAGE
100
200
300
400
500
600
700
800
900
1000
EQUIVALENT WEIGHT OF TNT (LBS)

FIGURE 5A

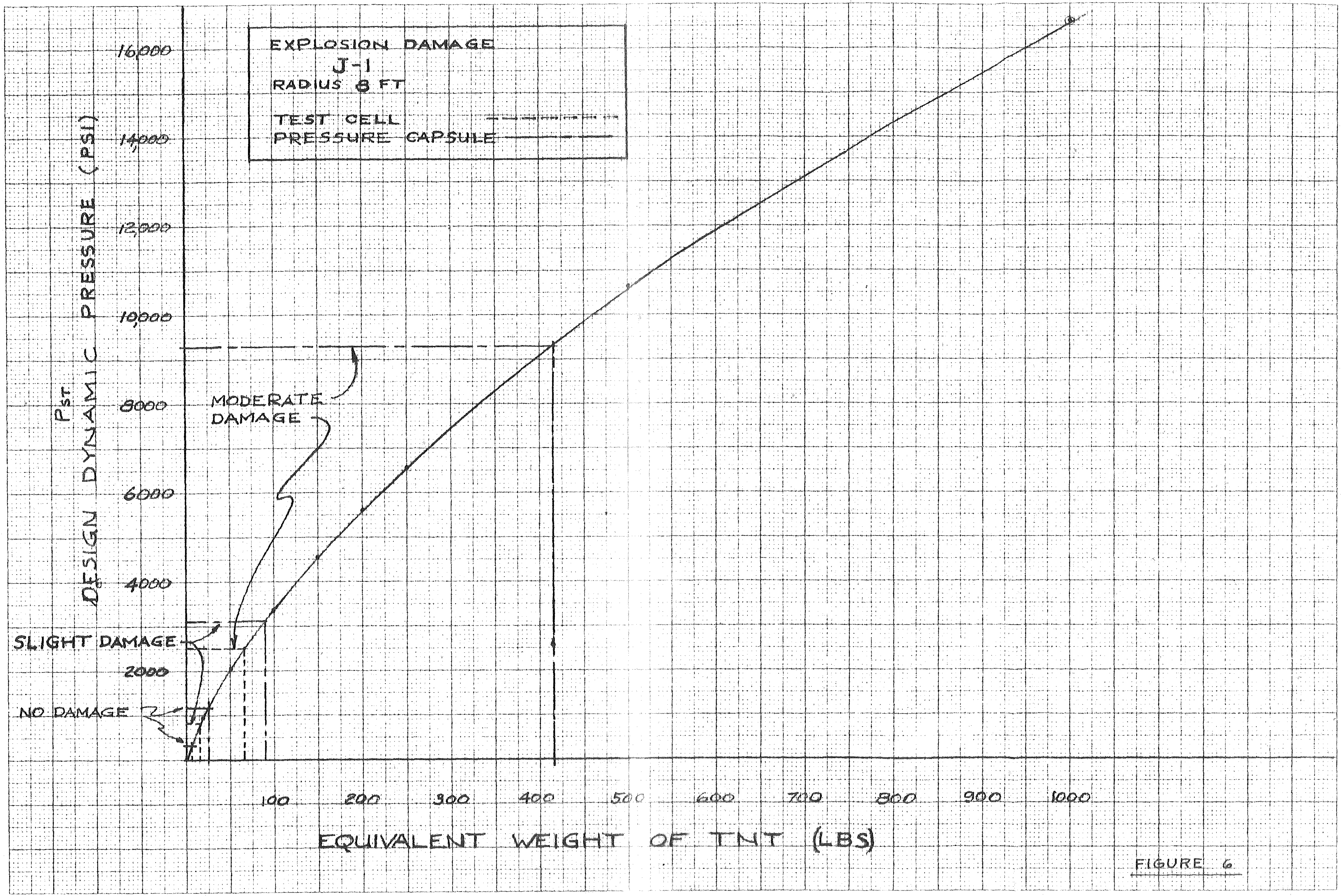

EXPLOSION DAMAGE
J-1
RADIUS 8 FT
TEST CELL
PRESSURE CAPSULE
P_{ST}
DESIGN DYNAMIC PRESSURE (PSI)
16,000
14,000
12,000
10,000
8000
6000
4000
2000
MODERATE DAMAGE
SLIGHT DAMAGE
NO DAMAGE
100
200
300
400
500
600
700
800
900
1000
EQUIVALENT WEIGHT OF TNT (LBS)

FIGURE 6

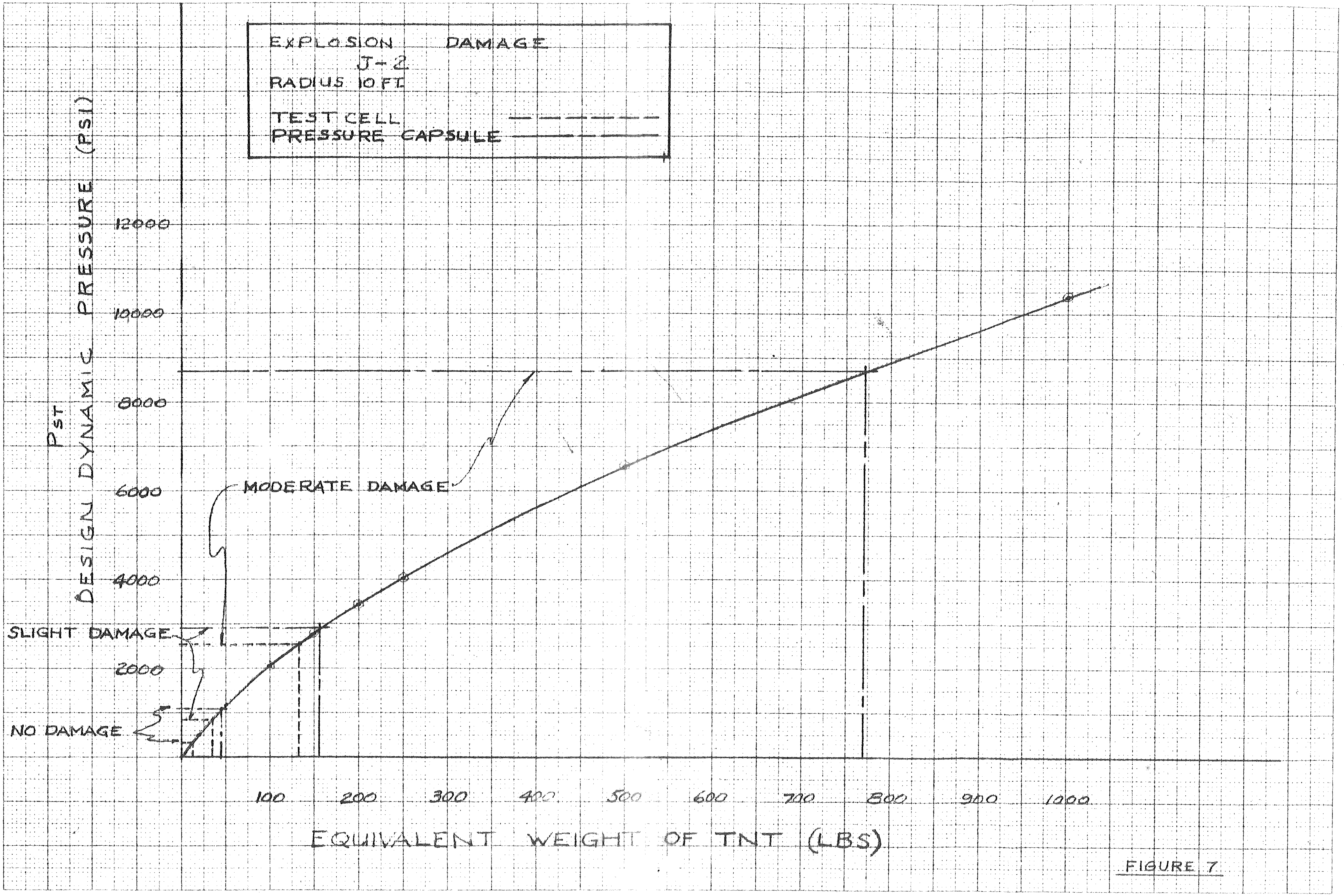

EXPLOSION DAMAGE
J-2
RADIUS 10 FT.
TEST CELL
PRESSURE CAPSULE
Pst
DESIGN DYNAMIC PRESSURE (PSI)
12000
10000
8000
6000
4000
2000
MODERATE DAMAGE
SLIGHT DAMAGE
NO DAMAGE
100
200
300
400
500
600
700
800
900
1000
EQUIVALENT WEIGHT OF TNT (LBS)

FIGURE 7

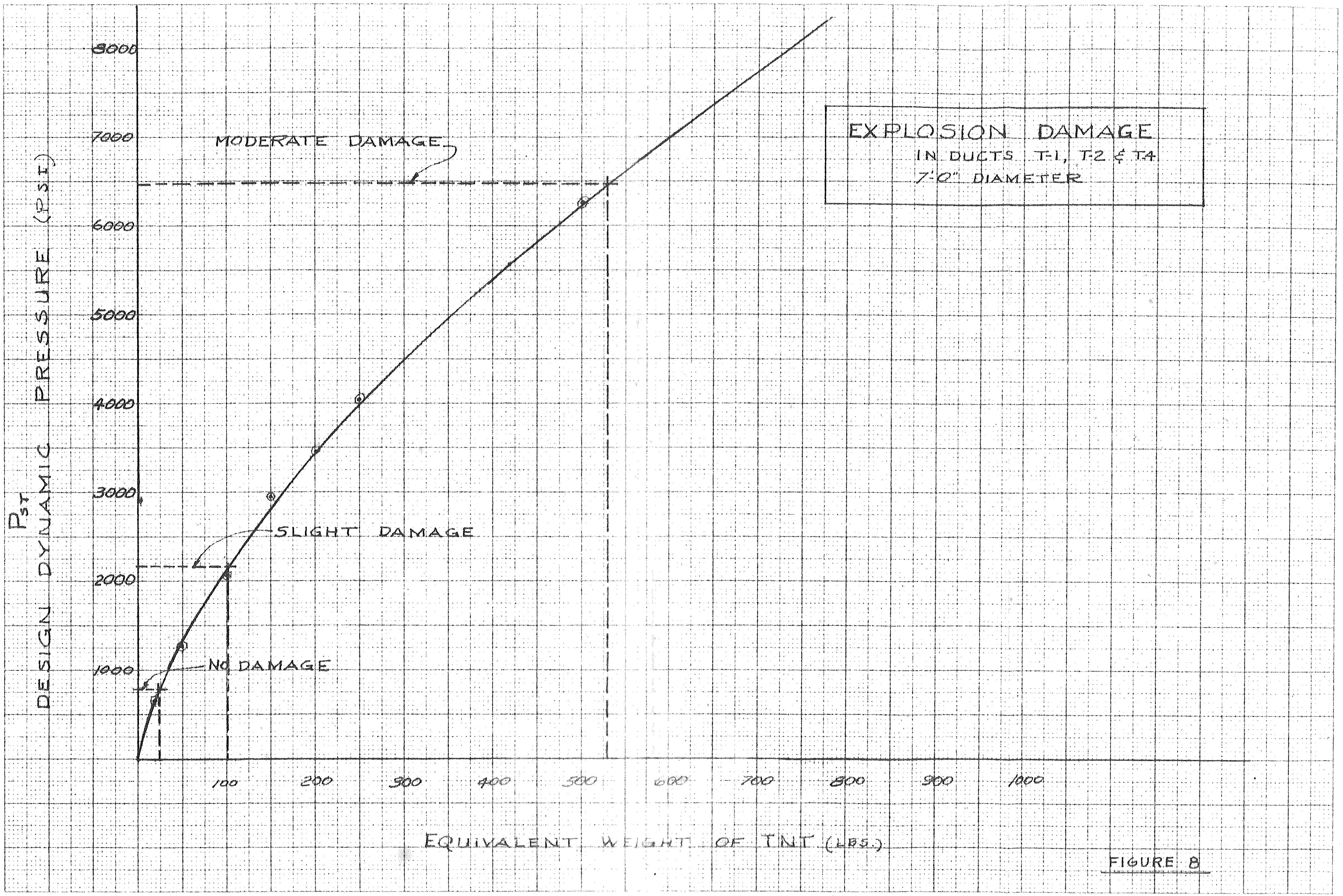

EXPLOSION DAMAGE
IN DUCTS T-1, T-2 & T-4
7'-0" DIAMETER
MODERATE DAMAGE
SLIGHT DAMAGE
NO DAMAGE
P_{ST}
DESIGN DYNAMIC PRESSURE (P.S.I.)
8000
7000
6000
5000
4000
3000
2000
1000
100
200
300
400
500
600
700
800
900
1000
EQUIVALENT WEIGHT OF TNT (LBS.)

FIGURE 8

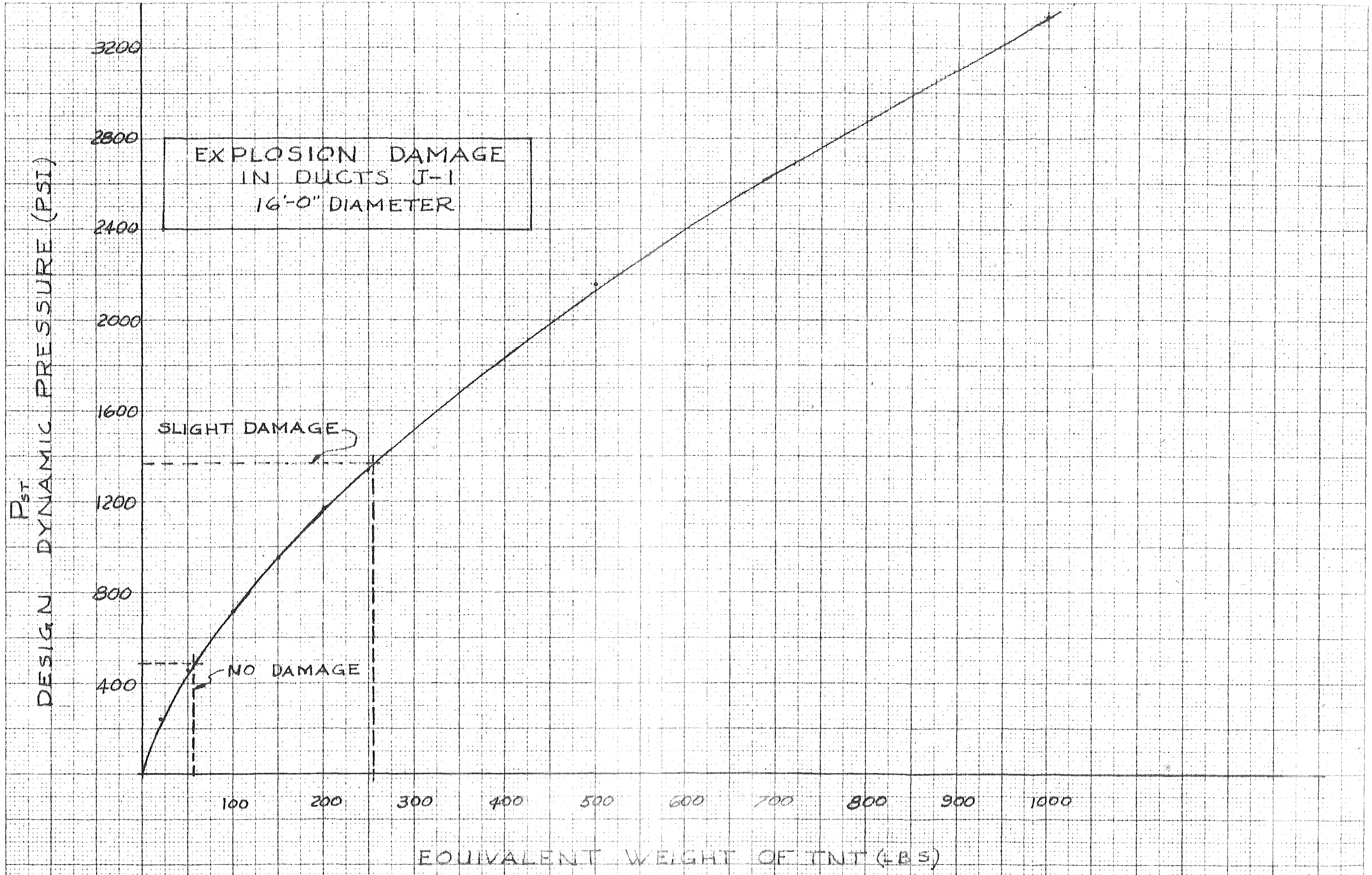

EXPLOSION DAMAGE
IN DUCTS J-1
16'-0" DIAMETER
P_{ST}
DESIGN DYNAMIC PRESSURE (PSI)
3200
2800
2400
2000
1600
1200
800
400
SLIGHT DAMAGE
NO DAMAGE
100
200
300
400
500
600
700
800
900
1000
EQUIVALENT WEIGHT OF TNT (LBS)

FIGURE 9

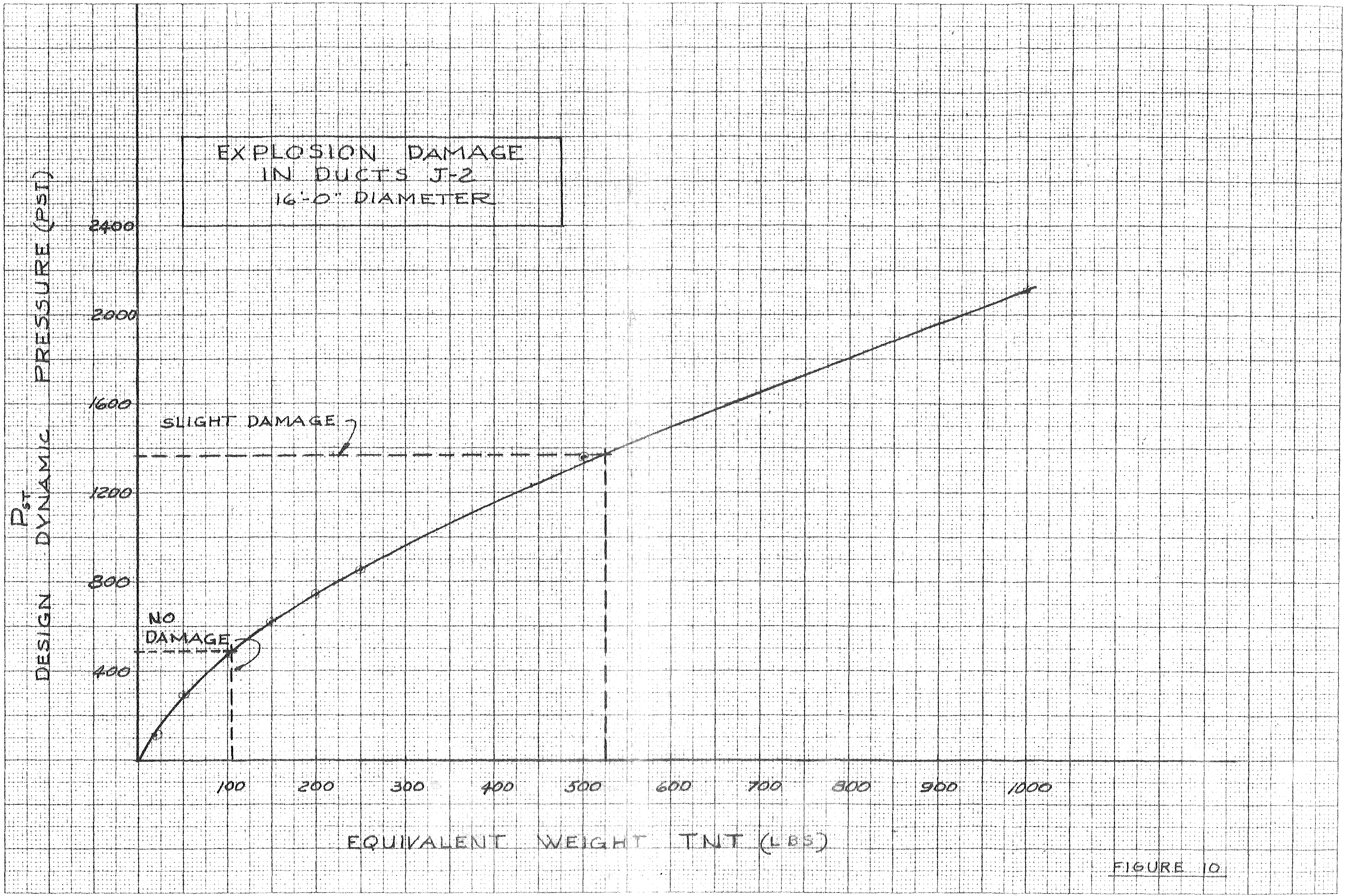
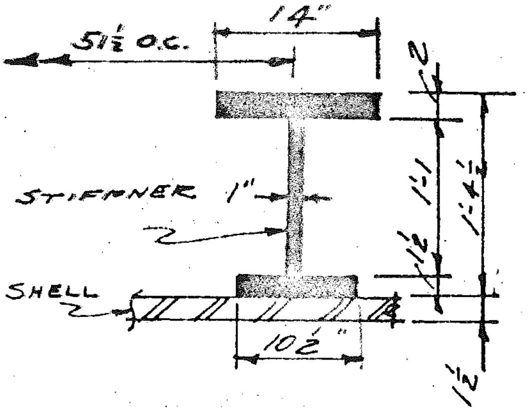

EXPLOSION DAMAGE
IN DUCTS J-2
16'-0" DIAMETER
DESIGN DYNAMIC PRESSURE (PSI)
P_{st}
2400
2000
1600
1200
800
400
SLIGHT DAMAGE
NO DAMAGE
100
200
300
400
500
600
700
800
900
1000
EQUIVALENT WEIGHT TNT (LBS)

FIGURE 10

V. CALCULATIONS

STRENGTH OF TEST CELLS AND DUCTS



TEST CELL T-1, T-2

STIFFNER AREAS

1. TOP FLANGE 14×2 = 28
2. WEB 13×1 = 13
3. BOT. FLANGE $10\frac{1}{2}\times 1\frac{1}{2} = 16$
4. SHELL $12\times 1\frac{1}{2} = 18$

TOTAL AREA = 75 □"

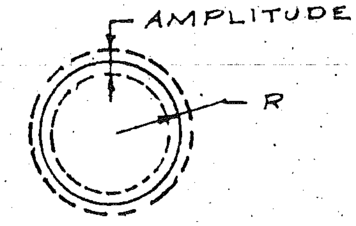
AREA/LIN. IN. $= \frac{75}{51.5} = 1.45$ □"/Lin. In.

AREA OF SHELL = 1.5 □"/Lin. In.

NOTE: THUS THE AREA OF STIFFNER REPLACES THE AREA REMOVED FOR OBSERVATION HOLES.

NATURAL FREQUENCY OF SHELL (NO STIFFNERS)

* RADIAL VIBRATION. $r = 74"$

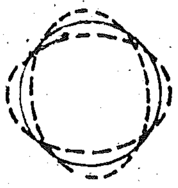


$$f_n = \frac{1}{2\pi}\sqrt{\frac{Eg}{\gamma r^2}} = \frac{1}{2\pi}\sqrt{\frac{29\times 10^6 \times 32.2 \times 144}{485 \times 6.17^2}}$$

$$= 430 \text{ CPS}$$

$$T = \frac{1}{f_n} = .0023$$

* FLEXURAL VIBRATION



$$f = \frac{1}{2\pi}\sqrt{\frac{EgI\, i^2(1-i^2)^2}{\gamma A r^4\,(1+i^2)}}$$

$$= \frac{1}{2\pi}\sqrt{\frac{29\times 10^6 \times 386 \times 1 \times 2^2(1-2^2)^2}{0.28 \times 5.32 \times 74^4\,(1+2^2)}}$$

$$= \frac{1}{2\pi}\sqrt{1790}$$

$$f = 6.74 \text{ CPS}$$

$$T = 0.148 \text{ SEC.}$$

$\gamma = 485$ #/ft³ (steel)

$= .28$ #/in³

$g = 32.2$ ft/sec²

$= 386$ "/sec²

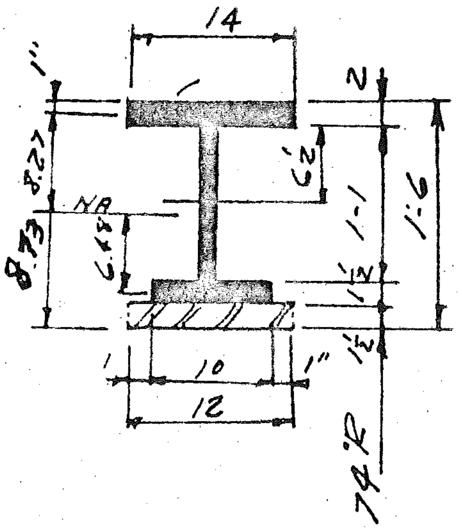
$$\frac{I}{A} = \frac{bt^3}{12bt} = \frac{t^2}{12} = \frac{1\frac{1}{2}^2}{12} = \frac{1}{5.32}$$

i = No. of VIBRATIONS (ASSUME = 2)

* SEE VIBRATION PROBLEMS IN ENGR. – BY TIMOSHENKO P. 429 P. 426

TEST CELL T-1, T-2

FREQUENCY OF STIFFENERS



FOR N.A.

	SECTION	AREA	$\bar{x}$	$A\bar{x}$
1	TOP FLANGE	28	0	0
2	WEB	13	7.5	97.8
3	BOT. FLANGE	15	14.75	221.5
4	SHELL	18	16.25	292.0
5	Σ	74		611.3

$\therefore \frac{611.3}{74} = 8.27''$ TO NA

FOR I_{oo}

	SECTION		I_o	A	d^2	Ad^2
1	TOP FLANGE	$\frac{14 \times 2^3}{12}$	9.3	28	8.27^2	1920
2	WEB	$\frac{1 \times 13^3}{12}$	183	13	$.77^2$	8
3	BOTT FLANGE	$\frac{10 \times 1.5^3}{12}$	2.8	15	6.48^2	630
4	SHELL	$\frac{12 \times 1.5^3}{12}$	3.4	18	8^2	1150
			198.5			3108

$I_{oo} = 198.5 + 3108 = 3306.5$

$A = 74 \times 51.5$

$\frac{I}{A} = \frac{3306.5}{74 \times 51.5} = .870\ ''^2/\text{LIN INCH}$

$$\frac{\frac{I}{A}\ \text{STIF} = }{\frac{I}{A}\ \text{SHELL} = }\ \frac{.870}{.187} = 4.65$$

FREQUENCY FOR STIFFENER SHELL

$f = 6.74$ CPS $\times 4.65 = 31.4$ CPS

$\therefore T = .32$ SEC.

STRENGTH OF TEST CELLS AND DUCTS

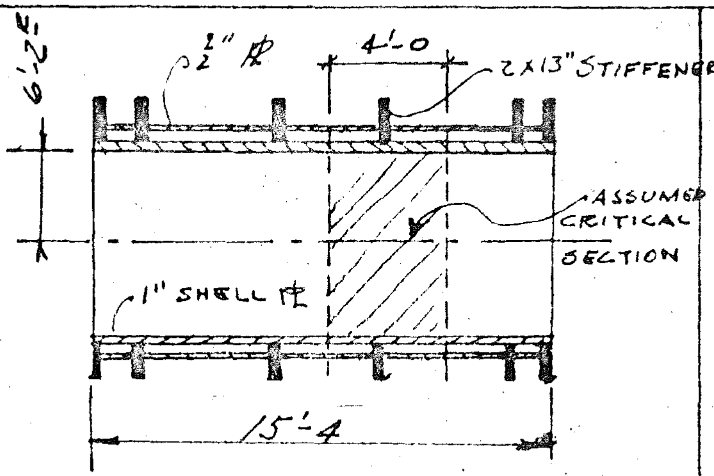
TEST CELL T-1, T-2 & T-4

		SHELL 74" RAD.	BOLTS T_1, T_2 ONLY	DUCTS 84" DIA.
YIELD POINT		30,000 PSI *	80.000 PSI *	30.000 PSI *
ULTIMATE		55 TO 65000 PSI	100,000 PSI	55 TO 65,000 PSI
NET AREA		1.5 sq in/in	6.72 sq in/ft	0.5 sq in/in
ALLOWABLE INTERNAL PRESSURE		$\frac{A \times f_A \times d}{r} = P_A$	$\frac{A \times f_A \times d}{12r} = P_A$	$\frac{A \times f_A \times d}{r} = P_A$
	NO DAMAGE	$\frac{1.5 \times 30{,}000}{74} \times 2.2$ = 1340 PSI	$\frac{6.72 \times 80{,}000 \times 2.2}{12 \times 74}$ = 1300 PSI	$\frac{.5 \times 30{,}000}{42} \times 2.2$ = 788 PSI
	SLIGHT DAMAGE	$\frac{1.5 \times 55{,}000}{74} \times 3.33$ = 3730 PSI	$\frac{6.72 \times 100{,}000 \times 3.33}{12 \times 74}$ = 2520 PSI	$\frac{.5 \times 55000}{42} \times 3.33$ = 2190 PSI
	MODERATE DAMAGE	$\frac{1.5 \times 55000}{74} \times 10$ = 11200 PSI	$\frac{6.72 \times 100{,}000}{12 \times 74} \times 10$ = 7560 PSI	$\frac{.5 \times 55000}{42} \times 10$ = 6600 PSI

A = AREA OF PLATE OR BOLT
f_A = ALLOWABLE STRENGTH
r = RADIUS
d = DAMAGE INDEX
P_A = ALLOWABLE CELL PRESSURE

* STEEL FOR SHELL & DUCTS ASTM A-201
STEEL FOR BOLTS ASTM A-193

TEST CHAMBER T-4 (FIXED SECTION)



SECTION

GROSS HOOP AREA

1. SHELL P = 1"/in
2. STIFF = $\frac{26}{48}$ = .54 □"/in
3. JACKET = .5

TOTAL 2.04

ASSUME WATER JACKET & HOLE COVERS MAKE UP THE LOSS OF STIFFNESS OF THE SECTION DUE TO THE HOLES

∴ THE ASSUMED EFFECTIVE AREA = 1.5 □"/in

NATURAL FREQUENCY

1. RADIAL FREQUENCY SAME AS T-1 & T-2

$T = .0023$ SEC.

2. FLEXURAL VIBRATION (NO STIFFENERS)

$$f = \frac{1}{2\pi}\sqrt{\frac{EgI\,i^2(1-i)^2}{\gamma A r^4(1+i^2)}}$$

$\gamma = 485\ \#/ft^3 = .28\ \#/in^3$

$g = 32.2$ ft/sec²

$= 386$ "/sec²

$$\frac{I}{A} = \frac{bt^3}{12bt} = \frac{t^2}{12} = \frac{1}{12}$$

i = No of VIBRATIONS (ASSUMED 2)

$r = 74$ in

$$f = \frac{1}{2\pi} = \sqrt{\frac{29\times10^6\times386\times2^2(1-2^2)^2}{.28\times12\times74^4(1+2^2)}}$$

$$= \frac{1}{2\pi}\sqrt{800} = 4.5 \text{ CPS}$$

$$T = \frac{1}{f} = \frac{1}{4.5} \quad .222 \text{ SEC.}$$

TEST CELL J-1

FREQUENCY OF TEST CELL

1. RADIAL FREQUENCY

$$f = \frac{1}{2\pi}\sqrt{\frac{Eg}{\gamma r^2}} = \frac{1}{2\pi}\sqrt{\frac{29\times10^6\times386}{.28\times96^2}} = 330 \text{ CPS}$$

$\therefore T = .0031$ SEC.

2. FLEXURAL FREQUENCY

$$f = \frac{1}{2\pi}\sqrt{\frac{EgI\,i(1-i^2)^2}{\gamma A r^4(1+i^2)}} = \frac{1}{2\pi}\sqrt{\frac{29\times10^6\times386\times8.6\times18}{.28\times90.2\times10^6\times48\times5}}$$

$f = 2.7$ CPS.

$\therefore T = .37$ SEC.

$r = 97.4''$ $\quad r^4 = 90.2\times10^6$

$$\frac{I}{A} = \frac{d^2}{12} = \frac{\frac{1}{2}^2}{12} = \frac{1}{48}$$

$$+\frac{1\frac{3}{8}^2}{12} = \frac{1.9}{12} = \frac{7.6}{48}$$

$$\text{TOTAL } \frac{I}{A} = \frac{8.6}{48}$$

$$\frac{i(1-i^2)^2}{1+i^2} = \frac{2(1-4)^2}{1+2^2} = \frac{18}{5}$$

3. STRENGTH OF SHELL

STEEL ASTM A 203A

YIELD POINT = 37,000

ULTIMATE = 65 To 77,000

4 HATCH CONNECTION

MILD STEEL

YIELD = 33 000

ULTIMATE = 60,000

5. KEY BOLTS

YIELD = 40,000 PSI

ULTIMATE = 70,000 PSI

		* SHELL TEST CELL	HATCH CONN.	KEY BOLTS
NET AREA		12 sq in/ft	6.67 □"/lin ft	4.2 □"/lin ft
ALLOWABLE INTERNAL PRESSURE		$A\times\frac{f_A\times\alpha}{r}$	$\frac{A f_A \alpha}{12r}$	$A\frac{f_A\ \alpha}{12r}$
	NO DAMAGE	$\frac{12\times37000\times2.2}{96\times12}$ = 845 PSI.	$\frac{6.67\times33000\times2.2}{12\times96}$ 420 PSI	$\frac{4.2\times40000\times2.2}{12\times96}$ = 321 PSI
	SLIGHT DAMAGE	$\frac{12\times65000\times3.3}{96\times12}$ = 2250 PSI.	$\frac{6.67\times60.000\times3.3}{12\times96}$ 825 PSI	$\frac{4.2\times70000\times3.3}{12\times96}$ 850 PSI
	MODERATE DAMAGE	$\frac{12\times65000}{96\times12}\times10$ 6760 PSI	$\frac{6.67\times60000\times10}{12\times96}$ 2480 PSI	$\frac{4.2\times70000\times10}{12\times96}$ 2550 PSI

* FOR PRESSURE CAPSULE SEE Pg. 58

STRENGTH OF TEST CELL J-2

1. RADIAL FREQUENCY

$$f=\frac{1}{2\pi}\sqrt{\frac{Eg}{\gamma r^2}}=\frac{1}{2\pi}\sqrt{\frac{29\times106\times386}{.28\times120^2}}$$

RADIUS = r = 10'

f = 270 CPS

$\therefore$ T = .0037 SEC.

2. FLEXURE FREQUENCY

$$f=\frac{1}{2\pi}\sqrt{\frac{E g I\, i^2(1-i^2)^2}{\gamma A r^4\,(1+i^2)}}=\frac{1}{2\pi}\sqrt{\frac{29\times10^6\times386\times3\times18}{.28\times120^4\times12\times5}}$$

f = 2.1 CPS

$\therefore$ T = 0.47 SEC

$$\frac{I}{A_1}=\frac{d^2}{12}=\frac{\frac{9}{16}^2}{12}=\frac{.31}{12}$$

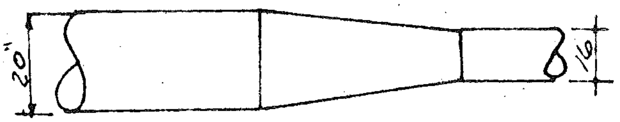
$$\frac{I}{A_1}=\frac{1\frac{5}{8}}{12}=\frac{2.64}{12}$$

$$\text{TOTAL }\frac{I}{A}=\frac{2.95}{12}$$

3. ALLOWABLE PRESSURE
SHELL ASTM A 203A

		PRESSURE CAPSULE	TEST CELL	
		$1\frac{5}{8}$ SHELL	$1\frac{3}{8}$ SHELL	KEY BOLTS
YIELD POINT ULTIMATE		37000 PSI 65-TO 77000 PSI	37000 PSI 65 TO 77000 PSI	40,000 PSI 70,000 PSI
NET AREA		1.625 □"/in	1.375 □"/in	5.25 □"/LIN ft
ALLOWABLE INTERNAL PRESSURE		$\frac{A\times f_A\times d}{r}$	$\frac{A\times f_A\times d}{r}$	$\frac{A\times f_A\times d}{12r}$
	NO DAMAGE	$\frac{1.625\times37000\times2.2}{120}$ = 1100 PSI	$\frac{1.375\times37000\times2.2}{120}$ 933 PSI	$\frac{5.25\times40000\times2.2}{12\times120}$ = 321 PSI
	SLIGHT DAMAGE	$\frac{1.625\times65000\times3.3}{120}$ 2900 PSI	$\frac{1.375\times65000\times3.3}{120}$ 2490 PSI	$\frac{5.25\times70,000\times3.3}{12\times120}$ = 850 PSI
	MODERATE DAMAGE	$\frac{1.625\times65000\times10}{120}$ 8000 PSI	$\frac{1.375\times65000\times10}{120}$ 7450 PSI	$\frac{5.25\times70000\times10}{12\times120}$ 2550 PSI

STRENGTH OF DUCTS J-1 & J-2
AND
J-1 PRESSURE CAPSULE



DUCT J-2

ALLOWABLE PRESSURE IN 16" DUCTS.			J-1 PRESSURE CAPSULE
		$\frac{5}{8}$ SHELL	$1\frac{3}{8}$ SHELL
YIELD POINT ULTIMATE		30.000 PSI 55.000 PST	37,000 PSI 65,000 PSI
NET AREA		.625 □"/in	1.375 □"/IN.
ALLOWABLE INTERNAL PRESSURE		$\frac{A \times f_A \times d}{r}$	$\frac{A \times f_A \times d}{r}$
	NO DAMAGE	$\frac{.625 \times 30{,}000 \times 2.2}{12 \times 8}$ 427 PSI	$\frac{1.375 \times 37{,}000 \times 2.2}{96}$ 1165 PSI
	SLIGHT DAMAGE	$\frac{.625 \times 55000 \times 3.3}{12 \times 8}$ = 1190 PSI	$\frac{1.375 \times 65{,}000 \times 3.3}{96}$ 3100 PSI
	MODERATE DAMAGE	$\frac{.625 \times 55000 \times 10}{12 \times 8}$ = 3590 PSI	$\frac{1.375 \times 65{,}000 \times 10}{96}$ 9300 PSI