Environmental Impact Analysis Process

ENVIRONMENTAL RISK ASSESSMENT

AIR FORCE, SPACE DIVISION

BERYLLIUM PROPELLANT FACILITY

EDWARDS AIR FORCE BASE, CALIFORNIA

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DEPARTMENT OF THE AIR FORCE

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ENVIRONMENTAL RISK ASSESSMENT
FOR THE
BERYLLIUM PROPELLANT FACILITY

Prepared for

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PREFACE

This report is submitted as the Risk Assessment of the risks during testing, and on-base handling, transportation and storage in satisfaction of Item 6.1.9 of Contract F04701-86-C-0051. The contract agent is the Department of the Air Force, Headquarter Space Division (SD/DEK). The contract project title is "Architect-Engineering Services for Environmental Risk Assessment for Beryllium Rocket Test Facility at Edwards AFB, California". Work under this contract was performed under the technical direction of Major Mark C. Mondl (SD/DEV).

1. INTRODUCTION

The U.S. Air Force is proposing to develop a facility at the Air Force Rocket Propulsion Laboratory (AFRPL), Edwards Air Force Base, California for the testing of solid rocket motors (SRMs) with propellants containing beryllium. The rocket motor propellant will range in weight from seven (7) to one hundred fifty (150) pounds. Beryllium powder, when inhaled, is a potentially toxic material. An environmental risk assessment is required per Air Force Regulation (AFR) 19-2. The assessment will support efforts to site the test facility, develop site mitigation measures, recommend engineering design specifications to reduce environmental impacts, insure all environmental regulations are met and provide the necessary studies to obtain permits for operation of the facility.

The risk assessment (RA) will consist of analyses of the risks from potential accidents associated with the operation of the test facility. This will consist of the following elements:

1. A quantitative analysis of the risks associated with catastrophic failure or explosion of the beryllium rocket motor during testing.

2. A qualitative risk analysis associated with accidents involving the beryllium rocket motor while in storage at the test site or during transfer from storage and set up in the test facility.

3. A comparison of the risks from this facility with other comparable risks.

The risk analyses are based on worst case scenarios assuming the maximum rocket motor propellant weight possible for each scenario considered. Although the risks from explosive overpressures and expelled fragments will be addressed, the primary focus will be on the possibility of releasing beryllium to the environment.

1.1 Summary of Findings

Risks evaluated included on-base transportation, handling and storage and test firing of the SRMs. A conservative approach was taken for the analysis. At all times the maximum amount of beryllium propellant possible in a location was assumed to be there (eg. 700 pounds of propellant in storage, 150 pound motor for testing). Failure probabilities developed for test firings were statistical ninety percent upper confidence bounds. No credit was taken for control of beryllium release by either the protective canisters in which the rocket motors are transported and stored nor by any of the buildings in which an accident may occur. Adverse atmosphere stability conditions were selected. Populations at risk were taken as those at the end of the proposed extended test program. No credit was taken for protection to populations by the buildings in which they are housed.

Even with all of these degrees of conservatism the incremental risk due to this project was calculated to be only 2×10^{-7} cancers per year. For purposes of comparison with other types of risks it is useful to express this in the form of annual probability that an exposed individual develops cancer. On this basis the annual project risk was calculated to be less than 7×10^{-11} cancers per exposed person with a still lower risk of death. This is about equal to the probability of being killed by a meteorite impact and is about 250 times less than the chance that a person will be killed by watching color television.

1.2 Report Organization

Chapter 2 of this report defines the facilities and SRM parameters assumed for this study. Section 3 presents a summary of relevant information acquired on solid rocket motors and propellants, including historical accidents. Section 4 defines the proposed credible accident scenarios. Chapter 5 presents a discussion of the possibility of breaching the MTC as a result of these scenarios. Section 6 describes possible accident scenarios in transportation, handling and storage of the SRMs. Section 7 presents a discussion of the consequences of the different accident scenarios. Section 8 provides a comparative risk analysis. Section 9 contains a glossary of abbreviations and terms used in this report.

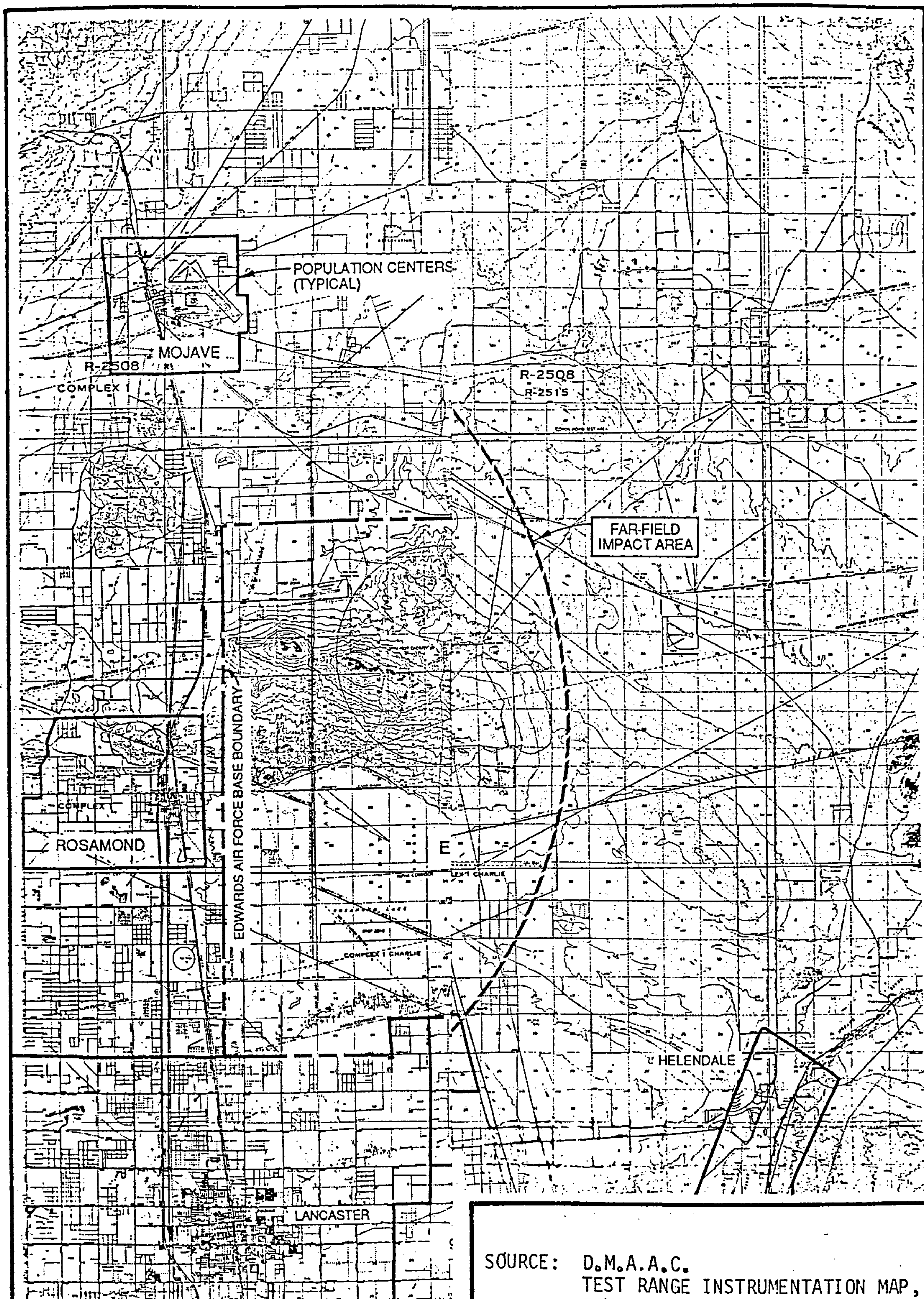
2. FACILITY OVERVIEW

The purpose of this section is to provide an overview of the aspects of the facility pertinent to this risk analysis and the solid rocket motors (SRMs) to be tested. Figure 2-1 indicates the location of the proposed facility with respect to surrounding communities. (Impact areas marked refer to regions potentially at risk from an airborne beryllium release). Figure 2-2 indicates the locations within the Air Force Rocket Propulsion Laboratory (AFRPL) grounds of the high altitude test facility, the two candidate storage locations, and the built-up area of AFRPL. Table 2-1 presents estimates of populations within the impact areas during the period of the proposed test program.

The high altitude test facility includes an existing Control Building, a Toxic Control Building (TCB) for the build up and preparation of SRMs for testing, a motor test cell (MTC) and a containment vessel (CV) into which the rocket motor exhaust gases are discharged during the test firing. Figure 2-3 indicates the arrangement of the MTC and CV. Table 2-2 defines key parameters for these facilities.

Figures 2-4 and 2-5 provide sketches of the primary candidate SRM storage facility (building 9635) and the alternative candidate (building 8915) respectively. The security and fire control systems (see section 6) will be upgraded for building 9635 if it is selected. Table 2-3 summarizes key characteristics of each of these facilities.

The SRMs to be tested will range in size up to 150 pounds of propellant. At present, for planning purposes, it has been assumed that over the three year planned duration that there will be 65 tests consisting of 50 firings of 70 pound BATES motors and 15 firings of lightweight case 150 pound motors. During the following four years an additional 100 motors



Figurs

SOURCE: D.M.A.A.C.
TEST RANGE INSTRUMENTATION MAP,
EDWARDS AFB CALIFORNIA AIM LG.,
EDITION 6 SEPTEMBER, 1983

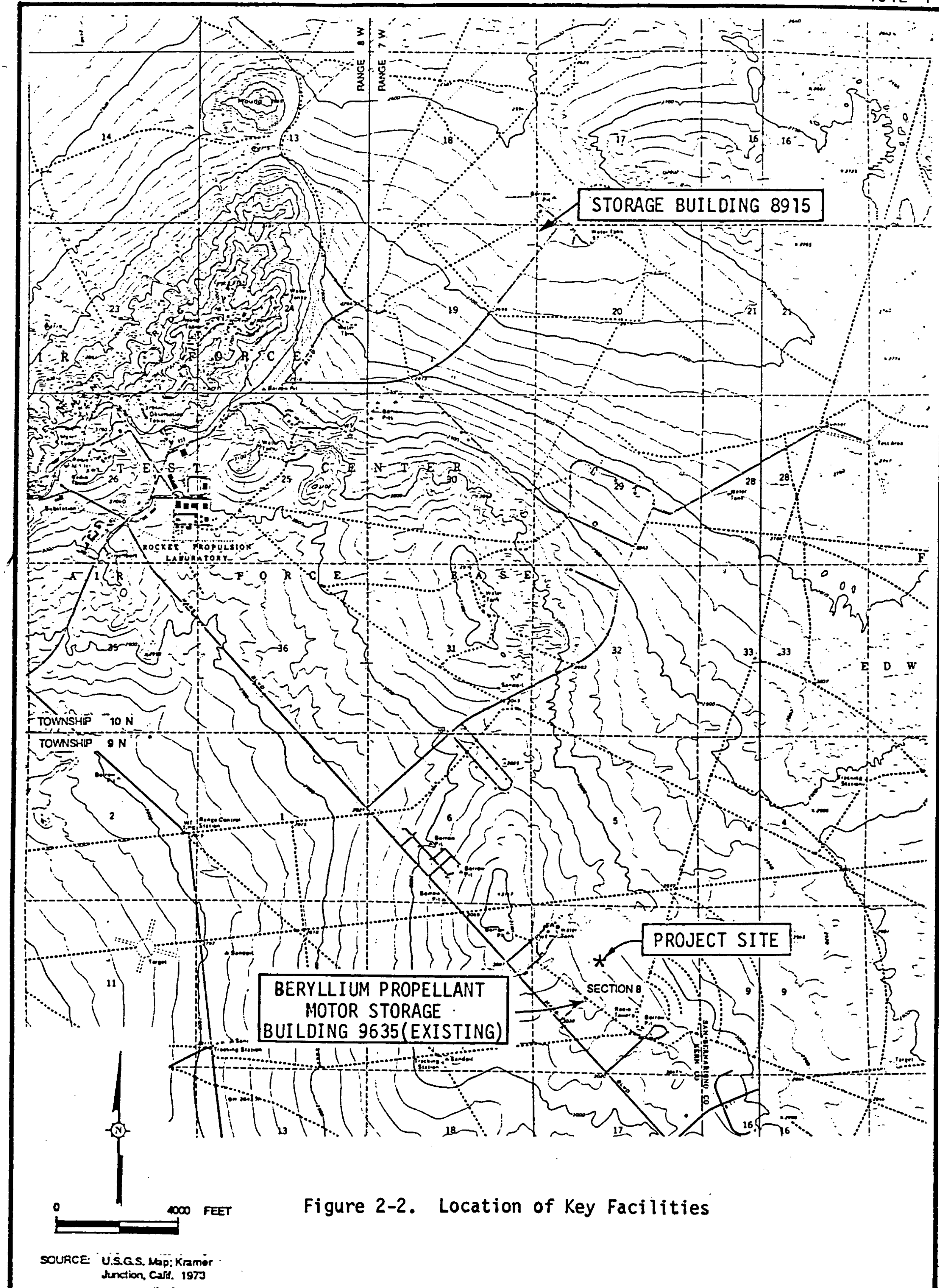


Figure 2-2. Location of Key Facilities

Table 2-1. Estimated Populations* at Risk

Location/Year	1988	1989	1990	1991	1992	1993	1994
RPL	670	670	670	670	670	670	670
Boron	2270	2285	2300	2310	2320	2330	2340
Sunhill Ranch Airport	170	185	200	215	230	250	270
Census Tract 9001	10	15	20	22	24	26	30
RPL Gate	5	5	5	5	5	5	5
Hwy 395	360	432	432	504	504	576	576
Hwy 58	288	360	360	360	468	468	468
Estimated Number of Test Firings	27	28	10	25	25	25	25

* Estimated Populations Within Farfield Impact Area (see Figure 2-1)

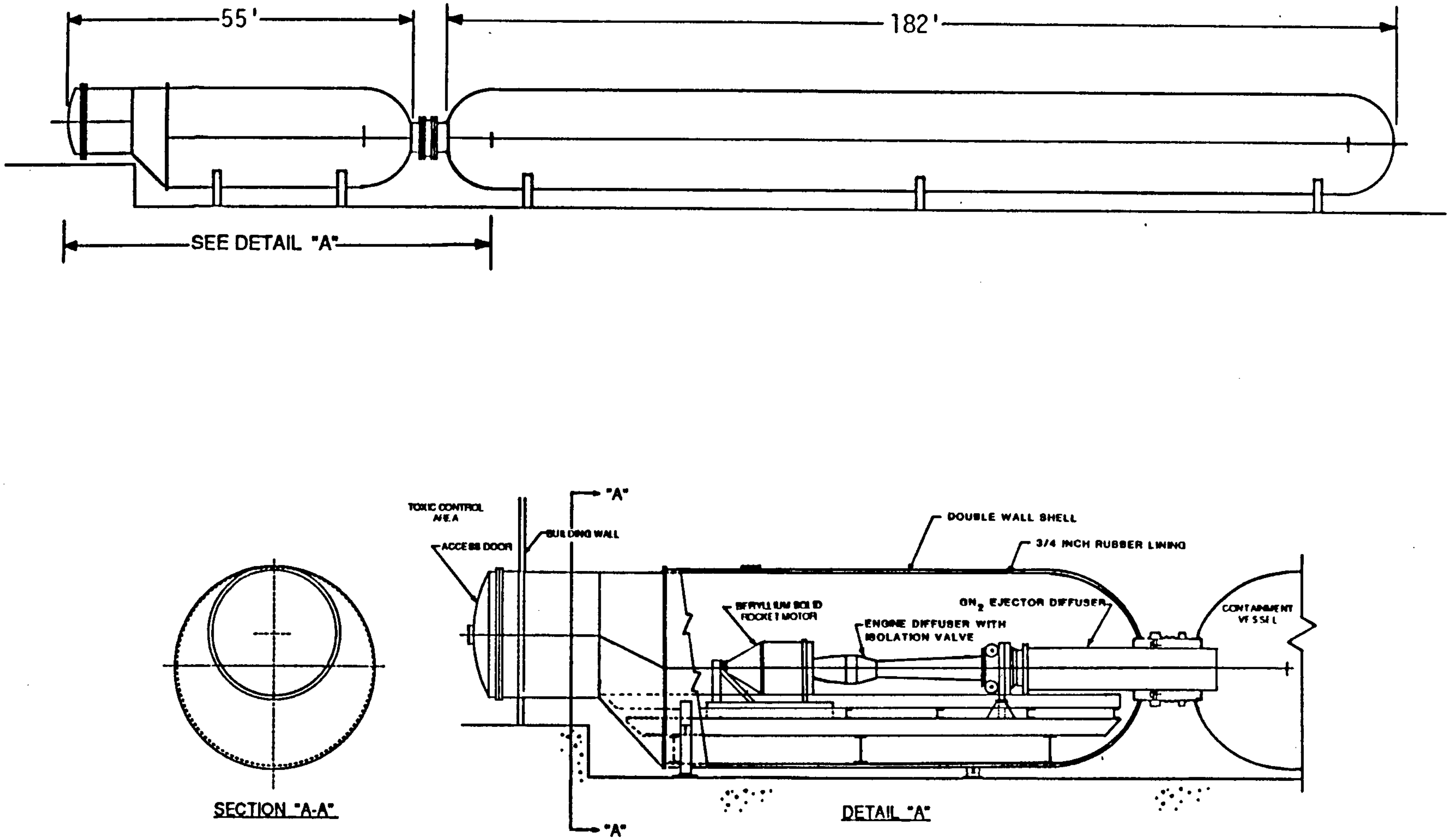


Figure 2-3. Motor Test Cell and Containment Vessel Beryllium Propellant Facility

SOURCE: BECHTEL NATIONAL INC.
SAN FRANCISCO CA.
BERYLLIUM PROPELLANT FACILITY
EXISTING ALTITUDE CHAMBER
FILE NO. 23325621 SHEET:SK-M-1
REVISED 11/13/86

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Table 2-2. MTC and CV Design Parameters

Four Sections to MTC:

Test Chamber:	Diameter = 16 ft, Length = 32 ft, Constant Diameter Section
	Hemispherical Head: 8 ft Radius
	inner Wall Thickness = 0.25 in
	Outer Wall Thickness = 0.4375 in
	Standoff Connector Bolts = 6 in. Spacing
	Lining = Approximately 0.75 in. EPDM Rubber
Transition Section:	Maximum Diameter = 16 ft
	Minimum Diameter = 10.5 ft
	Length = 5.5 ft
	Wall Thickness = 0.5 in
Toxic Control Area:	Diameter = 10.5 ft
	Length = 5.5 ft
	Wall thickness = 0.5 in
Torospherical Head:	Head radius = 10.5 ft
	Wall Thickness = 0.375 in
	Length = Approximately 30 in.
Volume:	Approximately 9800 ft^3
Material:	A-36 steel

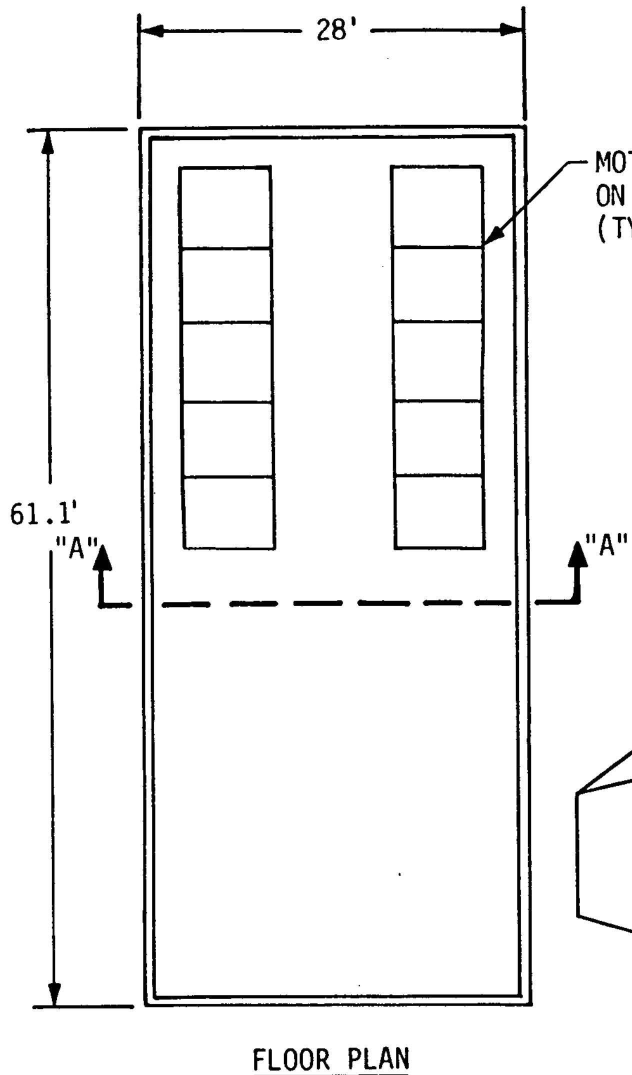
MTC penetrations (Cables, N_2 lines, ports), end cap and access door to be designed as strong as the MTC steel wall

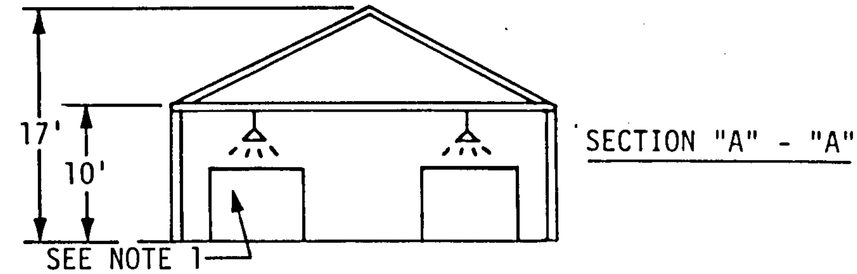
MTC communicates during testing operations to Containment Vessel (CV) by an approximate 24 inch minimum diameter diffuser equipped with an isolation valve and an annular nitrogen ejector to prevent back flow of exhaust into the MTC while the valve is closing.

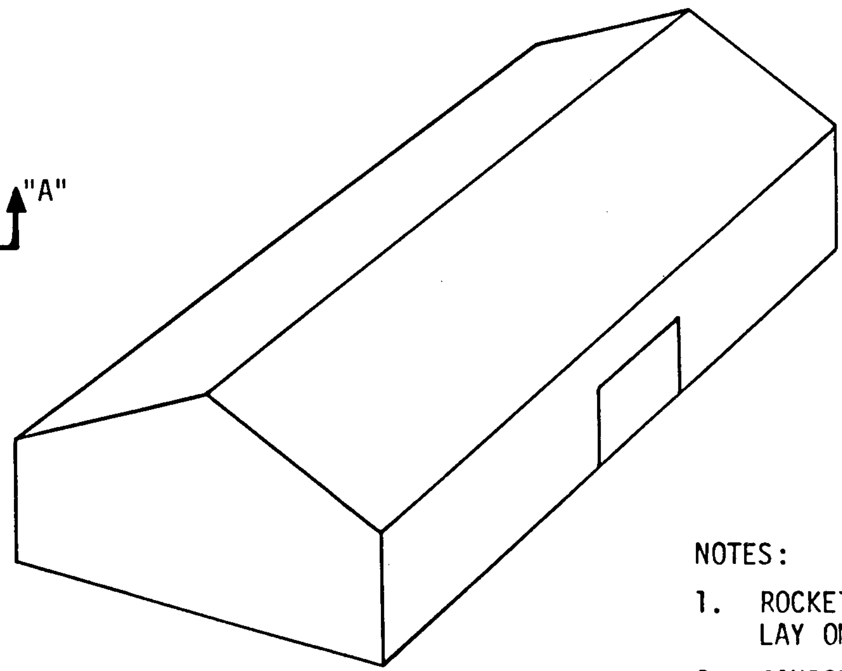
MTC to be provided with a pressure blowout device (24 inch diameter frangible disc, 6 psid burst pressure, connecting to CV)

Containment Vessel

Length = 182 ft, Radius = 8 ft
Volume = Approximately 35500 ft^3



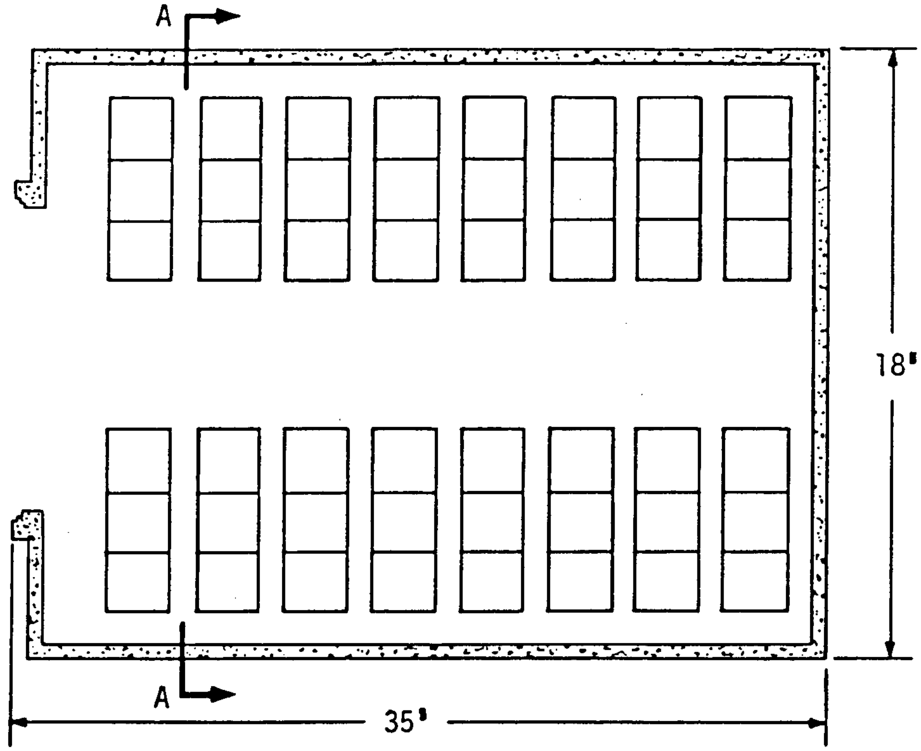




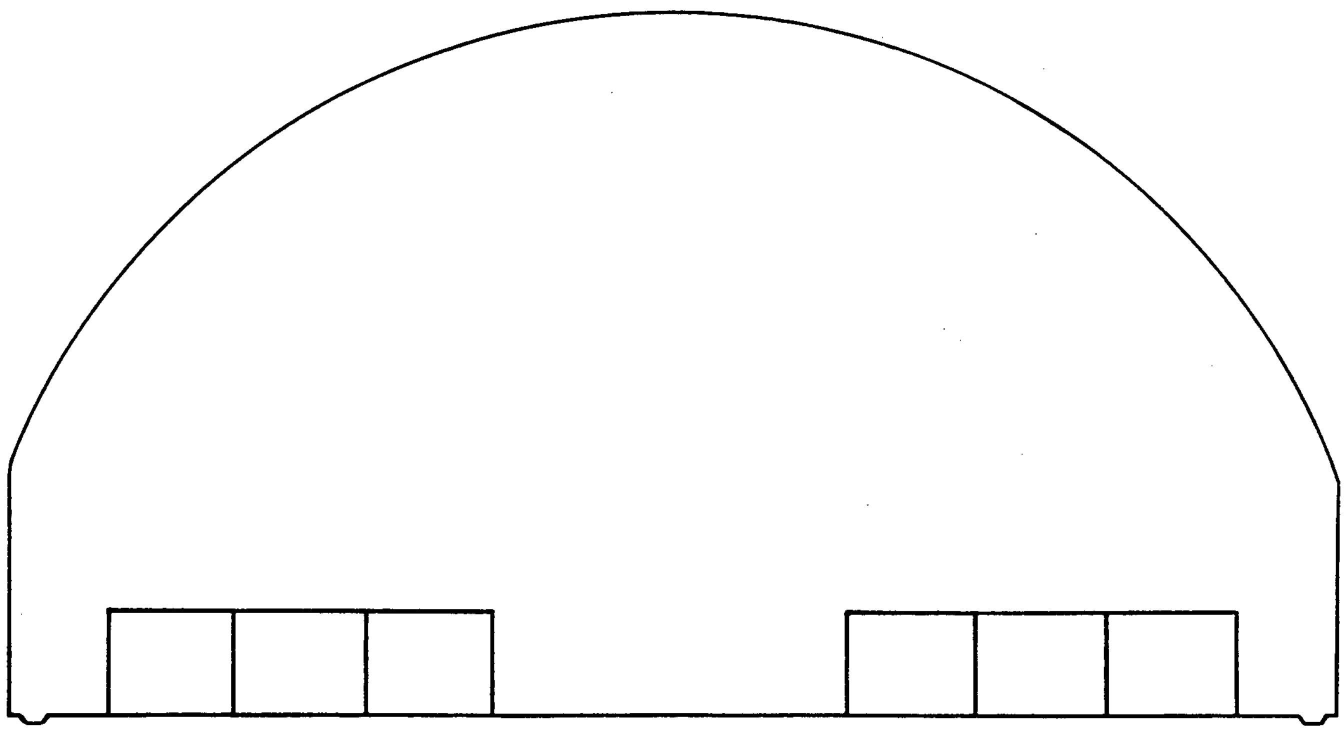
NOTES:

1. ROCKET MOTORS IN THE CANISTERS LAY ON PROTECTIVE WOODEN PALLETS.
2. CANISTERS ARE ELECTRICALLY GROUNDED.
3. NO STACKING OF MOTOR PALLETS.
4. MAXIMUM STORAGE OF 10 MOTORS(70 lb.) OR 700 lbs. OF PROPELLANT

Figure 2-4. Building 9635
Primary Motor Storage
Beryllium Propellant Facility



PLAN VIEW



SECTION A-A

Figure 2-5. Building 8915
Alternative Motor Storage Candidate

Table 2-3. Present Characteristics of Candidate Storage Facilities

BUILDING 9635:

Plan Dimensions: 61.1 ft x 28 ft

Facility Type:
- Sheet Metal on Steel Frame
- No Interior Partitions
- Polyurethane foam wall lining
- Standard single personnel entrance door and sliding (garage type) double door
- Building windows

Fire Load
- Be SRMs
- 3 Inch Thick Polyurethane liner
- Approximately 20% Floor space used

Fire Protection: Wet sprinkler system

Travel Distance to RPL gate: 5.25 miles

Travel Distance to TCB: 0.81 miles

BUILDING 8915

Plan Dimensions: 35 ft x 18 ft

Facility Type:
- "Igloo"
- Reinforced concrete walls, corrugated metal arch roof
- 80% underground
- No interior partitions
- Steel plated doors

Fire Load
- Be SRMs
- Other (more thermally vulnerable SRMs)
- Most floor space used

Fire Protection: CO_2 fire extinguisher

Travel Distance to RPL gate: 2.5 miles

Travel Distance to TCB: 4.5 miles

will be tested. Approximately two thirds of these will be 50 pound motors; the remaining one-third will be 150 pound motors. All cases and nozzles will be light weight to flight weight. The maximum number of firings currently planned in any year is 28.

Among the SRM characteristics that dominate the degree of risk the following deserve to be highlighted: (1) propellant weight, (2) propellant explosive classification, (3) beryllium content of the propellant, and (4) motor case/nozzle type.

Propellant weight has a direct bearing on the explosive and energy release potential of the SRM as well as the amount of beryllium products which may be released in the event of an accident. The test program was originally defined as using class 1.3 propellants. These propellants are characterized as burning vigorously so that fires are difficult to put out. Explosions involving these propellants are usually pressure ruptures of containers, detonation of these propellants does not involve the entire propellant mass. Instead the explosion fades leading to ejection of propellant chunks or continued burning of the remaining propellant.

As a consequence of the increased SRM performance that may be achievable using class 1.1 propellants and the uncertainty in the explosive characteristics of the propellant formulations being developed, a ground rule for the risk analysis is that all SRMs will be <u>assumed</u> to use class 1.1 propellants. Class 1.1 propellants are described as "principally a blast hazard and may be expected to mass-detonate when a small portion is initiated by any means" (AFR 127-100). Thus, the assumption of class 1.1 propellant is conservative in that it results in all the propellant being exploded. This produces higher shock overpressures and fragment velocities than would be expected from a class 1.3 propellant.

The primary effect on the risk analysis of the beryllium content of the propellant is the amount of airborne beryllium compounds that will be generated by an accident. An upper bound value of 20 percent of the propellant is used for the analysis. Table 2-4 outlines the health effects.

The motor case and nozzle design affects the likelihood of certain types of failures and the anticipated consequences. The heavy walled steel (BATES) type cases may preclude a pressure rupture of a failed SRM under conditions for which the light weight motor cases may fail. On the other hand, should a BATES motor case fail the resulting fragment environment is expected to be more severe than that resulting from a light weight case.

A second distinction is the manner in which the SRMs are shipped and stored. All of the motors to be tested in BATES type cases are stored without nozzles and with an opening in the dome end for the subsequent insertion of an igniter. Some of the light weight motors will have a sealed dome and some of them will have a nozzle wound as an integral part of the case. In the event that an SRM is inadvertantly ignited prior to moving it to the test cell, those motors with an opening in the dome will not be able to develop any significant directed thrust. SRMs with sealed domes and those with sealed domes and nozzles will be able to generate thrust directed toward the aft end of the SRM should they be ignited in storage and thus may pose additional hazards from the thrusting SRM.

Key SRM motor characteristics are summarized in Tables 2-5 and 2-6.

Table 2-4. Beryllium Toxicology (Page 1 of 2)

- Primary Pathway to Hazard Human Beings is Inhaling Be Compounds' Dust [24*]
- Three Levels of Consequences [24]
    - Acute Beryllium Disease
    - Chronic Beryllium Disease
    - Carcinogenesis
- Greater Toxicity Associated with "Low Fired" (500°C) Be Oxide than "High-Fired" (1600°C) [24]
- Temperature of Combustion is Highly Correlated with Solubility of Oxides and Degree of Hydration [34]
- Acute Beryllium Disease [2]
    - Causes Swollen & Hyperemic Mucous Membranes, Bleeding, Fissures and Ulceration
    - Intense Exposure can Lead to Pneumonitis
    - Generally, Recovery Expected in Several Weeks after Removing Exposure
    - Described as Resulting from Massive Doses

* Numbers as superscripts refer to references at the end of this report

Table 2-4. Beryllium Toxicology (Page 2 of 2)

- Chronic Beryllium Disease [2]
    - Symptoms Include Dyspnea, Weight Loss, Coughing, Fatigue and Chest Pain
    - Generally Long Latency Before Symptoms Show
    - Appears to be Associated with Hypersensitive Individuals
    - Data Suggests Current Standards Must be Exceeded for Chronic Be Disease Threshold

- Carcinogenesis [9, 16]
    - No Definitive Evidence as Carcinogen in Humans
    - Based on Animal Studies is a Potential Human Carcinogen
    - Mean Estimate of Probability of Carcinogenesis is 2.4×10^{-3} from a Continuous Lifetime of Exposure to a Concentration of 1 Microgram per Cubic Meter

Table 2-5. Assumed Solid Rocket Motor (SRM) Design Parameters

- Motor Cases
  - Heavy Walled (such as BATES Motors) to be Used to Test Propellants and Nozzles
  - Light (or Flight) Weight with Low Margins of Safety to be Used in Casing Design Tests
  - Casing Material could be Steel (Heavy Walled), Titanium or a Composite (Light Weight/Flight Weight) (Filaments of Graphite, or possibly Kevlar, with Epoxy)
- Motor Dimensions for Analysis
  - Standard 70 lb BATES Motor
    Outside Diameter = 12.8 inches
    Wall Thickness = 0.375 inches
    Length = 20.4 inches
  - 150 lb Lightweight Motor
    Outside Diameter ≤ 48 inches
    Wall Thickness = 0.001 - 0.1 inches
    Length (with nozzle) < 75.0 inches
- Propellant Density = 0.06 lb_m/in^3
- Propellant Burn Rate = 20 lb_m/sec

Table 2-6. Typical Beryllium Test Motor Propellant Compositions

PROPELLANT WITH HMX OXIDIZER	WEIGHT PERCENT
Ammonium Perchlorate (oxidizer)	51
Beryllium (fuel)	20
HMX (oxidizer)	19
HTPB (binder)	10
PROPELLANT WITHOUT HMX OXIDIZER	
Ammonium Perchlorate (oxidizer)	70
Beryllium (fuel)	20
HTPB (binder)	10

Typical Beryllium Test Motor Exhaust Compositions

EXHAUST COMPONENT	WEIGHT PERCENT	
	WITH HMX	WITHOUT HMX
BeO	38	43
$BeCl_2$	13	18
BeX	8	5
CO	21	19
H_2	3	3
HCl	3	4
N_2	13	8
EXHAUST HEAT CAPACITY (CAL/100g °K)	144	250
EXHAUST RATIO OF SPECIFIC HEATS	1.1	1.1

Source: Atlantic Research Corporation, November 1986.

3. SOLID ROCKET MOTOR/SOLID PROPELLANT EXPLOSIVE CHARACTERISTICS AND HISTORICAL ACCIDENTS

The purpose of this section is to present the findings from literature/library searches and document reviews and discussions with various professionals involved in the field of SRM failure analysis. The tables and figures displayed reflect the discrepancies that exist in the literature among various sources. This is a result of incomplete data requiring extensive judgments of investigators to interpret what occurred for different accidents. The attempt has been to summarize what has been learned about SRM failure characteristics, solid propellant explosive potential and pertinent SRM accidents. In later sections key analysis assumptions are identified before they are used.

3.1 SRM Detonation

Information obtained pertaining to the detonation of an SRM is presented in Table 3-1 (note that the table refers to Figures 3-1 and 3-2). In general, the table presents observations and study results based on SRM detonation accidents or tests.

3.2 Fragments Resulting from SRM Explosions

Solid rocket motors which explode (pressure rupture/deflagrate or detonate) produce high velocity case fragments and, except for a mass detonating motor, solid propellant fragments. Case fragments could potentially puncture through the MTC wall and propellant fragments could detonate upon wall impact. Thus it is important to estimate the mass, size and velocities of fragments. Table 3-2 presents the limited data that was found on the subject.

Table 3-1. SRM Detonation

- Information to Date Indicates that a Detonation During Ignition or Burn is not Credible unless a Motor Malfunction Occurs

  Excerpt from ESMC 84-1[15] (Approximate Wording)

  "There is no full scale data that indicates that motor detonations have occurred unless preceded by a malfunction -- the initial malfunction event that always preceded a detonation is a motor chamber failure, loss of nozzle or other loss of integrity which dramatically affects the propellant grain"

- Identified Cases where SRMs Detonated (without High Velocity Impact of the Motor) During Trident Motor Tests
  - One or Two Trident Second Stage Motors Detonated During Static Tests with a Motor Case Failure
    - Kevlar Composite Motor Cases
    - Class 1.1 Cross Link Double Base Propellant (Fairly Brittle)
  - One Trident First Stage C-4 Motor Detonated in Flight Due to Destruct Action
    - Apparently a Kevlar Case Operating at 1200-1300 psi
  - Postulated that the Rebound Action of the Relatively Flexible Kevlar Case, at Depressurization, caused Propellant Damage and a Deflagration to Detonation Transition (DDT)

Table 3-1. SRM Detonation (Continued)

- Basic Parameters Affecting Propellant Detonability are [15]
  - Roughness
  - Response to Shock (Shock to Detonation Transition [SDT] Susceptibility)
  - XDT (Propellant impact break-up Followed by DDT) Impact Induced Detonation Susceptibility (Impact Causing Grain Pulverizing with Convective Burning Leading to Detonation)
  - Granular Bed Characteristics
  - Motor Characteristics (Geometry, Diameter, Chamber Pressure, Case Bonding Technique, Propellant Residue Grain)
  - Propellant Critical Diameter

- Estimates of TNT Yields from Tests Involving the Explosion of Solid Propellant Motors (Approximately 7300 lbs of Propellant Each) Using a Primer Charge of 96 lbs of Composition C-4 [21]
  - Class 1.3 Motor Estimates Ranged from about 20% to 30%
  - Class 1.1 Motor Estimates Ranged from about 144% to 174%

- The Generally Accepted TNT Yield for the Detonation of a Class 1.1 Propellant is 125% with a Range of about 120% to 140%

- Three Credible Scenarios were Defined to Explain Trident C-4 Program SRM Detonations (Based on "An Extensive 6-Year Study") [23] (See Figure 3-1)
  - <u>Shear</u> Scenario Involves a Case Rupture Resulting in Large Forces on the Case and Propellant Grain and Propellant/Case Bond 'Shear' Failure Occurring within Milliseconds of the Rupture

Table 3-1. SRM Detonation (Continued)

  - Propellant Characteristically Fails in a Principal Stress Mode (i.e. Cracks Develop at 45° to the Shear Force)
  - Damaged Propellant 'Bed' Ignites from Exposure to Combustion or from Friction
  - Bed Undergoes Deflagration to Detonation Transition (DDT)
  - Remaining Propellant Grain Detonation is Initiated by the Bed Detonation
- Impact Scenario Involves a Case Rupture Resulting in Grain Fragmentation, Repressurization and a Second Fragmentation and Blowout Event
  - Propellant Fragments Enter the Blowdown Gas Stream and can be Accelerated to High Velocities
  - Fragments Detonate Upon Impact with 'Hard' Targets (Test Chamber Wall, Etc.)

- Two Mechanisms of Impact Detonation Identified
  - Classical Shock to Detonation Transition (SDT)
  - Fragment Impact Breakup and Deflagration to Detonation Transition (Called XDT)
- Some Fragments may Impact One-Another in Air and Strike a Surface Together ("Pick-up") - or Impact a Surface and Then be Hit by Following Fragments ("Tandem Impact") - Resulting in Greater Sensitivity to Detonation
- A Fragment Detonation May 'Throw' to Adjacent Fragments and/or the Remaining Principal Grain Causing them to also Detonate ("Sympathetic Detonation")

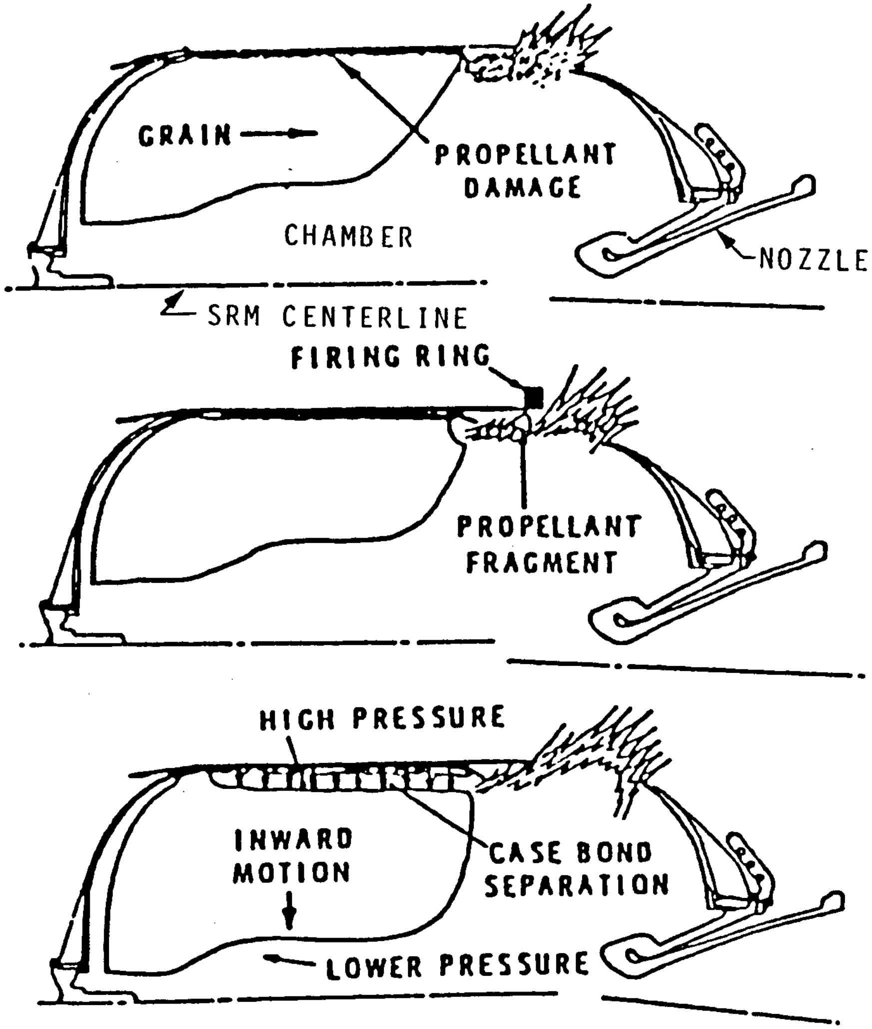
- Implosion Scenario Involves a Case/Propellant Bond Failure (By Some Means) with Burning at the Grain Periphery

Table 3-1. SRM Detonation (Continued)

- Bond Failure can Occur Prior to or Following Case Rupture, and may Result from Bond Shear Forces
- Inward Motion of the Propellant Grain Results from Large O.D. to I.D. Pressure Differentials on the Grain WEB
- The Grain Centerport Closes and Extensive Grain Breakup Near the I.D. (Implosion Damage) Bed May Occur
  - DDT of the Implosion Bed Occurs and may be Followed by Sympathetic Detonation of the Grain

- A Flow Diagram for SRM Detonation, Involving the Three Above Defined Detonation Scenarios, is Presented in Figure 3-2 [23]

- Project Sophy Demonstrated that Class 1.3 Propellant is Hard to Detonate



SHEAR

- DOME RUPTURE
- PROPELLANT/CASE BOND SHEAR FAILURE
- DDT IN SHEAR BED
- GRAIN SYMPATHETIC DETONATION

IMPACT

- CASE RUPTURE
- PROPELLANT FRAGMENTATION
- FRAGMENT IMPACT DETONATION
- MOTOR SYMPATHETIC DETONATION

IMPLOSION

- CASE BOND FAILURE
- HIGH PRESSURE DIFFERENTIAL
- CENTERPORT CLOSURE
- PROPELLANT-PROPELLANT IMPACT DETONATION (FAST)
- PROPELLANT FRAGMENTATION AND DDT (SLOW)
- GRAIN SYMPATHETIC DETONATION

Figure 3-1. Most Likely Detonation Scenarios[23]

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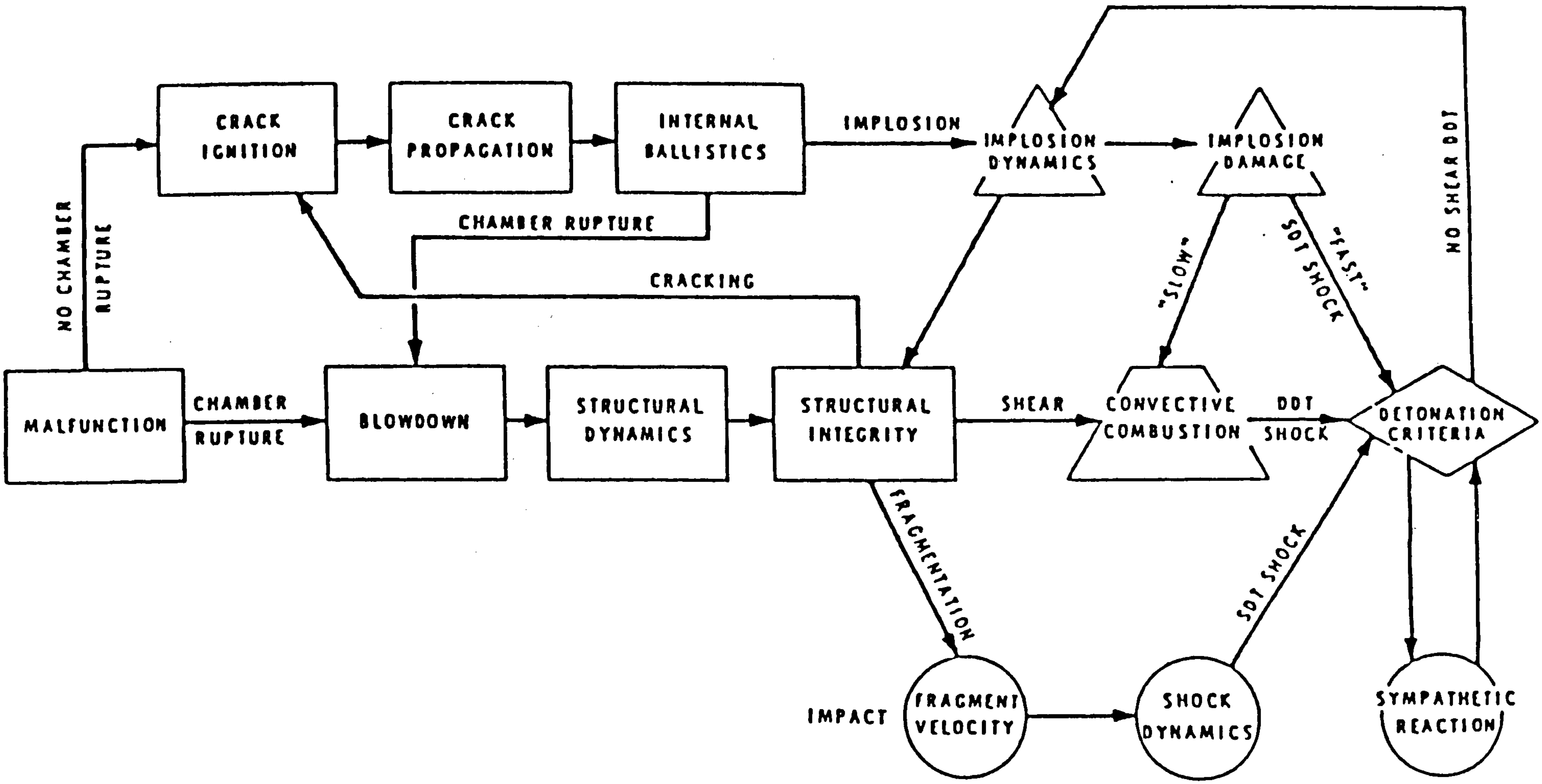

Figure 3-2. Detonation Predictive Model [23]

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Table 3-2. Fragments Resulting from SRM Explosions

- Limited Full Scale SRM (Trident, Etc.) Failure Data Gave Velocity Estimates Ranging from about 50 to 850 fps [14]

- Tend to Get Many Small Propellant Pieces

- Based on Results of Seven Tests where Solid Propellant Motors were Exploded by Subjecting them to a Severe Explosive Shock using a High Explosive Primer Charge (Usually 96 lbs of Composition C-4) [21]
    - Motors Contained either Class 1.3 or Class 1.1 Propellant, Approximately 7300 lbs of Propellant Each
    - Five of the Test Involved Two Motors Placed Side by Side or Stacked
    - It was Estimated that About 10% of the Propellant Fragments Thrown Out from an Explosion were Burning
    - Propellant Fragments from the Explosion of a Single Class 1.3 Motor
        - Traveled up to 3000 Feet
        - The Largest Fragments Tended to Travel the Furthest
        - Maximum Fragment Weight was Well Over 10 lbs
    - The Explosion of a Single Class 1.1 Motor Involved Essentially all of the Propellant; The Remainder was Ejected in the Form of a Few Firebrands

- Propellant Fragment Velocities (Ejected from a Ruptured Case) of up to 1400 fps have been Observed in (Trident) C-4 Case Ruptures[23]

- Most fragment velocities from pressure ruptures are in the range 400 - 1100 fps [44]

3.3 Propellant Impact Detonation

As mentioned in Section 3.2, solid propellant pieces can detonate on impact. Both class 1.1 and class 1.3 propellants can detonate, dependent on the fragment mass and velocity. The 'detonation' for class 1.3 propellant is a fading detonation giving a much lower yield than for class 1.1 propellant. Information acquired on propellant impact detonation is presented in Table 3-3.

3.4 Propellant Explosive Classification

The explosive classification of the solid propellant to be used in the Beryllium Propellant Facility is vital to defining the worst case explosive accidents which can occur. The potential loading conditions, and thus the likelihood of breaching the MTC, are much more severe for a propellant which can mass detonate (class 1.1) than for one which cannot sustain a detonation (class 1.3). The current ground rule is that the propellant may be class 1.1. As is discussed in Section 5, the mass detonation of a class 1.1 will most probably breach the MTC for the postulated design. Information gathered on the explosive classification of solid propellant is presented in Table 3-4.

3.5 SRM Historical Accidents

Undoubtedly the best means of ascertaining what types of catastrophic accidents could occur in the MTC is to study information on historical accidents. Of particular interest are those that have occurred during static tests in test chambers. The historical accident data obtained are presented in Table 3-5. Note that Table 3-5 refers to Table 3-6 through 3-10.

Table 3-3. Propellant Impact Detonation

- Velocity Required to Initiate Detonation (Critical Velocity)
  - Impact Velocity Required to Cause an Explosive Reaction Increases with Decreasing Propellant Fragment Mass[11]
  - Damage (Porosity) can Reduce the Energy Required to Induce an Explosive Reaction by at Least 50% (Per Project Sophy Tests)[11]
  - Full Scale Large SRM Impact History Indicates a Threshold Critical Velocity of 300 fps for Both Class 1.1 and 1.3 Propellant, However the Velocity will Increase Significantly for Smaller Masses of Propellant [11]
    - The Impact Surface for the Large Scale Explosive Reactions Seemed to Make Little Difference (Concrete, Sand or Water)
    - Data Indicates that there is no Significant Difference in the Critical Velocity for 1.1 and 1.3
  - May be able to Estimate Critical Velocity as a Function of Propellant Fragment Diameter using the Rinder Formula (See Figure 3-3) [11]
    - Agrees with Some Work Done by Lawrence Livermore Lab (LLL)
    - Gives a Critical Velocity of About 4000 fps for 5 in Diameter and 2000 fps for a 10" Diameter
  - Propellant Threshold Impact Velocities to Initiate Detonation, as a Function of Fragment Radius, were Estimated for the Trident C-4 Program Propellant Designated 'VRP' (C-4 Tactical FS and SS) - See Figure 3-4
  - Trident Motor Detonation Investigation and Other Miscellaneous Tests Show Conclusively that Impact Induced Explosion Reactions of Either Class 1.1 or Class 1.3 Propellants are a Function of Mass and Damage (Porosity) [11]

Table 3-3. Propellant Impact Detonation (Continued)

- Increased Mass Lowers the Velocity Required for an Explosive Reaction

- Increased Damage (Defined by Surface to Volume Ratio) Lowers the Critical Velocity and Increases the Yield

- Project Sophy Established that Composite, Class 1.3 Propellant has a Critical Diameter of 90 in. to 100 in Below Which a Detonation Cannot be Sustained Throughout the Mass of Propellant [11]
- Data from full scale large SRM impacts indicate equivalent TNT yields of [11]
    - Approximately 125% for Class 1.1 Propellants (Mass Detonation)
    - 8% to 25% for Class 1.3 Propellants (Fading Detonation)
- The Impact Detonation Phenomena is Either
    - A Shock to Detonation Transition (SDT), or
    - An 'XDT' where a Delayed Detonation Results Due to Propellant Grain Damage (Break-up) and 'Convective Burning' Leading to Initiation of a Detonation (Studied by LLL)

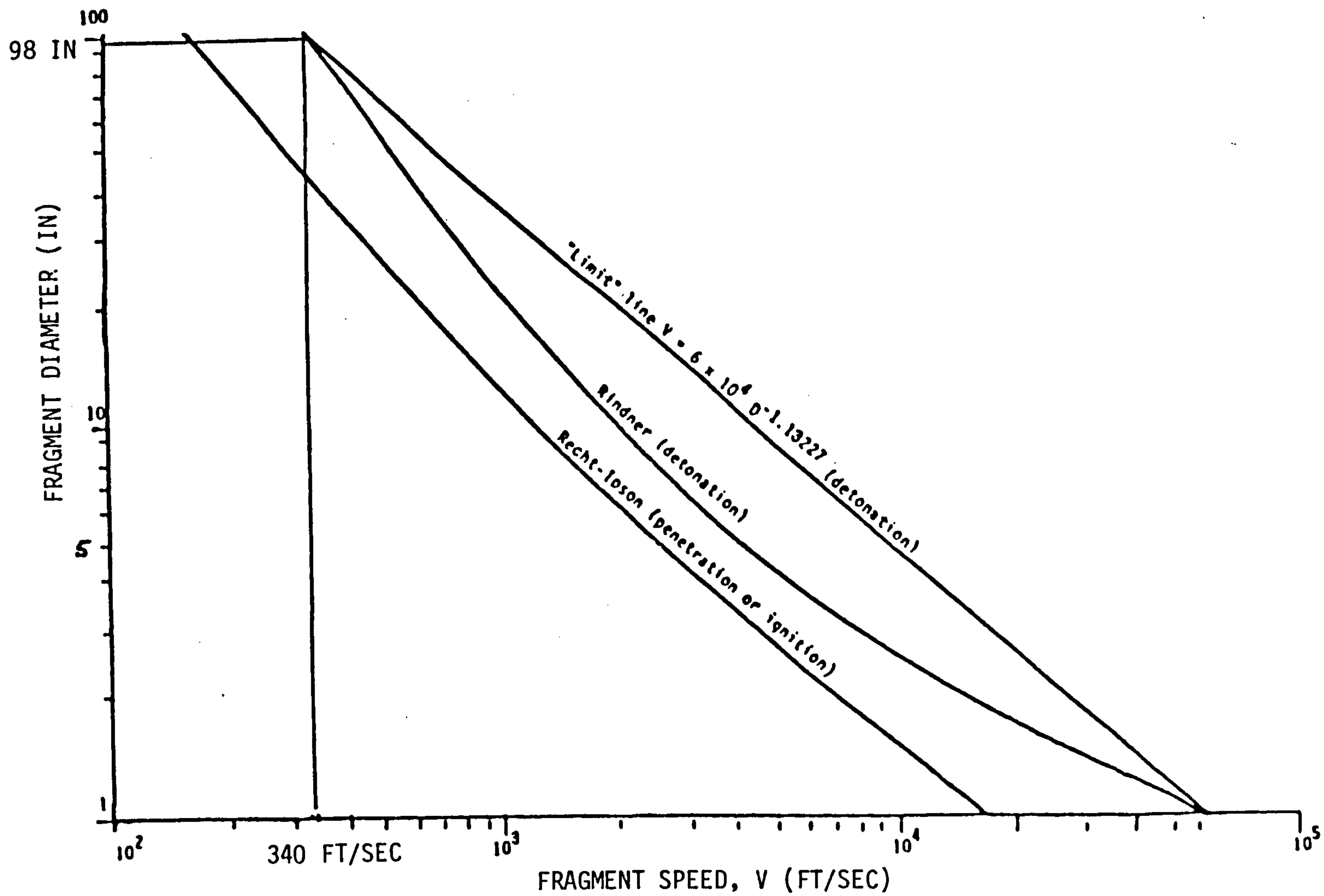

Figure 3-3. Critical Velocity vs. Diameter (Initiation/Detonation of Propellant TP-H-1148)[11]

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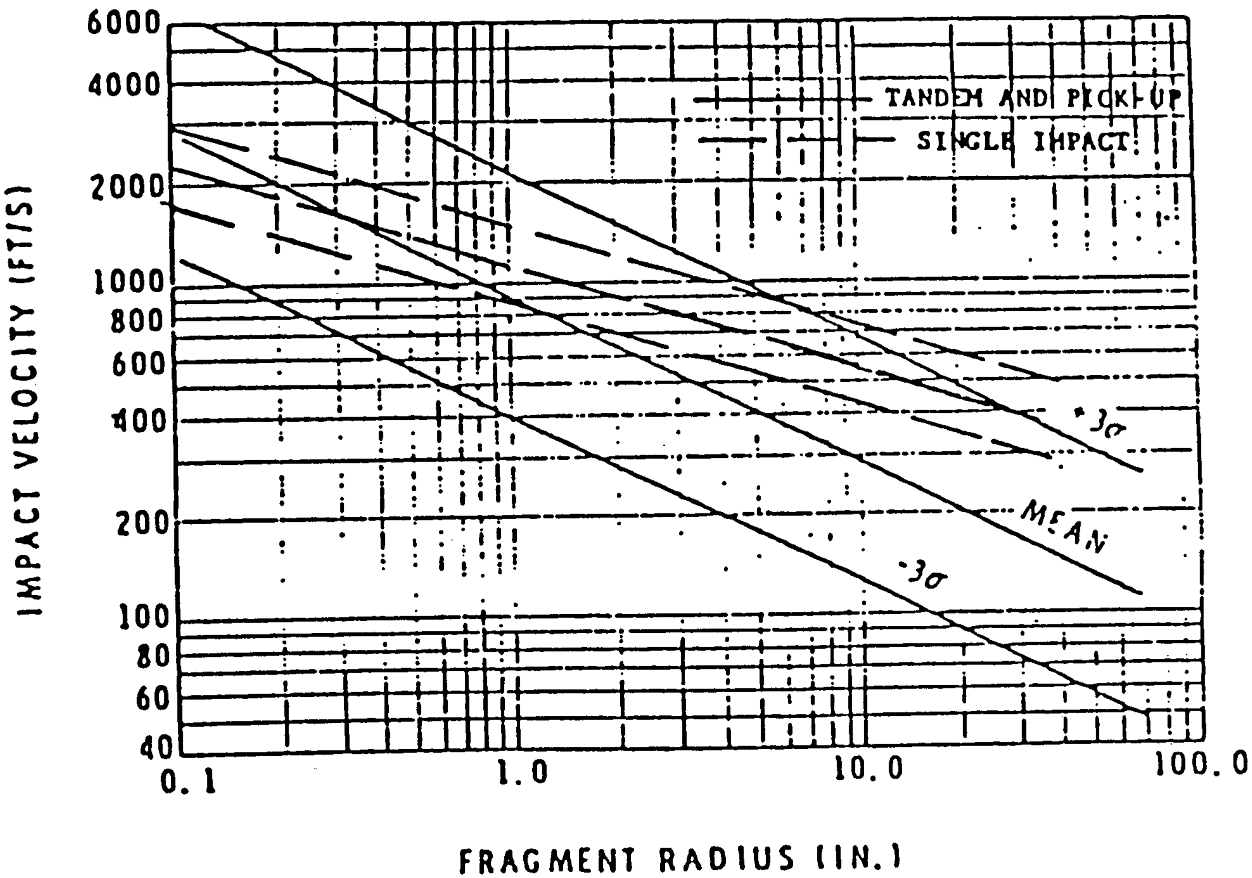

Figure 3-4. Critical Impact Velocities as a Function of Radius (VRP Propellant)[2]

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Table 3-4. Propellant Explosive Classification

- The Explosive Classification of Solid Propellant is Determined by the "Card Gap Test"[17]

    - Typically a Sample of Propellant is Placed in a Steel Tube, Capped on one end by a Mild Steel Plate
    - A Series of Thin (~ .25 mm) Discs (Cards) are used on the other end of the Tube to Apply a Shock Load to the Propellant
    - The Number of Cards is Varied to Determine the Maximum Number for Which a Detonation of the Propellant will be Initiated
    - The Principle Here is that for each Propellant there is some Minimum Shock Strength which will Just Cause Transition
    - The Classification (1.1 or 1.3) is Determined by the Number of Cards Required
    - Care Must be Taken in Using the Results of this Test to Determine the Detonability of Larger Masses of Propellant
    - Several "Professionals" Working in the Field Expressed Concern with the Reliability of the Test

- Explosive Classification Definitions

    - Class 1.1

        - "Principally a Blast Hazard and may be Expected to Mass-Detonate when a Small Portion is Initiated by any Means" (AFR 127-100)
        - "Practically Instantaneous Explosion or Detonation of Virtually the Entire Quantity may be Expected"[13]

Table 3-4. Propellant Explosive Classification (Continued)

- Class 1.3
  - "Burns Vigorously and the Fires are Difficult to Put Out. Explosions are Usually Pressure Ruptures of Containers and do not Produce Propagating Shock Waves or Damaging Blast Overpressures Beyond Intermagazine Distance" (AFR 127-100)

- Propellant Classification of Some Common SRMs [25]

ICBM Testing at AEDC

Motor	Propellant WT(K-LB)	Class/Div	TNT Equiv. (K-LB)
Peacekeeper Stage II	55	1.3	--
Peacekeeper Stage III	16	1.1	20
Minuteman II/III Stage II	14	1.3	--
Minuteman I/II Stage III	4	1.1	5
Minuteman III Stage III	7	1.3	--
Poseidon Stage II	16	1.1	20
Trident I Stage II	17	1.1	21
Trident I Stage III	4	1.1	5

- Concern has been Expressed [14, 26, 27] Regarding the Effect of Using Beryllium on the Detonability (Classification) of the Propellant- i.e. Beryllium could cause Classification to Change from 1.3 to 1.1 by Altering the Characteristics (Brittleness, Frangibility, etc.) of the Propellant

Table 3-5. SRM Accidents

- Static Firing of a Minuteman Motor, Attempting to Replicate a Failure Causing Rupture of the Motor Case
  - Propellant Class 1.3
  - Test At AEDC Facility
  - Got Larger Explosion than Expected, Causing Significant Movement of a Test Chamber Cover Weighing Several Tons

- Motor Detonations Occurring During the Trident C-4 Program (Hercules Motors) (as a consequence of experience in this test program current C-4 propellants are much less brittle, hence less likely to detonate)

  See Tables 3-6 and 3-7

- Peacekeeper Stage III Explosion at AEDC Facility

  See Table 3-8

- Historical Solid Rocket Motor Mishap Data was Obtained from the Air Force Inspection and Safety Center (AFISC) at Norton AFB and Information on Selected (Potentially Pertinent) Mishaps is Presented in Table 3-9

- Historical Solid Rocket Motor Firing History of Air Force Rocket Propulsion Laboratory Test Area 1-42 is presented in Table 3-10

Table 3-6. [23]

Hercules Full Scale Motor Detonations (C-4 Program)

MOTOR	PROPELLANT	TEST DATE	SEQUENCE OF EVENTS
BE-14	VID	April '68	Pressure normal (hot) for 20 seconds Max Pressure 920 psi Apparent Aft rupture @ 23.7 seconds Detonation 3.5 ms after Rupture
SST-004 (Early C-4)	VLZ	May '74	Pressure normal for 17 seconds Max Pressure 1760 psi Apparent Aft rupture @ 17.6 seconds Detonation 3.3 ms after rupture
SD-0021 (C-4 FS or SS)	VOY	June '75	Pressure 100-300 psi high Max Pressure 1550 psi Aft rupture @ 25.1 seconds Detonation 2.5 ms after rupture
FX-0004 (C-4 Intermediate FS or SS*)	VRO	May '76	Command destruct (Fwd) @ 4.0 seconds Max pressure 1020 psi Blowdown and repressurization to ~ 1000 psi detonation 192 ms after rupture

*FS = First Stage
SS = Second Stage

Table 3-7. [23]
Hercules Subscale Detonation Summary (C-4 Program)

UNIT	SIMULATION	PROPELLANT	PROPELLANT WEIGHT (LBS)	BEHAVIOR
3SF-24A	SST-004 with Fwd Defect and Aft Rupture	VLZ	3700	Rapid Defect Propagation Detonation 8 ms after Rupture
3SF-32	SST-004 with Fwd Defect and Aft Rupture	VLZ	3700	Rapid Defect Propagation Detonation 42 ms after Rupture
LAM-59*	SD-0021 with Aft Rupture	VO	~100	Detonation 16 ms after Rupture
LAM-105*	SD-0021 with Aft Rupture	VRL	~100	Detonation 16 ms after Rupture

*LAM = Lightweight analog motor

Table 3-8. Peacekeeper Accident [28] (Page 1 of 3)

- Peacekeeper Stage III Propellant Motor Exploded During Static Test
  - Propellant Classification 1.1
  - Test Chamber Evacuated to Simulate Flight Altitude
  - Accident Occurred about 57 Seconds into the Test with the Motor Pressure at Approximately 600 psi and with 1100 to 1300 Lbs of Propellant Remaining
  - Motor Casing Weighed Approximately 1500 Lbs
  - Test Cell was 16 ft Diameter, 50 ft Long, 0.5 in Thick

- The Test Chamber and the Containment Building were Destroyed by the Explosion
  - A 6 Ton Hatch Cover was Thrown 125 ft
  - Many Small Pieces of Unburned Propellant were Found (Pieces up to about 18 in^3 were Found up to 600 ft away)
  - Windows were Broken out to about 1000 ft
  - The Large Sizes of the Test Cell Pieces and the Relatively Large, Varied Sizes and the Shapes of the Motor Casing Pieces indicated a Deflagration instead of a Total Motor Detonation
  - Pieces of the Test Cell Wall had "Dents" indicating Possible Propellant Impact Detonations

- Three Root Causes of the Accident were Considered
  - Total Motor Detonation
  - Pressure Burst of the Motor Case
  - Partial Detonation with Expelled Propellent Pieces Detonating on Impact

Table 3-8. Peacekeeper Accident[28] (Page 2 of 3)

- Total Motor Detonation, by Classic Deflagration to Detonation Transition (DDT), is not Considered Probable Since
  - DDT Originates Inside the Motor and Usually Consumes all of the Propellant
  - Approximately 10 Lbs of Unburned Propellant was Found
  - DDT Event Would take Place in Fractions of a Millisecond while the Motor Continued to Function for Several Milliseconds after Failure Initiation per the Test Data
  - Motor Case and Test Cell Fragments were not Characteristic of a Detonation

- A Simple Pressure Burst was Discounted Since
  - Would Not have Caused Severity of Damage which Resulted
  - Would have Extinguished the Remaining Propellant and Most Would have been Recoverable
  - The Motor Chamber Pressure was Decreasing at the Time of Failure

Table 3-8. Peacekeeper Accident [28] (Page 3 of 3)

- A Partial Detonation is Deemed Most Likely with the Following Scenario
  - Motor Case Burst due to Degraded Strength Resulting from Overheating from an Anomalous Burn Surface
  - Propellant Fragments were Expelled at High Velocities and those with Sufficient Velocity (~780 Fps for this Propellant) Mass Detonated Upon Test Cell Impact

- An Alternative Scenario is as Follows
  - An Anomalous Grain Burn Surface of the Propellant Caused a Deflagration Near the Nozzle Causing Dynamic Motor Case Rupture
  - Propellant was Released into the Cell
  - The Increase in Propellant Burn Area caused a Pressure Build-Up in the Test Cell Greater than the Diffuser could Dissipate
  - The Test Cell Burst Due to Overpressurization

Table 3-9.
Selected Historical Solid Rocket Motor Mishaps (page 1 of 4) 42

Source/No./ Motor/Propellant	Test Description	Failure Description	Damage Description
AFISC 45-26-88-391 Star-48	Qualifying Test T-3 test cell, 110,000 ft altitude, 100 rpm, 85 sec test firing.	Rocket motor failed at forward dome area at 23 sec, aft dome and nozzle assembly ejected,	Test cell thrust stand and spin rig assembly damaged.
AFISC 55-21-97-291 Star-30b Class 1.3	Acceptance Test T-3 test cell, 100,000 ft altitude, 60 rpm.	Rocket motor nozzle failure, exit cone ejected at 6 sec, nozzle throat ejected at 23 sec 1100 lbs of propellant left	Damage to lighting system from debris, and wiring and ignition system from excessive heat.
AFISC 65-21-94-112 Star-30c Class 1.3	Acceptance Test T-3 test cell, 100,000 ft altitude, 60 rpm, 700 lbs propellant left	Rocket nozzle failure, exit cone failure and ejection at 4 sec, nozzle throat failure & ejection at 17sec, additional 11 sec of burning.	Damage to lighting system by debris and to wiring and instrumentation by flame and excessive heat
AFISC 55-21-90-171 Star-37f Class 1.3	2nd Qualification Test T-3 test cell 100,000 ft altitude, 45 rpm, 1952 lbs unburnt propellant left	High instantaneous thrust, exit cone failed and ejected at 10 sec, nozzle throat failed and ejected at 20sec, no additional burning.	Damage to lighting system by debris, to cables and fixtures by excess heat, and to thrust stand by high instantenous thrust.
AFISC 34-31-95-141 Judi weather probe	Judi weather probe launch the rocket failed to lift off, motor continued to burn for 4 minutes.	Material failure, 6 of the 12 propellant grains showed 4 to 5 inch longitudinal cracks when x-rayed.	Rocket destroyed.

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Table 3-9.
Selected Historical Solid Rocket Motor Mishaps (page 2 of 4)

Source/No./ Motor/Propellant	Test Description	Failure Description	Damage Description
AFISC 84-21-97-151 PWN-89 (Loki-Dart)	Loki Rocket Launch 40 sec of weak burning, the payload was ejected from launcher at 110 sec and impacted 30 ft away.	Random propellant failure.	Rocket destroyed.
AFISC 35-21-83-131 SRKTMIR	Igniter Volume Simulation Motor case rupture, at 0.8 sec the nozzle separated and was thrown 1000 ft laterally.	Motor Case rupture, the motor case burned through after insulation fracture, the motor case pressure was 820 lbs, but previously sustained 1030 lbs	Missile Destroyed.
AFISC 13-21-99-122 Aim-4A Missile	Aim-4A Launch from F102A missile exploded after 1.7 sec of powered flight.	Material failure, cracked propellant in rocket motor.	No injuries or aircraft damage, missile destroyed
AFISC 13-31-97-212 Aim-46 Missile Motor	Training Launch - F106A, Co-Altitude firing attack on a mace drone, missile exploded at 1.7 sec 500 ft in front of aircraft	Slight crack in the propellant grain of the rocket caused explosion,	No injuries or damage to the aircraft, missile destroyed
AFISC 13-21-90-121 Aim-7E Missile Motor	Training launch from F-4C missile exploded at 2.0 sec after motor ignition guidance and control and warhead sections tumbled,	Crack in propellant grain caused the explosion after motor ignition The missile was known to have been dropped.	Missile destroyed.
AFISC 13-21-98-161 Aim-7E Missile	Training Launch from F-4D the missile exploded at 1.9 sec after the motor ignition.	Crack in propellant grain of the rocket motor.	No damage or injuries

Table 3-9.
Selected Historical Solid Rocket Motor Mishaps (page 3 of 4)

Source/No./ Motor/Propellant	Test Description	Failure Description	Damage Description
AFISC 85-26-87-261 Bomarc Rocket	Target Launch rocket motor flame at 0 and 1.8 sec,lift off at 2.7 sec, max altitude 268 ft, impact 60ft away	Excessive overpressure at ignition, at ascent whole fuselage was engulfed in flame, motor section detached and impacted 3 miles away	Motor initiator severed fuel and hydraulic lines in the missile disabling thrust control, missile destroyed.
AFISC 24-31-93-251 LGM-30B Stage II	Static Firing Test hot gas release at ignition, gas inpiaged on motor forward dome, dome separated at .324 sec	Motor failed through forward dome, sporadic burn and hot gas release through nozzle and aft dome.	Reparable missile damage
AFISC 65-21-85-331 LGM-30G Minuteman Missile	Operational Test Launch A stage III motor failure at 78 sec, missile guidance system shutdown at 180 sec	Burn-through of a stage III motor in the area of aft dome.	Missile destroyed.
AFISC 45-21-93-151 LGM-30B Missile	Static Test Thrust termination failed at 13 sec after ignition due to a hot gas leak	port closure no. 1 O-ring damaged during assembly in manufacture.	Reparable missile damage, major damage to motor stand, stage III firing harness, instrumentation and wiring on firing pad
AFISC 14-26-87-141 LGM-30 Minuteman stage 3 Class 1.3	Development Test Over-pressure of 865 lbs. at 8 sec, motor case burst at 11 sec	Burn-through of the III stage motor case, case proofed to 780 lbs. and designed for 950 lbs. burst.	Reparable missile damage
AFISC 24-21-93-191 LGM-308 III Stage	Static Test thrust termination port no. 2 failed at 19 sec	O-ring caused a failure of the thrust termination post no. 2, (frangible sector did not detonate until ejection from motor to impact).	Reparable missile damage

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Table 3-9
Selected Historical Solid Rocket Motor Mishaps (page 4 of 4)

Source/No./ Motor/Propellant	Test Description	Failure Description	Damage Description
AFISC 54-21-83-301 BQM-34A Target Drone	Initial Motion Launch loss of thrust at 1 sec, Drone pitched up, rolled, and hit the ground	Propellant failure of the M77A1 Rato Bottle caused deflagration and rupture of the 3,000 psi igniter safety diaphragm.	Target Drone destroyed
AFISC 14-21-81-261 AGM-69A Missile	Missile Launch Motor case failure at 3.2 sec into the second pulse born, the missile broke into three pieces	Increase in propellant burn area caused a rapid increase in the internal pressure in motor case,	Missile destroyed
AFISC 55-26-88-222 M-X Stage II	Contractor Motor Test Structural failure of the motor case at .260 sec	Increased burn surface area caused a pressure of 2700 psi in motor case (50% above normal), thus a simultaneous rupture of aft, mid, & forward sect.	Major damage to the high altitude test facility; camera, mounts, wiring, instrumentation, and int. structures lost
AFISC LGM-118 Peacekeeper Stage 3 NEPE (WAY) Class 1.1	Test Cell (AEDC), motor case failure with 1291 lbs (prefire weight 15622 lbs) propellant remaining	Propellant fragments expelled from failing motor at high velocity (>780 fps) and detonated upon impact with adjacent structures (i.e. SDT).	Test cell completely destroyed, 6 ton north hatch found 125 ft away

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Table 3-10.
Historical Solid Rocket Motor Firing History at AFRPL Area 1-42[45]

POTENTIALLY PERTINENT MOTOR MALFUNCTIONS

FIRING NO.	DATE	COMMENTS
206	10 Dec 75	Lost cloth cone.*
237	2 Jun 76	Lost cloth cone.*
260	10 Jan 77	Lost squib - minor damage to forward closure.
376	10 Jan 78	Nozzle failure; separated and fracture
426	6 Feb 79	Burn-thru between fore-end closure and motor case.
427	8 Feb 79	Good test; looks like a small pin hole at flange on skirt. Will repair.
581	7 Oct 80	Exit cone failure resulting in aft dome material failure; motor reignited after shutting down steam plant.
657	23 Jul 81	Slight burn-thru of exit cone; some damage to motor case
660	4 Aug 81	Exit skirt looks slightly damaged; will replace.
684	12 Feb 82	Severe nozzle cracks.
704	4 Jun 82	Lost exit cone -Nozzle and 55" diffusor**

----Shut down facility to install 77" diffusor: Jun - Oct 82----

No further malfunctions occurred after October 1982

*These were experimental exit cones, not BATES type.

**Personnel accounts indicate that motor lost throat pack, resulting in abnormally large motor mass flow. Propellant left motor and adhered to the diffusor wall, causing warpage.

4. CATASTROPHIC ACCIDENT SCENARIOS

Based primarily on the information collected (summarized in Section 3), five credible accident scenarios have been identified. These are listed in Table 4-1. The first scenario, mass detonation of the SRM, is the worst case accident in that subsequent breaching of the MTC and release of beryllium to the atmosphere is highly probable, if not a certainty. The focus of the MTC penetration analysis, presented in Section 5, is on this worst case mass detonation event. It must be kept in mind, however, that this event is only credible for a mass detonating, class 1.1 propellant.

The second scenario, partial detonation, represents a less severe event but one which may be credible for both a class 1.1 and class 1.3 propellant motor. A fading detonation could conceivably be initiated in a class 1.3 propellant by a severe shock and/or propellant damage, such as could result from the 'shear' or 'implosion' scenario presented in Table 3-1. If a detonation initiates in a class 1.1 motor it would normally be expected to proceed to a full mass detonation. A partial or fading detonation of either class of propellant would result in both propellant and case fragments being expelled at high velocities with possible secondary detonations at propellant fragment impact.

The third scenario, pressure rupture, is considered to be the most probable catastrophic event. Many motor case or nozzle failures have occurred in both static and in-flight tests. In many cases a failure, particularly a nozzle failure, will result in a rapid drop in motor chamber pressure and the extinguishing of the propellant. However, if the failure propagates, both propellant and motor case fragments can be thrown out at fairly high velocities. Propellant fragments having sufficient mass and velocity can detonate (a fading detonation for a class 1.3 propellant) upon impact with the MTC wall or any other hard surface.

The fourth catastrophic scenario, SRM tears free and detonates, is included but is considered to be a highly unlikely event. Normally the tie down structure strength would far exceed the strength of the motor case, and case failure would occur before a motor could tear free. If, however, an intact motor did tear free (due to tie down error, etc.) it could accelerate into the MTC wall and, with sufficient velocity, detonate. A detonation could be initiated in either a class 1.1 or a class 1.3 propellant, with the detonation fading for a 1.3.

The fifth scenario, burnthrough with a blow torch effect, was initially considered credible for a heavy walled motor case where a burnthrough may not propagate rapidly to case breakup. While no accident data have been found which demonstrate this type of event, it will be seen subsequently that this does not pose a risk of breaching the MTC.

As a consequence of design revisions since the preliminary draft risk assessment was issued, all of the scenarios described above can be almost ruled out for the MTC at atmospheric pressure. A software interlock is being incorporated in the facility design to preclude ignition until the MTC is closed and evacuated to the designated test pressure. In addition, a "fail-safe" mechanism is being designed into the MTC hatch.

The hatch will be fastened to the MTC by swinging bolts passing thru a flange and secured by tightening a dog drawing the hatch toward the MTC (see figure 4-1). An inflatable seal between the hatch and the MTC will be inflated, sealing the chamber and forcing the hatch against the dog. MTC evacuation will then begin. If the hatch has not been properly dogged, satisfactory evacuation will not be possible. Should an explosion occurr in the MTC, the blast forces on the inflatable seal will be radial, deforming it in the direction of the MTC axis and improving the hatch seal.

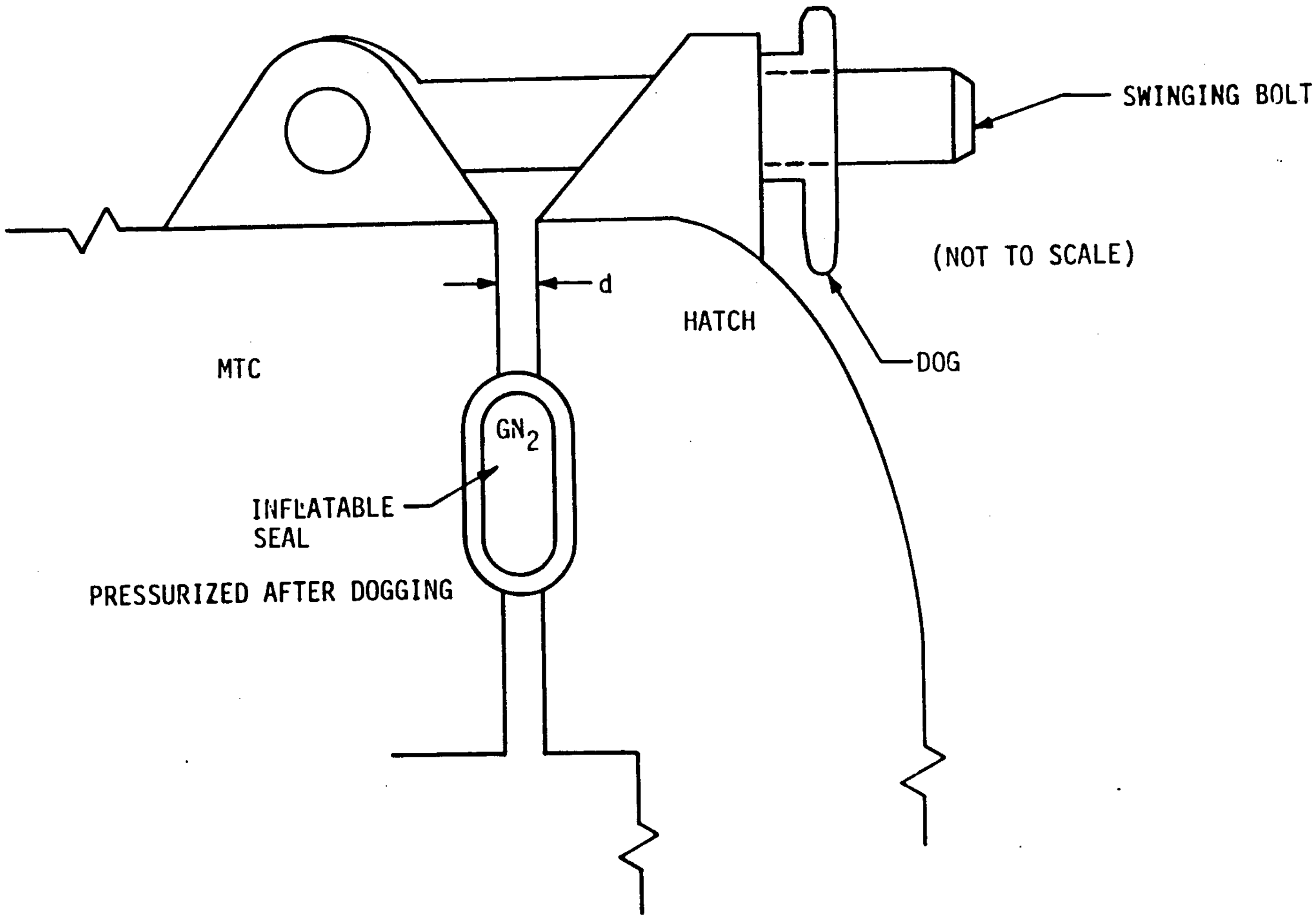

Figure 4-1. MTC Hatch Seal

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Table 4-1. Potential Catastrophic Accident Scenarios

1. Mass Detonation of the SRM (125% TNT Yield)
   - Detonation Shock Wave Strikes MTC Wall
   - High Velocity Motor Case Fragments Impact MTC Wall

2. Partial Detonation of the SRM
   - Propellant Fragments having Critical Mass/Velocity Detonate on MTC Wall Impact
   - High Velocity Motor Case Fragments Impact MTC Wall

3. Pressure Rupture of the SRM due to Case/Nozzle Failure or Overpressurization
   - Propellant Fragments Having Critical Mass/Velocity Detonate on MTC Wall Impact
   - Motor Fragments Impact MTC Wall

4. SRM Tears Free and Detonates on MTC Impact

5. SRM Case Burnthrough Occurs Resulting in a "Blow Torch" Acting on the MTC Wall

Note: While All Scenarios Could Theoretically Occur with the MTC at Atmospheric Pressure or at Simulated 110,000 ft (0.1 Psi)

- Because of previously described procedural and MTC Design modifications SRM ignition at atmospheric pressure is only regarded as credible given a handling error.
- Scenarios at atmospheric pressure thus need two failures.
- Occurrence at Simulated 110,000 ft, where Intentional SRM Ignition Takes Place, is <u>Much</u> More Likely
- The Initial Pressure Significantly Affects the Blast Shock and Pressure Loads on the MTC Wall

In addition to the improved design, administrative procedures will be employed to minimize the frequency of human error.

Thus, this section will only address catastrophic accidents at reduced MTC chamber pressure. Accidental ignition and other potential catastrophic accidents at atmospheric pressure are regarded as low probability events resulting from handling and will be discussed in the section addressing accidents resulting from handling.

Breach of the MTC

The accident scenarios discussed above could potentially result in a breach of the MTC due to one or more of the following modes:

a. MTC structural failure due to a detonation shock wave.

b. MTC pressure rupture due to the quasi-static pressure following a shock wave, or due to pressure build up from a deflagration.

c. Local MTC wall penetration due to the combined impact and blast loads resulting from the detonation of a propellant piece at MTC wall impact.

d. Local perforation of the MTC wall due to case fragments impacting the MTC wall at high velocity.

e. Burn through of the MTC wall by a 'blow torch' resulting from hot gases venting through a hole in a motor case.

The feasability of breaching the MTC by these modes is presented in Section 5.

Probability of Occurrence

Two sets of data have been acquired which provide an indication of the probability of occurrence of the catastrophic accident scenarios. The first of these is the history of solid rocket motor firings at AFRPL Test Area 1-42[45]. This consisted of a mixture of test firings of class 1.1 and class 1.3 SRMS containing 70 pounds of propellant in a high altitude simulation chamber. The second data set was from an MX Stage III Hazards Analysis[23][1] where an attempt was made to estimate the probability of a detonation for three failure scenarios: 'shear', 'implosion', and 'impact' (see descriptions in Table 3-1). Probabilities are presented for both a Trident C-4 first stage motor firing for one second and an MX Stage III motor firing full duration (MX results are given for both flight and static development test conditions). The propellant in both motors is class 1.1. As a consequence of the size of these motors these results are not directly applicable to the beryllium rocket tests but are used as an initial point of reference for probability of detonation.

Results are summarized in Table 4-2 together with the more directly applicable results of AFRPL testing. The first part of the table presents statistical estimates of various types of SRM malfunction probabilities based upon the AFRPL data. The point estimates are the number of failures divided by the number of tests. In addition to point estimates one sided upper confidence bounds were calculated. When a sample (in this case the AFRPL test data) is developed under the same conditions as the application for which probabilities are to be inferred

[1]Numbers in superscripts refer to References listed at the end of this report.

Table 4-2a. Statistical Estimates of SRM Malfunction Probabilities [45]

Type of Malfunction	Point Estimate	Fifty Percent Upper Confidence Bound	Ninety Percent Upper Confidence Bound
Any Serious Malfunction*	6.4×10^{-3}	6.7×10^{-3}	1.2×10^{-2}
Motor Case/ Nozzle Burn-thru	2.5×10^{-3}	3.4×10^{-3}	6.8×10^{-3}
Loss of Nozzle Cone	2.5×10^{-3}	3.4×10^{-3}	6.8×10^{-3}
Motor Case Failure	1.3×10^{-3}	2.0×10^{-3}	4.9×10^{-3}
Detonation	0.0	9.2×10^{-4}	2.9×10^{-3}

Table 4-2b. SRM Detonation Probabilities [23]

	PROBABILITY OF DETONATION ESTIMATE		
	SHEAR SCENARIO	IMPLOSION SCENARIO	IMPACT SCENARIO
TRIDENT C-4 FIRST STAGE TO 1 SECOND	7×10^{-9}	3.2×10^{-6}	2.5×10^{-6}
MX STAGE III FULL DURATION STATIC DEVELOPMENT TEST	$<7 \times 10^{-8}$	VIRTUALLY ZERO	$<3 \times 10^{-5}$

---

*Summary line for listed malfunctions. Values for this line are computed by summing the number of failures for the following four lines to obtain the total number of serious failures and then calculating the three statistics - point estimate and the two upper confidence bounds.

the point estimates are "best" estimates in the sense that they minimize the chance of underestimating or overestimating the true probabilities. When, as in this study the consequences of underestimating the true probability is more undesirable than overestimating it, an alternative estimator is preferable. If it is assumed that there are no significant differences between the AFRPL test area 1-42 test firing history and the proposed test firings in the beryllium rocket high altitude test chamber then the preferred alternative estimator is an upper confidence bound. For nine samples out of ten developed under these conditions the observed failure probabilities will be less than the tabulated ninety percent confidence bounds.

The entry "Any Serious Malfunction" is based on the four immediately following malfunction categories. Note that confidence bounds for individual malfunctions cannot be added to produce a confidence bound for all malfunctions.

Note that the ninety percent upper confidence bound for detonations is two orders of magnitude larger than the MX stage III detonation estimates. No detonations were reported in the AFRPL sample; yet at this confidence level the probability is higher than the point estimate would be for a single failure. At this confidence level the sample size would have to increase by an order of magnitude without a failure to reduce the confidence bound estimate by an order of magnitude. While the known differences between this test and the MX stage III would tend to make the detonation probability of MX higher than the beryllium test motors, the more conservative estimates based on the AFRPL experience are used in the subsequent analysis.

5. ANALYSIS OF MTC FAILURE

5.1 Introduction

The catastrophic accident scenarios postulated in section 4 involve three mechanisms for breaching the MTC: 1) a rupture of the MTC due to excessive internal pressure, 2) perforation of the MTC wall by high velocity SRM fragments, and 3) burn-through of the MTC wall following an SRM case burnthrough. Although a discussion of all three mechanisms is presented for completeness, it will later be shown that the only credible mechanism for breaching the MTC is perforation by high velocity SRM fragments.

The evaluation of the possibility of MTC failure due to a motor failure was performed in parallel with the design of the beryllium propellant facility. As a result the baseline analysis was performed for a single walled MTC; subsequent refinements of the analysis have addressed the design modifications to the MTC. Consequently, the discussion refers to the performance of the baseline design as a frame of reference and indicates the differences in performance expected with the final design.

The analysis of "worst case" scenarios involving an SRM failure during a test included an assessment of the possibility of failure of the MTC by the three named mechanisms. Although the focus of the investigation was on the results of a motor detonation, lesser accidents were also considered.

The basic approach to analyze the detonation of the SRM was to describe it in terms of equivalent TNT. This enables one to use the large body of experimental/analytical data on explosive effects of TNT.

5.2 MTC Pressure Rupture Response

An SRM detonation within the MTC causes a rapid loading which can be approximated by a rapidly decaying shock wave plus a more slowly decaying quasi-static pressure. These pressures are a function of the charge weight (equivalent TNT), the distance between the SRM and the MTC wall, and the ambient atmospheric pressure at the time of motor detonation.

A simplified analysis was performed to assess the effects of these key parameters. The assumptions made in the analysis are listed in Table 5-1.

The primary mode of response of the MTC was assumed to be in the "hoop" mode. As a result the structure was idealized as a single-degree-of-freedom (SDOF) system subjected to a time varying forcing function representing a uniformly applied pressure loading to the inside of the MTC. The loading time-history was assumed to be a shock wave described as a simple triangular pulse with an instantaneous rise time, having a specified peak pressure and an impulse determined from standard shock wave parameters for TNT, together with a quasi-static pressure applied for a significantly greater duration than the first natural mode[17,29]. The shock wave duration, T_d, was then determined from

$$T_d = 2I_R/P_R$$

where: I_R = reflected impulse
P_R = reflected peak pressure

Since the normal operating conditions specify a simulated altitude of 110,000 feet (0.1 psi), the standard TNT blast parameters were modified using Sachs' law for high altitude bursts[17].

Table 5-1. Motor Test Cell Detonation Analysis Assumptions

- Test Cell Response Described by Hoop Stress Mode (SDOF)
- Internal Uniform Pressure Load Determined for Equivalent Spherical TNT Detonation
- Reflected Pressure Calculated Assuming Detonation at Centerline of Test Cell with Normal Incidence
- Blast Wave Parameters Determined Using "Cube-Root" Scaling (1 Atm) and Sachs' Law (High Altitude)
- Quasi-Static Pressures (Blowdown) Determined from "Explosion Hazards and Evaluation" [17]

Table 5-2. MTC Structural Idealizations

- Motor Test Cell Dimensions
  - 16 Ft Diameter, Volume = 9800 cubic feet
  - Steel - A-36, Yield Strength (F_y = 36000 Psi)

- Motor Test Cell Resistance Function - Elastic/Perfectly Plastic

  Maximum Resistance = (F_y x T_s)/R
  - T_s = MTC Wall Thickness
  - R = MTC Radius

- Failure Criteria
  - Ductility Factor = $\frac{Y_{max}}{Y_{el}} > 10$
  - Y_{max} = Maximum Radial Displacement of the MTC Wall
  - Y_{el} = Radial Displacement of the MTC Wall at Initial Yielding of Steel

To obtain an estimate of the likelihood of a pressure rupture, the structural resistance of the MTC was idealized as an elastic/perfectly plastic material. A failure criterion was established which defined failure as a ductility ratio greater than 10, where the ductility ratio is defined as the maximum radial displacement of the cell divided by the cell wall displacement at initial yielding of the steel. This is considered reasonable for a mild steel such as A-36. The structural parameters and failure criteria used in the analysis are summarized in Table 5-2.

5.3 Pressure Rupture Results

The results of the pressure rupture analysis are typically presented in terms of required MTC wall thickness as a function of the quantity of explosive (expressed in terms of equivalent TNT). The SRM size was fixed at 150 pounds of propellant. A TNT equivalency range of 10 percent to a full 125 percent of the total propellant weight was considered. (A given TNT equivalent weight may be achieved by different combinations of TNT equivalency and amount of propellant involved. Thus, a 10 percent TNT equivalency for 100 pounds and 100 percent TNT equivalency for 10 pounds of propellant both result in 10 pounds TNT equivalence). The required steel thickness was determined to the nearest 0.125 inch.

First, the shock loading was considered. Two sources were used to define the applied shock loading (the reflected pressure, P_R and the reflected impulse, I_R). For the MTC initially at 1 atmosphere internal pressure, the results using each of these sources are compared in Figure 5-1. The upper curve is obtained using Air Force Manual AFM 88-22[29] while the lower curve was obtained using Baker, et al.[17]. The difference in results illustrates the degree of uncertainty in the

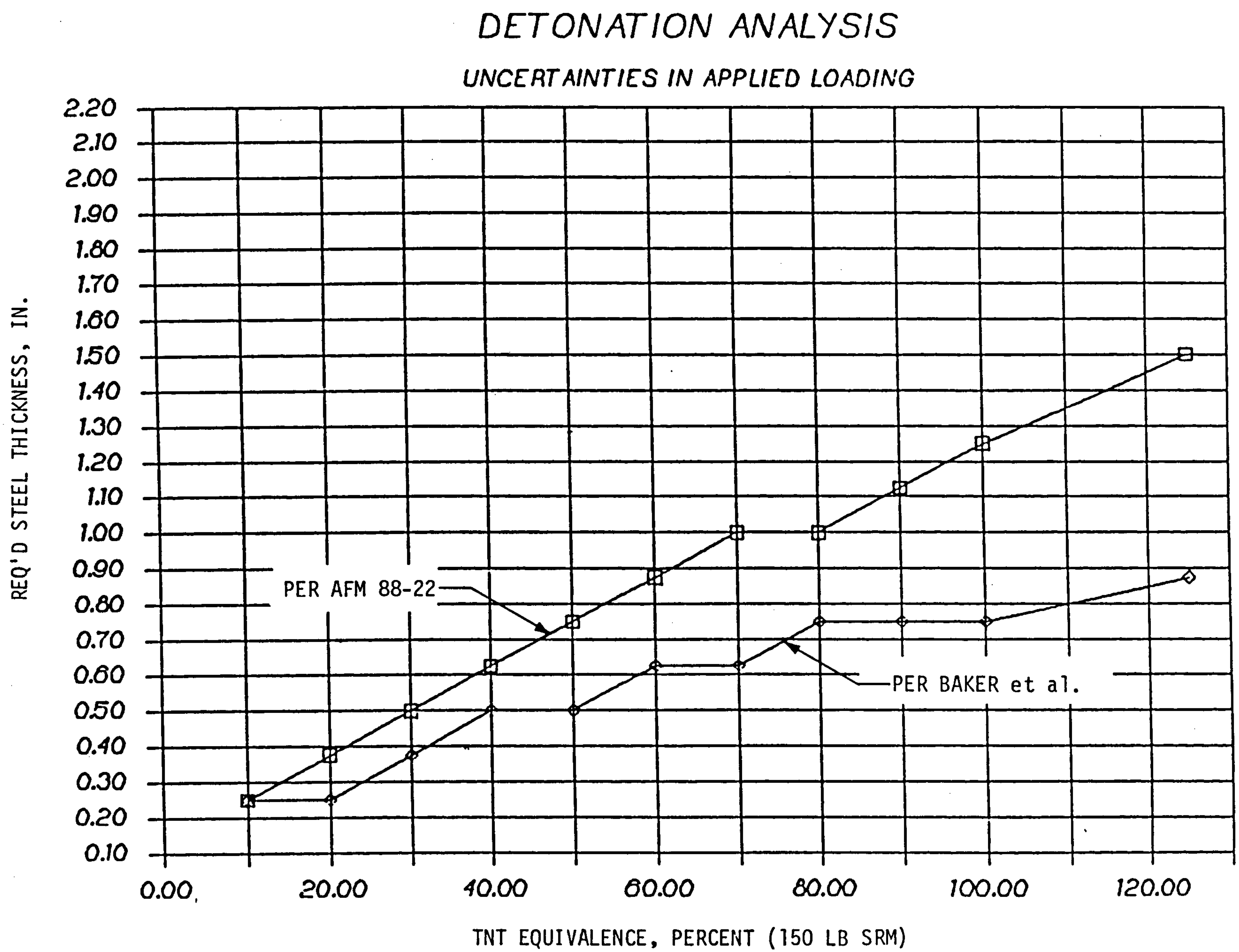

Figure 5-1. MTC Pressure Rupture at 1 Atmosphere

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applied loading. For the purpose of this investigation the more conservative blast parameters given by AFM 88-22 are used for the remainder of the analyses.

The above results for an explosion at one atmosphere are presented as a baseline reference case. Since the ambient atmospheric pressure within the cell at the time of a possible detonation is expected to be less than this, the peak shock pressure will also be less. According to Sachs' law the peak reflected pressure, P_R, is a function of the ambient internal MTC pressure, P, according to the following expression:

$$P_R = P_{R_o} (P/P_o)$$

where

P_{R_o} = peak reflected pressure at sea level
P_o = atmospheric pressure at sea level (14.7 psi)

To illustrate the effect of decreasing the internal pressure in the MTC a series of calculations were performed for a 125 percent TNT equivalent detonation at several different MTC internal ambient pressures. These results are presented graphically in Figure 5-2. The wall thickness requirements decrease dramatically with decreasing pressure. At a pressure of 0.1 psi (i.e. 110,000 feet) the required steel thickness is less than 0.25 inches Conversely, for a 0.5 inch wall (the thinnest portion of the MTC wall), the maximum internal pressure at the time of detonation cannot exceed 3 psi.

A variation on the above scenario was also considered because of the sensitivity of shock pressure to internal MTC pressure at the time of detonation. It is possible for the SRM motor case to sustain a burn-through venting a portion of the exhaust into the MTC prior to a detona-tion. While a realistic failure of this type would result in only a

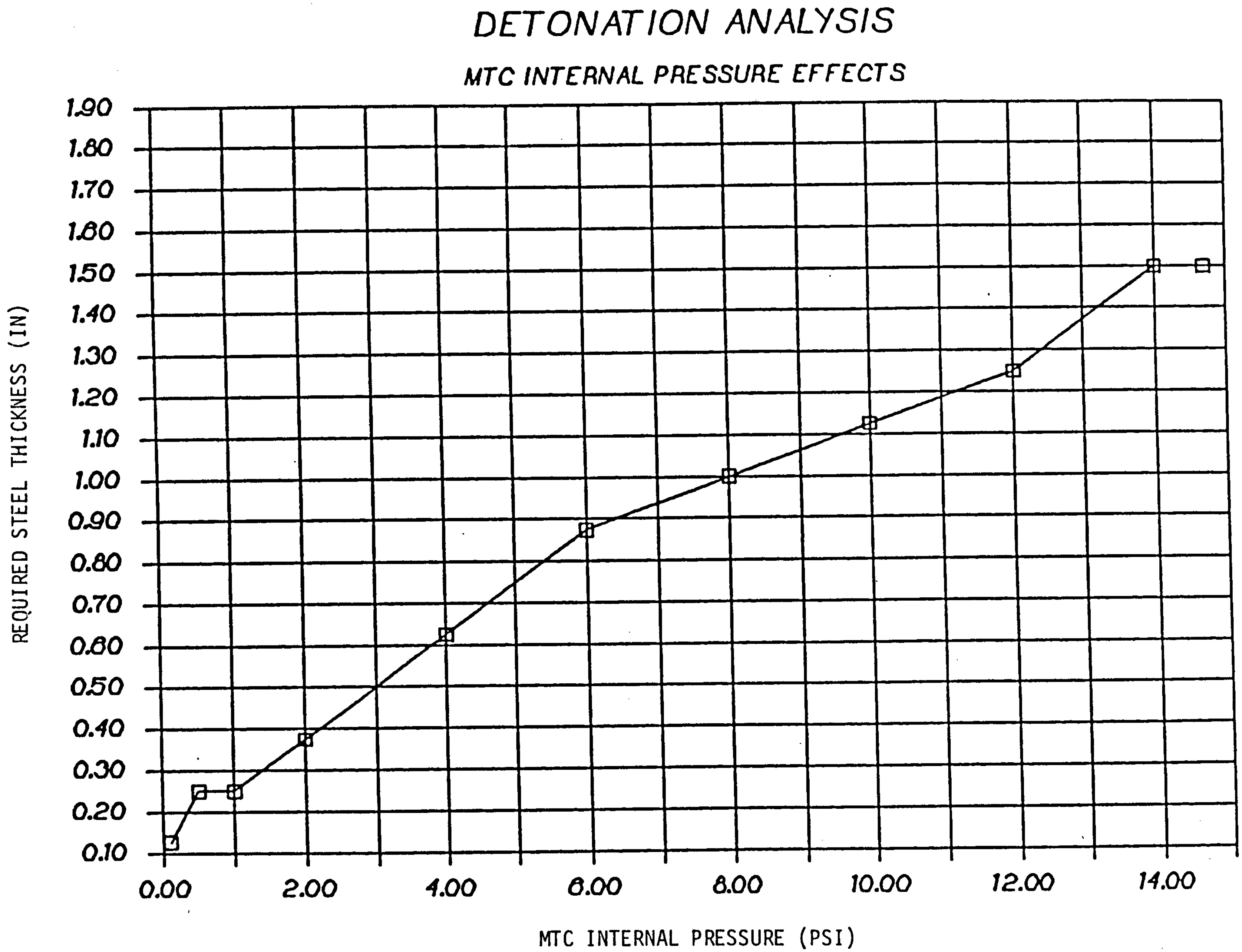

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Figure 5-2. Effect of MTC Internal Pressure at Detonation (187.5 Pounds TNT Equivalence) portion of the combustion products venting to the MTC and the remainder passing into the CV, as a bounding case it was assumed that immediately after the SRM was ignited, a malfunction occurred which caused all of the exhaust products to remain inside the MTC. This would cause the internal pressure within the MTC to increase. Subsequently a detonation of the remaining propellant was assumed to occur. For the following analysis it was assumed that the pressure increase in the MTC is proportional to the increase in the CV calculated by ARC for a normal firing:

$$P_{MTC} = \frac{P_{CV} \quad V_{CV}}{V_{MTC}} \qquad (T_{MTC} = T_{CV} \text{ i.e. same temperature in both vessels})$$

ARC calculations show for a complete 10 seconds burn of a 150 lb motor the pressure in a 30,000 ft^3 CV increases from 0.1 psia to 5.5 psia. Thus the maximum pressure increase in the 9800 ft^3 MTC is:

$$P_{MTC} = 5.4 \times \frac{30,000}{9,800} = 16.53$$

Since the ARC calculations indicate that the MTC pressure will be built up to 0.3 psia before the diffuser is fully started the ambient pressure P_a at any given time during the 10 second burn is conservatively assumed to be given by

$$P_a = 1.653t + 0.3 \text{ (psia)}$$

Since 150 pounds of propellant are burned in 10 seconds the ambient pressure can be expressed in terms of weight of propellant remaining, W_p, as

$$P_a = 0.110(150 - W_p) + 0.3 \text{ (psia)}$$

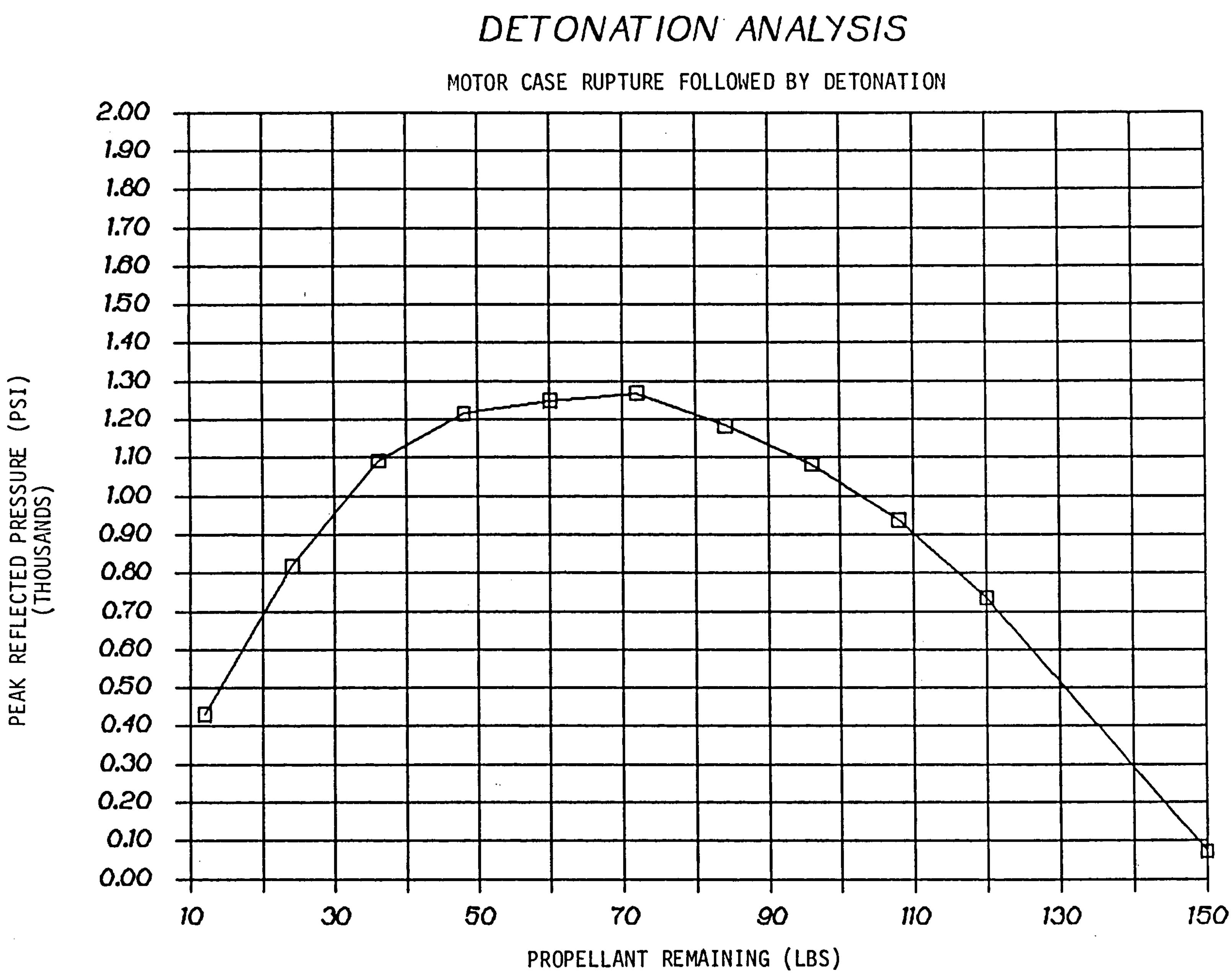

Figure 5-3. Peak Reflected Pressure for SRM Exhaust To MTC Followed by 125 Percent Detonation

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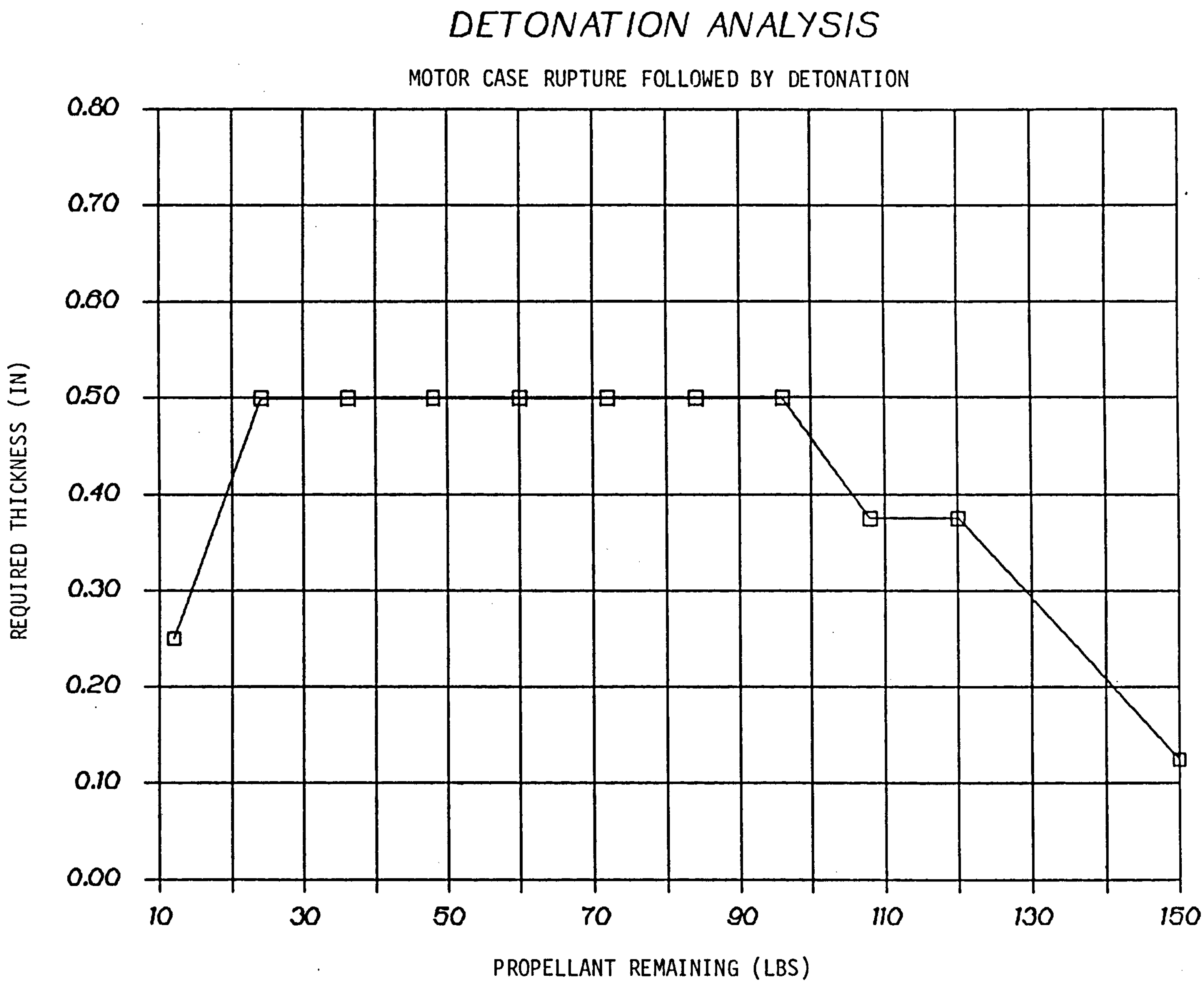

Figure 5-4. Required MTC Wall Thickness to Resist Shock Overpressure for MTC Pressure Buildup Followed by 125 Percent Detonation

1612-4

This expression can be combined with the relationship for reflected pressure in terms of ambient pressure to obtain the critical combination of propellant weight and ambient pressure in the MTC. The results are presented graphically in Figures 5-3 and 5-4. The "stairstep" nature of the plots in Figures 5-4 and 5-5 is due to the required thickness of steel being determined to the nearest 0.125 inches. The above analyses show that the greatest threat of MTC rupture occurs for a remaining propellant weight of between about 45 and 95 pounds. More importantly the required thickness to prevent rupture is 0.5 inches. The MTC design thus appears adequate to resist this scenario assuming that there are adequate connections between the inner and outer wall so that the double wall section behaves (in terms of rupture) as a single wall equal in thickness to the sum of the two walls (i.e. 0.25 + 0.4375 = 0.6875 inches). (The connection of the two walls by connector bolts separated by six inches make this a reasonable assumption.)

The above analyses show that shock pressures are not critical at an operating MTC pressure of 0.1 psia, even for a pressure buildup scenario, or even for a full 125 percent detonation. However, the longer duration quasi-static pressures must also be considered . The peak quasi-static pressure, P_{QS}, is not as sensitive to the ambient atmospheric pressure as is the peak reflected shock pressure. The peak absolute quasi-static pressure P_A is simply

$$P_A = P_{QS} + P_o$$

where P_o is the ambient internal pressure.

Using the predictions of P_{QS} for a TNT explosion in a chamber[17], and assuming the duration of the loading is very long compared to the response period of the MTC (i.e., a step pulse of infinite duration),

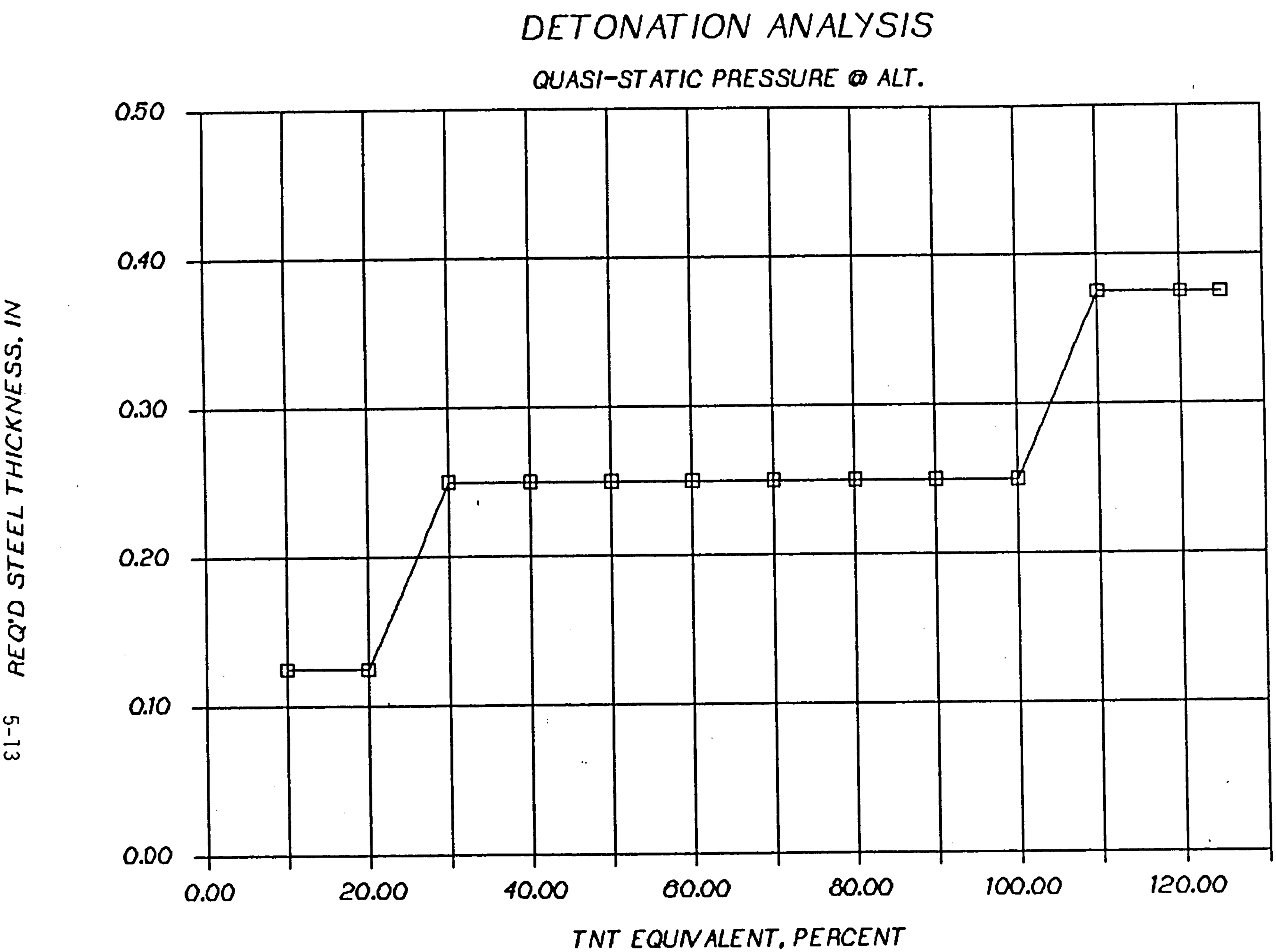

Figure 5-5. MTC Wall Thickness Required for a Quasistatic Pressure from 150-LB SRM Rupture at a Simulated 110,000 Ft Altitude

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the required thickness to resist this quasi-static pressure at simulated altitude (i.e., 110,000 feet) without rupture was calculated. The quasi-static pressure is a function of charge weight and MTC volume (V_{MTC} = 9800 cubic feet). The results are shown as a function of percent TNT equivalence in Figure 5-5 for a detonation at 110,000 ft. (i.e., P_O = 0.1 psi). Assuming a 125 percent TNT detonation (188 pounds) a wall thickness of 0.375 inches is required. This is three times greater than the corresponding required thickness of 0.125 inches based on shock loading at altitude (P_O = 0.1 psi) given in Figure 5-2. Since the quasi-static pressure is relatively insensitive to the internal pressure, P_O, shock pressures govern for a detonation at one atmosphere. (Shock pressures scale by the ratio of internal pressures; quasi-static pressures are affected by the internal pressure additively). In fact, as illustrated in Figure 5-2, the internal pressure in the MTC need only build up to about 4 psi before shock pressures begin to govern.

5.4 Primary Fragment Penetration of MTC Wall

The second major hazard resulting from an SRM motor detonation is the impact of high velocity fragments against the MTC wall. If the SRM is assumed to act as an equivalent cylindrical cased explosive charge, high velocity case fragments (referred to as primary fragments) may perforate the MTC wall if the velocity and corresponding mass exceed a critical value.

For this investigation, fragment velocities were computed using procedures outlined in AFM 88-22[29] for explosives within cylindrical containers. Again, the explosive behavior of the SRM propellant is assumed to be described by an equivalent quantity of TNT.

The AFM 88-22 procedure is based on empirical data for explosives contained in mild steel cases. The key parameters are quantity of explosives and weight of the cylindrical portion of the metal case. The number and weight of primary fragments are functions of the thickness and diameter of the casing. Since the 150 pound SRMs will be flight weight motors with filament wound cases they will present a less lethal fragment environment that the BATES motors. Consequently the fragment analysis was performed for a 70 pound BATES motor. The motor case dimensions are

Outside diameter	- 12.8	inches
Wall thickness	- 0.375	inches
Length	- 20.4	inches

The initial fragment velocity as a function of quantity of TNT is shown in Figure 5-6. All fragments are modeled as having the same initial velocity.

To determine whether a fragment will perforate the MTC wall both the velocity and weight of the fragment are needed. It is assumed that the critical fragment is the one with the largest mass per AFM 88-22. For this analysis the largest fragment has a weight of 0.48 pounds. Three different penetration models were employed and the results compared giving an indication of the uncertainties involved. For all of the models the fragment was assumed to be a solid cylinder whose length is equal to the case thickness. The diameter was then calculated for the maximum fragment weight of 0.48 pounds resulting in a maximum fragment diameter of 2.4 inches.

The results of the penetration analyses are summarized in Figure 5-7.

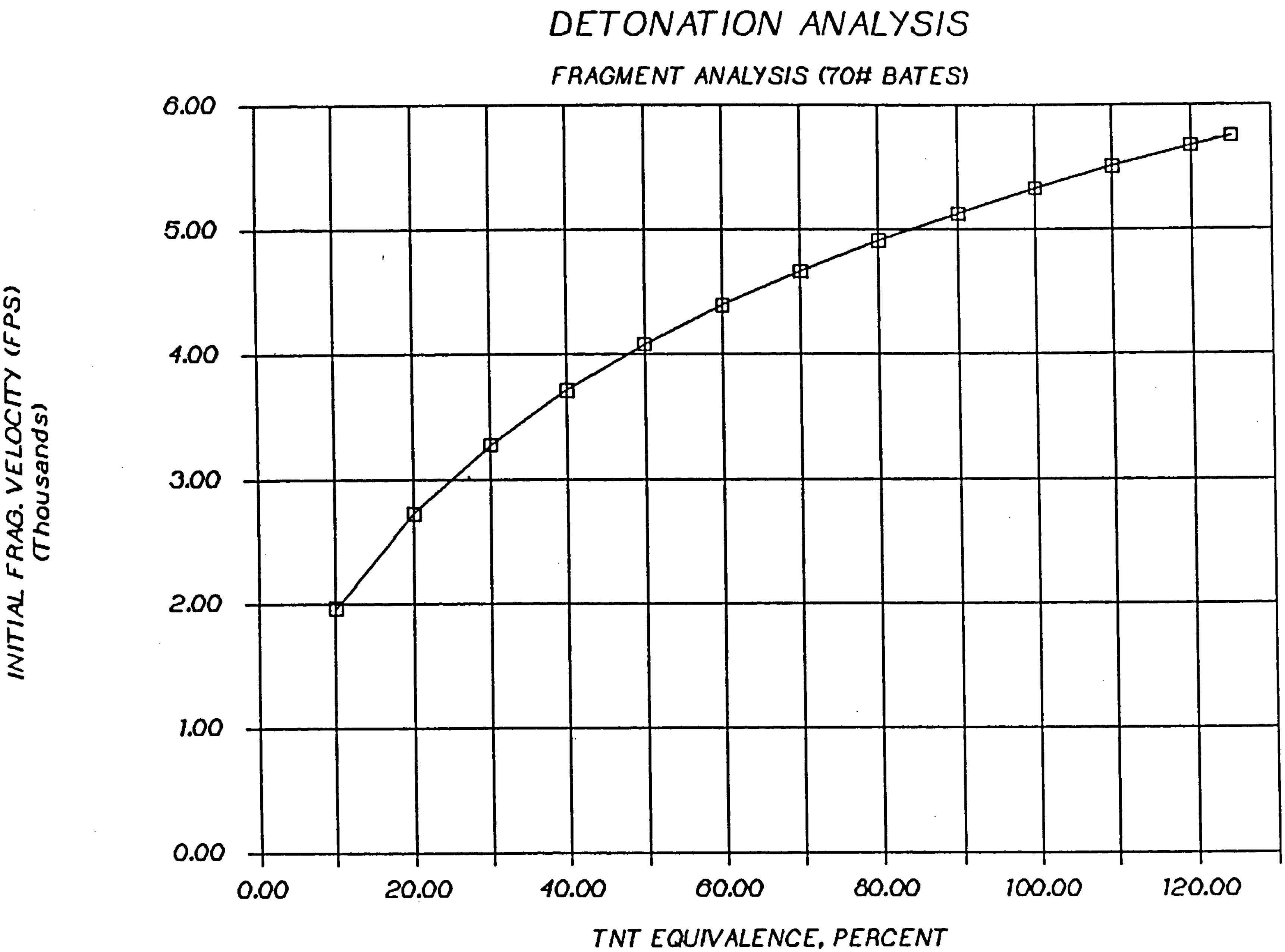

Figure 5-6. Primary Fragment Velocities From Detonation of 70-Pound BATES Motor

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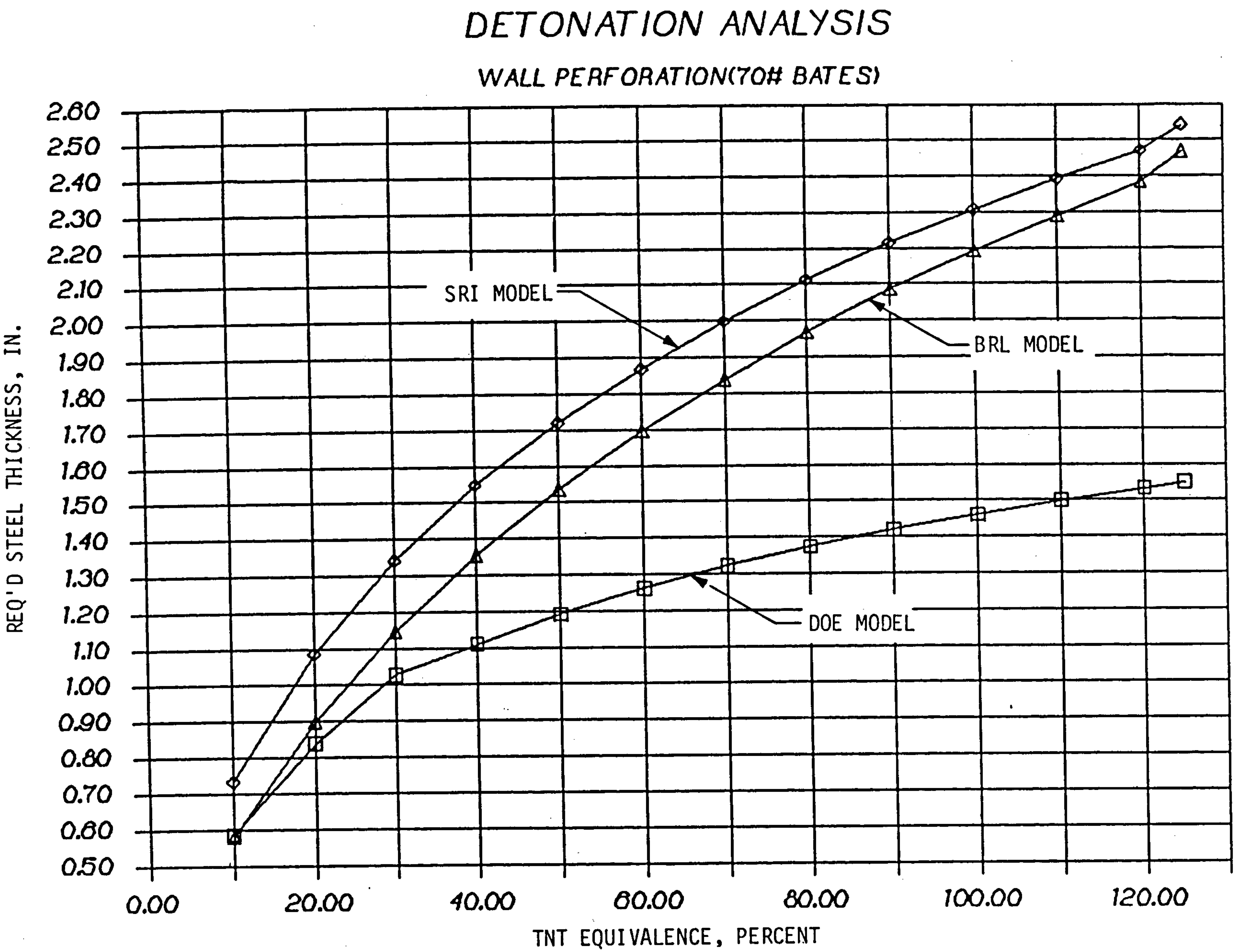

Figure 5-7. Penetration Analysis of MTC Wall From Fragments From Detonation of 70-Pound BATES Motor

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The required thickness is defined as that thickness of the MTC wall for which the primary fragment just completely penetrates (i.e., perforates), emerging with zero velocity. The three penetration models used are referred to as the Department of Energy (DOE) model, the Stanford Research (SRI) model, and the Ballistic Research Laboratory (BRL) model[6]. As can be seen in Figure 5-7, the SRI and BRL models predict significantly larger required thicknesses than the DOE model. Nevertheless, all three models indicate that the original design MTC wall thickness of 0.625 inches will only resist a small, 10 percent detonation (15 pounds of TNT) without perforation. For a full 125 percent detonation (188 pounds of TNT), a wall thickness of more than 1.625 inches is required, even by the lower bound DOE model.

Since isolated perforations of the wall do not necessarily lead to a catastrophic MTC failure and beryllium release as would a pressure rupture the number of fragments capable of puncturing the original MTC wall thickness of 0.625 inches was calculated using the SRI model and AFRM 88-22[29] for different TNT equivalencies. The results are presented in Figures 5-8 and 5-9 in terms of propellant remaining and equivalent TNT respectively. The large number of fragment perforations above a 10 per cent TNT equivalence (7 pounds) indicated severe damage to the MTC. Thus, if catastrophic damage from large numbers of fragment punctures are to be avoided it would appear that the MTC would have to be designed to resist the largest fragment as given by Figure 5-7.

Fragment penetration of the double wall of the MTC was investigated to determine the benefit, if any, of the use of a double wall tank. The 0.25 inch inner wall and the 0.4375 inch outer wall were assumed to be separated by a small void space. The penetration analysis involved calculating the residual velocity of the fragment after perforation of the inner wall to establish the required outer wall thickness to prevent

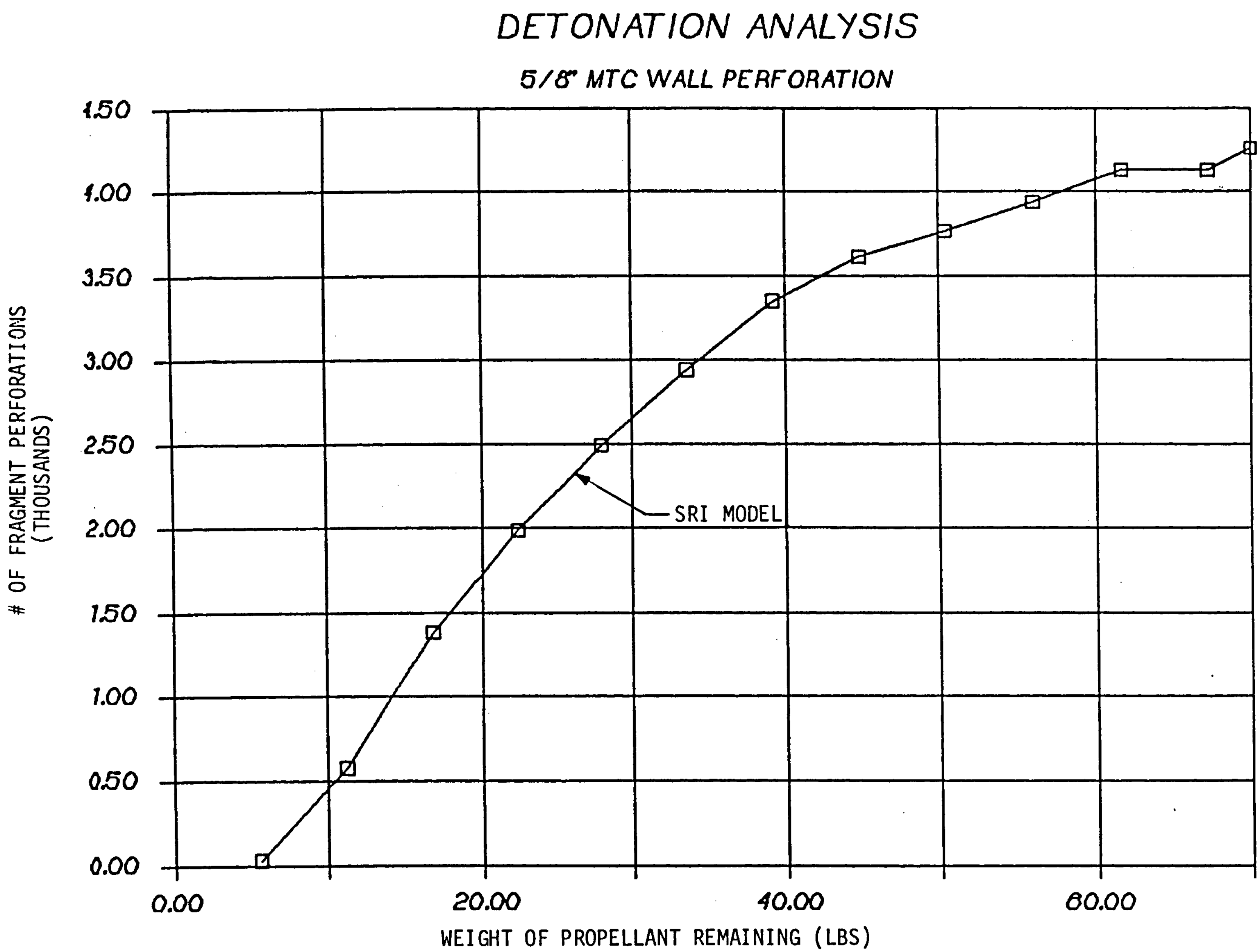

Figure 5-8. Number of Fragment that Perforate MTC Wall (5/8") in Terms of Propellant Weight at Detonation (125 Percent Yield)

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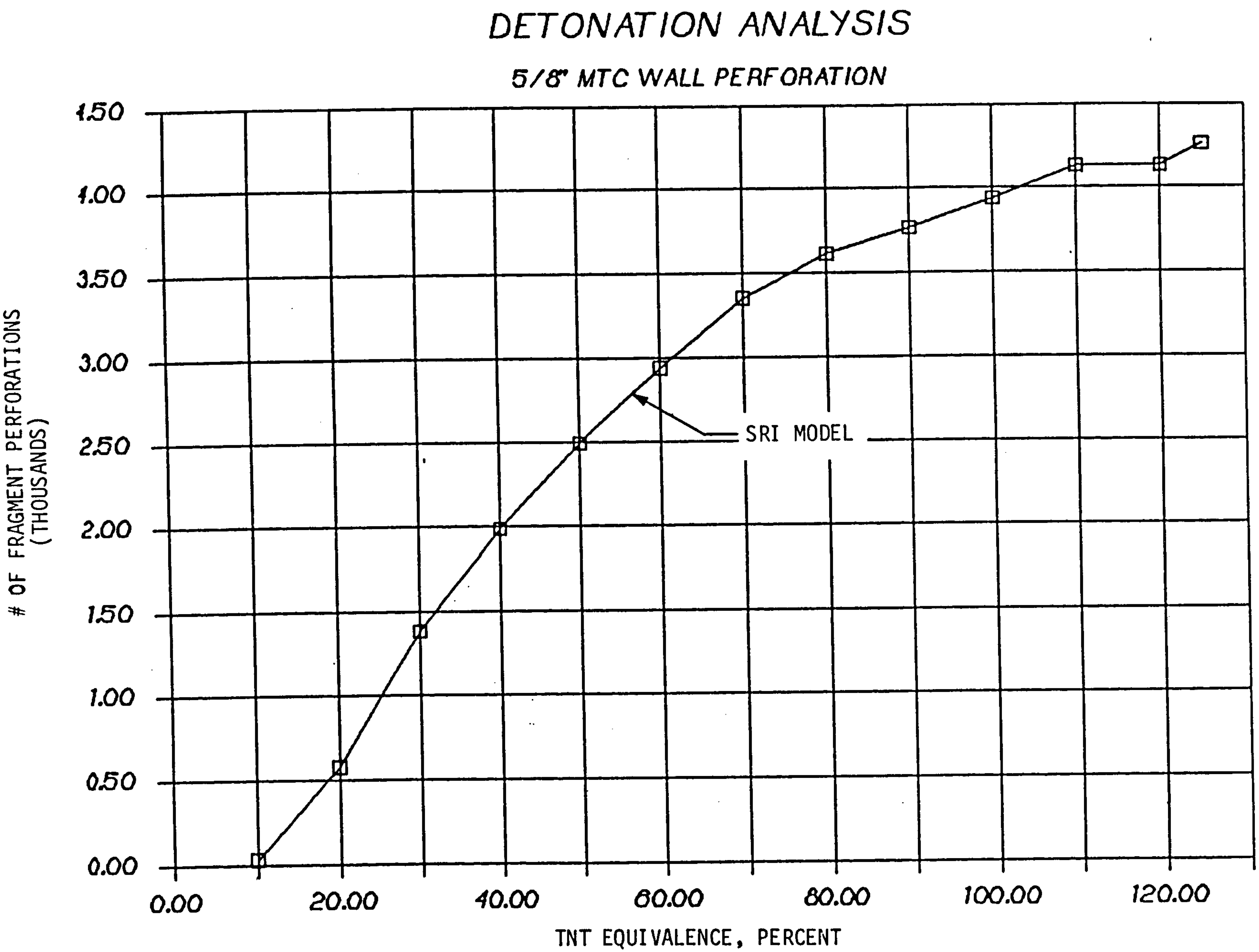

Figure 5-9. Number of Fragments that Perforate MTC Wall (5/8") in Terms of TNT Equivalence (70-Pound BATES Motor)

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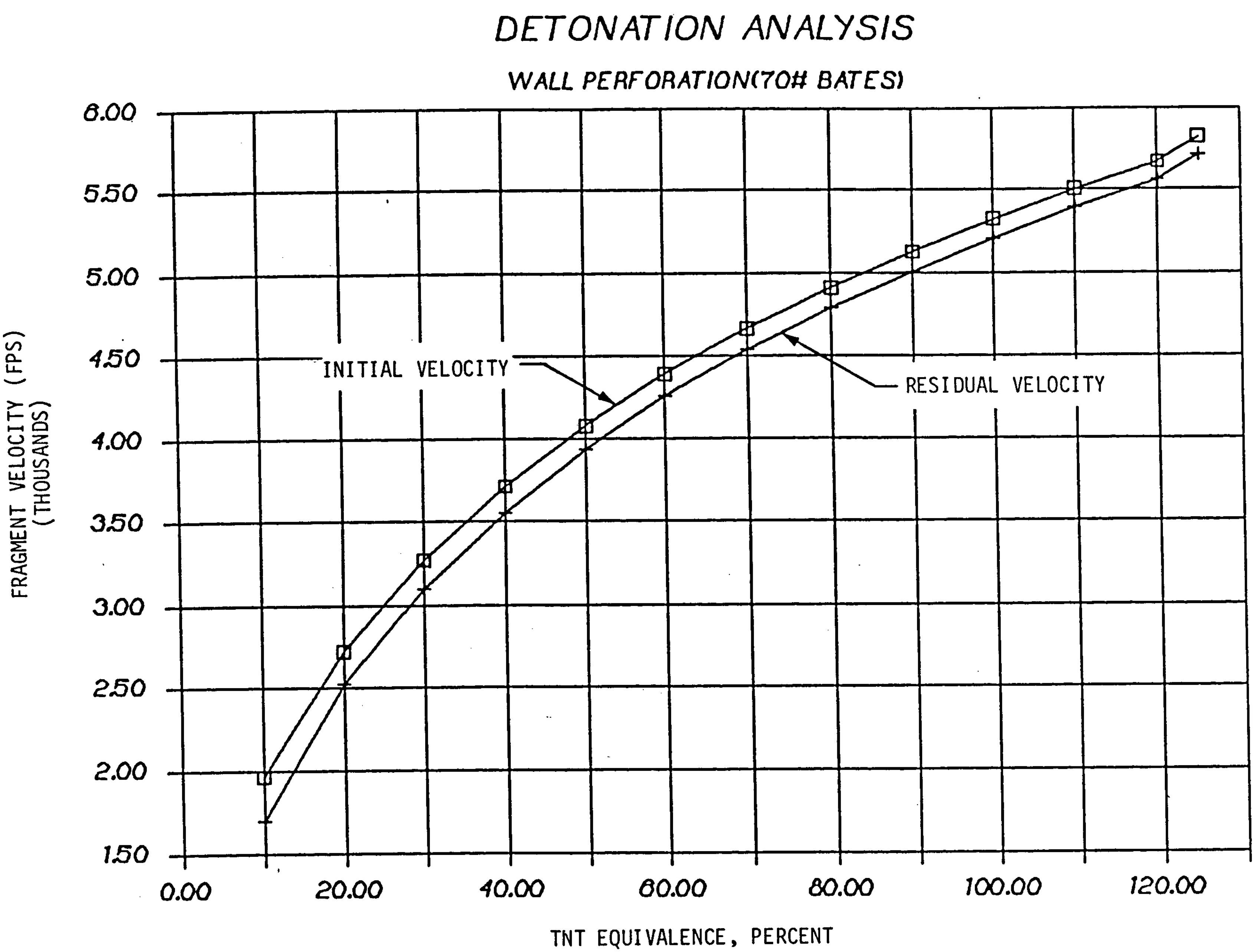

Figure 5-10. Initial and Residual Velocity for Perforation of Inner MTC Wall (0.25 in) (70-Pound BATES Motor)

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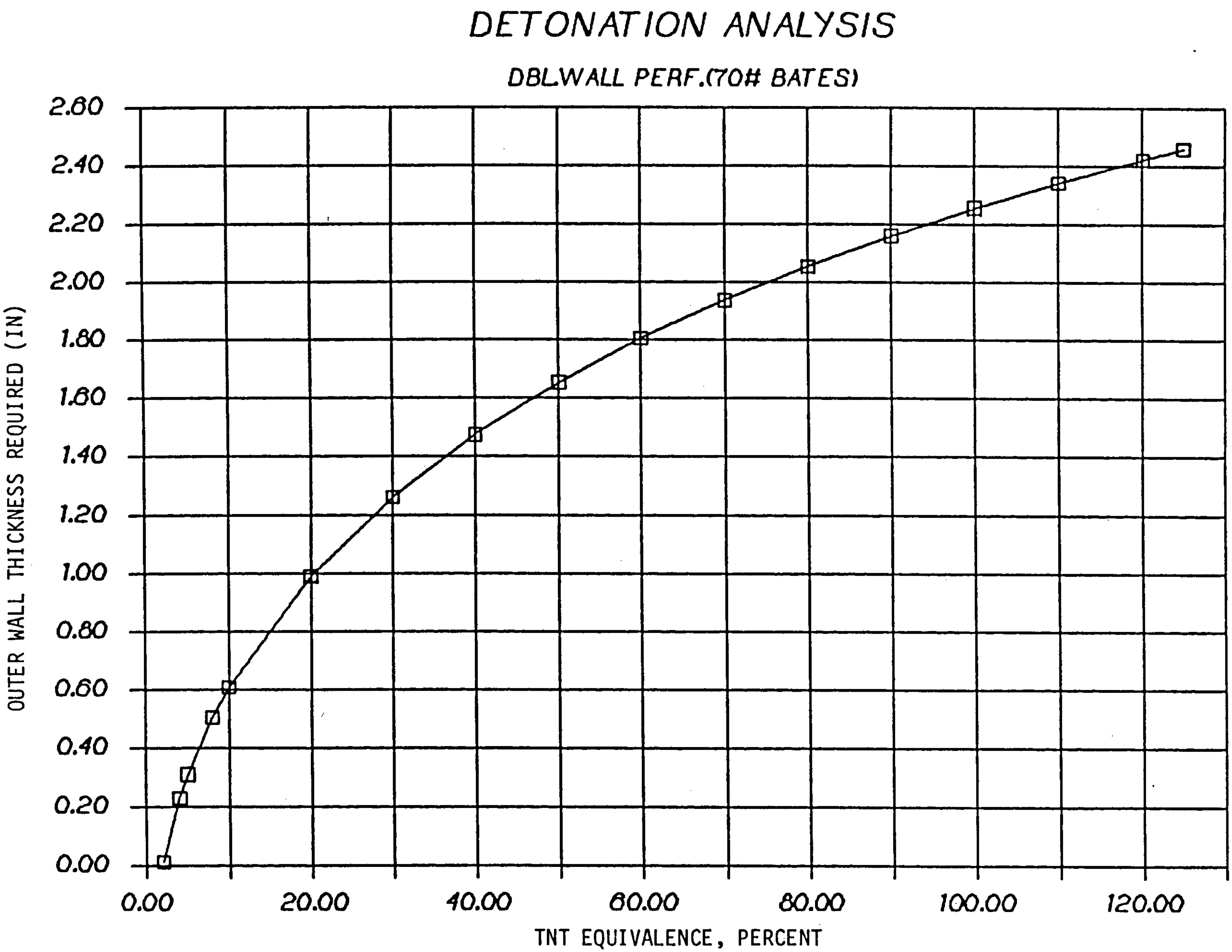

Figure 5-11. Required Outer Wall Thickness for Double Wall MTC to Prevent Fragment Perforation (70-Pound BATES Motor)

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perforation. The following expression for the residual velocity, V_R was used:

$$V_R^{1.8} = V_0^{1.8} + V_P^{1.8}$$

where

V_0 = fragment initial velocity (prior to striking the inner wall)
V_p = the velocity required to just perforate the inner wall (i.e. V_R=0).

The results of the analysis are summarized in Figures 5-10 and 5-11. The reduction in fragment velocity due to the inner wall is quite small. The required thickness for a 10% TNT equivalent detonation (7 pounds TNT equivalence) is greater than the actual thickness of the MTC outer wall, indicating perforations. In fact, the double wall MTC has only about 88% of the resistance of the original single 0.625 inch wall. Specifically the 0.625 inch wall will prevent fragment perforation of a 7.8% TNT detonation compared to a 6.9% detonation for the double wall section.

5.5 MTC Detonation Analysis Summary

Two MTC structural failure modes were investigated for a SRM detonation. Results of the analyses show that primary fragment penetration governs the required thickness of the MTC wall. The penetration analysis assesses the capability of the double MTC wall to withstand a perforation of the wall at approximately 8 percent detonation (5.5 pounds TNT), based on a 70 pound BATES motor.
For a pressure rupture, a 0.5 inch MTC wall may withstand a 125 percent detonation (188 pounds of TNT) at 110,000 ft. and a 30 percent detonation (45 pounds of TNT) at sea level.

5.6 Fragments from SRM Motor Case Burst

Earlier portions of this section discussed the risk of penetrating the MTC by fragments resulting from a detonation of the propellant. A second, more probable, failure mode which may generate fragments is a motor case burst. This will typically result in both motor case fragments and propellant fragments.

Although fragment detonation velocities have been studied extensively because of their importance to the design of munitions, the data base for motor case bursts is somewhat sparser. Two sources of data were identified which provided pertinent information: studies addressing velocities imparted to fragments from bursting pressure vessels[17,44] and range safety breakup studies for testing missiles and launch vehicles[43]. The data from these sources indicates that when no detonation has occurred typical fragment velocities are in the range of 200 to 600 feet per second. Upper bounds to fragment velocities are approximately 1100 feet-per second.

AFRPL tests[30] indicates that a one-half inch thick EPDM rubber coating on the test cell would make a detonation on impact unlikely at these speeds. (Thus, the current design which includes a three-quarter inch rubber lining would be still safer). Although a fragment detonation on impact for a fragment subjected to a tandem impact process cannot be ruled out, the data provided[30] suggest it is unlikely. Moreover as previously discussed the pressure loading from a detonation in the MTC provides a minimal threat of breaching the MTC.

Adequate data were not available to determine the number and size fragments that might result from a pressure rupture, let alone to correlate size with velocity. If the motor case breaks into small fragments MTC wall penetration is not expected. On the other hand, motor case rupture into fewer large pieces may penetrate the MTC.

As a baseline, assume the motor case fragments into rectangular strips with their long axis along the motor axis. Assume that the fragments are equal in size and have sufficient weight at the upper bound velocity to just penetrate the MTC, if ejected radially. If it is assumed that velocities have a Gaussian distribution, one fragment of sufficient velocity to penetrate the MTC will be generated. Should fragments impact end on, lower velocities will be required for penetration. This is, however, regarded as unlikely. Moreover, the larger fragment velocities are more likely with small pieces than with larger pieces. Thus, the expected outcome of an SRM case rupture is damage to the MTC with a low probability of penetration of the cell by a small number of fragments. Nevertheless, should such penetration occur because of the size of the fragment required, massive damage to the MTC is expected.

5.7 MTC Wall Burnthrough from "Blow Torch" Effect

In Section 4, a blow torch effect scenario was postulated. The scenario consists of a motor case burnthrough resulting in a sustained secondary exhaust flame directed toward the side of the MTC. Since a lightweight motor case would be expected to come apart within a short time after burnthrough, this is considered to be a potential concern for the BATES motors only.

A bounding analysis was performed to assess the credibility of breaching the MTC by the heat resulting from the secondary exhaust plume. Two conditions were reviewed qualitatively to define a bounding case.

The first condition examined was a motor case burnthrough resulting in a small (relative to the cross section of the nozzle area) hole in the motor case. The second condition was a hole in the side of the motor case comparable in size to the nozzle area. The first case results in an overexpanded plume with an associated cooling before reaching the MTC wall. The second case results in a concentrated secondary exhaust flame at the MTC wall. Exhaust flame temperature was taken from the Bechtel Design Criteria[31]. Even though it is possible that such a large secondary opening in the SRM will cause the motor to be extinguished it was assumed, conservatively, that instead the effect was to extend the burn time by fifty percent.

The temperature of the inner MTC wall was calculated[32, 33] and was found to be well under the melting point of steel.

Consequently, the "blow torch" scenario is not expected to breach the MTC.

6. RISK DURING ON-BASE TRANSPORTATION, HANDLING AND STORAGE

The SRMs will be brought into the facility through the Air Force Rocket Propulsion Laboratory (AFRPL) guard gate entrance. The SRMs will be delivered to the AFRPL in sealed aluminum shipping canisters. These canisters will have shock isolation systems to prevent mechanical damage to the motor and will be electrically grounded to reduce the risk of electro-static discharge as an ignition mechanism.

Peripheral seals around joints will ensure no leakage of beryllium from inside the container in the event the motors are damaged in handling. The rocket motors will be transported from the guard gates to the storage facility (either building 9635 or building 8915) where they will be offloaded by a diesel powered forklift into the storage facility (see Figure 6-1). The shipping containers will not be opened until they are in the toxic control building (TCB). When a motor is to be tested it will be loaded, still in its canister, by a diesel forklift into a pick-up or a flatbed truck and secured against any movement. The rocket motor will then be transported to the toxic control building (TCB) where it will be offloaded by a diesel forklift and placed in the TCB. Another electric forklift, dedicated for use in the TCB, will move the container into position so the motor can be lifted from the container with an overhead rail hoist. The motor will then roll along a rail into the motor test cell (MTC) where it is bolted down. While at the AFRPL, the rocket motor will not be lifted more than 4 feet above the ground. It will take approximately 3 hours to secure the rocket motor to the thrust stand. Finally, the igniter is placed into position, the MTC is closed, evacuated to the simulated altitude and the rocket test is started[54]. Figure 6-2 shows the typical motor test firing operations.

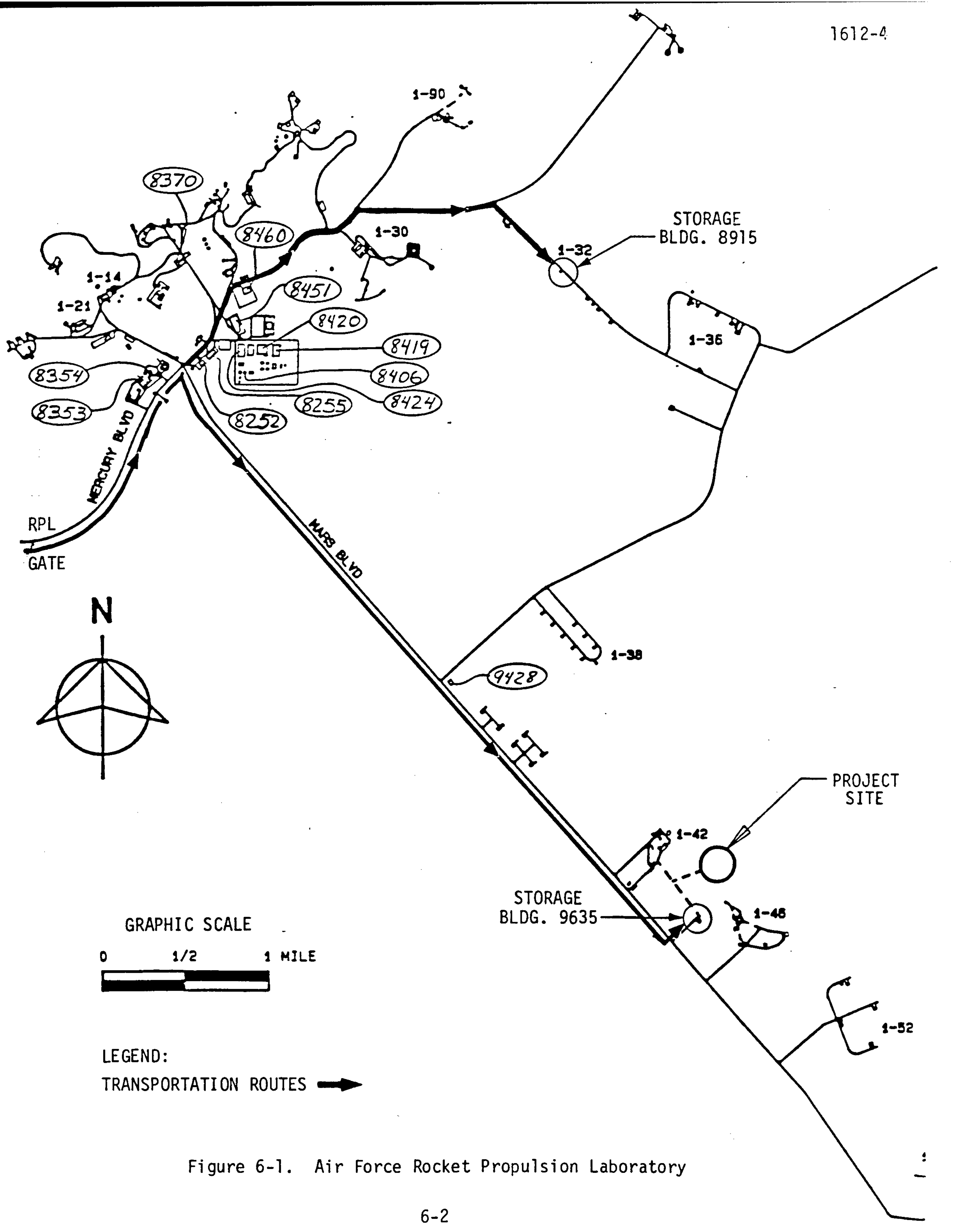

Figure 6-1. Air Force Rocket Propulsion Laboratory

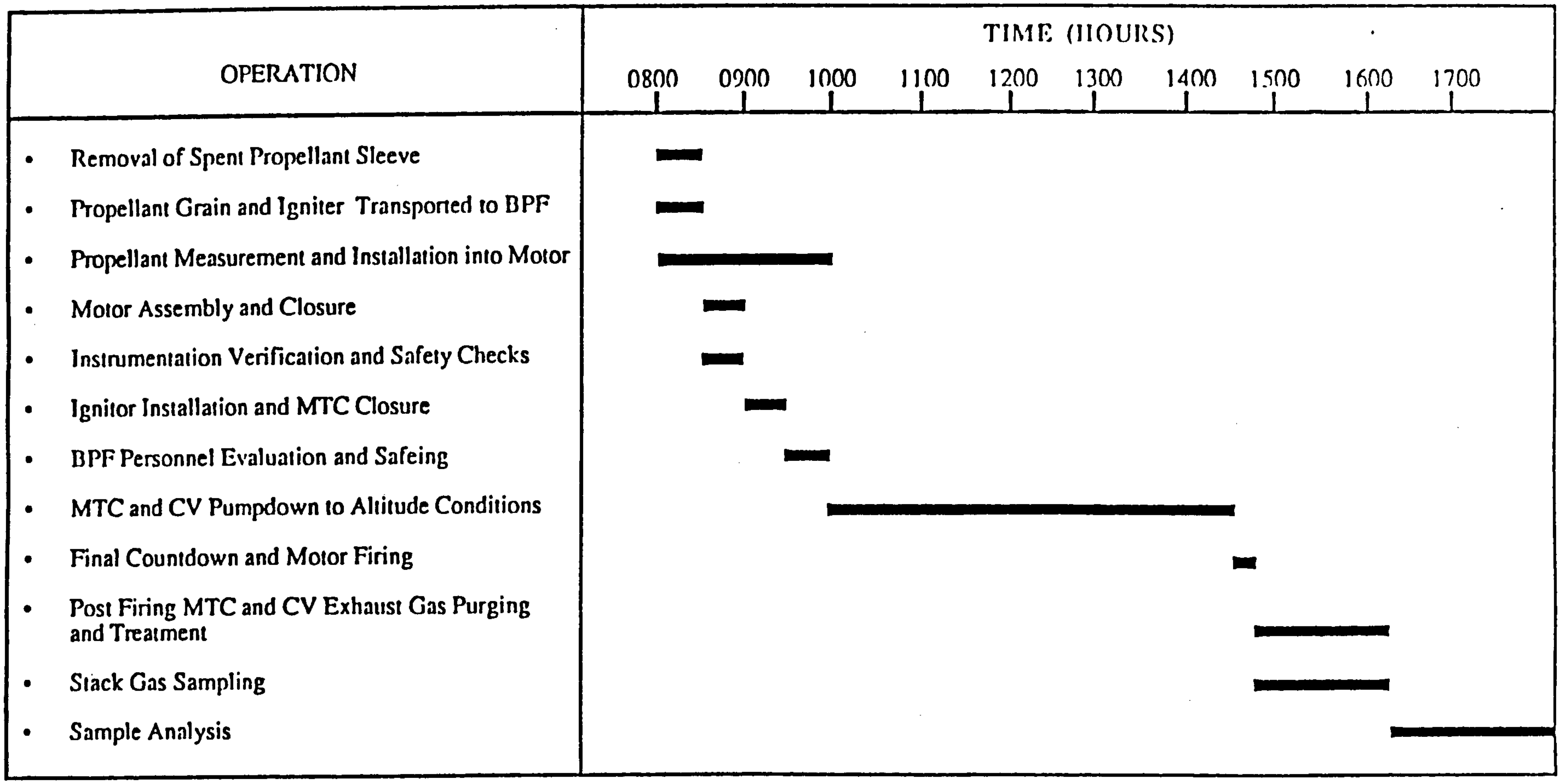

Figure 6-2. Typical Motor Test Firing Operations

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6.1 Description of Storage Facilities

The locations of the two alternative candidate storage facilities, buildings 9635 and 8915, are shown in Figure 6-1. Table 6-1 summarizes key features of these buildings. The descriptions of these storage facilities are presented below.

Building 9635:

This storage facility has a concrete foundation with a steel I-beam frame covered by sheet metal walls. The walls are lined with a 3-inch foam polyurethane coating on the inside. The facility dimensions are 61.1 feet by 28 feet. There are no interior partitions so it appears like an open warehouse. The building is provided with lightning protection and a heating and cooling system for consistent temperature control of the SRMS. The facility contains a wet fire sprinkler system designed to activate at a temperature of 185° F. As depicted on Figure 6-1, this facility is approximately 3.5 miles away from the main part of AFRPL (the most populated area). The surrounding foliage around this storage facility is minimal and could not sustain an exterior fire long enough to threaten the contents of the storage facility.

This building will be modified if it is selected for storing the beryllium propellant. These modifications will improve both the safety and security of the building. The present building insulation will, if ignited, support a high temperature fire which will produce toxic fumes; it may be replaced with a fire resistant insulation or one treated with a fire retardant. The present fire sprinkler system has an adequate water supply, although the current sprinkler heads will need to be replaced with heads which are activated at lower temperatures. With these modifications the system would be

Table 6-1. Present Characteristics of Candidate Storage Facilities

BUILDING 9635:

Plan Dimensions: 61.1 ft x 28 ft

Facility Type:
- Sheet Metal on Steel Frame
- No Interior Partitions
- Polyurethane foam wall lining
- Standard single personnel entrance door and sliding (garage type) double door
- Building windows

Fire Load
- Be SRMs
- 3 Inch Thick Polyurethane liner
- Approximately 20% Floor space used

Fire Protection: Wet sprinkler system

Travel Distance to RPL gate: 5.25 miles

Travel Distance to TCB: 0.81 miles

BUILDING 8915

Plan Dimensions: 35 ft x 18 ft

Facility Type:
- "Igloo"
- Reinforced concrete walls, corrugated metal arch roof
- 80% underground
- No interior partition
- Steel plated doors

Fire Load
- Be SRMs
- Other (more thermally vulnerable SRMs)
- Most floor space used

Fire Protection: CO_2 fire extinguisher

Travel Distance to RPL gate: 2.5 miles

Travel Distance to TCB: 4.5 miles

expected to control 97% of the fires in the facility.[62] (Installation of rate of temperature rise heat sensors with a direct alarm connection to the base fire department would further reduce the chance of an uncontrolled fire.) On the basis of security concerns, it is anticipated that the windows will be eliminated and the doors redesigned. While there is no plan to make the building airtight, it is anticipated that this will reduce the flow of any combustion products from the building.

Building 8915:

This storage facility is an earth covered, "Igloo" type with a floor area measuring approximately 35 feet by 18 feet. The igloo walls are composed of reinforced concrete; the roof is corrugated metal. The igloo is 80% underground with only the front face exposed. The front face is made up of steel plated doors hinged on the outside to the reinforced concrete walls. This storage facility contains heating and cooling units for proper climate control. This facility does not contain a fire sprinkler system but does contain portable CO_2 fire extinguishers. The immediate encompassing area is secured by a locked chain link fence. The surrounding desert foliage is insufficient to sustain a fire of any hazardous magnitude.

Currently, this facility is used to store SRMs with propellants containing nitro compounds (more thermally and shock sensitive). There are no interior walls to segregate the stored SRMs so it also appears like an open warehouse.

Based on an inspection of these facilities and conversations with AFRPL personnel, the SRMs will be stored according to the following criteria:

- SRMs are stored in aluminum shipping canisters
- While in storage SRM cases are grounded

- SRMs are stored on wooden cradles
- Wooden cradles are not stacked
- Wooden cradles are arranged horizontally in rows with adjacent cradles touching
- A maximum of ten 70 pound beryllium SRMs will be in the storage facility at one time (i.e., a maximum of 700 pounds propellant weight in some combination of SRMs)

6.2 Storage Related Risks

The following are potentially credible initiating mechanisms that can occur during the storage of the SRMs:

- Fire
- Lightning
- Earthquake
- Electro-static Discharge (ESD)
- Aircraft Crash
- Handling

Fire data was obtained from AFRPL characterizing the number of fires that have occurred in their solid propellant storage facilities and the amount of storage at risk. From 1970 to present, AFRPL has a record of a single fire in their solid rocket propellant facilities. During this time period some eighteen storage facilities were employed, accounting for an average of 9800 square feet of storage in use at any time. A direct application of this data results in estimates of 6.0×10^{-6} fires per square foot per year of 3.3×10^{-3} fires per storage facility. Using this fire (per unit area) rate results in annual fire probabilities of 1.0×10^{-2} and 3.8×10^{-3} for buildings 9835 and 8915 respectively. (The area in these facilities is above the average storage area per facility during this baseline period.)

The one fire in a solid propellant storage facility at AFRPL during this period of time began in an air conditioning system and spread through the ducts to the building insulation. Once the insulation was involved the fire rapidly spread throughout the building causing the stored propellant to burn. The facilities being considered for storage of the beryllium propellant will have significant differences from the facility in which the fire occurred as noted earlier. As a consequence, data assembled for other similar fiacilities was used to develop a cross-check onthese numbers and a guide for their application. Fire frequency estimates were developed independently for as many Naval occupancy types as possible[47]. The fire occurrence data were taken from the Navy and Marine Corps Fire Experience (Ashore) reports and the corresponding real property data from the Inventory of Military Real Property. Seven years of data with 10,613 loss fires were used. Fire rates (fires per square foot per year) were calculated for each occupancy type by dividing the number of fires by the product of the total floor area of the buildings in that occupancy category with the number of years (seven) of data being analyzed. Based upon this source, the fire frequency of a magazine, ordnance, and/or chemical storage facility is 1.11×10^{-6} fires per square foot per year.

It should be noted that these probabilities are estimates of the annual probabilities of ignition of fires generating losses large enough to be reported. The data upon which they were based did not identify the following significant factors about the facilities within the data base:

- Were they provided with fire alarms of any kind?
- Were they patrolled, and with what frequency?

- Were they provided with automatic fire sprinklers?
- Although the facilities involved served similar functions, the time period covered was more than ten years ago. What significant changes have occurred in that interval (eg. upgrades in electrical installations and buildings insulation) that may alter the probability of fire ignition and spread?

It is likely that some of the answers to these questions would tend to make the likelihood of fire for the storage facility greater than that suggested by the data base and the answers to others would tend to support lower fire risks.

A direct application of this fire rate to buildings 9635 and 8915 produces annual probabilities of 1.90×10^{-3} and 6.00×10^{-4} respectively. These probabilities will be used to represent the likelihood of a fire induced SRM ignition while in storage. Since this does not account for the possibility that a fire may be extinguished prior to SRM ignition, this will tend to produce a conservative result.

With the anticipated upgrade of building 9635 (removal of the polyurethane insulation and replacement of the sprinkler heads with lower temperature heads (nominally 135°F), the chance of a fire ignited in this building spreading to the SRMs is estimated to be only 3×10^{-2}.[62] Thus, with these upgrades the probability of an inadvertent SRM ignition from an accidental fire would be 5.70×10^{-4}.

Once a fire spreads to the SRMs because they are customarily stored with their wood cradles abutting each other it is reasonable to assume that a fire that reaches the portion of the facility in which the SRMs are stored will involve all of the storage cradles. Hence, it will be conservatively assumed that a storage are fire will involve all stored SRMs.

Earthquake

Two initiating mechanisms for an SRM accident may be generated by an earthquake - these are mechanical shock and fire. The most likely source of mechanical shock is falling debris.

Assuming the roof of the facility is 15 feet high, the maximum velocity achieved by a chunk of falling material would be 31.1 ft/sec. Although SRM damage may result from such falling debris a shock-to-detonation from the collapsing storage structure is not possible.

An estimate of the probability of an earthquake induced fire may be made by the following relationship

$$Pr(\text{earthquake caused fire}) = \sum_j Pr(I_j)F[D(I_j)]$$

where I_j = intensity of earthquake shaking

D = structural damage level expected at specified intensity

F = probability of fire ignition given a level of damage

This equation is dependent on the frequency-intensity relationships[60], the relationship of damage to shaking intensity [61], and the probability of fire ignition at a given level of damage[52].

The functional relationships relating fire ignition to damage levels[52] are still the subject of research. The values used are believed to be conservative because they are derived from experience with more sources of ignition.

Lightning

The probability of a lightning strike is small for either storage facility. A proper lightning protection system further protects the contents of the candidate storage facilities from detonation/ignition during any lightning strike.

Electro-Static Discharge (ESD)

On the basis of AFRPL operational procedures ESD is regarded as a low probability hazard for the storage of these SRMs. The SRMs are protected by a sealed aluminum enclosure that nullifies the effects of ESD. Furthermore, the SRMs will be grounded while in storage thus eliminating the possibility of related electro-static discharges. The nitro-based rocket motors were also noticed to be protected by a similar enclosure.

Aircraft Crash

The probability of any aircraft mishap is 3.0×10^{-6} per operation[53]. The likelihood of a crash into different sectors surrounding a runway (see Figure 6-3) given that a crash occurs are tabulated in Table 6-2 as developed by this reference. For the Edwards AFB runway closest to the storage facilities, the storage facilities lie in sector (4). Sector (4) has a conditional crash probability of 0.030.

Assuming that all 75,000 operations per year at Edwards AFB involve this runway, the annual probability of an airplane crash somewhere in sector (4) is 6.75×10^{-3}. Since the area of sector (4) is approximately new

1.46×10^9 square feet while the area of the storage facility is only 1711 square feet, the probability of impacting the facility must be reduced by this ratio. This gives a probability of an airplane crash into the storage facility of 7.9×10^{-9}. This contribution to the risk is insignificant as it is three orders of magnitude lower than the three initiation probability.

Handling in Storage Facility

The primary opportunity for a handling incident in storage is while the forklift operator is picking up SRM pallets. One study[55] which examined handling risks for Army SRMS estimated the probability of a forklift operator error resulting in missing a pallet and striking stored munitions as 4×10^{-5} per operation. Because the operator could correct the problem should he notice it in time this is conditioned by a probability of 2×10^{-3} that the operator will fail to notice it in time and a probability of 0.25 that the forklift, on striking the munitions, penetrates. This gives a probability of 2×10^{-8} per pallet lift. Assuming approximately 10 pallet lifts per SRM to be tested this results in a maximum of 5.6×10^{-6} SRM punctures per year. An SRM puncture may result in a deflagration, but only under ideal circumstances (eg. grain damage by rupture, spark on withdrawing forklift tine which is in immediate proximity of damaged grain etc). Consequently, the likelihood of a deflagration from this mechanism is at least an order of magnitude lower. Thus, the contribution of handling errors to the probability of an accident in the storage area is small in comparison to the general fire risk.

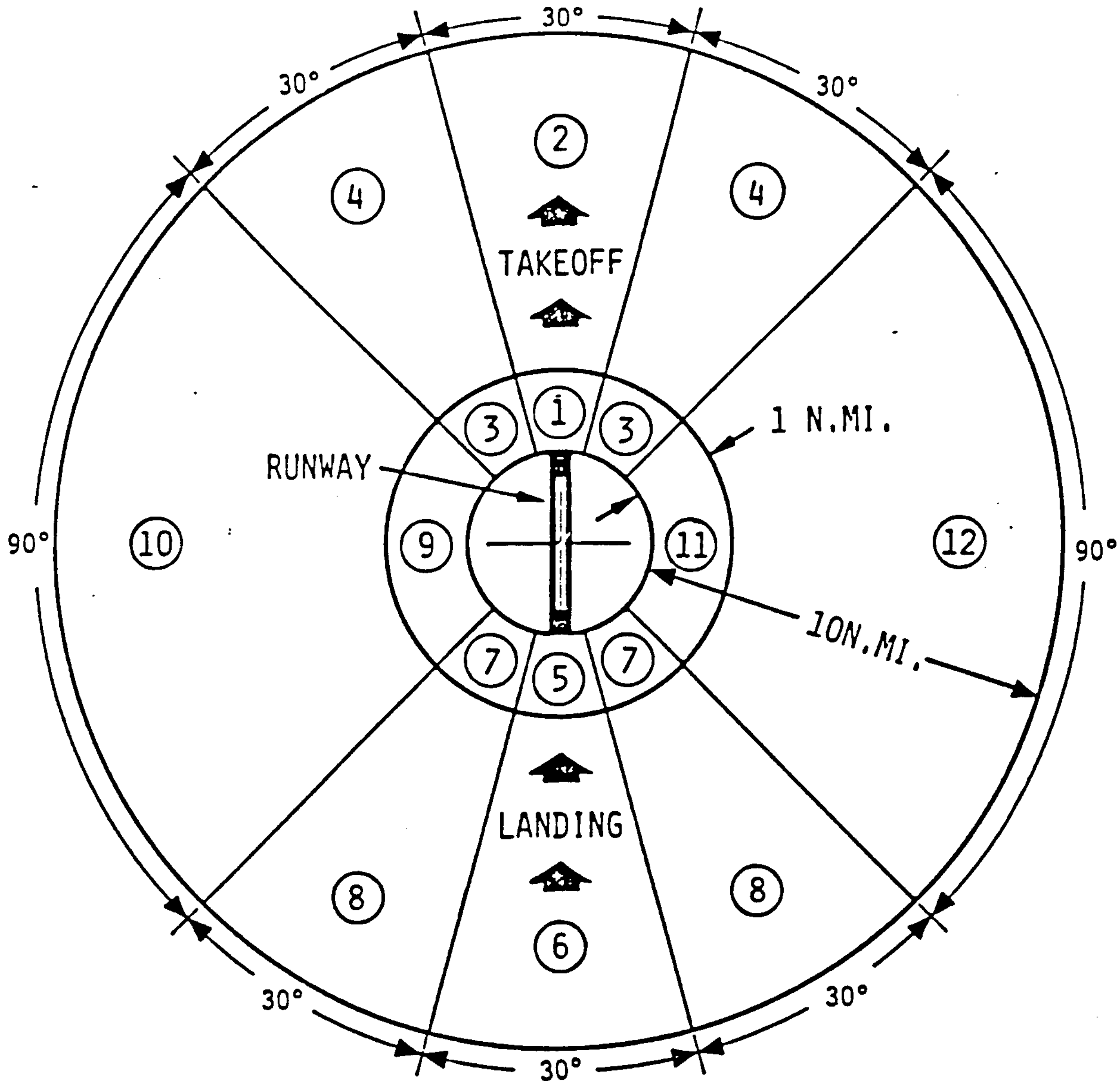

Figure 6-3. Impact Sectors for Generic Runway

Table 6-2. Baseline Crash Location Conditional Probability Distribution[53]

SECTOR*	NUMBER OF CRASHES	CRASH PROBABILITY**
1	36	.098
2	37	.100
3	7	.019
4	11	.030
5	67	.182
7	4	.011
8	8	.022
9	5	.014
10	9	.024
11	4	.011
12	8	.022
ON RUNWAY ***	106	.287

*See Figure 6-3 for identification of sector numbers

**Based on a total of 369 crashes within 10 n mi of a base in the 1977-1981 and 1968-1972 samples

***These data have no effect in the model since there is no public casualty potential from crashes occurring on the runway

Storage Risk Summary

The candidate initiating mechanisms for an SRM accident resulting in a beryllium release in the storage facility have been reviewed on a semi-quantitative basis. The risk of uncontrolled fires (random fires or earthquake caused fires) was determined to be significantly higher than any other initiating mechanism. The following are the estimate annual probabilities of an accidental SRM ignition in storage and subsequent beryllium release:

Location	Probability
Building 9635 As Is	1.90×10^{-3}
Building 9635 With Fire Upgrades	1.63×10^{-5}
Building 8915	6.99×10^{-4}

6.3 On Base Transportation Related Risks

While a number of candidate initiating mechanisms were examined (including natural hazards, airplane crashes and traffic accidents) the only one deemed reasonably credible was traffic accidents. This is due to the low probabilities of the other events and the relatively brief period of time the SRMs are in transit.

An accident during the transportation of an SRM may create up to four different hazarding mechanisms due to the SRM: 1) fire, 2) blast, 3) high velocity fragments and 4) airborne beryllium particles. The first three hazardous mechanisms will pose a threat only in the immediate vicinity of an accident. The fire threat is at the accident site; fragment and blast hazards - even in the unlikely event of a detonation - are likely to be largely confined to a radius of a quarter mile about the scene of the accident. The airborne beryllium particles will, on the other hand, be carried substantial distances downwind. Because of the restricted additional consequences of a detonation beyond any other beryllium release the analysis will focus on the possibility of the release of beryllium.

Figure 6-1 depicts the locations of the AFRPL gate, the project site and the two candidate storage facilities. Table 6-3 summarizes worst case on base transit distances for the two storage locations.

Data assembled[48, 49, 50] based on truck accidents on public roads was used to estimate the probability of traffic accidents. Since this is based on traffic levels and the level of care tolerated on public roads and AFRPL is a restricted facility, these estimates are undoubtedly conservative.

Table 6-3. On-Base Transportation Summary

Storage Location	Route Segment	Maximum Annual Distance Traversed (Miles)*
Building 9635	RPL Gate To Storage	147
	Storage To TCB	23
	Total	170
Building 8915	RPL Gate To Storage	70
	Storage To TCB	126
	Total	196

*Based on a maximum of 28 tests/year

Because the SRM shipping containers offer significant levels of isolation from shock and electrostatic discharge, it is anticipated that only accidents producing a severe fire environment which in combination with the forces of the accident ruptures the aluminum shipping containers subjecting the SRM to a sustained heating will cause a release of beryllium to the atmosphere. The accident rate associated with this type of accident has been conservatively taken as the accident rate for all fire accidents, 1×10^{-7} per mile. As noted in the previous section ignition of the SRM will require that it be exposed to a specified temperature for a given period of time. No attempt has been made to assess the fraction of the fire accidents which will subject an SRM to this type of a thermal load. Table 6-4 presents the resulting maximum estimated annual probabilities of beryllium release from an accident during on base transportation.

Table 6-4. Probability of Release of Beryllium During On-Base Transportation

Storage Location	Route Segment	Probability Per Year
Building 9635	RPL Gate To Storage	14.7×10^{-6}
	Storage To TCB	2.3×10^{-6}
	Total	1.7×10^{-5}
Building 8915	RPL Gate To Storage	7.0×10^{-6}
	Storage To TCB	1.26×10^{-5}
	Total	1.96×10^{-5}

Because the route from the AFRPL gate to building 8915 passes along a road through the heart of the AFRPL facility along Mercury boulevard the additional risks of shrapnel and blast must be considered for this facility. An accident along this approximately one mile long stretch poses a potential risk to AFRPL personnel from shrapnel should a deflagration occur. The estimated annual probability of occurrence of a fire accident along this route segment (based on 28 tests per year) is 2.8×10^{-7}. Some fraction of those accidents will evolve to produce blast or shrapnel hazards.

6.4 Handling Related Risks in the MTC

AFRPL handling procedures are designed to minimize the risk of an explosion or premature ignition in the MTC. Consequently, the credible initiating events for a release of beryllium during handling are results of deliberate or negligent deviations of AFRPL personnel from established procedures. In the absence of these deviation from procedure an initiating event resulting from handling is not credible. AFRPL procedures require grounding of the SRM at all times while in the MTC or storage areas. In addition the wires of the igniter are twisted to short it out and preclude ESD as a source of ignition. Moreover, the SRM is kept in its shipping container until it is brought to the MTC and at no time is it raised more than four feet above the ground thus ruling out mechanical shock as a source of detonation.

On the other hand, deliberate deviations from procedures can and do occur. While countdown procedures require grounding straps for workers in the MTC to further reduce the risk of ESD; operationally, AFRPL management has waived this procedure because of the greater risks to the workers of falling as compared to the risk from ESD. While this is a redundant measure of protection other deviations from procedure may not involve redundant safety mechanisms.

In addition to deliberate exceptions to procedures premature ignition may be caused by human error (failure to short the igniter followed by exposure to ESD, improper inspection of rocket motors for grain around threads and subsequent ignition during tightening of bolts, etc). However, AFRPL area 1-42 does not report any instances of these failures in 787 tests. While at the ninety percent confidence level the probability of occurrence is approximately 3×10^{-3} per test for handling associated with the test area, the ARC experience[18] at the same confidence level results in a probability per test approximately a factor of ten smaller.

7. ACCIDENT CONSEQUENCES

The previous two sections developed scenarios which may result in hazardous conditions as a result of damage to the beryllium fueled SRMs and estimated the probability of occurrence of these scenarios. This section will address the adverse consequences which may result. Evaluation of consequences will be organized by the location where an accident can occur.

7.1 Accidents Inside the MTC

Two credible scenarios were defined resulting in hazardous conditions from accidents inside the MTC. The first of these was a detonation or pressure rupture of an SRM during a test firing resulting in puncturing of the MTC walls by high velocity fragments. This failure is given a probability of 3×10^{-3} per test.(Based on the one-side ninety percent upper confidence bounds for failure probabilities derived from AFRPL data.) This failure will result in severe damage to the MTC and release to the atmosphere of the combustion products of the SRM including potentially hazardous beryllium compounds. Because most of the fragments generated will be ejected radially from the SRM, damage to the CV is expected to be minimal. Even if the CV is ruptured it is unlikely that any significant quantity of deposited beryllium compound will be resuspended based on ARC experience.

The only personnel potentially at risk to the blast and shrapnel hazard are located inside the protective structure of the Firing Control Building about 2000 feet from the MTC. At this distance the fragments and blast wave are not expected to pose a threat to these personnel. A somewhat larger population may be exposed to the airborne beryllium compounds depending on wind conditions. Since firing operations will occur only when the wind is light and variable, or blowing in a 210 to 290 degree corridor, for much of the time the only populations at risk will be passengers in cars driving along route 395. Other populations are placed at risk only when the wind is light and variable.

The second scenario identified was a handling error inside the MTC resulting in premature ignition. This failure is modeled with a probability of 3×10^{-4} per test.(Based on a one-sided ninety percent upper confidence bound derived from the ARC data.) If this occurs it is most likely to happen after the SRM is secured to the test stand. The exhaust products of such a firing would be free to vent to the TCB. With prompt evacuation of all personnel from the MTC and TCB after premature ignition, personnel exposure to beryllium exhaust compounds will be minimal, since the TCB is expected to contain most of the exhaust. If the exhaust vents to the outside, the same populations will be at risk as described for the first scenario. Generation of a blast and shrapnel environment as a consequence of a premature ignition will require either an SRM that would have malfunctioned with normal ignition or sufficient mishandling to not only ignite the SRM but also to damage the propellant grain. Both of these are regarded as unlikely events.

As previously noted, there is no definitive evidence that beryllium can produce cancer in human beings. Nevertheless, in order to consider the most adverse outcomes possible from this project this possibility will be addressed. Since airborne beryllium exposure levels to create a potential cancer risk are lower than dose levels for chronic or acute beryllium disease, the potential for cancer occurrence was taken as the consequence of concern. A continuous lifetime (70 years) exposure to a concentration level of one microgram of beryllium per cubic meter leads to a mean estimated probability of carcinogenesis of 2.4×10^{-3} [9, 16].

One of the most conservative models for assessing the risk in the low dose range is the One Hit Model[59] which has the form

$$P(d) = 1 - \exp(-Ld)$$

where L is the mean lifetime risk and d is the dose.

When the product Ld is small this becomes

$$P(d) = Ld$$

or

$$P(d) = 2.4 \times 10^{-3} d$$

If an individual's only exposure to beryllium (or most significant exposure to beryllium) is from a single accident, a one time dose, D $\mu g\text{-}min/m^3$ can be considered as an exposure to a unit dose for a duration of D minutes. Averaging over a lifetime of 70 years, an equivalent dose is computed as

$$D_e = D / \ (60 min/hr)(24 hr/day)(365\ days/yr)(70\ yr)$$
$$= 2.72 \times 10^{-8} D,\ \mu g/m^3$$

Combining the above relationships gives an expression for the probability of cancer given a one time exposure of level D as

$$P(D) = 6.53 \times 10^{-11}\ D$$

Thus, for a group of N people exposed to the same one time dose the expected number of cancers is

$$C = 6.53 \times 10^{-11}\ ND$$

To allow for the possibility the TCB does not contain the exhaust from a handling induced ignition the probability of an initiating event was taken as 3.3×10^{-3} per test or (based on 28 tests per year) 9.24×10^{-2} per year.

Dosages were estimated for AFRPL, Boron, cars along highway 58 and cars along highway 395 using the dispersion calculations of ESA[51] (See Table 7-1) and supplemental calculations by ESI for C stability and a 300 meter height for the stabilized cloud of combustion products. Annual risks (expected number of cancers) at a given location were calculated by

$$R = 6.53 \times 10^{-11} \{(P_F)(N) \sum_j (D_j)(P_{W_j}/P_{WF})\}$$

where the summation is over the different wind conditions that can affect a location, and P_F is the annual probability of a failure resulting in a beryllium exhaust release, P_W is the probability of wind which affects a location and P_{WF} is the probability of wind conditions allowing a test firing.

This results in the following annual increased number of cancers:

Boron & Highway 58	4.97×10^{-8}
AFRPL	2.04×10^{-8}
Highway 395	1.41×10^{-7}

Summing these annual risks results in a total annual risk for an accident in the test cell of 2.1×10^{-7} cancers per year, or 6.3×10^{-11} cancers per person exposed per year.(Population within area of significant risk is 3358)

This estimate embodies the following conservatisms:

- Ninety percentile confidence bound on failure probability
- No credit taken for TCB control of release from handling accident
- No credit taken for beryllium exhaust contained by MTC or not airborne
- Maximum size (150 pound propellant) SRM assumed to detonate at ignition
- No credit taken for protection of exposed population from beryllium by buildings
- Conservative model for predicting carcinogenesis
- Maximum percentage beryllium in propellant
- Projected population for last year of operation

Table 7-1. Centerline Dose (μg-min/10kg-m^3) vs Atmospheric Stability Class and Cloud Height[51]

	0.2	0.3	0.4	0.5	0.6	0.7	0.8	1.0	2.0	5.0	10.0	20.0
H = 200 m												
X,km	-0.4	-0.3	-0.2	-0.1	0.0	0.1	0.2	0.4	1.4	4.4	9.4	19.4
A	0	2	155	722	1115	1052	852	508	70	12	7	4
B	0	0	0	6	51	165	320	590	551	123	33	8
C	0	0	0	0	0	1	4	40	528	340	119	36
D	0	0	0	0	0	0	0	0	3	161	241	160
H = 300 m												
X,km	-0.6	-0.5	-0.4	-0.3	-0.2	-0.1	0.0	0.2	1.2	4.2	9.2	19.2
A	0	0	1	74	388	607	624	450	69	12	7	4
B	0	0	0	0	0	2	11	73	349	116	32	8
C	0	0	0	0	0	0	0	0	80	239	108	35
D	0	0	0	0	0	0	0	0	0	7	61	86
H = 400 m												
X,km	-0.5	-0.4	-0.3	-0.2	-0.1	0.0	0.1	0.3	1.3	4.3	9.3	19.3
A	0	0	0	3	89	281	403	380	69	12	7	4
B	0	0	0	0	0	0	0	4	184	106	32	8
C	0	0	0	0	0	0	0	0	6	146	94	34
D	0	0	0	0	0	0	0	0	0	0	9	36
H = 500 m												
X,km	-0.8	-0.7	-0.6	-0.5	-0.4	-0.3	-0.2	0.0	1.0	4.0	9.0	19.0
A	0	0	0	0	13	105	230	305	68	12	7	4
B	0	0	0	0	0	0	0	0	81	95	31	8
C	0	0	0	0	0	0	0	0	0	78	78	32
D	0	0	0	0	0	0	0	0	0	0	1	11

7.2 Accidents in Storage Facility

Section 6 argued that for each of the candidate storage facilities, the primary accident of concern was fire leading to an ignition or deflagration of one or more stored SRMs. In contrast to the test cell accidents it is possible that personnel might be inside the storage facility when an accident occurs. Because of the hazards created when an SRM is ignited or when it deflagrates, fire control procedures should clearly define when personnel should leave the storage area and seek protection. It is assumed in the following discussion that this is sufficiently well defined so that storage workers are not subjected to significantly greater hazards than other personnel at AFRPL.

In the event of SRM ignition some level of effective thrust may be imparted to the SRM. The level of thrust so achieved would be expected to be highest for the lightweight SRMs with sealed domes and integrally wound nozzles and lowest for the SRMs without nozzles or dome seals. The former are expected to constitute only a small fraction of the SRMs to be tested. The exhaust gases of an inadvertently ignited SRM will vent through holes in the shipping canister. Thus, any thrust vector achieved is unlikely to be through the SRM center of mass and while thrusting inside the canister it is likely to follow a high erratic path. Moreover, it is possible that the thrusting SRM will tear open the canister and, in so doing, rupture the SRM case. As a consequence of considerations such as these and experience which suggests that the area reached by a small, escaped missile is less than a few hundred yards this hazard warrants no further consideration.

As a consequence of the location of both building 8915 and building 9635 blast and shrapnel are only hazards to workers in the storage locations or in the immediate vicinity. People at the other nearest AFRPL facilities are not expected to be hazarded by blast and shrapnel.

Following the same procedure outlined for evaluating the number of additional cancers per year expected from accidents in the MTC, the following results were obtained for accidents in the storage areas:

	As Is	Upgraded
Building 9635		
Boron and Highway 58	6.33×10^{-9}	1.90×10^{-10}
AFRPL	1.57×10^{-9}	4.70×10^{-11}
Highway 395	1.04×10^{-9}	3.12×10^{-11}
Total	9.0×10^{-9}	2.68×10^{-10}
Building 8915		
Boron and Highway 58	5.20×10^{-9}	
AFRPL	4.54×10^{-10}	
Highway 395	9.61×10^{-10}	
Total	6.61×10^{-9}	

Thus, if the storage facilities were used in their present condition an annual increase of 6.61×10^{-9} additional cancers per year or 2.0×10^{-12} per person exposed would result for building 8915, and an annual increase of 9.0×10^{-9} additional cancers or 2.7×10^{-12} per person would result for building 9635. With the anticipated upgrades to building 9635 the annual cancers increase expected from the use of that facility would be only 2.7×10^{-10} or 8.0×10^{-14} per person exposed.

7.3 Transportation Risks

As a consequence of the low probability of an on base transportation accident involving the SRMs this aspect of operations has a minimal impact. For most of the transportation route beryllium dosages will be comparable to that from an MTC accident with several orders of magnitude lower probability. For the portion of the route from the AFRPL gate to building 8915 passing through the main portion of AFRPL dosages to AFRPL personnel will be considerably higher. A conservative calculation based on placing all of the personnel in these buildings at the closest point to the road results in only 6×10^{-12} expected cancers per year. Thus, the cancer risk for transporation is negligible.

Probably the greatest risk from transportation of the SRMs is to the driver. The presence of an SRM will somewhat increase his chance of injury from fire or shrapnel. Increased risks to the driver should be addressed by training him as to appropriate procedures in the event of an accident.

Within the same region of AFRPL there is a 2.8×10^{-7} per year probability of an accident that could endanger other personnel.(Based on the fire accident rate of 1.0×10^{-7} per mile, 28 trips per year, and a critical distance of 1 mile during which AFRPL personnel are at risk along the route from the AFRPL gate to building 8915.) Normal setbacks of buildings from the road will protect most AFRPL personnel with the possible exception of foot and auto traffic in the immediate area. Selection of time of day for transportation and procedures to avoid other traffic can further reduce this risk.

7.4 Risk Summary

Risk from beryllium induced cancer was quantified for on base operations based on a series of conservative assumptions. The annual number of cancers expected so calculated from the proposed operation is less than 2.2×10^{-7}. Expressed on the basis of increased annual risk per person the value is 6.6×10^{-11}. This risk, as will be seen in the discussion in the next section, is several orders of magnitude below commonly experienced risk and any standard of acceptable risk.

8. ACCEPTABILITY OF RISK LEVELS

In order to place the risks from the proposed beryllium rocket test facility into perspective it is necessary to examine what the criteria are for acceptable risk. Lowrance[34] has identified a set of guidelines that, to the extent a risk is consistent with them, enhance the chance it will be accepted. These are:

- Reasonableness
- Custom of usage
- Prevailing professional practice
- Best available practice, highest practicable protection, lowest practicable exposure
- Degree of necessity or benefit
- No detectable adverse effects

It is important to observe that these guidelines include value judgments. Consequently, meeting all of the requirements except the last by no means assures that a risk will be universably acceptable. Table 8-1 identifies some further consideration in safety judgments posed by Lowrance. The scales in Table 8-1 have been marked to indicate approximate ratings for the beryllium rocket test facility. Where a distinction is expected between on-base working populations and off-base populations they have been separately marked. Since the most probable adverse health consequence from a mishap may be cancer, the risk is a "dread" disease with only partially reversible consequences. On the other hand, the number of people who will be affected is small. Since the American people tend to be more adverse to risks resulting in large numbers of casualties than to smaller numbers, this will tend to mitigate the perception of cancer as a "dread" disease.

Table 8-1. Considerations Influencing Safety Judgments[34]

Risk assumed voluntarily	——R————O——	Risk borne involuntarily
Effect immediate	————————X——	Effect delayed
No alternatives available	—————X—————	Many alternatives available
Risk known with certainty	——X————————	Risk not known
Exposure is an essential	—R————————O—	Exposure is a luxury
Encountered occupationally	R—————————O—	Encountered non-occupationally
Common hazard	—————————X—	"Dread" hazard
Affects average people	————————X——	Affects especially sensitive people
Will be used as intended	X——————————	Likely to be misused
Consequences reversible	———————X———	Consequences irreversible
Expected to affect few	X——————————	Expected to affect many

R = RPL WORKERS
O = OFFBASE POPULATIONS
X = COMMON TO BOTH POPULATIONS

Historically, as part of the decision process in evaluating acceptable risks at the National Test Ranges, an important element has been how essential the particular operation with which the risk is associated is to the United States national defense and the current level of international tensions. When both of these levels are higher, greater risks are deemed justifiable. (In the extreme case of a test essential to the national defense during wartime, relatively high risks would, presumably, be tolerated).

Although the factors mentioned provide a context for setting a level to be regarded as acceptable, it is necessary to establish a "scale" against which a given risk may be judged. Potentially useful empirical criteria for supplementing these guides include:

- Comparison with natural background
- Comparison with accustomed hazards
- Comparison with occupational exposure precedents
- Results of public referenda/polling

Figure 8-1 indicates the frequency versus number of fatalities in the United States from various natural hazards and man caused events. It indicates a defacto tolerance by society of higher frequencies of occurrence for events which produce fewer fatalities at a time. Figure 8-2 classifies individual annual risks according to expressed societal attitudes towards risk (acceptable/unacceptable) and actions being taken to mitigate risks (risks accepted/risks unaccepted). It indicates that while risks as high as 10^{-2} are being tolerated by society that our expressed preferences for acceptable risks are considerably lower.

Two of the major distinctions between acceptable and unacceptable risks are based on the perceived benefits derived and whether or not the risk is voluntary. Figure 8-3 presents an update to the classic work of Starr showing these distinctions.

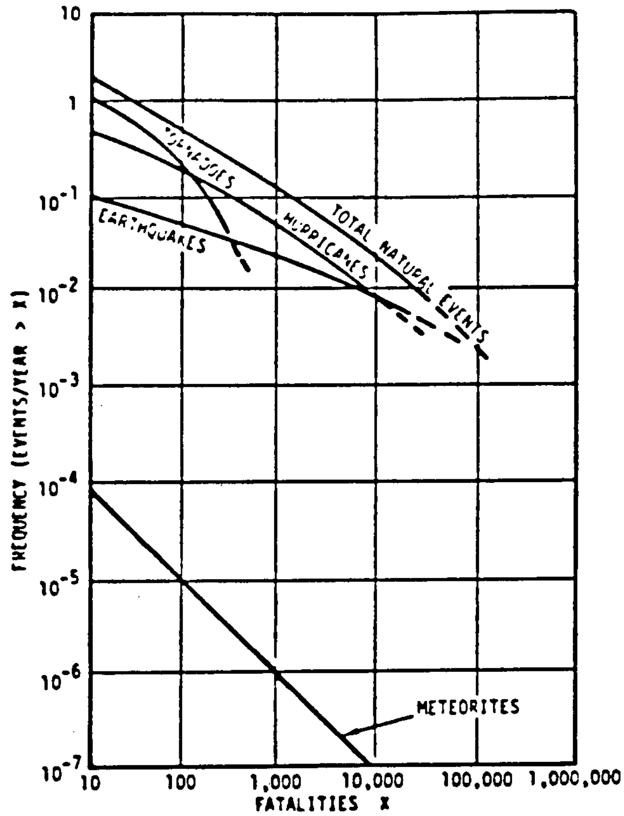

Figure 8-1a. Frequency of Natural Events Involving Fatalities[35]

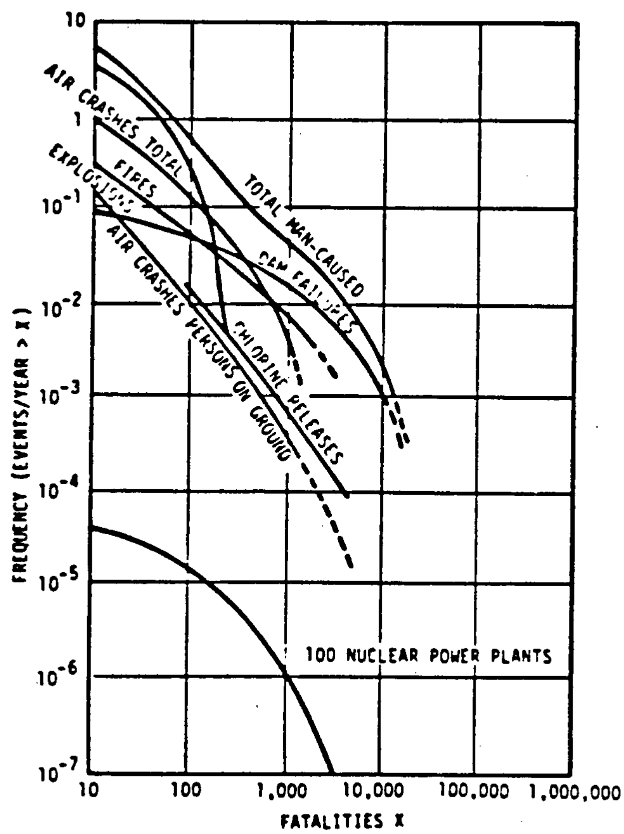

Figure 8-1b. Frequency of Man-Caused Events Involving Fatalities[35]

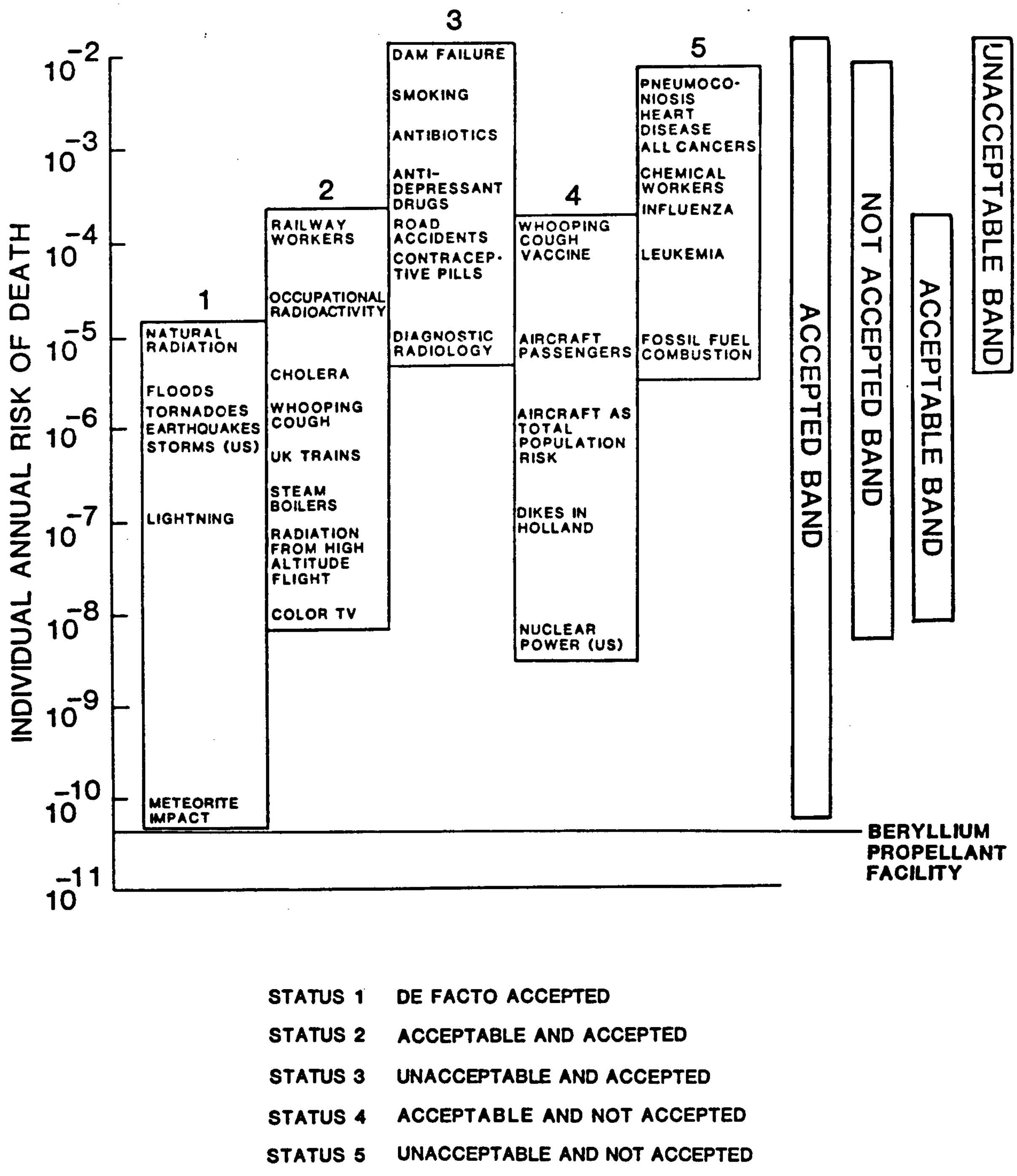

Figure 8-2. Status of Acceptability of Comparable Ambient Risks[36]

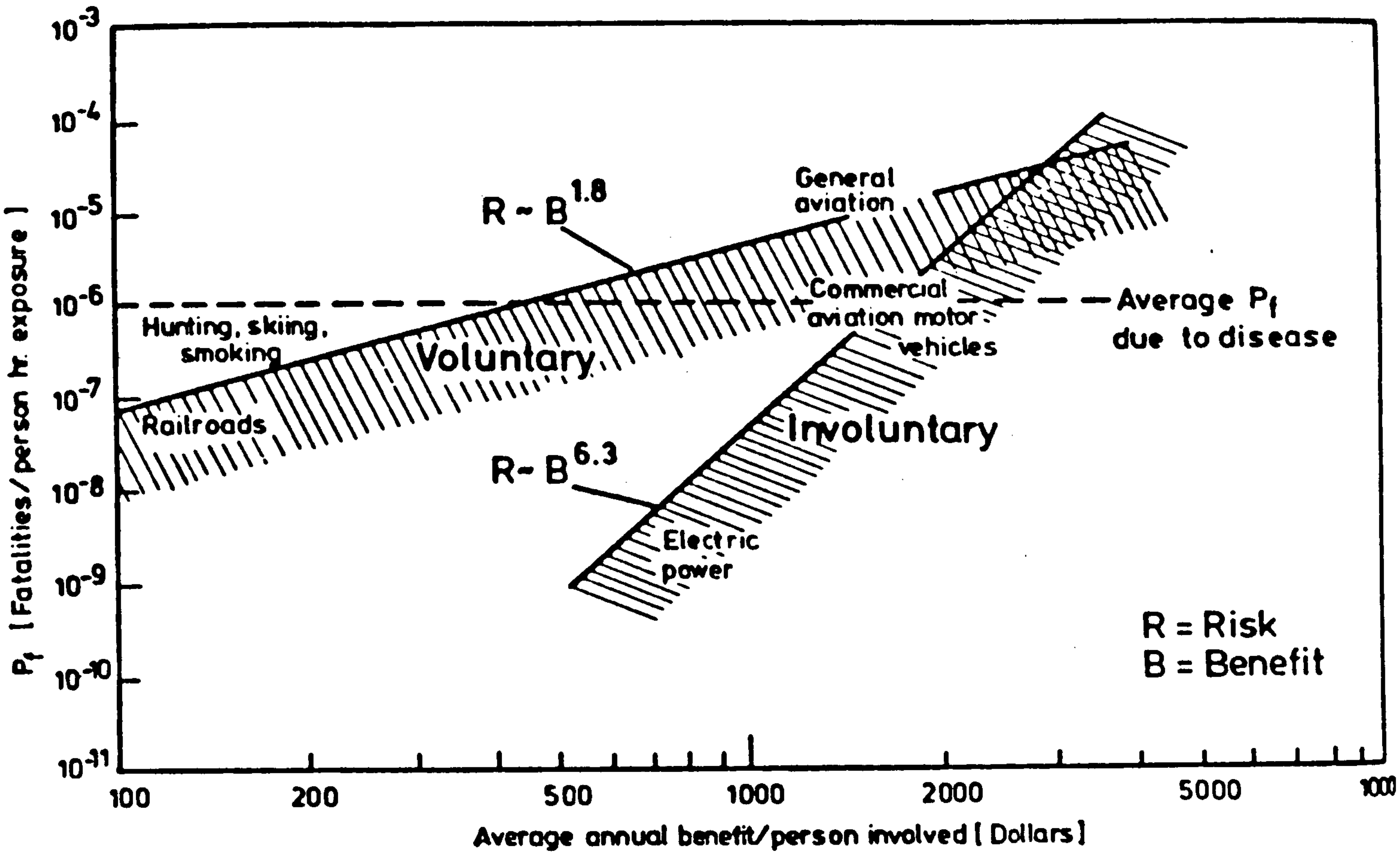

Figure 8-3. Otway and Cohen's Rebuttal to Starr[37]

Table 8-2a. Army Munitions Accident Categories and Effects on System[41]

ACCIDENT CATEGORY	EFFECTS ON SYSTEM	
	EQUIPMENT	PERSONNEL
IA	SL or LSED	----------
IB	----------	D or PTD
IIA	CSD or SED	----------
IIB	----------	PPD
IIIA	MSD or SED	----------
IIIB	----------	TTD or LOST TIME INJURY NOT COVERED BY CATEGORY IB or IIB
IV	NO DAMAGE	NO INJURY

SL = SYSTEM LOSS
CSD = CRITICAL SYSTEM DAMAGE
MSD = MINOR SYSTEM DAMAGE
LSED = LARGE SCALE ENVIRONMENTAL DAMAGE
SED = SOME ENVIRONMENTAL DAMAGE
D = DEATH
PTD = PERMANENT TOTAL DISABILITY
PPD = PERMANENT PARTIAL DISABILITY
TTD = TEMPORARY TOTAL DISABILITY

Table 8-2b. Army Munitions Acceptable Risk Criteria (Mean Values; Design Goals)[41]

ACCIDENT CATEGORY	ACCIDENTS PER FACILITY-HR.	ACCIDENTS PER MAN-HR.
IA	10^{-6}	-
IB	-	10^{-7}
IIA	10^{-5}	-
IIB	-	10^{-6}*
IIIA	10^{-3}	-
IIIB	-	10^{-6}*
IV	1	1

*NOTE: The sum of the probabilities of a category IIB or IIIB accident occurring shall be 10^{-6} per man-hour or lower.

The major difficulty that has been encountered in using this type of risk/benefit analysis to justify accepting additional risks is that frequently the parties forced to accept the risk receive only some fraction of the benefit generated. Moreover, their perceived benefit is frequently less than their objectively evaluated benefit, while their perceived risks are frequently much larger.

A number of researchers have proposed standards for acceptability of risk. Starr[38] expresses acceptable level of involuntary risk in terms of relative value of benefits as follows:

Annual Fatality Risk	Required Relative Benefit
1×10^{-7}	10
1×10^{-6}	150
1×10^{-5}	900
1×10^{-4}	1,500
1×10^{-3}	12,000
1×10^{-2}	1,000,000

As "calibrations points" he notes that the annual risks from natural hazards are approximately 1×10^{-6} while those from disease are approximately 1×10^{-2}.

Okrent and Whipple[39] proposed the following standards for acceptability

- 1 or 2×10^{-4} expected fatalities per individual per year at 90% confidence for "essential" hazardous technologies

- 10^{-5} for "beneficial" technologies
- 2×10^{-6} for technologies not generally beneficial to society

Phillipson and Donaldson[40] as part of an LNG risk analysis developed criteria which considered whether a risk was voluntary and the degree of uncertainty in quantifying the risks and mitigations. For voluntary risks they proposed the following levels

Maximum Risk	Acceptability
1×10^{-6}	Acceptable
1×10^{-5}	Marginally Acceptable
1×10^{-4}	Possibly Unacceptable
1×10^{-3}	Probably Unacceptable

For involuntary risks they suggest two orders of magnitude lower levels of risk.

Qualitative interpretations of these degrees of acceptability that they considered to be appropriate for the risks in LNG operations are:

- Acceptable - The combined risks plus uncertainties meet conservative requirements for safety, as inferred from Starr.
- Marginally Acceptable - Until the uncertainties in their estimates are better resolved, it cannot be demonstrated that these risks are acceptable. However, for such risks, mitigating measures are known that could reduce them to acceptable levels, despite the uncertainties.

- Possibly Acceptable - These risks may generally be considered unacceptable. Mitigating measures can be conceived of that might be able to reduce them sufficiently to make them acceptable.

- Probably Unacceptable - Even if uncertainties could be resolved, these risks would most likely turn out to be considered unacceptable. Mitigating measures adequate to reduce them to acceptable levels are not now defined.

All of the standards cited have been developed for nonmilitary personnel. Somewhat higher risks may be deemed acceptable for certain hazardous military operations. For example, the Army Munitions Acceptable Risk Criteria[41] allow a risk of 1×10^{-6} accidents resulting in permanent partial disability per man hour. Should this same individual be exposed to the same risk for a man year, this would result in a risk of 2×10^{-3}. (This example is somewhat artificial in that constant exposure is unlikely.) Nevertheless, it is indicative of the somewhat higher risks which may be tolerated under very special circumstances.

In this section a number of criteria have presented characterizing commonly used criteria for the acceptability of risks. The proposed program meets five of the six guidelines proposed by Lowrance:

Site selection was made with regard to the highest practicable protection and the lowest practicable exposure of the public. The facility design as undergone constant scrutiny by the U.S. Air Force and a group of environmental contractors and has included consultation by industry experts involved in the operation of high altitude solid rocket motor test chambers to assure reasonableness of the design and proposed operation of the facility and conformance with customary usage and prevailing professional practices. Finally, there is a high degree of necessity of the development of this facility because it is essential to the Strategic Defense Initiative Kinetic Energy Weapons program.

While it cannot be said that there are <u>no</u> adverse effects possible from the program (Lowrance's sixth criterion), the full spectrum of numerical criteria for acceptable risks have been presented in this section. The very conservatively calculated annual cancer risks per person from this project are less than 6.6×10^{-11} for all options. The annual risk per person of death is still lower. This level of risk is several orders of magnitude smaller than those proposed by any standard and thus should be regarded as acceptable.

9. GLOSSARY

9.1 Abbreviations

ABBREVIATION	DEFINITION
AEDC	Arnold Engineering Development Center
AFISC	Air Force Inspection and Safety Center
AFRPL	Air Force Rocket Propulsion Laboratory
Atm	Atmosphere (used as a unit of pressure)
BATES	Ballistic Test Evaluation and Scaling (solid rocket motor)
CAL	Calorie
CV	Containment Vessel
DDT	Deflagration to detonation transition
ESD	Eletro-static discharge
fps	feet per second
FS	First Stage
ft	feet
g	grams
in	inches
lb	pounds (force)
lbm	pounds (mass)
LLL	Lawrence Livermore Laboratory
max	maximum
mm	millimeter
MTC	Motor Test Cell
psi	pounds per square inch (unit of pressure)
psia	absolute pressure in units of pounds per square inch
psid	differential pressure in units of pounds per square inch
rpm	revolutions per minute
SDOF	Single degree of freedom
SDT	Shock to detonation transition
sec	seconds
SRM	Solid rocket motor
SS	Second Stage
TCB	Toxic Control Building
XDT	Propellant fragment impact breakup and deflagration to detonation transition

9.2 Definitions

TERM	DEFINITION
A-36 Steel	ASTM designation for a steel alloy rated at 36000 psi (yield strength)
Anomolous burn surface	Propellant burn surface resulting from damage to the propellant
Class 1.1 Propellant	A propellant which is principally a blast hazard; it may be expected to mass detonate when a small portion is initiated
Class 1.3 Propellant	A propellant which burns vigorously resulting in fires which are difficult to put out. Explosions are usually pressure ruptures.
Critical Diameter	Diameter of a propellant chunk required to sustain a detonation
Critical Velocity	Impact velocity required to initiate detonation of a propellant piece
Deflagration	A violent chemical reaction in which the shock wave stretches out because it is not of sufficient amplitude to propagate supersonically
Detonation	A violent chemical reaction generating a shock wave which propagates supersonically
Ductility ratio	The ratio of the deformation of a material to yield deformation; often used as a measure of how close to failure a structure is stressed
Fading detonation	An explosion of a sufficiently small amplitude so that the shock wave propagation becomes subsonic after some time so that it becomes a deflagration
Grain	A piece of propellant

Hoop mode	The response of a cylinder to an internal blast wave in the form of a radial expansion resulting in a tangential strain along the circumference of the cylinder
Isolation valve	A valve in the diffuser that is shut at the conclusion of SRM burn to prevent exhaust products from returning to the MTC
Mild Steel	A medium strength, ductile, low carbon steel
Quasi-static pressure	A pressure representing the effects of explosion produced gas pressure build up; this pressure is a function of the shape of the blast wave and the period of the container in which the explosion occurs
Statistical one-sided upper confidence bound	When information about a population is deduced from a sample drawn from that population, there is uncertainty in the inferred parameters. The upper confidence bound is an estimate devised so that a specified fraction of the time the true value will not (due to the uncertainty exceed the estimate
Supersonic diffuser	A flow channeling device, flared at both ends, place between the motor nozzle and the CV to provide aerodynamic isolation. It enables the MTC to reamin at a nominal 0.1 psi during motor burn while the CV pressure rises (still below atmospheric pressure)
Time varying forcing function	A waveform whose amplitude varies with time

TNT Equivalency	A scaling factor relating the explosive yield of one material to an equal mass of TNT.
Triangular pulse loading	A time varying load in which the amplitude is described as linearly increasing as a function of time to a maximum and then linearly decreasing to zero
Uniformly applied load	A load resulting in a constant pressure across the surface to which it is applied
VID, VRP, VLZ, VOY, VRO, VO, VRL	Designations of propellants employed in the Trident (C-4) program (None of these use beryllium as fuel)

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