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ROCKET PROPULSION HAZARD SUMMARY: SAFETY CLASSIFICATION, HANDLING EXPERIENCE AND APPLICATION TO SPACE SHUTTLE PAYLOAD

by

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FOREWORD

This final report presents the results of a literature survey and study effort performed by Vought Systems Division (VSD) of the Vought Corporation to determine the hazards of Shuttle payload propulsion systems. This report contains a discussion of the methods and purpose of hazard classification for transportation and storage, handling/safety procedures and requirements, quantitative hazard assessment techniques of solid and liquid rocket systems, a preliminary hazard analysis of rocket systems for Shuttle payload, and a hazard comparison of solid and liquid systems. The study was conducted under NASA Contract NAS1-12500, Task R-150.

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TABLE OF CONTENTS

TABLE OF CONTENTS (CONTINUED)

Page

TABLE OF CONTENTS (CONTINUED)

TABLE OF CONTENTS (CONTINUED)

TABLE OF CONTENTS (CONCLUDED)

LIST OF FIGURES

LIST OF FIGURES (CONTINUED)

LIST OF FIGURES (CONTINUED)

LIST OF FIGURES (CONCLUDED)

LIST OF TABLES

GLOSSARY OF TERMS

ABBREVIATIONS

ACS – Attitude Control System
AFETR – Air Force Eastern Test Range
AFETR/SEN – Missile Safety Branch, AFETR Safety Office
AL – Aluminum
AP – Ammonium Perchlorate
CKAFS – Cape Kennedy Air Force Station
DESB – Defense Explosive Safety Board
DOD – Department of Defense
DOT – Department of Transportation
EMI – Electromagnetic Interferences
GSE – Ground Support Equipment
HDA – High Density Acid
HMX – Cyclotetramethylene Tetranitramine
H_2O_2 – Hydrogen Peroxide
IRFNA – Inhibited Red Fuming Nitric Acid
JSC – Johnson Space Center
KSC – Kennedy Space Center
LH_2 – Liquid Hydrogen
LMSC – Lockheed Missile and Space Company
LO_2 – Liquid Oxygen
MMH – Monomethylhydrazine
NC – nitrocellulose
NG – Nitroglycerin
N_2H_4 – Hydrazine
N_2O_4 – Nitrogen Tetroxide
P – Overpressure
PHA – Preliminary Hazard Analysis
PBAN – Polybutadiene Acrylic–Acrylonitrile Binder
R – Range
RCS – Reaction Control System
RDX – Cyclotrimethylene Trinitramine
RFI – Radio Frequency Interference
RP-1 – Hydrocarbon Fuel
SAMSO – Space and Missile Systems Organization
SAMTEC – Space and Missile Test Center
SE – Missile Ground Safety Office
SOP – Standard Operating Procedure
STS – Space Transportation System

GLOSSARY OF TERMS (CONTINUED)

t — Time
TOPs — Technical Operating Procedure
TVOPA — 1, 2, 3 — tris [$\alpha\beta$ — bis (difluoramino) ethoxy] propane
UDMH — Unsymmetrical Dimethylhydrazine
VAFB — Vandenberg Air Force Base
Vi — Velocity or Impact Velocity
W — Weight of Explosive
W_p — Propellant Weight
Y — Terminal Yield
Y_m — Maximum Yield

SYMBOLS

λ — Ground Range Scale Factor $R/W^{1/3}$
σ_c — Pseudocritical Geometry (Critical Geometry)

DEFINITIONS

BASIC EXPLOSIVE TERMS RELATED TO ROCKET PROPELLANTS

Explosive	Any material which decomposes exothermically over a short time period to yield high gas pressure or shocks (impulse) in the immediate vicinity.
Propellants	High energy materials which are employed in such an environment that they react (sometimes at a high rate) but without the destructive forces of an explosive. Under certain conditions these materials will also function as explosives.
Explosive Decomposition	A chemical reaction or change of state occurring in a material which, at a given time, may exist in one of four stages; i.e., initiation, deflagration, transition or detonation.
Initiation	That stage in an explosive decomposition in which a stimulus (i.e., heat, shock, etc.) has initiated a decomposition but the decomposing substance has not released sufficient energy to proceed beyond the burning stage.
Deflagration	The second stage of the explosive decomposition process in which a self-sustaining reaction is being carried out. Heat is transferred from the reacted to the unreacted material, causing further reaction. Generally deflagration is a very slow process and dependent on ambient pressure.

GLOSSARY OF TERMS (CONTINUED)

Transition	The 3rd stage of an explosive decomposition in which rate increases from deflagration to a high velocity reaction usually called detonation.
Detonation	A steady high-stage rate consumption of the explosive in which energy liberated is transmitted to the unburned layers of explosive by means of shock waves. In most condensed explosions the rate at which the detonation passes through the explosive is 5-8 mm/μsec.
Explosion	(A more generalized term than explosive decomposition) The sudden release of energy usually in the form of large volumes of gas which exert pressure on the surrounding medium. Depending on the rate at which energy is released, an explosion can be categorized as a deflagration, detonation, or the rupture of a pressure vessel.

GENERAL EXPLOSIVE TERMS

Air Blast	The destructive energy imparted to the atmosphere surrounding an explosion.
Blast Yield	Energy release in an explosion inferred from measurements of the characteristics of blast waves generated by the explosion.
CBGS	Confined by Ground Surface. A liquid propellant explosion occurring on the ground after spill and mixing.
CBM	Confined by Missile. An explosion within the tankage of a liquid propellant vessel or rocket.
Critical Diameter (D_C)	The minimum diameter for solid propellant which will sustain detonation when configured as a solid right cylinder.
Explosive Yield	Energy released in an explosion, often expressed as a percent or fraction of energy which would be released by the same mass of a standard high explosive such as TNT.
Fallback	An accident in which a launch vehicle settles or falls back to earth in initial stages of launch.
Hazard	A situation which may result in death or injury to personnel, or in damage to property. Includes effect of fire, flash, explosion, shock, concussion, fragmentation, corrosion and toxicity.

GLOSSARY OF TERMS (CONCLUDED)

HVI	High Velocity Impact. A liquid propellant explosion occurring after a vehicle with unburned propellant impacts the earth at relatively high velocity.
Ignition Time	Time after beginning of an accident involving liquid propellants at which initiation of an explosion occurs.
Overpressure	The transient pressure exceeding the ambient pressure, manifested in the shock (or blast) wave from an explosion. The variation of the overpressure with time depends on the energy yield of the explosion and the distance from the point of burst. The peak overpressure is the maximum value of the overpressure at a given location and is generally experienced at the instant the shock (or blast) wave reaches that location.
Pseudo-critical Geometry (σ_C)	An empirical relationship for hollow-core non-solid circular shapes which is defined as four times the ratio of the cross-sectional area to total perimeter for the smallest sample size that can sustain detonation.
Safe and Arm Device (S&A)	An electro-mechanical device used to insure initiation of pyrotechnic train on proper command and to prohibit initiation of the train by an inadvertent firing signal.
Side-on Impulse	Integral of time history of side-on overpressure
Side-on Overpressure	Blast wave overpressure in an undisturbed blast wave.
Standoff Distance	Distance from center of an explosion.
Sub-critical Diameter	Diameter smaller than the critical diameter.
Super-critical Diameter	Diameter greater than the critical diameter.
Terminal Yield	Blast yield from measurements made far enough from an explosion that the waves are similar to those generated by a specified mass of TNT.

1.0 SUMMARY

The federal, state, and municipal governments regulate the transportation and storage of explosives by law. The Department of Transportation (DOT) and the Department of Defense (DOD) are the federal regulatory agencies. The DOT classification for transportation, the military classification for quantity-distance, and hazard compatibility grouping used are presented; however, the tests required to establish the hazard classification do not show this total response of a solid propellant motor under the influence of a large explosive donor. There are some industry developed tests which are possibly more relevant in determining sensitivity of propellants to an impact/shock environment in the absence of a large explosive donor and these are also discussed.

The safety procedures and requirements of a Scout launch vehicle, Western and Eastern Test Range and the Minuteman, Delta, and Poseidon Programs are reviewed and summarized. In reviewing the safety requirements and practices of these programs, it was determined that the basic hazardous situations guarded against were common to all solid rocket programs.

Hazardous environments of major concern are impact, shock, friction, radio frequency, static or stray electrical energy and excessive temperatures. Handling safety requirements are not generally based on the hazard of explosion or detonation of the solid rocket but the primary concern is premature ignition. Impact and shock environments are primarily a concern from the standpoint of damage which will cause system failure upon normal ignition. The static electricity or stray electrical energy hazard is reduced by using proper grounding of systems, personnel ground devices, terminating operations during electrical storms, reducing or eliminating RFI during launch, using safe/arm devices and other shunting and shielding techniques. Requirements of the Space Transportation System safety program include safety reviews from the subsystem level to the completed payload. The Scout safety procedures will satisfy a portion of these requirements but additional procedures need to be implemented to comply with the system safety requirements for Shuttle operation from the Eastern Test Range.

To determine the hazards associated with solid and liquid propellants due to ignition, explosion or detonation; impact, donor charge and missile accident data were reviewed. The relative safety of solid rocket motors is shown from these data. A review of component and system accidents showed that most were caused by procedural or design deficiencies. Proper attention in these two areas throughout system design provides for safe vehicle processing.

Impact velocity testing and data show that the inert-explosive/burn regions for composite and composite-modified double-base propellants are about the same but the composite-modified double-base propellant had a lower impact velocity for possible detonation than the composite

propellants. An impact velocity is excess of about 52 ft/sec (15.8 m/sec) and 59 ft/sec (17.9 m/sec) would be required for the Antares II X259 and the Altair IIIA, respectively, to cause a hazardous condition.

Data show that composite propellants are relatively safe from donor charge detonation when a sub-critical diameter, below 64.2 inches, for a PBAN composite propellant is used. However, double-base propellants and composite propellants with high energy additives in the range of 10 percent or more by weight have critical diameters of two inches or lower.

The characteristics of an explosion or detonation of solid and liquid propellant systems can be determined from the figures presented in the text. Parameters such as TNT equivalency, overpressure, fragmentation, fireball size and duration are shown.

A preliminary hazard analysis approach was used to analyze the hazardous situations of liquid and solid rocket propulsion systems and their interface with the Orbiter vehicle. The third and fourth stage solid rocket motors of the Scout launch vehicle were used as typical propulsion systems. It was determined that safety procedures, qualification tests, payload pallet design, thermal insulation, and electrical system design consideration can be used to provide hazard reduction or elimination.

Liquid systems normally contain inherent hazards in at least three areas: high pressure gas systems, ordnance devices and propellants. The main concern related to liquid systems is to provide an environment such as temperature, shock, vibration, impact or tank pressures which will prevent the fuel and oxidizer from mixing, in any form, inadvertently.

A comparison of preliminary hazard analyses of the liquid and solid propellant systems show that liquids inherently have more hazardous situations or conditions which could be catastrophic or critical to the Shuttle system than solid propellant systems. From a system's viewpoint the solid system should be considered much safer than a liquid system and more desirable for use as a Shuttle payload system.

2.0 INTRODUCTION

Liquid rocket propulsion systems have been used extensively in previous manned spaceflight programs with high success. With the advent of the Space Transportation System, many types of vehicles were and are considered candidates as payloads in this system. Shuttle payloads proposed included a number of the upper stage vehicles, such as Agena, Centaur, Transtage, Burner II and upper stages of Scout and Delta which could be used to deliver payloads to orbits beyond the Orbiter vehicle operating mode or the basic launch vehicle orbit capabilities. Most of the systems under consideration in the early 1970's utilized liquid cryogenic or storable propellant systems. Safety/hazard studies were performed on these liquid systems to determine the hazardous situations or effects that could occur by using payloads that contained liquid propellant as payloads in the Orbiter. It was determined that many safety features were required, such as inert gas purge bags, dual propellant isolation solenoid or squib valves, dual electrical systems, special design considerations for dumping propellants and special safety/operating procedures. The solid propellant safety question came to the forefront because of the inherent design simplicity of the solid propellant rocket system. In fact, the Shuttle strap on booster system was changed from a liquid to a solid propellant system in the early 70's. In view of this, the present study was undertaken to address the hazard of solid rocket motors as a payload in the Shuttle Orbiter vehicle. In this report the U. S. Customary Units are used and SI Units follow in parentheses or conversion factors are provided. This format is followed throughout except for temperature which is presented in some cases as ^{o}C.

2.1 Scope

The scope of the study was based on the interface of the Space Transportation System Orbiter vehicle and the Scout launch vehicle third stage, Antares II X259, and the fourth stage, Altair IIIA solid propellant motors. These motors are composite-modified double-base propellant, Department of Transportation Class A, Department of Defense Class 7; and composite propellant, Department of Transportation Class B, Department of Defense Class 2, respectively. Even though the Scout solid motors were used as a baseline, the study is applicable to composite and double-base rocket motors in general. Also, to enhance the study on solid propellant systems a portion of the study was delegated to liquid propellant systems.

The liquid propellant portion of the study was based on the Scout launch vehicle hydrogen peroxide (H_2O_2), monopropellant, reaction control system and the Agena unsymmetrical Dimethylhydrazine (UDMH) – high density acid (HDA), bipropellant system. The liquid study portion can also be considered applicable to liquids in general except in those cases where the type of fuel or oxidizer present a unique situation, such as the low temperatures of liquid oxygen and liquid hydrogen. In these unique situations special considerations must be addressed in order to ascertain the hazardous situations and develop resolution criteria.

2.2 Study Objectives

The study involved the consideration of five different but related subject items. These items and their objectives are:

1. Hazard Classification For Rocket Propellants – The objective was to review the solid propellant explosive classification methodology and criteria used by the Department of Transportation (DOT) and the Department of Defense (DOD) and determine if the classification is applicable to the Shuttle program solid rocket system payloads.

2. Rocket Safety Requirements and Experience – The objective was to identify hazards associated with the handling of solid rocket motors by reviewing the handling procedures and hazardous incidents of other programs.

3. Assessment Techniques–Solid and Liquid Propulsion Systems – The objective was to develop a quantitative assessment technique which would establish the threshold required to create a hazardous situation and the possible consequences of the situation. The technique was to be developed from data obtained from literature on controlled tests.

4. Preliminary Hazard Analysis of Rocket Systems for Shuttle Payload – The objective was to review the Shuttle operating environment and determine incidents which could lead to a hazardous situation when considering a solid or liquid propellant system as a payload and to evaluate and compare the hazards involving liquids and solid propulsion systems based on the shuttle flight operating modes and hazardous conditions.

3.0 HAZARD CLASSIFICATION FOR ROCKET PROPELLANTS

3.1 Introduction

Accidental ignition of combustibles or explosives can cause extensive material damage to facilities, human injury, and fatalities. Table 3-I presents data on vapor cloud explosions and gives the monetary loss in millions of dollars, as well as the number of fatalities. Damage by an explosion is caused by the heat and/or detonation effects which are caused by the tremendous release of energy which are sufficient to cause blast waves and heat radiation. Figure 3-11 shows the blast damage that occurs due to overpressure as a function of scaled distance. From this data, it can be determined that 3000 pounds of TNT gives an overpressure of about .006 psi at approximately 5 miles and represents the limit for glass breakage. Overpressure of about 0.1 psi causes about 50 percent glass breakage at 2800 feet and probable total destruction of a reinforced concrete building at 10 psi overpressure at 140 feet. If the explosive weight is reduced to 2.0 pounds of TNT and .5 psi overpressure, it can be determined that this blast effect would be noted at 95 feet. This would represent the distance and overpressure for minor structural damage. To protect life and property, safety precautions must be provided to preclude inadvertent exposure of facilities and personnel to such hazards. The method used by the governments — federal, state, municipal, for this purpose is regulation by laws.

3.2 Responsible Federal Agencies

3.2.1 Department of Transportation (DOT). — Section 833, Title 18 of the United States Code provides that:

> Any person who knowingly delivers to any carrier engaged in interstate or foreign commerce by land or water, and any person who knowingly carries on or in any car or vehicle of any description operated in the transportation of passengers or property by any carrier engaged in interstate or foreign commerce by land, any explosive, or other dangerous article, specified in or designated by the Department of Transportation pursuant to Section 834 of this chapter, under any false or deceptive marking, description, invoice, shipping order, or other declaration or any person who so delivers any such article without informing such carrier in writing of the true character thereof, at the time such delivery is made, or without plainly marking on the outside of every package containing explosives or other dangerous articles the content thereof, if such marking is required by regulations prescribed by the Department of Transportation, shall be "fined" or imprisoned, as provided in the Act.

Also Section 834 of the Act authorizes the Department of Transportation (DOT) to formulate regulations for the safe transportation of hazardous materials. The DOT regulations formulated and issued for the transportation of hazardous materials is contained in the Code of Federal Regulations — Title 49 (49CFR), reference 1. In accordance with 49CFR, no explosive (except properly packaged

TABLE 3-1. – A FEW RECENT VAPOR CLOUD EXPLOSIONS WHICH PRODUCED BLAST DAMAGE (REF. 2)

Location and state	Fuel and quantity	Delay time to ignition	Loss dollars & fatalities	TNT yield based on overpressure	Evidence for detonation	References
Berlin, N.Y. July 26, 1962	LPG 1,500 kg	Minutes	$200,000 10	Unknown	Dwelling exploded	Walls '63
Lake Charles, LA August 6, 1967	Butane Butylene 9,000 kg	Unknown	$35 M 7	9,000 to 11,000 kg (10%)	Not reported	Goforth '69
Pernis, The Netherlands Jan. 20, 1968	H.C. Slops	> 13 min.	$46 M 2	18,000 kg (–)	Fire before severe explosion	MSAPH '68* Fontein '70
Franklin Co., MO Dec. 9, 1970	Propane 30,000 kg	13 min.	$1.5 M 0	45,000 kg (10%)	Pump house destroyed by internal explosion	Burgess and Zabatakis '73 NTSB '72a†
East St. Louis, IL Dec. 22, 1972	Propylene 65,000 kg	> 5 min.	$7.6 M	1,000 to – 2,500 kg (.3%)	Box car destroyed by internal explosion	Strehlow '73a NTSB '73a
Elixbourough, England June 1, 1974	Hot Cyclohexane 50,000 kg	> 1 min.	> $100 M	18,000 to 27,000 kg (5%)	Fire before severe explosion	Kletz '75 Kinnersly '75 Slater '74
Decatur, IL July 19, 1974	Propane 65,000 kg	> 5 min.	$15 M	5,000 to 10,000 kg (2%)	Fire before explosion. Box car destroyed by internal explosion	Benner '75

* MSAPH = Ministry of Social Affairs and Public Health
† NTSB = National Transportation Safety Board

test samples) can be transported by common carrier, whether military or civilian, if it has not been classified by similarity or testing by the Department of Defense or the Bureau of Explosives and approved by DOT. Therefore, it is the responsibility of DOT to provide regulation for the proper protection of the public during transportation of hazardous materials by common carriers. Rules are formulated by the DOT Hazardous Materials Regulations Board which is composed of the Assistant Secretary of Safety and Consumer Affairs, Commandant U. S. Coast Guard, Federal Aviation Administration, Federal Highway Administration, and Federal Railroad Administration. The signature of the Board member adopting a regulation for a mode of transportation determines the applicability of that notice or rule to that mode of transportation. Where more than one mode is involved, the requisite number of authorized signatures is involved. Any person may petition the board to issue, amend, or repeal a rule. Also, a petition can be filed to obtain a special permit for a waiver or exemption from the provisions in 49CFR pertaining to explosives.

3.2.2 Department of Defense (DOD). – The Department of Defense through the activity of the Department of Defense Explosive Safety Board (DDESB or ESB) sets forth joint regulations for explosive hazard classification procedures. Specifically, their interest lies in manufacturing, testing, handling, reworking, disposal, transportation, storage, and siting to prevent hazardous conditions from occurring which could endanger life and property inside and outside DOD installations. The DDESB is composed of a chairman and a member from each of the Military Departments. It is required by DOD Directive 5154.4, reference 3, that the Secretaries of Military Departments and Directors of the Defense Agencies, or their designees, must perform evaluation and tests to assign hazard classifications for military handling, storage, group compatibility, and transportation of explosives.

The transportation classification is required to meet the DOT regulations. Hence, a complete hazards classification consists of quantity-distance class, storage compatibility group, DOT class, and DOT marking. These requirements are outlined in the DOD Document DOD4145.26M, reference 4.

3.3 Classification

In 49CFR (paragraph) 173.50, "an explosive is defined as any chemical compound, mixture, or device, the primary or common purpose of which is to function by explosion, i.e., with substantially instantaneous release of gas and heat, unless such compound, mixture, or device is otherwise specifically classified. . ." Explosives which are acceptable for transportation are classified by the DOT into three (3) classes.

(a) Class A – detonates or is of maximum hazard
(b) Class B – flammable or fire hazard
(c) Class C – minimum hazard

These three classes are aids in helping the DOT to formulate regulations for proper separation and packaging of hazardous items during freight transportation. When shippers abide by the regulations the extent of damage can be minimized in case of accident.

3.3.1 Testing. – Classification testing can be performed by either the Bureau of Explosives or DOD, 49CFR 173.86. Since the DOT accepts the testing provided by either of these agencies, it basically shows DOT recognition of the DOD Technical Bulletin, DSAR8220.1, reference 5, also known as TB700-2, NAVORDINST8020.3,TO 11A-1-47. TB700-2 specifies testing to be performed to classify bulk explosive and solid propellant compositions to meet DOT regulations and testing of assembled rocket motors for quantity-distance criteria determinations.

3.3.1.1 Bulk solid propellant: Figure 3-1 gives an outline of the tests to be performed for DOT requirements. Tests include the following:

(a) Detonation Test – A solid lead cylinder 1½-inch diameter by 4 inches high is placed upon a mild steel plate, SAE1010 to 1030, ½-inch by 12 inches. A 2-inch cube of propellant is placed on top of the lead cylinder and a No. 8 blasting cap is positioned on top centerline of the propellant cube and fired. Deformation of the lead cylinder is evidence of detonation. This test is performed a minimum of five times. If this test is positive, the Bureau of Explosives requires the impact sensitivity test.

(b) Impact Sensitivity Test – A propellant sample 0.20-inch diameter by 0.10-inch long is placed in the cup assembly of the Bureau of Explosives impact apparatus and the weight is dropped on the sample from 3-3/4 inches or 10 inches, 10 trials, respectively. The reaction is tabulated under the heading of explosion, flame and noise, decomposition, no reaction, etc.

(c) Ignition and Unconfined Burning Test – The 2-inch propellant cubes are placed 1) singularly, 2) in line in a group of four, on a bed of kerosine-soaked sawdust and the sawdust ignited with an electric match-head. The results are recorded under the headings of "exploded" or "average burning time".

(d) Thermal Stability – A 2-inch propellant cube is placed in a constant temperature explosion-proof oven. The temperature of the oven is held at 75^{o}C for a period of 48 hours. The results are recorded as explosion, ignition and change in configuration.

(e) Card Gap Test – This test is not performed by the Bureau of Explosives unless required by the user. DOD requires this test as part of TB700-2. A 6-inch square by 3/8-inch thick mild steel plate, SAE1010-1030, is supported above the ground. Resting on top of the steel plate is a cardboard tube which contains a steel, cold-drawn seamless tube, SAE1050, 1-7/8-inch-OD by 0.219-inch wall by 5¼ inches long and containing the cast propellant sample. This steel-sample tube is placed above the witness plate with an air gap of 1/16 inch. Two pentolite pellets, 2-inch diameter by 1-inch long are placed above the steel tube-sample and one engineer's special blasting cap J-2 is placed at top centerline of the pentolite pellets. The test samples and apparatus are controlled to 25^{o}C ± 5^{o}, and a firing test is performed. If the propellant sample detonates without a cellulose acetate card between it and the pentolite boosters, a series of tests are performed with a given number of cellulose acetate cards. Cellulose acetate cards 2-inches in diameter by 0.01 inch thick, are placed between the charge and test sample based on the "detonation – no detonation" situation. A series of tests are performed until the number of cards is obtained to give a 50 percent probability of detonation.

Date ____________________

Sponsoring Agency ____________________

Contract No. ____________________

Propellant Identity (Type No.) ____________________

Propellant Spec. ____________________ Batch ____________________

Mfg. Date ____________________

Detonation Test

	Exploded Yes	Exploded No	Burned Yes	Burned No	Fragmented Yes	Fragmented No
No. 8 Blasting Cap Test I	___	___	___	___	___	___
Test II	___	___	___	___	___	___
Test III	___	___	___	___	___	___
Test IV	___	___	___	___	___	___
Test V	___	___	___	___	___	___

Samples: Five 2-inch cubes. Test: One blasting cap per sample.

Ignition & Unconfined Burning Test

	Exploded Yes	Exploded No	Average Burning Time Seconds
One 2-inch cube	___	___	___
One 2-inch cube	___	___	___
Four 2-inch cubes	___	___	___

Samples: Six 2-inch cubes. Test: Ignite & burn unconfined.

Thermal Stability Test

	Explosion Yes	Explosion No	Ignition Yes	Ignition No	Change in Configuration Yes	Change in Configuration No
One 2-inch cube	___	___	___	___	___	___

Samples: One 2-inch cube Test: 48 hours at 75° C. in vented oven.

Card Gap Test 50% Value (No. of Cards)

Impact Sensitivity Test

Bureau of Explosives Impact Apparatus

Ten 3¾″ (± 1/16″) Drop Test 10 Trials			Ten 10″ (± 1/16″) Drop Test 10 Trials		
No. of Trials Exhibiting			No. of Trials Exhibiting		
Explosion Flame and Noise	Decomposition Smoke No Noise	No Reaction No Smoke No Noise	Explosion Flame and Noise	Decomposition Smoke No Noise	No Reaction No Smoke No Noise

Approved:

Test Director ____________________ Test Department Head ____________________

Assigned Classification	
ICC Forbidden	
ICC Restricted*	
ICC Class A	
ICC Class B	

DOD Approval

Signature ____________________

Title ____________________

Organization ____________________

*Shipping Instructions are to be requested from ICC (para 3–13*a*(2).

FIGURE 3-1. – SAMPLE SUMMARY DATA SHEET, TB700-2

3.3.1.2 Assembled motors: Figure 3-2 presents an outline of the minimum testing which may be performed on assembled solid rocket motors to determine the effect of an explosion on like items and mixed classes, on a remaining assembled vehicle and the firing of a destruct system relative to the individual motor and the assembled vehicle. The results of these types of tests may be used for siting flight test stands or tactical siting of assembled missiles. Limited quantity research items not used as standard military items are exempt from performing these types of tests if the DOT Class A and the appropriate military hazard class are acceptable. Generally the tests outlined in TB700-2 Chapter 3 are not performed by non-military organizations on launch vehicles.

3.3.2 Assignment of Classifications. – For DOT and military purposes, the above testing results are interpreted and classified as follows:

(a) DOT "Forbidden" if the following occurs (see also 49CFR 173.51): Thermal stability test results in either an explosion, burning, or marked decomposition of the sample.

(b) DOT Restricted. Compositions with an explosive impact sensitivity of less than 4 inches of drop height will not be shipped until shipping instructions have been requested and received from the Department of Transportation.

(c) DOT Class A – (Military Class 7) (see also 49CFR 173.53) if one or more of the following occur:

1. Detonation and card gap tests have determined a detonation sensitivity value of 70 or more cards.
2. Impact sensitivity test produces an explosion above 4-inches of drop height.
3. Ignition and unconfined burning test produces a detonation.

(d) DOT Class B – (Military Class 2) (see also 49CFR 173.88) if all of the following occur:

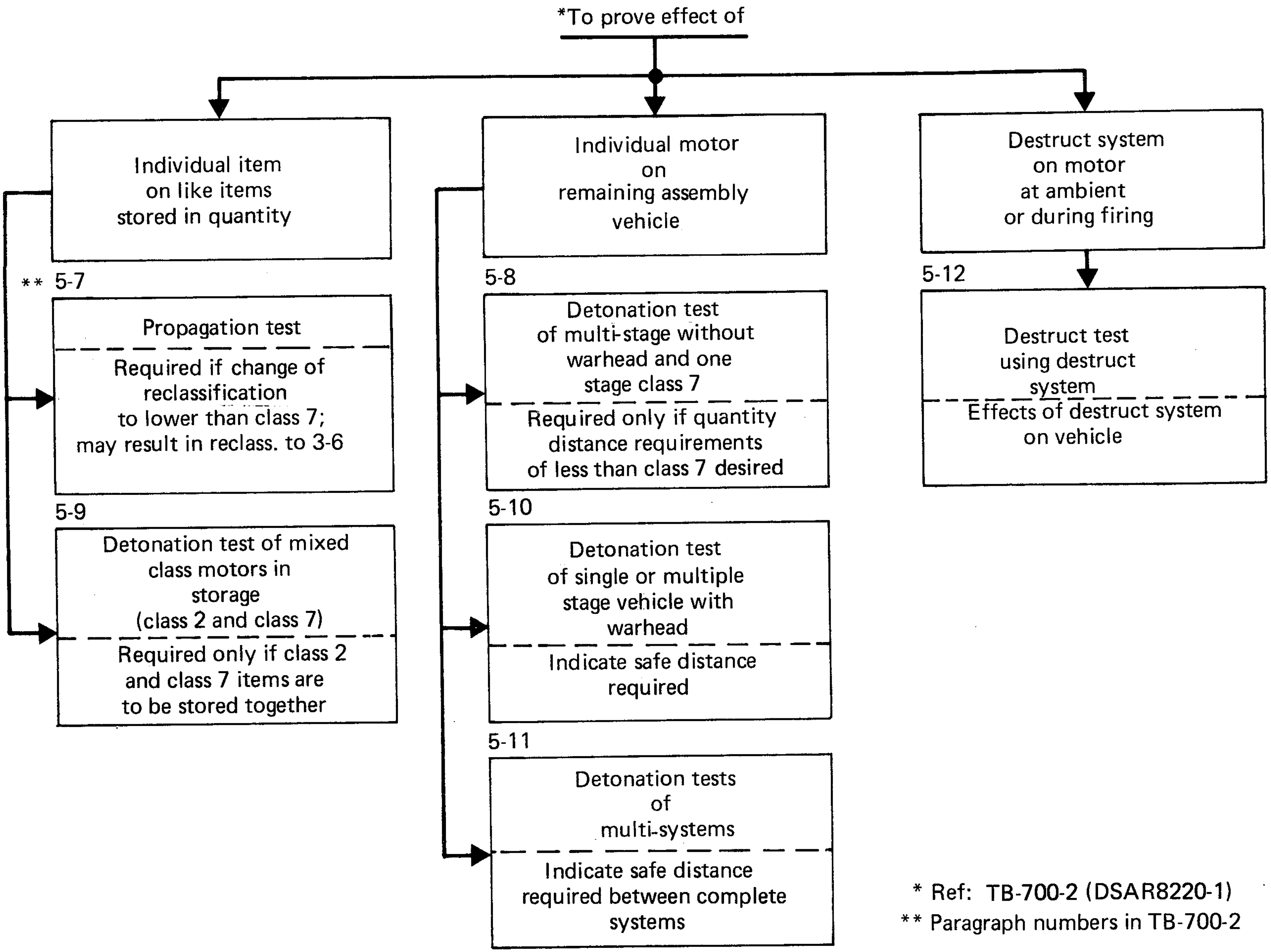
1. The ignition and unconfined burning test did not result in an explosion.
2. The Thermal Stability Test did not result in an explosion, burning, or marked decomposition.
3. Detonation and card gap tests have indicated a detonation sensitivity value of less than 70 cards or no reaction at zero cards.

(e) DOT Class C – (Military Class 1) – Those explosives not in the above Class (A) or (B) and considered a minimum hazard.

3.3.3 Quantity-Distance Standards. – As shown in paragraph 3.3.2, when a propellant is classified for DOT transportation requirements, a DOD military class is also assigned by correlation for quantity-distance purposes. DOD 4145.26M, reference 4, Part 7 outlines the DOD standards for quantity-distance storage of solids type explosives and Part 8 covers liquid propellants.

3.3.3.1 Solid propellant classes: The DOD classes for solid propellants are described as follows:

(a) Class 1 (Fire Hazards) are "Items which present a high fire hazard with no blast hazard and virtually no fragmentation or toxic hazard beyond the fire hazard clearance ordinarily specified for high-risk material." Items in this class consist of



* Ref: TB-700-2 (DSAR8220-1)
** Paragraph numbers in TB-700-2

FIGURE 3-2. – MINIMUM TEST CRITERIA FOR DOD ROCKET MOTORS OR DEVICES CONTAINING SOLID PROPELLANT

small arms ammunition without explosive projectiles, fuse lighters and squibs.

(b) Class 2 (Fire Hazards) are "Items which burn vigorously with little or no possibility of extinguishment in storage situations. Explosions normally will be confined to pressure ruptures of containers and will not produce propagating shock waves or damaging blast pressure beyond the magazine distances . . .". Items in this class are military pyrotechnics, solid propellants in bulk and in containers (composite propellants such as used in the Scout launch vehicle Castor II rocket motor are Class 2).

(c) Class 3, 4, 5 and 6 (Combined Hazards) are items "which the principal hazards may be fragments, toxicity, or blast, either individually or in combination. . .". Items in this class are small arms ammunition with explosive bullets and hand grenades. These classes are not of interest for the Scout vehicle.

(d) Class 7 (Mass Detonating Hazards) are items "most of the entire quantity of which will explode virtually instantaneously when a portion is subject to fire, to severe concussion or impact, to the impulse of an initiating agent, or to the effect of a considerable discharge of energy from without". Items in this class are bombs, detonators, demolition explosives, missile war-heads, rockets and components having mass-detonating characteristics. Rocket motors, such as the Antares X-259, which contain double base propellants are considered in this class.

There are other military classes rated higher than 7 by the different military branches but are of no interest for this study.

3.3.3.2 Liquid propellant classes: Liquid propellants also constitute types and degrees of hazards and are separated into hazard groups and storage compatibility for quantity-distance storage rather than the class separation of solids. These hazard groups are as follows:

(a) Group I are liquids which are considered the least hazardous. There is a fire hazard potential and some degree of separation distance is required. Items such as alcohols, hydrocarbon fuels and nitrogen tetroxide are in this group.

(b) Group II are liquids which are strong oxidizers and cause vigorous oxidation which results in serious fires. Items such as 52% hydrogen peroxide, liquid fluorine, liquid oxygen and oxygen difluoride are in this group.

(c) Group III are liquids which present a hazard from pressure rupture of the storage container because of fire or deflagration, and vapor phase explosions which result in fragmentation of container or adjacent material. Items such as hydrazine, hydrazine-UDMH, liquid hydrogen and monomethylhydrazine are in this group.

(d) Group IV are liquids which, like the mass-detonating solid explosives, cause blast overpressures as well as severe fragment hazards from containers and surrounding material. Items such as nitromethane and tetranitromethane are in this group and under certain conditions 52% hydrogen peroxide is included in this group.

It is of interest to note at this time that the Space Transportation System uses a Class II solid propellant for the two (2) main boosters and liquid oxygen (Group II) and liquid hydrogen (Group III) for the main liquid boost propulsion system. The Orbiter reaction control system uses monomethylhydrazine (Group III) as the fuel and nitrogen tetroxide (Group I) as the oxidizer. The Scout vehicle contains Class 2 and 7 solid propellant rocket booster motors and 90% hydrogen peroxide (Group II or Group IV) liquid propellant in the reaction control system.

3.3.4 Compatibility Groups. – Solid and liquid propellants are both separated into compatibility groups using an alphabetical title, such as, Group A, Group B, etc. Even though both types of propellant use the same grouping title they are not comparable. The purpose of the classification is to separate the different explosives into groups which can safely be stored together. Additional and specific information should be obtained from reference 4 or the appropriate volumes of manual CPIA/194, reference 6.

3.4 Validity of Classifications

The Department of Defense Explosive Safety Board, the Department of Transportation and the Bureau of Explosives were contacted to discuss the testing requirements for the classification of rocket propellants as explosives. The consensus received from these contacts is that the testing required for transportation classification and the established quantity-distance requirements with the grouping for compatibility storage has performed and still performs satisfactorily to protect public and private property. The tests required provide an indicator of what to expect of large batches of propellants under various environments as a minimum. Those showing unsatisfactory results are forbidden or restricted. However, the DDESB is a proponent for the utilization of the card gap test on all explosives tested so that relative sensitivity can be determined. The Bureau of Explosives does not require the card gap test and does not require the impact sensitivity test unless positive response is obtained on the detonation test.

Some in industry, reference 7, do not believe that the mandatory tests of TB700-2 are totally relevant and that as the ingredients of Class 2 propellants are modified with high energy ingredients to increase performance the characteristics of a Class 7 propellant are soon reached. It is recommended in reference 7 that relevant tests must be used to determine the proper hazard classification. Three tests indicated to have been used during the last decade and determined to be relevant are the Shotgun, Susan and Flying Plate tests. Characteristics of these tests are as follows:

(a) Shotgun Test – A sample of propellant is fired from a shotgun against a flat plate with a velocity between 100 and 2700 feet per second. There are at least two areas where data can be obtained from this type testing. The first data represents the velocity at which ignition of the sample occurs upon impact and then the higher velocity where detonation occurs. A series of tests can be performed on various types of compositions or propellants at the same critical dimension to obtain an impact velocity map. Results of various full scale tests (ref. paragraph 5.3.1) can also be located on the velocity-critical dimension plot to show the scaling from sub-scale to full-scale tests. The second data is obtained from the propellant particles. The propellant particles obtained from impacts below the ignition threshold are placed into a pressure bomb and ignited. The pressure rise vs time is measured. The measured response is rated to level of quickness (psi per sec). This test is designed to indicate quickness between different propellant types or compositions if the propellant shatters upon impact and an initiation stimulus is received at the same time. The greater the quickness, the greater the susceptibility to detonation.

(b) Susan Test – A propellant sample of one pound or less is mounted in the front surface of a 10-12 pound projectile and fired from a converted naval gun at velocities from 100 to 1200 fps onto a solid steel target. The blast overpressure, emitted light and the time between impact and blast wave observation are measured. An energy of reaction is determined and noted on a scale up to 100 as a function of impact velocity. This test is designed to assess the relative behavior (sensitivity) of the propellant to impacts during operation usage. The energy of reaction can be plotted as a function of impact velocity. Hercules, Magna, Utah,has found that this test is not very useful in separating the various propellants but it does help separate the propellants from the high explosives such as TNT and RDX.

(c) Flying Plate Tests – A flat plate is propelled at samples of propellant. Based on the thickness of the flat plate the weight and velocity of the plate can be varied. In this method the pulse width of the shock pressure imparted to the propellant sample can be varied. Knowing the flying-plate velocity, the shock pressure generated on impact at the plate-propellant interface can be determined by the Hugonist reflection method.

3.5 Conclusion

Solid and liquid propellant motors in the passive state contain a large amount of potential energy. The release of this energy in an uncontrolled situation can cause extensive damage to facilities and personnel. The federal, state and municipal governments regulate the transportation and storage of explosives by laws. The Department of Transportation (DOT) and the Department of Defense (DOD) are the federal regulatory agencies. They require that explosives be tested for hazard classification. The testing is performed by the Bureau of Explosives or the Department of Defense. The hazard testing requirements for solid explosives (propellants) for both civilian and military applications are basically outlined in DOD Technical Bulletin, DSAR8220.1. The liquid explosives (propellants) are also tested in similar fashion for hazard classification.

The DOT classification for transportation, the military classification for quantity-distance and the hazard compatibility grouping used at present are believed to be satisfactory for the purpose intended. However, these tests do not show the total response of a complete, assembled solid propellant rocket or vehicle on the launch pad under the influence of a large explosive donor, motor dropping during build-up and a fallback during launch.

In the last few years industry has used some additional tests which they feel are more relevant in determining sensitivity of propellants to an impact/shock environment in the absence of the huge donor explosion. These tests are the shotgun, susan and flying plate. The other alternatives are full scale drop tests of the actual motors to be considered for use and testing for shock sensitivity with large donor explosions. Further characterization of solid propellant rockets should require full scale temperature sensitivity testing similar to methods outlined in Appendix B.

4.0 ROCKET SAFETY REQUIREMENTS AND EXPERIENCE

4.1 Introduction

Safety is of primary concern when using any component which has high potential energy that can be readily transformed to kinetic and thermal energy. A solid or liquid propellant rocket system contains all the required constituents to sustain a combustion process and under certain conditions a fire, explosion/deflagration or detonation can occur. The inadvertent release of this energy in either a controlled or uncontrolled mode can cause severe personnel injury or death and extensive damage to facilities. Government and industry have developed safety principles over the years through the process of decision-making based on scientific data and industry practice with system feedback for safety criteria modification. This method has provided a data base to the extent that well characterized propellant formulations can be used extensively and safely. With the advent of the anticipated utilization of solid propellant rockets as a subsystem of a payload to be carried into orbit by the manned space Shuttle-Orbiter vehicle, safety of solid propellants in the shuttle environment was a logical consideration. A natural approach to this consideration is to review the safety and handling procedures of various existing programs and to collect historical hazardous situations or incidents that have occured. This information can be used in comparison with the Scout launch vehicle safety criteria and procedures to determine if present Scout requirements could result in a hazardous situation. The results of this effort are presented in this section of the report.

4.2 Safety Procedures

4.2.1 Scout. — The Scout launch vehicle processing and safety requirements are controlled through the Standard Operating Procedure (SOP) manual. However, as outlined in SOP Volume III, Section 1, Rocket motors and Pyrotechnics Manual, the detailed safety precautions such as smoking restrictions and open flame regulations are not covered by the SOP; but the range safety requirements prescribed at each range site rule. Basic ordnance operation safety requirements which are adhered to are as follows:

(a) Maximum of five (5) persons are present during live motor processing.
(b) Personnel wear safety clothing.
(c) Personnel use only approved tools and equipment.
(d) Operations are terminated when electrical storms are within area.
(e) Proper grounding is used at all times, especially during open propellant rocket motor processing or when the initiators and igniters are installed.
(f) Initiator pins or wires shorted with approved shorting devices.
(g) Equipment maintenance performed per requirements.
(h) Cautious handling of explosives to prevent dropping.
(i) Transporting and storage of rocket motors is according to Department of Transportation classification and storage is per quantity distance standards, as they are applicable to the site Range Safety.
(j) Rocket motors are stored within certain temperature limits.

Basic hydrogen peroxide safety requirements which are adhered to are as follows:

(a) A large quantity of water is available during handling of H_2O_2 and spillage is flushed at once.
(b) Use of buddy system during H_2O_2 drainage, transfer and sampling operations, with one man assigned to the water source.
(c) Protective clothing is worn to prevent clothing fires.
(d) All lines and fittings, which have contained H_2O_2, are flushed with water before handling and repair and subsequent repassivation performed.
(e) All materials combustible with H_2O_2 are kept away from handling and storage areas except as required.
(f) All open systems are protected from contamination by compatible plugs or covers.
(g) All equipment and containers used with H_2O_2 are clean and passivated.
(h) All pressurization nitrogen used with H_2O_2 is dry, filtered, and oil free.
(i) Storage containers are inspected periodically for signs of leakage and activity. Steps to control activity are taken at once.
(j) Good ventilation is maintained in storage areas.
(k) Protective face shields are used during H_2O_2 handling.
(l) Vapor inhalation is cautioned against.

Within the context of the SOP, notes, cautions and warnings are outlined as necessary before given tasks. "Notes" specify to the operators that special care must be taken so that a task will be performed properly. The "Caution" note specifies to the operators that damage to the equipment may result if procedures are not followed. The "Warning" note is the most important from a hazard viewpoint because it specifies to the operators that procedural error can cause loss of life or serious personnel injury.

SAMTEC 127-1, reference 8, Range Safety Manual, outlines the safety considerations for Systems Analysis, Flight Analysis, Pad Safety and Flight Operations. The SAMTEC ordnance safety requirement is summarized as follows:

> The accomplishment of work involving ordnance materials, missile fuels and oxidizers, high pressures, and nuclear components, will be in accordance with approved detailed procedures. Chronology will be maintained and departures from the approved procedures will not be allowed without approval for the variance. The agency responsible for performing the hazardous work will prepare the required detailed procedures for the work and secure SAMTEC/SE approval prior to work accomplishment.

The approved detail procedures take into consideration the contents of 1STRADM 127-200, reference 9, Missile Mishap Prevention; AFM 127-100, reference 10, Explosive Safety Manual; AFM 127-101, reference 11 Accident Prevention Handbook.

The Vought field operations are conducted under the "NASA/DOD Scout Launch Complex Safety Plan". This Safety Plan is approved by Vought Safety; Vought Launch Operations; USAF Chief, Scout Division 6595th STG and SAMTEC Missile Ground Safety. The Plan requires compliance with the above referenced documents, as well as other referenced applicable Government documents issued by the Department of Defense, Department of Transportation, Occupational Safety and Health Act, NASA Safety and Health Clause. The Plan also specifies that the Scout Field Supervisory Personnel will be responsible for carrying out the duties of the Task Supervisor as outlined in 1STRADM 127-200, Chapter 7, which states:

> "While the requirements contained in this manual are primarily designed for hazardous/dangerous operations, the basic safety philosophy applies for all operations conducted at Vandenberg. IF YOU ARE THE TASK SUPERVISOR, YOU MUST INSURE THAT ALL SAFETY REQUIREMENTS ARE MET."

In fulfilling this required duty, there are ten basic tasks that must be performed. These are summarized as follows:

1. Activate control area using barriers and warning devices.
2. Remove non-essential personnel from the control area.
3. Pre-task briefing of special procedures.
4. Verify that communication, safety devices, safety equipment, hazard detection devices, etc., are available and operable.
5. Verify that all support personnel are standing by and that the support is maintained during hazardous operation.

6. Maintain strict compliance with all safety criteria, procedures, checklists as required during the task. This includes clothing and equipment.
7. Verify that the work area housekeeping is in order.
8. Verify personnel have knowledge of specific procedures which are required if a mishap occurs.
9. Announce the start/stop of operations and the proper release of all support personnel.
10. Call a "Hold" or "No Go" if conditions exist that are unsafe.

Scout procedures and safety requirements have provided for a highly safe and successful program over the past 16 years. These same procedures and safety requirements, modified to meet the Space Transportation System (STS) Program requirements and the Eastern Test Range requirements should perform satisfactorily when using the Scout vehicle as a payload on the STS.

4.2.2 Minuteman (MM). – The Boeing facility at Hill AFB, Ogden, Utah, was visited to review the procedures used during processing of the three MM solid rocket motors which are DOT Class B, Military Class 2. The safety procedures, such as caution and warning notes, are an integral part of the Boeing procedural type documents. Since the solid rocket motors are delivered fully assembled, e.g., nozzle and igniter installed, guidance propulsion system installed, safe/arm and arm devices installed, the safety requirements are minimal except in cases where open grain conditions may be required. A document which compliments the procedural document is the Integrated Record System Operation (IRSO) document which is the quality type check-off of the procedural steps.

The main procedural safety consideration is the system "ground" which must be installed at all times and interconnected between the transporter motor-cradle and assembly building rail. Other safety requirements take into consideration the proper setting of transporter brakes, maximum wind allowable for motor transfer and temperature limits. Additional standard ordnance safety precautions are taken when the ordnance type items are installed in the transition sections. These requirements are grounding of components, conductive work surfaces, leg and wrist stats and limited numbers of personnel in the facility during hazardous operations. All electrical checks of the vehicle systems are performed remotely from a blockhouse which is integral with the assembly building.

Facility safety items include quick release escape doors, soft panel escape walls and a large impaler. The impaler is located at the forward dome end of the third stage motor. If the motors are inadvertently ignited the impaler will penetrate the third stage motor and destroy the forward propulsive capability. This system was tested during the early stages of the program to demonstrate safety, reference 12.

The Scout safety requirements must be more severe than those for the Minuteman program because of an open propellant grain condition when the solid rocket igniters and the Antares II nozzle are installed. Otherwise, the Minuteman impaler GSE was the only safety device utilized which is of basic difference from the Scout system. MM test flight operations are performed under the basic Air Force documents (SAMTECM 127-1, Range Safety Manual), reference 8, and Launch Complex Safety Operating Procedures, reference 13, used at Vandenberg AFB (VAFB) on the

Scout program. When a MM vehicle is launched from VAFB, the Minuteman System Safety outlined in 1STRADM 127-200, Amendment 1, reference 9, is applicable. These requirements are of similar nature to the Scout launch vehicle requirements which were discussed in paragraph 4.2.1.

4.2.3 Delta Program. – The Delta launch vehicle is launched from the Western and Eastern Test Ranges. The Solid Rocket Field Handling Manual, reference 14, and Launch Preparation Document, reference 15, for the spacecraft solid rocket, TE-M-364-4, were reviewed for safety considerations.

4.2.3.1 Receiving and inspection: The Field Handling Receiving and Inspection Document, reference 14, is used at the launch site for receiving and inspection. This document was prepared by the manufacturer, Thiokol Corp., Elkton Division and it contains in Section 3.0 a safety summary. This summary specifies that the composite propellant solid rocket motor is Department of Transportation, Class B and military class 2. It is noted that there are basically three areas where hazardous conditions can exist during handling, storage, and inspection of the TE-M-364-4 rocket motor. These areas are generally common to all solid rocket motors and are as follows: (1) thin sections of propellant which are friction and impact sensitive, (2) propellant temperature sensitivity and (3) induced static electricity or stray current.

The basic composite propellant system is classified non-detonatable and insensitive to shock; however, thin sections of propellant are sensitive to friction and impact. This is especially true around areas with threaded surfaces such as the igniter port threads.

It is stated that the most likely cause of an accidental ignition is exposure to temperatures in excess of 250°F. Instantaneous auto-ignition is said to occur at temperatures above 500°F but propellant decomposition and subsequent auto-ignition may occur at lower temperatures.

To prevent static electricity around the motor special precautions are taken to have the system always grounded to the surroundings. To prevent stray electrical current in the pyrogen initiators, shorting plugs are used, and to prevent inadvertent ignition of the pyrogen from the initiators, a safe/arm unit is utilized. The safe/arm unit is the only safety feature used on this rocket motor which is different from Scout.

4.2.3.2 Launch preparation document: The Launch Preparation Document, reference 15, is a typical document used by McDonnell Douglas for spacecraft upper stage buildup and erection. This document is similar to the standard operating procedures used on the Scout program. The procedure is prepared to meet the range requirements as outlined in AFETRM 127-1, reference 16, and KMI 1710.1B/SF, reference 17, and are supplemented by program safety manuals and plans. Task 3 of the Launch Preparation Document covers the third stage motor receiving inspection and leak check before vehicle assembly. In this task a safety requirements checklist, Figure 4-1 is provided to clearly make known the unsafe conditions which occur during the processing per Task 3. The exterior of the procedure package and the applicable tasks are noted on the first page with a note notifying the operator that the procedure or task contains hazardous operations. The task also contains a list of safety requirements such as safety hazards, safety equipment, and safety rules/regulations. Step 1 of Task 3 is safety verification. The check-off is to verify that all safety rules and

SAFETY REQUIREMENTS CHECKLIST			
CONDITIONS	CONDITIONS EXIST		SAFETY REQUIREMENTS REFERENCES & REMARKS
	NO	YES	
OXYGEN RICH ATMOSPHERE	X		
GASEOUS OXYGEN OPERATIONS	X		
LIQUID OXYGEN OPERATIONS	X		
HANDLING LH_2 LN_2 FLUORINE OR OTHER HAZARDOUS GASES OR LIQUIDS	X		
EXPLOSIVE DEVICES–HANDLING, INSTALLING, CONNECTING, ETC	X		
CENTRIFUGE TESTING–HIGH SPEED, LIVE GRAIN, BIO-TECH (HUMAN)	X		
ENTERING HI/LO TEMPERATURE CHAMBERS (FOR INSPECTION, ETC.)	X		
HIGH OR LOW PRESSURES (HYDRAULIC PNEUMATIC SYS, BURST TESTS, ETC.)		X	2250 PSIG GN2
POTENTIAL CORONA OR ARC–OVER IN COMBUSTIBLE AREA OR ATMOSPHERE	X		
POTENTIAL VOLTAGE OR CURRENT HAZARDS	X		
PROPELLANTS		X	SOLID PROPELLANT MOTOR
NUCLEAR RADIATION MATERIALS OR EQUIPMENT	X		
TOXIC OR FLAMMABLE	X		
ELECTROSTATIC HAZARDS	X		
ELECTROMAGNETIC OR RF RADIATION	X		
OTHER		X	THIRD STAGE MOTOR
NOTE: NO HAZARDOUS CONDITIONS EXCEPT THOSE SPECIFIED ABOVE WILL EXIST IN THIS TEST ACTIVITY.			

SAFETY MONITOR RECORD

SIGNATURE OF MONITORING SAFETY ENGINEER ______________________ DATE ________

SAFETY MONITOR'S SIGNATURE ______________________ DATE ________

DELEGATION AUTHORIZED BY ______________________ DATE ________

LAUNCH OPERATIONS ______________________ DATE ________

FIGURE 4-1. – SAFETY REQUIREMENTS CHECKLIST regulations have been complied with before beginning work on the subsequent steps. Warning and caution notes are used throughout the procedure to gain the attention of the operator. The basic safety considerations utilized in the handling of the motor are the assurance of a good ground of all parts during phases of processing, prevention of static electricity from individuals and protection against dropping or impacting the motor. Generally the safety precautions utilized by the Scout program are similar to the Delta program. However, the format and requirements in the Delta procedures appear to match the requirement in reference 16, where the Scout procedures are designed to meet the Western Test Range requirements.

4.2.4 Poseidon Program. – The Poseidon first stage solid propellant motor is a DOT Class B, Military Class 2, and the second stage solid propellant motor is a DOT Class A, Military Class 7. The solid rocket motors are delivered with the nozzle and igniter installed and open grain configuration is present only during internal pressure checks or during unusual operations that require removal of the igniter or nozzle. Since electrical squibs are not installed in the type igniter utilized, there is minimum hazard from inadvertent igniter activation throughout processing.

The program uses basically two types of procedures for processing the solid rockets, Ordnance Procedures and Processing Work Segments; however, there are Ordnance Data Procedures used at dock side and in the fleet. The Ordnance Procedures (OP), such as NAVORD OP 3667 consist of Processing Work Sections. These sections contain all the detail procedures, cautions, warnings and notes which are required to perform a given task on all types of various components which also includes items other than ordnance. These OPs are used to train personnel in all tasks and safety requirements for vehicle processing. The Processing Work Segments (PWS) are written to process the vehicle in task segments. These PWSs are written from the information in the OPs but in a manner which requires that the technician be knowledgeable and well-trained in the Processing Work Section of the OPs. However, the PWSs include warnings, cautions and notes to draw attention to various areas of tasks being performed. The PWSs are also written to show that the technician has task buy-off requirements and also the inspector has audit and buy-off requirements. A good feature of this system is the requirement for a roving inspector. This inspector checks at random the completed work task as well as the Processing Completion Report which is the quality type check-off of the procedural steps.

The main procedural safety consideration is the system 'ground' which is installed at all times during transportation, storage, receiving and processing. Other safety features include conductive floors in processing area, leg and wrist stats, soft roof panels, safety warning circuit on the door latches leading to the radiographic inspection room, insulation links in cranes or hoists to prevent RFI and EMI transfer, limitation to a single hazard operation in an area at a given time and limited number of personnel present during a hazardous operation. Additionally a good quality assurance program is used to provide for regular inspection of test equipment, cranes and hoists.

In comparison with the Scout system, the main difference in the processing lies in the procedures. The Poseidon program has the Processing Work Sections and Processing Work Segments. The Scout program uses Standard Operating Procedures which combine the two documents of the Poseidon program. It should be noted that the Poseidon program is in the process of changing to the single procedure approach; however, no accidents have occurred to cause this change. Also, the Poseidon program uses pink colored inserts to promote attention to recent procedure changes.

4.2.5 Eastern Test Range Requirements. – Cape Kennedy Air Force Station (CKAFS) has contained within its confines the launch complexes, explosive safe areas, and missile and spacecraft assembly and checkout buildings. Therefore, the Air Force has the responsibility for the overall safety operations and has established safety requirements to be followed at CKAFS. The safety of NASA operations at the range is ultimately the responsibility of the Director, Kennedy Space Center (KSC). Safety policies and regulations governing launch operations have been established by KSC. However, NASA operations in AFETR areas are performed in compliance with the AFETR safety regulations. Hazardous operations at the range must have prior approval from the KSC and AFETR safety groups. The basic restraining regulations which the launch vehicle configuration and operations must meet at the KSC or AFETR are the following, respectively: (a) KSC Safety Program with Attachments, KSC General Safety Plan, KMI 1710 1B/SF, reference 17; (b) Range Safety Manual, AFETR Manual (AFETRM) 127-1, reference 16.

4.2.5.1 AFETRM 127-1 Safety requirements: In this document it is specified that all hazardous missile/space vehicle systems must be designed, tested, operated and approved in accordance with requirements set forth in chapters 3 and 5. Chapter 3 outlines the prelaunch and abort operations and the required Range approvals. Chapter 5 outlines the missile operations requirements that are imposed on the Range User by Range Safety. These two chapters are the most important from the standpoint of hazardous operations of solid rocket motors, liquid propellants, pressurized systems and ordnance items.

4.2.5.1.1 AFETRM 127-1 Chapter 3 – A Missile Systems Prelaunch Safety Approval (MSPSA) document is required before any hazardous missile/space vehicle operations are performed at the AFETR. Formal approval for operations will not be given until the Missile System Prelaunch Safety Package is approved. This safety package must contain specified data on propulsion, pressurization, ordnance, toxic materials, electrical and when used, radioactive materials. When this data on hazardous systems has been presented and approved by the required launch site Safety organizations, vehicle and equipment components and their interfaces with other systems will not be modified without prior approval by the Missile Safety Branch, AFETR Safety Office (AFETR/SEN). All changes to approved hazardous procedures also require prior approval by AFETR/SEN.

System safety per MIL-STD-882, reference 18, is mandatory for all departments and agencies of the Department of Defense. This document outlines the concept and defines the System Safety as "the optimum degree of safety within the constraints of operational effectiveness, time and cost, attained through specific application of system safety management and engineering principles throughout all phases of a system's life cycle." This MIL-STD-882 approach to system safety is recommended to non-military users. Preliminary hazard analyses of the system are performed to identify hazards and inherent risks. This subject is discussed further in Section 6.0 Preliminary Hazard Analysis of Rocket Systems for Shuttle Payload.

System design and requirements must be considered in any acceptable System Safety Plan. The referenced document should be reviewed for further details on this subject.

4.2.5.1.2 AFETRM 127-1 Chapter 5 – Operation requirements are levied on the Range User by Range Safety. Specifically included in the requirements are hazardous operations procedures. Those operations which are classified hazardous pertain to such items as ordnance materials, missile propellants and pressures over 500 psi. Procedures for hazardous operations must be written in a clear and concise manner so that people will understand them in the clearest and most logical manner in order that each step will be performed safely. The following information is required in all operating procedures:

(a) Title page with all approval signatures and dates
(b) The purpose with brief discussions of the task, operation, test or checkout and normal schedule in relation to launch
(c) A short warning or caution note must identify the hazardous item, material and/ or operation. A specific note must appear before the hazardous operation and general caution and/or warning notes must be included in the preface. Hazardous configuration of the system before and after the operation must be defined
(d) Listing of reference documents
(e) A list of required tools
(f) The location where the operation or the system is to be performed and the location of the system at all times
(g) A listing by title of the required personnel for operations
(h) Pad Safety witness requirements must be stated in preface.

Once again the detailed safety requirements to be adhered to during hazardous operations are numerous. Further information on these requirements can be found in the reference document.

4.2.5.2 KMI 1718.1B/SF KSC General Safety Plan: This document provides guidelines and assigns the responsibilities for the implementation of the Kennedy Space Center Safety Program and Safety Plan. Major safety problem areas are defined and the controls, procedures and plans are specified to minimize safety hazards. The KSC Safety Program requires the following items to be performed:

(a) Develop greater safety controls, procedures, and standards for specific areas
(b) Develop safety operating procedures to be utilized by operational personnel in hazardous operations
(c) Develop safety standards and criteria for the design and fabrication of equipment and facilities
(d) Develop accident investigation and reporting procedures
(e) Evaluate accidents and injuries for cause

(f) Plan, train and promote activities to improve the level of safety performance
(g) Create safety committees to insure the most technically qualified personnel will evaluate hazards and recommend corrective action.

Attachment A to KMI 1710.1B/SF provides the specifics of the KSC General Safety Plan, and NASA contractors must follow the requirements of this document when operating at the Range. However, for this study several chapters are of special interest since they pertain to hazardous operations as follows:

(a) Chapter 4 — Propellant Safety
(b) Chapter 5 — Ordnance and Explosive Safety
(c) Chapter 6 — Pressure Systems
(d) Chapter 8 — Operation Safety

The one common factor underlying the safety operations in each of these chapters is the preparation and enforcement of explicit safety procedures. This is further stated in Chapter 8 as follows:

> Detailed operating procedures will be used for both hazardous and non-hazardous operations. Adequate procedures promote safety by ensuring that operations are performed completely and in a planned sequence. Operating procedures will be processed in accordance with KMI 1710.13.

KMI 1710.13, reference 19, defines Technical Operating Procedure (TOP) as any document which identifies/authorizes work to be done and provides detailed instructions for its accomplishment. TOP's are divided into Category I or II depending upon the type of operation to be performed as follows:

> <u>Category I TOPs</u>: Documents which provide detailed instructions for verifying functional operation of Ground Support Equipment (GSE) and procedures which provide detailed instructions for operational checkout, servicing, handling, and transporting space vehicle or space vehicle components during prelaunch and launch operations. Repetitive hazardous and nonhazardous operations use Category I TOPs. Test and Checkout Procedures (TCPs) are examples of Category I TOPs.

> <u>Category II TOPs</u>: Documents which authorize work, provide engineering instructions, establish a method of work control. This type procedure is usually written for a "one-time" operation to perform special tests or authorize temporary installations, removals, or replacements. It may be used for "one-time" hazardous operations and for repetitive nonhazardous tasks when the work is of a limited scope which does not economically justify preparation of a Category I TOP.

Each hazardous Category I TOP will include a safety requirement section that meets the following criteria:

1. The specific hazard in the procedure must be identified
2. Required safety equipment for each hazard must be identified
3. Safety rules and regulations unique for each hazardous operation must be specified.

Each Category I TOP which contains hazardous operations must be identified on the front cover with red letters at least 3/16" high as follows:

"THIS PROCEDURE CONTAINS HAZARDOUS OPERATIONS"

Each sequence, paragraph or section will be identified by either (a) Letter 'H' in margin; (b) Stripe through hazardous portions or (c) Warning or caution notes preceding any hazardous operational step. Category II TOPs must be identified by a statement, "THIS (IS) (IS NOT) A HAZARDOUS PROCEDURE" with the approving organization signature and date. The processing channels for Category I and II TOPs, except unmanned launch operation (ULO) TOPs, will be processed as shown in Figures 4-2 and 4-3. TOPs for unmanned launch operations (ULO) submit procedures for approval through a member of the Safety Office Staff Representative (SOSR). The member is co-located with the ULO. The Scout Program is a ULO and the standard operating procedures now in use were not required to be processed through the manned launch operation channels at AFETR or KSC Safety Office.

4.2.6 Space Transportation System (STS)

4.2.6.1 Introduction: NASA Johnson Space Center (JSC) has prepared a safety document, Safety Policy and Requirements for Payloads Using the National Space Transportation System, reference 20, whose aim is to establish a set of minimum safety requirements for payload developers. These safety requirements aid in determining if the payload is safe to carry on the STS but yet permits flexibility in the verification options and levels. The safety policy for the STS user should contain those requirements that will logically protect flight and ground personnel, the public property, environment, elements of the STS and one payload from another.

4.2.6.2 Safety requirements: The basic safety requirements that are required in a payload user's program and for technical design considerations are as follows:

(a) Hazard Analysis
(b) Hazard Classification Levels
(c) Hazard Reduction Procedure and Hazard Control Actions
(d) Safety Assessment Reviews
(e) Safety Compliance Data Packages
(f) Accident/Incident/Mission Failure Investigation and Reporting
(g) Radioactive Systems Data
(h) Design and Operational Requirements

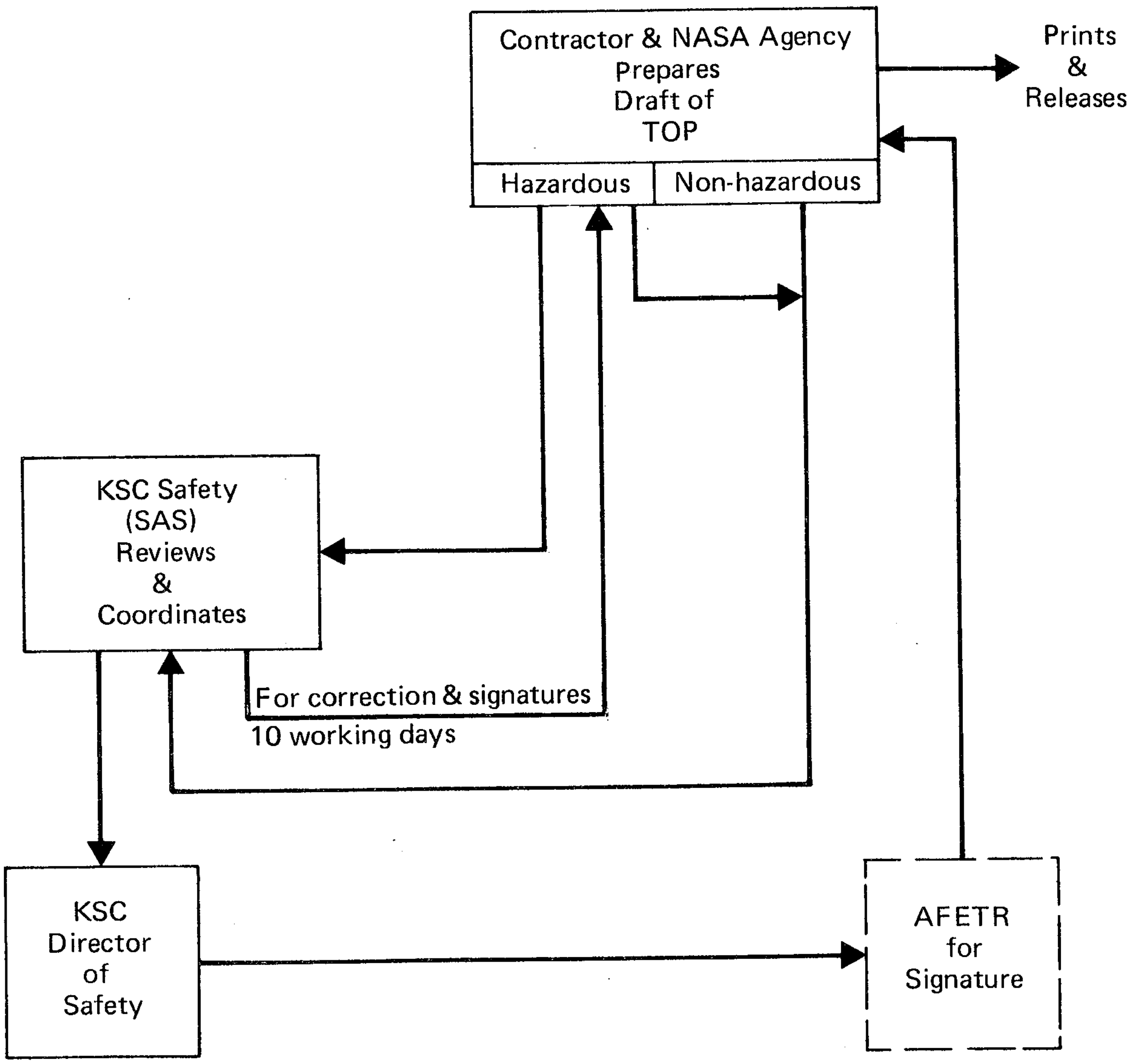


FIGURE 4-2. – CATEGORY I TOP SAFETY REVIEW PLAN

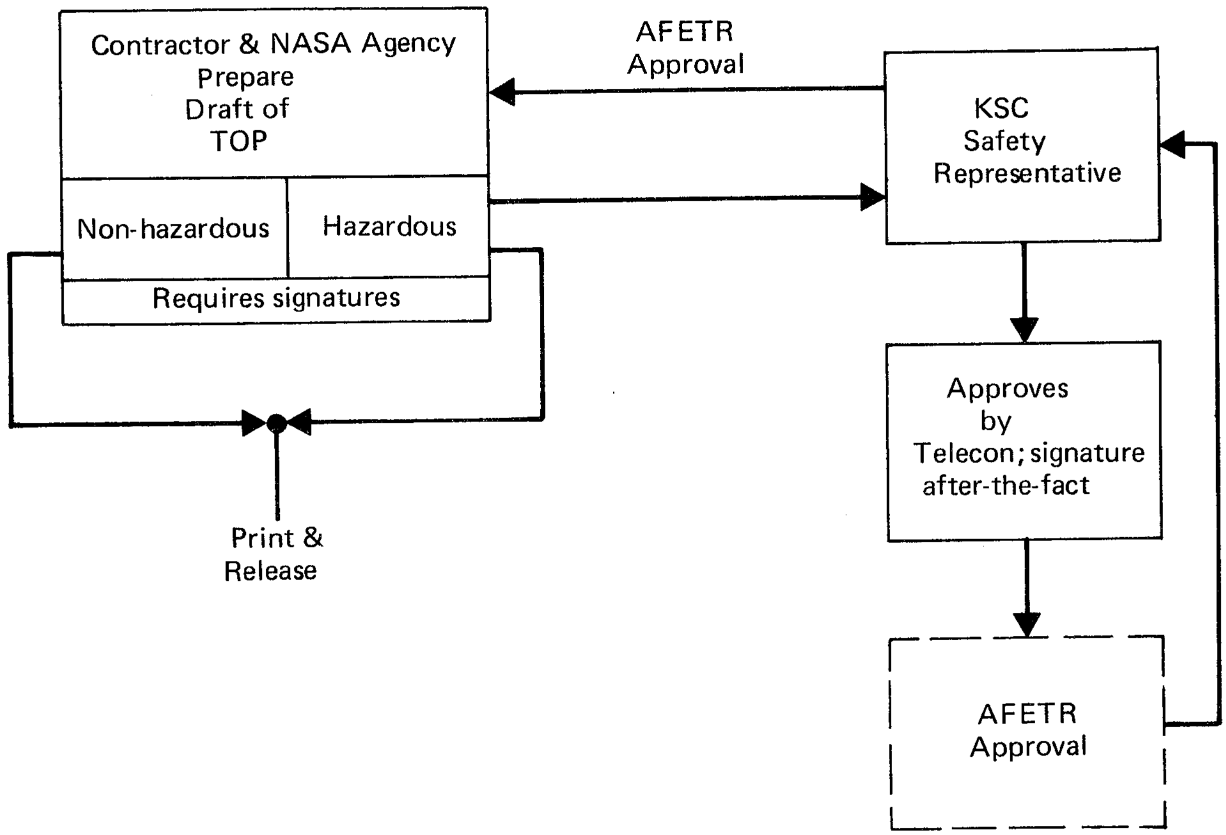


FIGURE 4-3. – CATEGORY II TOP SAFETY REVIEW PLAN

4.2.6.2.1 Hazard analysis, classification and control — At the present, it is a requirement that the STS User Agency will systematically analyze his payload for hazardous systems. Sources of hazards may be the environment, personnel error, design characteristics, operational necessity, procedural deficiencies or hardware malfunctions. NASA JSC recommends that the analysis of hazard sources should be conducted early in the payload development phase so that status of corrective actions to eliminate the hazards can be reviewed at each program design review. The hazard sources must ultimately be classified into uncontrolled and controlled classes. In the natural course of events, it is expected that all hazard sources will be eliminated or controlled. The control of hazards will be provided by the following:

(a) Design Features
(b) Safety Devices
(c) Warning Devices
(d) Special Procedures

Residual hazards shall be identified and justification for acceptance provided, together with procedures to avoid the hazardous conditions. The system safety approach in reference 20, is specifically outlined in the NASA System Safety Manual, reference 21, and is in consonance with the requirements set forth in Chapter 3 of the NASA Safety Manual, reference 22.

4.2.6.2.2 Safety reviews — The general purpose of the safety review is to assess the compliance with safety requirements and the elimination and/or prevention of hazardous sources in the system. With this viewpoint the Safety Policy and Requirements document prepared by NASA JSC presents requirements which are directed toward a new payload which will be designed and developed from the beginning. It is believed that this is shown by the requirement that safety reviews will be accomplished progressively on individual payload elements (black-box level) prior to acceptance by and shipment to a spacecraft integrator and again on the complete spacecraft prior to acceptance and shipment to the launch area for integration to the STS. It is required that each level of organization will prepare and present a Certificate of Safety Compliance and that the responsibility for presenting the Safety Compliance moves up the approval ladder in the same way that the "next assembly" is moving up. Since the NASA Scout vehicle is an operational launch system with an extensive history, some deviation from these requirements will be required. The general approach for obtaining approval of deviations is through the waiver system. To avoid reversals on granting of waivers by the final payload acceptance authority, waiver requests should be provided at the time the deviation requirement is generated.

4.2.6.2.3 Safety Compliance and Range Safety (SCRS) — Items (e) through (h) of the above paragraph 4.2.6.2, Safety Requirements, are basically those required by the Eastern Test Range as presented in AFETRM 127-1, reference 16. Therefore, the preparation of the safety compliance data and range safety package as required by the range will suffice for the STS program. However, of special importance in the SCRS document is the requirement for procedures covering hazardous operations. NASA documents, references 19, 23 and 24 must be considered when preparing the required procedures. Item (h), Design and Operational Requirements, requires special considerations by the STS user agency.

Some of these considerations are summarized as follows:

(a) Payload generated hazards must be minimized at all times, especially during Orbiter landing and post-landing operations. The design and operation shall not impose restrictions on normal or contingent Space Shuttle Operations in which safety of the STS or crew may be affected.

(b) A safe interface between user payload, STS and GSE shall be provided. A hazard shall not result from any single procedural error and at least two procedural operations must be performed before initiation of safety-critical functions.

(c) Payload data which is critical to safety shall be provided by redundant transmittal. A possible requirement of the system is the provision for remote safeing commands from the Orbiter. Safety-critical data or control functions must be capable of being tested from the Orbiter, Spacelab, or ground where applicable.

(d) Hazardous materials shall not be released into Orbiter payload bay. All liquid propellants and pressurized systems shall be dumped overboard during an abort unless proven safe.

(e) Components or substances which are hazardous because of incompatible materials, electrical potential differences or chemical incompatibility shall be separated to the maximum extent possible.

(f) Flame propagation paths and ignition sources shall be prevented to the maximum extent possible where flammable materials are used.

(g) Structural failure of payload mounting or support bracketry due to stress-corrosion shall be prevented.

(h) Materials which produce significant odors or toxic out-gassing shall be avoided in manned pressurized compartments. Payload components carried in the Orbiter cabin shall be designed to NHB 8060.1A.

(i) Pyrotechnic subsystems and devices shall meet safety provisions of JSC 08060, Spaee Shuttle System Pyrotechnic Specification.

(j) Pressure Vessel Safety Standard NSS HP 1740.1 or other approved documents.

(k) Safety equipment shall be designed and safety procedures established to minimize risk and control hazards on the ground and in flight.

(l) Emergency or backout procedures shall be developed for payloads during ground and flight anomalies.

(m) Destruct systems shall not be used unless a waiver is granted.

(n) Inadvertent operation of propulsion systems shall be prevented by design. Main engine firing and stage separation, where inadvertent operation results in a catastrophic condition, will require three (3) failures or operator errors for inadvertent operation.

(o) Retrievable payloads shall include provisions to permit preretrieval safeing to be verified by the Orbiter and Ground Station prior to retrieval.

(p) Safety-critical payload elements shall be designed or protection provided to preclude hazards to the ground and flight crew in case of lightning strikes.

4.3 Handling Specifications

As was noted in discussing the safety procedures, there are three environments considered to be hazardous when handling solid rocket motors. It is standard procedure for the handling specifications to provide precautions to prevent inducement of these hazardous conditions. These hazardous conditions cover the following environments:

(a) Impact, shock and friction
(b) Static or stray electrical energy
(c) Excessive temperatures.

The most common approach to hazards assessment has been sensitivity testing of subscale samples to establish the tendency of a material to initiate or explode. The data generated by sensitivity testing are usually abstract and the results expressed in such terms as the 50% probability of initiation or explosion. From data such as this, one is able to make a conclusive statement such as, 'A' is more sensitive than 'B'. However, one cannot conclude that 'A' or 'B' constitute a hazard in any given situation. The historical approach has been that 'A' is some standard explosive such as TNT, RDX, or PETN and that the sensitivity test results are based on some given uniform specification sample and test equipment. Subsequently, with historical data on full scale handling, transportation, field check-out, launch, motor fallback to pad, cook-off test, drop tests, detonation shock sensitivity, projectile impact, and other similar tests, a historical confidence for 'normal', and to some degree, 'abnormal' rocket motor handling has developed. Since it is too expensive to purchase full scale solid rockets to perform all these type tests on a new motor design, solid rocket motor users have had to rely on hazard qualification by subscale tests or similarity to other previous full scale tests. Due to the lack of knowledge on the full hazard characterization of each unique solid propellant-liner-motor case-igniter system the industry has operated around this deficiency by using safety and handling criteria to preclude hazardous conditions. Motor testing and classification for transportation and storage have been presented in Section 3.0.

4.3.1 Impact, Shock and Friction. – If a solid rocket motor is impacted due to being dropped or projectile impingement-penetration, the kinetic energy must be transformed and transferred in keeping with the law of conservation of energy. This energy is dissipated through the phenomenon of shock, friction, and permanent deformation.

Friction can occur in at least two modes, the first mode is the friction generated at the projectile and propellant interface upon penetration as well as the friction which occurs between the damaged case (liner)-propellant interface. The second mode is the interface movement between particles in the propellant due to a shearing motion. As one can readily ascertain, the severity of these friction modes is different for each unique solid rocket. The propellant modulus of elasticity, solids loading, particle size, oxidizer type, case liner material and thickness, and case material all have their effect on the dissipation of the energy. If the magnitude of the energy to be dissipated is of low order, it will not trigger the release of the propellant potential energy; therefore, a safe condition exists.

Shock loads during handling are induced into the rocket motor in at least two ways. The first occurs when the motor is dropped and the second occurs when a projectile contacts the motor surface. Shock loads also are induced from one propellant particle to the next when the propellant is sheared by projectile penetration.

Friction and normally shock are the result of some form of impact. Impact due to dropping is the most prevalent environment during normal handling and processing. Since it is so difficult to quantify the hazardous threshold of impact, the handling manuals usually provide a warning on impact sensitivity as follows:

(a) The propellant is classified non-detonatable and insensitive to shock

(b) Thin sections or films of propellant are sensitive to friction and impact.

4.3.2 Static or Stray Electrical Energy. – When handling or working around electro-explosive devices, flammables or explosives and solid rocket propellants, precautions are required to prevent stray electrical currents from entering the system. Electrical current can be induced into the system by static electricity, electrical equipment, radio frequency energy, lightning, or electrical system malfunctions. These electrical sources are basically divided into two ignition modes: (a) ignition through electrical squibs, and (b) ignition of the fuel (solid propellant or atmosphere). During vehicle build-up and solid rocket motor handling, these two ignition modes are eliminated by the grounding of systems; personnel wearing conductive shoes, and leg and wrist stats, as required; quality control calibration and testing of electrical equipment; non-spark producing tools and shorting caps on electrical squibs; squibs not installed until all vehicle checks completed; no work on hazardous operations in area during electrical storms; or RF transmitters turned off during hazardous operations. When required, handling manuals specify various combinations of the above safety procedures.

4.3.3 Temperatures. – During normal handling operations temperature is generally not a problem. Auto-ignition temperatures are usually above 250°F (except for long term exposure) and generally around 400-500°F and are a function of time exposure. Procedures usually give temperature limits of motors from the standpoint of preventing damage. However, any operation which could produce a high temperature hot spot would be considered a hazardous operation or condition.

4.4 Hazardous Incidents and Results

It is rather difficult to obtain data on hazardous incidents which have or may have occurred on various programs. This could be due to the following reasons:

(a) A reportable incident is defined as one which requires a report to be submitted under DOT regulations that require evacuation of an area or similar protective measures to be taken. Therefore many incidents are not of reportable nature.

(b) Reports of incidents are not common knowledge on a program and a request can be answered easily by saying "no incidents", "I'm not aware of any problems", or "that data is so old I don't know where it is stored".

4.4.1 General. – References 25 and 26 present summaries of accidents/incidents which occurred during the manned space programs from 1963 through 1971. Reference 25 covers accidents/incidents for the time period of 1961-1969 and represents the review of 10,000 case documents with the selection of a total of 508 summaries. Reference 26 covers the time period of 1970-1971 and represents the review of 5000 case documents and the selection of an additional 223 summaries for a total of 732 cases to cover years 1961-1971. Figure 4-4 shows the percentage distribution of the accidents/incidents by systems. As shown the ordnance systems accounted for only 2 percent; propulsion systems, 6 percent; fuel/propellant systems, 10 percent; pressure systems, 19 percent; and transport/handling systems, 12 percent. These systems accounted for about 50 percent of all occurrences. Figure 4-5 shows the variation of accidents/incidents by program activity. As shown, operational test and checkout accounted for the largest percentage, 45% and secondly manufacturing, 34%. Operational test and checkout includes all tests of assembled vehicles and all testing at field sites, including integrated tests and pre-launch checkout. Manufacturing is classified as functional checkout of systems, subsystems or components. These accidents/incidents by causes are further broken down by software and hardware deficiencies, Figure 4-6. The percentages shown are based on the total cases represented in each class of accidents/incidents causes in relation to the total number, 732, of case summaries. As shown, deficiencies in procedures and work control represented the two highest classes in software, and design deficiencies stand out as the largest contributor by far in hardware.

From these data it can be readily determined that for our consideration in this study accidents/incidents occurred mostly during operational test and checkout of pressure systems, fuel propellant systems, transportation/handling systems and propulsion systems which were caused by either procedural or design deficiencies.

Design deficiency was defined in reference 25 and 26 as any design specification inadequacy, resulting in deficient hardware which contributed to the occurrence of an accident/incident. Factors considered were omission of essential information, failure to specify safety devices or warnings, failure to determine stress/fatigue and other operational/interface factors, errors in material selection, or clerical errors in drawings and specifications. An example of an accident/incident in this class was the X-248 solid rocket motor used on the Delta Program which had a design deficiency in the igniter which permitted firing by static electricity when the non-conductive polyethylene cover was pulled down over the system.

A procedural deficiency was defined as any case in which formal procedures contributed to accidents/incidents causes as a result of failure to prepare procedures, failure to follow procedures, deviations from procedures during a test, failure to coordinate concurrent tests, ommissions of essential information in procedures, clerical errors in procedures, use of wrong procedures, or failure to update procedures. An example of this type accident/incident was the blowing of nitrogen and

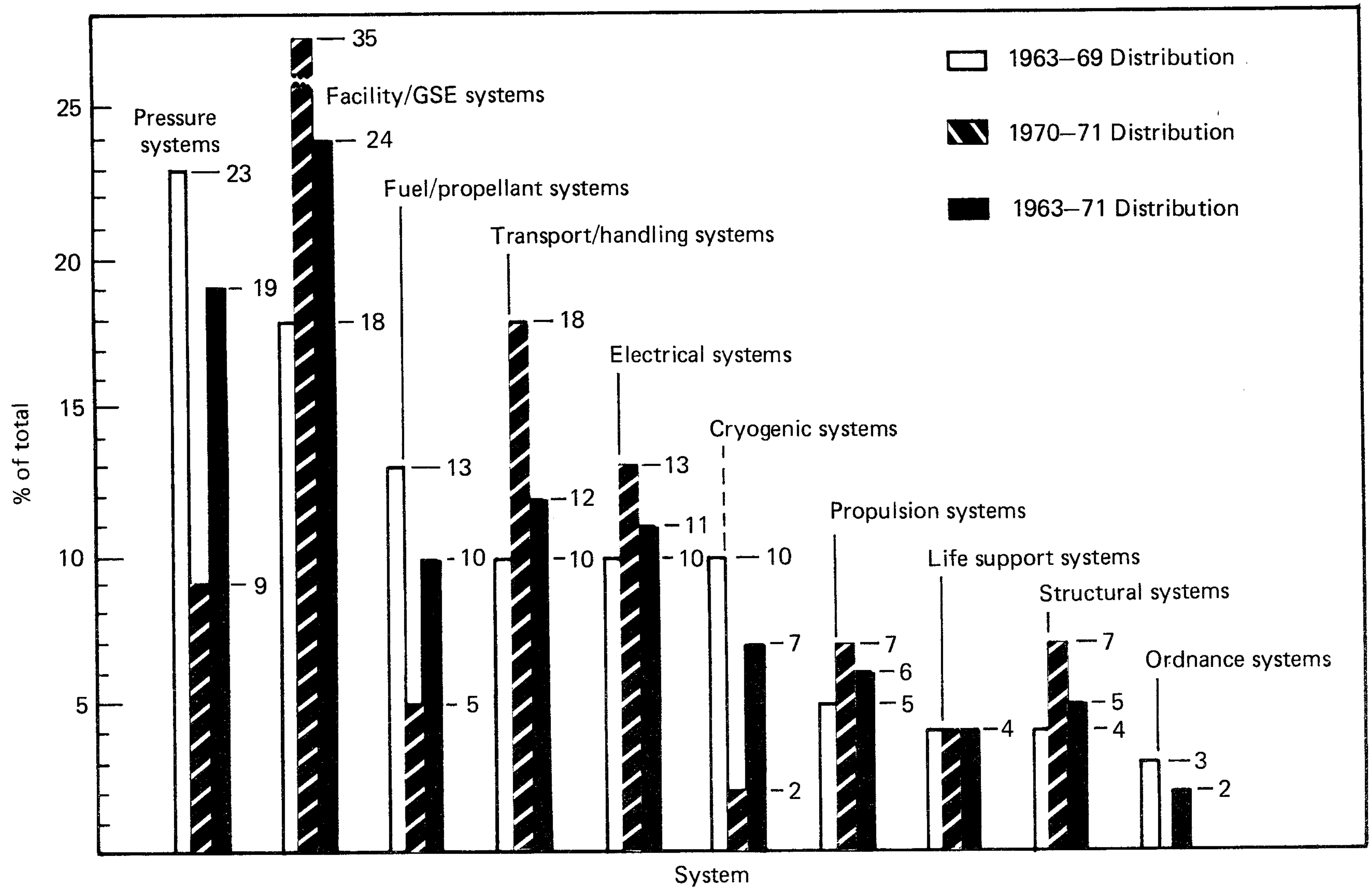


FIGURE 4-4. – DISTRIBUTION OF ACCIDENT/INCIDENTS BY SYSTEM

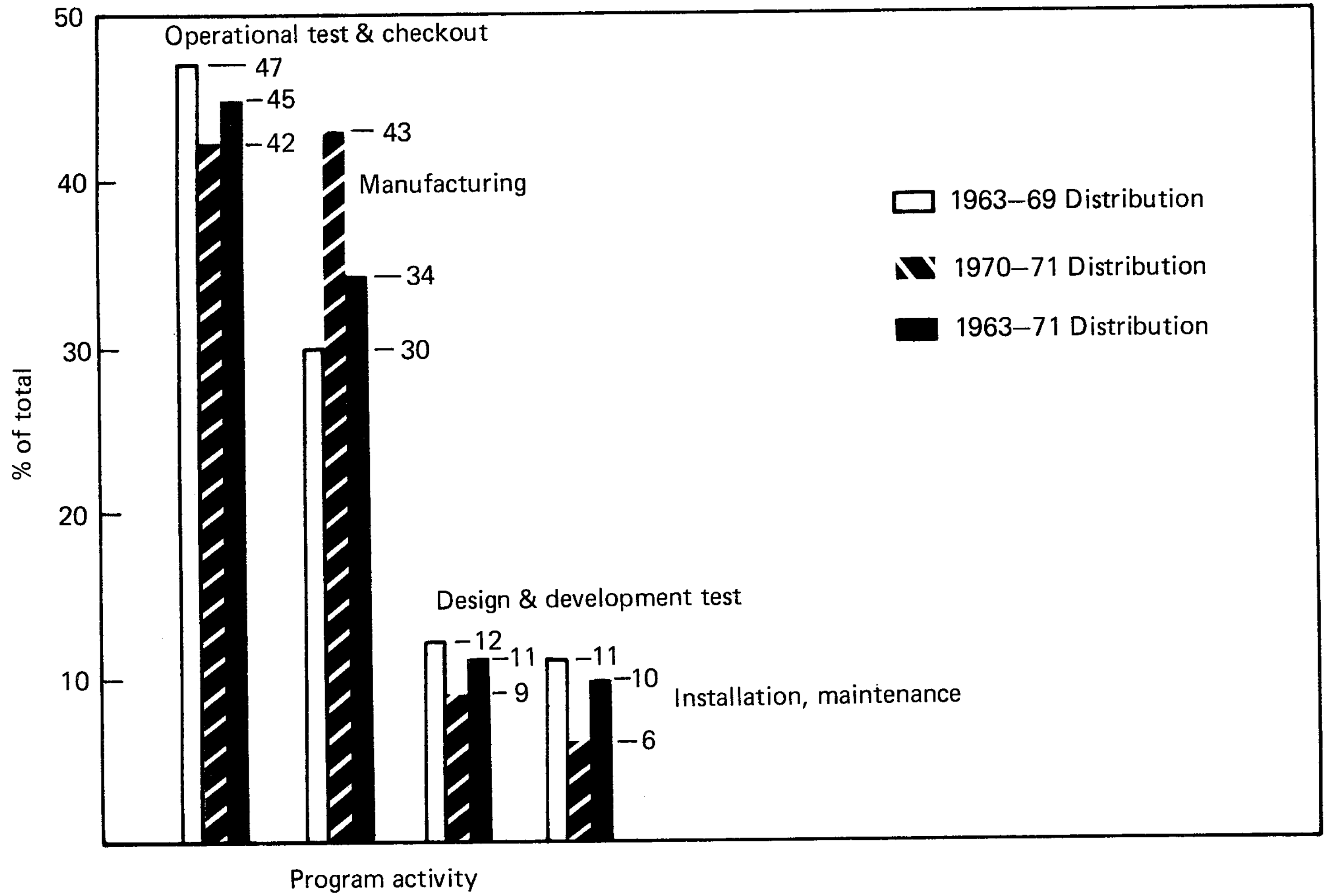


FIGURE 4-5. – DISTRIBUTION OF ACCIDENT/INCIDENTS BY PROGRAM ACTIVITY

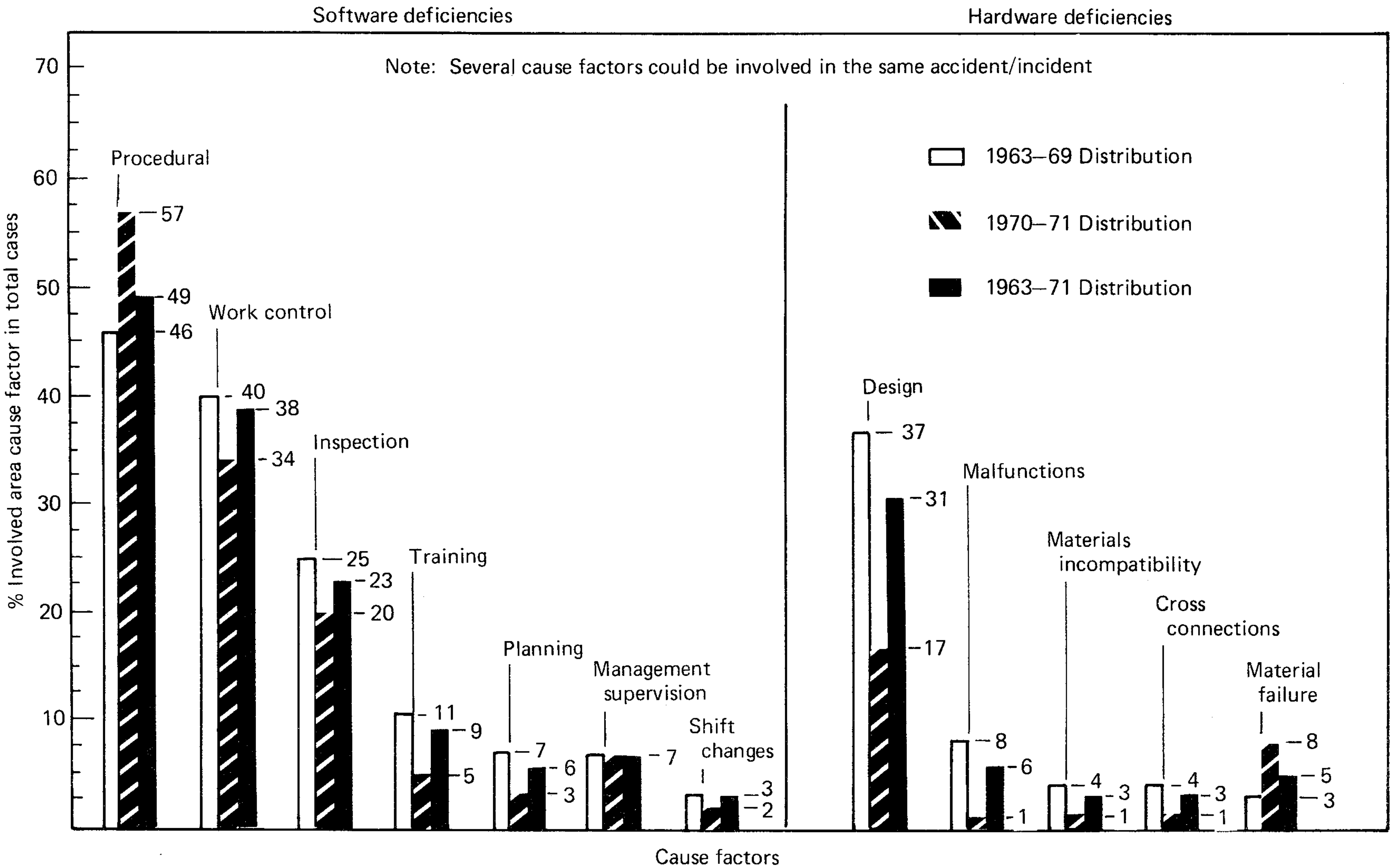


FIGURE 4-6. – DISTRIBUTION OF ACCIDENT/INCIDENTS BY CAUSES FROM 732 CASES

fuel residue through a hydrazine engine fuel scrubber, fuel valve, catalyst bed and out the engine exhaust into the face of a workman. This accident was caused by the failure to follow procedures and the absence of safety provisions in the procedures to protect operators.

It should be noted that the data presented on propulsion systems in references 25 and 26 represents mostly liquid systems rather than solid propellant systems. The closest system that relates to solid rocket hazard accidents/incidents is the ordnance system. As shown, this represented only 3 percent of the distribution. Due to the similarity to the handling and safety requirements of solid rockets and ordnance items in general, it is believed that the 3 percent distribution is representative for solid rocket motors. Due to the complexity of liquid systems versus solid rockets, it is believed that accidents/incidents occurrences are several magnitudes greater than that expected during solid system operations. However, errors which cause hazardous incidents in solid or liquid systems can be just as catastrophic in nature.

4.4.2 Liquid System Incident Reports. – A summary of selected hazardous incidents obtained from Reference 25 and selected from existing documentation of accidents or incidents on Manned Space Flight programs is presented herein.

Records reviewed in Reference 25 included existing records of NASA Hdqs., NASA field centers concerned with space programs and 18 contractors, associate contractors and subcontractors on space programs. The majority of accidents/incidents selected, occurred during various phases of the Apollo Program with the remainder selected from other manned space programs.

Table 4-1 presents the pertinent data related to these selected events along with the cause.

4.4.3 Solid System Incident Reports. – A review of hazardous incidents or accidents reported to the DOD Explosive Safety Board (DESB) was conducted at their facility and through the explosives accident-incident abstracts, references 27 through 31. Two-hundred and ten (210) incidents were reviewed and are categorized as follows:

Type Incident	Number	Percent, %
Propellant Processing	128	61
Test Firings	22	11
Curing/Temperature Cycling	16	8
Transportation	15	7
Storage	9	4
Other – Not Relevant	11	5
Other – Relevant	9	4
	210	100

As indicated by the table, 61% of the reported incidents occurred during propellant processing operations including mixing (46), extruding/pressing (40), drying (8), sawing/cutting (22), stripping/disassembly (5), casting (3), rolling (2), and scrape down (2). These incidents involve conditions

TABLE 4-1. – SELECTED LIQUID SYSTEM INCIDENT REPORTS (REF. 25)

Category	Accident/Incident Description	Causes
Pressure Systems	Booster stage burst during fuel tank leak check. The tank was overpressurized because pressure sensors were disconnected by first shift and the second shift was not notified. Stage was destroyed. Seven men injured and minor damage to the facility.	Failure to transfer information from one shift to another and lack of overall integrated test procedures for the test. Contributing causes were use of unqualified vent valves, overstressing of the stage during test installation and inadequate training of test conductor and crew.
	During development tests, a GH_2 test tank was overpressurized and ruptured, resulting in destruction of the tank dome and fatal injury to two personnel.	Pressure relief valves were set too high. Contributing cause was failure to depressurize tank while working on it, and failure of the test conductor to be aware of activities in his scope of responsibility. Procedures for personnel safe distances during pressure tests were not followed.
Propulsion Systems	During installation of a low thrust engine for test runs, a small amount of hydrazine fuel found in the connecting fuel line was attempted to be purged. Failure to close-off the engine valve prior to purging the GN_2 permitted 30 psig GN_2 to be forced through the fuel scrubber, the engine valve, catalyst bed, and out the engine exhaust. Fuel residue and a mixture of gases was blown into an employee's face causing considerably injury.	Test operator's failure to follow established procedures which required closure of the engine valve prior to purging operations. Contributing cause was the absence of provisions and safeguards in operating procedures to protect operators during purging.
	During maintenance engine run-up on a space flight training vehicle, the fuel tank ruptured during pressurization causing destruction of the tank, and minor injury to two persons. An unauthorized high pressure source was used to pressurize the tank. The procedure being followed was not applicable to the configuration of the vehicle.	Overpressurization resulting from erroneous pressure readings caused by a "sneak circuit" and a lack of pressure relief devices in the system. Contributing causes were inadequate test, quality and inspection procedures. Discipline and control were inadequate as evidenced by use of unauthorized high pressure equipment on low pressure systems and lack of certification of equipment operator.
Fuel/Propellant Systems	While replacing a faulty valve in a fuel system on a facility engine test stand being activated, two (2) maintenance personnel were injured by release of nitrogen tetroxide under pressure.	Maintenance crews were not adequately briefed as to hazards of the operation, exchange of information at shift change was not affected and supervision failed to ensure that pressure was released prior to the operation. Contributing causes were inadequate inspection and work control procedures.
	A propellant system exploded during a test when N_2O_4 was introduced to the system due to residual cleaning fluid in the system (Halogenated Carbon solvents).	Failure to properly purge the system after using cleaning solvents and failure to determine the compatibility of solvents with N_2O_4.

which will not be encountered during handling/flight on the Shuttle and hence are not relevant to this study.

The second most common cause of incidents occurred during static firing. These incidents involve such things as premature ignition and explosion of the test article. All of the incidents reported would have presented no problem to the Shuttle provided that:

(a) a well engineered firing circuit had been used
(b) a sufficient distance between the motor and the Shuttle was obtained prior to ignition.

The third type of incident involved curing and temperature cycling. Incidents reported tend to be unresolved but appear to be generally:

(a) Experimental propellants which prove to be unstable
(b) Malfunctions of the heating equipment

Since the above incidents are related to processing problems, they do not constitute a threat to the Shuttle.

The fourth type of incident occurs during transportation. In general, reported incidents tend to increase confidence in solid rocket motors.

Case 1423 – Illinois – 28 November 1970 – Baggett Transportation Company truck collided with a passenger car (icy road). Trailer overturned. No explosion or fire resulted.

Case 1425 – Charleston N. C. – 1971 – Driver left highway, ran into fuel tank at service station. Tank burst into flames causing a rejected Polaris rocket motor to detonate low order. (Polaris Facility reports that the motor ignited).

Case 1433 – New Mexico – 22 July 1970 – American Farmlines Transportation Company truck left roadway to avoid hitting car, struck culvert. Motor containers scattered over highway. No explosion or fire resulted.

Case 1445 – Indiana – 11 November 1970 – Truck stopped at rail crossing, struck by car. No explosion or fire resulted.

Case 1511 – Mississippi – 19 October 1969 – 8 box cars (Class B, 5 rocket motors) piled up going into siding. No explosion or fire resulted.

Case 1515 – New Mexico – 4 January 1970 – Driver apparently fell asleep. Truck overturned. Cargo of 2 MK30 Mod 2 rocket motors spilled. No explosion or fire resulted.

Case 1518 – Kentucky – 23 October 1968 – Train derailment due to brake failure. Car caught fire, cause unknown, but suspected due to smoldering of adjacent cars. No explosion resulted but the motors are assumed to have burned as the result of the fire.

Case 1521 – Texas – 13 February 1970 – Truck tire blew out and overturned the flatbed trailer carrying a first stage Polaris solid rocket in a shipping container. No explosion or fire resulted.

Several of these incidents involved fatalities due to the collision which occurred. One of the incidents (Case 1425) involved low order detonation which was caused by an external fire. Only in the case of the train wreck (Case 1518) is there a remote possibility that a rocket motor ignited as a result of the collision.

The fifth type of incident occurs during Storage — The cause for this class of incidents is generally unknown. However, the propellants in motors stored in the Shuttle bay should be well qualified, so that no threat of spontaneous ignition will be present.

The sixth type of incident is not considered relevant to the study and occurs during Processing, ground fires and vapor incidents.

The seventh type of incident which is potentially relevant includes:

(a) Radiofrequency/static electricity ignition — Generally speaking, solid propellants will not ignite due to these causes but some initiator components may. Good initiator design and a mechanical safe and arm will eliminate these hazards.

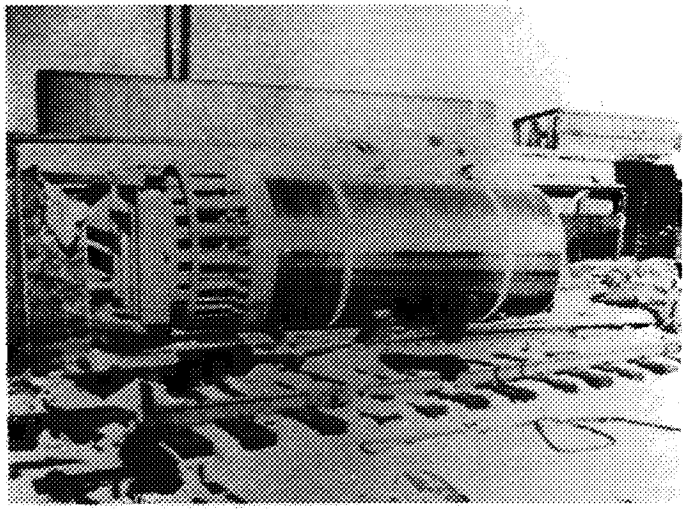
A classical example of an inadvertent ignition of a solid rocket motor from static electricity occurred on April 14, 1964 during checkout and assembly of an Altair X-248 at the eastern test range, Delta Program. It was subsequently determined that static electricity could be transmitted from the polyethylene plastic cover or the plastic cover of the nozzle opening to the forward dome of the motor and into the suppressor paddle. Mounted on the suppressor paddle was the igniter basket which contained the igniter pellets and the low resistance squibs. The static electricity provided sufficient energy to ignite the squibs. An X-248 also ignited in Tulsa, Oklahoma while suspended from a cable on a crane. A redesign of the igniter and the spraying of a special coating on the basket and paddle eliminated this problem.

(b) External fire — External fires can ignite solid motors and can turn a problem into a castastrophy.

A summary of some miscellaneous reports involving solid rocket motors which illustrate some of the above types of incidents follows.

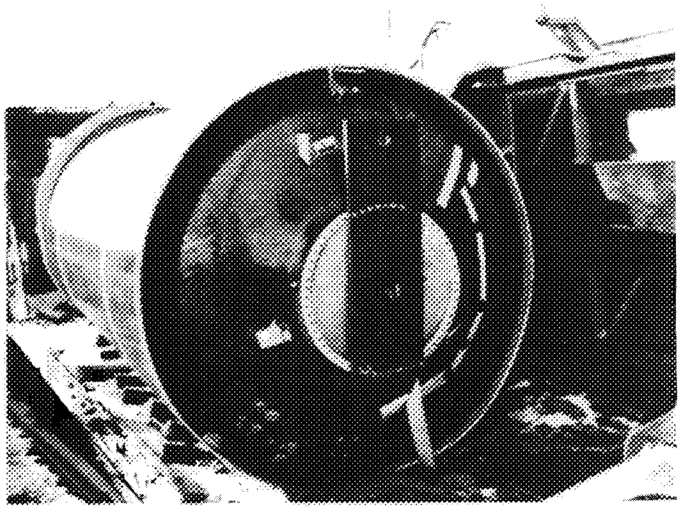
4.4.3.1. Polaris and Poseidon Programs: There have been a number of transportation incidents with the Polaris and Poseidon solid motors. One incident was the fallback of a Polaris missile 100 feet to the water with no ignition, explosion or detonation. Also a flatbed trailer truck carrying two first stage Polaris motors turned over on the highway near Fort Leonard Wood, Missouri. The truck was traveling about 65-75 MPH and it skidded on its side for about 175 feet before coming to rest. The two motors were in their shipping containers and were supported inside these containers with air springs. There was no extensive damage to the containers and no ignition of the motors.

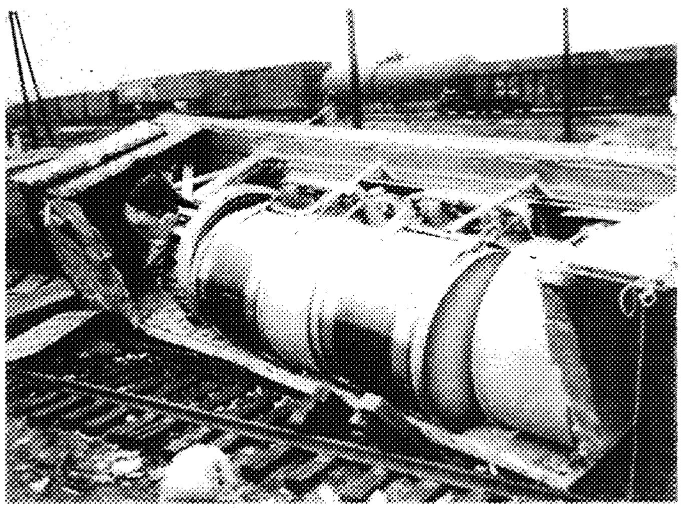
There have been at least two major transportation accidents with Poseidon motors. In 1971 a railroad flat car containing two trailer transporters derailed in East St. Louis, Missouri. The bed came loose from the wheels and tilted to one side while traveling at about 10 MPH turning the vans on their sides on the rail bed. One van contained a first stage Class B motor and the other van contained two second stage Class A motors. Figure 4-7 shows the configuration of these motors after the van bodies were removed. The motors received some damage but no exposed propellant occurred. In 1975 a



Side view
1st Stage composite motor with tarvan cut away

Looking aft
1st Stage composite motor





Side view
Two – 2nd Stage composite modified double base motors with tarvan cut away

FIGURE 4-7. – POSEIDON SOLID ROCKET MOTOR TRANSPORTATION ACCIDENT – RAILWAY YARD

railroad flat car containing two trailer transporters carrying first stage Class B motors derailed in the Hamelet, North Carolina railyard. These transporters also fell to their sides and the motors received damage but the accidents did not result in any exposed propellant and no ignition occurred. Another incident consisted of a complete missile which was being removed from a container liner in the vertical position. The missile fell about 12 inches and caused damage to the aft support ring. There were other minor incidents where the fiberglass cases received minor damage during handling. Indications are that it is not often that a motor rejection occurs. A rejection did occur as the result of an accident of a motor on a roller cradle which was being rolled from magazine storage. The cradle wheels hit the rail stops which caused the motor to tip over on the igniter-end causing case damage. No ignition has occurred during any Poseidon handling or transportation accidents.

4.4.3.2 Minuteman program: A large number of interstate and on-facility shipments of individual motors and assembled vehicles have been made with only six known accidents. Three transporter/erectors ran off the road and resulted in solid rocket damage but no ignition, explosion or detonation. One transporter/erector tipped over during erection with damage to the solid rockets but no ignition, explosion or detonation. In another case the transporter/erector fell and impacted on the front retracted parking wheels. Structural damage occurred but no rocket ignition, explosion or detonation. Also, the brakes locked on a transporter trailer and the resulting accident damaged two second stage solid rockets but no ignition, explosion or detonation occurred. There have been at least three aborted Minuteman launches at the Eastern Test Range. The third stage motors on flights FTM-412 and 418 fell 11600 feet and 1900 feet, respectively, to the water without any reaction. The third stage of FTM-422 fell 3800 feet to the ground and burned.

4.4.3.3 Scout program: In 1963 vehicle S-110, reference 32, experienced a nozzle failure on the first stage Algol solid rocket motor. An altitude of 1260 feet had been obtained when the linear shape charges of the second and third stages were fired, 4.29 and 4.26 seconds flight time, respectively. The second and first stage motors landed in the marsh about 0.9 miles from the launcher and the upper three stages landed on or near the launch pad. The first and second stage burned with no explosion or detonation as did the third and fourth stage motors. The fifth stage motor broke open but did not ignite, explode or detonate. The first, second and fifth stage motors contained composite propellants while the third and fourth stage motors contained composite modified double base propellants.

In July 1967 an Antares II X259 solid rocket motor was static fired in an effort to substantiate failure modes postulated due to the Scout vehicle failure S-152C. At 25 seconds after rocket motor ignition a linear shape charge was fired. The case was split longitudinally and propellant and pieces of the case were thrown as far as 300 feet. The propellant and debris continued to burn for about 30 minutes. This test confirmed that the linear destruct charge (ρ_{RDX} = 200 grain/ft) would not detonate the DOT Class A, Military (Class 7) propellant.

4.5 Conclusions

A solid propellant rocket system contains all the required constituents to sustain a combustion process and if certain type damage or critical flaws are present in the system, abnormal motor operation, explosion/deflagration or detonation could occur during motor operation. Upon review of the Scout launch vehicle standard operating procedures and the Scout launch complex safety plan it was determined that precautions and requirements are satisfactory to prevent known hazardous situations as outlined in Western Test Range documents. There are three areas of hazardous environments that are covered by safety procedures.

(a) Impact, shock and friction
(b) Static or stray electrical energy
(c) Excessive temperatures.

The basic handling concern is not generally based on the hazard of explosion/deflagration or detonation of the solid rocket but the primary concern is premature ignition. Impact and shock environments are primarily a concern from the standpoint of damage which will subsequently cause system failure upon normal ignition. The hazard of static or stray electrical energy is reduced or eliminated in a number of ways. These include the proper grounding of the system at all times, personnel wearing grounding devices, terminating operations during lightning, storms, terminating or reducing the output of RFI during the final launch sequence, using safe/arm devices on the motor igniter with a shielded electrical system and the use of a shunting device during the handling of all squib devices. Properly maintained temperature control of facilities used for solid rocket handling coupled with established safety and hazard prevention procedures, should eliminate the auto-ignition concern.

In reviewing the safety requirements and practices of other programs it was determined that the basic hazardous situations of concern were common to the Scout launch vehicle. This was not unexpected since industry safety practices, Department of Transportation and Department of Defense standards and launch complex safety requirements are based on the same basic standards. When operating out of the Kennedy Space Center the contractor must use Category I Technical Operating Procedures (TOPs) for repetitive hazardous and nonhazardous operations. The hazardous procedures must contain at least 3/16" red letters on the front cover which identifies the procedure as containing hazardous operations. The first page of the procedure contains a safety requirements checklist and required signature authorization. These two requirements are major safety attention features and are not utilized in the Scout standard operating procedures.

Under the present requirements of the Space Transportation System a contractor must provide a detailed safety program which provides for detail safety reviews from the black box level to the completed payload. These safety reviews will terminate in a Safety Compliance document. This document with the Range Safety document is submitted to the Eastern Test Range for approval before operations can be performed at NASA or Air Force facilities on the Range. The standard Scout documents can be used to satisfy a portion of these requirements but additional effort will be required to satisfy these Shuttle requirements.

In reviewing component and system incidents/accidents it was concluded that most of the hazardous situations were caused by either procedural or design deficiencies. Proper attention to these two areas throughout system design or modification will provide a high confidence level in system safety and vehicle processing. System safety requirements are discussed further in Section 6.0.

5.0 ASSESSMENT TECHNIQUES–SOLID AND LIQUID PROPULSION SYSTEMS

5.1 Introduction

Safety is a primary concern when handling or utilizing any solid or liquid propellant system. When considering solid or liquid propellant rockets as propulsion systems of payloads for the Space Transportation System, it is desirable to have a hazard assessment technique. This technique would identify threshold hazard parameters, such as impact velocity, and the effect of the hazard if it occurred, such as overpressure.

A thorough survey of available literature, data, test reports, etc., was conducted in an effort to define the thresholds required to create a hazardous situation as well as to define the possible consequences of the situation. A review of available literature yielded considerable information concerning liquid propulsion system hazards but somewhat limited information concerning solid rocket motor hazards. The most definitive source of information concerning these systems and the hazards associated with them are the test reports on projects Pyro and Sophy respectively.

Project Sophy dealt exclusively with composite propellants. Data on composite-modified double base propellants is available in the form of test reports performed on missile systems and motors as well as private industry research and development reports. This data is not as well defined in terms of varying parameters as the composite data. The literature survey failed to disclose any conclusive hazard evaluation method which is applicable to both composite and composite modified double base (CMDB) solid propellant systems. In an effort to evaluate the effects and hazards of CMDB propellants, much reliance has been placed on pooled test data and results.

Several valuable sources are available to aid in the assessment of hazards of liquid propellants. These works contain studies, theoretical analyses, and detailed graphs and charts pertaining to the various parameters involved. A discussion of techniques and a list of these references is provided.

Therefore, this task provides generalized boundary limits for specific hazard threshold and effect parameters rather than providing specific methods of analysis.

The threshold hazard parameters investigated are:

- Impact Velocity
- Critical Diameter
- Pseudocritical Geometry
- Initiation Criterion

The hazards effects are:

- Peak side-on Overpressure
- Positive Phase Impulse
- TNT Equivalency/Terminal Yield
- Fireball/Firebrand Effects
- Fragmentation

5.2 Findings from Propellant Test Programs

Aside from solid motor hazard classification tests on specific motors as performed for the Defense Explosive Safety Board (DESB), there was little data obtained under controlled conditions prior to 1965. Since that time several test programs have been conducted in order to obtain experimental data which could be used in determining the credible damage from assembled propulsion systems. The two most extensive programs performed, (Project SOPHY and PYRO) are summarized here.

5.2.1 Project Sophy. – This project was performed for the purpose of evaluating the explosive hazard characteristics of solid propellant rocket motors. Tests were performed at the Air Force Rocket Propulsion Lab in two phases – Sophy I and Sophy II. The details of these tests are reported in two summary reports, references 33 and 34.

These tests were conducted with standard ANB–3226 PBAN propellant, RDX adulterated and unadulterated. The tests were identified in general terms as:

1. Critical diameter
2. Pseudocritical geometry
3. Sensitivity tests
4. Propellant defects study

Critical diameter testing of typical Military Class 2 (composite) propellant was performed and the critical diameter concept extended to include several propellant grain configurations. Pseudocritical geometry testing included solid right circular cylinders and modified cylinders approximating various grain patterns typical of solid motors. An empirical relationship between the cross-sectional area and total perimeter was identified to define critical pseudocritical geometry characteristics.

In the tests, a degree of enrichment with RDX was used to assure mass detonation of the test sample. To assure detonation, the initial test specimens were detonated with an excessively large quantity of TNT which was much greater than the threshold for reaction. By gradual reduction of RDX enrichment and increasing test specimen diameter, it was possible to identify a critical diameter of approximately 64 inches for a composite propellant right solid circular cylinder. Additional tests were performed to determine the minimum shock pressure required to initiate detonation as a function of propellant diameter. Results obtained from RDX adulterated propellants and extrapolated to unadulterated propellants indicated that Class 2 solid motors near their critical diameter would mass detonate when exposed to an overpressure of 25 kilobars (263,593 psi) or greater.

5.2.2 Project Pyro. – Project Pyro was initiated to examine the explosive characteristics of hypergolic and cryogenic propellants for the purpose of predicting the credible damage potential which can be realized from an accidental explosion. The propellants investigated were nitrogen tetroxide and Aerozine 50 (hypergolic), LOX/RP-1 and LOX/LH_2 (cryogenic). Propellant weights up to about 100,000 pounds were used for the cryogenic combinations and up to 1000 pounds for the hypergolic combination. The two major boundary conditions selected for testing were confinement-by-missile (CBM) and confinement-by-the ground (CBGS). These were considered to be the two major classes of propellant interaction resulting from accidental mixing due to a failure. The basic data obtained from these tests were peak-overpressure and positive-phase impulse, both as a function of distance from the propellant explosion. Equivalent explosive weights (determined separately for peak-overpressure and the positive-phase impulse) and thermal data including total heat flux, gas temperatures, and radiant heat flux were also obtained. Additionally, the influence of vehicle (or propellant tank) impact velocity on fallback, missile or vehicle geometry, tank ullage volume, total quantity of propellants and other factors were examined in the program and are discussed in detail in the final report, reference 35.

5.3 Solid Propellant Systems

There are two general types of solid chemical propellants presently in use; composite and composite modified double-base propellants (hereafter referred to as double base propellants or by abbreviated form CMDB).

The composite propellants have two important ingredients, a fuel and an oxidizer, neither of which would burn satisfactorily without the presence of the other. Often these consist of crystalline, finely ground oxidizers dispersed in a fuel binder polymer matrix. Typical existing rocket motor propellant compositions contain (% weight) Ammonium Perchlorate (60-75%), aluminum (15-22%), and a binder system (12-35%).

Double base propellants are essentially higher energy propellants containing unstable chemical compounds, such as nitrocellulose or nitroglycerin, which are capable of combustion in the absence of all other material. These propellants have the oxidizer and fuel present in a single (colloidal) phase of plasticized nitrocellulose with the addition of various stabilizers.

Typical existing rocket motor propellants contain blends of nitrocellulose (14-32%) and nitroglycerin (10-33%) and are often mixed with ammonium perchlorate (5-20%) and aluminum powder (17-28%) to form higher performance double base composite propellants. Additionally, many high performance double base propellants contain high energy additives such as HMX (20-26%) which increase the motor performance as well as its sensitivity. In establishing an assessment technique of the hazard of these motors, great dependence has been placed on published test data relating to explosions and detonations of composite and double-base propellants. Data of this type is scattered and often related to unpredicted (and therefore not instrumented) missile system failures. Controlled tests of rocket motor propellants are very expensive due to the destructive nature of the test as well as the cost of the motors. The data presented in the following sections is based on information derived from controlled tests performed by military agencies, accident reports, as well as information obtained from rocket motor manufacturers.

Due to the limited source of experimental data, it is the objective of this section to provide an indication of the boundary conditions and trends pertaining to hazard parameters, rather than specifically presenting an analysis technique.

An attempt will be made to treat first the environmental parameters which can constitute a motor hazard, and then the parameters which can result from the consequences of a motor explosion/detonation.

5.3.1 Hazard Thresholds

5.3.1.1 Impact velocity: In addition to the usual environments arising from handling and storage of solid rocket motors, the possibility of inadvertent earth impact during Space Shuttle loading operations must be considered. This situation can arise from an equipment and/or operator malfunction during the hoisting of a solid rocket motor onto the Shuttle. In an effort to determine the thresholds of motor ignition, explosion, or detonation resulting from an impact, data has been compiled on various impact tests, accidents, missile fallback data, shotgun tests, and flying plate tests, references 7, 12, 36, 37, and 38.

Figures 5-1 and 5-2 show the data compilation of impact velocity (V_i) as a function of scaled weight $\frac{1}{W_p 1/3}$ for composite and double base propellants, respectively, (W_p) is propellant weight in lbm. A subjective extrapolation between existing data points has been attempted. The lower line in each figure represents the boundary between an "inert" region where impact of a mass propellant will not result in a reaction, and an "explosion/burn" region where impact could result in propellant burning and/or propellant break-up with propellant particles and fragments ejected.

The upper boundary line in each figure represents the transition region where full reaction of the impacting propellant could take place resulting in a detonation.

The region of most interest for rocket motor handling is the inert region where no reaction will take place. This region appears to be identical for both composites and double base propellants.

It should be noted that the compilation of impact data did not account for any attenuation which might be present. Small scale tests such as the Shotgun Tests and some Flying Plate Tests are for unrestrained samples of propellant. In large missile fallback data, drop tests, etc., the rocket motor propellant is encased and a degree of attenuation is present due to the case and vehicle interstage structure.

From the figures, it is possible to estimate the marginal condition at which the impact velocity for a specific mass of propellant becomes "critical".

For example, from Figure 5-1 a Scout 4th stage composite rocket motor weighing approximately 600 pounds is estimated to achieve a critical velocity of 59 ft/sec. This velocity is equivalent to a free-fall height of 54 feet. Likewise, a Scout 3rd stage, composite-modified double base rocket motor, weighing approximately 2560 pounds, is estimated to achieve a critical velocity of 53 ft/sec, equivalent to a drop height of 44 feet.

These curves are again, intended only to show generalized hazard regions and are limited by the small data samples that comprise them. As an extension of Figures 5-1 and 5-2 the available kinetic energy ($1/2\ MV_i^2$) of the impacting propellant mass has been plotted on Figure 5-3 as a function of the propellant weight for both composite and double base propellants. The generalized regions of detonation, explosion/burn, and no reaction are again shown separated by extrapolated lines between existing data points.

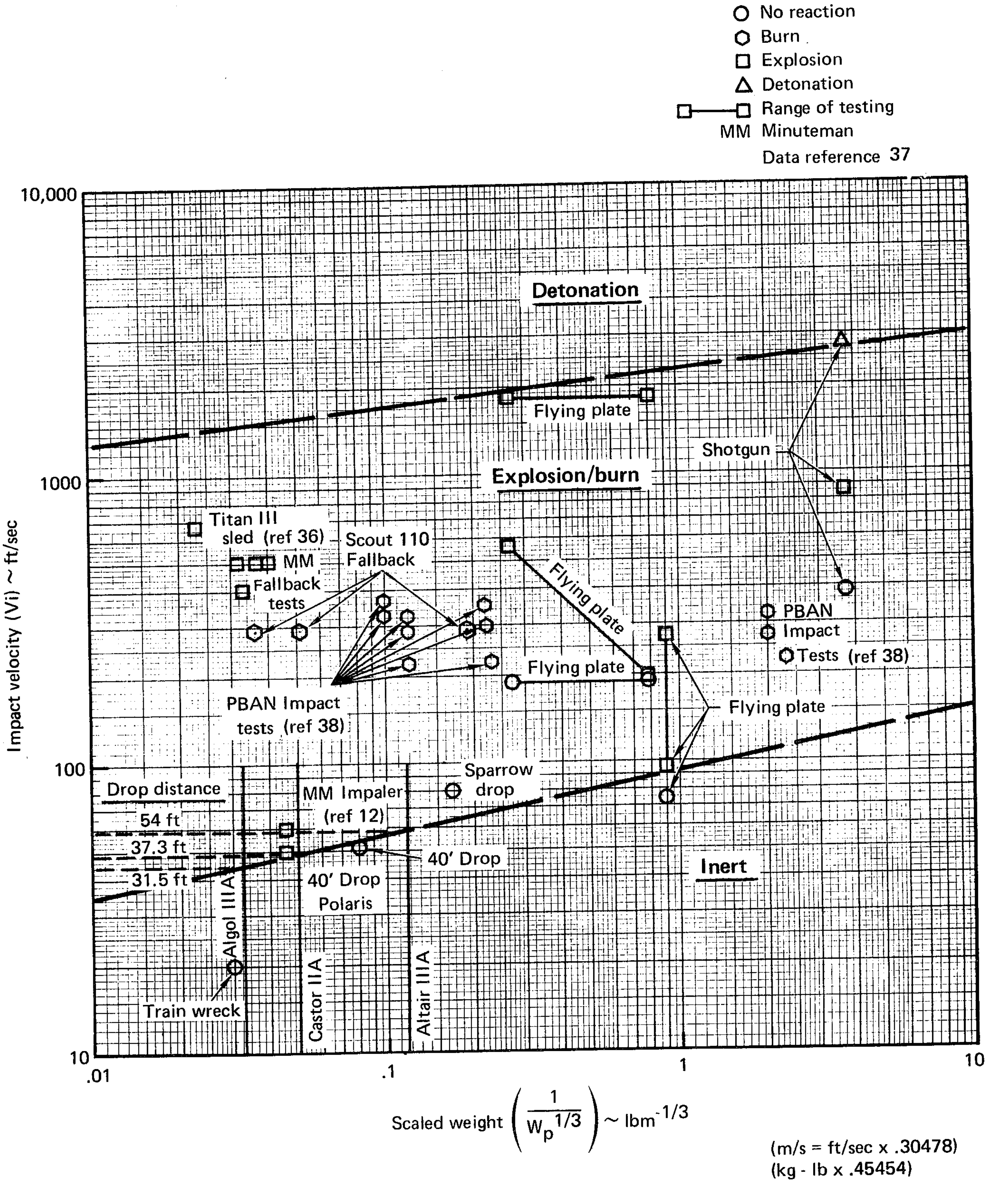


FIGURE 5-1. – COMPOSITES: IMPACT VELOCITY VS. PROPELLANT WEIGHT

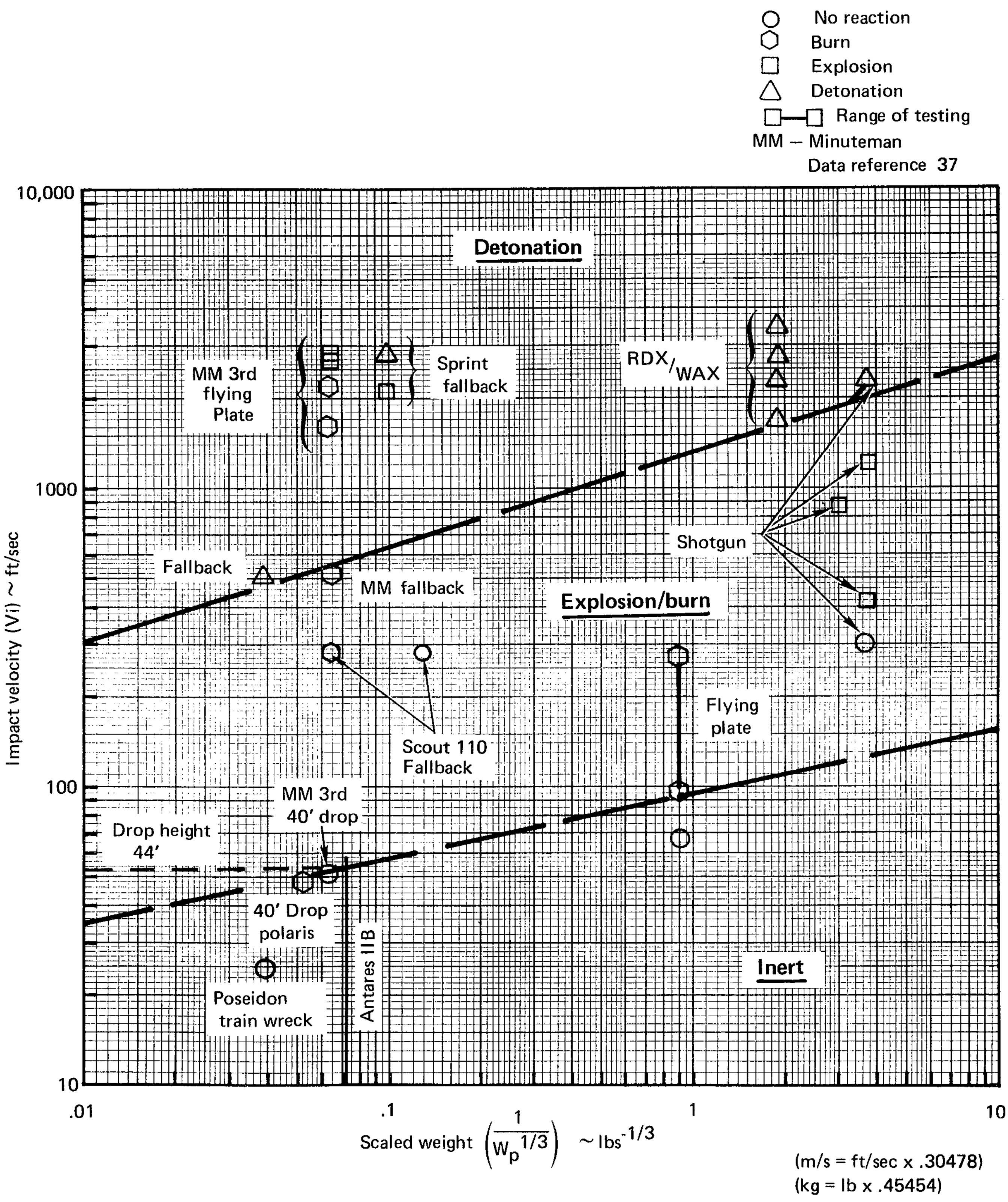
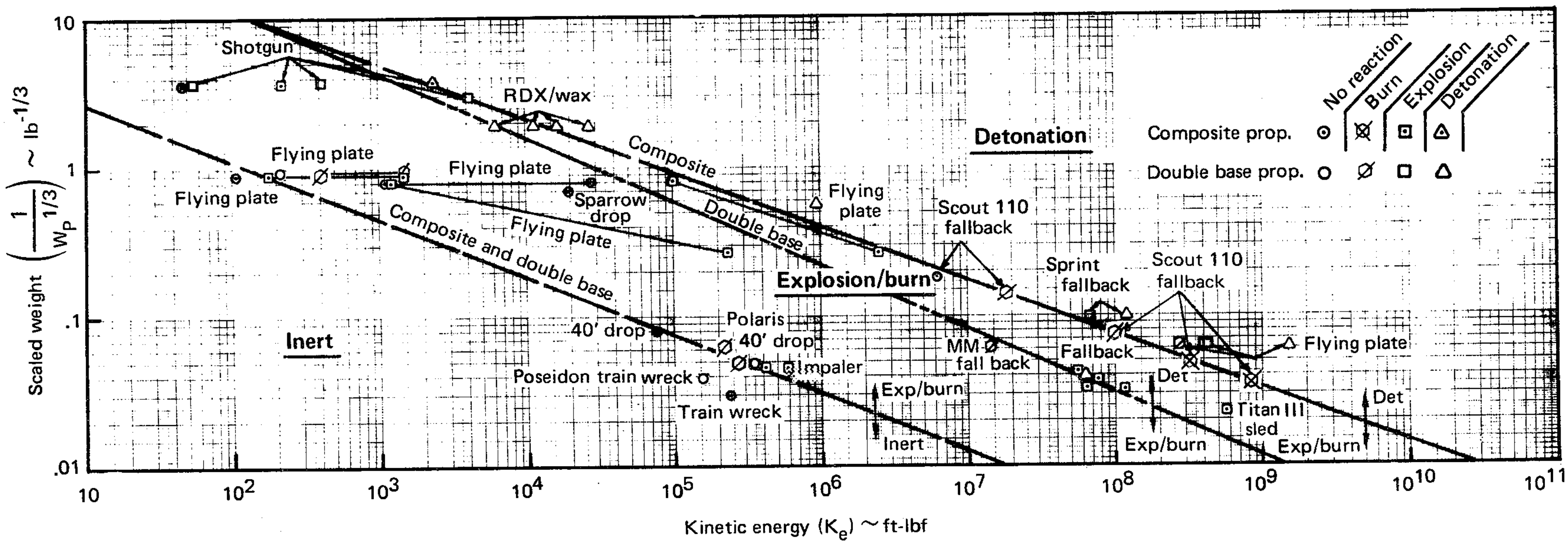


FIGURE 5-2. – DOUBLE BASE (CMDB): IMPACT VELOCITY VS. PROPELLANT WEIGHT



(J = N-m = ft-lbf x 1.356)

FIGURE 5-3. – PROPELLANT KINETIC ENERGY (AT IMPACT) VS PROPELLANT WEIGHT

5.3.1.2 Detonation sustainment—composite propellants: The ability of a solid propellant grain to sustain detonation has been established for composites by the testing performed by the Sophy project, references 33 and 34. Although the test program was limited to composites with PBAN binder, the concepts of critical diameter pseudocritical geometry and minimum shock pressure were evaluated and provide great insight as to the hazardous potential of composite motors in general. The findings of project Sophy can be applied to composite propellant motors with constituents having approximately the following compositions: 69% weight ammonium perchlorate (AP), 15% weight aluminum (AL), and 16% weight polybutadiene acrylic and acrylonitrile binder (PBAN). The above ratios are representative of many Class 2 composite propellants in use today.

5.3.1.2.1 Critical diameter (D_c) – This parameter is defined as the minimum diameter for solid propellant configured as a solid right cylinder which will sustain detonation. Project Sophy critical diameter tests were performed selecting logical configurations of solid right cylinders varying in diameter from 4 to 72 inches. The length to diameter ratios for all samples was four. Initially, a degree of enrichment with RDX was used to assure mass detonation of the sample. These initial detonations were accomplished by an over-charge of TNT which was much greater than the threshold for reaction; thus assuring detonation if the test specimen was greater than critical diameter. By gradually reducing the RDX enrichment and increasing the sample diameter, it was possible to identify a critical diameter of approximately 64.2 inches for a composite solid cylinder near the above chemical composition. For grains adulterated with RDX, the critical diameter relationship is shown in Figure 5-4 as a function of the weight fraction of RDX in the propellant.

5.3.1.2.2 Pseudocritical geometry (σ_c) – The pseudocritical geometry (σ_c) of a non-solid circular shape is defined as four times the ratio of the cross-sectional area to the total perimeter, for the smallest sample size that can sustain detonation. Critical geometry testing performed under project Sophy included solid right circular cylinders and modified cylinders approximating various grain patterns typical of solid motors. Internal grain configurations included circular, square, rectangular, triangular and cross-core patterns. Analysis of the experimental evidence showed that the pseudocritical geometry (σ_c) is approximately equal to 92% of the critical diameter (D_c) of the material.

$$\sigma_c = \frac{4\,A_{cr.\,sect}}{P} = .92\,D_c$$

Figure 5-5 shows the pseudocritical dimensions for various shapes obtained from reference 33.

An example of calculation of the pseudocritical geometry of a composite propellant rocket motor is given:

Motor: Scout 4th stage – Altair IIIA
Motor Outer Diameter (D_o): Approx. 19 inches
Motor Core Diameter (D_i): Approx. 4.1 inches

Pseudocritical Geometry:

$$\sigma_c = \frac{4A}{P} = \frac{(4)\left(\frac{(\pi)}{4}\left(D_o^2 - D_i^2\right)\right)}{\pi\left(D_o + D_i\right)}$$

$$\sigma_c = \frac{(19^2 - 4.1^2)}{(19 + 4.1)} = 14.9 \text{ in.}$$

For PBAN propellant $D_c = 64.2$ (ref. 34)

$$\sigma_c \text{ PBAN} = .92\ D_c = .92\ (64.2) = 59.1 \text{ in.}$$

Therefore the Altair IIIA has a pseudocritical geometry of 14.9 inches which is less than the minimum 59.1 inches required to sustain detonation.

Since the critical diameter for sustainment of detonation of a composite propellant motor has been found (Project Sophy) to be in the order of 64 inches, the majority of composite solid rocket motors which are candidates for Space Shuttle use are relatively safe for use due to their subcritical size.

This conclusion must be justified by the realization that given sufficient donor charge, a subcritical size rocket motor will react to the explosion with large pieces of propellant and fragments being ejected in the reaction.

It should also be noted that if a composite propellant composition is adulterated with high energy constituents, the critical diameter will be reduced thus increasing the propellant's susceptibility to detonation.

However, even though a given solid propellant motor configuration is capable of sustaining detonation, this does not mean that the motor will detonate. A second condition must be present, namely; sufficient stimulus from a given donor charge.

5.3.1.2.3 Initiation criterion – The tests performed during Project Sophy included the determination of overpressures required to detonate a composite solid rocket motor. Having determined the threshold overpressure for detonation, a method would then exist for determining the donor size. The following was concluded in Project Sophy:

> The minimum shock pressure required to initiate detonation was determined as a function of charge diameter for three (3) RDX-adulterated propellants, using the card-gap test technique. These data were extrapolated to unadulterated propellant by comparing the trends, with respect to RDX content, of the minimum shock pressure required near the critical diameter and the minimum pressure required in the ideal-diameter region. From the data near the critical diameters, it is estimated that for unadulterated propellant the minimum shock pressure required at the critical diameter is 25 to 30 kbar. This estimate would be greatly improved by acquisition of additional data from adulterated propellants near their critical diameters. In the ideal-diameter region, the data indicate that the minimum initiating pressure required for ANB-3226 is 8 to 10 kbar.

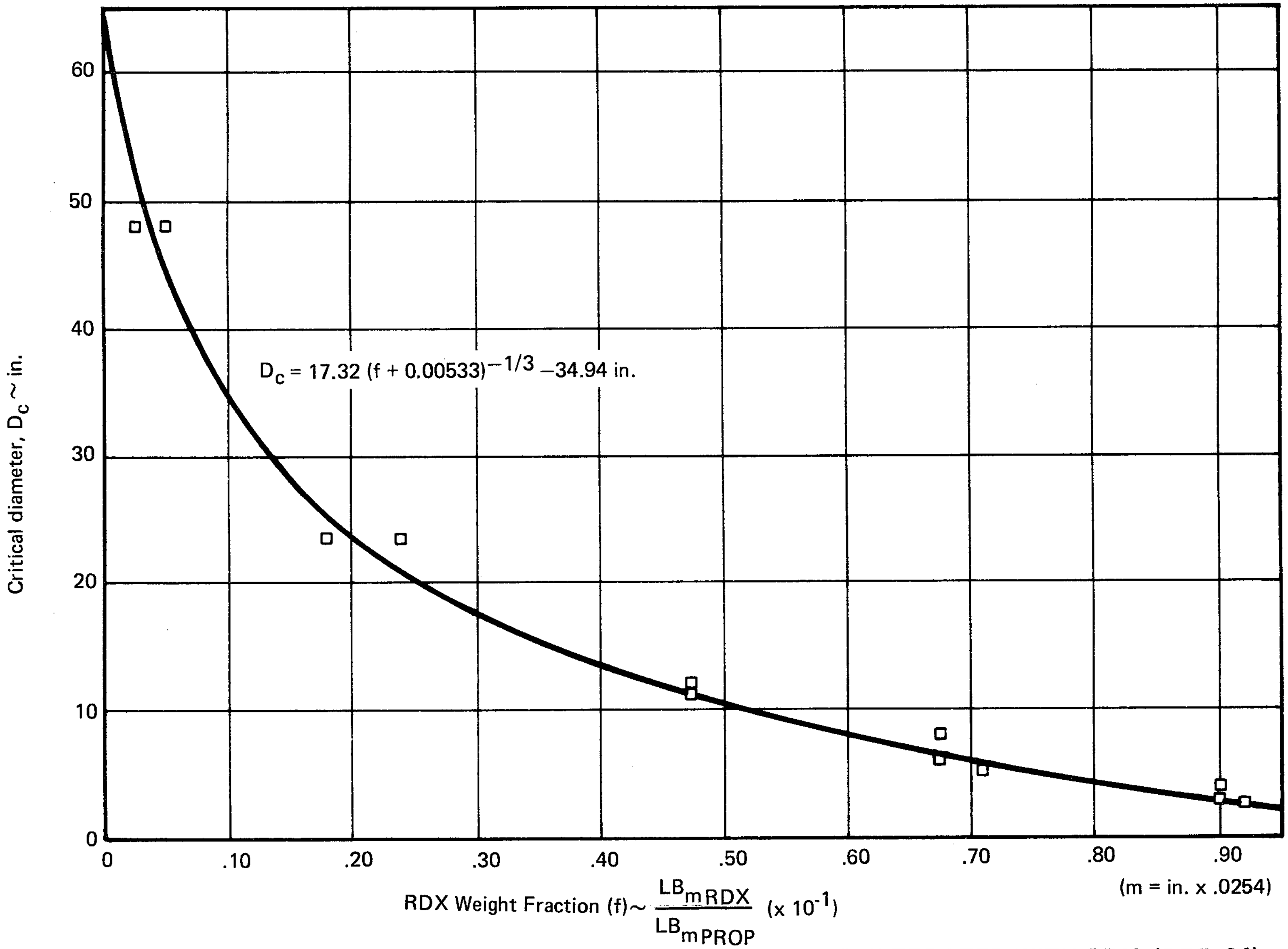


FIGURE 5-4. – DETONATION MODEL FOR ANB-3226 PROPELLANT ADULTERATED WITH RDX (REF. 34)

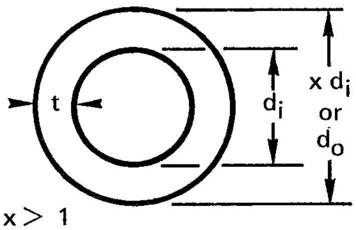
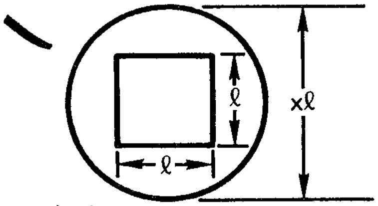
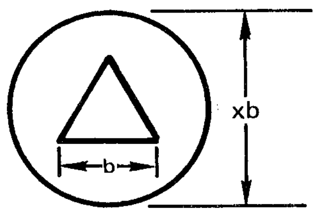
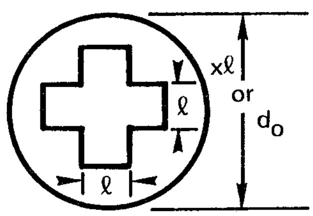
Shape and characterizing dimensions	Pseudo critical value of characterizing dimensions
Circular core  Where: x > 1	$d_{i_c} = \left(\frac{1}{x-1}\right) \sigma_c$ or if d_i is fixed $d_{o_c} = d_i + \sigma_c$
Square core  Where: x > 1	$\ell_c = \left(\frac{\pi x + 4}{\pi x^2 - 4}\right) \sigma_c$
Equilateral triangle core  Where: x > 1	$b_c = \left(\frac{\pi x + 3}{\pi x^2 - \sqrt{3}}\right) \sigma_c$
Cross core  Where: x > 1	$\ell_c = \left(\frac{\pi x + 12}{\pi x^2 - 20}\right) \sigma_c$ or if ℓ is fixed $d_{o_c} = \frac{\sigma_c}{2} \left[1 + \sqrt{1 + \frac{16 \ell}{\pi \sigma_c} \left(5 \frac{\ell}{\sigma_c} + 3\right)}\right]$

FIGURE 5-5. – PSEUDO CRITICAL DIMENSIONS OF VARIOUS SHAPES – PERFORATED GRAINS (REF. 33)

The ideal diameter (for mass detonation) was described as approximately 4 to 5 times the critical diameter thus requiring very large motor diameters to meet the condition of lower initiating pressure.

Data obtained from NOL card-gap tests, reference 39, of other conventional composite propellants (polyurethane, polyvinyl chloride, or polysulfide rubber binder) indicated that these propellants could not be detonated in the subcritical diameters tested. The incident pressure in these tests was in the order of 100 kbars.

5.3.1.3 Detonation sustainment – CMBD propellants: Published data on double base propellants is not as readily available as composite propellants. There has not been any major full scale testing effort of the magnitude of Project Sophy conducted to define propellant characteristics. The Navy has not released the latest results of testing on the cross-linked double base propellant development for the C4. Existing data used in this task has been obtained mainly through discussions with propellant manufacturers and published reports of known characteristics of CMDB propellants and on military test reports. In an effort to catagorize the parameters applicable to double base propellants a comparison has been made of these propellants to composite propellants based on availability of data.

5.3.1.3.1 Critical Diameter – Due to the nature of double base propellants, high energy additives are often used in their formulations to provide higher performances. Cyclotetramethylene Tetranitramine (HMX) is often used as high energy additive for double base propellants as well as nitroglycerin (NG) and nitrocellulose (NC). Many military solid rocket motors and some NASA solid launch vehicles motors use HMX. The Scout third stage rocket motor (Antares IIB) contains 19.5% HMX in its formulation (CYI propellant). Figure 5-6, reference 7, shows the effect of high energy ingredients on critical diameter as well as explosive booster size required to detonate solid propellants. Although the data points for donor size and critical diameter have not been verified in this study the curve does show the general relationship for critical diameter with increasing weight fractions of high energy ingredients. The NOL card-gap test (paragraph 3.3.1.1e) is shown superimposed on Figure 5-6. The location corresponds with the Tetryl donor weight used to detonate the cylindrical propellant specimen tested.

Figure 5-7 is a presentation of the critical diameter-weight fraction data and better shows this relationship.

The data presented in these figures gives an indication of the relative sensitivity of double base propellants to an explosive donor.

5.3.1.3.2 Shotgun quickness test – Data generated from the Trident Motor Detonation Investigation Program show that the most probable cause of propellant detonation during a motor test is from severe propellant breakup combined with a confining environment that allows sufficient heat impulse and pressure increase to cause runup from deflagration to detonation, reference 40. A test presently used to indicate the susceptibility of the propellant to fracture into small fragments under high shear loads is the shotgun/relative quickness test. The shotgun quickness test (paragraph 3.4a) is a measure of the breakup characteristics of solid propellant by determining those effects

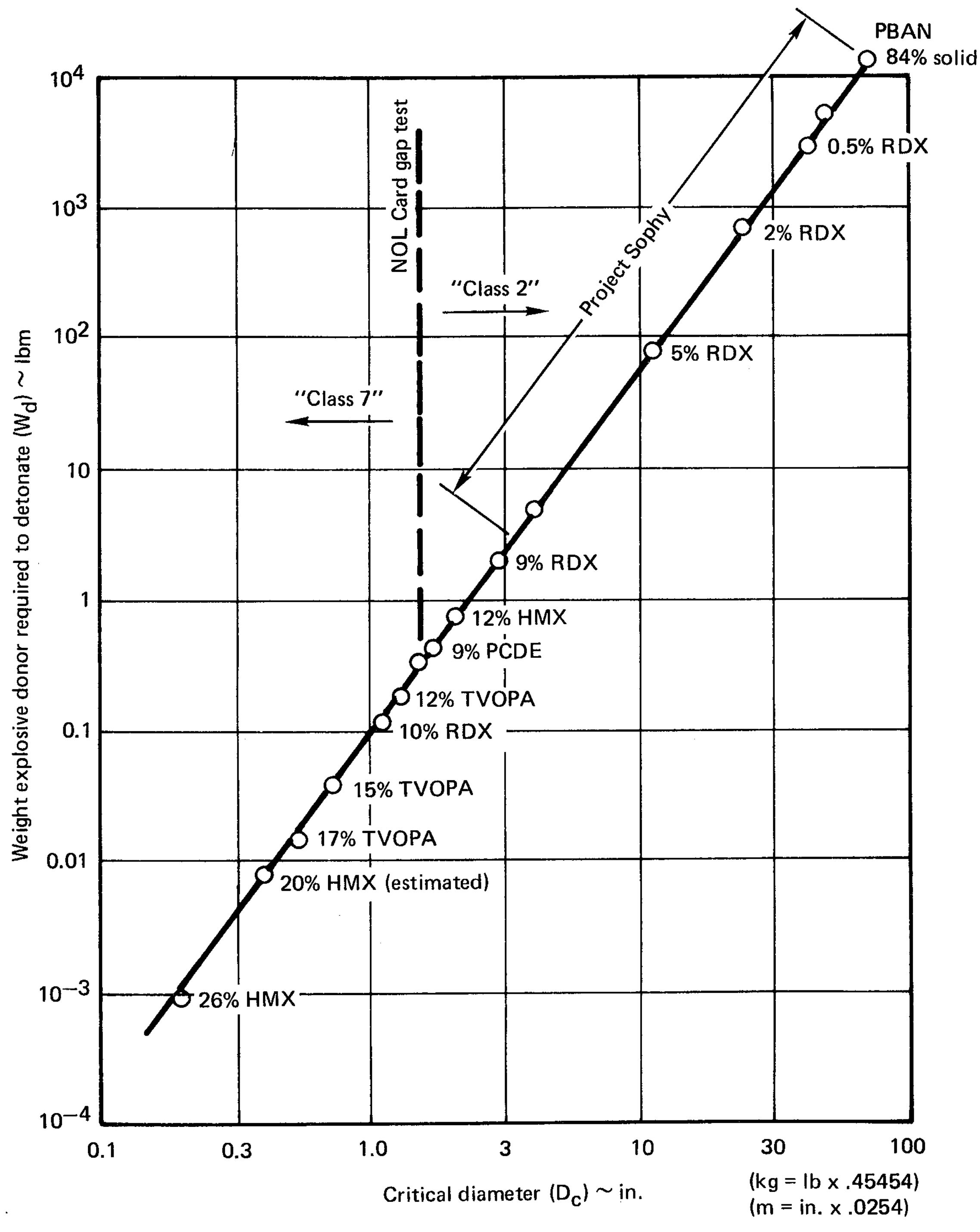
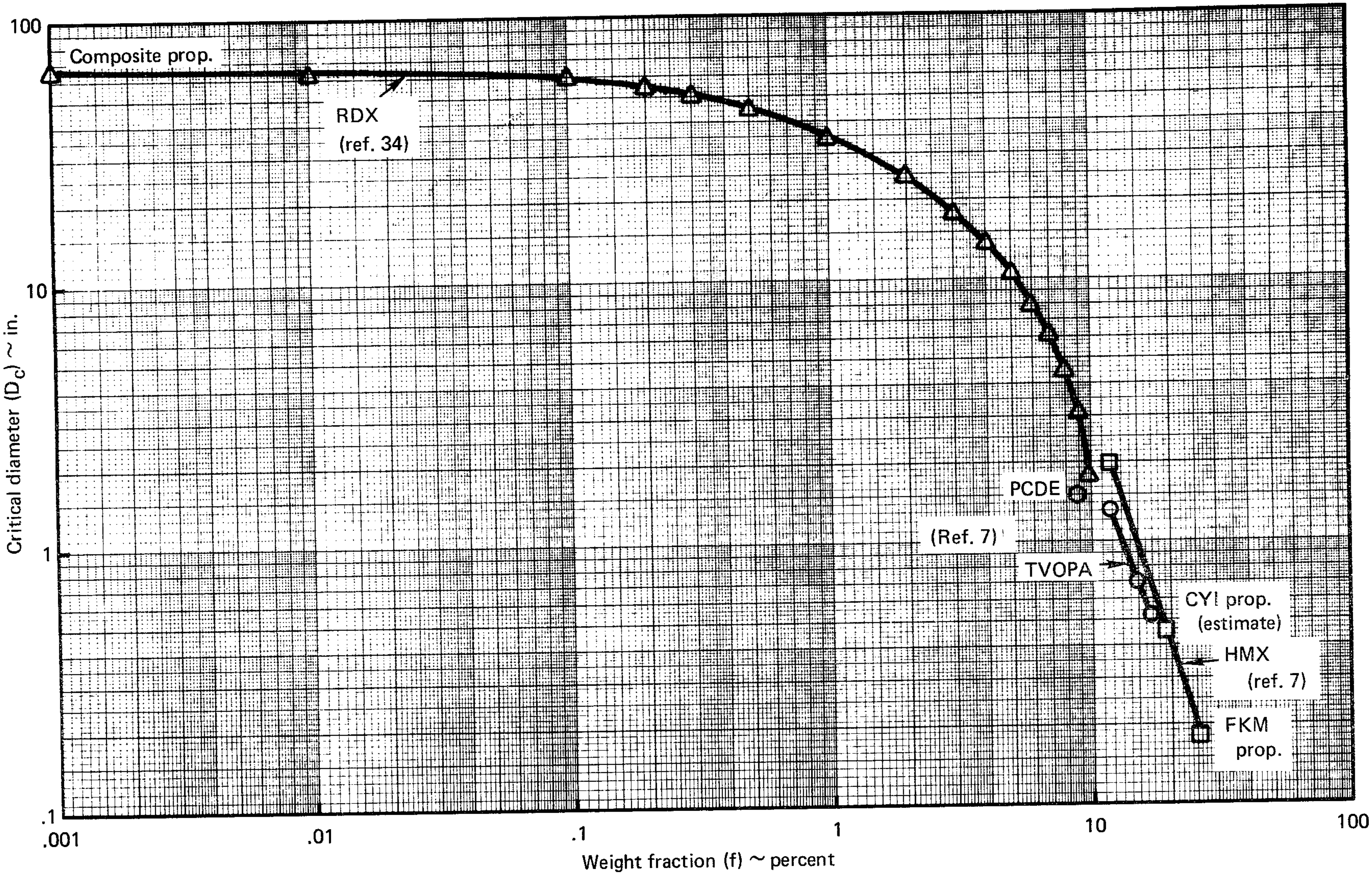


FIGURE 5-6. – EFFECT OF HIGH ENERGY INGREDIENTS ON CRITICAL DIAMETER AND EXPLOSIVE BOOSTER SIZE REQUIRED TO DETONATE SOLID PROPELLANTS (REF. 7)



(m = in. x .0254)

FIGURE 5-7. – CRITICAL DIAMETER VS. PERCENT WEIGHT FRACTION which occur as a function of impingement velocity such as sample breakup and initiation, burning, or explosion. The pressure rise rate in a closed bomb is a function of surface area (and therefore breakup), burning rate, flame temperature and gas production. However, for similar propellants, differences in pressure rise rate are almost entirely due to surface area (breakup). The propellant resistance to breakup, thus the susceptibility to conditions which may result in propellant detonation, can be compared among propellants by comparing the sample quickness as a function of impact velocity.

Figure 5-8 shows a quickness-impact velocity comparison for various propellants, reference 41 and 47. CYI and FKM are composite-modified double base (CMDB) propellants containing 19.5% and 26% HMX respectively. VOP, VLZ, and VPT are cross-linked double base (XLDB) propellants. TP-H-1123 and TP-H-1016 are composite propellants containing approximately 70% and 77% ammonium perchlorate respectively. A comparison of these curves shows that CMDB propellants which have been used over the last 10-15 years, experience considerably less damage at any given impact velocity than the composite or XLDB propellants formulations shown.

5.3.1.3.3 NOL Card Gap Test – Additional Data on propellant shock sensitivity, reference 39 has been obtained on different types of composite and double base propellants. These results have also been compared with better known military explosives. The testing that was conducted is based on the NOL card-gap tests. Although, in these tests, conventional composites (polyurethane, polyvinyl chloride, or polysulfide rubber binder) could not be detonated in the diameters tested (diameter tested was below critical diameter) double base propellants did detonate readily. Figure 5-9 shows the relative shock sensitivity (defined in terms of the number of sensitivity cards at the 50% probability of detonation) vs. the effects of temperature. Marked changes in temperature do not appear to induce comparable changes in sensitivity and such changes as do occur are generally in the expected direction, i.e., rising temperatures increase detonatability. Figure 5-10 taken from reference 39 and 44 shows the pressure pulse vs. the attenuator thickness (corresponding to the number of cards required to obtain 50% detonation probability). Although the actual pressure required to detail a response in a given solid rocket configuration may vary somewhat from the indicated value, the relative sensitivity of various propellants can be seen.

Superimposed on Figure 5-10 are the detonating pressure values for CYI (used on Scout 3rd stage Antares IIB) CYH, and EJC CMDB propellants, TP-H-3335 high energy composite propellant (21.6% HMX), and TP-H-3062 composite propellant (used on Scout 4th stage Altair IIIA). The data for the above propellants was obtained from published NOL card-gap test reports, reference 45, 46, and 43 and gives an indication of the relative sensitivity of these propellants. As can be seen, the detonation thresholds for these present day CMBD propellants is in the order of 30 to 44 kbars.

It should be noted that since the NOL card gap test is conducted with subscale samples which are subcritical for composite propellants and super-critical or near critical for CMDB propellants, the incident pressures reflect the higher sensitivity of CMDB propellants.

When comparing the incident pressure of full-scale motors, the composite propellant incident pressure (Project SOPHY) is lower than that of CMDB propellants. However, it should be recognized

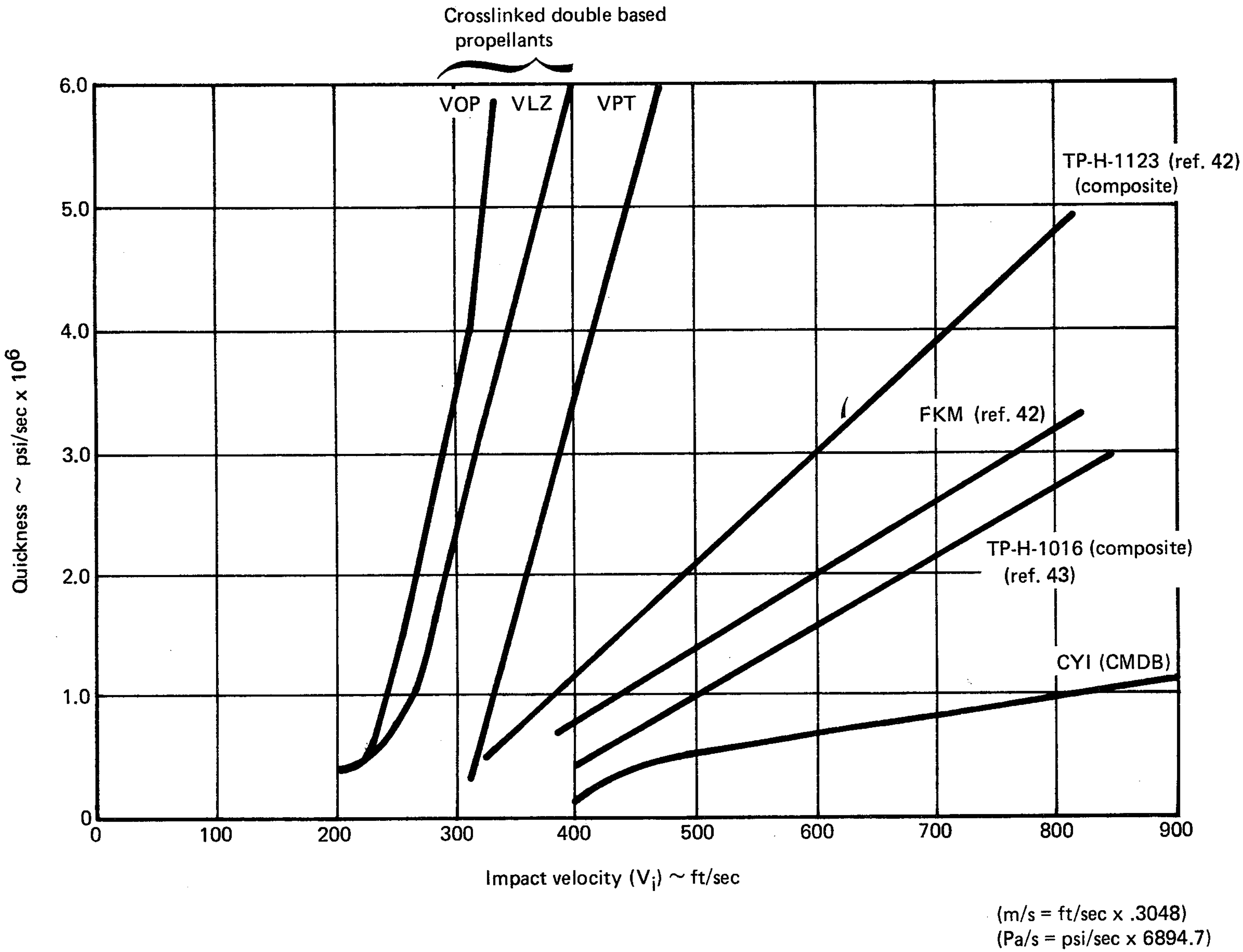


FIGURE 5-8. – QUICKNESS VS. VELOCITY COMPARISON OF VARIOUS PROPELLANTS (REF. 41)

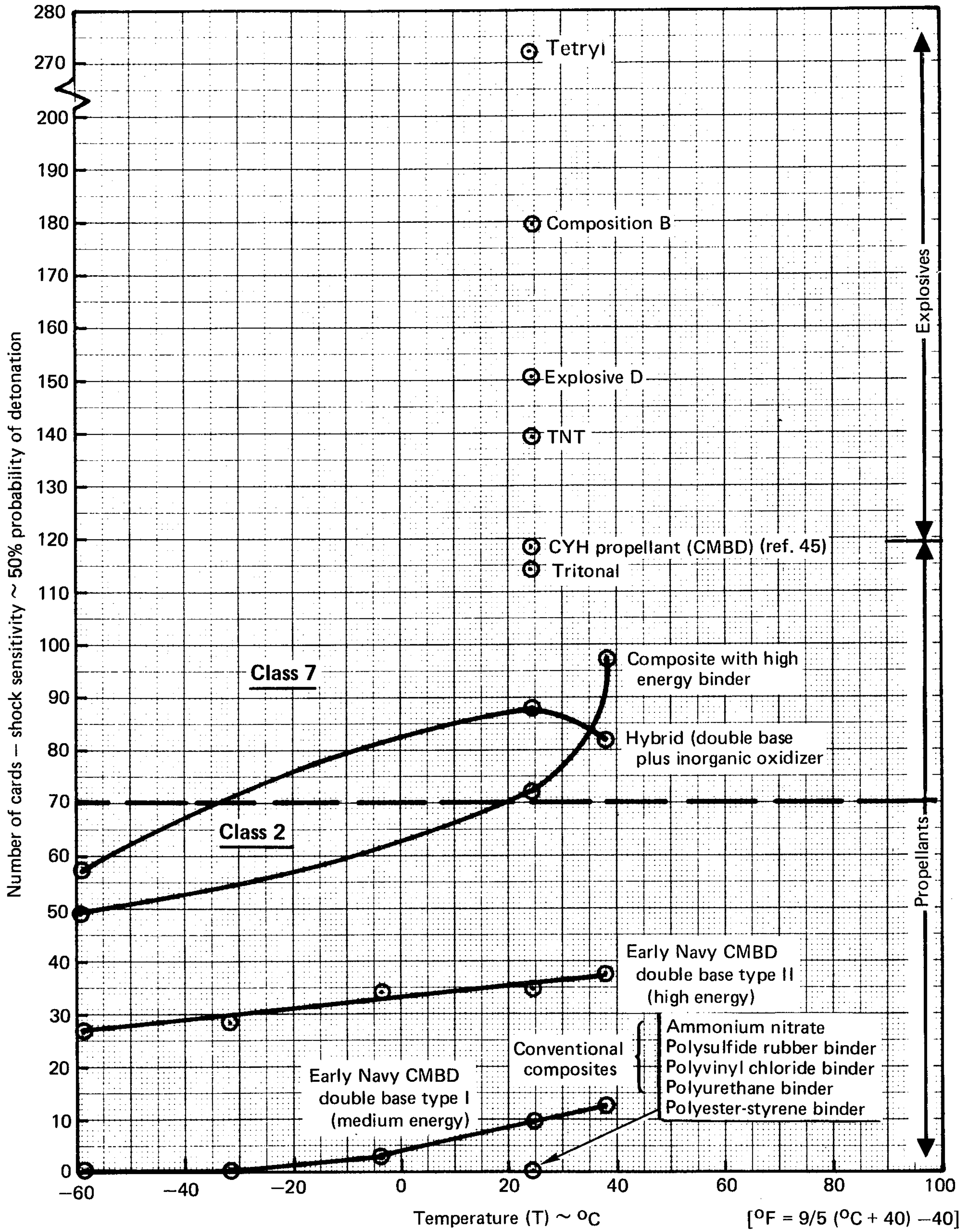


FIGURE 5-9. – CARD GAP TEST: NUMBER OF CARDS VS. TEMPERATURE (REF. 39, 44)

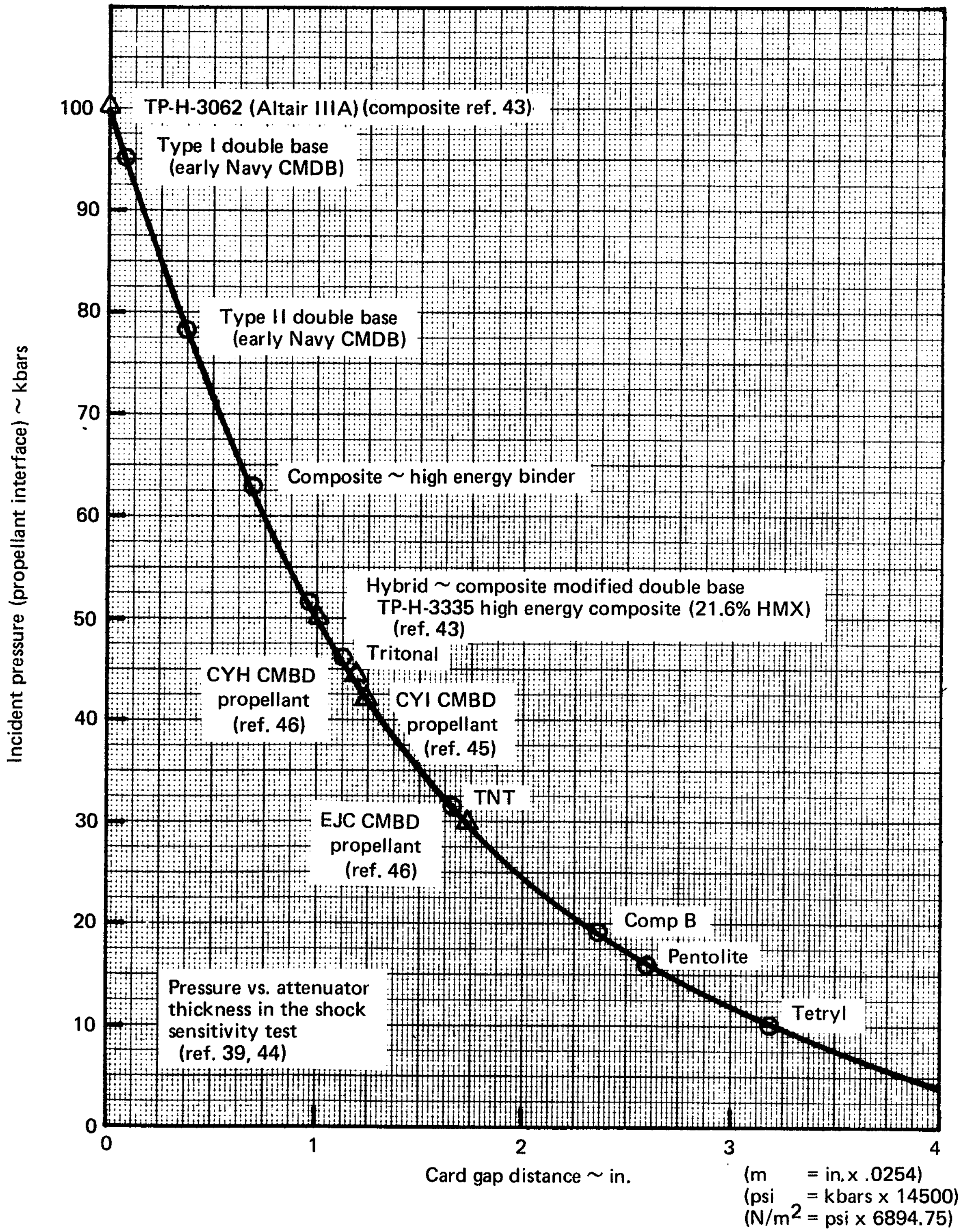


FIGURE 5-10. – INCIDENT PRESSURE IN CARD GAP TEST

that the critical diameter of the composite propellants tested is very large (62.4 in.) and that smaller diameter motors will not detonate; that is to say that full-scale composite propellants appear to be less sensitive than full-scale CMDB propellants as long as their diameters are less than critical.

5.3.2 Hazard Effects. – Most of the material damage caused by detonation or explosion is due mainly–directly or indirectly–to the shock (or blast) wave which accompanies the explosion. Structures will suffer some damage from air blast when the overpressure in the blast wave, i.e., the excess over the atmospheric pressure (14.7 pounds per square inch at standard sea level conditions), is about 0.5 pound per square inch or more. The distance to which this overpressure level will extend depends on the yield or size of the explosion, and on the height of the burst. In considering the destructive effect of a blast wave, one of its important characteristics is the overpressure. Classically, the properties which are usually defined and measured are those of the undisturbed or side-on wave as it propagates through the air. The peak side-on overpressure is the maximum value of the overpressure at a given location generated by the undisturbed shock wave.

5.3.2.1 General scaling laws: Scaling laws, reference 47 used to calculate the characteristic properties of the blast wave from an explosion of any given energy if those for another energy are known. With the aid of such laws, it is possible to present data for a large range of weights in a simple form.

Theoretically, a given pressure will occur at a distance from an explosion that is proportional to the cube root of the energy yield. Full-scale tests have shown this relationship between distance and energy yield to hold over a wide range of explosive weights (up to and including a megaton). According to this law, if d_1 is the distance (or slant range) from a reference explosion of W_1 pounds at which a specified hydrostatic overpressure or dynamic pressure is found, then for any explosion of W pounds, these same pressures will occur at a distance d given by:

$$d/d_1 = (W/W_1)^{1/3}$$

Cube root scaling can also be applied to arrival time of the shock front, positive phase duration, and impulse, with the understanding that the distances concerned are themselves scaled according to the cube root law. The relationships may be expressed in the form

$$\frac{t}{t_1} = \frac{d}{d_1} = \left(\frac{W}{W_1}\right)^{1/3} \quad \text{and} \quad \frac{I}{I_1} = \frac{d}{d_1} = \left(\frac{W}{W_1}\right)^{1/3}$$

where t_1 represents arrival time or positive phase duration and I_1 is the impulse for a reference explosion W_1, as before, d_1 and d are distances from ground zero. If W_1 is taken as 1 pound, then the various quantities are related as follows:

$$t = t_1 \times W^{1/3} \text{ at a distance } d = d_1 \times W^{1/3}$$

and

$$I = I_1 \times W^{1/3} \text{ at a distance } d = d_1 \times W^{1/3}$$

Throughout the Sophy and Pyro works blast yield is expressed as percent yield, based on an average of pressures and impulses measured at the farthest distance from the source when compared to standard reference curves, reference 48, for TNT surface bursts (terminal yield). Hopkinson's blast scaling is used when comparing blast data for tests with the same propellants and failure conditions, but different mass of propellant. So, the blast parameters P (peak side-on overpressure) and $I/W^{1/3}$ (scaled impulse) are plotted as functions of $R/W^{1/3}$ (scaled distance λ), after being normalized by the fractional yield.

Figure 5-11 shows the peak-overpressure as a function of ground range scale factor (λ) for TNT as normally presented in literature, reference 2. The use of this data can be simplified by using the run-around chart in Figure 5-12.

TNT is the base or standard to which other explosives and propellants are normally referenced, however, some use PETN or Tetryl as a reference.

5.3.2.2 Peak side-on overpressure: The characteristics of pressure waves, particularly peak side-on overpressure and specific impulse, are used extensively on developing damage estimates from propellant explosions.

A review of available overpressure data related to solid rocket motor explosions/detonations shows considerable scatter of data. This can generally be attributed to variable conditions leading to the explosion, i.e., if the motor detonated or exploded, the location of donor charge relative to the acceptor, configuration of rocket motors, interstage structure spacing, type of test, impact or donor charge.

Figure 5-13 shows the peak side-on overpressure vs. ground range scale factor, λ, for several tests. λ is defined as the ground range (R) from the reference explosion divided by the cube root of the reference propellant weight ($W^{1/3}$). The data shown by Figure 5-13 indicates the peak side-on overpressure upper limits that can be expected for typical composite or double base propellants. In cases where a motor detonated, such as the project Sophy adulterated composite propellant motor, the overpressure recorded is the greatest.

Rocket motors which exhibited deflagration or explosion with large pieces of burning propellant (firebrands) and case scatter, the recorded overpressure is much less. The curve for TNT is shown for reference.

5.3.2.3 Positive overpressure impulse: Figure 5-14 gives the scaled positive overpressure impulse $\left(\frac{I}{W^{1/3}}\right)$ as a function of ground range scale factor, λ, for several solid propellant rocket motors. It represents the area under the positive phase of the pressure time curve. The scatter of data, as for overpressure, can be attributed to variable conditions. Deflagration/explosion resulting in propellant scatter generally results in lower impulse than a detonation. Figure 5-14 gives an indication of the upper limits that can be expected for typical composite or double base propellants. A reference curve for TNT is shown for comparison.

5.3.2.4 TNT Equivalency: The free-air equivalent weight of a particular propellant or explosive is the weight of a standard explosive, e.g., TNT, required to produce a selected shock wave

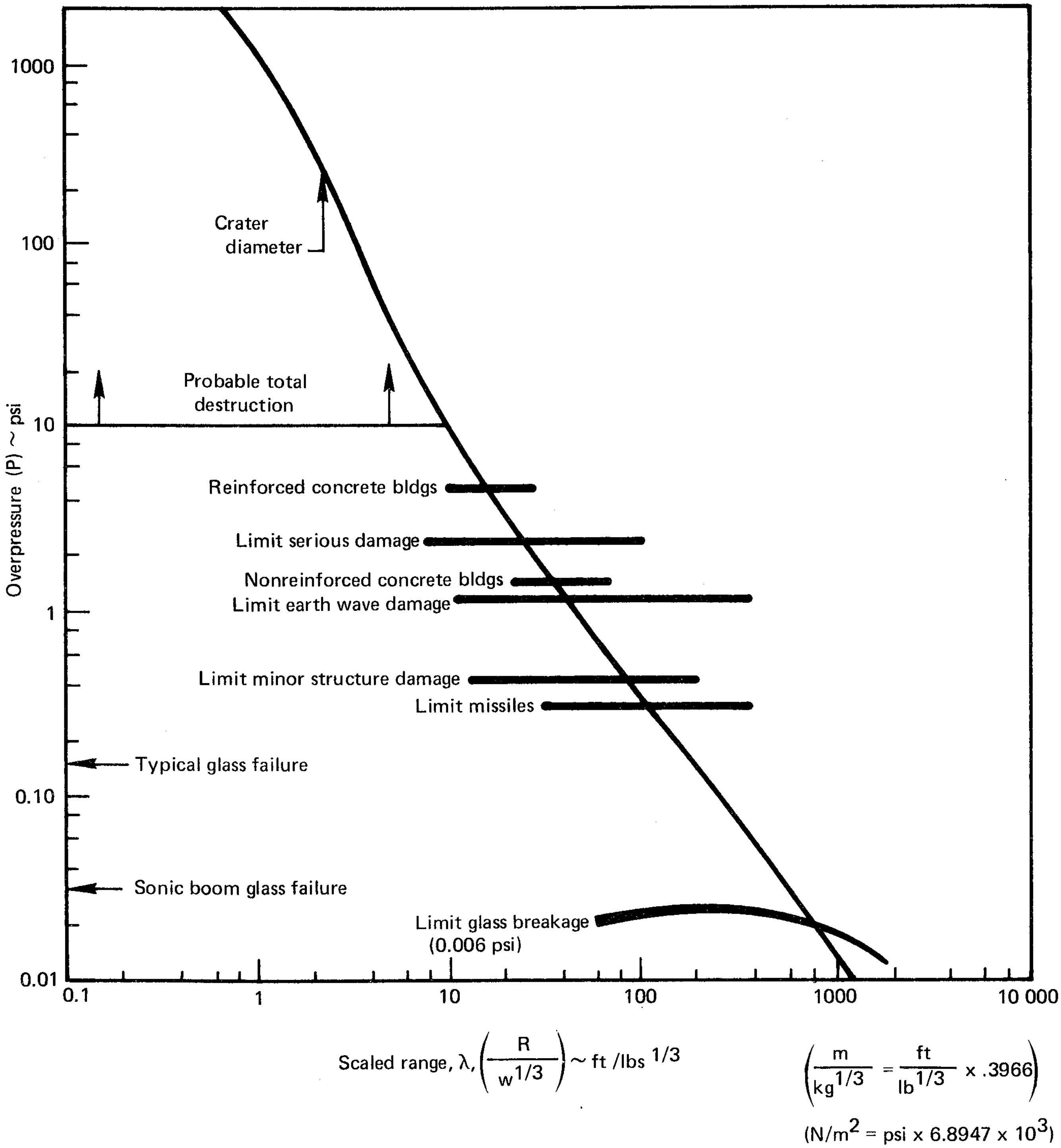
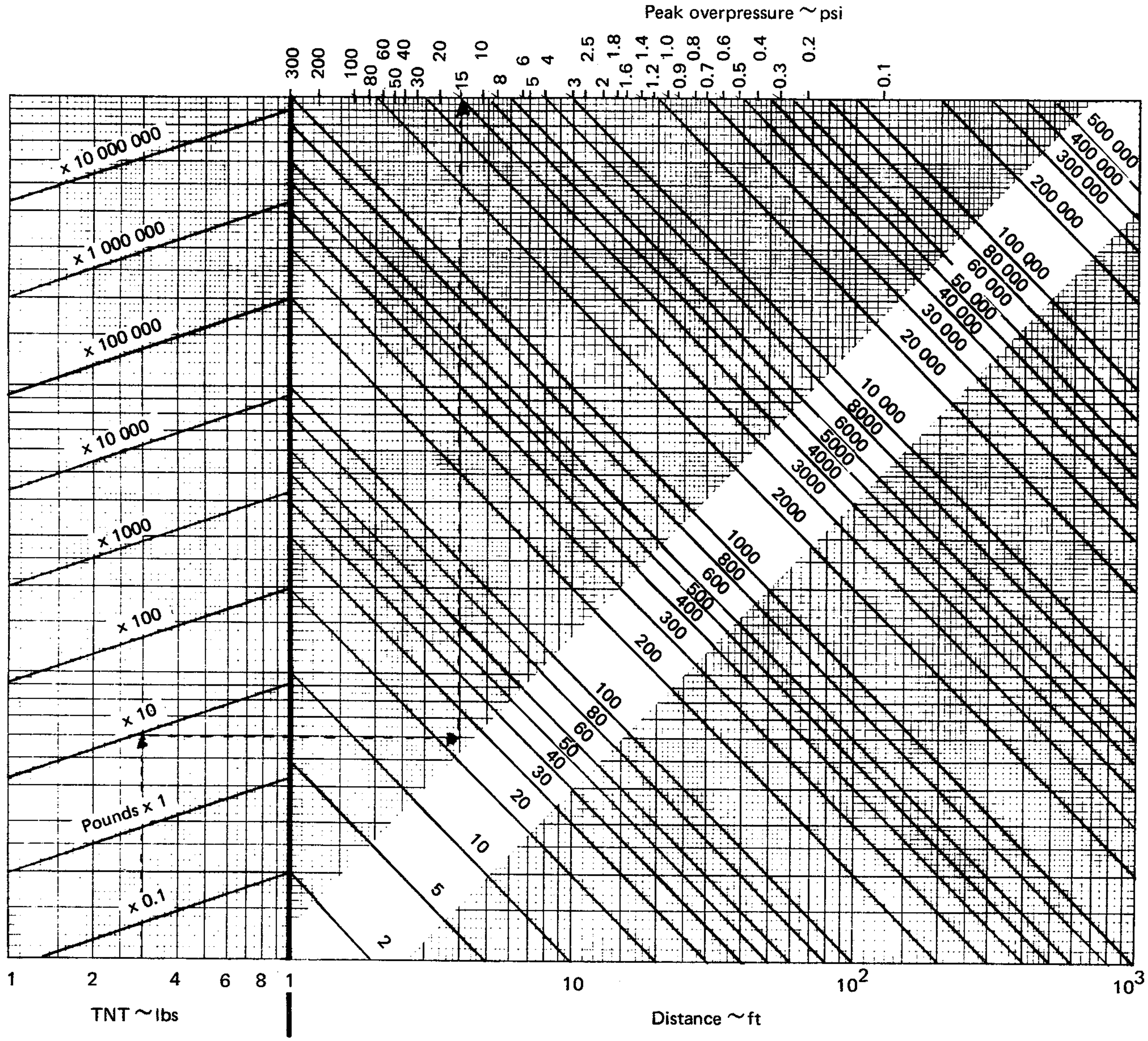


FIGURE 5-11. – OVERPRESSURE SCALED DISTANCE PLOT SHOWING TYPICAL LEVELS FOR BLAST DAMAGE (REF: 2)



Peak over-pressure (psi)	Effect
0.2	Limit for uncontrolled area. No significant damage to personnel or facilities
0.4	Limit for unprotected personnel
0.5 to 1	Breakage of window glass
0.75	Limit for windowless, ordinary construction
1 to 2	Light to moderate damage to transport-type aircraft
3	Exposed man standing face-on will be picked up and thrown; very severe damage, near total destruction to light industrial buildings or rigid steel framing; corrugated steel structures less severely damaged
3 to 4	Severe damage to wooden frame or brick homes
4 to 6	Complete destruction of aircraft or damage beyond economical repair
5	Possible ear damage, exposed man standing side-on will be picked up and thrown; complete destruction of wooden frame or brick homes; severe battering of automobiles and trucks
6	Moderate damage to ships
6 to 7	Moderate damage to massive, wall bearing, multi-story buildings
7	Possible internal injuries to human beings
9	Complete destruction of railroad boxcars
10 to 12	Serious damage to and sinking of all ships
12	Possible lung injuries to exposed personnel
20 to 30	50% probability of ear drum rupture
25	Probable limit of thermal injury

Example:

Detonation of 30 pounds of TNT results in a peak overpressure of 15 psi at 25 feet.

FIGURE 5-12. – PEAK OVERPRESSURE AND DISTANCE FOR TNT SURFACE BURST

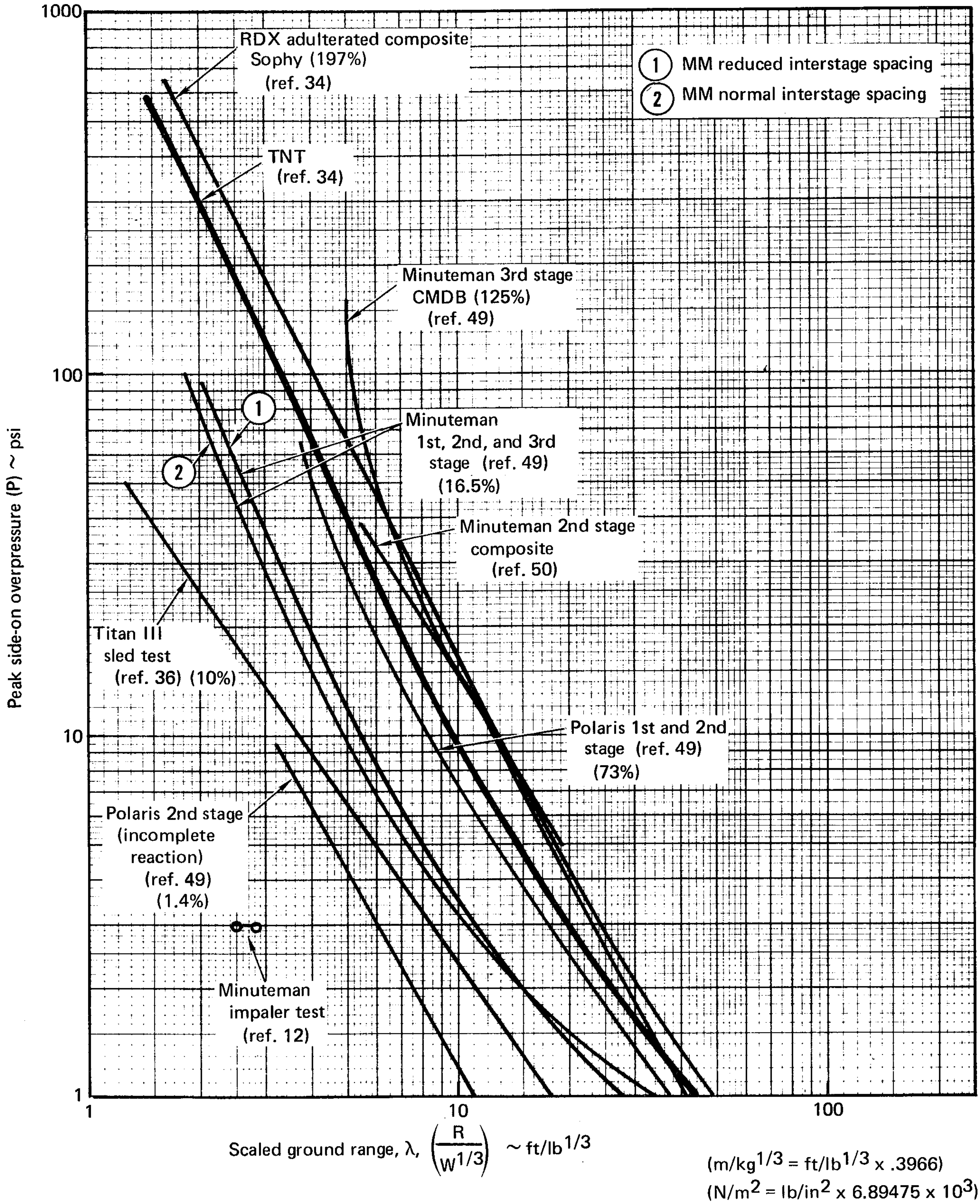
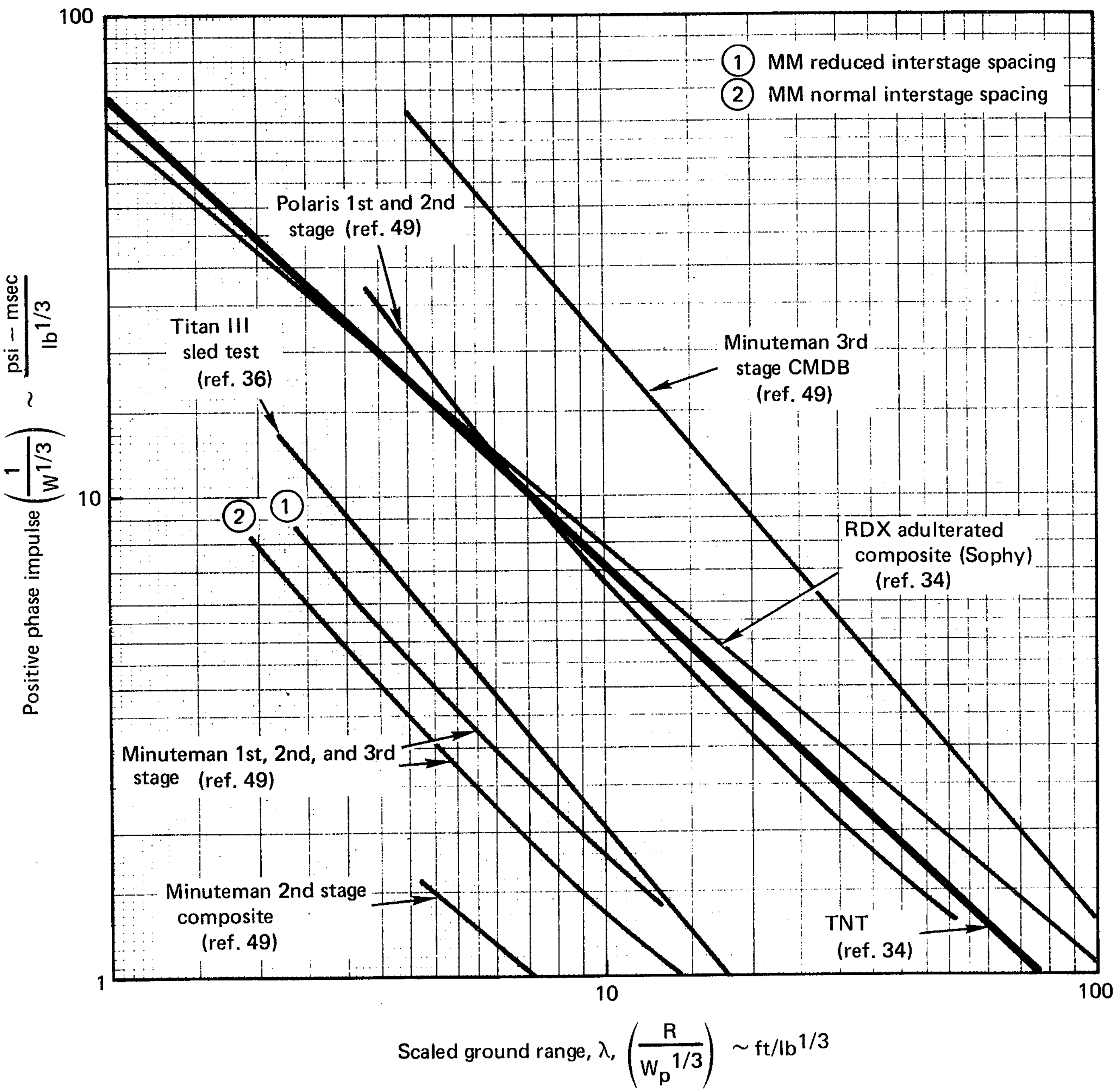


FIGURE 5-13. – PEAK SIDE-ON OVERPRESSURE VS. SCALED GROUND RANGE



$$\left(\frac{m}{kg^{1/3}} = \frac{ft}{lb^{1/3}} \times .3966\right)$$

$$\left(\frac{N/m^2}{kg^{1/3}} = \frac{psi - msec}{lb^{1/3}} \times 8.9766\right)$$

FIGURE 5-14. – POSITIVE PHASE IMPULSE VS. SCALED GROUND RANGE

parameter of equal magnitude to that produced by a unit weight of the propellant or explosive in question.

A given explosive may have several equivalent weights, depending on the shock wave parameter selected, i.e., it can be based on peak overpressure or positive impulse. Propellant TNT-equivalence can be obtained by cubing the ratio of the λ for propellant to the λ for TNT at any given overpressure level, reference 34.

$$\left(\frac{\lambda_P}{\lambda_{TNT}}\right)^3 \times 100 = \% \text{ TNT Equivalence}$$

Figure 5-13 shows the solid propellant rocket explosive overpressure to be on either side of the TNT curve, thus indicating TNT equivalencies above and below 100%. Since the propellant curves do not parallel the TNT curve, it can be seen that TNT equivalency is not constant but varies as a function of range. Explosive donor type tests conducted by the Naval Weapons Center on explosive equivalency of Class 2 (composite type) and Class 7 (composite modified double base type) motors, reference 49, showed the explosive behavior to take two forms. For higher yield tests (> 100%) the peak overpressure yield tends to decrease with increasing range. In the lower yield tests (< 100%) the peak overpressure yield tended to increase with increasing range, the yields tending toward a constant value (terminal yield) at long distances. The results of these tests indicated that class 7 motors (CMDB) tested were capable of producing yields averaging 130% of TNT, and Class 2 motors (composite) produced yields as large as 40%. Combined tests of composite and double base motors resulted in yields from 105 to 123%.

Data from Project Sophy, reference 34 obtained from RDX adulterated composite propellant tests indicated an average (over range measured) peak side-on overpressure TNT equivalence of approximately 197%. Similar data on impulse-TNT equivalence indicated values which varied substantially both with range and weight with an average of approximately 114%.

It is brought forth from Project Sophy that terminal yield is defined as the average of the TNT equivalences based on both peak overpressure and impulse over the ranges that these tests included. The terminal yield of detonating adulterated and unadulterated propellant is 168%. The terminal yield for the nondetonating propellant is 156%.

It should be noted that the nature of these tests biases these data because all samples are nearly critical and those that failed to detonate still contributed most of their energy to the fading detonation. Much smaller samples certainly would have correspondingly lower TNT equivalents and terminal yields.

Shown in parenthesis on each curve of Figure 5-13 is the reported value of terminal TNT equivalency for various tests. Although there exists considerable difference in terminal yield equivalency data, it can be seen from the Minuteman 3rd stage data that the TNT equivalency can be considerably higher at close range approaching a lesser value at larger distances.

Figure 5-15 shows the reported TNT equivalency (terminal yield) as a function of total weight (propellant weight plus donor charge weight) for several composite and double base propellant explosive donor tests, references 47 and 37. Combined tests in which a double base propellant motor was detonated and used as a donor charge for a composite motor are also shown.

The upper limit of terminal yield (based on available data) has been indicated on Figure 5-15 for each propellant type and for combined tests so that a comparison can be made with the Project Sophy limits.

As can be seen, actual test data from composite propellant rocket motor tests does not approach the limits established by Sophy. This may be due to the sub-critical size of the motors tested where only a "partial" detonation or explosion was achieved. Terminal yield TNT equivalency for composite modified double base propellant motors of 130-140% shown on Figure 5-15 is in agreement with the reported equivalency of 130% reported by Hercules Incorporated, reference 46.

5.3.2.5 Fireball effects: The most extensive source of fireball data resulting from solid propellant motor detonation or explosion has been obtained from Project Sophy, reference 34 Fireball data were recorded and reduced from a total of 16 atmospheric ground tests made using right circular cylinders of propellant varying from 11 to 72 inches in diameter and length 4 times the diameter. The propellant was initiated by a TNT donor charge constituting approximately 1/5 of the total test weight. Fireball diameter was taken to be the maximum horizontal dimension of the fireball, not the height of the fireball above the ground. While the exact shapes of these plots differed considerably from test to test there were certain similarities. In every case, both the height and diameter of the fireball increased rapidly to a maximum value, or plateau. The fireball decay pattern differed markedly from test to test.

Figure 5-16 summarizes the main fireball characteristics as a function of total propellant weight. Total sample explosive weight (propellant plus TNT donor weight) had to be used since it was impossible to isolate that portion of the fireball caused by the TNT donor. Typical solid rocket motors are shown superimposed on the curves at their appropriate weight.

It must be remembered that the Sophy Tests were basically atmospheric propellant critical diameter ground tests and that the fireball characteristics of the detonating and non-detonating propellant are for a composite formulation with a weight fraction of 69% total oxidizer and 15% aluminum. This is, however a representative formulation of many composite propellants in use. The Sophy Tests were conducted with samples that were nearly critical or supercritical. Since the literature survey did not reveal any published fireball data on subcritical diameter solid rocket motors or on exoatmospheric tests, care should be exercised in using these correlations since very subcritical samples and vacuum testing cannot be expected to produce equivalent data.

5.3.2.6 Firebrand effects: Collected data on various composite and double base propellants show that both types exhibit an ignition type reaction at near identical velocity/mass test conditions, reference Figures 5-1 and 5-2. The difference in response to impact varies from burning to explosion. Explosions or incomplete detonations are often characterized by showers of burning propellant fragments or "firebrands" over a wide area. Although data of this nature is limited due to the unexpected nature of rocket motor impact occurrences, some limited data has been compiled, reference 7, and is presented in Figure 5-17.

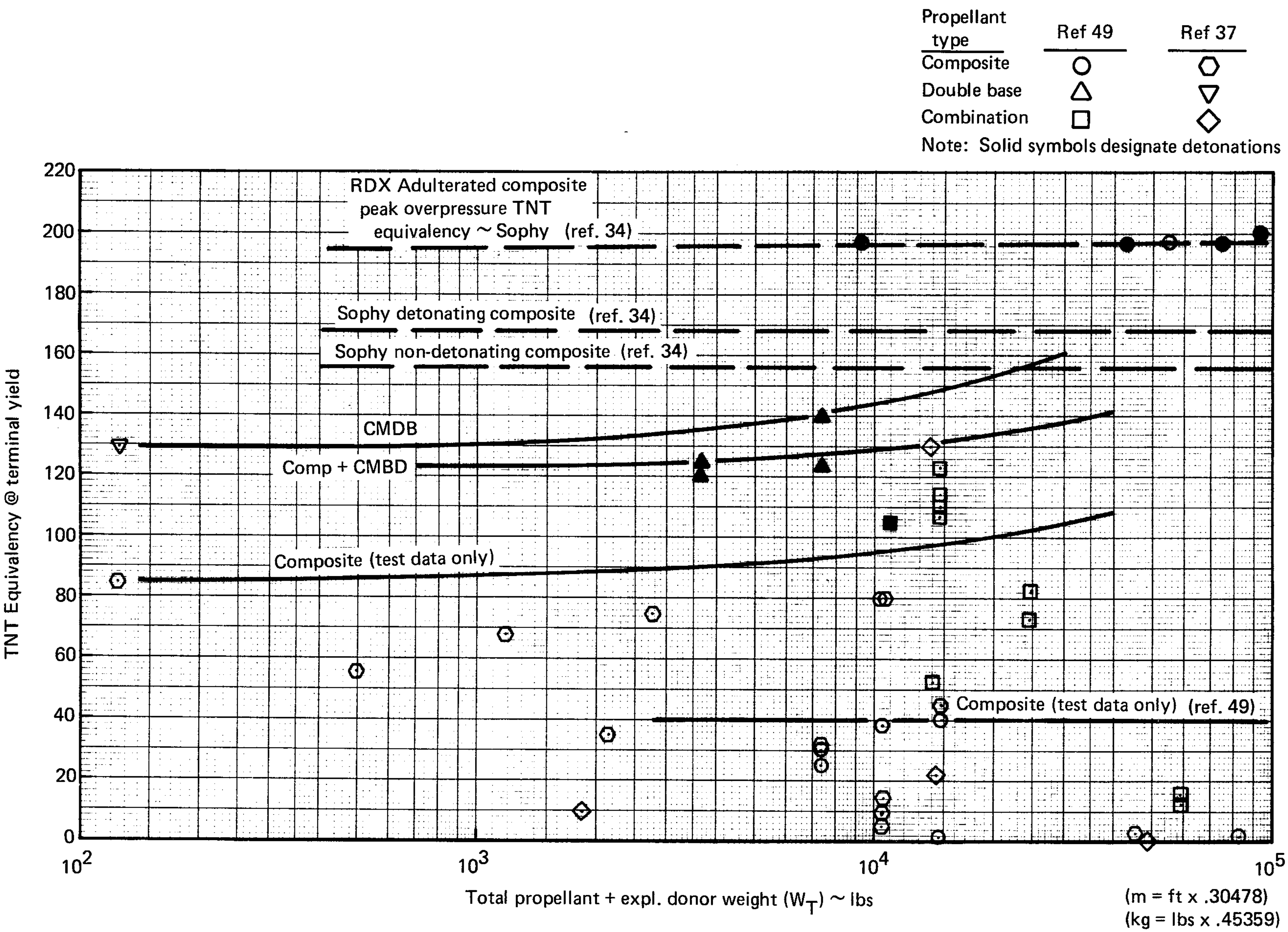


FIGURE 5-15. – TNT EQUIVALENCY AT TERMINAL YIELD – SOLID PROPELLANT SYSTEMS

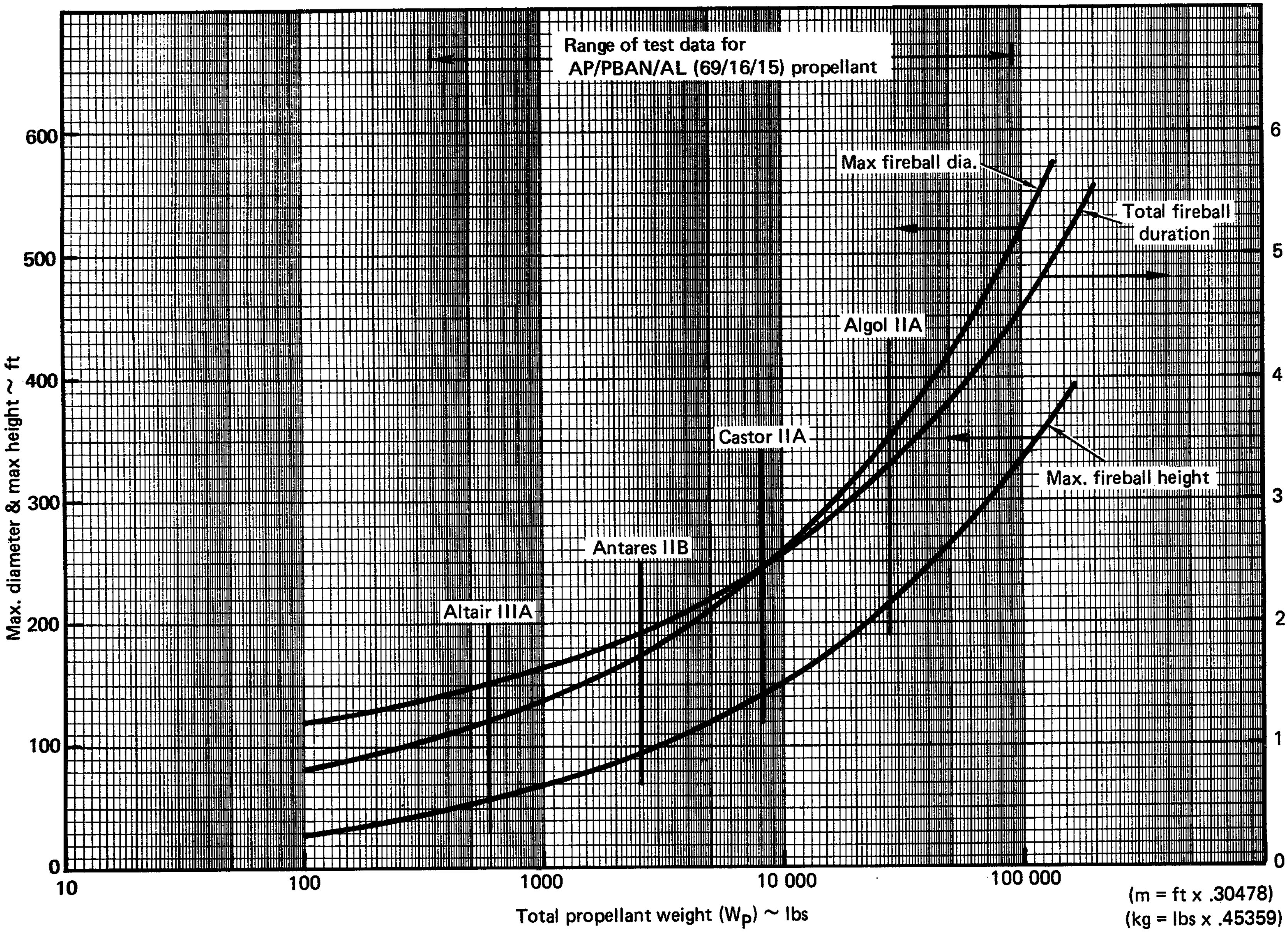
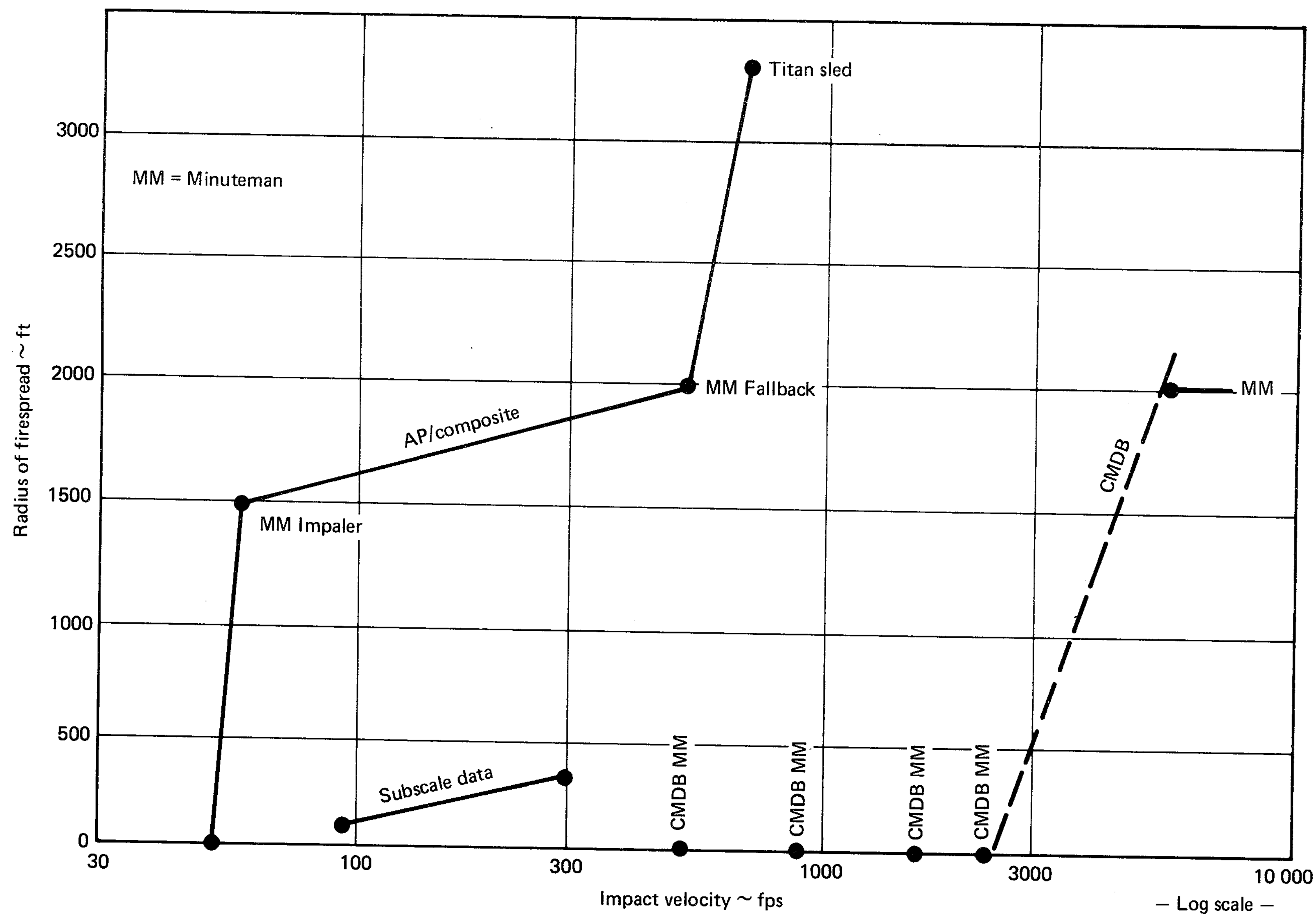


FIGURE 5-16. – ESTIMATES OF FIREBALL CHARACTERISTICS – SOLID SYSTEMS



(m = ft. x .30478)

FIGURE 5-17. – MAXIMUM FIREBRAND THROW DISTANCES FOR SOME SOLID PROPELLANTS (REF. 7)

5.3.2.7 Fragmentation: Existing available fragmentation data, references 7 and 49, resulting from solid rocket motor explosions/detonations has been compiled and is presented in Figure 5-18. These data were obtained from explosive donor tests and from impact tests performed by military agencies.

In general, the majority of data obtained is from composite propellant rocket motors. Data from composite modified double base propellants is limited. A maximum fragment radius limit line has been superimposed on the figure to designate the maximum limit observed from available data. A second curve obtained from reference 51 shows the limits established by the U. S. Air Force Eastern Test Range based on actual Polaris and Minuteman Missile Explosions/Detonations. The fragment range data is plotted as a function of total weight (propellant plus explosive donor) for donor tests and as a function of propellant weight for impact tests.

Fragment studies performed on Minuteman and Polaris Motors, reference 49, indicated that only those tests involving motors with metal casings resulted in significant fragment debris. A typical fragment density/ground range relationship is shown in Figure 5-19 for a Polaris detonation test involving a 8,870 lb. CMDB second stage and a 15,200 lb. composite first stage. In this test, the motors were placed vertically and a 96 lb. explosive booster was used to initiate the 2nd stage. The estimated terminal yield based on total propellant weight was 73 percent. Pieces of burning propellant were widely scattered with pieces of unburned propellant found propelled to 1800 ft. and motor parts found at distances out to 2500 ft.

Although this example is shown for a moderate yield explosion, it is probably representative of the yields expected for composite propellant rocket motor explosions. Higher yields, representative of CMDB propellant motors, may or may not generate fragments over a wider range depending on whether the motor case material is metal or fiberglass.

5.4 Liquid Propellant Systems

One extremely important fundamental fact concerning liquid propellants is that their potential explosive yield is very high, but their actual yield is much lower. This situation occurs because the propellant and oxidizer are never intimately mixed in the proper proportions before ignition.

The explosive potential of a given liquid propellant combination in accidental failure is not a unique value, but depends on the manner in which propellants are brought together during the failure process and on the time of ignition.

Presently, there are at least four methods for estimating yield of liquid propellant explosions which, unfortunately, do not necessarily give the same predictions: One method is based on Project Pyro results, reference 35, and two of the others are the "Seven Chart Approach" and the "Mathematical Model" of Farber and Deese, reference 52. The fourth approach, which is really based on the previous three methods, was developed by Baker, et al., reference 53, and is easy to use and readily adaptable to the calculation of explosive yield.

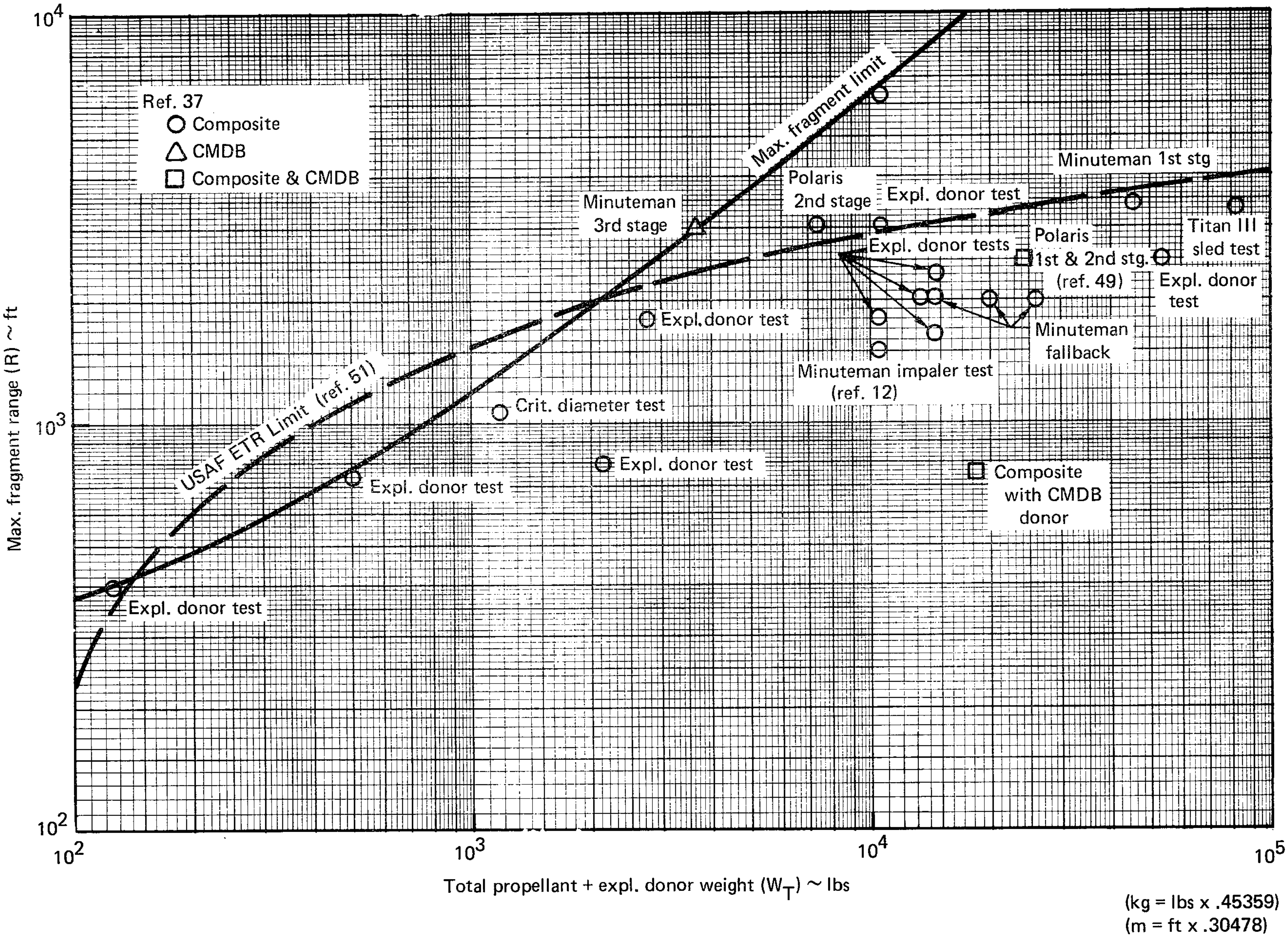
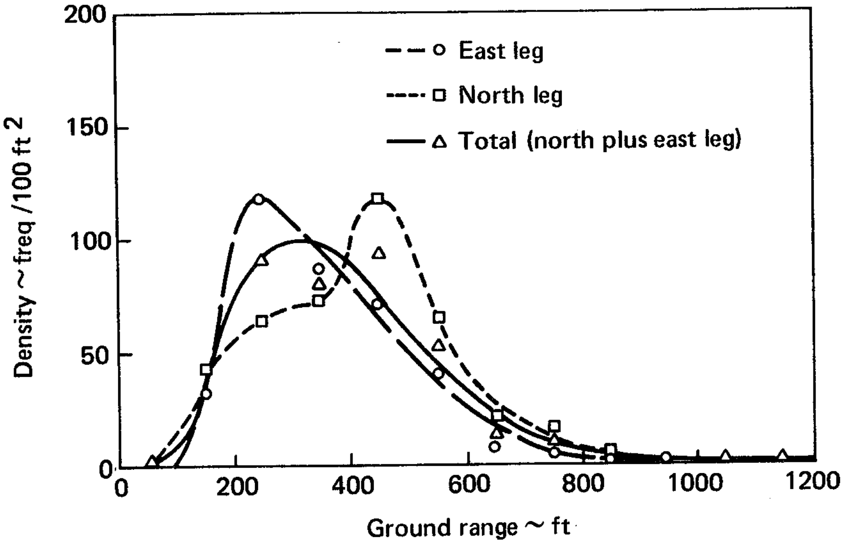
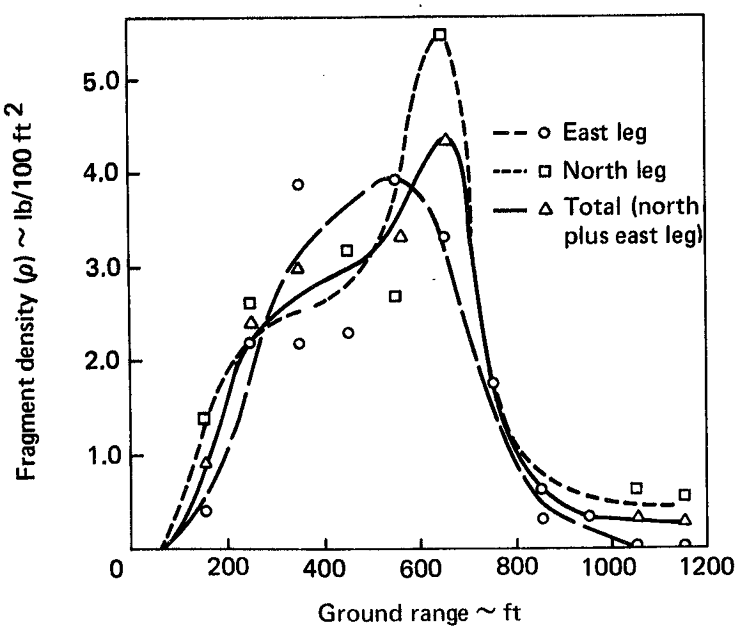


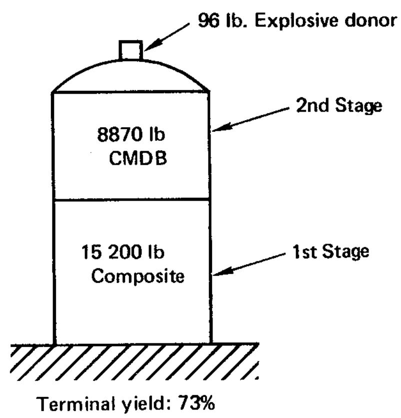
FIGURE 5-18. – MAXIMUM FRAGMENT RANGE – SOLID PROPELLANT SYSTEMS



Fragment density by frequency versus ground range



Fragment density by weight versus ground range



(m = lb x .45454)

$$\left(\frac{kg}{m^2} = \frac{lb}{100\ ft.^2} \times 4.8926 \right)$$

$$\left(\frac{Freq.}{m^2} = \frac{Freq.}{100\ ft.^2} \times 10.7639 \right)$$

FIGURE 5-19. – FRAGMENT CHARACTERISTICS FOR POLARIS EXPLOSIVE DONOR TEST (REF. 49)

The data presented in this Section is based on project Pyro results and has been taken from reference 54 which was based on reference 53.

In this section, three types of fuel and oxidizer combinations and three different modes of mixing will be considered. The three types of propellants are:

1. Hypergolic Propellant – Which is in widest use. A fuel of 50% N_2H_4 – 50% UDMH and an oxidizer of N_2O_4 in a mass ratio of 1:2.
2. Liquid Oxygen – Hydrocarbon – This propellant uses kerosene (RP-1) as a fuel and liquid oxygen (LO_2) as the oxidizer in stoichiometric mass ratio of 1:2.25.
3. Liquid Oxygen – Liquid Hydrogen – This propellant is an entirely cryogenic combination of liquid hydrogen (LH_2) fuel and liquid oxygen (LO_2) oxidizer in stoichiometric mass ratio of 1:5.

The three modes of mixing (failure modes) discussed are:

1. Confinement by Missile (CBM) – This type of accident consists of failure of an interior bulkhead separating fuel and oxidizer and all propellant mixing is confined within the tankage.
2. Confinement by Ground Surface (CBGS) – This type of accident includes impacts at various velocities on the ground, with all tankage ruptured, and subsequent ignition resulting from propellant mixing on the ground surface.
3. High Velocity Impact (HVI) – This type of accident involves high velocity impact of a missile after launch.

5.4.1 Explosive Yield. – From the test results reported in references 35, 55 through 57 and presented by reference 54, a number of observations were made regarding blast yields from liquid propellant explosions.

1. Yield is quite dependent on the particular fuel and oxidizer being mixed.
2. The yield is very dependent on the mode of mixing of fuel and oxidizer, i.e., on the type of accident which is simulated. Maximum yields are experienced when intimate mixing is accomplished before ignition.
3. On many of the liquid hydrogen/liquid oxygen (LH_2/LO_2) tests (regardless of investigators), spontaneous ignition occurred very early in the mixing process, resulting in very low percentage yields.
4. Yield is very dependent on time of ignition, even ignoring the possibility of spontaneous ignition.
5. Blast yield per unit mass of propellant decreases as total propellant mass increases.
6. Variability in yields for supposedly identical tests was great, compared to variability in blast measurements of conventional explosives.

Table 5-I provides a sequence to be used in determining the explosive yield of various propellant/oxidizer combinations and failure modes. To use the table, identify the type of propellant and type of accident. Then the proper sequence in "Part 1" should be followed after making the necessary assumptions (e.g., ignition time or impact velocity and type of surface impacted) to arrive at a value

for explosive yield. Explosive yield should then be determined by using the method depicted in "Part 2" which involves the use of Figure 5-20 and multiplier factors. The smaller value for explosive yield determined in "Part 1" and "Part 2" is the correct value. This value can then be used to determine an effective weight of propellant, and pressure and impulse at scaled distances.

All of the Pyro experiments, on which the prediction curves in this section are based, were conducted on the ground surface, with no cratering. When the curves are used to predict blast yields for explosions occurring in flight or far enough above the ground that the shock wave reflection does not occur, one must account for the absence of the "perfect" reflecting surface. This is done by dividing the blast yields calculated from curves in this section by a factor of two.

Figure 5-20 is a normalized plot for all propellants and should be used as an upper limit for explosive yield. It should be used to obtain the normalized explosive yield (Y) which is then multiplied by the multiplier factor for the specific propellant used. The explosive yield obtained is the terminal yield (based on TNT equivalence) and can be greater than 100%. Whenever the value of percent explosive (terminal) yield, determined by using Table 5-I, exceeds the value of Figure 5-20, the value from Figure 5-20 is the correct choice.

5.4.1.1 Hypergolic (50% N_2H_4 – 50% UDMH fuel and N_2O_4 oxidizer in mass ratio of 1:2): Hypergolic meterials, by definition, ignite spontaneously on contact, so it is not possible to obtain appreciable mixing before ignition unless the fuel and oxidizer are thrown violently together. Ignition time is therefore not an important determinant of blast yield for hypergolics, but impact velocity and degree of confinement after impact are important factors. If a CBM or CBGS failure mode is being considered, percent explosive yield can be acquired from Table 5-II. If a HVI failure mode is assumed, then percent explosive yield can be determined from Figure 5-21. The percent yield determined by any one of these methods must then be compared to the percent yield determined from the weight of the propellant, Figure 5-20. The smaller of the two is the correct choice.

5.4.1.2 Liquid oxygen – hydrocarbon (RP-1 fuel LO_2 oxidizer in mass ratio of 1:2.25): Because liquid oxygen/hydrocarbon propellants are not hypergolic, considerable mixing can occur in various types of accidents, and time of ignition after onset of mixing is an important determinant of blast yield. For the case of mixing and an explosion within the missile tankage (CBM), percent explosive yield can be determined by assuming an ignition time and then examining Figure 5-22.

In using Figure 5-22 and subsequent similar "shaded" graphs, the shaded portion represents an area in which data from actual propellant blasts was found. The central solid line is an estimate of the most likely occurrence and, for most cases, is the recommended choice. Conservative estimates of explosive yield can be made by choosing the uppermost boundary of the shaded area.

The vertical depth of the shaded area at any abscissa indicates the total range of data, and therefore the total uncertainty in the estimate. For simulated fallback on the launch pad (CBGS), impact velocity as well as ignition time are important parameters in estimating blast yield. A two-step approach has been developed to calculate blast yield. After assuming an impact velocity, maximum percent yield (Y_m) can be determined from Equation 5-1:

$$Y_m = 5\% + \frac{(6.82\%)\ V_i}{(3.28106)\ \text{ft/sec}}, \quad 0 \leqslant V_i \leqslant = 55.12172\ \text{ft/sec} \qquad (5\text{-}1)$$

TABLE 5-I. – SEQUENCE FOR DETERMINATION OF EXPLOSIVE YIELD *

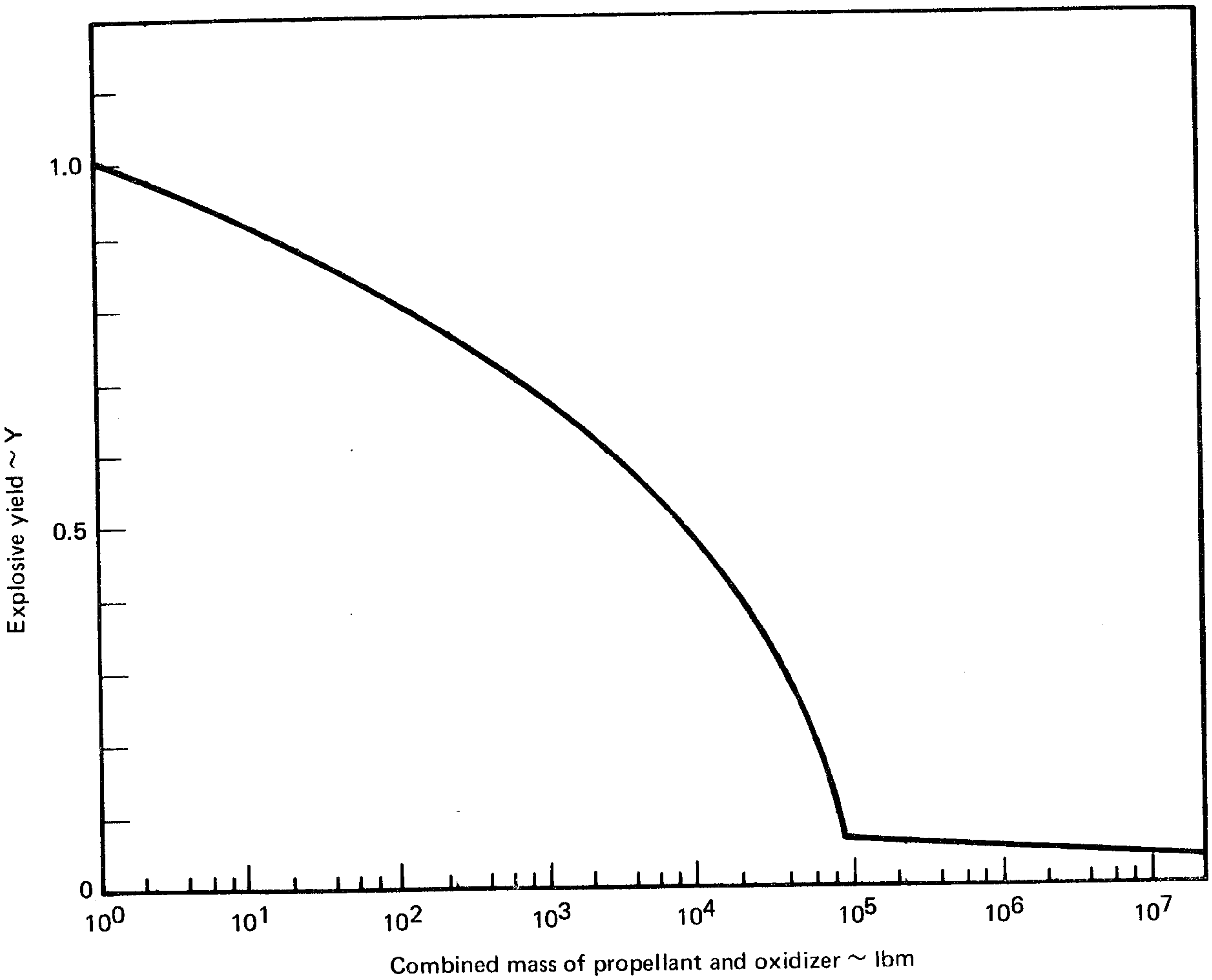
Type of propellant & oxidizer	Type of accident failure mode	Sequence **	
		Part 1	Part 2 (check)
Hypergolic (50% N_2H_2 – 50% UDMH/N_2O_4)	CBM	Table 5-2	Figure 5-20
	CBGS	Table 5-2	Figure 5-20
	HVI	Figure 5-21	Figure 5-20
Liquid Oxygen – Hydrocarbon (LO_2/RP-1)	CBM	Figure 5-22	Figure 5-20
	CBGS	Equation (5-1) Figure 5-23	Figure 5-20
	HVI	Figure 5-24	Figure 5-20
Liquid Oxygen – Liquid Hydrogen (LO_2/LH_2)	CBM	Figure 5-25	Figure 5-20
	CBGS	Equation (5-2) Figure 5-26	Figure 5-20
	HVI	Figure 5-27	Figure 5-20

* For explosions occurring far above the ground ($H/W^{1/3} > 10$ m/kg$^{1/3}$, where H is height above the ground), blast yields calculated from curves in this section should be divided by two.

** Correct choice is the smaller of Part 1 and Part 2.

TABLE 5-II. – ESTIMATE OF TERMINAL YIELD FOR HYPERGOLIC CBM AND CBGS (REFERENCE 54)

Failure mode	Terminal yield range (%)	Estimated upper limit
Diaphragm rupture (CBM)	0.01 – 0.8	1.5
Spill (CBGS)	0.02 – 0.8	0.5
Small explosive donor	0.8 – 1.2	2
Large explosive donor	3.4 – 3.7	5
Command destruct	0.3 – 0.35	0.5
310 – ft drop (CBGS) (m – .370478 ft)	1.5	3



Multiplier factors:

(1) Hypergolic – 240%

(2) LO_2/RP-1 – 125%

(3) LO_2/LH_2 – 370%

(kg = lbm x .45454)

FIGURE 5-20. – ESTIMATED TERMINAL YIELD AS A FUNCTION OF COMBINED PROPELLANT AND OXIDIZER MASS (REF. 54)

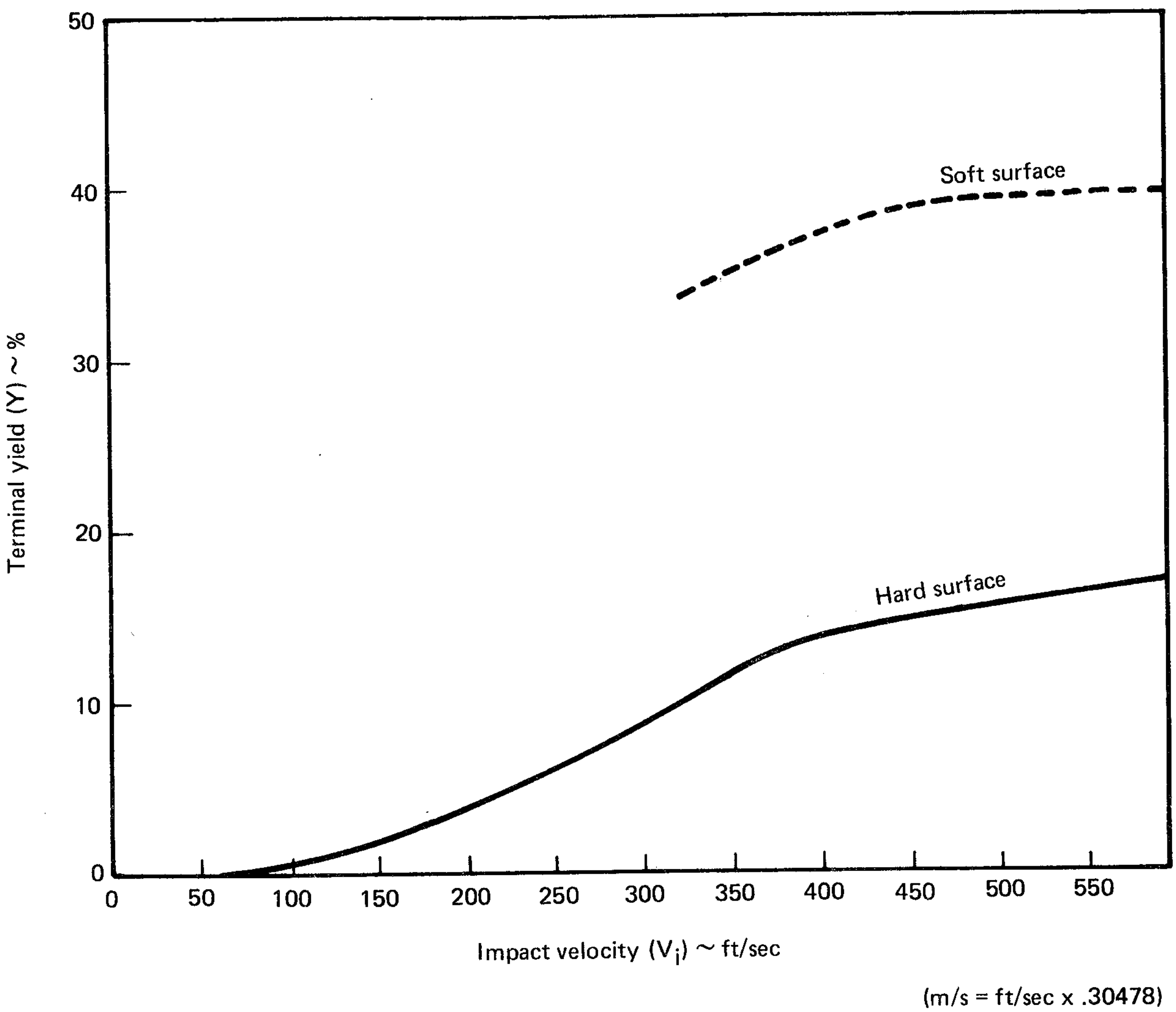


FIGURE 5-21. – TERMINAL YIELD VS IMPACT VELOCITY FOR HYPERGOLIC HVI (REF. 54)

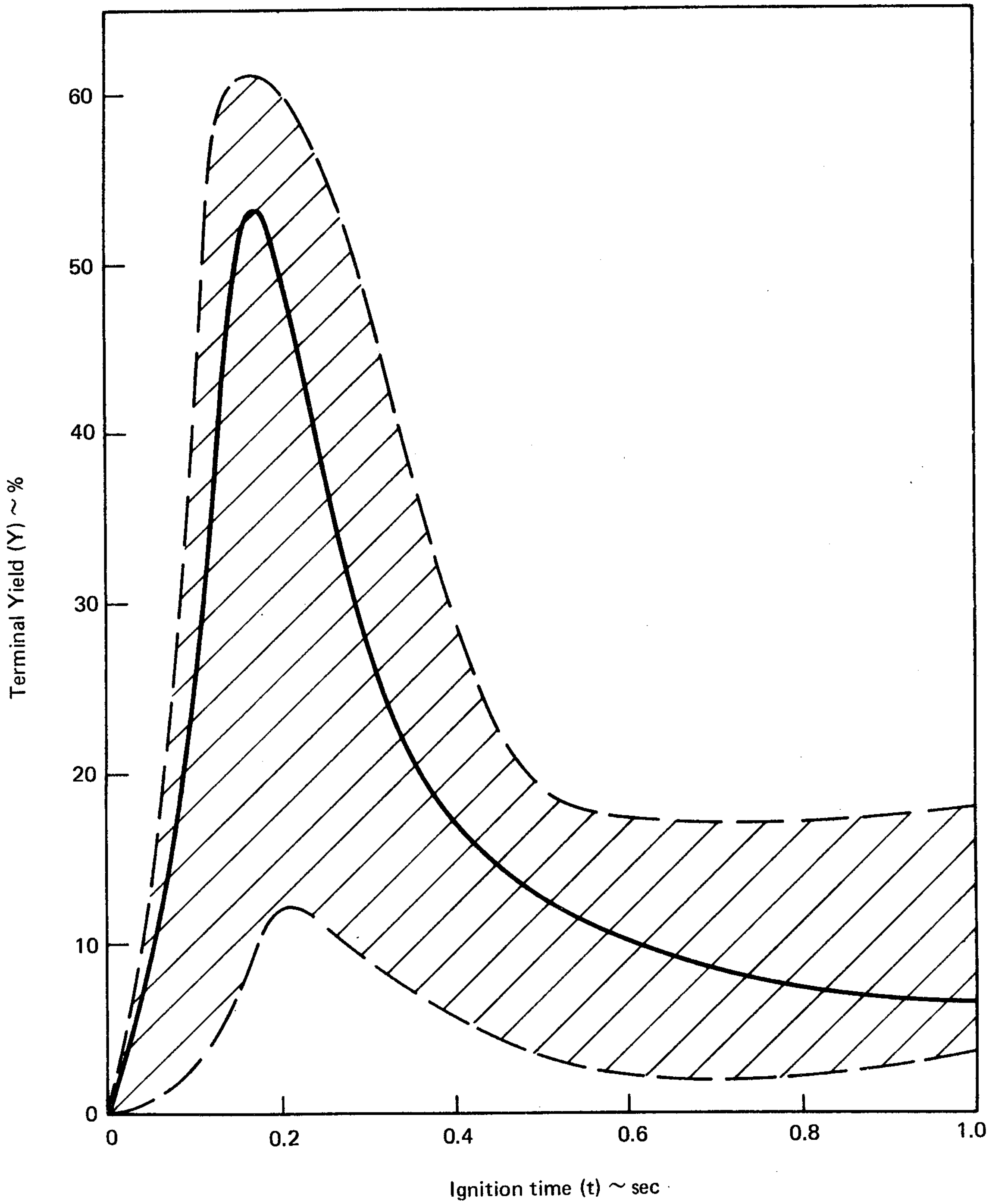


FIGURE 5-22. – TERMINAL YIELD VS IGNITION TIME FOR LO_2/RP-1 CBM (REF. 54)

Where Y_m is expressed in percent and V_i is in feet per second. Percent explosive yield can then be determined from Y_m and an estimate of ignition time by using Figure 5-23. The determination of explosive yield for the HVI failure mode is somewhat simpler because there is little ignition delay and therefore only the impact velocity affects yield. Thus, blast yield can be acquired by using Figure 5-24 directly. The percent yield determined by any one of these methods must then be compared to the percent yield determined from the weight of the propellant, Figure 5-20. The smaller of the two values is the correct choice.

5.4.1.3 Liquid oxygen – liquid hydrogen (LH_2 fuel and LO_2 oxidizer in mass ratio of 1:5): The determination of explosive yield, for the entirely cryogenic combination of liquid hydrogen (LH_2) fuel and liquid oxygen (LO_2) oxidizer is similar to that of liquid oxygen-hydrocarbon propellants. For the CBM case, it is necessary for one to assume an ignition time and then use Figure 5-25 to find the explosive yield. For the CBGS case, an impact velocity is assumed and maximum percent yield (Y_m) can be determined from Equation (5-2):

$$Y_m = 10\% + \frac{(4.43\%)\ V_i}{13.28106\ \text{ft/sec}}, \quad 0 \leq V_i \leq 80.0577\ \text{ft/sec} \qquad (5\text{-}2)$$

Where Y_m is expressed in percent and V_i is in feet per second. Percent explosive yield can be determined from Y_m and an estimate of ignition time by using Figure 5-26. For high velocity impact (HVI), the blast yield is dependent only on the impact velocity and can be acquired from Figure 5-27 directly. The percent yield determined by any one of these methods must then be compared to the percent yield determined from the weight of the propellant, Figure 5-20. The smaller of the two values is the correct choice.

Examples for determining explosive yield taken from reference 54 are shown in Appendix A.

5.4.2 <u>Peak Side-On Over Pressure and Impulse (Reference 54).</u> – Throughout the Pyro work, reference 30, blast yield is expressed as percent yield, based on an average of pressures and impulses measured at the farthest distance from the source when compared to standard reference curves for TNT surface bursts (terminal yield). Hopkinson's blast scaling is used when comparing blast data for tests with the same propellants and failure conditions, but different mass of propellant. Therefore the blast parameters, peak side-on overpressure (P) and scaled impulse ($I/W^{1/3}$) are plotted as functions of scaled distance ($R/W^{1/3}$) after being normalized by the fractional yield. This procedure is equivalent to determining an effective mass of propellant (W) for the blast from the following equation:

$$W = W_T \times \frac{Y}{100} \qquad (5\text{-}3)$$

Where W_T is total mass of propellant and oxidizer, and Y is terminal blast yield in percent. Because the data are normalized by comparing to TNT blast data, the effective blast energy (E) can be obtained by multiplying W by the specific detonation energy of TNT,

1.4×10^6 ft lbf/lbm (4.18×10^6 J/kg).

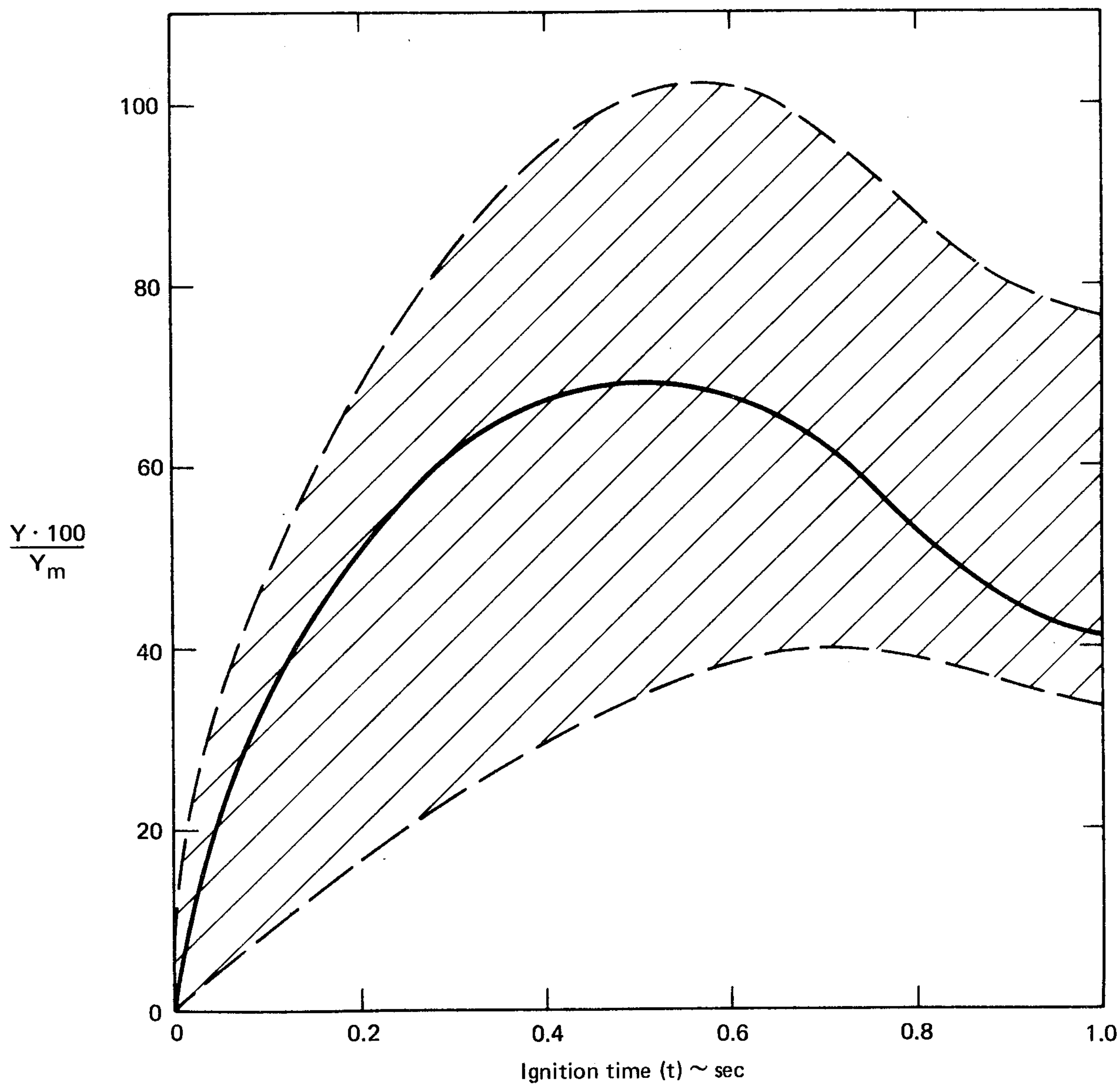


FIGURE 5-23. – NORMALIZED TERMINAL YIELD VS IGNITION TIME FOR LO_2/RP-1 CBGS (REF. 54)

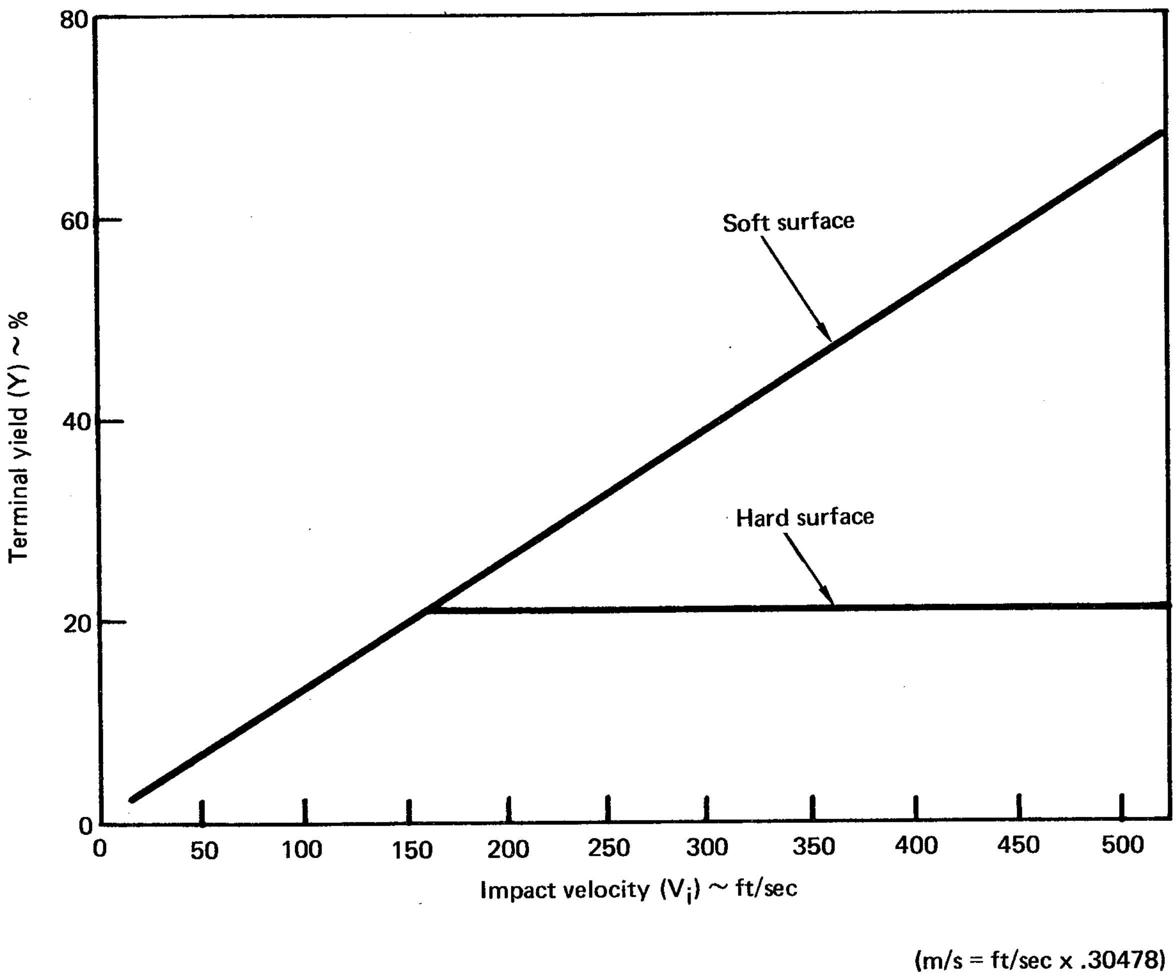


FIGURE 5-24. – TERMINAL YIELD VS IMPACT VELOCITY FOR LO_2/RP-1 HVI (REF. 54)

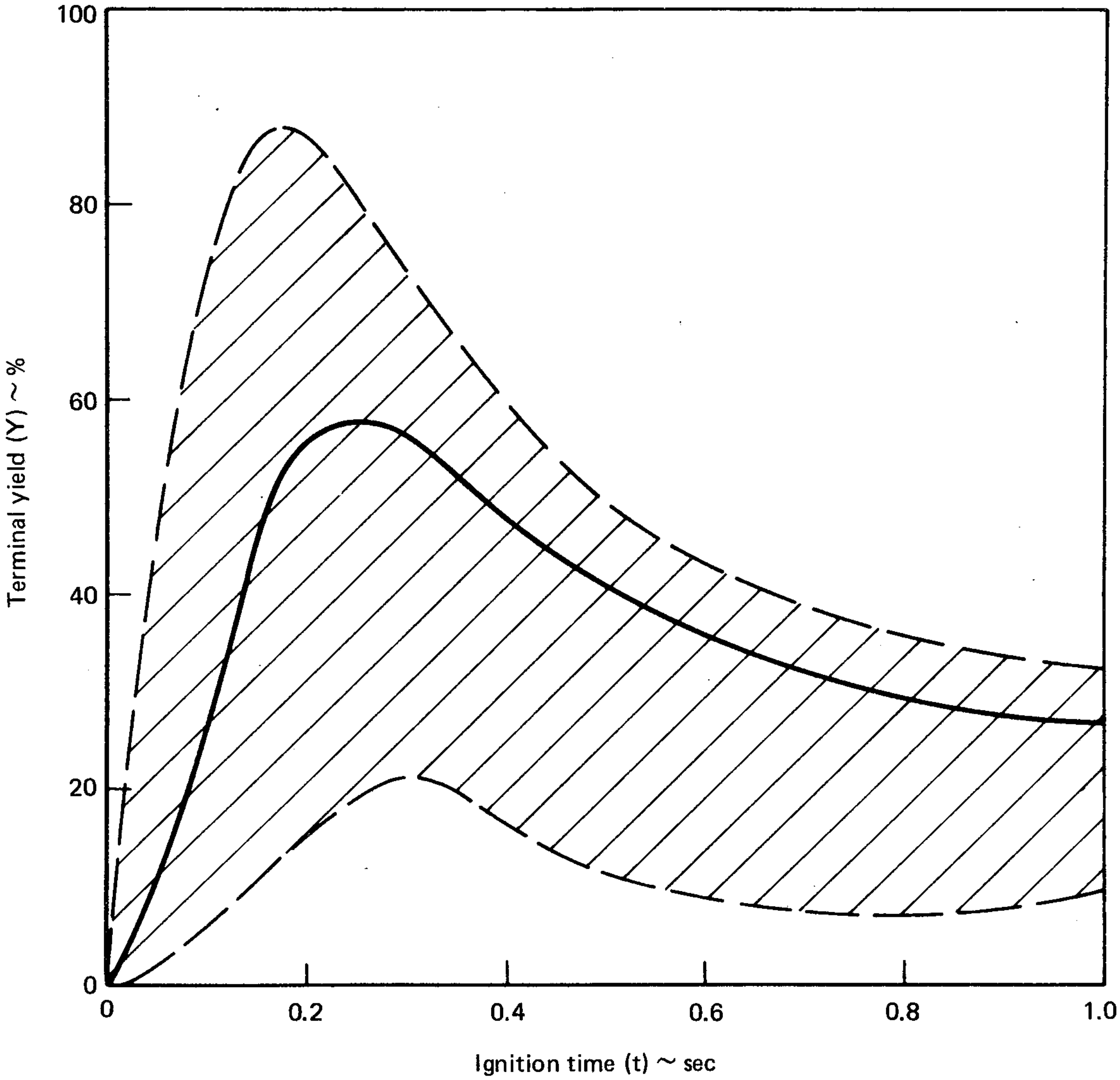


FIGURE 5-25. – TERMINAL YIELD VS IGNITION TIME FOR LO_2/LH_2 CBM (REF. 54)

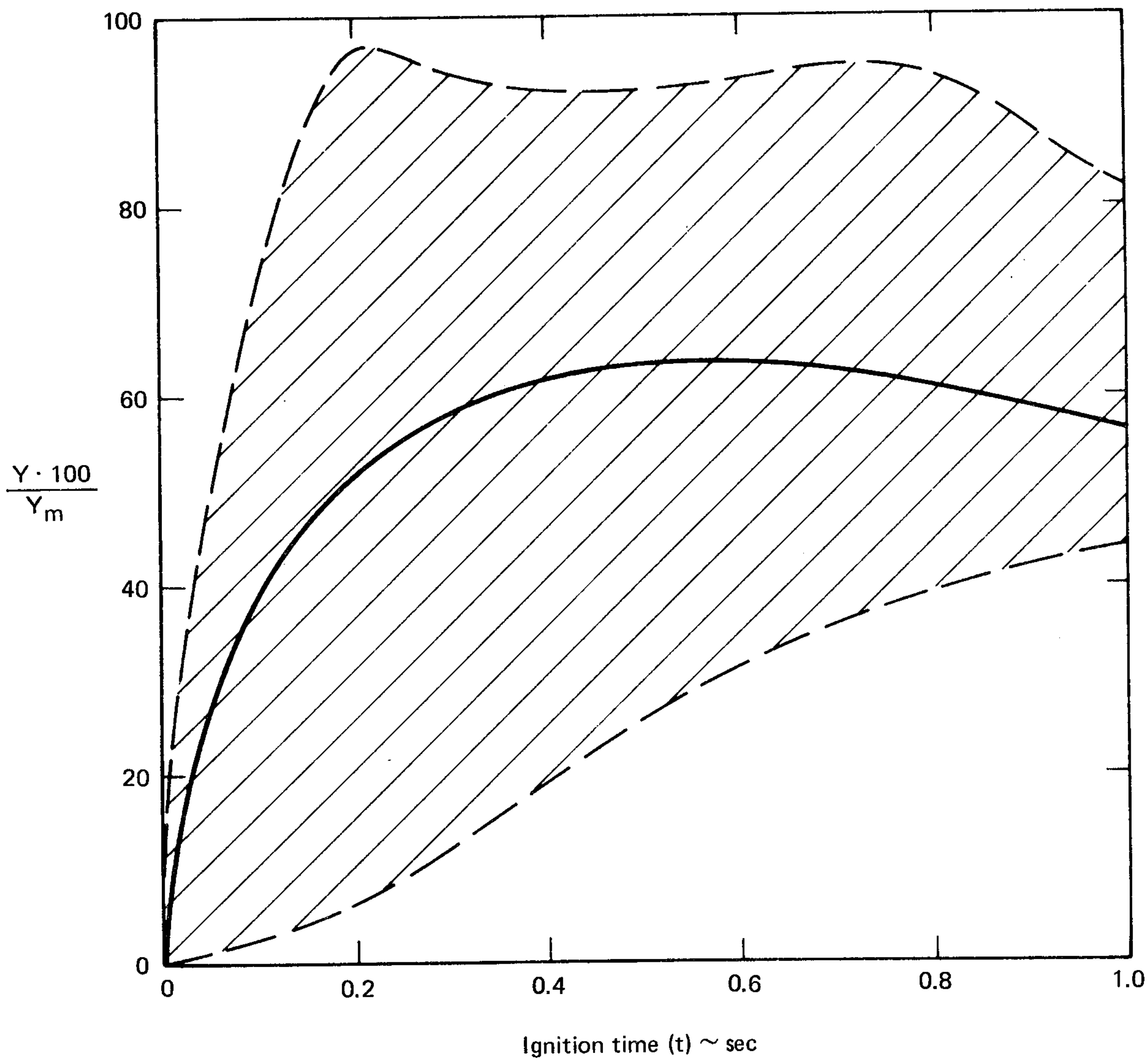


FIGURE 5-26. – NORMALIZED TERMINAL YIELD VS IGNITION TIME FOR LO_2/LH_2 CBGS (REF. 54)

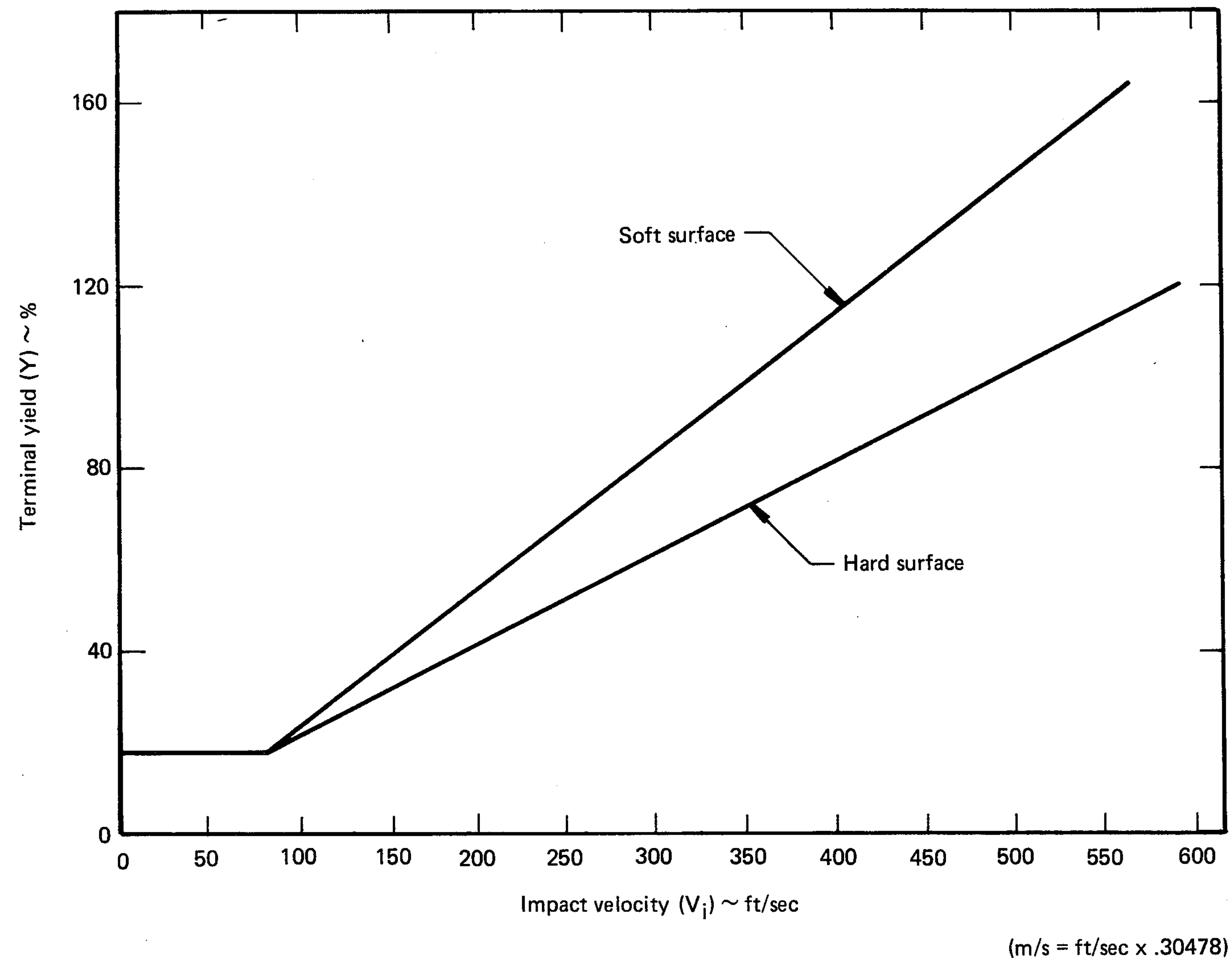


FIGURE 5-27. – TERMINAL YIELD VS IMPACT VELOCITY FOR LO_2/LH_2 HVI (REF. 54)

Table 5-III contains the different propellant failure mode combinations under consideration and the figure numbers of the graphs needed to determine peak side-on overpressure and scaled specific impulse as a function of scaled distance for each accident situation. The procedure for finding peak side-on overpressure and specific impulse are as follows:

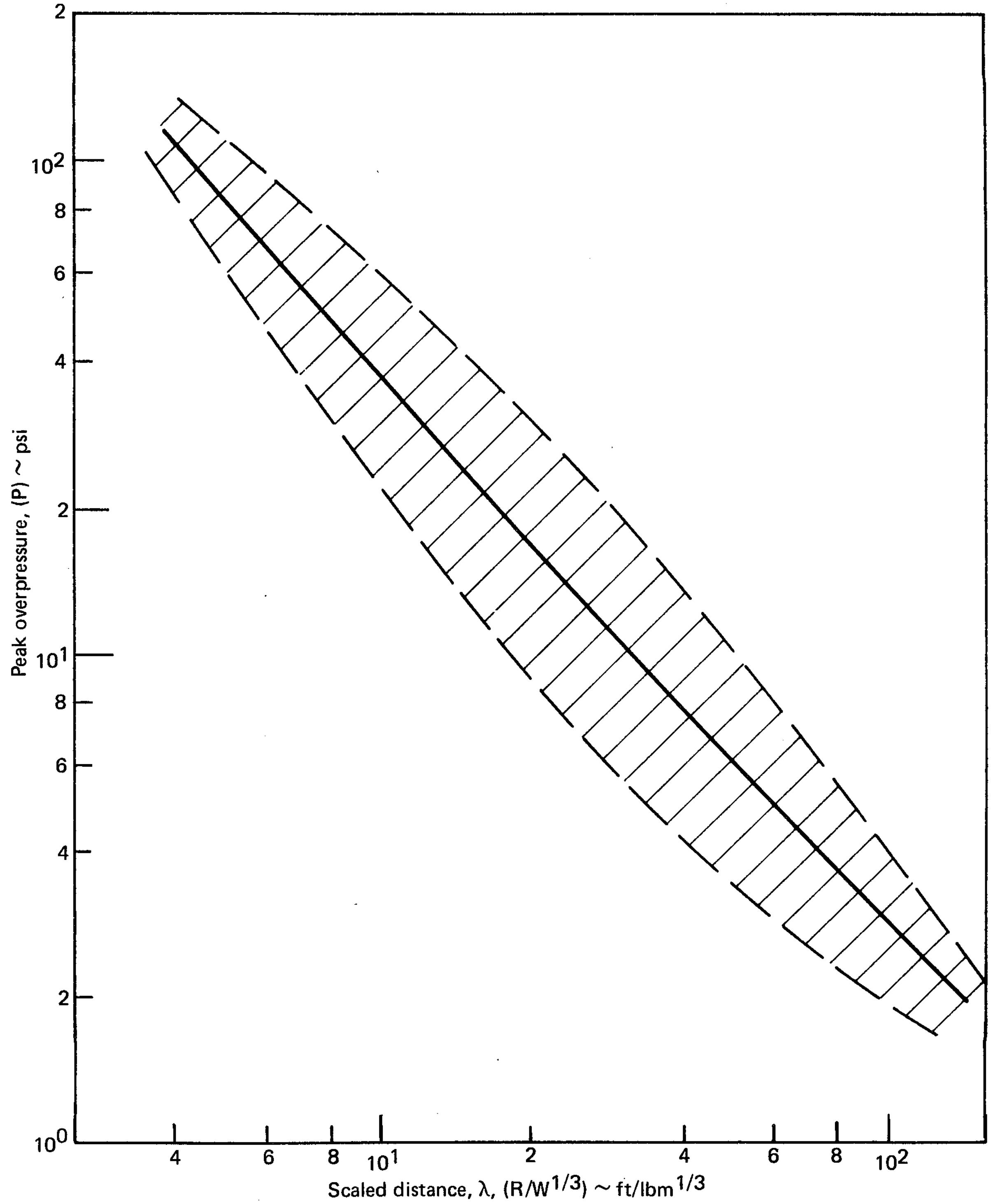
1. Calculate terminal yield (Y) using methods discussed in Paragraph 5.4.1
2. Determine the effective mass of propellant and oxidizer (W) from Equation (5-3).
3. Choose a specific standoff distance (R) from the center of the anticipated blast and calculate scaled distance ($R/W^{1/3}$).
4. Examine Table 5-III and acquire the proper figure numbers for finding peak side-on overpressure (P) and scaled impulse ($I/W^{1/3}$) for the particular propellant/oxidizer and failure mode under consideration.
5. Determine peak side-on overpressure (P) from the appropriate Pressure versus Scaled Distance curve and the predetermined scaled distance ($R/W^{1/3}$).
6. Determine scaled impulse ($I/W^{1/3}$) from the appropriate scaled positive impulse versus scaled distance curve and the predetermined scaled distance ($R/W^{1/3}$).
7. Calculate specific impulse (I) from scaled positive impulse ($I/W^{1/3}$). That is

$$I = \left(\frac{I}{W^{1/3}}\right)(W^{1/3}) \qquad (5\text{-}4)$$

Examples for determining peak side-on overpressure and impulse taken from reference 54 are shown in Appendix A.

TABLE 5-III. – GUIDE TO SELECTION OF PROPER GRAPHS FOR THE DETERMINATION OF PRESSURE AND SPECIFIC IMPULSE (REF. 54)

Type of propellant & oxidizer	Type of accident (failure mode)	Peak side-on overpressure (P)	Scaled impulse ($I/W^{1/3}$)
Hypergolic (50% N_2H_4 50% UDMH/N_2O_4)	CBM	Figure 5-28	Figure 5-30
	CBGS	Figure 5-28	Figure 5-30
	HVI	Figure 5-29	Figure 5-30
Liquid Oxygen – Hydrocarbon (LO_2/RP-1)	CBM	Figure 5-31	Figure 5-33
	CBGS	Figure 5-32	Figure 5-34
	HVI	Figure 5-32	Figure 5-34
Liquid Oxygen – Liquid Hydrogen (LO_2/LH_2)	CBM	Figure 5-35	Figure 5-37
	CBGS	Figure 5-36	Figure 5-38
	HVI	Figure 5-36	Figure 5-38



(N/m^2 = psi x 6.8947×10^3)

($m/kg^{1/3}$ = ft/lbm$^{1/3}$ x .3966)

FIGURE 5-28. – PRESSURE VS. SCALED DISTANCE. HYPERGOLIC PROPELLANT; CMB AND CBGS FAILURE MODES. (REF. 54)

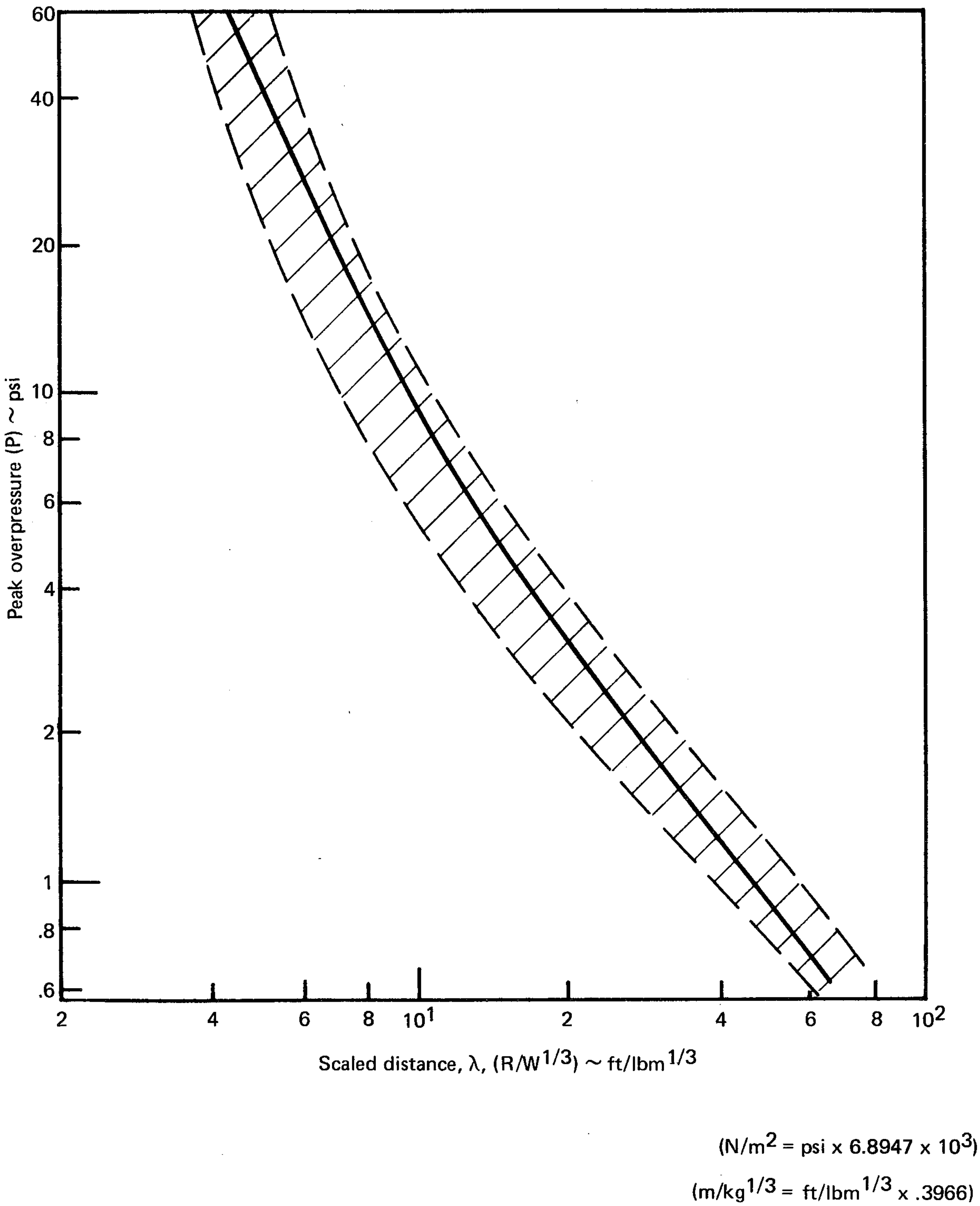
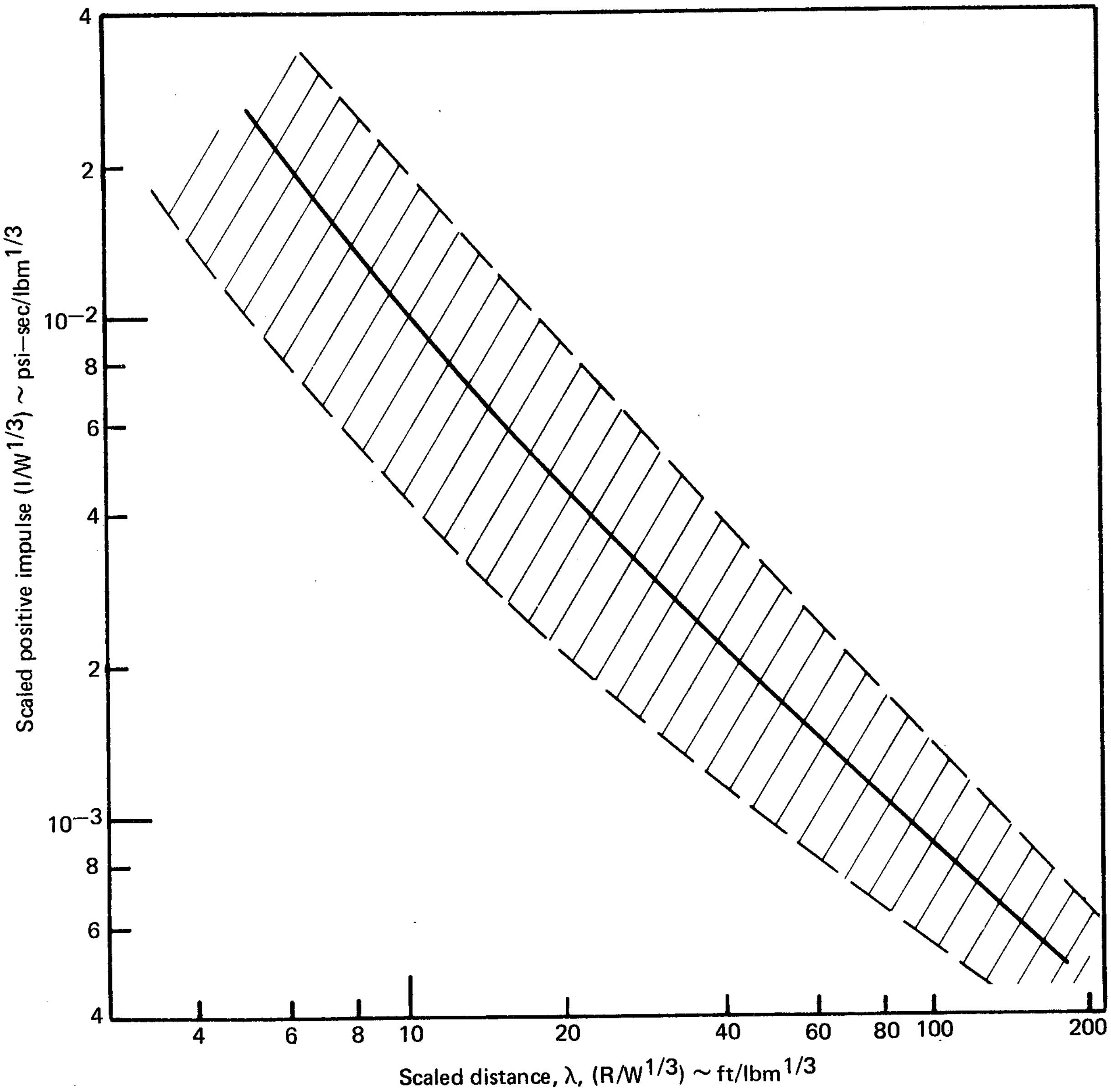


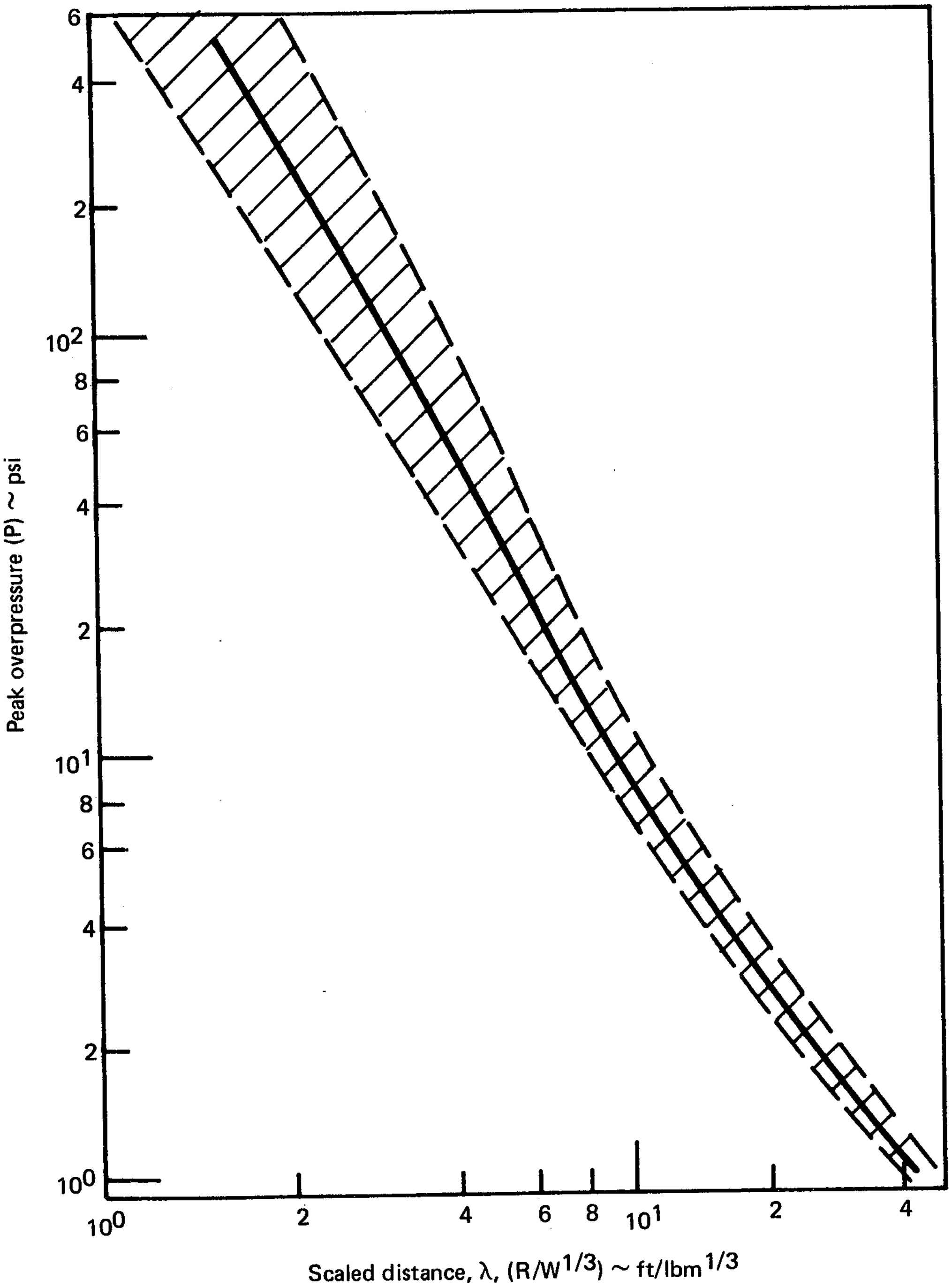
FIGURE 5-29. – PRESSURE VS. SCALED DISTANCE. HYPERGOLIC PROPELLANT; HVI FAILURE MODE. (REF. 54)



$(N/m^2/kg^{1/3} = psi\text{–}sec/lbm^{1/3} \times 8.9766 \times 10^3)$

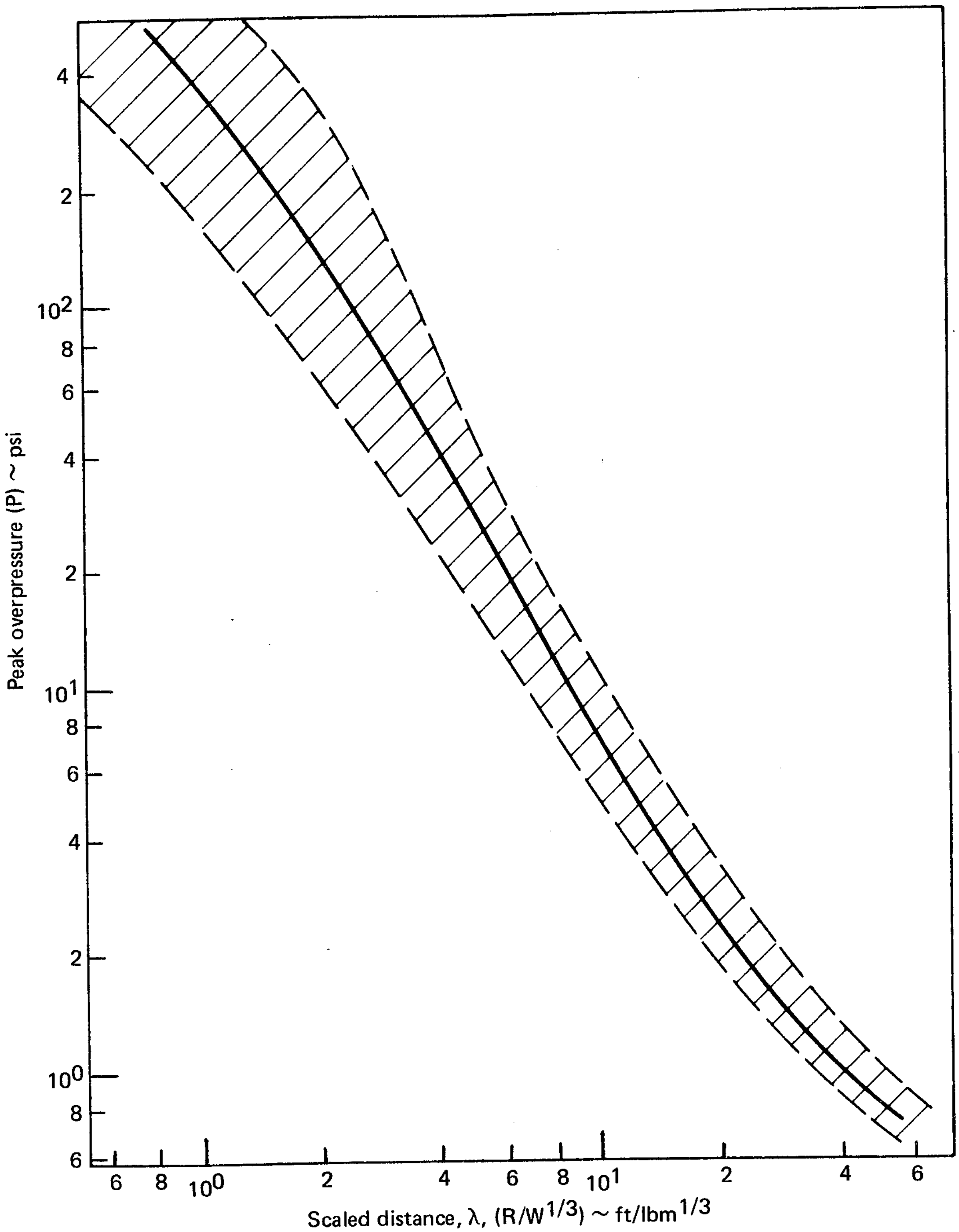
$(m/kg^{1/3} = ft/lbm^{1/3} \times .3966)$

FIGURE 5-30. – SCALED POSITIVE IMPULSE VS. SCALED DISTANCE. HYPERGOLIC PROPELLANT; CBM, CBGS AND HVI FAILURE MODES. (REF. 54)



(N/m^2 = psi x 6.8947 x 10^3)
($m/kg^{1/3}$ = $ft/lbm^{1/3}$ x .3966)

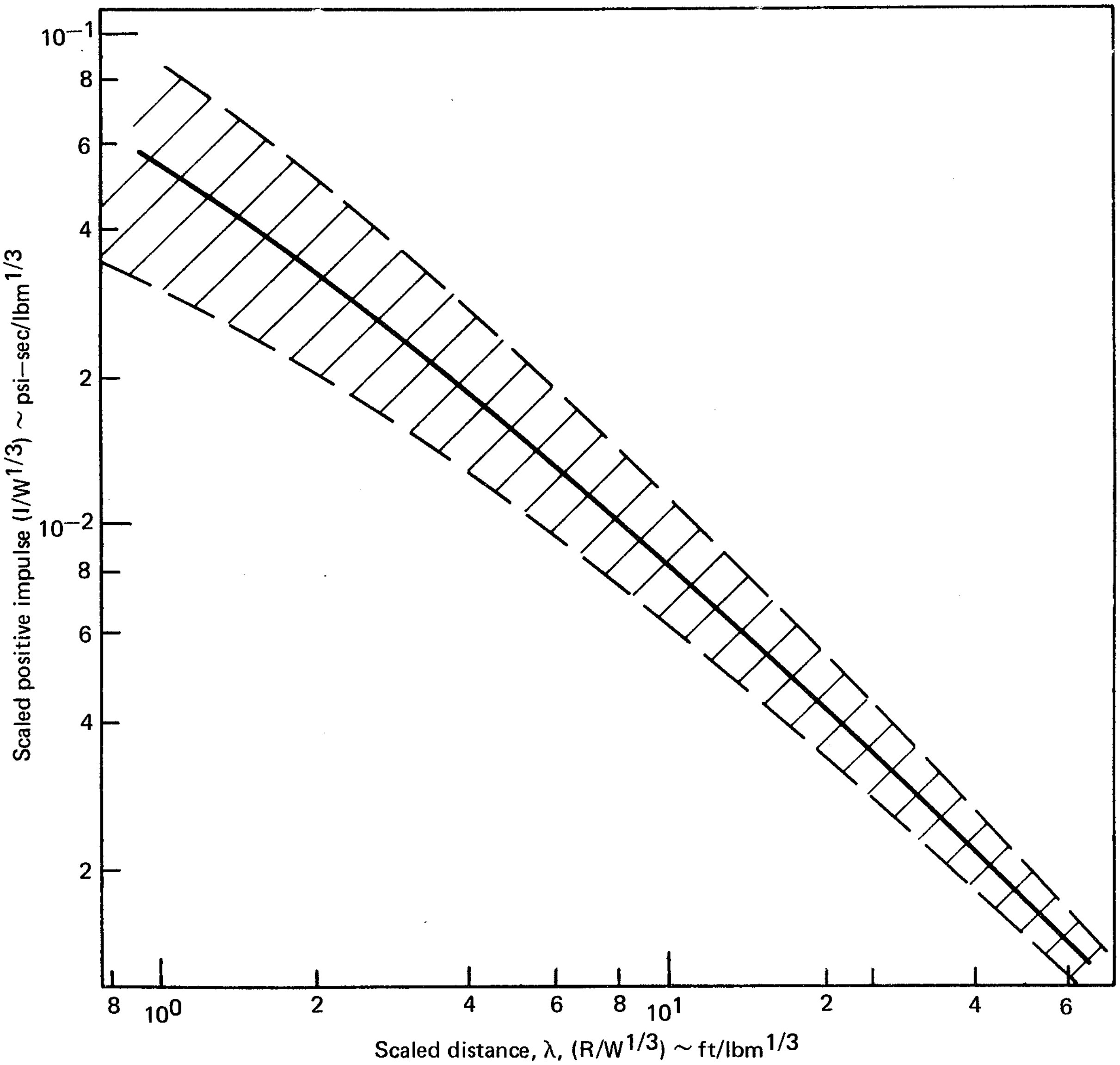
FIGURE 5-31. – PRESSURE VS. SCALED DISTANCE. LO_2/RP–1 PROPELLANT; CBM FAILURE MODE. (REF. 54)



(N/m^2 = psi x 6.8947 x 10^3)

($m/kg^{1/3}$ = $ft/lbm^{1/3}$ x .3966)

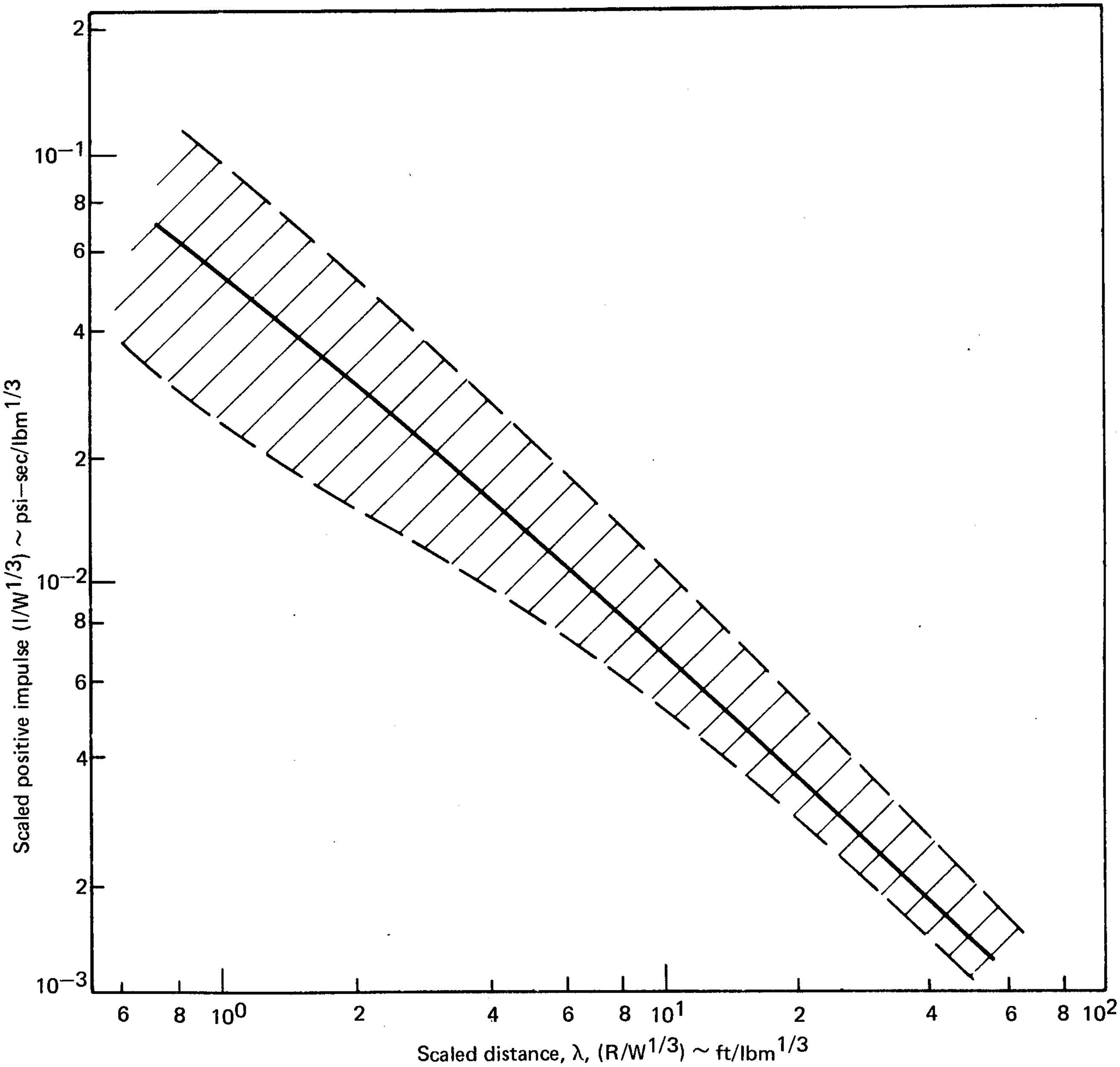
FIGURE 5-32. – PRESSURE VS. SCALED DISTANCE. LO_2/RP–1 PROPELLANT; CBGS AND HVI FAILURE MODES. (REF. 54)



($N/m^2/kg^{1/3}$ = psi–sec/$lbm^{1/3}$ x 8.9766 x 10^3)

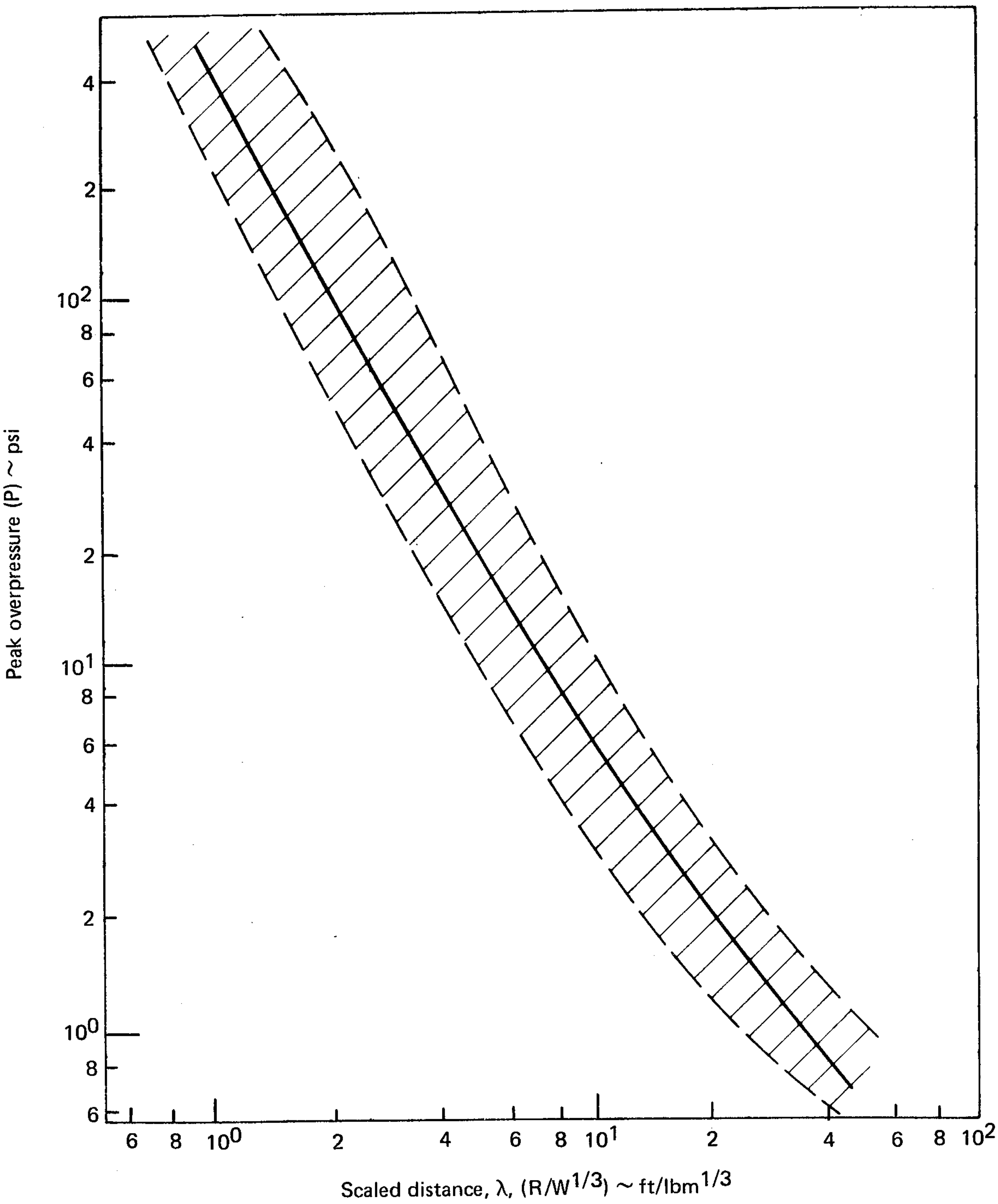
($m/kg^{1/3}$ = ft/$lbm^{1/3}$ x .3966)

FIGURE 5-33. – SCALED POSITIVE IMPULSE VS. SCALED DISTANCE. LO_2/RP–1 PROPELLANT; CBM FAILURE MODE. (REF. 54)



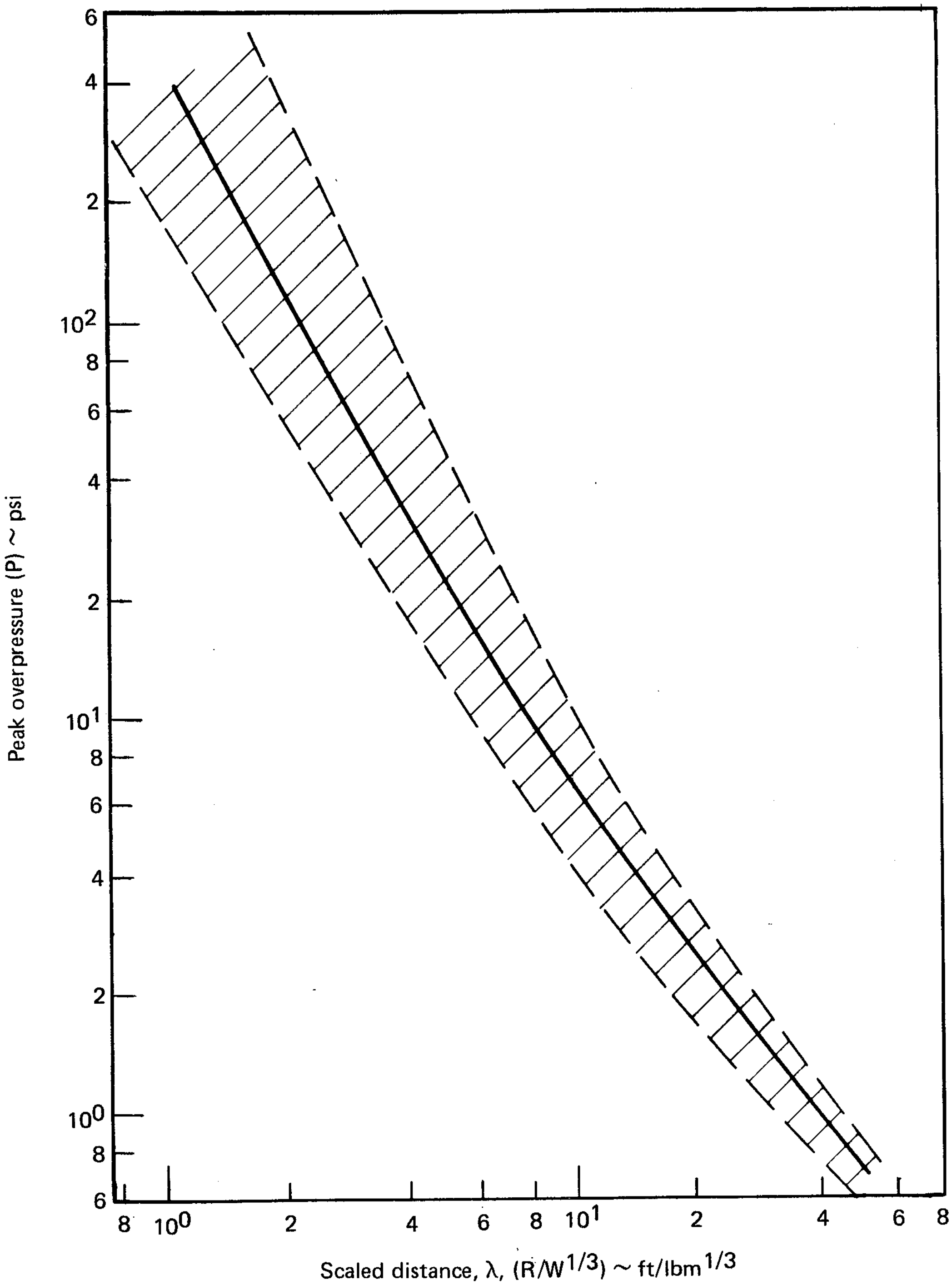
($N/m^2/kg^{1/3}$ = psi–sec/$lbm^{1/3}$ x 8.9766×10^3)
($m/kg^{1/3}$ = ft/$lbm^{1/3}$ x .3966)

FIGURE 5-34. – SCALED POSITIVE IMPULSE VS SCALED DISTANCE. LO_2/RP–1 PROPELLANT; CBGS AND HVI FAILURE MODES. (REF. 54)



(N/m^2 = psi x 6.8947 x 10^3)
($m/kg^{1/3}$ = $ft/lbm^{1/3}$ x .3966)

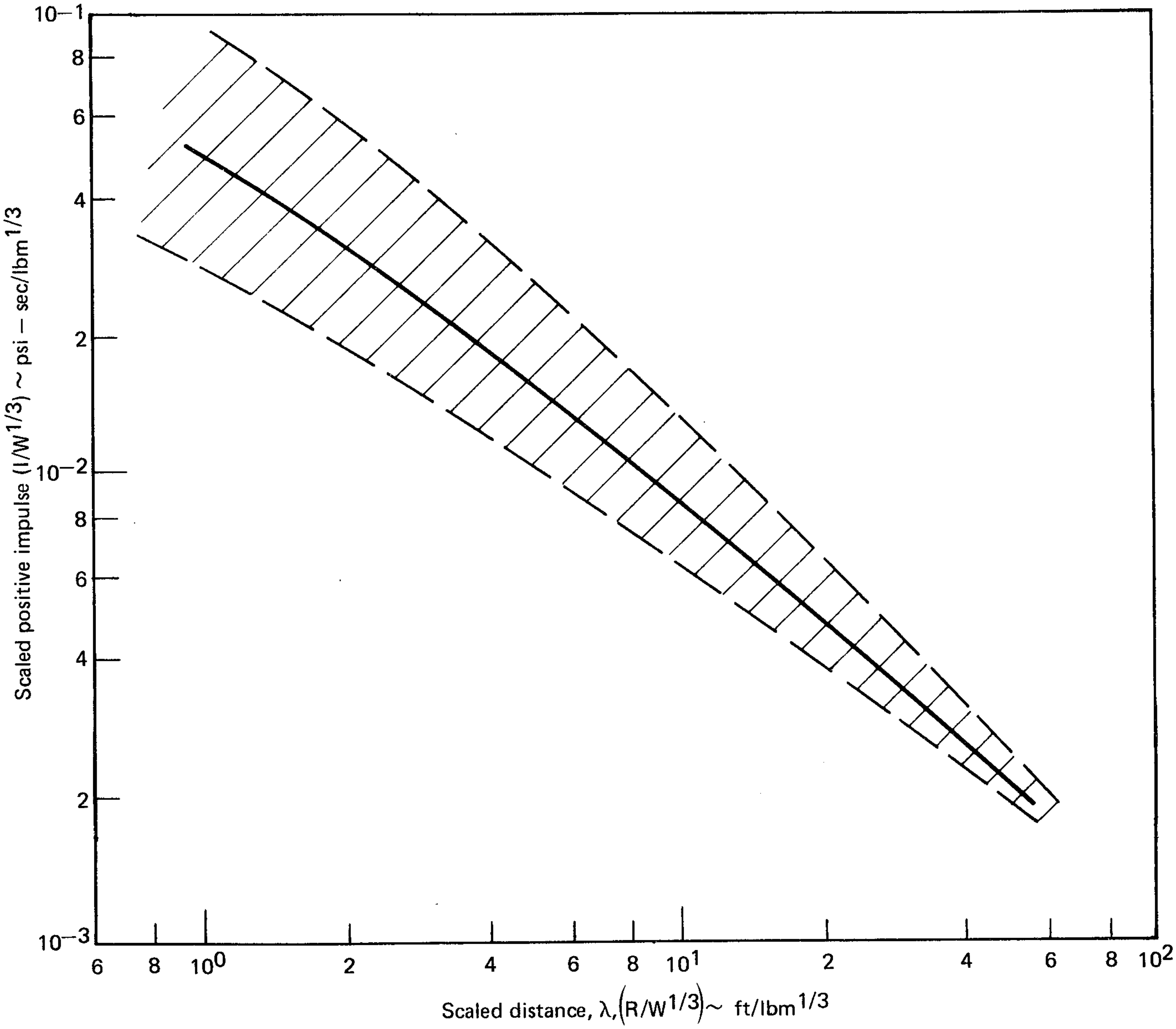
FIGURE 5-35. – PRESSURE VS SCALED DISTANCE. LO_2/LH_2 PROPELLANT; CBM FAILURE MODE (REF. 54)



(N/m^2 = psi x 6.8947 x 10^3)

($m/kg^{1/3}$ = $ft/lbm^{1/3}$ x .3966)

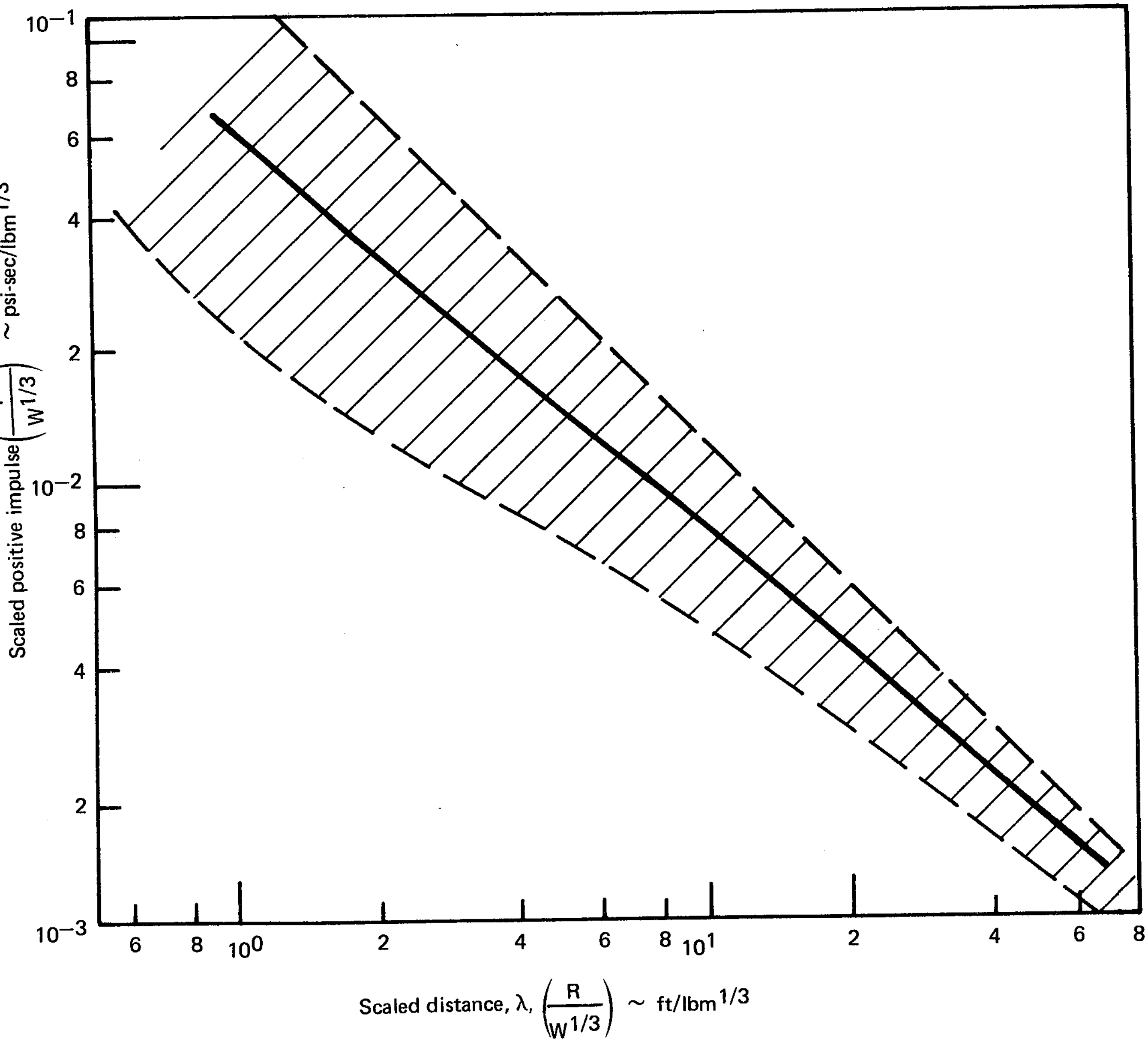
FIGURE 5-36. – PRESSURE VS SCALED DISTANCE. LO_2/LH_2 PROPELLANT; CBGS AND HVI FAILURE MODES. (REF. 54)



($N/m^2/kg^{1/3}$ = psi – sec/lbm$^{1/3}$ x 8.9766 x 10^3)

($m/kg^{1/3}$ = ft/lbm$^{1/3}$ x .3966)

FIGURE 5-37. – SCALED POSITIVE IMPULSE VS SCALED DISTANCE. LO_2/LH_2 PROPELLANT; CBM FAILURE MODE (REF. 54)



($N/m^2/kg^{1/3}$ = psi–sec/lbm$^{1/3}$ x 8.9766 x 10^3)

($m/kg^{1/3}$ = ft/lbm$^{1/3}$ x .3966)

FIGURE 5-38. – SCALED POSITIVE IMPULSE VS SCALED DISTANCE. LO_2/LH_2 PROPELLANT; CBGS AND HVI FAILURE MODES (REF. 54)

5.4.3 Fireball Effects

5.4.3.1 Characteristics: The fireball generated by the explosion of propellant mixtures can constitute a hazard primarily through heat transfer to an object or structure immersed in it.

Gayle and Bransford, reference 58, have derived empirical expressions for the dimensions and duration of a fireball associated with an explosion of liquid bi-propellants. Equations 5–5 and 5–6 relate the fireball dimension in terms of equivalent diameter (D), in feet, and the fireball duration, τ, in seconds, to the total propellant (fuel plus oxidizer) weight (W) in pounds, for the propellant combinations LO_2/RP-1, LO_2/LH_2, LO_2/RP-1 and LH_2, and N_2D_4/N_2H_4 – UDMH (50:50)

$$D = 9.56\, W^{0.325} \qquad (5\text{-}5)$$

$$\tau = 0.196\, W^{0.329} \qquad (5\text{-}6)$$

The estimated error expected in D is 30% and in τ is 84% since some of the fireball observations used to derive the empirical relations were markedly asymmetrical. The magnitude of the departure from the diameter given by equation 5–5, is indicated by data from an actual Titan test that involved 100,000 pounds of LO_2/RP-1; wherein the maximum fireball horizontal dimension was estimated to be from 800 to 1000 feet, while equation 5–5 yields an equivalent diameter of approximately 400 feet.

Equations 5–5 and 5–6 are shown plotted on Figure 5-39 along with equations 5-7. In a related Saturn Program investigation of fireball characteristics, J. B. Gayle, reference 59, derived similar diameter/duration/propellant weight relationships which are shown in Figure 5-40. These relationships are very similar to Gayle and Bransford's empirical relations and differ by only 3% and 10% for maximum diameter and duration time, respectively, in the range of Space Shuttle application (100 to 10,000 lb. total propellant weight). In a discussion of Gayle's expressions by R. W. High, reference 60, the author attributes the scatter of test data (shown on Figures 5-40A and B) to the difficulty of estimating the end point of incandescent gases in the presence of smoke and water vapor and from variations in the test failure mode. In his conclusion, however, High considers the equation to furnish a reasonable estimate of fireball duration.

5.4.3.2 Heat flux density: Heat flux data obtained from the literature survey is based primarily on information published on project Pyro, reference 35. A discussion of this data taken from reference 35 follows.

Curves from which the heat flux density versus time within the fireball can be obtained for a given propellant weight are given on Figures 5-41 and 5-42 for the LO^2/RP-1 and LO_2/LH_2 propellant combinations, respectively. The time in these figures is given in seconds by,

$$\tau_o = C\, W^{1/3} \qquad (5\text{–}7)$$

The total propellant weight (W) is in pounds, and the value of C is 0.113 for LO_2/RP-1, Figure 5-41 and is 0.077 has LO_2/LH_2, Figure 5-42. Two curves are presented in each figure. One is the "bounding curve", which is an estimate of the upper bound of the heat flux density and

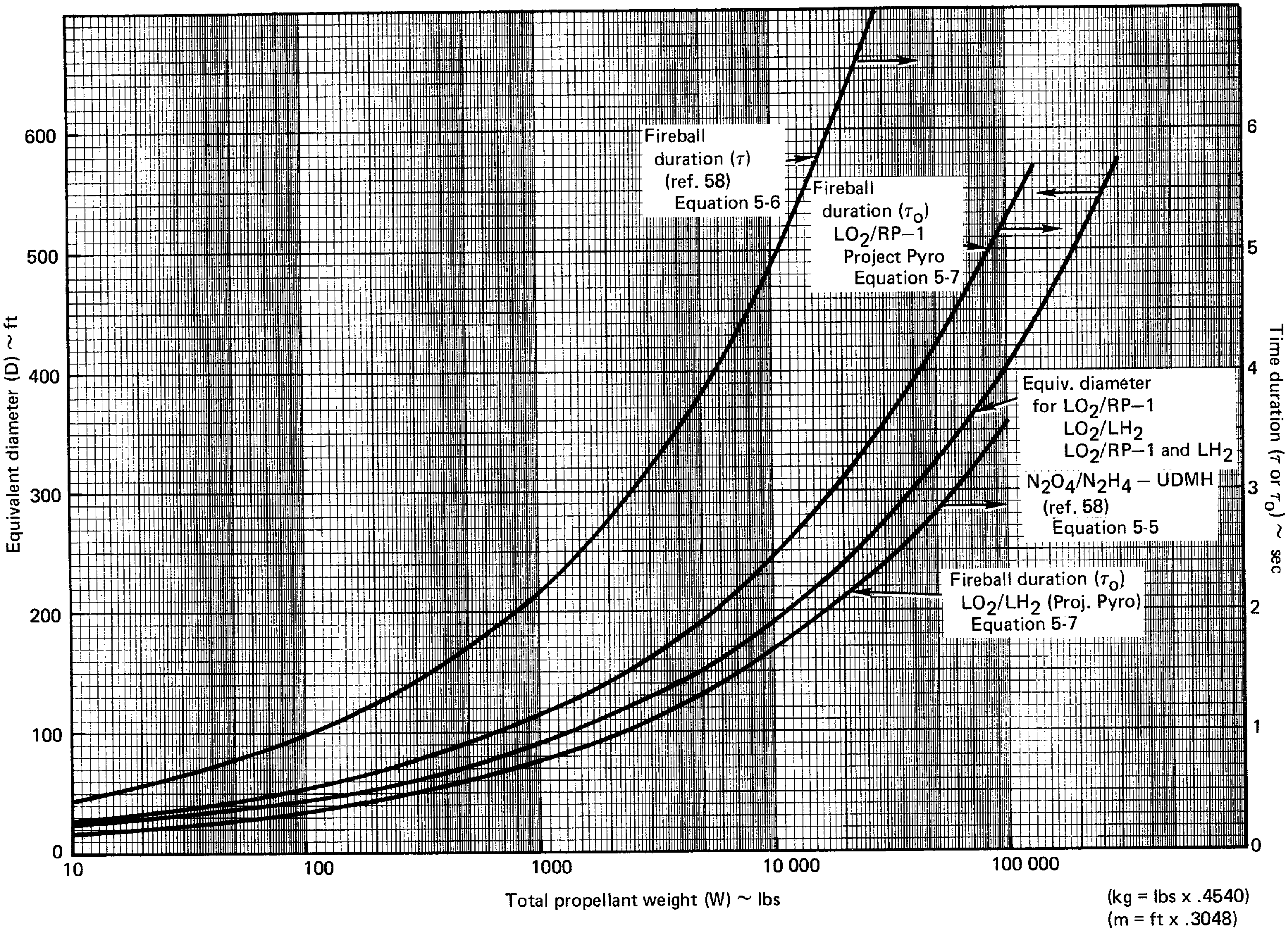
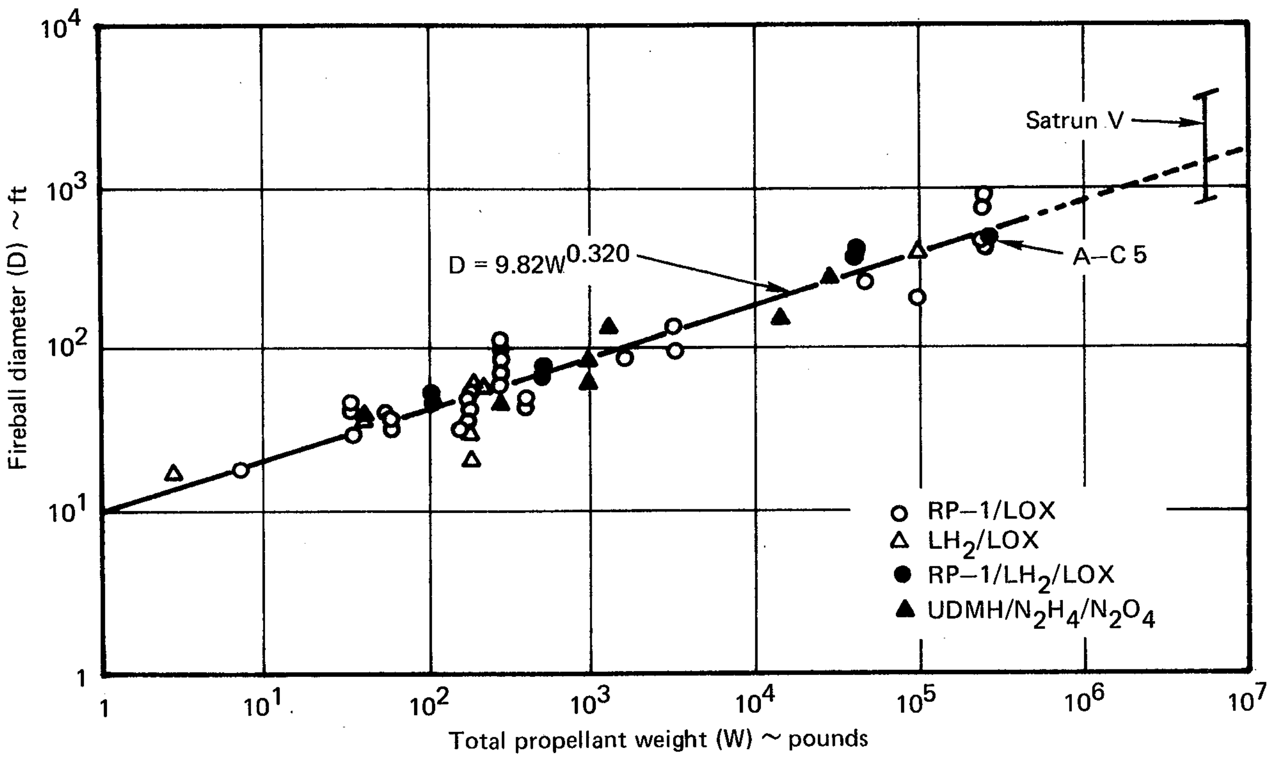
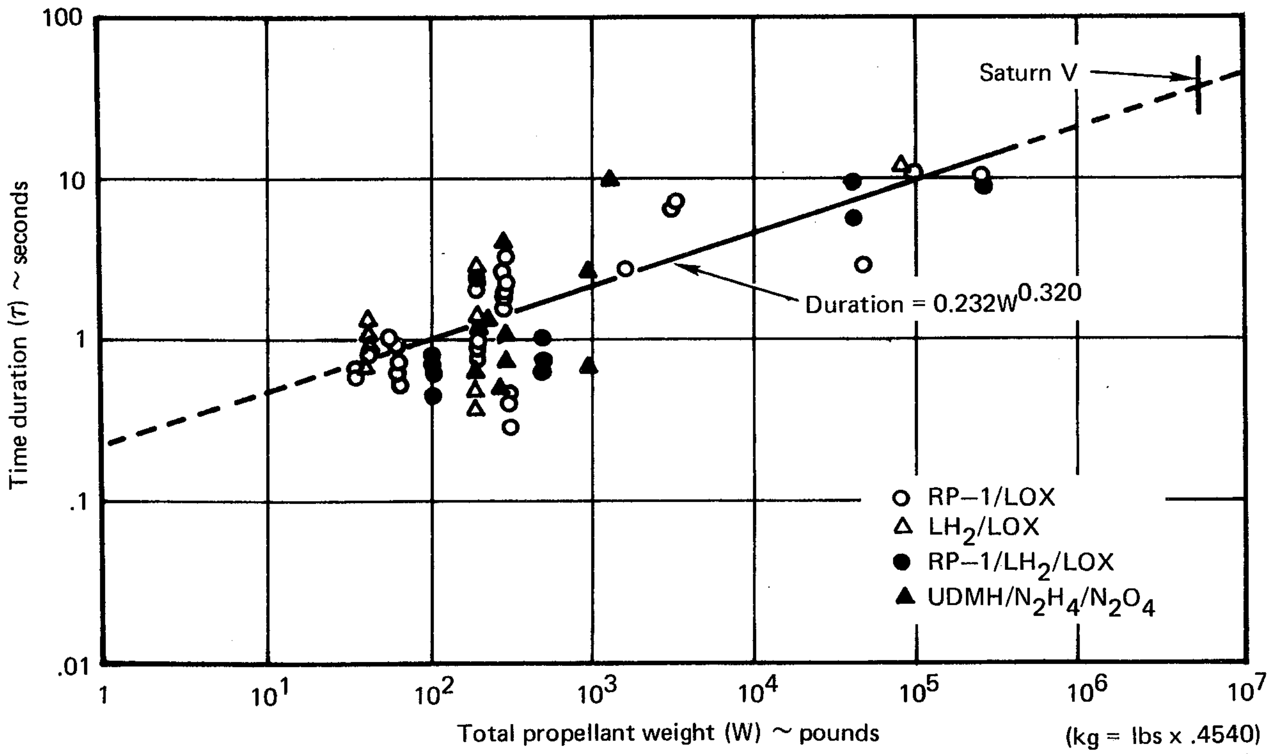


FIGURE 5-39. – ESTIMATES OF FIREBALL CHARACTERISTICS – LIQUID SYSTEMS



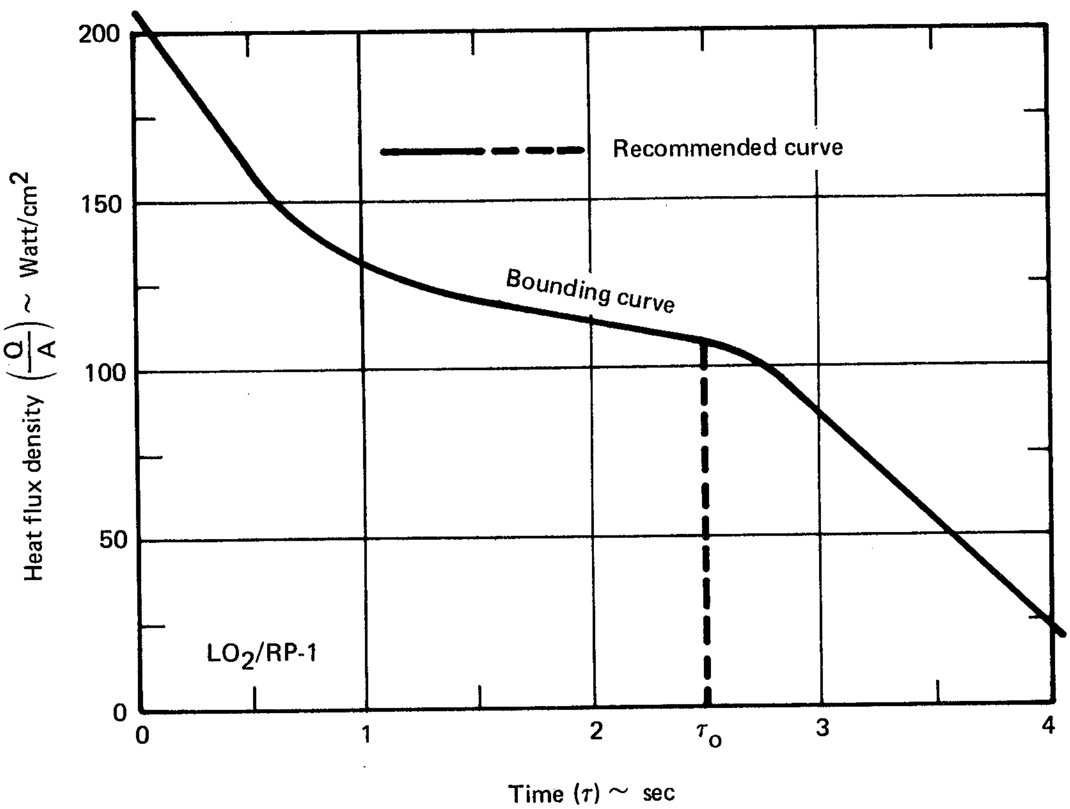
A. Fireball diameters for various weights and types of propellants



(kg = lbs x .4540)
(m = ft x .3048)

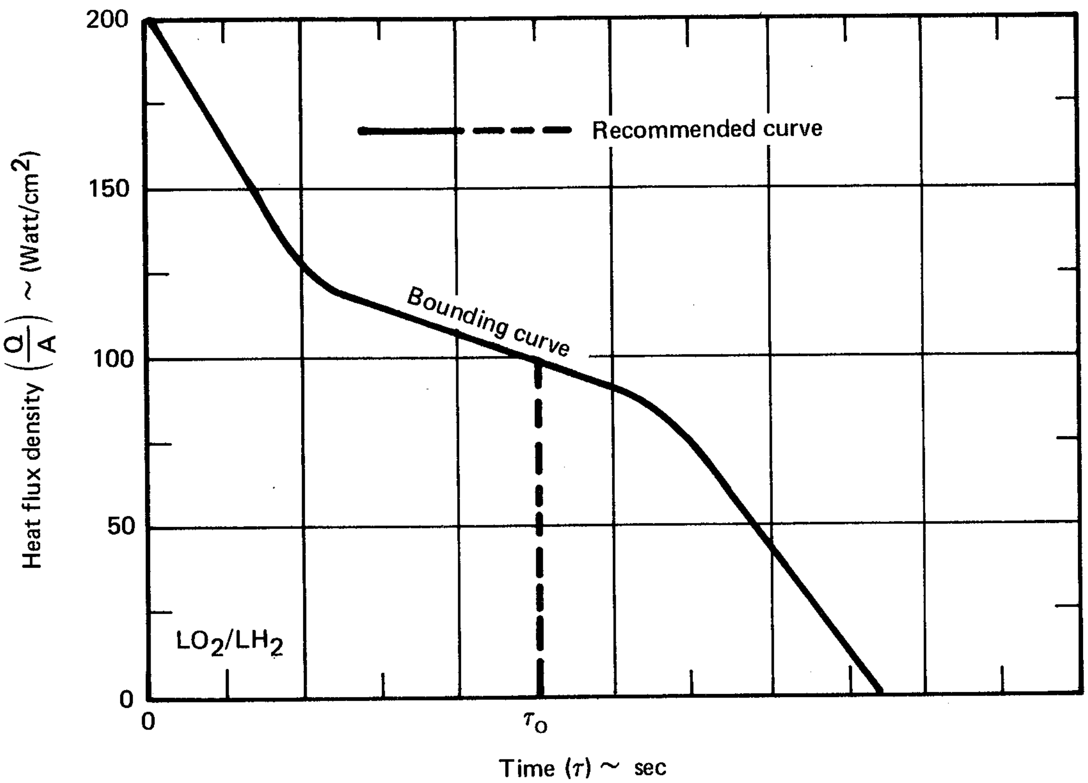
B. Fireball duration for various weights and types of propellants

FIGURE 5-40. – SATURN FIREBALL CHARACTERISTICS (REF. 59)



Note: C = 0.113

FIGURE 5-41. – BOUNDING AND RECOMMENDED HEAT FLUX DENSITY CURVES (REF. 35)



Note: C = 0.077

FIGURE 5-42. – BOUNDING AND RECOMMENDED HEAT FLUX DENSITY CURVES (REF. 35) is primarily based on the analysis of heat flux density data that were obtained from eleven 25,000-lb propellant tests, five of LO_2/RP-1, and six of LO_2/LH_2.* The remaining curve, designated the "recommended curve", is superimposed on the bounding curve out to a time, τ_0, given by Equation 5-7, – where it abruptly decreases to zero. The recommended curve is based primarily on analysis of the data from the eleven 25,000-lb tests mentioned above, and implicitely contain the constraint that the probability of exceeding the cumulative heat flux density associated with the recommended curve (the time integration of the heat flux density from time equal zero to τ_0) is 1%. The variation of the heating pulse with propellant weight, that is, the scaling implicitely contained in Figure 5-41 and 5-42 and Equation 5-7, assumes the following:

(a) The duration of the heating pulse will increase with the cube root of the propellant weight, as implied by the empirical relation Equation 5–6.

(b) The heat flux density at a scaled time, using the above cube root time scaling, will be invariant with variation in propellant weight.

The second statement is based on the invariance of fireball temperatures (measured) from scale to scale.

No consideration has been given in the 'bounding' or 'recommended' curves for the emission of radiant energy from the surface of an immersed object, but this emission can substantially reduce the transfer rates from those given in the curves as the surface temperature of the object becomes a significant fraction of the fireball temperature, approximately 3681°F (2027°C). A reduction occurs similarly for the convective component of transfer. Any other corresponding modifications of heat transfer from the curves are not considered here.

Several other qualifications of the 'bounding' and 'recommended' curves should be noted.

(a) The heat flux density measurements upon which the curves are primarily based were obtained from instruments that were fixed in space; thus, a modified heat flux density may be appropriate for objects which, for example, become prematurely ejected from the fireball (due, for instance, to blast wave forces). For many circumstances, the modification would be a reduction of the total heat transfer, first, due to the tendency to reduce the time that an object is immersed, and second, due to a reduction in the convective heat transfer component, since the motion imparted to the object by the blast wave forces would tend to reduce the relative velocity between the object and the surrounding gas. Rotary motion imparted to the object, however, would generally result in an increased transfer rate at given locations on the object.

---

*Data from which the heat flux density may be evaluated for the N_2O_4/50% N_2H_4-50% UDMH propellant combination are extremely limited. Examination of these data suggests that the heat flux density is somewhat less in magnitude than the bounding curves given for LO_2/RP-1 and LO_2/LH_2 in Figures 5-41 and 5-42, but that the heating durations are perhaps somewhat larger.

It can be seen from Equation 5–7 that the heating durations (τ_0) of Figure 5-41 and 5-42 (of either the bounding or recommended curves) increase with the cube root of propellant weight. Therefore, for small propellant quantities, say 1000-lb or less, the fireball duration is insufficient for appreciable motion (rise) of the fireball, and the fireball duration is then essentially synonymous with the heating duration of an object that is fixed in space. For larger propellant quantities, 25,000-lb and more, significant motion does occur and the heating duration of a fixed object is therefore less than the fireball duration. Thus, the ratio of the heating duration of a fixed object to the total fireball duration is some function of the propellant weight. The curves of Figure 5-41 and 5-42 are based on measurements fixed in space at the 25,000-lb level, and extrapolation to other propellant weight levels through Equation 5–7 inherently assumes an invariance of this ratio of durations. For application to weights in excess of 25,000-lb, it is nevertheless recommended that Equation 5–7 be used in conjunction with the curves of Figure 5-41 and 5-42, although it is expected that the curves would be somewhat conservative. For extrapolation to significantly lesser weights, τ_0 should be larger than given by Equation 5–7; more specifically, at the 1000-lb (or less) level, τ_0 , as given by Equation 5–7, should be increased by a multiplying factor of approximately 1.2 and 1.6 for LO_2/RP-1 and LO_2/LH_2, respectively.

It is possible that the heat transfer hazard can be intensified by the occurrence of chemical activity between the fireball constituents – notably the oxidents – and the surface of an object immersed in the fireball. Predictions of the rates (or existence) of the associated chemical reactions are not included in this report, in part due to the heavy dependence of such reactions on the particular application that is, on the molecular constituents of the object and surface temperature attained. The latter, in turn, depends on the configuration and thermal properties of the object. (The reaction also depends critically, of course, on the concentrations of various atomic and molecular species – and their excited and ionized states – present in the fireball.) Chemical activity is mentioned and should be considered in any application – particularly when comparatively large propellant quantities are involved – because the reactions can provide an energy contribution (not included in Figure 5-41 and 5-42) to the object.

The heat flux density measurements upon which the curves of Figures 5-41 and 5-42 are based were obtained at locations no closer to the "center of explosion" than about one-fifth of the radius of the fireball, and it would be expected that the heat transfer rates, at least during the initial "small" fraction of the fireball duration, could be somewhat more severe at or "very near" the center of explosion. Passive sensors capable of providing crude indications of comparatively severe heat transfer were deployed in the central region (within a few feet of the planned ignition point) throughout most of the eleven 25,000-lb tests mentioned above, and a single positive indication was obtained. Specifically, from 0.1 to 0.2 in. was ablated from the surface of a solid aluminum structure in such a way as to suggest comparatively large heat flux densities over limited times, for instance, of the order of 1000 watt/cm^2 for 2 sec. (A thorough analytic evaluation of the possible ranges of heat transfer parameters resulting in the above ablation has not been performed; for details of the aluminum structure and its ablation, see reference 35, Appendix C of Volume 1.) It is not clear if chemical activity, as mentioned in the previous paragraph, was an energy contributor.

5.4.4 Fragmentation. – Space vehicle fragments generated during accidental explosions can come from several sources. They can be pieces of the exploding vessels/tanks, or pieces of wreckage from an impact which also results in an explosion, or nearby objects accelerated by the blast waves from the explosion.

The methods for estimating initial fragment velocities for various types of accident and geometry, fragment ranges, fragment mass distributions, depths of penetration, striking velocities have been treated at depth by various authors and will not be presented here. The reader is referred to reference 54 and 61 for detailed discussion.

An indication of the fragment propagation range taken from reference 61 is shown in Figure 5-43. The maximum fragment range units as a function of TNT equivalence are given based on available fragment data points from launch vehicle incidents with the upper boundary considered applicable to high order explosive reactions of propellants and the lower boundary applicable to widely distributed and low order reactions (deflagration/low order explosion).

Figures 5-44 and 5-45 show the total weight and number of fragments for the specific tests shown in Figure 5-45. Table 5-IV summarizes the fragment data used in the curves.

5.5 Gas Pressure Vessel Hazards

When a pressurized gas-filled vessel bursts it generates a shock wave which is in many ways similar to the one generated from a TNT explosion. The overpressure behind this shock wave may be quite large and capable of causing damage.

The TNT equivalency of compressed gas obtained from reference 62 is shown in Figure 5-46. The equivalency is shown for gas ($\gamma = 1.4$) expansion to one atmosphere pressure. The figure is based on the gas behaving like a perfect gas over the range of pressures and temperatures involved. It is also assumed that the gas expands adiabatically (no heat transfer) and isentropically (maximum energy release). The results should be very good for the one atmosphere case, but some errors can be expected at the highest pressure shown for this case, and for the full range for the vacuum case, because of liquefaction and solidification of the gas at the extremely low temperatures to which it expands.

To obtain peak side-on overpressure and positive phase impulse for a pressure vessel burst, Figure 5-46 can be used to obtain TNT equivalency and Figure 5-47 can then be entered by converting the distances involved to scaled distances $\lambda = \left(\frac{\text{Ground Distance}}{\text{Weight}_{TNT}^{1/3}}\right)$.

Peak overpressure can alternately be obtained by using Figure 5-12 directly.

Fragmentation parameters are covered at great length by several publications and the reader is referred to references 54 and 61 for a detailed discussion.

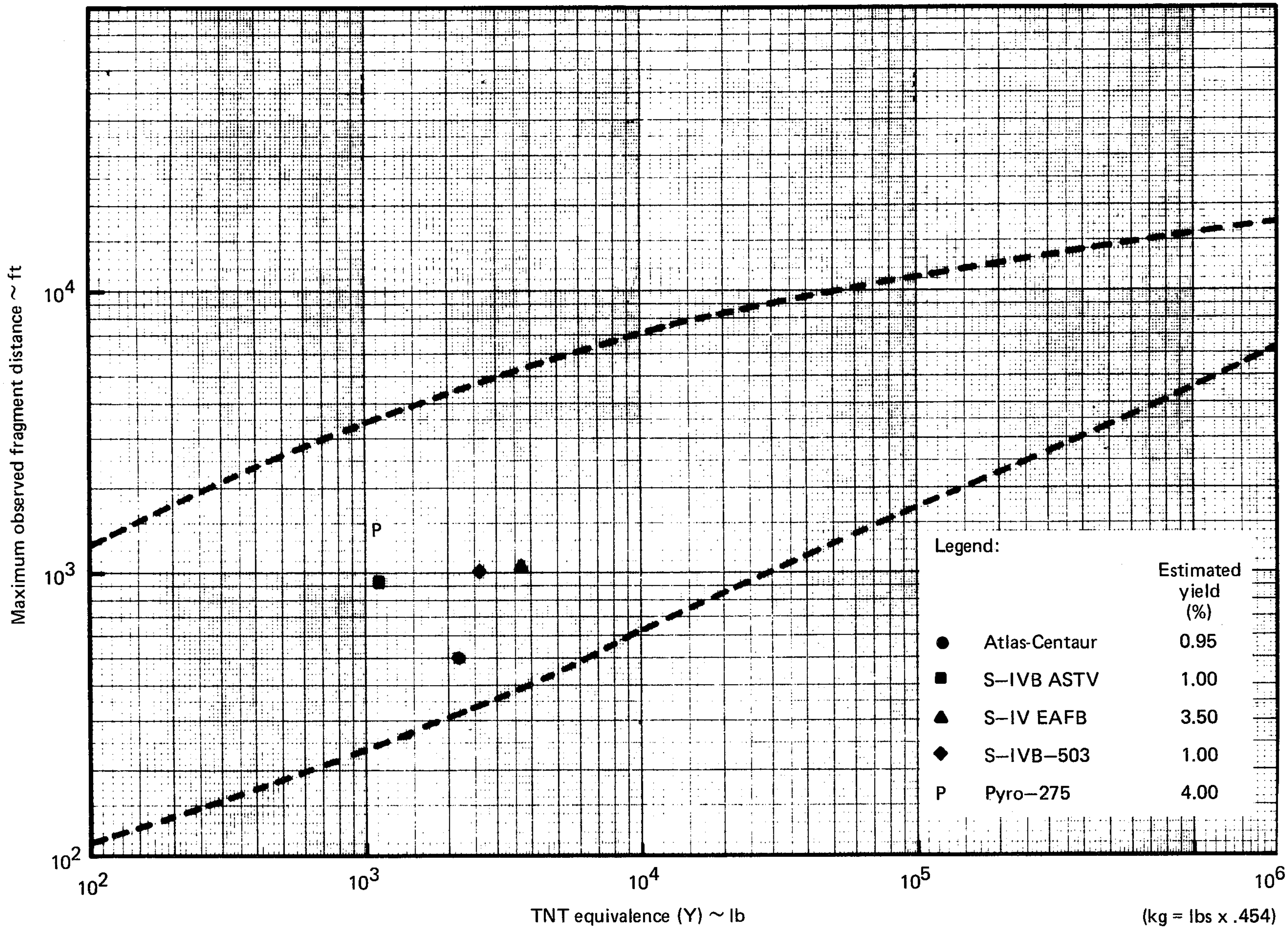


FIGURE 5-43. – ESTIMATED TNT EQUIVALENCE VS. MAXIMUM FRAGMENT DISTANCE FOR ACTUAL SPACE VEHICLE EXPLOSIONS (REF. 61)

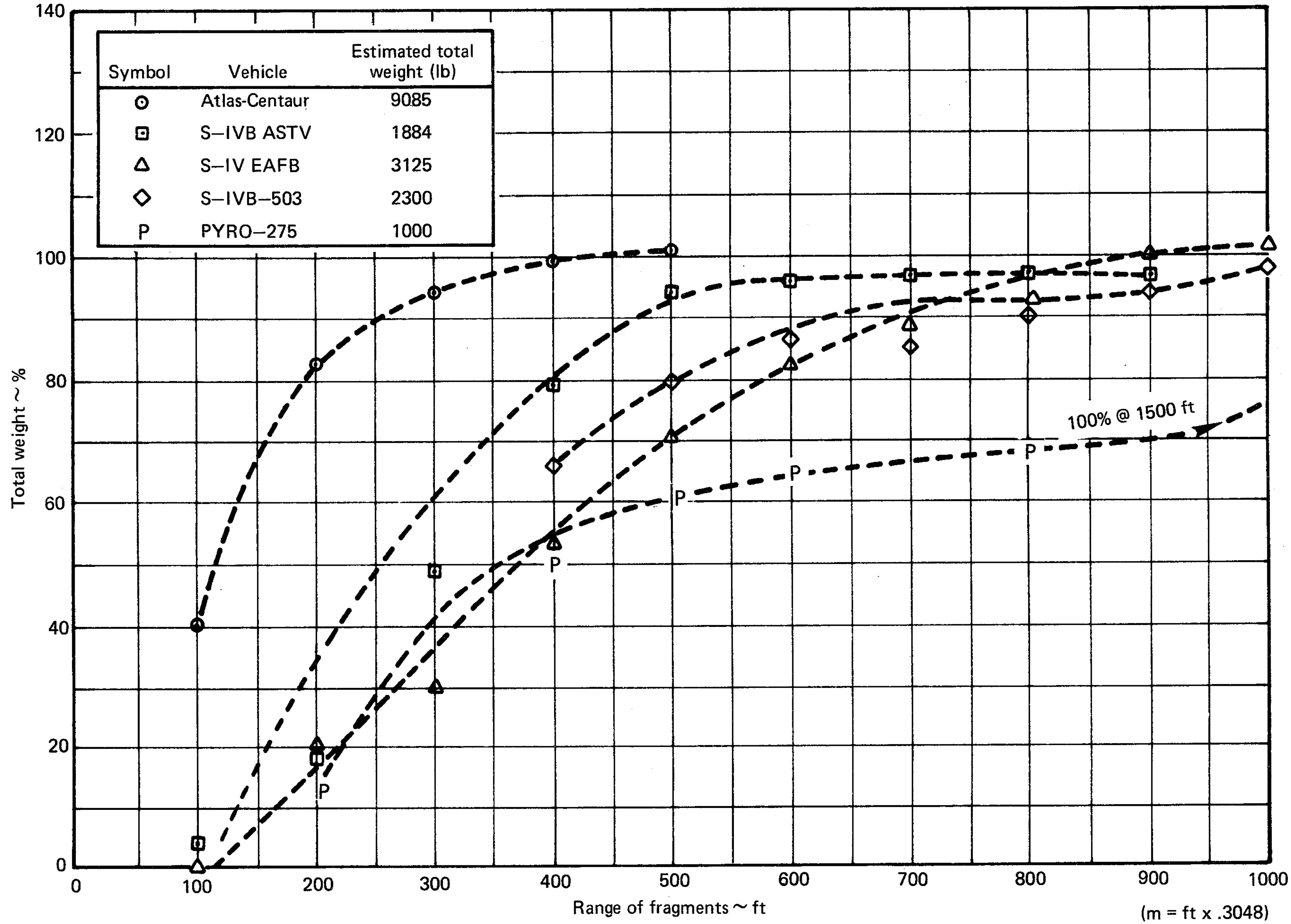


FIGURE 5-44. – PERCENTAGE OF TOTAL WEIGHT OF VEHICLE FRAGMENTS WITHIN RANGE INDICATED (REF. 61)

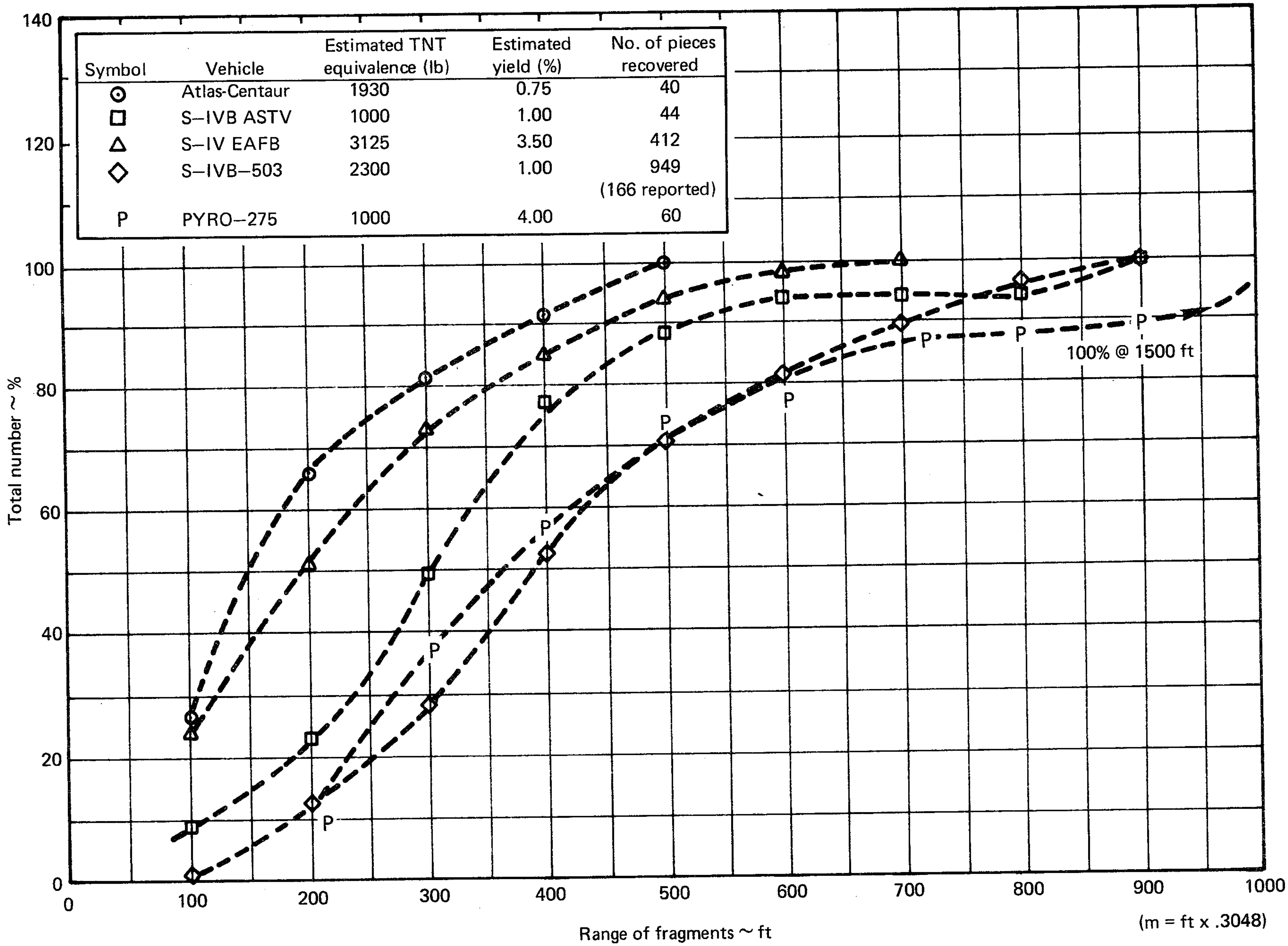


FIGURE 5-45. – PERCENTAGE OF TOTAL NUMBER OF VEHICLE FRAGMENTS WITHIN RANGE INDICATED (REF. 61)

TABLE 5-IV. – FRAGMENT DATA FROM SELECTED SPACE VEHICLE EXPLOSIONS (REF. 61)

Vehicle site/date	Propellant/ lb	Yield TNT (%)/lb	Incident	Number of fragments/ weight, lb	Source	Major fragment radius, ft	Average fragment density/10,000 ft^2 outside fragment radius
S–IV–ASTV Douglas-Sacramento 1-24-64	LO_2/LH_2 100,000	(1%) 1,000	Explosion Overpressurization of LOX tank to 100 psia	262 Total 44 Wt'd 1,882	Investigation of S–IV Vehicle explosion by J. B. Gayle	400	.31
Atlas Centaur KSC 3-2-65	LO_2/LH_2 30,000 LO_2/RP-1 172,000 Total 284,000	(0.75%) 1,930	Launch At T 1.1 sec. the booster engine cut-off at T 1.63 vertical vel. = 0. Vehicle fell back bursting the booster tanks	40 9,085	Investigation of the Atlas Centaur Vehicle explosion by S. S. Perlman	400	.29
S–IV–EAFB Edwards 7-14-65 Test Vehicle Run 062	LO_2/LH_2 91,000	(3.5%) 3,200	Induced failure 18 in. ram on inter-tank bulkhead	412 3,125	Project PYRO Quarterly Progress Report 9/65	500	.5
S–IVB–503 Douglas-Sacramento 1-20-67	LO_2/LH_2 231,000	(1%) 2,300	Explosion On repressurization. Wrong type welding rod, titanium spheres	166 1,426	Report of Investigation S–IVB–503 Incident 1-20-67 by Kurt B. Debus, KSC	600	.81
PYRO–275 (Test Tanks) AFRPL Edwards 3-22-67	LO_2/RP-1 25,000	(4%) 1,000	Tank rupture Self-ignition after 500 milliseconds of mixing	60 1,628	Project PYRO Reports 3-67, 6-67	500	.30

(kg = lb x .454)
(m = ft x .3048)

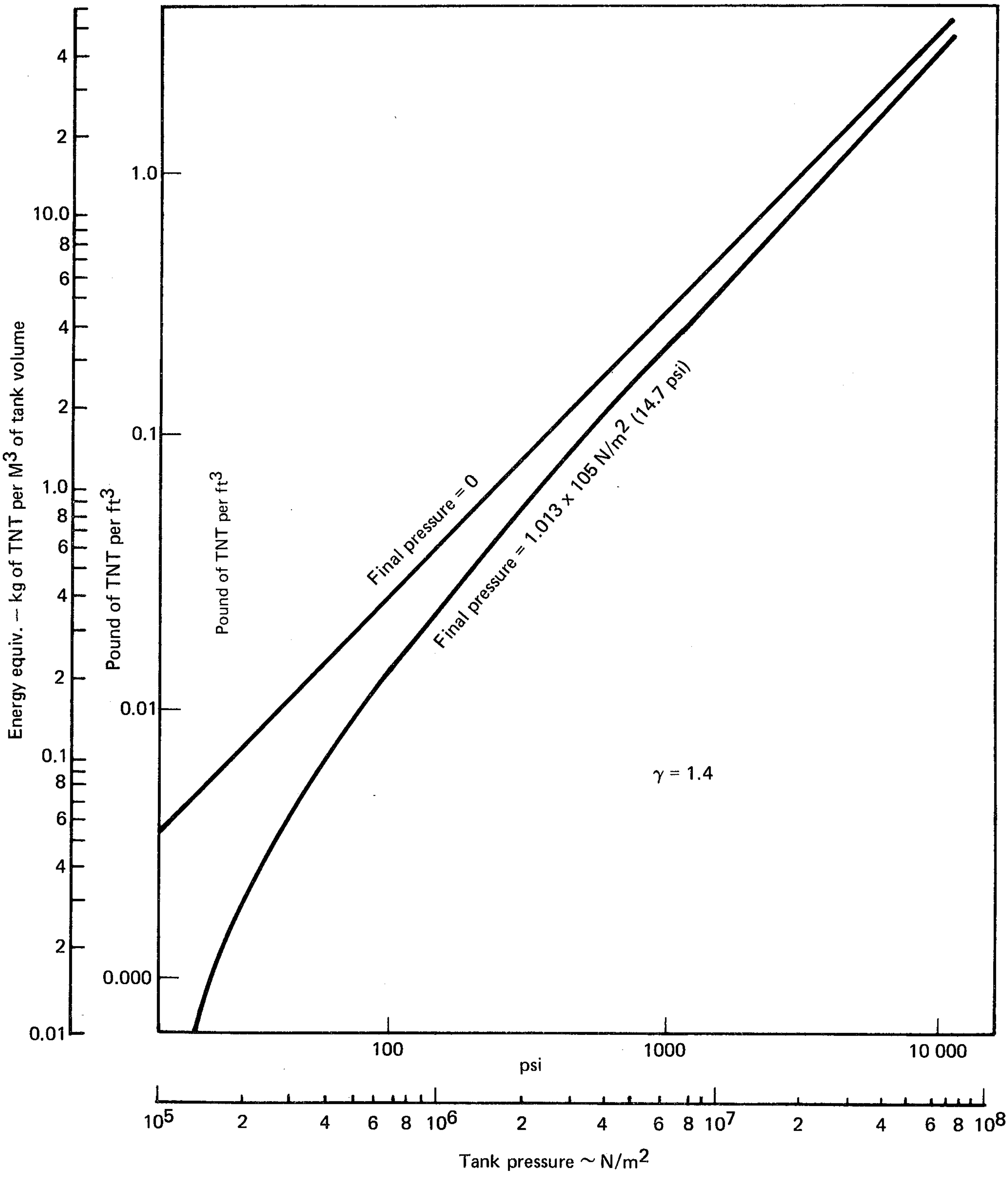
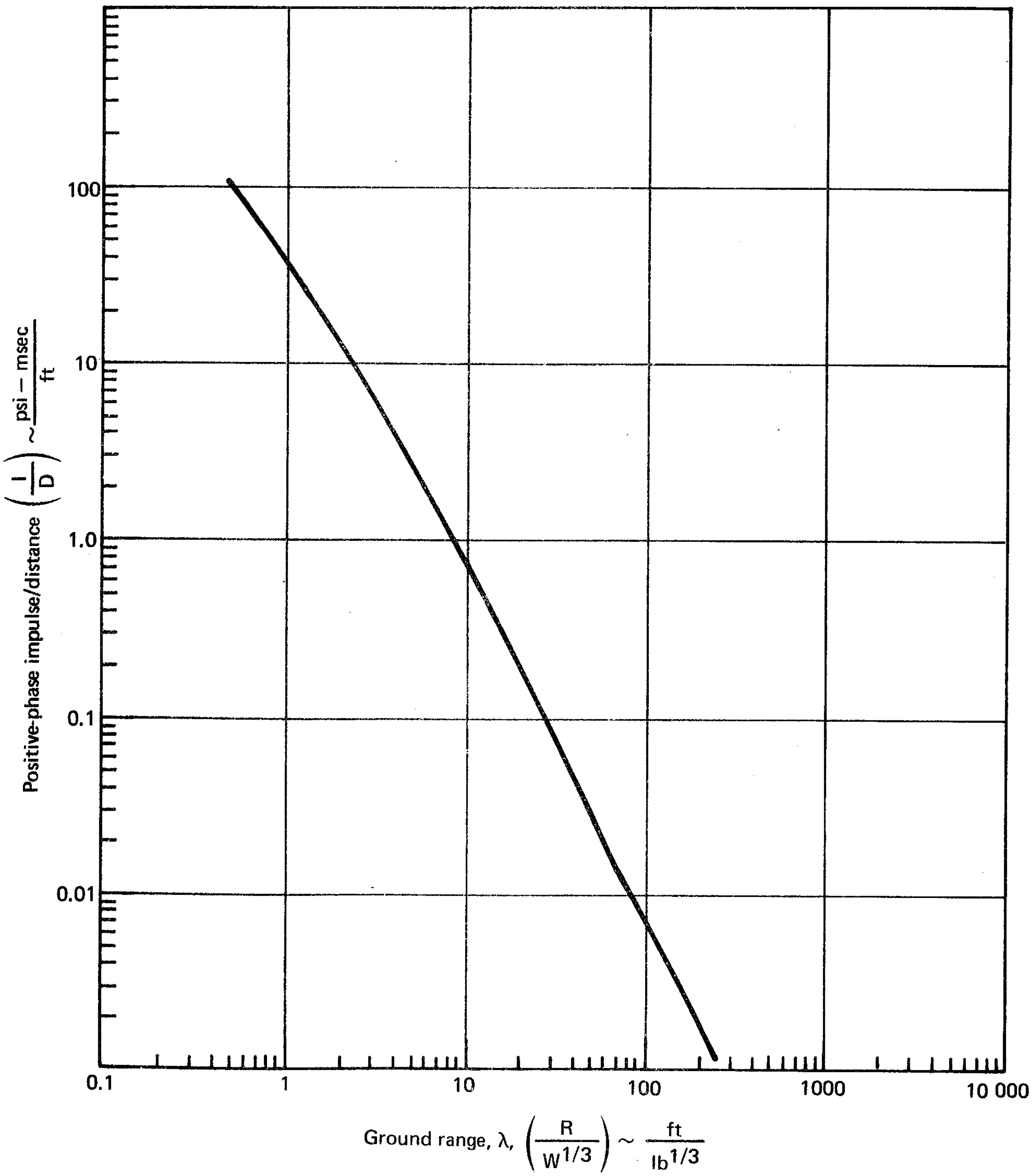


FIGURE 5-46. – COMPRESSED GAS TNT EQUIVALENT (REF. 62)



$\left(\frac{m}{kg^{1/3}} = \frac{ft}{lb^{1/3}} \times .3966\right)$

$\left(\frac{N/m^2 \cdot ms}{m} \quad \frac{psi\text{–}msec}{ft} \times 2.2621 \times 10^4\right)$

FIGURE 5-47. – PEAK OVERPRESSURE AND POSITIVE-PHASE IMPULSE VS SCALED DISTANCE FOR TNT SURFACE BURST (REF. 35)

The largest anticipated usage of compressed gas for Space Shuttle payloads is expected to be associated with upper stage vehicles requiring propellant system pressurization gases, and with Space Station modules which require atmospheric pressurization and re-pressurization gases. Scout, for example, requires a nitrogen pressurization source for the reaction control system. A "B" stage nitrogen tank pressurized to 3000 psi (2.1×10^7 N/m^2), with an internal volume capacity of .223 ft^3 (.0063 m^3), has a TNT equivalency, from Figure 5-46, of .1736 lb. (.0788 kg).

From Figure 5-47, the peak side-on overpressure and positive phase impulse estimated at a distance of 5 feet would be:

$$\lambda = \frac{5 \text{ ft}}{(.1736 \text{ lb})^{1/3}} = 8.963$$

Therefore P = 125 psi at λ = 8.963 and

$$\frac{I}{D} = \frac{.95 \text{ psi} - \text{msec}}{\text{ft}} \left(2.1489 \times 10^4 \ \frac{\text{N/m}^2\text{—ms}}{\text{m}} \right)$$

Therefore I = (.95) (5) = 4.75 psi — msec (3.2749 N/m^2—ms)

5.6 Summary

A literature review yielded considerable information concerning liquid propulsion system hazards but somewhat limited information concerning solid rocket motor hazards. The most revealing information was obtained from Projects Pyro (liquid propellants) and Sophy (solid propellants). However, the results presented were based on a number of other sources.

In an effort to determine the thresholds of a solid propellant motor ignition, explosion, or detonation resulting from an impact, data were compiled on various impact tests, accidents, missile fallback data, shotgun tests and flying plate tests. A subjective extrapolation between the data points was performed so that the interfaces between the inert-explosive/burn and explosive/burn-detonate regions could be delineated. It was found that the composite and composite-modified double base (CMDB) propellants had about the same interface between the inert-explosive/burn regions but the higher energy release interface was lower for the CMDB system.

Critical diameter tests performed by Project Sophy have identified a minimum critical diameter of 64.2 inches for solid cylindrical PBAN composites having a weight composition of 69% AP and 15% AL. The pseudocritical geometry has been shown to be approximately 92% of the critical diameter. These relationships indicate that composite solid rocket motors which are candidates for Space Shuttle use and have similar compositions are relatively safe from donor charge detonation when they are of subcritical size.

Double base propellants investigated and composite propellants with high energy additives have been found to have critical diameters which decrease with increasing degree of high energy enrichment. The critical diameter is in the order of 2.0 inches or less which is small compared to the 64.2 inches for PBAN propellants.

The threshold overpressure for detonation of PBAN composites has been established by Project Sophy to be 25 to 30 kbars for propellants near their critical diameters (64.2 in.) NOL card-gap tests of composites have shown that they will not detonate in the subcritical diameter size (less than 2.0 in.) with incident pressures in the order of 100 kbars. Data on double base propellants, based on NOL card-gap tests (test samples less than 2.0 in. in diameter), indicates detonation thresholds of the order of 30 to 44 kbars for the propellants investigated.

The effects of solid propellant motor explosion/detonations have been characterized in terms of resulting near side-on overpressure, impulse, TNT equivalency, fireball/firebrand effects, and fragmentation. Data presented provides methods for estimating the required values of these parameters.

TNT equivalencies have been obtained from various test programs and have been defined in general terms as follows:

Composite propellants near their critical diameters of the composition used in Project Sophy are capable of explosive yields of 156% to 168% based on combined overpressure and impulse data. These propellants can show higher yields (197%) based on peak side-on overpressure only.

Actual tests of smaller rocket motors indicate that these yields are rarely achieved and that composites achieve yields in the order of 85% TNT equivalency while double base propellants can achieve yields up to 140% TNT equivalency. Combined tests of double base and composite propellants in which the former was used as the donor achieved yields in the order of 125% TNT equivalency.

Liquid propellant system hazards have been evaluated on the basis of three types of fuel and oxidizer combinations and three different modes of mixing. Hypergolic propellants (50% N_2H_4 – 50% UDMH and N_2O_4), RP-1-LO_2, and LH_2-LO_2 were evaluated in the confinement by missile, confinement by ground surface, and high velocity impact failure modes. Tables and figures are provided so that calculations of explosive yield, peak side-on overpressure, and impulse can be performed. Determination of fireball effects, heat flux density and fragmentation based on test results obtained from Project Pyro and other tests is presented and will provide an insight of the magnitudes of the parameters involved.

Gas pressurization bottles also can provide an explosive yield, peak side-on overpressure if ruptured. Figures are also presented so that these parameters can be determined for bottles pressurized up to 10,000 psi (6.894×10^7 N/m^2).

6.0 PRELIMINARY HAZARD ANALYSIS OF ROCKET SYSTEMS FOR SHUTTLE PAYLOAD

6.1 Solid Propellants

6.1.1 Introduction. – A Preliminary Hazard Analysis (PHA) of the Scout propulsion system has been performed in order to determine the possible hazards of utilizing the Scout upper stage solid Consideration Tree, Figure 6-1. The analysis was based on the upper stage solid rockets of the Scout vehicle; however, it is applicable to solid rocket propulsion systems in general, except the reaction control system which is unique to the Scout system.

6.1.2 System Safety Program. – A System Safety Program is required in order to assure compliance with the requirements outlined in the NASA Headquarters Safety Policy and Requirements Document, reference 20.

A hazard analysis as described in NASA System Safety Manual, reference 21, has a logic sequence of events as follows: (a) General Safety Studies, (b) Preliminary Hazard Analysis, (c) Fault Hazard Analysis, (d) Logic Diagram Analysis, and (e) Procedures Analysis. In Figure 6-2, these analyses are shown relative to the program activity phases. DOD components follow a System Safety Program as outlined in MIL-STD-882, reference 18. These are as follows: (a) Preliminary Hazard Analysis, (b) Subsystem Hazard Analysis, (c) System Hazard Analysis, and (d) Operating Hazard Analysis. SAMSO has documented these requirements in reference 63 and outlines the program as consisting of a Preliminary Hazard Analysis, Operating Hazard Analysis, Fault Hazard Analysis, Fault Tree Analysis, Software Hazardous Effects Analysis, and Cable Failure Matrix. In Figure 6-3 the SAMSO approach to safety analyses events and program milestone coordination are shown. A Space Transportation System user must have a System Safety Program and plan for performing these analyses in an orderly and timely manner so that hazards will be identified with subsequent elimination, reduction, control, or placarding of each critical and catastrophic hazard. The approach used by SAMSO, as outlined in reference 63, is the System Safety Program developed for the Minuteman Program by the Boeing Aerospace Company. The purpose of each of the required analyses is discussed in the following paragraphs.

6.1.2.1 Preliminary Hazard Analysis: This analysis is used by the contractor to identify and document the system/subsystem hazards recognized in the early conceptual and design phases so that by process and /or procedural constraints the hazards can be eliminated or minimized to an acceptable level.

TABLE 6-I. – PRELIMINARY HAZARD ANALYSIS–SOLID PROPULSION SYSTEM

Hazard	Ultimate effect	Safety tree number	Intermediate effects		Preventive action	Scout status of implementation
Shuttle or Scout non-propulsion system fire	Severe shuttle damage or loss	1.1	Premature motor ignition or detonation	High motor temperatures	Utilize motors of high auto-ignition temperatures	Motor auto-ignition temperatures are as follows: 3rd stage – $392^{\circ}F$ ($200^{\circ}C$) 12 min. 4th stage – $300^{\circ}F$ ($149^{\circ}C$) 24 hrs. no ignition spin motor – $350^{\circ}F$ ($177^{\circ}C$) 8 hrs.
					Thermally insulate the motors to protect from max. shuttle bay temperature of $150^{\circ}F$ ($65.5^{\circ}C$) during launch	OPEN
					Utilize motors which have propellant that is resistant to detonation in a fire	No known case of solid motor detonation during cook-off. Cook-off can cause an explosion-deflagration
	Shuttle damage or loss	1.2	Scout propulsion system fire	Ignition of Scout propulsion system materials	Select system materials that are resistant to combustion	Because of H_2O_2 systems Scout is designed with low combustion materials

TABLE 6-I. – PRELIMINARY HAZARD ANALYSIS–SOLID PROPULSION SYSTEM – Continued

Hazard	Ultimate effect	Safety tree number	Intermediate effects		Preventive action	Scout status of implementation
Shuttle or scout non-propulsion system fire (continued)	Severe shuttle damage or loss	1.3	Explosive rupture of motor case	High temperature causing propellant grain cracks or bond separation resulting in case rupture when motor is ignited during normal launch	Abort motor ignition if a fire occurs in the vicinity of the motor and propellant flaw is suspected	Must be defined in mission procedures: OPEN
					Delay first stage ignition of the payload until sufficient separation exists so that shuttle cannot be damaged by ignition of flawed motor	Must be defined in mission procedures: OPEN
	Shuttle damage or loss	1.4	Shock, fragmentation, fire, chemical attack of materials, or toxicity resulting from RCS system rupture or leak	Thermal over-pressurization of RCS system	Provide pressure relief to exterior of the shuttle	OPEN
					Provide warning regarding personnel hazards to operating personnel	Standard operating procedures contain warning, caution, and notes regarding RCS system hazards
Scout propulsion system fire	Severe shuttle damage or loss	1.1	Premature motor ignition or detonation	High motor temperatures	Utilize motors of high auto-ignition temperatures	Motor auto-ignition temperatures are as follows: 3rd stage – $392^{o}F$ ($200^{o}C$) 12 min. 4th stage – $300^{o}F$ ($149^{o}C$) 24 hrs. no ignition spin motor – $350^{o}F$ ($177^{o}C$) 8 hrs.
					Thermally insulate the motors to protect from max. shuttle bay temperature of $150^{o}F$ ($65.5^{o}C$) during launch	OPEN

TABLE 6-I. – PRELIMINARY HAZARD ANALYSIS–SOLID PROPULSION SYSTEM – Continued

Hazard	Ultimate effect	Safety tree number	Intermediate effects		Preventive action	Scout status of implementation
Scout Propulsion system fire (continued)					Utilize motors which have propellant that is resistant to detonation in a fire	No known case of solid motor detonation during cook-off. Cook-off can cause explosion-deflagration
	Severe shuttle damage or loss	1.2	Explosive rupture of motor case	High temperature causing propellant grain cracks or bond separation resulting in case rupture when motor is ignited during normal launch	Abort motor ignition if a fire occurs in the vicinity of the motor such that propellant flaw is suspected	Must be defined in mission procedures: OPEN
					Delay first stage ignition of the payload until sufficient separation exists so that shuttle cannot be damaged by ignition of flawed motor	Must be defined in mission procedures: OPEN
Environmental heating	Severe shuttle damage or loss	1.1	Premature motor ignition or detonation	High motor temperatures	Utilize motors of high auto-ignition temperatures	Motor auto-ignition temperatures are as follows: 3rd stage – 392°F (200°C) 12 min. 4th stage – 300°F (149°C) 24 hrs. no ignition spin motor – 350°F (177°C) 8 hrs.
					Thermally insulate the motors to protect from max. shuttle bay temperature of 150°F (65.5°C) during launch	OPEN

TABLE 6-I. – PRELIMINARY HAZARD ANALYSIS–SOLID PROPULSION SYSTEM – Continued

Hazard	Ultimate effect	Safety tree number	Intermediate effects		Preventive action	Scout status of implementation
Environmental heating (continued)					Utilize motors which have propellant that is resistant to detonation in a fire	No known case of solid motor detonation during cook-off. Cook-off can cause an explosion-deflagration
					Conduct qualification tests to demonstrate insensitivity to expected environmental temperature extremes	OPEN
	Severe shuttle damage or loss	1.2	Explosive rupture of motor case	High temperature causing propellant grain cracks or bond separation resulting in case rupture when motor is ignited during normal launch	Abort motor ignition if a fire occurs in the vicinity of the motor and propellant flaw is suspected	Must be defined in mission procedures: OPEN
					Delay first stage ignition of the payload until sufficient separation exists so that shuttle cannot be damaged by ignition of most flawed motor	Must be defined in mission procedures: OPEN
					Conduct qualification tests to demonstrate insensitivity to expected temperature extremes	OPEN
	Shuttle damage or loss	1.4	Shock, fragmentation, fire, chemical attack of materials, or toxicity resulting from RCS system rupture or leak	Thermal overpressurization of RCS system	Provide pressure relief to exterior of the shuttle	OPEN
					Provide personnel warning in procedures regarding RCS system hazards	Standard operating procedures contain warning, caution, & notes regarding RCS system hazards
					Provide adequate safety margins in nitrogen & hydrogen peroxide reservoir design	Reservoir proof pressure is 1.5 times operating pressure and burst pressure is 2.5 times operating pressure

TABLE 6-I. – PRELIMINARY HAZARD ANALYSIS–SOLID PROPULSION SYSTEM – Continued

Hazard	Ultimate effect	Safety tree number	Intermediate effects		Preventive action	Scout status of implementation
Environmental heating (continued)					Conduct qualification tests to demonstrate insensitivity to expected temperature extremes	Some tests performed OPEN
					Thermally insulate sections to protect from max. shuttle bay temperature of 150°F (65.5°C) during launch	OPEN
Meteoroid impact (this hazard exists only during orbit phase)	Severe shuttle damage or loss	1.1	Premature motor ignition or detonation	Energy impacted by meteoroid causing propellant ignition	Minimize exposed vehicle skin	Analyses indicate that present concept affords sufficient protection
	Shuttle damage or loss	1.2	Explosive rupture of motor case	Energy impacted by meteoroid causes propellant grain crack resulting in case rupture when motor is ignited	Minimize exposed vehicle skin	Analyses indicate that present concept affords sufficient protection
					Abort normal motor ignition if propellant flaw is suspected	Appropriate warning should be included in deployment procedures OPEN
					Delay first stage ignition of the payload until sufficient separation exists so that shuttle cannot be damaged by ignition of flawed motor	Must be defined in mission procedures: OPEN
	Severe shuttle damage or loss	1.4	Shock, fragmentation, fire, chemical attack of materials, or toxicity resulting from RCS system rupture or leak	Meteoroid impact with RCS system causing leak or rupture	Provide protection of RCS system from meteoroid impact	RCS system is contained entirely within airframe

TABLE 6-I. – PRELIMINARY HAZARD ANALYSIS–SOLID PROPULSION SYSTEM – Continued

Hazard	Ultimate effect	Safety tree number	Intermediate effects		Preventive action	Scout status of implementation
Fragment impact from shuttle or non-propulsion system rupture or explosion	Severe shuttle damage or loss	1.1	Premature motor ignition or detonation	Fragment impact energy insufficient to cause severe shuttle damage may cause motor ignition or detonation	Conduct qualification tests to demonstrate motor insensitivity to fragment impact	OPEN
	Severe shuttle damage or loss	1.2	Explosive rupture of motor case	Fragment impact energy insufficient to cause severe shuttle damage directly may cause propellant grain flaw resulting in explosive rupture of motor case when motor is ignited	Abort normal motor ignition if propellant flaw is suspecte suspected	Mission procedures: OPEN
					Delay first stage ignition of the payload until sufficient separation exists so that shuttle cannot be damaged by ignition of flawed motor	Must be defined in mission procedures OPEN
	Shuttle damage or loss	1.4	Shock, fragmentation, fire, chemical attack of materials, or toxicity resulting from RCS system rupture or leak	Fragment impact energy insufficient to cause severe shuttle damage directly may cause rupture or leak of RCS system	Provide protection of RCS system from fragmentation	RCS system is located entirely within missile airframe
					Provide personnel warning in procedures regarding RCS system hazards	Standard operating procedures contain warning, caution, & notes regarding RCS system hazards
Environmental vibration	Severe shuttle damage or loss	1.1	Premature motor ignition or detonation	Vibration energy absorbed by motors may cause ignition or detonation. Considered a very low probability. No known occurrence	Conduct qualification tests to demonstrate motor insensitivity to vibration	Some test performed OPEN
					Design payload pallet to attenuate vibration	OPEN

TABLE 6-I. – PRELIMINARY HAZARD ANALYSIS–SOLID PROPULSION SYSTEM – Continued

Hazard	Ultimate effect	Safety tree number	Intermediate effects		Preventive action	Scout status of implementation
Environmental vibration (continued)	Severe shuttle damage or loss	1.3	Explosive rupture of motor case	Vibration energy absorbed by motors causing cracks in propellant grain resulting in case rupture upon ignition	Abort normal motor ignition if propellant flaw is suspected	Must be defined in mission procedures: OPEN
					Design payload pallet to attenuate vibration	OPEN
					Delay first stage ignition of the payload until sufficient separation exists so that shuttle cannot be damaged by ignition of flawed motor	Must be defined in mission procedures: OPEN
	Shuttle damage or loss	1.4	Shock, fragmentation, fire, chemical attack of materials, or toxicity resulting from RCS system rupture or leak	Structural failure of RCS system causing leak or rupture	Design RCS system to withstand expected environment	OPEN
					Conduct qualification tests to demonstrate ability to withstand vibration	RCS system components are tested to the following minimum level: • time per axis: (seconds) 80 • frequency (Hz) 20 to 2000 grms 10.55
					Design payload pallet to attenuate vibration	OPEN
					Provide personnel warning in procedures regarding RCS system hazards	Standard operating procedures contain warning, cautions & notes regarding RCS system hazards

TABLE 6-I. – PRELIMINARY HAZARD ANALYSIS–SOLID PROPULSION SYSTEM – Continued

Hazard	Ultimate effect	Safety tree number	Intermediate effects		Preventive action	Scout status of implementation
Environmental shock	Severe shuttle damage or loss	1.1	Premature motor ignition or detonation	Shock energy absorbed by motors may cause ignition or detonation	Conduct qualification tests to demonstrate motor insensitivity to shock	OPEN
					Design pallet to attenuate shock	OPEN
	Severe shuttle damage or loss	1.2	Explosive rupture of motor case	Shock energy absorbed by motors causing cracks in propellant grain resulting in case rupture upon ignition	Abort normal motor ignition if propellant flaw is suspected because of excess shock loads	Must be defined in mission procedures OPEN
					Delay first stage ignition of the payload until sufficient separation exists so that shuttle cannot be damaged by ignition of flawed motor	Must be defined in mission procedures OPEN
	Shuttle damage or loss	1.4	Shock, fragmentation, fire, chemical attack of materials, or toxicity resulting from RCS system rupture or leak	Structural failure of RCS system causing leak or rupture	Design RCS system to withstand expected environment	OPEN
					Conduct qualification tests to demonstrate ability to withstand shock	RCS system components are tested to the minimum level of at least 30g in any direction OPEN
					Design pallet to attenuate shock	OPEN
					Provide warning regarding personnel hazards to operating personnel	Standard operating procedures contain warning, cautions, & notes regarding RCS system hazards

TABLE 6-I. – PRELIMINARY HAZARD ANALYSIS–SOLID PROPULSION SYSTEM – Continued

Hazard	Ultimate effect	Safety tree number	Intermediate effects		Preventive action	Scout status of implementation
Shock from shuttle or Scout non-propulsion system rupture or explosion	Severe shuttle damage or loss	1.1	Premature motor ignition or detonation	Shock energy insufficient to cause severe shuttle damage may cause motor ignition or detonation	Conduct qualification tests to demonstrate motor insensitivity to shock	OPEN
	Severe shuttle damage or loss	1.3	Explosive rupture of motor case	Energy insufficient to cause severe shuttle damage directly may cause propellant grain flaw resulting in explosive rupture of motor case when motor is ignited	Abort normal motor ignition if propellant flaw is suspected	Must be defined in mission procedures OPEN
					Delay first stage ignition of the payload until sufficient separation exists so that shuttle cannot be damaged by ignition of flawed motor	Must be defined in mission procedures OPEN
Electrical fault	Severe shuttle damage or loss	1.1	Premature motor ignition or detonation	Spurious electrical signal in ignition circuit	Design ignition system to minimize likelihood of spurious electrical signal	Shielded twisted wiring OPEN
					Utilize electro-mechanical safe and arm devices to protect motors from spurious electrical signals including those due to EMI and RFI	Safe/arm relays in ignition circuit OPEN
	Shuttle damage or loss	1.2	Fire	Electrical fault resulting in fire	Design electrical circuits to minimize likelihood of fire	Fire retarding cover on wiring OPEN
					Select propulsion system equipment that are resistant to combustion	Because of H_2O_2 system design with low combustible materials

TABLE 6-I. – PRELIMINARY HAZARD ANALYSIS–SOLID PROPULSION SYSTEM – Concluded

Hazard	Ultimate effect	Safety tree number	Intermediate effects		Preventive action	Scout status of implementation
Electrical fault (continued)	Shuttle damage or loss	1.4	Shock, fragmentation, fire, chemical attack of materials, or toxicity resulting from RCS system rupture or leak	Thermal overpressurization of RCS system caused by fire in the vicinity of the system	Provide nitrogen and hydrogen peroxide relief connections to the exterior of the shuttle	OPEN
					Provide warning regarding personnel hazards to operating personnel	Standard operating procedures contain warnings, cautions, and notes regarding RCS system hazards
Corrosion	Shuttle damage or loss	1.4	Shock, fragmentation, fire, chemical attack of materials, or toxicity resulting from RCS system leak	Loss of RCS system structural integrity	System materials are to be resistant to corrosion	Materials selected to be compatible with H_2O_2
					Provide warning regarding personnel hazards to operating personnel	Standard operating procedures contain warnings, cautions, and notes regarding RCS system hazards

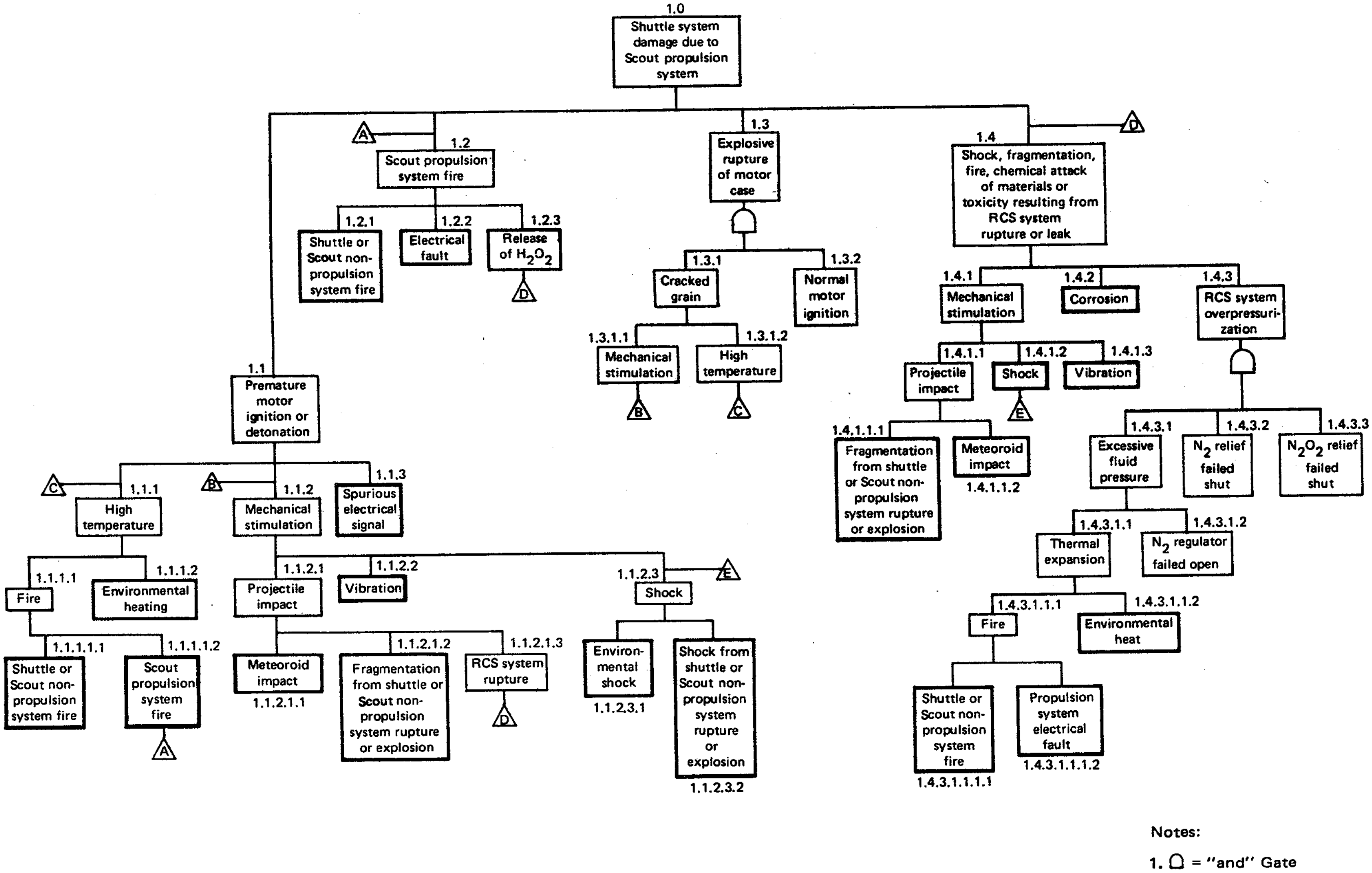


FIGURE 6-1. – SOLID PROPELLANT ROCKET SAFETY CONSIDERATION TREE

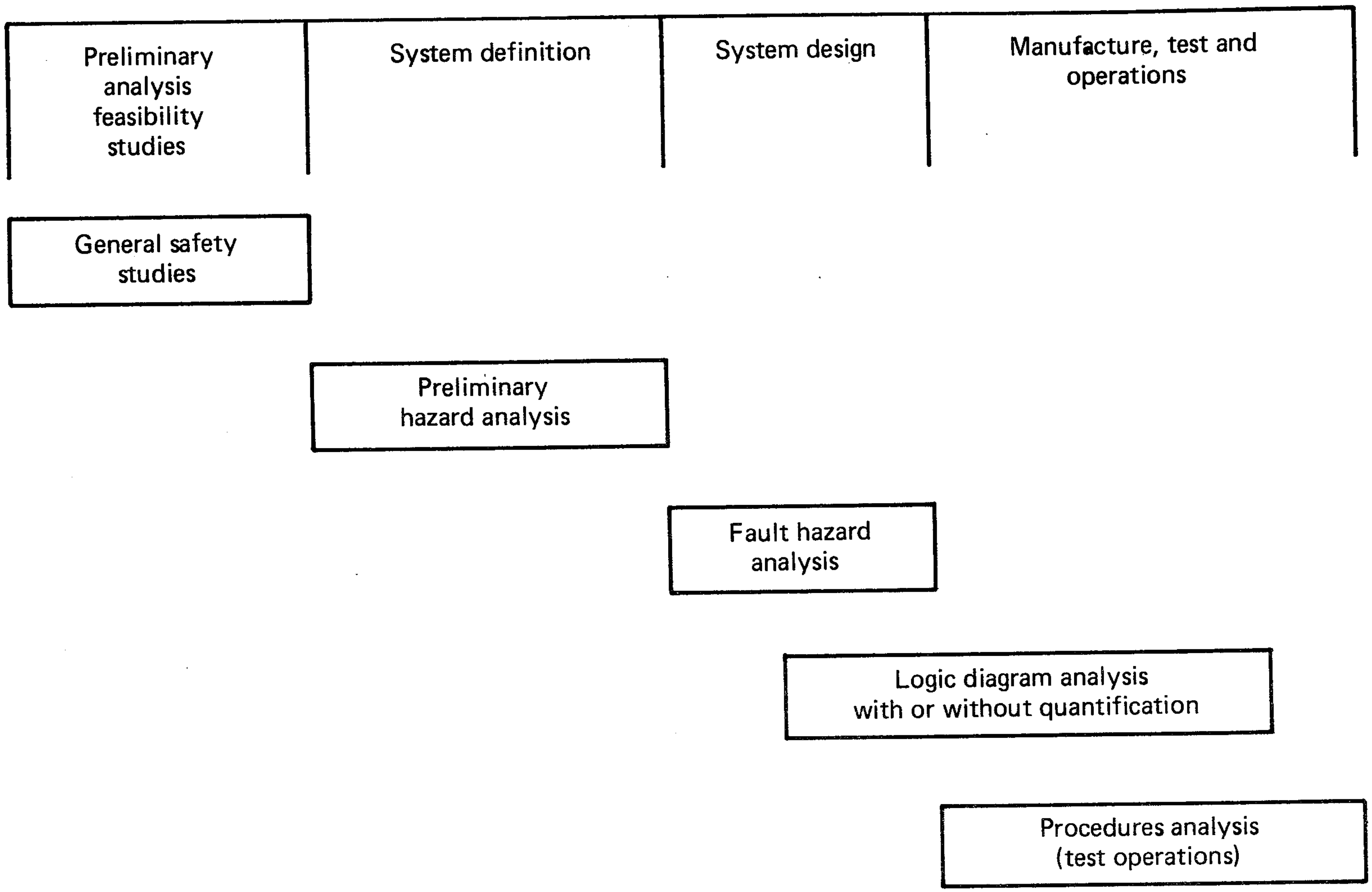


FIGURE 6-2. – SAFETY ANALYSIS – PROGRAM ACTIVITY RELATIONSHIP

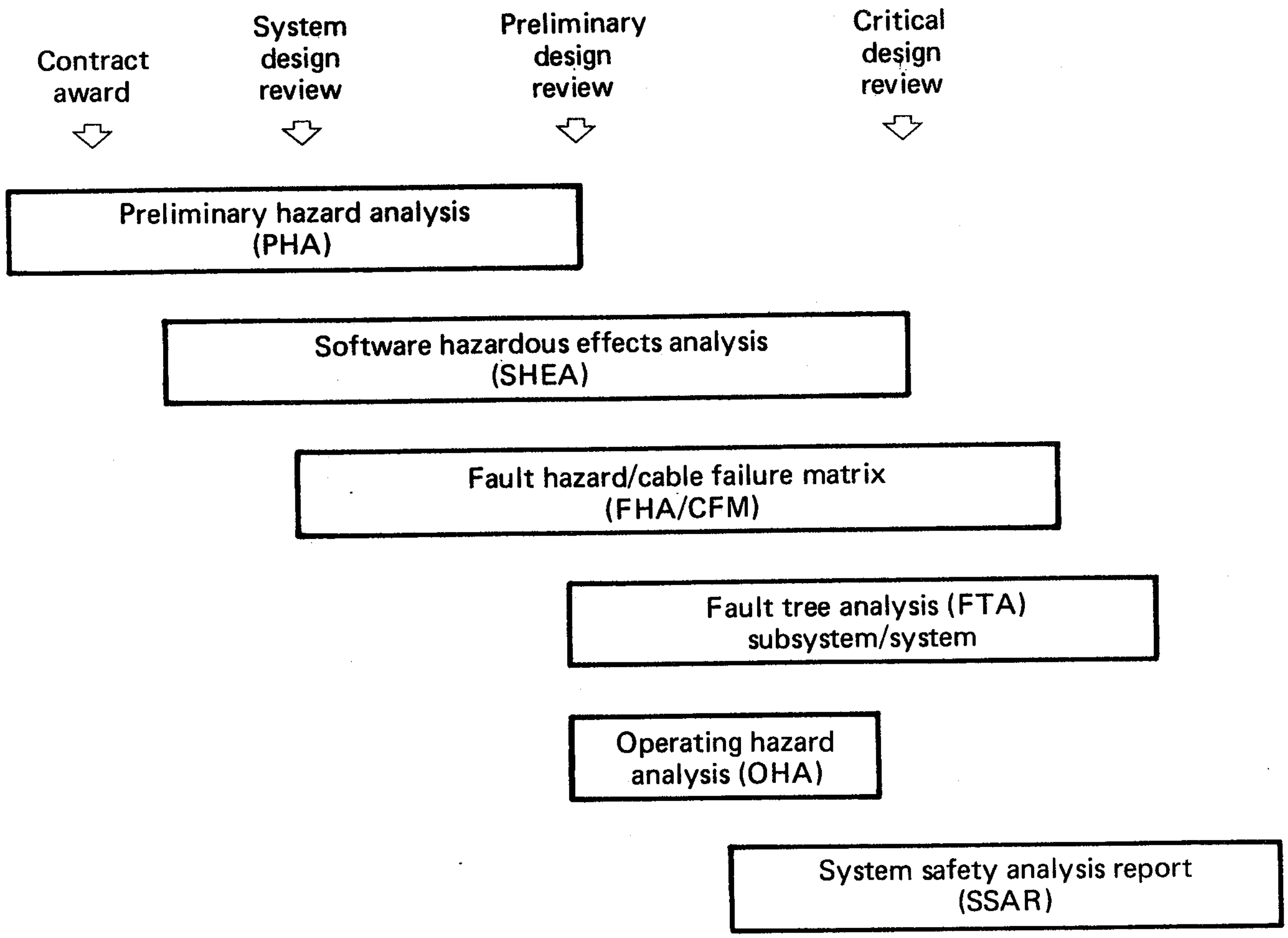


FIGURE 6-3. – SYSTEM SAFETY ANALYSES EVENTS AND MILESTONES

6.1.2.2 Operating Hazard Analysis: This analysis us used by the contractor to provide the basis for the preparation of procedures for:

1. Rendering the subsystem/system safe under normal and emergency conditions
2. Emergency escape or egress and rescue operations
3. Ground handling and transportation operations and environments
4. Operating and maintenance operations, including warning and caution notes
5. Identification of a hazardous period time span and actions required to control the identified hazard
6. Recovery procedures for potential accidents.

6.1.2.3 Fault Hazard Analysis: This analysis is performed to monitor and control the design process in therms of system safety. This method/process uses established failure modes, failure rates, failure effects, and established hazard classifications. On complex systems, this analysis may be made up of several analyses accomplished on units which make up the configuration item.

6.1.2.4 Cable Failure Matrix: This analysis is a shorthand method used to concisely represent many of the possible combinations of failures which can occur within the cable assembly. The predominant failure events depicted from the analysis are added to the Fault Hazard Analysis.

6.1.2.5 Fault Tree Analysis: This analysis provides a means for determining and graphically presenting the events or combinations of events which will cause a defined, undersired event. It also provides a basis for assessing the prbability of occurrence of these events, either by statistical or simulation methods.

6.1.2.6 Software Hazardous Effects Analysis: This analysis is performed on software to ensure that system interlocks and functional electromechanical controls are incorporated to prevent system functional hazards from being initiated by the software system.

6.1.3 Scout Vehicle Description. – For the purpose of identifying the possible hazards and consequences associated with utilizing a solid propulsion system as a Shuttle payload, the upper stage of the Scout propulsion system were selected as a typical system. The Scout upper stage propulsion system, shown in Figure 6-4, consists of two solid rocket motor stages and associated attitude control and stabilization motors. The Antares II X259 is a composite modified double base solid propellant rocket motor (Department of Transport ation (DOT) Class A, Military Class 7) and is utilized for third stage propulsion. A hydrogen peroxide propellant reaction control system (RCS) is contained in the C-section and is used for attitude control. This RCS system uses four 48 lb thrust motors for pitch and yaw control during third stage burn. During coast, the 14 lb motors are throttled to 3 lbs for yaw and roll control and two 2 lb motors provide pitch control. The Altair III is a composite propellant solid rocket (DOT Class B, Military Class 2) and is used for fourth stage propulsion. This stage is spin-stabilized by composite solid propellant spin motors which are located on the D-section between the third and fourth stages. The vehicle may be configured with a variety of solid propellant spin motors, depending on the mission payload.

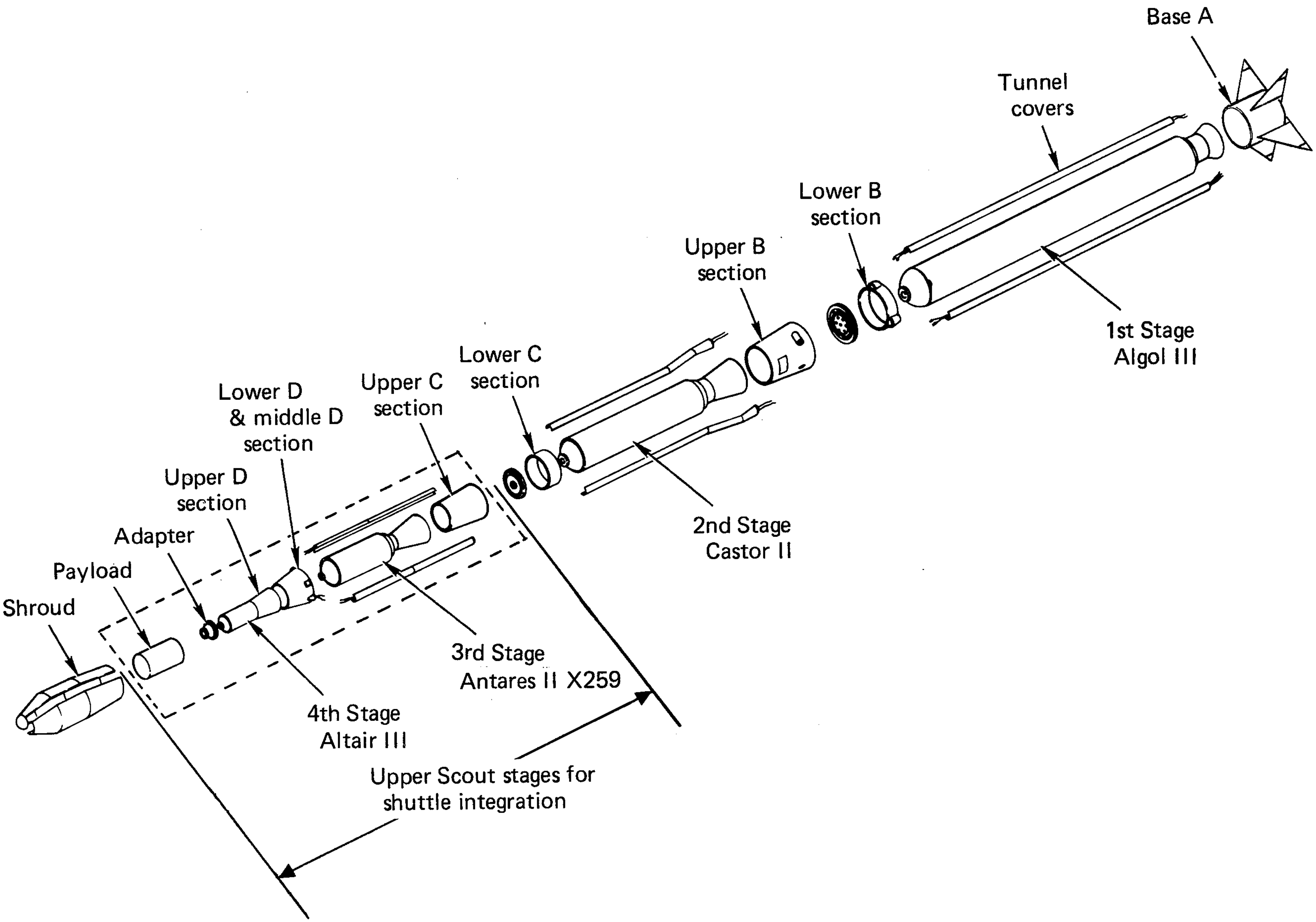


FIGURE 6-4. – SCOUT UPPER STAGE PROPULSION SYSTEM

6.1.4 Space Shuttle System Description. – The Space Shuttle system, shown in Figure 6-5, is comprised of two composite propellant solid rocket boosters (DOT Class B, Military Class 2), the external propellant tank, and the Orbiter vehicle. The solid rockets are ejected at burn-out and are retrieved by parachute for subsequent refurbishment and reuse. The external propellant tank is ejected before injection into orbit and is not retrieved. The main propulsion system is the three liquid rocket engines contained in the Orbiter. The solid rocket boosters augment main engine thrust during lift-off and early boost.

6.1.4.1 Mission Phases: Figure 6-6 shows the typical Orbiter vehicle mission phases examined in this study. The mission consists of launch pad operations, boost, orbit, payload deployment, de-orbit, and land or abort phases.

6.1.4.2 Launch Pad Operations: A typical ground flow is shown in Figure 6-7 and the associated time line is shown in Figure 6-8. As noted in the time line, the last thirty hours are launch pad operations. Figure 6-9 presents an expanded schedule of the launch pad operations. It was considered that during this phase, the Scout system would be brought to the pad and hoisted into the Orbiter in a vertical position. During the launch pad operation, the significant characteristics of the Shuttle/Scout system are as follows:

- There is no propellant in the external tank or the Orbiter until the final ten hours
- All explosive bolts, separation nuts, spin motors, and main rocket motor initiators in the Scout vehicle are removed until after the Scout is installed in the Orbiter
- The Scout nitrogen tanks are unpressurized and hydrogen peroxide tanks contain no fuel until after the Scout is installed in the Orbiter.

6.1.4.3 Boost Phase: The boost phase consists of all operations from launch to Shuttle external tank separation. During this phase, the payload is subjected to the environment induced by the Shuttle, including thermal, pressure, shock, vibration, acceleration, and acoustic noise. During this phase, the significant configuration features are as follows:

- The Shuttle's solid rocket boosters burn for approximately two minutes after launch pad ignition
- The Shuttle's three main rocket engines operate from launch pad ignition until main engine cut out (MECO) before injection into orbit. At that time, the external tank is separated from the Orbiter
- The Scout payload separation nuts, explosive bolts, spin motors, and main rocket initiators are safed through safe-arm latching relays
- All Scout batteries are uncharged
- The Scout RCS fuel tanks contain hydrogen peroxide in expulsion bladders but the bladders are not pressurized. Pressure build-up is relieved through a pressure relief valve, decomposition chamber in the Scout vehicle and a bleed line in the Shuttle
- The Scout nitrogen system upstream of the regulator is pressurized to 3000 psi
- Orbiter pressure is equalized to ambient pressure through bleed ports
- Orbiter payload bay doors are closed until orbit injection has been established.

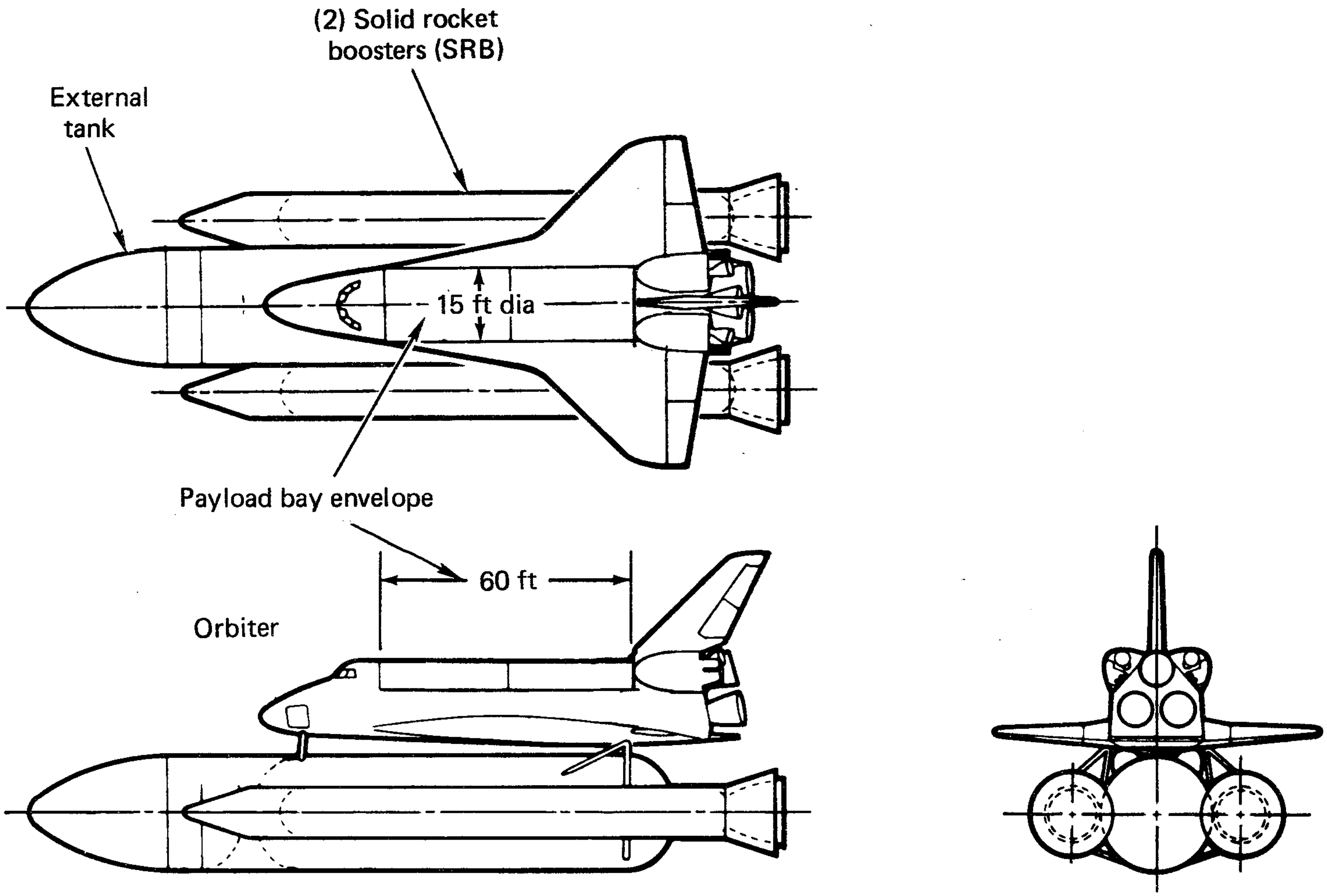


FIGURE 6-5. – SPACE SHUTTLE FLIGHT SYSTEM

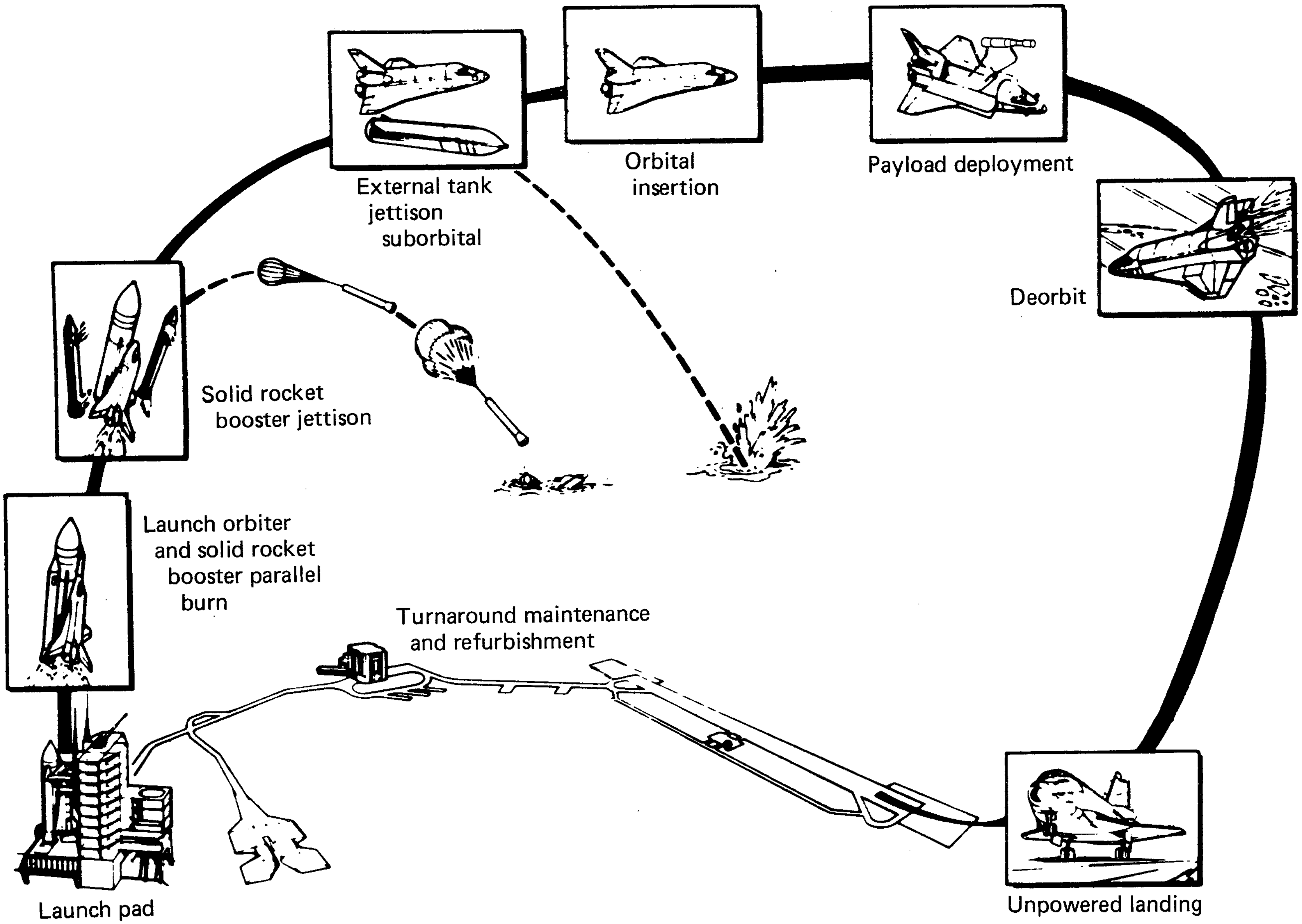


FIGURE 6-6. – TYPICAL ORBITER VEHICLE MISSION PHASES

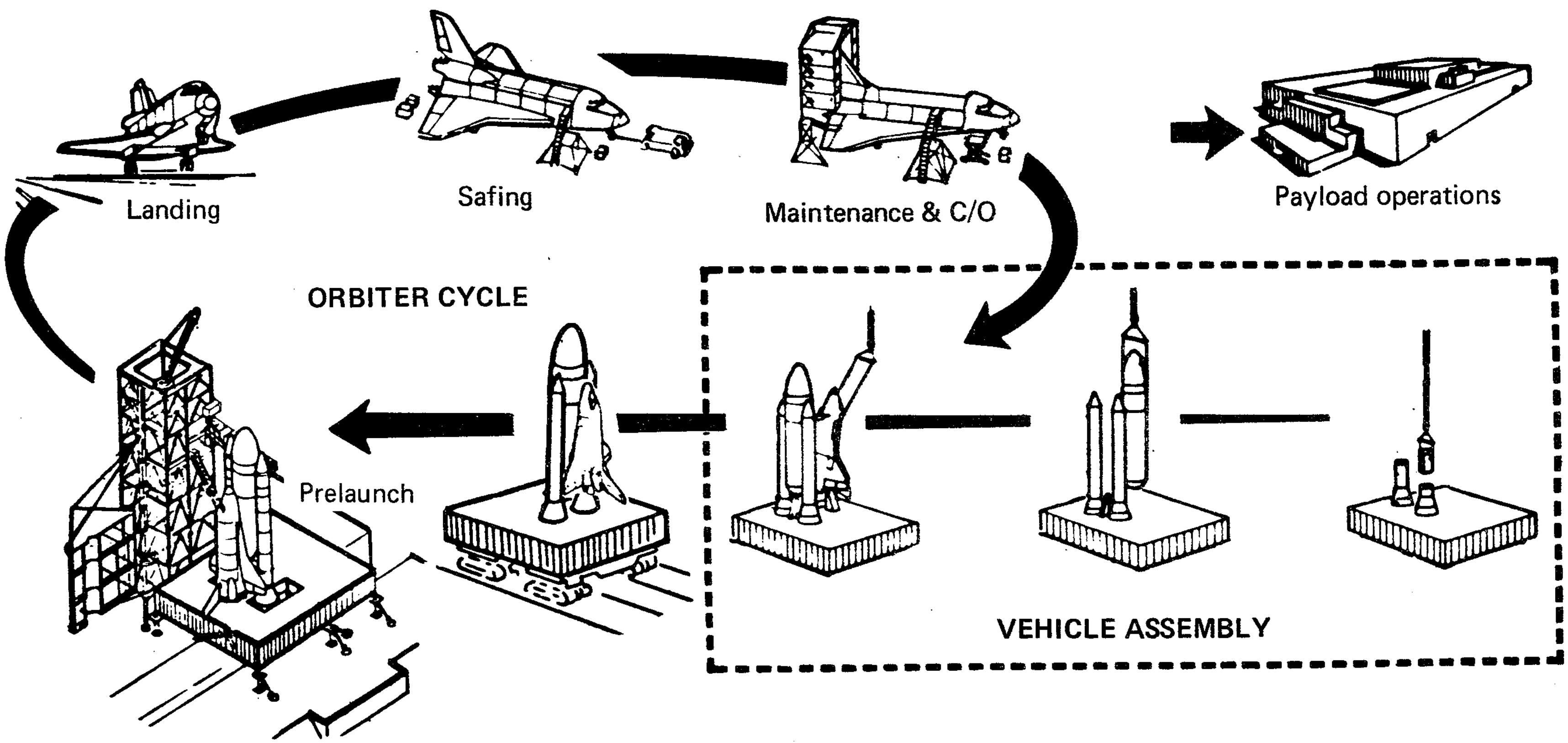


FIGURE 6-7. – KSC SPACE SHUTTLE SYSTEM GROUND FLOW

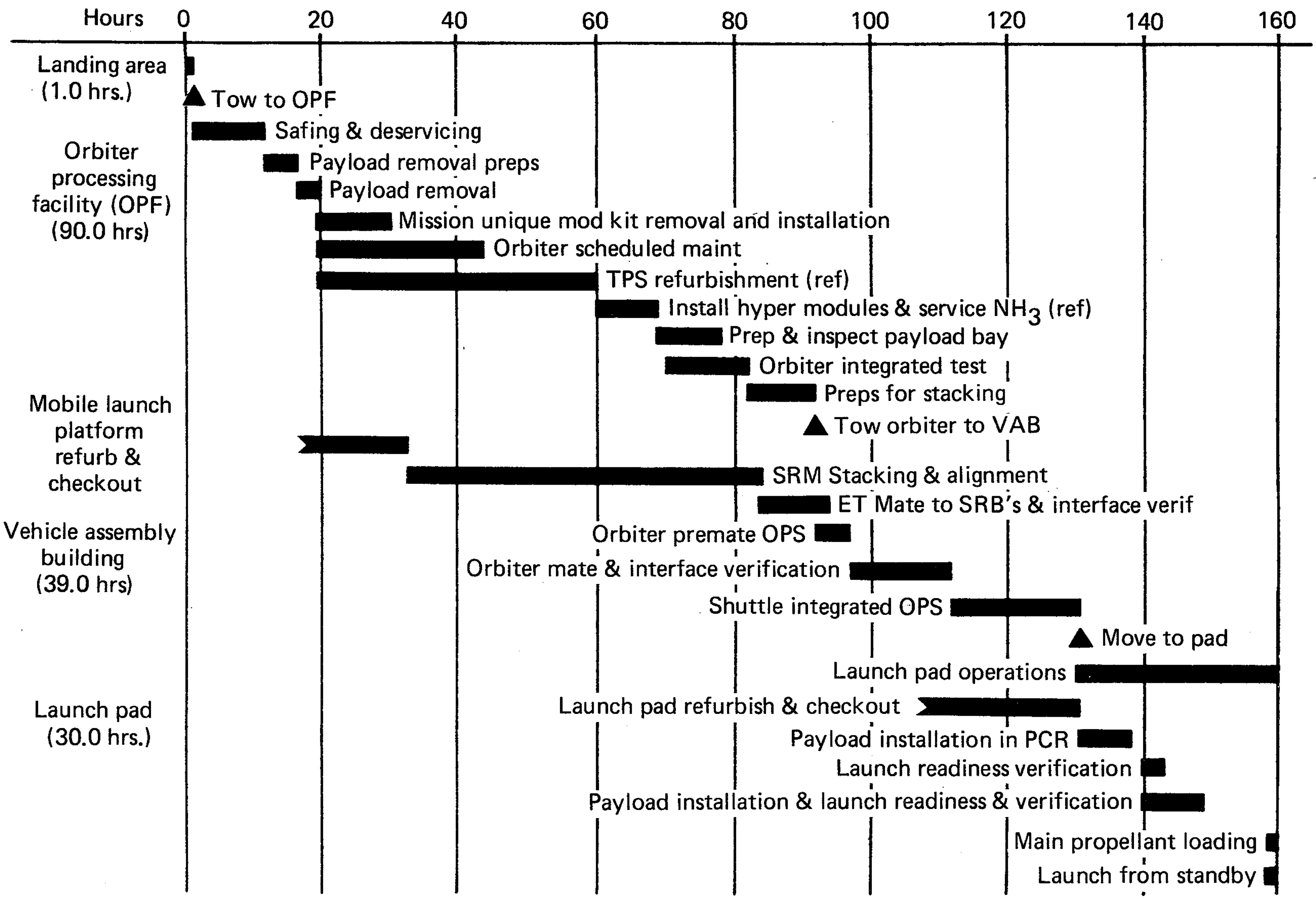


FIGURE 6-8. – TIMELINE ALLOCATION PAYLOAD INSTALLATION AT LAUNCH PAD

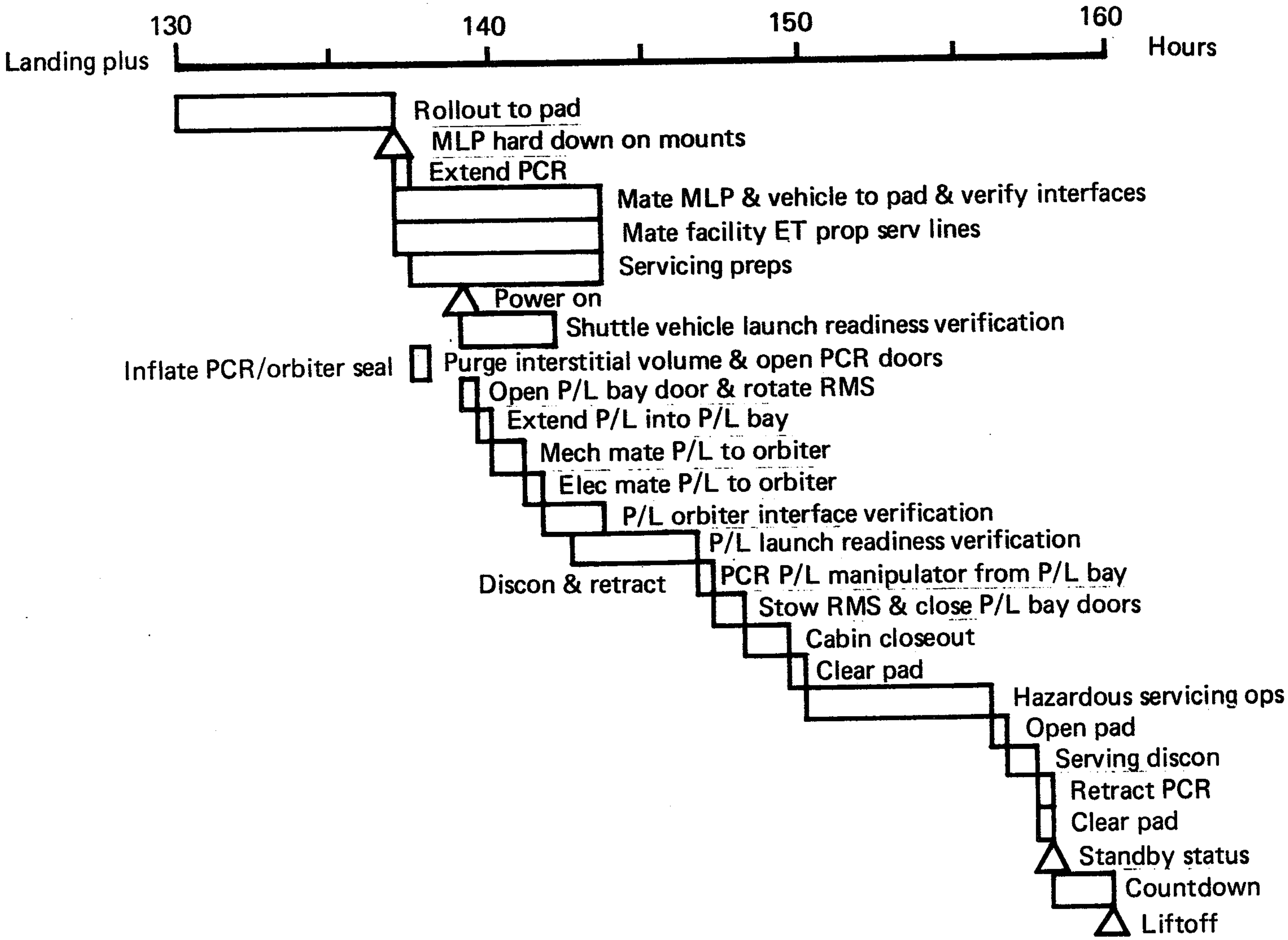


FIGURE 6-9. – 30 HOUR PAD OPERATIONS ALLOCATION AT LAUNCH PAD

6.1.4.4 Orbit Phase: The orbit phase begins with orbit injection and is terminated by de-orbit. Deployment of the payload occurs during this phase unless the deployment is aborted. The significant configuration characteristics of the orbit phase are as follows:

- The Scout payload separation nuts, explosive bolts, spin motors, and main rocket initiators are not armed until after payload deployment
- The Scout batteries are uncharged until all systems are checked and final count has commenced.
- The hydrogen peroxide bladders are pressurized just prior to removal from the payload bay.

6.1.4.5 De-Orbit Phase: De-orbit normally occurs after the payload has been deployed. However, de-orbit may occur after the mission has been aborted during the boost and orbit phases. The significant characteristics of the configuration are as follows:

- Payload bay doors are closed, containing the Scout
- Payload bay vents are opened after re-entry heating in order to equalize pressure
- Scout nitrogen and hydrogen peroxide systems are dumped prior to de-orbit
- The ignition system and all ordnance items are safed and the ignition batteries are discharged if they were charged during a deployment attempt.

6.1.4.6 Landing Phase: The landing phase may be necessary at any point in the boost phase and is necessary after de-orbit. The system is assumed to be in the safe condition as outlined in the de-orbit phase discussion.

6.1.5 Shuttle/Scout Preliminary Hazard Analysis (PHA). – The Scout propulsion system PHA, which was conducted to identify hazards associated with the Space Shuttle/Scout concept, was devised by first constructing a modified Fault Tree which descriptively is called a Safety Consideration Tree, submitted as Figure 6-1, and then completing the PHA of Table 6-1. The Safety Consideration Tree was used to effect an orderly examination of the concept so that all possible hazards associated with assembled solid rocket motors and interfacing hydrogen peroxide fueled reaction control systems could be considered. Similar to the fault tree technique, the Safety Consideration Tree is constructed by examining the undersired event and then the causes of each event digressively until the hazard or intermediate hazard is identified. "OR" gates in the tree are assumed to exist where no gate is indicated and "AND" gates exist where indicated.

The Preliminary Hazard Analysis, Table 6-I, is used to describe each of the possible hazards and the intermediate/ultimate effects identified in the Safety Consideration Tree. Also provided are safety requirements and Scout implementation techniques, as are available. A numbering system has also been utilized to simplify cross-reference between the Safety Consideration Tree and the PHA table.

6.1.5.1 Sources of Shuttle System Damage: The Scout propulsion system PHA addresses the possible Scout propulsion system hazards that can result in Shuttle damage or loss in the typical

Space Shuttle/Scout mission profile. The hazards and their associated consequences are considered to be those of a typical solid propulsion system. Shuttle system damage or loss due to the Scout propulsion system can occur as a result of premature solid rocket motor ignition, case rupture, detonation, fire, and chemical attack/toxicity; or explosion resulting from RCS system rupture or leak. The hazards which could cause these occurrences are designated by the bold outlined blocks in the Safety Consideration Tree and are listed in the "HAZARD" column of the PHA. The numbering system assists in cross reference.

6.1.5.2 Shuttle or Scout Non-Propulsion System Fire: A fire of the Shuttle or Scout system other than propulsion may be of such small magnitude that Shuttle damage does not directly result. However, it is possible for a fire of that magnitude to cause auto-ignition, explosion or detonation of a nearby motor which would result in Shuttle loss. A possible exception to that result is the premature ignition of a spin motor. Spin motor ignition would not cause the pressure limits of the cargo bay to be exceeded, but Shuttle damage could result. This hazard is minimized by utilizing motors of high auto-ignition temperatures and also by using propellants that ignite rather than detonate in a fire. Scout motor auto-ignition temperatures are presented in the PHA.

A fire in the Shuttle or Scout system, other than the propulsion system, which is too small to cause Shuttle damage directly or ignition of the motors may cause ignition of other materials thereby creating a fire of larger magnitude. The resulting fire may cause Shuttle system damage or loss directly and may cause premature motor ignition explosion or detonation. Battery acids from unsealed batteries can cause fires of this nature, however, this problem is eliminated by using squib activated-sealed batteries. Also spreading of a fire which is not propulsion system related can be minimized by using non-combustible materials. It should be noted that the payload bay has an inert atmosphere purging system to prevent this occurrence during the final stages of launch pad operation. Furthermore, in orbit the payload bay is in a vacuum so that an oxidizing material must be present in addition to a combustible material for a fire to propagate.

Although a Shuttle or Scout non-propulsion system fire may not cause severe Shuttle damage or loss directly, Scout motor ignition or propulsion system fire, it could cause deterioration of the case or bond system which could result in a failure when the motor is ignited during the normal payload launch sequence. If fire of significant magnitude is detected in the vicinity of the motor prior to deployment, the launch can be aborted in order to prevent explosive rupture of the motor case. In any case, one basic requirement of payload launch is that sufficient distance between the payload and the Orbiter is obtained before any attempt is made to arm the system and ignite the first solid rocket motor.

A fire in the Shuttle or Scout system can also cause overpressurization due to the temperature of the RCS system. Such overpressurization can lead to an RCS system leak or rupture resulting in release of hydrogen peroxide to the confines of the payload bay or the generation of tank fragmentation and shock. The effects of leakage or tank rupture can cause Shuttle damage directly, may lead to premature ignition, explosion/deflagration of Scout motors, or cause a propagating fire. Overpressurization of the RCS system is prevented by providing pressure relief connections for both nitrogen and hydrogen peroxide to the Shuttle exterior. In the Scout system, hydrogen peroxide relief valve discharge is through a decomposition chamber to assure that the effluent fluid is not chemically hazardous. Further protection from hydrogen peroxide chemical hazards is afforded by including personnel warnings in the Standard Operating Procedures along with first aid information.

6.1.5.3 Payload Propulsion System Fire: The effects of a Scout propulsion system fire are similar to those of a Shuttle or Scout non-propulsion system fire. A fire of the Scout propulsion system can result in Shuttle system damage directly, may cause premature ignition or motor explosion/deflagration or cause damage or bond degradation. The effects of a Scout propulsion system fire, therefore, are minimized or controlled in the same manner as the effects of a Shuttle or Scout non-propulsion system fire explained in the preceding paragraphs.

6.1.5.4 Environmental Temperature: The temperature environment of the Scout propulsion system will be a result of the cargo bay temperature in all phases of the mission except orbit phase. During that phase, the payload bay doors are open and the environmental temperature results from solar radiation, earth albedo, earth radiation, and space sink.

Environmental heating of the payload may cause premature motor ignition or explosion/deflagration, bond degradation, or overpressurization of the RCS system. If payload motor temperatures rise to the point where auto-ignition or motor explosion/deflagration occurs, the Shuttle may be lost. This event can be avoided by adding insulation to the exterior of the motors, selecting and orbit missions which will limit the exposure time of the motors to solar heating or selecting motors whose auto-ignition temperatures are above the maximum expected temperature environment. Scout auto-ignition temperatures are presented in the PHA.

Even though ignition or explosion/deflagration are avoided by selecting motors with a high auto-ignition temperature, the temperature resulting from environmental heating may cause case or bond degradation. This occurrence can be avoided by utilizing motors that are designed and qualified for the expected maximum temperature environment. To reduce hazardous conditions the solid rocket motor ignition should be delayed until sufficient separation exists between the Orbiter and the payload.

Environmental heating can cause overpressurization of a liquid or gas RCS system resulting in RCS system leak or rupture. Shock, fragmentation, chemical attack, or toxicity resulting from this occurrence may cause Shuttle system damage directly or Shuttle loss if premature motor ignition or explosion/deflagration occurs. RCS system overpressurization due to environmental heating is prevented by designing RCS system components to withstand the increased pressure resulting from the most extreme heat environment, providing sufficient insulation to the RCS exterior or selecting an orbit mission which will limit the exposure time of the system to solar heating. The nitrogen and hydrogen peroxide storage reservoirs in the Scout vehicle have a proof pressure of 1.5 times operating pressure and a burst pressure of 2.5 times operating pressure. RCS pressure relief valve connections to the H_2O_2 and N_2 systems are provided in the Scout System and must be vented to the Shuttle exterior. The hydrogen peroxide discharges through a decomposition chamber which minimizes chemical reaction of raw hydrogen peroxide. Furthermore, warning notes should be included in the Standard Operating Procedures in the event that environmental heat causes release of hydrogen peroxide in the vicinity of personnel during launch pad operations. Qualification tests of the RCS system should demonstrate the capability to withstand the expected environment.

6.1.5.5 Meteoroid Impact: The meteoroid environment represents a projectile impact hazard. Meteoroid impact with a solid rocket motor may result in premature ignition, explosion, detonation, or case damage. Also, meteoroid impacts on the RCS system could cause an RCS system rupture or leak resulting in tank fragmentation, shock, fire, corrosion/reaction, or toxicity. The meteoroid impact hazard is present only during the orbit phase when the payload bay doors are open. An analysis, reference 64, has been conducted to determine the probability of meteoroid impact damage to the cases of the Antares X-259 and Altair III solid propellant motors in this environment. The analysis considers that only half the motor case area is exposed during the twenty-three hour orbit period, that the payload bay doors are open and additional deployment time of the vehicle before the first rocket motor is ignited. With these assumptions, the probability of motor case damage is .0037; therefore, the probability of premature motor ignition or detonation is small. Although this case damage probability is considered low, the effects of a case rupture hazard during solid rocket ignition may be eliminated by delaying ignition until sufficient separation exists between the payload and the Orbiter or abort the launch.

Meteoroid impact with RCS system components could cause RCS system leak or rupture resulting in tank fragmentation and shock, fire, corrosion/reaction, or toxicity. Such effects may cause direct Shuttle damage or may cause Shuttle loss indirectly by the resulting premature motor ignition or detonation. However, the Scout RCS system is completely enclosed within the transition section which is relatively invulnerable to meteoroid impact which minimizes this hazard.

6.1.5.6 Fragmentation From Non-Propulsion System Rupture or Explosion: Fragmentation damage similar to meteoroid impact damage may also be caused by a rupture or explosion of a Shuttle or payload system such as ignition batteries and oxygen tanks. Although this explosion or rupture may be of insufficient magnitude to cause significant Shuttle system damage directly, the fragments produced from this occurrence may cause premature solid rocket motor ignition, explosion/deflagration or case damage and/or RCS system leaks or rupture. This hazard may be minimized by using qualification tests to demonstrate that the motors are insensitive to projectile impact.

The solid rocket case or propellant bond damage can result in rupture of the motor case at ignition. This hazard is eliminated by aborting the mission.

Fragments from an explosion may cause an RCS system rupture or leak resulting in further fragmentation, shock, fire, corrosion/reaction, or toxicity. In the Scout system, protection is afforded the RCS by the transition sections skin and other missile equipment.

6.1.5.7 Environmental Vibration: Vibration environment is of concern during the boost and landing phases of the Shuttle mission. The vibration environment produces energy that is absorbed by the solid propellant rocket motors which could result in propellant cracks or bond separation of the propellant grain.

This type damage would result in an explosive rupture of the motor case upon ignition. Qualification tests should be used to demonstrate the motor's resistance to damage by vibration. Also, rocket motor ignition can be delayed until sufficient separation exists between the Orbiter and payload so that the Orbiter is not damaged by a rocket motor failure at ignition.

An RCS system leak or line rupture may result from vibration. Shuttle damage may result directly or indirectly from fire, corrosion/reaction or toxicity from H_2O_2. The RCS system should be designed and tested to the expected flight vibration so that this hazard may be eliminated. The RCS system components of the Scout vehicle have been qualified by tests and usage to demonstrate acceptance for Scout, however, the Scout environment must be compared to the Shuttle environment and additional qualification testing may be required.

6.1.5.8 Environmental Shock: As presented in reference 65, the shock induced into the payload by the Shuttle system is only of major concern during abort landing and aborted-mode handling. The solid rocket motors should be tested to determine their ability to withstand the specified shock loads.

Since the RCS system hydrogen peroxide and nitrogen pressure will be dumped for normal landing or abort landing there is no inherent hazard in this system during the landing phases.

6.1.5.9 Shock From Non-Propulsion System Rupture or Explosion: Mechanical shock or shock wave phenomena can result from a rupture or explosion in the Shuttle or payload systems other than the propulsion system. The magnitude of the shock may be insufficient to cause major Shuttle system damage directly, but it may result in Shuttle system damage indirectly by causing premature solid rocket motor ignition, explosion, detonation, case/propellant damage and RCS system rupture or leak. Premature motor ignition, explosion or detonation would result in Shuttle loss. This hazard can be minimized by demonstrating that the solid rocket motors are insensitive to shock stimulus. Qualification tests should be conducted to a level beyond the expected shock resulting from the most severe non-propulsion system rupture or explosion.

To eliminate the hazard which is inherent in motor case or propellant damage, the payload launch should be aborted or ignition should be delayed until safe separation exists between the Orbiter and the payload.

An RCS system rupture or leak which is caused by shock may result in additional fragmentation, shock, fire, corrosion/reaction, or toxicity. Minimization of this occurrence can be accomplished by qualification tests of RCS system components to the expected shock levels. The RCS system is normally protected from outside stimulus by the transition section skin, structure and other components.

6.1.5.10 Electrical Fault: An electrical fault in the payload propulsion system can cause premature ignition of payload motors, fire, or RCS system rupture or leak resulting from over-pressurization due to temperature. Since solid rocket motors are electrically initiated, a spurious electrical signal can cause premature motor ignition, resulting in most cases with Shuttle loss. Minimization of this hazard is accomplished by system design, operating procedures and pad safety procedures to ensure that no failure or operating errors will cause premature ignition. An electro-mechanical Safe and Arm device is the normal design feature which is employed to provide ignition train interruption. Squib shunts and electrical wiring shielding is also used to reduce or prevent RF signals from entering the ignition system. These devices prevent ignition due to component malfunction, radio frequency interference (RFI) and electromagnetic interference (EMI).

A fire resulting from an electrical fault can cause Shuttle system damage and loss if premature solid rocket motor ignition, explosion/deflagration occurs. Minimization of this hazard is accomplished by selecting heat resistant and non-flammable materials in and around electric circuits. Also a nitrogen purge system is used in the payload bay to prevent an oxidizing atmosphere during the final stages of launch pad operations. The system operates in a vacuum during orbit.

A fire resulting from an electrical fault can also cause thermal overpressurization of the RCS system resulting in a system leak or rupture. In addition to the safety provisions described in the previous paragraph, this hazard is minimized since there are pressure relief valves in the H_2O_2 and nitrogen systems. However, elevated temperature of an H_2O_2 tank without pressure build-up has resulted in an explosion during testing at the Vought Corporation, reference 66.

6.1.5.11 Corrosion: Corrosion of the RCS system components can result in an RCS system leak which may cause fire, corrosion/reaction, or toxicity. These effects can damage the Shuttle system directly or they can lead to more severe damage by causing a premature motor ignition, explosion, or detonation as a result of fire. Corrosion is prevented in the Scout RCS system by using components and tubing that are compatible with H_2O_2 and are resistant to corrosion. Also, personnel warnings are included in the Scout Standard Operating Procedures to inform personnel of the inherent hazards of the hydrogen peroxide system and safety training is provided the technicians.

6.1.6 RCS Propellant Selection. – Of primary concern in payload propulsion system design is the selection of the RCS system propellant. Since a variety of thrust magnitudes and burn times are desirable during a vehicle mission, the most feasible system is one using a liquid propellant. Hydrogen peroxide is utilized in the Scout Launch Vehicle to perform the "steering" function. Although hydrogen peroxide is hazardous to personnel and will react with a large variety of materials to generate sufficient heat for combustion, its monopropellant qualities enhance control of hazards.

Hydrazine is another monopropellant which has been used in upper stage RCS systems. Hydrazine (N_2H_4) vapors are flammable in all concentrations in air above 4.7 percent, reference 31. and is hypergolic with some oxidants such as hydrogen peroxide and nitric acid. Hydrazine is normally used as a monopropellant which is decomposed by a catalyst bed. Even though N_2H_4 is considered a storable propellant, precautions on corrosiveness and material compatibility must be adhered to. Other common RCS systems use bipropellants which are highly combustible and most frequently are hypergolic. Separate oxidizer and fuel storage is necessary which requires a more complex propellant system which reduces reliability and safety. These problems exist not only during flight but also during pre-launch fueling and checkout which requires two different sets of GSE for handling the fuel and oxidizer but requires additional safety and operating procedures.

Liquid propellant hazards are discussed in detail in Section 6.2.

6.2 Liquid Propellants

6.2.1 Introduction. — In reference 62, the Space Division of North American Rockwell performed a study for NASA, Manned Spacecraft Center, Houston, Texas. The study, Safety in Earth Orbit, examined specific safety issues regarding manned and unmanned payloads delivered to orbit by the Shuttle. The objective of one task of the study was to identify hazards associated with specific Orbiter payloads while in earth orbit and to determine safety requirements and guidelines. Orbiter payloads which were considered in the study are as follows:

- Agena
- Centaur
- Transtage
- Apollo Service Module (SM)
- Tug or Orbit-to-Orbit Shuttle (OOS)

In references 67 and 68 the Agena/Shuttle and Space Tug Shuttle, respectively, were studied and specific considerations were given to hazardous situations for normal mission phases. The results from reference 67 were used as the basis for the liquid system hazard study presented in this section.

6.2.2 Hazardous Elements. — In most upper stage payload propulsion systems, the inherent safety hazards can be divided into three distinct areas of consideration; (1) high pressure gas systems, (2) ordnance devices, and (3) propellants. Hazardous elements which are utilized in various propulsion systems can be further classified by the type of main propulsion propellant, type of pressurized container and gas, type of RCS propellants, corrosive fluids and attachment methods and/or pyrotechnics. In reference 62 the six different payloads considered were presented in a comparison tabulation to show the many different hazardous elements that are contained in typical upper stages. This comparison is shown in Table 6-11. The Agena system uses a bi-propellant storable propulsion system with unsymmetrical dimethylhydrazine (UDMH) as the fuel and high density acid (HDA) as the oxidizer. HDA is a mixture of inhibited red fuming nitric acid (RFNA) and nitrogen tetroxide (N_2O_4). The Agena inboard profile is shown in Figure 6-10 and the propulsion system schematic is presented in Figure 6-11. The main tank pressurization is accomplished by helium gas stored at approximately 3600 psig.

In reference 62 a hazard analysis of the Agena/Shuttle system was performed to identify the major hazards associated with each of the normal mission phases.

Mission phases for a typical Tug payload, as given in reference 68, is outlined below.

(1)	(2)	(3)	(4)	(5)
Preflight	Boost deploy	Tug free flight	Recovery/ entry	Post-flight
t = 146 hr	t = 3.9 hr to 8.2 hr	t = 24 hr to 30 days	t = 7 hr	t = 6.5 hr (Safeing) t = 112.5 hr (Turnaround)

TABLE 6-II. – HAZARDOUS ELEMENTS OF UPPER STAGE VEHICLES

		Agena	Centaur	Transtage	Burner II	SM	OOS/Tug	Toxicity	Fire	Corrosion	Explosion
Fluid propellants:											
Nitrogen tetroxide	(0)			X		X		X	X	X	
Aerozene -50	(0)			X		X		C	X		X
Hydrogen peroxide	(0)		X		X			X	X	X	X
Liquid oxygen	(0)		X			X	X	B	X		X
Liquid hydrogen	(F)		X			X	X	B	X		X
Monomethyl hydrazine	(F)					X		C	X		X
Water/glycol						X		X	X		X
Unsymmetrical dimethyl hydrazine	(F)	X						C	X		X
Inhibited red fuming nitric acid	(0)	X						X	X	X	X
Pressurized containers and gas:											
Helium tanks		X	X	X		X	X	A			
Nitrogen tanks		X		X	X	X		A			
Nitrogen tetroxide tanks				X		X		See above ↓			
Aerozene -50 tanks				X		X					
Hydrogen peroxide tanks			X		X						
Liquid oxygen tanks			X			X	X				
Liquid hydrogen tanks			X			X	X				
Monomethyl hydrazine tanks						X					
Water/glycol tanks						X					
Unsymmetrical dimethyl hydrazine		X									
Inhibited red fuming nitric acid		X						See above ↑			

B = Can cause severe burns and tissue damage on contact with skin

C = Extremely toxic when heated to decomposition

A = Simple asphyxiant

X = Applicable or present

(0) = Oxidizer

(F) = Fuel

TABLE 6-II. – HAZARDOUS ELEMENTS OF UPPER STAGE VEHICLES – Concluded

	Agena	Centaur	Transtage	Burner II	SM	OOS/Tug	Toxicity	Fire	Corrosion	Explosion
RCS propellants:										
Aerozene -50 + nitrogen tetroxide			X				C	X	X	X
Monomethyl hydrazine + nitrogen tetroxide					X		C	X	X	X
Hydrogen gas + nitrogen tetroxide							C	X	X	X
Pyrotechnics:										
Connections between modules-cutters					X					
Helium valves	X		X							
Solid propellant igniters				X						
Turbine start solid propellant charges	X									
Explosive bolts - payload separation	X	X	X	X	X	X				
Linear shaped charge - panel separation	X	X			X					
Destruct shaped charges	X	X	X	X	X	X				
External extensions - antennae					X					
Rocket engines: (Qty. indicated)										
Main engine	1	2	2	1	1	1-4				
RCS Engine		8	12	4	16	20				
Attachment methods:										
Explosive bolts				X						
Linear shaped charge	X	X	X		X					
Not defined						X				

B = Can cause severe burns and tissue damage on contact with skin
C = Extremely toxic when heated to decomposition
(0) = Oxidizer
(F) = Fuel
A = Simple asphyxiant
X = Applicable or present

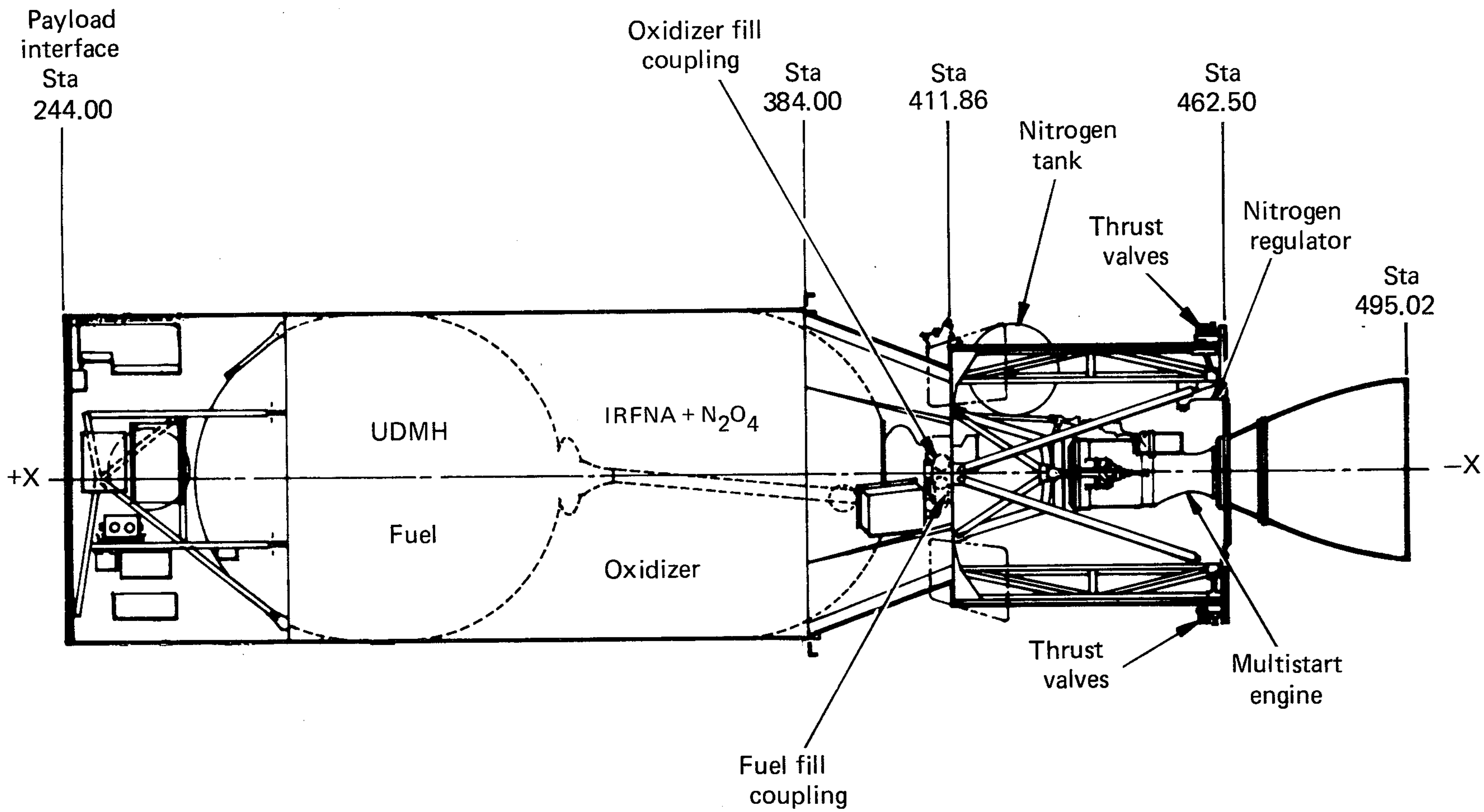


FIGURE 6-10. – AGENA INBOARD PROFILE

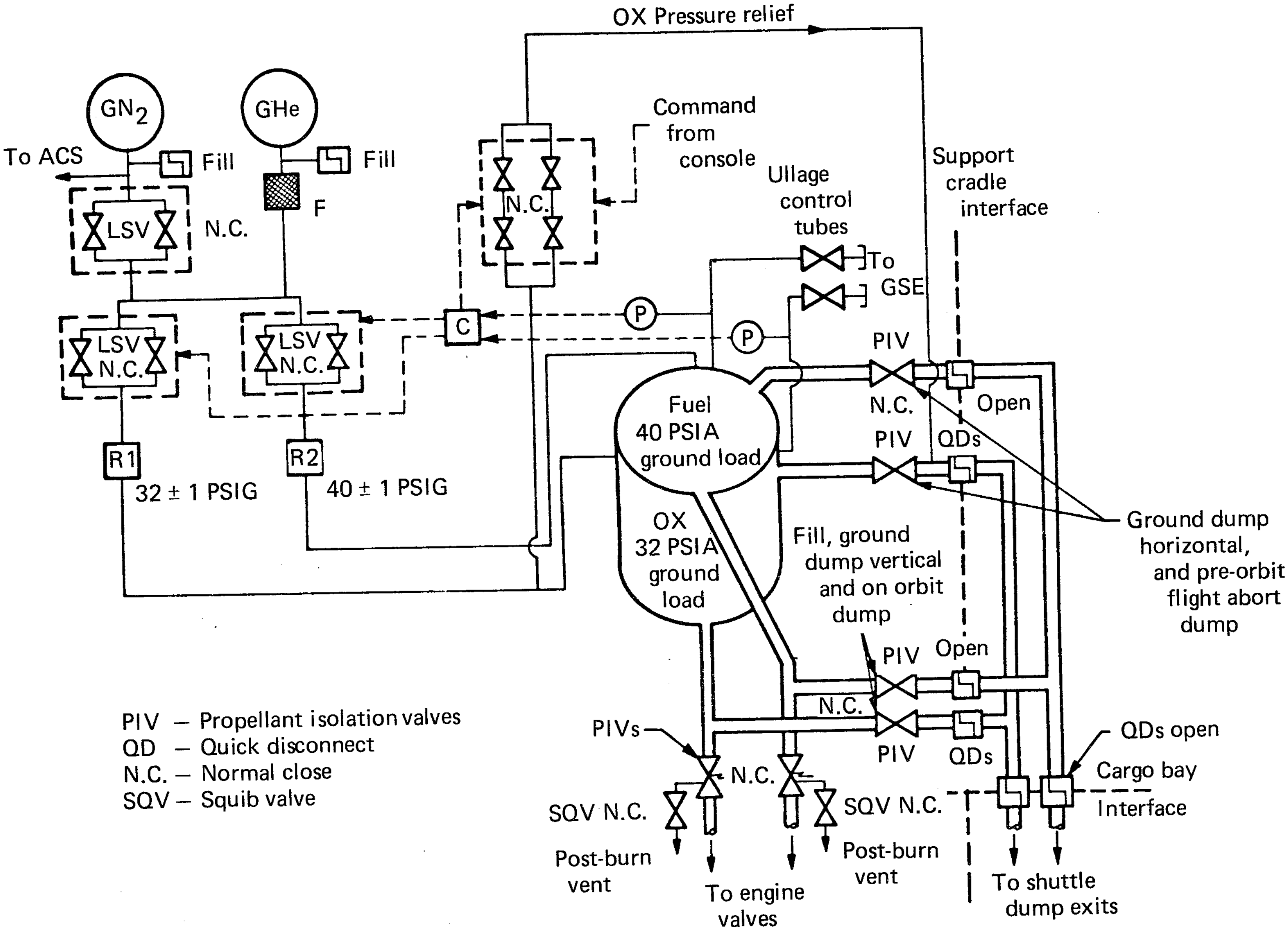


FIGURE 6-11. – AGENA PROPULSION SCHEMATIC

The mission phases for payloads other than the Tug will normally involve only Phase 1 and 2. Mission Phase 4 could be required if the payload launch is aborted and the payload is returned to earth with the Orbiter. In the Agena study, reference 67, the sequence of events for normal operation was divided into nine sets of operations. These operation sequence sets are shown in Table 6-III.

6.2.3 Hazard Analysis

6.2.3.1 Payloads-Hazard Classes: In reference 67 individual hazards from all five payload systems, shown in Table 6-II, were analyzed. The individual hazards were screened and consolidated into fifteen classes of hazards. These hazard classes are as follows:

1. Explosive/rupture of a pressurized container inside or near the Orbiter
2. Combination of mutually reactive fluids inside or near the Orbiter
3. Detonation of explosive charge inside or near Orbiter
4. Rapid decomposition of monopropellants inside or near the Orbiter
5. Uncontrolled combustion in an RCS engine inside or near the Orbiter
6. Leakage of corrosive fluids inside the Orbiter
7. Ignition of main rocket engine or RCS engine inside the Orbiter
8. Attachment points of payload breaks inside Orbiter
9. Loss of attitude of payload near Orbiter
10. Hang-up of payload during release from the Orbiter
11. Rupture of common bulkhead tanks of payloads in or near the Orbiter
12. Loss of pressurization in RCS system while in or near the Orbiter
13. Inability to dump propellants or pressurants during orbiter boost phase abort
14. Inability to dump propellants or pressurants of retrieval payloads
15. Inability to close cargo bay doors because of interference with the payload in the Orbiter bay.

Items 3, 8, 9, 10, 13, 14, and 15, almost 50 percent of the hazard classes, pertain to problems/failures which do not pertain directly to the propellants, propellant containers, or engines. However, the hazards do pertain indirectly to the propulsion system since the occurrence of the listed hazardous situations could cause damage to the payload/Orbiter which would result in fire, explosion and corrosive/toxic situations.

The Agena hazard analysis, reference 67, was divided into basically four parts as follows:

1. Hazard Diagrams (Safety Consideration Tree)
2. Hazard Review of Normal Operational Sequence of Events
3. Hazard Review of the Abort Sequence
4. Compilation of Potential Hazards

6.2.3.2 Hazard Diagrams: In the Agena study, as well as the study of reference 62, it was concluded that the four major categories of hazards which would be detrimental to the payload/Shuttle system and personnel were:

- Fire/Explosion
- Collision
- Contamination
- Toxicity

TABLE 6-III. – NORMAL OPERATIONAL SEQUENCE

Event No.	Sequence
1.0	Readiness area final loading and pressurization
1.0.1	Install pyro devices
1.0.2	Install batteries. Initiate battery monitoring. Do not switch to battery power
1.0.3	Transfer/load propellants. Activate leakage detection equipment and procedures
1.0.4	Fill He and N_2 bottles to flight pressures
1.0.5	Pressurize fuel and oxidizer tanks in sequence to launch pressures
1.0.6	Maintain safety monitor of temperatures, pressures, leaks, electrical power circuits, valve positions
1.1	Move Agena to Orbiter
1.1.1	Disconnect and cap propellant dump lines
1.1.2	Attach slings, cables, etc., and rotate Agena to horizontal attitude using overhead crane
1.1.3	Move Agena to transporter and mate in horizontal attitude
1.1.4	Transport Agena to Orbiter site
1.2	Mate Agena to Orbiter
1.2.1	Attach hoisting/handling equipment to support cradle
1.2.2	Unlatch and disconnect Agena/cradle from transporter
1.2.3	Hoist Agena/cradle, translate to Orbiter, and insert in payload bay
1.2.4	Secure cradle to Orbiter tiedown fittings
1.2.5	Connect dump lines to Orbiter propellant dump system
1.2.6	Connect power and instrumentation systems to Orbiter
1.2.7	Monitor safety instrumentation systems to Orbiter
1.3	Erect Orbiter and move to launch pad
1.4	Conduct pre-launch pad activities
1.4.1	Monitor safety and status instrumentation
2.0	Launch, ascent, and orbital quiescence
2.0.1	Monitor safety and status instrumentation
2.1	Pre-deployment activities
2.1.1	Transfer from Orbiter to internal Agena power
2.1.2	Attach manipulator arm to Agena
2.2	Deployment activities
2.2.1	Disconnect umbilicals for electrical power, fuel dump/vent and oxidizer dump/vent at Agena/cradle interface and retract lines
2.2.2	Unlatch and release Agena from support cradle
2.2.3	Deploy Agena/payload with manipulator
2.2.4	Command Agena telemetry ON via RF command link, and check RF link and telemetry are GO
2.2.5	Release and withdraw manipulator from Agena/payload
2.3	Separation activities
2.3.1	Move Orbiter away from Agena to prescribed distance
2.3.2	Activate Agena attitude control system by command
2.3.3	Arm Agena pyros and engine start cans by command, and start computer-controlled operational program.

Each of the major categories was analyzed by Lockheed Missile and Space Company (LMSC) by preparing hazard diagrams (similar to the solid rocket Safety Consideration Tree in Section 6.1). These four diagrams are presented in Figures 6-12 through 6-15. The events shown in these figures which are not enclosed in blocks were added for the present study. The events which are enclosed in bold blocks are those hazards that LMSC identified as being of major importance and required counteraction by design/testing, operation, procedure or equipment. The tabulation of the hazard analyses is presented in Table 6-IV.

6.2.3.3 Hazard Review – Normal Operational Sequence of Events: The operation sequences, Table 6-III, were screened to determine the most likely potential hazards. The results of this screening process are shown in Table 6-V. As shown, there were only ten operational events which survived the hazard screening process.

6.2.3.4 Hazard Review – Abort Sequence: Table 6-VI presents the assumed abort sequence for the sequential dump of oxidizer and then fuel. Presented in Table 6-VII is the hazard analysis for the abort sequences.

6.2.3.5 Hazard Analysis Summary: A compilation was made by LMSC on their Agena system based on each of the hazard analyses. The more significant hazards, the potential effects and proposed control were summarized and are presented in Table 6-VIII. In Table 6-VIII under 'HAZARD EFFECTS', the likelihood of occurrence is rated as certain, likely, possible, unlikely, and very unlikely. Those potential hazardous conditions which are classified as certain, likely, and possible are listed and the likelihood of the condition existing is placed in parentheses.

1. Propellant on-board for landing	(unlikely)
2. Oxidizer tank implosion with residuals present	(possible)
3. Propellant tank rupture/projectile penetration of tank	(unlikely)
4. Explosive mixture in dump lines	(possible)
5. Personnel errors	(prevented by design)
6. Oxidizer and/or fuel in payload bay	(unlikely)
7. Mixing of fuel and oxidizer	(unlikely)
8. Agena partially disconnected – deployed or damaged	(unlikely)

As can be seen from the above listing, only items 2 and 4 are shown as possible residual hazardous conditions. To reduce all hazardous conditions to this minimum level, the following preventive actions were outlined by LMSC:

Oxidizer/Fuel Dumping

(a) Redundant electrical system
(b) Leave oxidizer dump valve open following dump
(c) Eliminate bends and risers in dump lines
(d) Use inert gas purge in dump lines
(e) Use check valves on cradle side of dump line interface
(f) Redundant helium valves
(g) System designed to prevent inadvertent valve openings

As can be seen from the above listing, the elimination of hazardous conditions in liquid systems requires good system design, trained personnel, safe procedures and safe handling equipment.

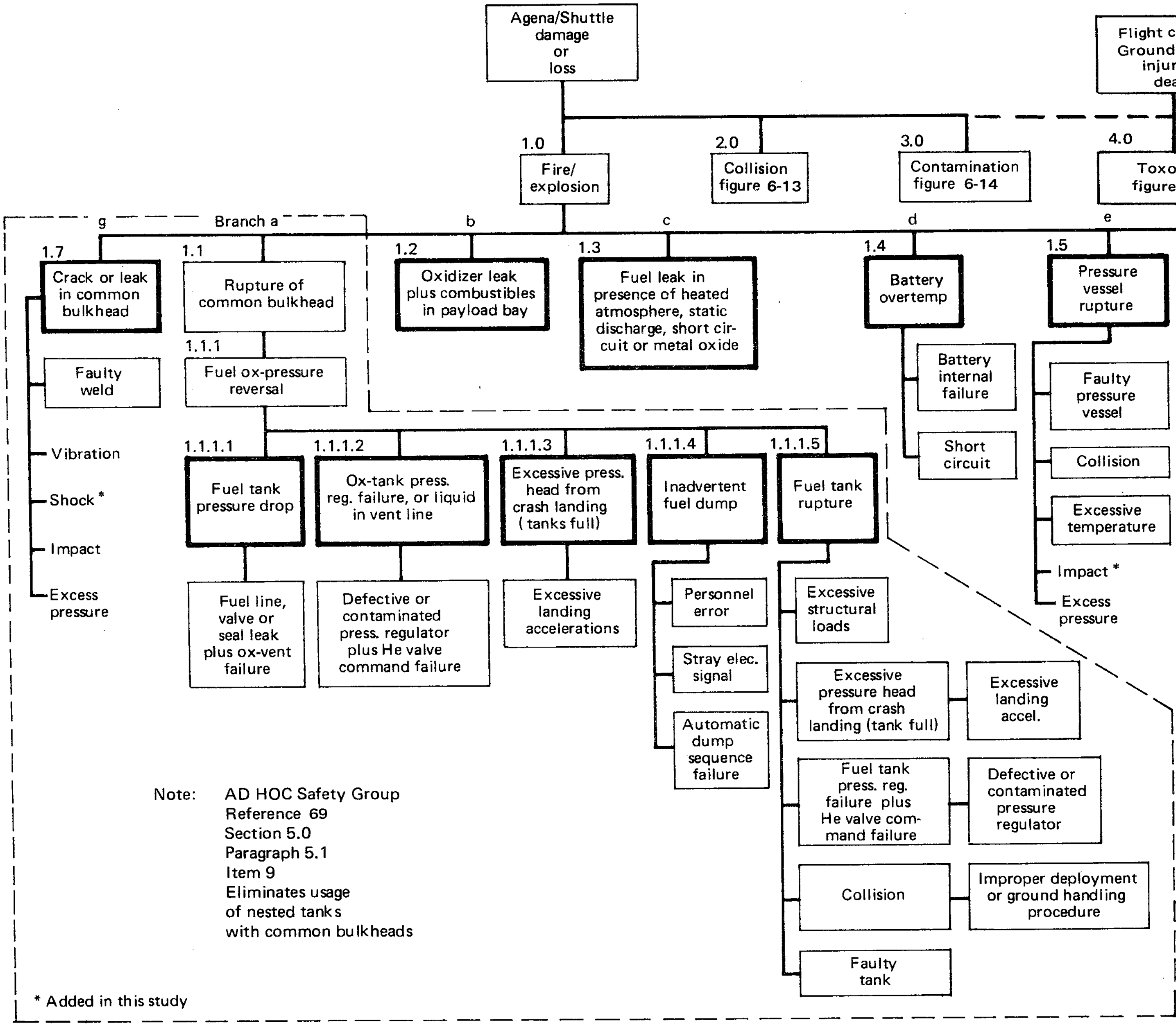


FIGURE 6-12. – FIRE/EXPLOSION HAZARD DIAGRAM

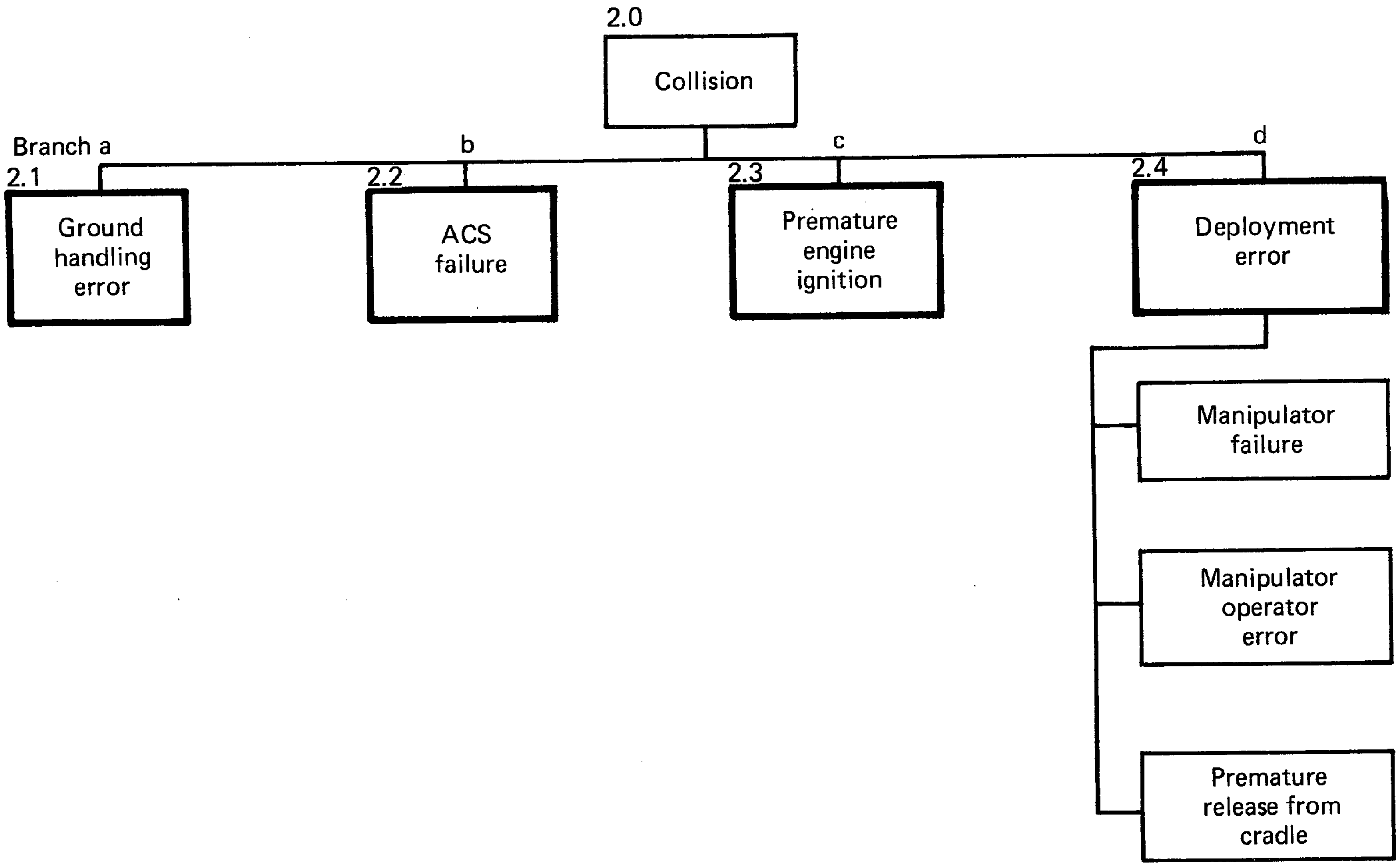


FIGURE 6-13. – COLLISION HAZARD DIAGRAM

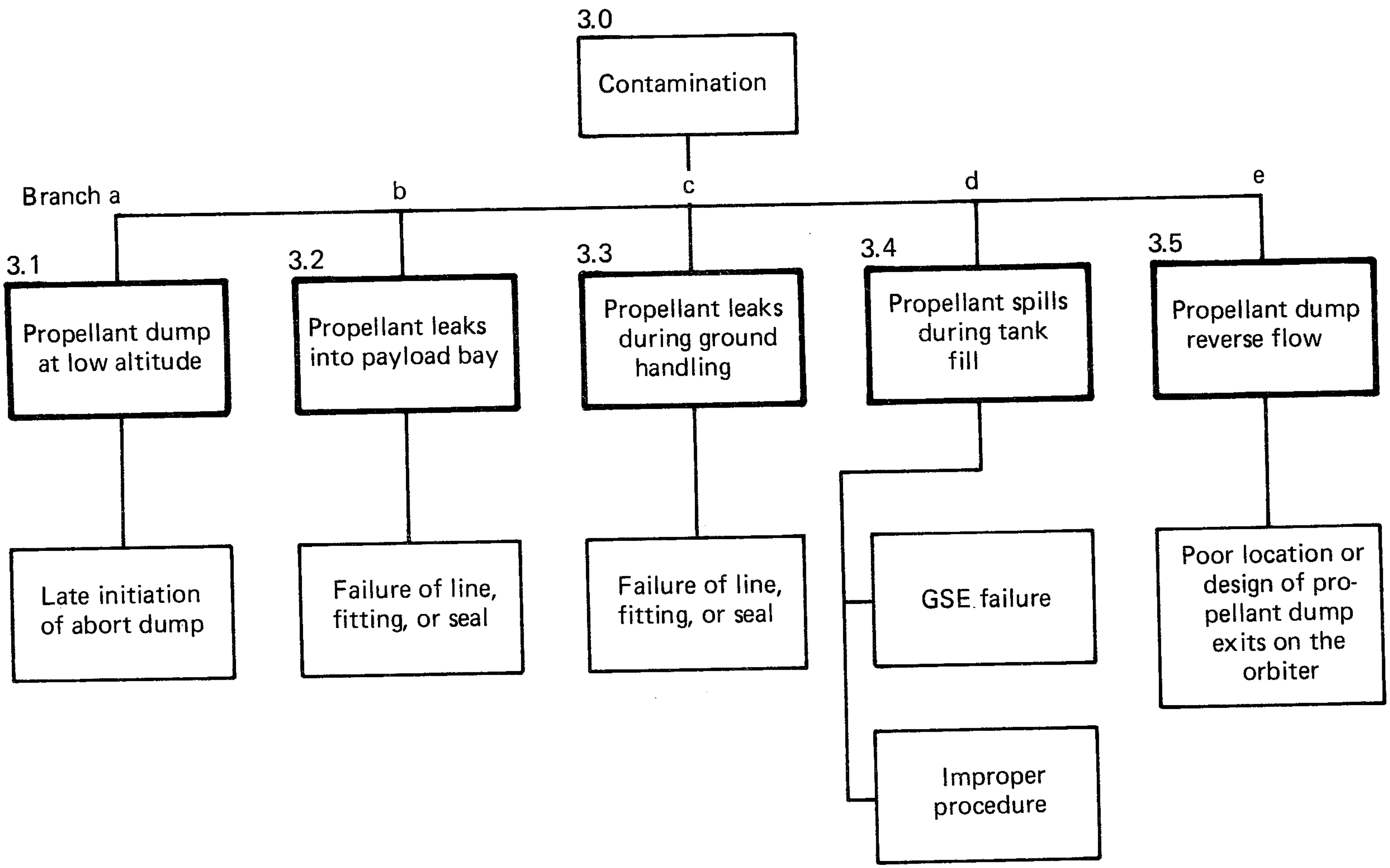


FIGURE 6-14. – CONTAMINATION HAZARD DIAGRAM

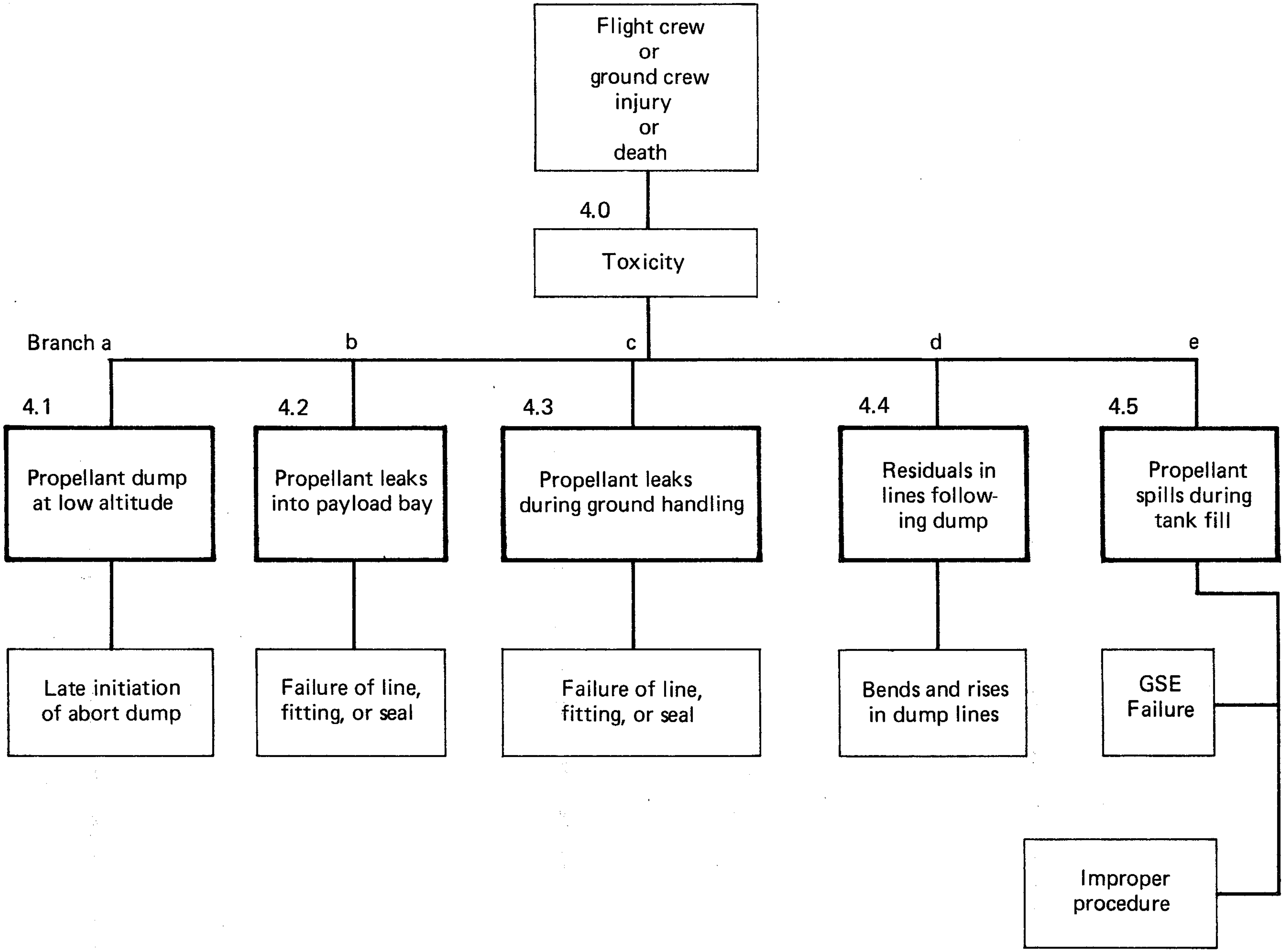


FIGURE 6-15. – TOXICITY HAZARD DIAGRAM

TABLE 6-IV. – AGENA PRELIMINARY HAZARD ANALYSIS

Hazard	Intermediate effect	Hazard branch number	Hazard cause	Counteraction
Fire/explosion	Rupture of common bulkhead in propellant tank	1.1.1.1	Fuel pressure leak plus oxidizer vent failure will cause pressure differential in tanks	1. Dual failure required before fire can occur 2. Component qualification and inspection 3. Safety monitor can increase fuel tank pressure by command
		1.1.1.2	Failed open oxidizer pressure regulator, plus oxidizer vent failure plus helium valve command failure will cause overpressurization	1. Triple failure required 2. Component qualification, inspection and test
		1.1.1.3	Excessive crash landing loads could cause excess loads on full propellant tanks	1. No hazard unless acceleration or shock loads exceed design 2. Dump propellants before landing
		1.1.1.4	Inadventent fuel dump could cause bulkhead failure and fire	1. Prevented by fail-safe system design and personnel training
		1.1.1.5	Fuel tank rupture could result in fire	1. Control acceleration 2. Dump propellant before landing 3. Component qualification, inspection and testing 4. Fail-safe procedures and equipment

TABLE 6-IV. – AGENA PRELIMINARY HAZARD ANALYSIS – Continued

Hazard	Intermediate effect	Hazard branch number	Hazard cause	Counteraction
Fire/explosion (continued)	Oxidizer leak plus combustibles in payload bay	1.2	Oxidizer combined with organic material may spontaneously ignite	1. Provide leak-tight propellant system 2. Provide helium purge bay 3. Keep combustible materials out of payload bay 4. Dump oxidizer if large leak occurs
	Fuel leak in presence of heated atmosphere, static discharge, short circuit, or metal oxide	1.3	Fuel combined with atmosphere and ignition may burn	1. Provide leak-tight propellant system 2. Provide helium purge bay 3. Keep metal oxides out of payload bay 4. Purge payload bay with inert gas while on ground 5. Control payload bay temperature 6. Eliminate ignition source 7. Dump propellant
	Battery overtemp	1.4	Overheated batteries can explode	1. Use overload devices for short circuit 2. Design, qualification, inspection, testing 3. Use current practices to prevent battery explosion 4. Use debris shield around battery

TABLE 6-IV. – AGENA PRELIMINARY HAZARD ANALYSIS – Continued

Hazard	Intermediate effect	Hazard branch number	Hazard cause	Counteraction
Fire/ explosion (continued)	Pressure vessel rupture	1.5	Pressure vessel rupture could be quite hazardous, damaging propellant tanks, equipment and shuttle, and injuring personnel	1. Control temperature 2. Depressurize tanks before landing 3. Certify tanks by design/ test 4. Maintain ultimate safety factor of 2.0 5. Protect tanks from impact or collision 6. Use debris shields
	Residuals in fuel dump line, plus ignition source	1.6	Fuel trapped in an open dump line following abort	1. Design dump lines for gravity drain 2. Close dump line exit on landing 3. Keep ignition sources away from orbiter 4. Purge dump lines
	Crack or leak in common bulkhead	1.7	Fuel and oxidizer mix through cracks causing reaction	1. Apply manufacturing, testing and inspection techniques that are proven 2. Maintain tank ΔP within required limits
Collision	1. Damage to Agena or Orbiter 2. Propellant leaks and fire/explosion	2.1	1. Ground handling errors or equipment failure	1. Develop procedures for equipment and ground handling 2. Train personnel

TABLE 6-IV. – AGENA PRELIMINARY HAZARD ANALYSIS – Continued

Hazard	Intermediate effect	Hazard branch number	Hazard cause	Counteraction
Collision (continued)		2.2	1. RCS motors fire out of control or fail during deployment	1. Establish adequate separation between Orbiter and Agena before activating Agena ACS 2. Redundant ACS components prevent loss of control
		2.3	1. Premature main engine ignition	1. Inhibit engine firing until arm command is given following adequate separation between Orbiter and Agena
		2.4	1. Manipulator failure 2. Operator error 3. Premature release of Agena	1. Design Agena cradle so that mission specialist must command release 2. Manipulator failure and operator error are the responsibility of the shuttle system
Contamination	1. Ground and streams/ rivers polluted	3.1	1. Failure to dump propellant at high altitude	1. No dumping below 2000 feet 2. Schedule dump at proper time
	1. Payload bay–Agena payload damaged 2. Fire/explosion	3.2	1. Propellant leaks in closed payload bay	1. Provide leak-tight propellant system 2. Purge payload bay with inert gas while on ground – vent in flight

TABLE 6-IV. – AGENA PRELIMINARY HAZARD ANALYSIS – Continued

Hazard	Intermediate effect	Hazard branch number	Hazard cause	Counteraction
Contamination (continued)	1. Payload bay, Agena payload, GSE damaged	3.3	1. Propellant leaks during ground handling	1. Provide leak-tight propellant system 2. Develop ground handling equipment and procedures to avoid damage to lines, fittings and seals.
	1. Orbiter, Agena payload, GSE, facility damage 2. Personnel injury or death	3.4	1. Propellant spills during fueling process	1. Use fail-safe fill equipment and procedures 2. Provide large quantities of water to dilute and wash away propellant 3. Observe safety practices 4. Train personnel
	1. Orbiter damage 2. Orbiter, Agena payload damage or fire	3.5	1. Propellants contact aft end of orbiter during dumping process 2. Propellants enter vents during dumping of propellants	1. Provide safe dump exit design and location through development and test 2. Dump propellants while vents are closed
Toxicity	1. Toxic fumes near ground 2. See 3.1	4.1	1. Failure to dump propellant at high altitude	1. No dumping of propellants below 2000 ft 2. Schedule dump at proper time
	1. Toxic environment in payload bay 2. See 3.2	4.2	1. Propellant leaks in closed payload bay	1. Provide leak-tight propellant system 2. Purge payload bay with inert gas while on ground–vent in flight

TABLE 6-IV. – AGENA PRELIMINARY HAZARD ANALYSIS – Concluded

Hazard	Intermediate effect	Hazard branch number	Hazard cause	Counteraction
Toxicity (continued)	1. Toxic environment in vicinity of Agena 2. See 3.3	4.3	1. Propellant leaks during ground handling	1. Provide leak-tight propellant system 2. Develop ground handling equipment and procedures to avoid damage to lines, fittings and seals 3. Provide propellant leak detectors and monitor
	1. Injury/death to personnel	4.4	1. Residuals at dump line exits or disconnects	1. Design dump lines for gravity drain following landing 2. Cover dump exits until line purge 3. Purge lines before disconnecting or working around dump exits
	1. Injury/death to personnel	4.5	1. Propellant spills during fueling process	1. Use fail-safe fill equipment and procedures 2. Provide large quantities of water to dilute and wash away spilled propellant 3. Observe safety practices 4. Train personnel

TABLE 6-V. – OPERATIONS SEQUENCE EVENT SCREENING

Potential hazard identification	Sequence of events	Class of events			Activity involves				Possible hazard exposure: Negl		Possible hazard exposure				Error, undesired event	Endangers			Control action: Preventive actions						Control action: Other
		Passive, unchanging	Adding/subtracting	Status change	Agena	GSE	Interfaces	Operations	Passive-monitor inspection event	Previous/existing procedure, experience	Fire/explosion	Toxicity	Contamination	Collision		Personnel	Shuttle	Agena/mission	Safety instrumentation	Warning devices	Monitoring procedures	Safety training	Maintenance inspect	Procedures/equipment	
	1 Load propellant and gas																								
	1.1 Install pyros		X		X					X															
	1.2 Install batteries		X		X					X															
	1.3 Load propellants		X		X					X															
	1.4 Load pressurants		X		X					X															
	1.5 Pressurize propellants		X		X					X															
	1.6 Monitor instruments	X			X				X																
	2 Move Agena																								
1.	2.1 Disconnect fill lines		X		X	X						X	X		Propellant in lines	X			X		X	X		X	
2.	2.2 Rotate and move to transporter			X	X	X								X	Cable or hndlg failure	X		X				X		X	
3.	2.3 Transport to Orbiter													X	Handling error	X		X				X		X	
	3 Mate Agena to Orbiter																								
	3.1 Attach hoisting equipment		X		X	X				X															
	3.2 Release from transporter			X	X	X	X		X																
4.	3.3 Move to payload bay			X	X									X	Cable or hndlg failure	X	X	X				X		X	
	3.4 Secure cradle to Orbiter			X	X		X		X																
	3.5 Connect dump lines			X			X		X																
	3.6 Connect power and instrumentation			X	X		X			X															
	3.7 Monitor safety via Orbiter			X			X		X																
	4 Erect and move to pad			X	X		X	X																	
	5 Prelaunch pad activities																								
	5.1 Monitor safety and status	X			X		X		X																
	6 Launch to orbit																								
	6.1 Monitor safety and status	X			X		X		X																
	7 Predeploy activities																								
	7.1 Transfer to internal power			X	X		X			X															
5.	7.2 Attach manipulator			X	X		X							X		X	X	X				X		X	Shuttle responsibility
	8 Deployment activities																								
6.	8.1 Disconnect umbilicals			X	X		X				X		X		a. No disconnect b. Partial disconnect c. Propellant leaked into dump lines	X	X	X	X		X				
7.	8.2 Release from cradle			X	X		X									X	X	X					X		
8.	8.3 Deploy Agena			X	X		X							X		X	X	X				X		X	Shuttle responsibility
	8.4 Command TM on and check			X	X		X			X															
9.	8.5 Release Agena			X	X		X								Arm not released	X	X	X					X	X	Shuttle responsibility
	9 Separation activities																								
10.	9.1 Move Orbiter away	X						X						X		X	X	X					X	X	Shuttle responsibility
	9.2 Activate ACS			X	X					X															
	9.3 Arm pyros and engine			X	X					X															

TABLE 6-VI. – SEQUENTIAL DUMP – OXIDIZER FOLLOWED BY FUEL

Event number	The following actions are taken by the mission specialist after initiation of shuttle abort
1.	He monitors shuttle acceleration and flight path and when SRM and main engine thrust is terminated, and the Orbiter is descending through the atmosphere with drag force resulting in a net propellant settling acceleration of 0.003g or greater, he arms the abort system and depresses an abort button to initiate the following programmed sequence
2.	Open He and N_2 control valves to pressurize fuel and oxidizer tanks
3.	Open the oxidizer forward dump valve
4.	When the oxidizer dump valve has been open 90 sec or more and tank pressure drops below 27 psi, close the He control valve supplying the oxidizer tank
5.	Open the fuel forward dump valve
6.	When the fuel tank dump valve has been open 40 sec or more and pressure drops below 35 psi, close the fuel forward dump valve
	<u>Landing</u>
7.	Land
	<u>Post landing</u>
8.	Connect fuel and oxidizer vent lines to GSE, reduce fuel tank pressure, close oxidizer dump valve, and purge dump lines
9.	Disconnect dump lines and electrical umbilical at Orbiter interface and release support cradle from Orbiter tiedowns
10.	Remove Agena/payload and cradle from payload bay and install in transporter
11.	Remove pyros
12.	Purge propellant tanks and lines through GSE
13.	Transport to refurbishment facility

TABLE 6-VII. – HAZARDS ANALYSIS FOR ATMOSPHERIC ABORT

Event No.	Potential hazard	Counteraction
1	Abort button pushed before propellants settled, resulting in possible loss of pressurant and failure to dump propellant. No hazard for normal entry and landing, if fuel tank remains pressurized	1. Provide accurate acceleration information to mission specialist. 2. Consider putting an accelerometer switch in the circuit to inhibit dump if propellants are not settled
2	a. He and/or N_2 control valves fail to open. Oxidizer and fuel only partially dump and tanks will not repressurize b. Fuel or oxidizer pressure regulator fails open	a-1 Parallel redundant valves preclude single point failure a-2 Inhibit dump valve until He valve is open b-1 Pressure controller modulates the corresponding fuel or oxidizer pressure control valve
3	Oxidizer forward dump valve fails to open. Oxidizer does not dump	1. Mission specialist can command oxidizer aft dump valve open and dump 1/2 of oxidizer load. Mission specialist must have indication of valve positions
4	He control valve to oxidizer tank fails to close. Pressurant is lost at a rapid rate. Fuel cannot be dumped	1. Inhibit fuel dump valve from opening while He control valve to oxidizer tank is open. Land with fuel
5	Fuel forward dump valve fails to open. Fuel does not dump	1. Mission specialist can command aft dump valve open and dump 1/2 of fuel load. Mission specialist must have indication of valve positions
6	Fuel dump valve fails to close. Pressurant is lost at a rapid rate. Tank cannot be repressurized	1. Land with both fuel and oxidizer tanks open to the atmosphere
7	No hazard on landing unless design crash landing loads exceeded, or residuals are trapped in fuel dump line	1. Keep ignition sources away from fuel dump exit following landing
8	Careless handling of propellant systems after landing could expose personnel to toxic propellants	1. Adequate procedures, equipment, and training
9	No hazard in disconnecting umbilicals if dump lines properly purged and tanks vented in previous step	1. Verify dump lines purged and tanks depressurized
10	Collision or impact if removal of Agena to the transporter is not properly handled	1. Adequate procedures, equipment, and training. Use extra care if tank partially or fully loaded
11	No unique hazards during removal of pyros	1. Use trained personnel and adequate procedures
12	Toxicity, contamination, fire, if tank and line purge not properly handled	1. Adequate procedures, equipment, and training
13	No hazard if transport is properly handled. Collision with careless handling	1. Adequate procedures, equipment, and training

TABLE 6-VIII. – HAZARD ANALYSIS SUMMARY

Hazard identification			Hazard effects				Control actions	
Error, malfunction; undesired event	Cause	Potentially hazardous condition	Potential consequences	Hazard* class	Likelihood of occurrence		Preventive actions	Corrective/remedial actions
					Condition	Consequences		
Dump initiated with propellants not settled, and system not designed to land fully loaded	Human error or indicator error	Pressurant lost; propellant not dumped	Tank rupture on–8g crash landing resulting fire	a	Unlikely	Very unlikely	Provide accurate acceleration info to mission specialist Put accelerometer switch in line to inhibit premature dump actuation	Stop dump before pressurant lost, and restart
Dump system control failure and system not designed to land fully loaded	Electrical failure or component failure	Propellant on-board for landing	Tank rupture on–8g,crash landing resulting in fire.	a	Possible	Likely	Redundant electrical system Redundant He valves	Use special care on landing
			Propellant in tanks during soft landing	c	Possible	Very unlikely	As above	Special care on landing and post landing
Dump system control failure	Oxidizer tank closed, but not repressurized for entry and landing	Oxidizer tank implosion with residuals present	Contamination, toxicity	b	Possible	Possible	Leave ox dump valve open following dump. Parallel redundant press. Control valves	None
Propellant spills during ground vent and line purge, tank drain following abort landing	Human error	Presence of toxic propellants	Toxicity	b	Unlikely	Unlikely	Procedures, equipment, and training	Remove personnel plus water deluge
Collision during ground handling	Equipment failure or human error	Propellant tank rupture	Fire, toxicity, contamination, injury	a	Unlikely	Possible	Fail-safe handling, equipment safe procedures, trained personnel	Remove personnel plus water deluge
Crash landing plus depressurized fuel tank, with full propellants	Excessive loads	Common bulkhead rupture **	Fire	a	Very unlikely	Certain	Special care on landing, retain pressurization gas to maintain fuel tank pressure	None

* (a) Catastrophic; (b) Critical; (c) Controlled

** Common bulkhead tanks not used on shuttle payloads

TABLE 6-VIII. – HAZARD ANALYSIS SUMMARY – Continued

Hazard identification			Hazard effects				Control actions	
Error, malfunction; undesired event	Cause	Potentially hazardous condition	Potential consequences	Hazard * class	Likelihood of occurrence: Condition	Likelihood of occurrence: Consequences	Preventive actions	Corrective/remedial actions
Pressure regulator fails open during propellant dump	Faulty regulator	Tank or common bulkhead rupture **	Fire, contamination	a	Possible	Likely	Use high reliability regulators. High system cleanliness. Use materials inert to propellants	Pressure controller modulates pressurant valve to control pressure. Oxidizer relief valve opens automatically
Residuals remain in fuel dump line	Dump line rises and bends, inadequate purge	Explosive mixture in dump line	Explosion, if ignition source is present	a	Possible	Possible	Eliminate bends and rises in dump line. Provide reliable purge with inert gas	Keep ignition sources away from fuel dump exit. Cap exits following landing until lines are purged
Fuel pressure leak and oxidizer vent failure	Faulty components	Common bulkhead rupture **	Fire	a	Unlikely. Dual equipment failure required	Certain	High reliability parts	Open fuel tank He valve to maintain tank pressure
Fuel tank overpressurized or punctured during abort or landing	Collision, excess loads, or failure of both fuel press. reg. and He valve command	Fuel tank ruptured	Fire	a	Unlikely. Out-of spec loads or dual equipment failure required	Likely	Care in handling. High rel parts. Fail-safe design. Dump propellant before landing	Command fuel vent open to reduce pressure
Inadvertent fuel dump	Common bulkhead rupture	Personnel error	Fire	a	Prevented by design	Possible	System design requiring deliberate action to arm, open He valves, and open dump valves, plus fuel dump inhibit if ox dump valve is not open	Command dump valve closed
Oxidizer leak	Faulty seal	Oxidizer in payload	Fire, contamination	a	Unlikely, based on Agena history	Possible	Redundant seals, high rel parts, inspection, careful handling, absence of organic materials in payload bay	Inert purge of payload bay while on the ground. Dump oxidizer

* (a) Catastrophic; (b) Critical; (c) Controlled

** Common bulkhead tanks not used on shuttle payloads

TABLE 6-VIII. – HAZARD ANALYSIS SUMMARY – Concluded

Hazard identification			Hazard effects				Control actions	
Error, malfunction; undesired event	Cause	Potentially hazardous condition	Potential consequences	Hazard* class	Likelihood of occurrence		Preventive actions	Corrective/remedial actions
					Condition	Consequences		
Fuel leak	Faulty seal	Fuel in payload bay	Fire, contamination	a	Unlikely, based on Agena	Possible	Redundant seals, high rel parts, inspection, careful handling, absence of metal oxides in payload bay	Inert purge of payload bay while on the ground. Dump propellants
Battery explosion	Internal failure or short circuit	Propellant tank penetrated by debris	Explosion and fire	a	Unlikely	Unlikely	Fail-safe battery design. Qual test, short circuit protection, Debris shields	
Pressure vessel rupture	Faulty pressurant tank	Propellant tank penetrated by debris	Fire, contamination, toxicity	a	Unlikely	Possible	Flight qual., factors of safety 2.0, inspection	
Propellant tank rupture	Faulty propellant tank	Propellant released	Fire, contamination, toxicity	a	Unlikely	Possible	Flight qual., inspection, factor of safety 1.4	Water deluge if prelaunch
Crack in common bulkhead **	Faulty tank	Comingling of fuel and ox	Fire	a	Unlikely	Certain	Manufacturing testing, and inspection techniques currently used on Agena, maintain ΔP within specs	
Dump lines wet during disconnect in orbit	Propellant dump valve leak or propellant vent	Propellant released into payload bay	Fire, contamination corrosion	a	Possible	Possible	Purge lines before disconnect. Check valves on cradle side of line interface	
Unsuccessful deployment in orbit	Equipment failure or handling error	Agena partially disconnected or deployed, or damaged	Orbiter-cannot safely reenter	a	Unlikely	Possible	Redundant release mechanisms and fail-safe restraints	EVA to release or reconnect

* (a) Catastrophic; (b) Critical, (c) Controlled

** Common bulkhead tanks not used on shuttle payloads

The main concern is to provide an acceptable environment (temperature, shock, vibration, impact, overpressurization) which will prevent the fuel and oxidizer from leaking or mixing in any form except in the engine combustion chamber.

Tank Rupture
- (a) Redundant electrical system
- (b) Use parallel redundant tank pressure control valves
- (c) Use fail-safe handling, equipment, procedures, trained personnel
- (d) Use high reliability regulators
- (e) Dump fuel/oxidizer before landing
- (f) System design to prevent inadvertent valve opening
- (g) Use high factor of safety on tank design

Propellant Leakage
- (a) Use fail-safe handling, equipment, procedures, trained personnel
- (b) Use redundant seals in valves and closures
- (c) Do not allow metal oxides or organic materials in the payload bay which react to propellant
- (d) System designed to prevent inadvertent valve openings
- (e) Use check valves on cradle side of dump line interface

Payload Release
- (a) Use redundant release mechanism

6.2.4 Liquid Propellants. – The hazardous and unique characteristics of liquid oxidizers and fuels, taken from references 6, 70 and 71 are presented below. A summary of the characteristics are presented in Table 6-IX.

6.2.4.1 Unsymmetrical Dimethyl Hydrazine (UDMH): UDMH is a clear, colorless liquid with a sharp ammoniacal or fishy odor. It is a fuel which is flammable in air over a very wide range of concentrations. It is hypergolic with some oxidants, including fuming nitric acids, nitrogen tetroxide, hydrogen peroxide, chlorine trifloride, and fluorine. Rags, cotton waste, wood scraps, excelsior, and other materials of large surface area that have absorbed UDMH may cause spontaneous ignition. A UDMH fire may be supported freely in air or it may be supported by an oxidizer, e.g., flare-type combustion. Due to the 3.1 psia (2.14×10^4 N/m^2) vapor pressure at 80^{o}F (26.7^{o}C) and a wide flammability range, the possibility of an explosive mixture forming over the liquid is very high. Ignition can occur from an open flame or electric spark. UDMH is a convulsant agent, an irritant to the respiratory tract and eyes, and may irritate the skin. It may be absorbed by the skin, taken orally, or inhaled. Animal studies indicate that a mild anemia may follow exposure and that the most serious after-effect is convulsions. Depending on the degree of exposure, these range from tremors to acute convulsions. Chronic low level exposures may cause anemia. UDMH is compatible with most common metals. There is no known limitation on the use of UDMH with nickel, monel or many of the 300 series stainless steels. Aluminum and its alloys are also good for UDMH service when the water content is low. Usable non-metals include teflon, unplasticized Kel-F, polyethylene and certain butyl rubbers.

TABLE 6-IX. – LIQUID PROPELLANT CHARACTERISTIC SUMMARY

Propellant	Flash point	Auto-ignition temp.	Flammability range	Vapor pressure	Threshold limit value	Material compatibility	Stability	Remarks
UDMH	Open cup 5°F (–15°C) Closed cup (TAG) 34°F (1.1°C)	482°F (250°C)	2% (LEL) to 90% by volume at ambient temperature	0.3 PSIA at 0° F (2.07×10^3 N/m^2 at –17.8°C) 1.0 PSIA at 40°F (6.90×10^3 N/m^2 at 4.4°C) 3.1 PSIA at 80°F (2.14×10^4 N/m^2 at 26.7°C) 8.4 PSIA at 120°F (5.80×10^4 N/m^2 at 48.9°C)	0.5 ppm (1 mg/m^3)	Compatible with most common metals. Unsat. with copper & high copper content alloys	Not shock or friction sensitive. Good thermal stability	Hypergolic with some oxidants. Large flammability range and high vapor pressure makes this fuel very hazardous
Liquid hydrogen	N/A	1075°F (579°C)	4 to 75% by volume at 68°F. (3.2 to 60 g/m^3 at 20°C)	1.9 PSIA at –433°F (1.31×10^4 N/m^2 at –258°C) 14.7 PSIA at –423°F (1.01×10^5 N/m^2 at –253°C) 23.7 PSIA at –420°F (1.63×10^5 N/m^2 at –251°C) 120 PSIA at –405°F (8.27×10^5 N/m^2 at –243°C) 162 PSIA at –402°F (1.12×10^6 N/m^2 at –241°C)	N/A	Compatible with many metals except non-austenitic ferrous alloys	Chemically stable when stored properly. Hydrogen-air mixture can be ignited by heat, spark or flame.	Ignites readily over a wide range of mixture with air. Not toxic but low temperatures present personnel hazard. Highly reliable refrigeration is required
Monomethyl-hydrazine	Open cup (TAG) 63°F (17.2°C) Open cup (Cleveland) 70°F (21.1°C)	382°F (194°C)	2.5% (LEL) to 98% by volume at 1 ATM. (1.013×10^5 N/m^2)	0.31 PSIA at 40°F (2.14×10^3 N/m^2 at 4.4°C) 1.0 PSIA at 80° F (6.9×10^3 N/m^2 at 26.7°C) 3.1 PSIA at 120°F (2.14×10^4 N/m^2 at 48.9°C) 7.9 PSIA at 160°F (5.45×10^4 N/m^2 at 71.1°C)	0.2 ppm (.35 mg/m^3) ceiling value, skin warning	Compatible with some metals	Stable except when influenced by copper, copper alloys, molybdenum or iron oxide catalyst	Flammable over a large range of concentrations. Hypergolic with some oxidants. Causes spontaneous ignition of many common materials

TABLE 6-IX. – LIQUID PROPELLANT CHARACTERISTIC SUMMARY – Concluded

Propellant	Flash point	Auto-ignition temp	Flammability range	Vapor pressure	Threshold limit value	Material compatibility	Stability	Remarks
Hydrogen peroxide 90%	Is not flammable but reacts with flammable materials	At 285^{o}F (140.5^{o}C) rapid boiling occurs and results in pressure increase in containers	26 to 100% by volume in air (explosive range)	.05 PSIA at 68^{o}F (3.45×10^2 N/m^2 at 20^{o}C) .17 PSIA at 104^{o}F (1.17×10^3 N/m^2 at 40^{o}C) .52 PSIA at 140^{o}F (3.59×10^3 N/m^2 at 60^{o}C) 1.38 PSIA at 176^{o}F (9.51×10^3 N/m^2 at 80^{o}C)	1 ppm Aerosal (1 mg/m^3)	Compatible with some aluminum alloys, stainless steels, plastics, lubricants. Specific materials must be selected carefully	Stable in properly passivated storage containers. Mixture with contaminants can be shock sensitive	Reacts very rapidly with many metals and organic contaminants. It actively supports combustion by liberating oxygen
Fuming nitric acids	Doesn't burn by itself	N/A	N/A Must be mixed with fuels	0.2 PSIA at 0^{o}F (1.38×10^3 N/m^2 at –17.8^{o}C) 2.7 PSIA at77^{o}F (1.86×10^4 N/m^2 at 25^{o}C) 5.0 PSIA at 100^{o}F (3.45×10^4 N/m^2 at 37.8^{o}C) 15.0 PSIA at148^{o}F (1.03×10^5 N/m^2 at 64.4^{o}C)	Nitric acid vapor 2 ppm (5 mg/m^3) Nitrogen dioxide 5 ppm (9 mg/m^3)	Compatible with many aluminum and stainless steels. Unsat. with many ferrous and metals	Stable to all types of mechanical shock and impact	Hypergolic with some fuels. Liberated fumes support combustion. Toxic properties of nitric oxides make this oxidant hazardous to personnel
Nitrogen tetroxide	Doesn't burn by itself	N/A	N/A Must be mixed with fuels	4.8 PSIA at30^{o}F (3.31×10^4 N/m^2 at 1.1^{o}C) 14.6 PSIA at 70^{o}F (1.01×10^5 N/m^2 at 21.1^{o}C) 38.6 PSIA at 110^{o}F (2.66×10^5 N/m^2 at 43.3^{o}C) 91.0 PSIA at 150^{o}F (6.27×10^5 N/m^2 at 65.6^{o}C)	NO_2 5 ppm (9 mg/m^3) N_2O_4 2.5 ppm (9 mg/m^3)	Compatible with most common metals. Moisture content is leading factor	Very stable at room temperature	Readily supports combustion. Hypergolic with many fuels. Toxic properties make this oxidant hazardous to personnel
Liquid oxygen	Doesn't burn by itself	N/A	N/A Must be mixed with fuels	37 PSIA at –280^{o}F (2.55×10^5 N/m^2 at –173^{o}C) 167 PSIA at –260^{o}F (1.15×10^6 N/m^2 at –151^{o}C) 615 PSIA at –190^{o}F (4.24×10^6 N/m^2 at –123^{o}C)	N/A	Compatible with many aluminum, steel, copper, and nickel alloys	Chemically stable. Not shock sensitive but may form shock sensitive mixture with fuel	Vigorously supports combustion. Not hypergolic but may form shock sensitive mixtures with fuels. Not toxic but low temperatures present personnel hazard. Highly reliable refrigeration is required.

6.2.4.2 Inhibited/Red Fuming Nitric Acid (RFNA, IRFNA): Red Fuming Nitric Acid is a fuming liquid which has the color of reddish brown. It is an oxidizer which will not burn by itself; however, the fumes liberated by nitric acids support combustion. Spills may ignite materials such as wood or rope, and the fire will be typical of the materials burning. Aniline and other hypergolic fuels quickly ignite on contact with this acid. Once ignited, fuels undergo flare burning in contact with the acids. Although nitric acid is stable to mechanical shock and impact, upon contact with certain fuels (such as aniline or furfuryl alcohol) it will react violently. It will form explosive mixtures with non-hypergolic fuels and with hypergolic fuels. RFNA in contact with any surfaces of the body destroys tissue by direct action. RFNA vapors are highly irritating and toxic to the respiratory tract. A fatal pulmonary edema may develop. Many types of aluminum and stainless steels are compatible with the fuming nitric acids. However, careful material selection is required because many ferrous and nonferrous metals and their alloys will react with fuming nitric acid, producing toxic oxides of nitrogen as well as failures from corrosion.

6.2.4.3 Nitrogen Tetroxide (N_2O_4): Nitrogen tetroxide is a heavy brown liquid and gives off yellowish to reddish brown fumes. It is an oxidizer which will not burn by itself, but will support combustion. When mixed with fuel, it is readily combustible and is hypergolic with a number of fuels including UDMH, hydrazine, aniline, and furfuryl alcohol. N_2O_4 mixed with other combustible liquids which are not hypergolic presents an explosive hazard, particularly when subjected to elevated temperatures, pressure, or impact.

N_2O_4 in liquid form destroys body tissue. Severe burns of the skin and eyes can result from contact with liquid N_2O_4. It volatilizes readily, giving off vapors containing a mixture of N_2O_4 and NO_2. Inhalation of the N_2O_4 and NO_2 vapors is normally the most serious hazard in handling N_2O_4 due to their low threshold limit values.

N_2O_4 is not corrosive to most common metals but the selection is governed by the water content of the N_2O_4. Plastics such as teflon, Kel-F and lubricants of the fluorolube family are all compatible with N_2O_4.

6.2.4.4 Liquid Oxygen (LO_2): LO_2 is a light-blue transparent liquid which has a boiling point of $-297.4^{o}F$ ($-183^{o}C$). It does not burn but vigorously supports combustion. Normally, it is not hypergolic with fuels. It will cause liquid fuels to cool and freeze if both liquids are brought together, resulting in a mixture that is shock-sensitive and which can react with the violence of a detonation. When mixed with LO_2, all fuels that burn represent an explosion hazard. These mixtures can be exploded by static electricity, mechanical shock, electrical spark, or other similar energy sources. When LO_2 is trapped in a closed system and refrigeration is not maintained, pressure rupture may occur.

The health hazards of LO_2 are associated with its very low temperature. If LO_2 is spilled on the skin, an injury resembling a burn will occur. Oxygen gas is not toxic when inhaled, but it can cause some irritation to the upper respiratory tract.

Materials used in LO_2 systems must possess acceptable physical properties at extremely low temperatures. Metals such as 18-8 stainless steel, monel, aluminum and copper can be used in LO_2 operations. Non-metals usable include teflon, Kel-F, asbestos and special silicone rubbers.

6.2.4.5 Liquid Hydrogen (LH_2): High purity LH_2 is a transparent, colorless and odorless liquid with a boiling point of -423^oF (-252.7^oC). It is readily ignited with air over a wide mixture range. A serious fire hazard always exists when hydrogen gas is present. Hydrogen will react violently with strong oxidizers and will ignite easily with oxygen. It reacts spontaneously with the fluorine and chlorine trifluoride. An explosion hazard can exist if liquid hydrogen is contaminated with oxygen or oxygen-enriched air.

If liquid hydrogen is spilled on the skin, it can cause injury like a frostbite/burn. In the gaseous form, hydrogen acts as an asphyxiant by reducing the amount of oxygen normally present in air.

Materials used in LH_2 systems must possess acceptable physical properties at extremely low temperatures. Several metals such as 300 and austenitic stainless steel, monel, aluminum and copper are acceptable for LH_2 application. Non-metals such as dacron, teflon, Kel-F and nylon are also usable.

6.2.4.6 Monomethylhydrazine (MMH): MMH is a clear, water-white liquid with an odor similar to that of ammonia. MMH is flammable in a broad range of concentrations in air. It is hypergolic with some oxidants such as hydrogen peroxide, nitrogen tetroxide, fluorine, haligen fluoride, and nitric acid. A film of MMH in contact with metal oxides, such as those of iron, copper, lead, magnesium, and molybdenum may ignite due to the heat of chemical reaction. Materials of large surface area such as rags, cotton waste, sawdust, excelsior, or other materials that have absorbed MMH may eventually cause spontaneous ignition. The vapors of MMH in air can be exploded by an electric spark or open flame. The liquid phase MMH is not sensitive to impact or friction.

MMH is a strong irritant and may damage eyes and cause respiratory tract irritation. It is a volatile caustic liquid which can cause system toxicity by absorption through the skin as well as by inhalation.

A few materials are acceptable for use in MMH systems. These materials include some 300 series stainless steels, nickel, and some aluminum alloys.

Non-metals such as teflon, Kel-F and high density polyethylene are also acceptable for MMH usage.

6.2.4.7 Hydrogen Peroxide (H_2O_2): H_2O_2 is a monopropellant and is an active oxidizing agent. It does not burn but vigorously supports combustion by oxygen liberation during decomposition. It reacts with many organic materials such as wood, cotton, grass, dirt, cigarette ashes, etc. It is also hypergolic with hydrazine and when mixed with organic solvents such as ketones, alcohols, and glycols, the solution becomes shock-sensitive. Materials containing silver, lead, chromium, mercury, and rust cause immediate decomposition. Explosions will occur from stored H_2O_2 when the containers are closed and contaminated. Principal personnel hazards involve contact of the liquid or vapor with eyes, inhalation of vapors, exposure of the skin to the liquid or high vapor concentrations and spillage on clothing resulting in fire.

Proper selection and passivation of materials for handling H_2O_2 are required. Aluminum and aluminum alloys, the 300 series stainless steels, Buna-N, Fluorel 2141, Kel-F, Viton A plastics and certain lubricants are compatible with H_2O_2.

6.3 Liquid/Solid Hazard Comparison

The inherent hazards involved in operations handling, transporting and storing of solid and liquid propellant systems are similar in many cases and yet very different in others because of their physical characteristics. In a liquid propulsion system the fuel and oxidizer must be transferred from tanks through valves, lines and fittings to a main combustion chamber. The delivery of the propellants from the tanks may require a gas pressurization system which pressurizes the storage tank to approximately 300-500 psi while a turbine pump system requires a low tank pressure. These type systems are usually complex, susceptible to leaks, contamination and hardware failures. By contrast, the solid propulsion system contains a solid propellant, generally classified as composite or double base, which is molded into the combustion chamber/storage chamber during manufacturing. Therefore, no special ground support equipment/facilities or complex fueling/safety procedures are required for field operations.

The primary hazards that operations, handling errors/malfunctions or extreme environments cause in liquid propellant systems are fire, explosions, toxicity and corrosion which occur because of leakage, spillage or mixing of the oxidizer and/or fuel. The primary solid propellant hazards are fire, explosion or detonation which may be caused by electrical signal, mechanical or blast shock, projectile penetration, high temperatures or some combination of these environments.

In order to compare the liquid and solid hazards the results of the solid rocket hazard study of Section 6-I was subjectively compared to the results of the liquid rocket hazard study of Section 6-2. The comparison is presented in Table 6-X. As shown, there are more hazardous incidents which could lead to catastrophic or critical conditions using a liquid system than when using a solid system. Therefore, the solid system should be considered safer than a liquid system from a system viewpoint.

6.4 Conclusions

The simplicity of solid propellant rocket handling and operation requirements make this type system a prime candidate for utilization on Shuttle payloads. Although the application of these systems present potential hazards to the Shuttle system, the hazards are readily eliminated, minimized or controlled to an acceptable level. Methods which assure that this has occurred are required as part of a system safety program. Detail hazard analyses are usually required on major programs. Hazard analyses outlined in the NASA System Safety Manual includes the following:

(a) General Safety Studies
(b) Preliminary Hazard Analysis
(c) Fault Hazard Analysis

TABLE 6-X. – LIQUID AND SOLID HAZARD CLASS COMPARISON

Error, malfunction; undesired event	Liquid	Hazard class C-Catastrophic CR-Critical	Solid	Hazard class C-Catastrophic CR-Critical
Shuttle or Scout non-propulsion system fire	Yes	C	Yes	C
Propulsion system fire	Yes	C	Yes	C
Environmental heating	Yes	CR	Yes	CR
Meteoroid impact	Yes	C	Yes	CR
Spurious electrical signals	No	Note 1	Yes	C
Vibration	Yes	C	Yes	CR
Fragmentation from shuttle or Scout non-propulsion system rupture or explosion	Yes	C	Yes	CR
Environmental shock	Yes	C	Yes	CR
Electrical fault	Yes	Note 1	Yes	C
Shock from shuttle or Scout non-propulsion system rupture or explosion	Yes	C	Yes	C
Corrosion	Yes	C	No – RCS system only	
Fuel pressure leak and oxidizer vent failure	Yes	C	No RCS system only	
Fuel tank over-pressurized or punctured during abort or landing	Yes	C	Puncture only	CR
Inadvertent fuel dump	Yes	C	No – RCS system only	
Oxidizer leak	Yes	C	No – RCS system only	
Fuel leak	Yes	C	No	

Notes:
1. Most liquid rocket systems require multiple valves to function before a critical or catastrophic condition can occur.

TABLE 6-X. – LIQUID AND SOLID HAZARD CLASS COMPARISON – Concluded

Error, malfunction; undesired event	Liquid	Hazard class C-Catastrophic CR-Critical	Solid	Hazard class C-Catastrophic CR-Critical
Battery explosion	Yes	C	Yes	CR
Pressure vessel rupture	Yes	C	No – RCS system only	
Propellant tank rupture	Yes	C	No – RCS system only	
Dump lines wet during disconnect in orbit	Yes	C	No	
Unsuccessful deployment in orbit	Yes	C	Yes	C
Dump initiated with propellants not settled and system not designed to land fully loaded	Yes	C	No	
Dump system control failure and system not designed to land fully loaded	Yes	C	No	
Propellant spills during ground vent and line purge, tank drain following abort landing	Yes	CR	No RCS system only	
Collision during ground handling	Yes	C	Yes	CR
Crash landing plus depressurized fuel tank, with full propellants	Yes	C	No RCS system only	
Pressure regulator fails open during propellant dump	Yes	C	No RCS system only	
Residuals remain in fuel dump line	Yes	C	No	

(d) Logic Diagram Analysis
(e) Procedure Analysis

In this study the preliminary hazard analysis approach was used to analyze the hazardous situations of solid rocket propulsion systems and their interface with the Orbiter vehicle. To perform the study, the third and fourth stages of the Scout launch vehicle were used as a typical propulsion systems. In general it was determined that safety procedures, qualification tests, payload pallet design, thermal insulation and electrical system design considerations can be used to provide hazard reduction or elimination. In reference to the Scout launch vehicle, the use of system and mission features such as over-board discharge of RCS system relief effluent, ignition delay until sufficient separation from the Orbiter is realized, and electro-mechanical safe and arm devices on the solid rockets can provide further hazard reduction.

Liquid systems, such as the Agena bipropellant or the Scout reaction control monopropellant system, are considered complex when compared to the typical solid rocket from the handling, checkout and operation standpoints. Liquid systems normally contain inherent hazards in at least three areas: high pressure gas systems, ordnance devices and propellants. The liquid propellants normally used in upper stage vehicles are not impact or shock sensitive when stored in an uncontaminated condition, however, when contaminated with other fluids some become sensitive. These inherent hazards become very vivid when incidents/accidents cause a fire, explosion, contamination reaction or toxic conditions. The main concern related to liquid systems is to provide an environment such as temperature, shock, vibration, impact or tank pressures which will prevent the fuel and oxidizer from mixing in any form inadvertently. Also liquid propellants provide handling hazards to personnel which range from skin burns, frostbite, and eye damage to toxic inhalation and skin absorption.

Solid propellant systems such as the Scout, Burner II and Delta upper stages, are considered in general to be simple systems when approached from the handling, checkout and operation viewpoint. Solid motors do present hazards from possible ignition, explosion/deflagration or detonation. However, extensive past usage of both liquid and solid systems has shown that most hazards can be eliminated or controlled by good system design, trained personnel, safe handling equipment and detailed safety/handling and checkout procedures. Also, the many inherent hazards involved with field handling of liquid propellants are mostly eliminated by the use of solid propellants.

It was shown from a comparison of the PHAs of the liquid and solid propellant systems that liquids inherently have more hazardous situations or conditions which could be catastrophic or critical to the Shuttle system than the solid propellant systems. From a system's viewpoint the solid system should be considered much safer than a liquid system and therefore more desirable for use as a Shuttle payload system.

APPENDIX A
SAMPLE CALCULATIONS
LIQUID PROPELLANT HAZARD EFFECTS

1.0 SAMPLE CALCULATIONS: LIQUID PROPELLANT HAZARD EFFECTS

1.1 Introduction

The following examples are presented so that the method of determining peak side-on overpressure, explosive yield and specific impulse for liquid propellants can be reviewed. These examples include the three (3) propellant mixing modes, confinement by missile (CBM), high velocity impact (HVI), and confinement by ground surface (CBGS).

1.2 Example 1:

Propellant — Hypergolic
Combined mass of propellant and oxidizer — 22,000 lbm (10,000 kg)
Failure mode — CBM

Solution: Examine Table 5—I for "Part 1" and "Part 2" solution sequences.

Part 1: Table 5—II implies that for the CBM failure mode,
Y = 0.01 – 0.8%
Using the higher portion for safety reasons,
Y = 0.8%

Part 2: Figure 5-20 implies that for a combined mass of propellant and oxidizer of 22,000 lbm (10,000 kg)
Y = (240%) (0.37) = 88.8%
where 240% is the hypergolic multiplier factor,
Y = 0.8%, the smaller value, is the correct choice.

Assume Standoff distance R (assumption) — 164 ft (50 m)

Solution:

(1) Terminal yield y = 0.8%

(2) $W = W_T \times \frac{1}{100\%}$

$W = 22{,}000 \text{ lbm} \times \frac{0.8\%}{100}$

W = 176 lbm (80 kg)

(3) Scaled distance $R/W^{1/3} = 164 \text{ ft}/176 \text{ lbm}^{1/3} = 29.31 \text{ ft/lbm}^{1/3}$ ($11.6 \text{ m/kg}^{1/3}$)

(4) Table 5—III indicates:
Acquire P, peak pressure, from Figure 5—28.
Acquire $I/W^{1/3}$, scaled impulse, from Figure 5—30.

(5) From Figure 5—28, P = 11.0 psi ($7.58 \times 10^4 \text{ N/m}^2$)

(6) From Figure 5—30, $I/W^{1/3} = .002 \text{ psi-sec/lbm}^{1/3}$ ($27 \text{ N/m}^2 \text{ s/kg}^{1/3}$)

(7) $I = \frac{I}{W^{1/3}}(W^{1/3}) = 1.112 \times 10^{-2}$ psi/sec (116.2 $N/m^2/s$)

1.3 Example 2:

Propellant – Hypergolic
Combined mass of propellant and oxidizer – 2200 lbm (1000 kg)
Failure mode – HVI
Impact velocity (assumption) – 459 ft/sec (140 m/s)
Type of surface impacted – hard

Solution: Examine Table 5–I for "Part 1" and "Part 2" solution sequences.

Part 1: Figure 5-21 implies that for an impact velocity of 459 ft/sec (140 m/s) onto a hard surface, Y = 15%.

Part 2: Figure 5-20 implies that for a combined mass of propellant and oxidizer of 2200 lbm (1000 kg)
Y = (240%) (0.6) = 144%
where 240% is the hypergolic multiplier factor
Y = 15%, the smaller value, is the correct choice.

1.4 Example 3:

Propellant and oxidizer – LO_2/RP-1
Combined mass of propellant and oxidizer – 22,000 lbm (10,000 kg)
Failure mode – CBM
Ignition time (assumption) – 0.2 seconds

Solution: Examine Table 5–I for "Part 1" and "Part 2" solution sequences.

Part 1: Figure 5-22 implies that for an ignition time of 0.2 seconds, Y = 52%

Part 2: Figure 5-20 implies that for a combined mass of propellant and oxidizer of 22,000 lbm (10,000 kg)
Y = (125%) (0.37) = 46%
where 125% is the LO_2/RP-1 multiplier factor.
Y = 46%, the smaller value, is the correct choice.

1.5 Example 4:

Propellant and oxidizer – LO_2/RP-1
Combined mass of propellant and oxidizer – 330,000 lbm (150,000 kg)
Failure mode – CBGS
Impact velocity (assumption) – 32.8 ft/sec (10 m/s)
Ignition time (assumption) – 0.5 seconds

Solution: Examine Table 5-I for "Part 1" and "Part 2" solution sequences.

Part 1: Equation 5-I implies that for an impact velocity of 32.8 ft/sec (10 m/s)

$$Y_m = 5\% + \frac{(6.82\%)}{(3.28106 \text{ ft/sec})} 32.8 \text{ ft/sec}$$

$$Y_m = 5\% + 68.2\%$$

$$Y_m = 73.2\%$$

Figure 5-23 implies that for an ignition time of 0.5 seconds

$$\frac{Y \times 100}{Y_m} = 70$$

or

$$Y = \frac{(70)}{(100)} Y_m$$

$$Y = \frac{(70)}{(100)} (73.2\%) = 51.2\%$$

Part 2: Figure 5-20 implies that for a combined mass of propellant and oxidizer of 330,000 lbm (150,000 kg)

$Y = (125\%)\ (0.05) = 6.25\%$

where 125% is the LO_2/RP-1 multiplier factor.

$Y = 6.25\%$, the smaller value, is the correct choice.

Standoff distance (assumption) – 328 ft (100 m)

Solution:

(1) Terminal yield $y = 6.25\%$

(2) $W = W_T \times \frac{y}{100\%}$

$$W = 330{,}000 \text{ lbm} \times \frac{6.25\%}{100}$$

$$W = 20{,}625 \text{ lbm } (9364 \text{ kg})$$

(3) Scaled distance $R/W^{1/3} = 328 \text{ ft}/(20625)^{1/3} = 12 \text{ ft/lbm}^{1/3}$ ($4.8 \text{ m/kg}^{1/3}$)

(4) Table 5-III indicates

Acquire P, peak pressure from Figure 5-32

Acquire $I/W^{1/3}$, scaled impulse from Figure 5-34

(5) From Figure 5-32, P = 5.5 psi (3.8×10^4 N/m^2)

(6) From Figure 5-34, $I/W^{1/3} = .0061$ psi-sec/lbm$^{1/3}$ (55 N/m^2/kg$^{1/3}$)

(7) $I = \frac{I}{W^{1/3}} (W^{1/3}) = 0.168$ psi sec (1160 N/m^2 s)

1.6 Example 5:

Propellant and oxidizer – LO_2/LH_2
Combined mass of propellant and oxidizer – 22,000 lbm (10,000 kg)
Failure mode – HVI
Impact velocity (assumption) – 131 ft/sec (40 m/s)
Type of surface impacted – hard

Solution: Examine Table 5-I for "Part 1" and "Part 2" solution sequences

Part 1: Figure 5-21 implies that for an impact velocity of 131 ft/sec (40 m/s)
Y = 30%

Part 2: Figure 5-20 implies that for a combined mass of propellant and oxidizer of 22,000 lbm (10,000 kg)
Y = (370%) (.37) = 137%
where 370% is the LO_2/LH_2 multiplier factor
Y = 30%, the smaller value, is the correct choice
Standoff distance (assumption) – 328 ft (100 m)

Solution:
(1) Terminal yield y = 30%

(2) $W = W_T \times \frac{y}{100\%}$

$W = 22{,}000 \text{ lbm} \times \frac{30\%}{100}$

W = 6600 lbm (3000 kg)

(3) Scaled distance $R/W^{1/3} = 328 \text{ ft}/(6600 \text{ lbm})^{1/3} = 17.5 \text{ ft/lbm}^{1/3}$ ($6.9 \text{ m/kg}^{1/3}$)

(4) Table 5-III indicates:

Acquire P, peak pressure, from Figure 5-36

Acquire $I/W^{1/3}$, scaled impulse, from Figure 5-38

(5) From Figure 5-36, P = 3.19 psi (2.2×10^4 N/m^2)

(6) From Figure 5-38, $I/W^{1/3}$ = .0051 psi-sec/lbm$^{1/3}$ (45 N/m^2/kg$^{1/3}$)

(7) $I = \frac{I}{W^{1/3}} (W^{1/3}) = 0.094$ psi sec (649 N/m^2)

APPENDIX B

MISCELLANEOUS STANDARD HAZARDS TESTING PROCESS

1.0 MISCELLANEOUS STANDARD HAZARDS TESTING PROCESSES

1.1 Introduction

The following standardized hazards testing processes were abridged from Vol II of reference 6 and are presented so that the reader may have a condensed reference of other hazard testing. Additional data, including sketches, a description of the testing apparatus and a discussion of application of the data, are contained in the given reference.

1.2 Differential Thermal Analysis (DTA)

(a) Objective — To detect exothermic and endothermic reactions in a propellant or constituent as heat is applied at a given input rate and to determine the relative magnitude of these exotherms and endotherms.

(b) Operating Principle — The sample and an inert reference material are heated simultaneously at the same caloric rate. The exotherm or endotherm is measured by the differing temperature recordings on a common time base.

(c) Test Analysis and Limitations — Differential thermal analyses for elevated temperature sensitivity have gained the widest acceptance of any thermal test for propellants, components, and intermediate mixtures. DTA yields not only decomposition temperatures at various rates of temperature rise but also, by proper selection of heating rates, thermodynamic constants which are useful in basic kinetics studies of propellant grain stability in large sizes. The DTA test has its greatest value in the detection of unsuspected endothermic or exothermic reactions of new compositions and providing qualitative estimates of their effect. Quantitative assessment of the effects required measurements of heat capacities and heat transfer constants.

1.3 Self-heating Test

(a) Objective — To determine the temperature at which a given mass and configuration of propellant will commence self-heating to destruction from its own decomposition exotherm.

(b) Operating Principle

(c) Cook-Off Tests — Progressively larger regular-shaped pieces of propellant(for example, right cylinders), instrumented with internal thermocouples, are maintained at elevated temperature under a constant heat-transfer environment until deflagration occurs.

(d) DTAs at Differing Heating Rates — The DTA is performed at a number of different heating rates from 1.0 to 10.0^{o}C per minute, and the data are plotted as log heating rate vs. $1/T$, where T is the absolute temperature of the first exotherm.

(e) Self-Heating Determination in an Isothermal Environment – The rate of change in temperature is measured at the center, the surface, and one point on a radius of cylindrical propellant charges being heated in a constant temperature bath of established heat transfer coefficient. For all determinations, it is necessary to acquire values on the propellant for thermal conductivity, density, and heat of explosion.

(f) Test Analysis and Limitations – The evaluation of kinetic constants on a larger scale than the DTA test is desirable in order to decrease the amount of extrapolation needed to predict the hazard for large motors by providing values at lower temperatures. In the case of the method which utilizes an isothermal environment, knowing the rate of temperature rise at that time when no temperature gradient exists at the center, allows calculation of activation energy, as does also measurement of the thermal gradient when equilibrium is established in the bath; provided in this latter case, that the right bath temperature has been selected.

The self-heating tests described here pertain only to finished, cured, homogenously mixed propellant. A further limitation is that one exothermic reaction must predominate and that it not be complexed with a simultaneous endotherm (for example a crystalline form change in the oxidizer). This is necessary in order to obtain sufficiently clearcut datum points to permit plotting of the curve for activation energy. The limitation of these self-heating tests to cured, homogeneous propellants without voids rules out their use for one of the most serious propellant processing hazards; namely, the destructive exothermic effect that results from high local concentration of reactive species during mixing (for example, high local concentrations of polymerization accelerators or burning rate catalysts with oxidizer). These high local concentrations can result from such factors as agglomeration, improper order of addition of components to the mixer, "dead spots" in the mixer movement, etc. The only known testing method for assessing this high local concentration hazard is to deliberately put together the anticipated mal-mixture and to test for exothermic effect at various concentrations by conventional DTA techniques.

1.4 Copper Block Test

(a) Objective – To express the auto-ignition temperature of the substance by an empirical test method.

(b) Operating Principle – A small sample is heated at a constant rate in a fixed environment until ignition occurs. The temperature of ignition is observed.

(c) Test Analysis and Limitations – This test is a simple, economical method for expressing the comparative stability of substances to heat. However, the auto-ignition temperatures obtained would differ in most cases if a different rate of heating was used. Also, it makes no provision for detecting more than one decomposition reaction, successive endotherms or exotherms, etc. Accordingly, the test is not nearly as informative as auto-ignition temperatures determined in the DTA.

1.5 Wenograd Test

(a) Objective – To determine the temperature of explosion under conditions of minimal heat transfer effects.

(b) Operating Principle – A small sample of the explosive is heated by electrical capacitor discharge. Electronic recording of the temperature at which explosion occurs is achieved within 20 microseconds by means of an oscilloscope.

(c) Test Analysis and Limitations – Thermal test methods described previously all have an appreciable heat transfer factor, such that recorded times and temperatures cannot be regarded as a true integral of the total heat input to the entire mass of the sample. In an effort to minimize this heat transfer lag, Wenograd devised an ohmic heating mechanism for a very small sample, with instrumentation for an electronic response triggering mechanism and temperature recording.

In a critical review and confirmation of the Naval Ordnance Laboratory's test result with the Wenograd test, workers at Stanford Research Institute affirmed that the test measures a "true" induction time for the explosive, rather than the time required for a physical effect, such as heatup of the sample. Explosion times in the Wenograd test are believed to have the same characteristic times as response in the impact test. The order of numerous explosives correlates well in the two tests.

1.6 Tallani Test

(a) Objective – To gauge the temperature sensitivity of materials by measurement of the gas evolution pressure.

(b) Operating Principle – The sample is placed in an enclosed system and is maintained at a constant elevated temperature in a heating block. The pressure and pressure-change-rate are plotted at fixed time intervals.

(c) Test Analysis and Limitations – The test is most useful as a sensitivity criterion for double base propellants and nitrocellulose. It has questionable utility for compounds containing the nitro or any other phosphoric groups except the nitrate group.

1.7 Standard Heat Tests

(a) Objective – To evaluate thermal stability by loss in weight at an arbitrary fixed temperature.

(b) Operating Principle and Test Description – A number of empirical heat tests can be used, adapted principally from the high explosives and pyrotechnics industries, e.g., the 75°C International Test and the 100°C Heat Test. In the Standard Heat Test, for example, a 0.6g sample is heated in an open test tube at 100°C for 96 hours. To qualify, an arbitrary value may be set, such as, the sample must lose less than 2% weight in 48 hours.

(c) Test Analysis and Limitations — As with most of these empirical tests, the results are meaningful only in comparison with substances of established sensitivity that have been tested in the past. The hazards analysis of manufacture of a new product could thus be comparatively expressed in this manner.

1.8 KI-Starch Test

(a) Objective — To evaluate the thermal stability of nitrato compounds by their time to react with a standard indicator paper.

(b) Operating Principal and Test Description — The potassium iodide-starch indicator paper test is conducted at 82.2°C for nitroglycerin and at 65.5°C for double base propellants and nitrocellulose. The test paper is moistened with a glycerin-water solution and the time to coloration is reported. Standard grades of military nitrocellulose are required to have a 65.5°C KI test value of 35 minutes minimum.

(c) Test Analysis and Limitations — The test is most useful as a sensitivity criterion for double base propellants and nitrocellulose. It has questionable utility for compounds containing nitro or any other phosphoric groups except nitrato.

1.9 Methyl Violet Test

(a) Objective — To evaluate the thermal stability of nitrato compounds by the time to react with standard indicator paper.

(b) Operating Principle and Test Description — Methyl violet indicator paper testing is done at 120°C for propellants and at 134.5°C for double base and nitrocellulose compositions. Samples are heated up to five hours and times are recorded to paper coloration, evolution of red fumes, and/or explosion of the sample.

(c) Test Analysis and Limitations — The test is most useful as a sensitivity criterion for double base propellants and nitrocellulose. It has questionable utility for compounds containing nitro or any other phosphoric groups except nitrate.

1.10 Electrostatic Discharge

1.10.1 Basic Electrostatic Discharge Test

(a) Objective — To determine whether an electrostatic discharge will initiate an energetic material.

(b) Operating Principle — Electrostatic energy stored in a charged capacitor is discharged to the sample material to be tested. Materials initiated below 0.015 joule are considered hazardous for direct handling since this value is approximately that which individuals can generate. In this case the Human Spark Discharge test (see 1.10.2) is employed.

(c) Test Analysis and Limitation — The electrostatic energy discharge to the test specimen is calculated from the relationship $E = ½ CV^2$ where E = energy (joules), C = electrical capacitance (farads), and V = charging potential (volts). Currently, electrostatic discharge data do not reflect energy losses in conductors, discharge gap, and resistivity of the test specimen. These factors lower the discharge energy and the rate at which the energy is delivered. In addition, this type of test method does not provide for testing at different discharge rates to simulate all possible process conditions.

1.10.2 Electrostatic Discharge Human Spark Test

(a) Objective — To establish the susceptibility of an energetic material to initiation when subjected to the electrostatic discharge generated by humans.
(b) Operating Principle — Electrostatic energy accumulated on an electrically isolated human is discharged to the sample to be tested.
(c) Test Analysis and Limitations — The electrostatic energy discharged to the sample is calculated by applying the relationship $E = ½ CV^2$ where E = energy (joules), C = capacitance (farads), and V = charging potential (volts). An average capacitance for the human body is 300 picofarads.* This technique does not allow for the different discharge rates that would be available from different individuals because of varying skin or contact resistances.

1.10.3 Electrostatic Hazards Analysis

(a) Objective — To quantitatively assess electrostatic discharge initiation hazards during handling and manufacturing activities involving combustibles, explosives and solid propellant materials.
(b) Operating Principle and Hazard Criteria — The Systems Engineering Approach to Hazards Analysis is used to make realistic estimates of the electrostatic hazard associated with handling or processing sensitive material. The response of materials to electrostatic discharge stimulus is determined initially in suitable tests which yield the "no initiation" energy (joules). This threshold value is compared to the electrostatic energy possible during manufacture determined by appropriate in-process measurement and/or theoretical calculations. Operations are considered hazardous when the electrostatic energy potential during the suspected operation exceeds the threshold initiation level for the subject material. The human body can precipitate an electrostatic discharge hazard when the material is initiated by electrical discharges less than 0.015 joule. Assessment of this situation requires employment of the Human Spark Discharge tests.
(c) Analysis Limitations — The simulated in-process tests are a more realistic analysis since the experiments take into account "energy losses" attributable to resistance (material, air gap, lines, etc.) and inductance and duplicate the rate at which energy is applied to the sample for a particular equipment piece or body. The threshold electrostatic discharge level obtained using the spark test may be conservative if

* 300 picofarads is consistent with the .015 joules energy of paragraph 1.10.1 at only 10,000 volts.

inductance and resistance generally are less than the environment under consideration. To be totally applicable the electrostatic discharge test equipment circuitry should duplicate these variables in the discharge path. This more costly and more extensive test procedure is needed only when the material is known to be borderline or when analysis shows that a hazard truly exists.

1.11 Thin Film Propagation Test

(a) Objective — To determine whether a thin film of explosive material, once initiated, can transmit to a more intense reaction and consume the material at this increased rate.

(b) Operating Principle — A liquid explosive of varying thicknesses simulating process conditions is initiated by impact, and the extent and rate of reaction are established by monitoring the pressure front accompanying the explosive reaction.

(c) Test Analysis and Limitations — Data from this test give the frequency and extent of propagation of reaction from an impact initiated sample. Also, the instrumentation employed gives the extent of a propagation as a function of time, thereby yielding propagation velocity. A typical set of data could be:

Propagation frequency	66%
Propagation extent	2 inches
Propagation velocity	1200-1500 meters/second

This test can be used to determine not only the effects of sample dimensions but also of energy input and materials of fabrication on the extent and velocities of the propagating reaction. Use of the test is limited to testing those materials reacting strongly enough to activate the pressure-sensitive probe system.

1.12 Dust Explosibility Test

(a) Objective — To determine whether a finely divided solid material will react explosively when dispersed in a gaseous medium and ignited.

(b) Operating Principle

(c) Threshold Dust Concentration — Finely divided explosive dusts are dispersed into an energy source in air to determine the threshold explosive dust concentration.

(d) Threshold Electrostatic Discharge — Dust air mixtures in the explosion range are subjected to condenser discharge sparks to determine the threshold electrostatic discharge energy for highly explosive dust-laden atmosphere.

(e) Test Analysis and Limitation — Data from this test are reported as threshold dust concentrations (oz/ft^3), meaning the concentration of dust must exceed this level to explode, and the threshold electrostatic discharge energy (joules), if exceeded, will initiate an explosive reaction in the dust/air mixture.

Test capabilities permit establishing explosibility characteristics of a material under different media for evaluating compositional effects, and the relative benefits of inert gases or additives for eliminating a dust explosion. The test yields relative values which are influenced by such factors as the chemical and physical properties of the dust, uniformity of the dust cloud, properties of the atmosphere, ignition source and environmental conditions.

1.13 Critical Height To Explosion (Transition) Test

(a) Objective – To determine if a material will react explosively when initiated by flame.

(b) Operating Principle – Materials are submerged and surface flame initiation under environmental process conditions to determine if a material will react explosively for a specific operation.

(c) Test Analysis and Limitations – Whether a material explodes or detonates is, for practical purposes, of little consequence since both reactions result in destruction of facilities and possible personnel injury. Since material explosion heights are generally lower than detonation heights, the safety of personnel and protection of plant operations dictate that the no-explosion level be employed in process hazard evaluation studies.

Critical heights to explosion (CH_e) data are reported as the material height (inches) above which an explosive reaction can occur for a given container diameter. The data are valid within the limits of test container sizes and confinement and assuming submerged initiation, equal to a 12 gram bag igniter. Application to process hazard analysis studies assumes the critical height to explosion increases with the charge diameter. It is expected that the effect of diameter on CH_e will diminish as this dimension increases. These data are representative of a highly transient reaction and may not be indicative of a situation where the material continues to burn. In the latter case, cook-off data would be more applicable. The critical height test permits testing of solids, liquids, and mixtures used in propellant manufacture. The test can also be used to verify benefits of recommended material modifications to eliminate or minimize transition hazards. Further, the test can be used to implement investigations of influencing factors such as initiation energy, density, temperature, design configuration, and degree and material of confinement.

1.14 Critical Diameter for Propagation Test

(a) Objective – To determine if a material will propagate an explosive reaction when subjected to induced shock and to establish the critical dimension for nonpropagation.

(b) Operating Principle – Materials are purposely shocked by pressures of a detonating high-energy donor to determine if a material dimension is capable of propagating an explosive reaction. The dimensions of the material are varied under specific environmental process conditions to establish the critical non-propagating dimension.

(c) Test Analysis and Limitation — Critical diameter data are reported as the confined or unconfined material diameter (inches) at which an explosion reaction will not be propagated. Application to process hazard analysis studies assumes an initiation has occurred and has progressed to an explosion reaction equal to or greater than that characteristic of the Composition C-4 booster material. Degree of confinement can influence test results and thus must be considered in applying the data.

The critical diameter test permits testing of solids, liquids, and mixtures that may occur during propellant manufacture. In addition, benefits of recommended material modification to eliminate potential propagation hazards are easily verified as are results of studies to investigate density, temperatures, confinement, and high and low-reaction rate phenomena with liquid and solid explosives.

1.15 Bottle Drop Test

(a) Objective — To assess the hazards associated with the inadvertent dropping of explosive liquids during transport or sampling.

(b) Operating Principle — Containers of explosive liquids, preferably of the same geometry as those used in the process, are dropped from various heights to determine if the test liquid can be initiated in this type of environment.

(c) Test Analysis and Limitations — Some explosive liquids have been initiated into low velocity explosive reactions by relatively small energy inputs; stress concentrations and cavitation in the liquid being deemed the mechanism of initiation. At the stage of development of a new explosive liquid when two to five pound quantities are available, this test has been used to assess the hazard of an inadvertent drop of the material. The bottle drop test has the limitation, as does all sensitivity testing, of possibly finding only an unsafe condition while giving no information as to a safe condition.

1.16 Shear Water Hammer Test

(a) Objective — To determine if a moving bed of an explosive mixture in a slurry form can be initiated by sudden deceleration.

(b) Operating Principle — Thus far, use-type tests in which the material in question is dropped or shot onto a steel plate have proved the most useful.

(c) Test Analysis and Limitations — Test results on the slurries investigated thus far have shown a velocity requirement greatly exceeding that available in the process.

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