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PRESSURE SYSTEMS ENERGY RELEASE PROTECTION
(GAS PRESSURIZED SYSTEMS)

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TABLE OF CONTENTS

1.0 INTRODUCTION (EXECUTIVE SUMMARY)

The history of the technological development of pressure systems is closely associated with the growth and development of various technologies, particularly during the nineteenth and twentieth centuries. Pressure systems refer to a closed boundary (such as a vessel, chamber, drum, pipe, tube, and barrel) in which interior environmental conditions are controlled in a fashion distinct from the external environmental conditions. Pressure systems are a vital part of aerospace, petrochemical, power, process, ordnance and energy production in general. The environment within and without the closed system varies from highly volatile media to inert fluids. In many applications, the effects (either combined or singly) of the properties of the media, pressure levels, and uncertainties in producing (design, material processing, fabrication) the pressure system can result in a hazardous situation in which an unexpected catastrophic failure of the system may occur. Pressure system failure may be defined (Brown [1976]) as "A breach of the containment surface due to structural or material degeneration; the occurrence of flaws; or deformation that involves the disruption of the vessel operation, requires repairs and presents a possible safety hazard." The severity of failure may be categorized into two types: disruptive (major repair or loss) and nondisruptive (remedial repair) (see USAEC [1974] and Phillips [1968]). The hazardous situations that may exist as a result of a catastrophic disruptive failure of the pressure system are: 1) the ejection or release of the contained media, 2) the kinetic energy imparted to the containment structure, and 3) the secondary effects as a consequence of items 1 and 2. Concern with respect to the hazardous nature of these systems has led to two broad areas of study:

1) product performance and
2) protection against hazardous failure or energy release protection.

Product Performance

Product performance concerns itself with design, analysis, testing, fabrication, inspection, and operation. The occurrence of numerous boiler explosions in the late nineteenth century in the United States gave rise to the ASME Boiler and Pressure Vessel Code (see Green [1955], and Farr [1982]). This code is mentioned here as an example of the philosophy of controlling or improving the product through performance criteria rather than design criteria in order to reduce the probability of failure and its severity. Performance (or design by analysis) criteria differ from specification (or formula) criteria in that performance criteria sets limits on material and/or structural response to loading whereas the latter attempts to set dimensional and material design limits.

Energy Release Protection

The study of energy release protection follows from the study of product performance in that the consequences or hazards of failure are deemed of such a severe nature and high financial liability that protection to personnel and property is provided in the form of barricading, containment, siting, and other active and passive methods. The prediction of the occurrence of Failure may be classified as either (1) deterministic (expected or temporal domain) or (2) probabilistic (statistical or event domain). Theoretically, energy is a function of product performance. For example, if one knows how and when failure of a system will occur, protection can be provided in the form of preventive, corrective, and/or hardware backup. Generally, failure is not known deterministically (as reflected by the use of factors of uncertainty in performance criteria); hence the designer is confronted with approximately the effect of product performance by either (1) the upper limits of uncoupling the effect of product performance (i.e. considering the "worst case" that failure occurs) or (2) the lower limit of developing a probabilistic or risk assessment. Early studies in this area were motivated by the occurrence of injury and severe damage resulting from the handling of ordnance and explosive chemicals adjacent to public and private property. One of the early studies (Assheton [1930]) into hazardous siting was initiated by Col. B.W. Dunn of the Bureau of Explosives in cooperation with the Institution of Makers of Explosives. Historically, there seems to have been a greater concern for vessels or closed systems that contain explosive media and the need to protect against their unexpected energy release as opposed to vessels or closed systems which contain non-explosive media, with a high energy release potential, (and hence a need for appropriate energy release protection). Energy release protection studies may be divided into five categories:

1) Object (target) site classification.
2) Source (location) of potential failure or rupture
3) Hazards produced by the source
4) Barricading and containment design
5) Distance siting criteria for source, barricade, and object.

At present, there exists no unified code and standard on pressure systems energy release. However, there is currently under development in the ASME Codes and Standards Group. The High Pressure Systems Committee that is developing guidelines through its Subcommittee 6000: Energy Release Protection. (See Table 2).

1.1 OBJECT CLASSIFICATION

Object Classification is a subjective quantifying of permissible relative degrees of protection or priority levels of exposure associated with a hazardous release of energy from a pressure system. These classifications (equated with priorities of protection) are usually expressed in terms of constants that are coefficients of the performance values and are a function of the hazard, barricading-containment, and distance criteria. Types of objects generally considered are: personnel, strategic equipment, facility buildings, and non-facility buildings. The importance and interrelationship between the hazards produced, the barricading-containment, and distance criteria with respect to object (target) site classification should recognize that differing objects may have different priorities with respect to the various hazards (overpressure, fragments, heat, biological, chemical, and radiation). For example, two objects may be highly sensitive to fragmentation; however, one may be insensitive to chemical or heat release by the system where as the other object may be highly sensitive to the chemical and heat release.

Existing codes, standards, or guidelines relating to various industrial hazards use either:

(1) the probability of injury or damage or
(2) a measure of intensity or magnitude (force, temperature, etc.).

For example, the ASME ANSI B31.8 [1975] utilizes a four class population density or probabilistic type of approach; however, the USDOD 5154.4S [1978] classification is determined by magnitudes of energy overpressure levels that may be sustained by the object (or receptor).

1.2 SOURCE (LOCATION) OF POTENTIAL FAILURE OR RUPTURE

This area of study concerns itself with:

1) the characteristics of the systems
2) the energy content
3) mechanics of failure

<u>Characteristics of the System</u>. The characteristics of the system are: 1) Classification of components - eg. closure (bolted, breech lock, etc.), piping, valves, rupture disk, etc., 2) Geometry, 3) Material properties, 4) Environmental conditions (internal, external); and 5) Mechanical Loads.

<u>Energy Content</u>. Energy content refers to the potential energy release within the closed system. Energy content is usually classified both into its constituent parts (such as pressure, chemical, etc.) and its total energy content. The interrelationship among the constituent contributions from the conversion of potential energy to kinetic energy is important to the determination of the quantity of the media that may be released (which was contained within the vessel or system). In the instance of explosive media, the estimate of energy content would include an estimate for primary and/or secondary hazardous reactions. Energy release may be influenced by the type of reaction, uniform or propagating, and characteristics of the hazard presented (depending upon whether detonation or deflagration occurs). Because a considerable amount of explosion data exists with TNT as the medium, there is a general practice to use pounds or tons of TNT as a measure of energy content for other media. For illustrative purposes, Tables 3 - 8 give a measure of energy content of various substances (Table 3 - high

explosives equivalent weight ratios, Table 4 - blast wave peak pressure and impulse ratio to TNT, Table 5 - liquid propellant percent equivalent TNT, Table 6 - heat of combustion ratios to heat of explosion for TNT, Table 7 - gas and dust ignition constant (this constant relates to maximum pressure rise rate in a closed vessel), and Table 8 - Rupture energy of gas and saturated water filled vessels). For pressurized fluid-filled vessels, it has been observed that high temperature saturated fluid (eg. water or liquified gases or , Table 5 - liquid propellant percent equivalent TNT, Table 6 - heat of combustion ratios to heat of explosion for TNT, Table 7 - gas and dust ignition constant (this constant relates to maximum pressure rise rate in a closed vessel), and Table 8 - Rupture energy of gas and saturated water filled vessels). For pressurized fluid-filled vessels, it has been observed that high temperature saturated fluid (eg. water or liquified gases) or provides critical input into the safe operation of pressure systems: 1) by providing a data base for statistical studies as to causes and modes of failure and 2) as a case study basis for evaluating a particular type of product design. Unfortunately, comprehensive data bases on pressures above 3,000 psi to 250,000 psi and chemical effects are not well documented. Surveys such as those by Kellerman [1966, 1967], Phillips [1968] and Smith [1974] direct our attention to the incidence of cracks or defects as a major cause of failures (89%): 35% are pre-existing from the manufacturer, 15% are a result of fatigue, and the likely location of cracks and defects are welds.

1.3 HAZARDS PRODUCED BY THE SOURCE OF FAILURE

The major hazards associated with a pressure system energy release are :

1) missiles
2) blast
3) foundation motion

} characterized by force/motions

4) temperature/heat
5) chemical
6) biological
7) radioactive

} characterized by object degeneration

The study of hazards produced by the source of failure of pressure systems represents by far the greatest area of study in energy release protection. A considerable amount of experimental, theoretical and numerical data exists; however most of this data comes from widely divergent sources. Most of these sources tend to be oriented to a particular industry such as ordnance, missile handling, nuclear, gas and steam turbine, and chemical.

Missiles. Fragments and missiles generated by the rupture or failure of pressure systems require numerous parameters to be evaluated by the designer in order to provide a reasonably high confidence level of safety for the protection of personnel and property. The attainment of a reasonably high probability of prediction is complicated by the complex nature of the dynamics of system failure from source to object. Upon failure of the source system, the missiles are given an initial velocity (see papers by Baker and Baum (edited by Brown [1984]) for estimated velocities of gas pressurized systems and Brown [1984] for general references). The missile may be a fragment of the system, a part (such as a valve or closure), or the entire system. The dispersion (direction and range) as well as the size and mass are crucial parameters in determining the relationship of siting criteria. Figure 11 illustrates one of several methods of plotting fragmentation parameters based upon experimental and/or accident data. The terminal ballistics of the missile and fragments will be influenced by all of these factors as well as the interaction of the fragments with the environment. In addition to the fragments generated during the rupture or failure of the pressure system, additional fragments may be produced through secondary impact such as spalling and scabbing of structures (particularly masonry) and residual fragment velocity (see Figure 17 and refer to Section 2.2 Barricade/Containment/Shelter: Protection, Subsection - Design) Finally, the mode of failure plays a significant role in the type of missiles that are generated, and in general there is an interrelationship among the parameters involved in the fragmentation process. However, the study of the fragmentation or missiles generated by the failure or rupture of a closed system may be divided into the following categories:

1) initial velocity
2) dispersion
3) size - mass
4) drag and lift - terminal ballistics
5) secondary fragments (see barricade impact)
6) type (shell, pipe, components, valves, etc.)
7) the relationship to the mechanism of the failure (i.e. fracture, creep, etc.)

Blast. Blast effects are considered one of the major energy outputs of a pressure system explosion, as a result of physical (pressure or mechanical) and/or chemical explosions. The study of blast wave effects has generally been divided into the following categories:

1) incident blast wave
   *overpressure
   *impulse
   *time (time of arrival and duration)
   *dynamic pressure
2) reflected wave
   *regular
   *irregular
3) height or depth of explosion (HOB) or (DOB)
4) contained explosions
   *quasi-static pressure
   *reflected pressure
5) characteristics of explosion
   *single vs. multiple
   *simultaneous vs. sequential
   *shape (point, line, etc.)
   *explosion and vessel interaction

Phenomenologically, the outward expansion of the high energy vapors or gases released from the explosion creates a severe, high magnitude pressure wave that travels initially at supersonic speeds. Behind the shock front is a region of high velocity air flow (dynamic pressure). At the shock front, the pressure, density and temperature rise very suddenly to a value greater than ambient atmosphere and then decay to values lower than ambient conditions. As the shock front (overpressure) passes, the air flow reverses its direction. Areas of study have generally been oriented to (1) the evaluation of the overpressure, dynamic pressure, impulse energy, wave front shape, reflection, and decay as a function of distance and (2) blast characteristics as a function of the explosive media. A number of other effects that have been investigated are the height of the blast (HOB), ground reflection and triple-point formation, below-ground explosion wave effects, blast-wave-generated missiles, blast wave interaction from multiple sources, etc. Because much of the earlier work done in this area was performed in connection with TNT or similar high explosives (HE), a considerable body of literature has evolved in which blast characteristics of a variety of media within the exploded vessel are correlated in terms of TNT performance or characteristics. Refer to Figure 4a for an illustration of scaled blast wave parameters: peak pressure (P_S), impulse (I), time of arrival and positive duration (τ), and note a discussion of pressure vessel failure blast wave provided by Baker (see Brown, ed. [1984]). The use of TNT blast characteristics (see Jensen [1972], Baker [1975,1978], and Brown, ed. [1984]) as a yardstick for other chemicals has its limitations. Figure 4b illustrates the typical pressure versus time curves for argon and condensed high explosives that characterize differences in blast wave behavior (see Held [1981]). Pohto [1971] provides one of the early discussions of blast and fragmentation code considerations in light of burst test of gas filled vessels.

Studies into the <u>damage effects by blast</u> have been oriented toward two general areas: 1) internal injuries to personnel as a result of pressure and 2) structural damage caused by pressure and wind blast. A considerable amount of literature exists in this area as a result of studies in munitions and chemical handling, storage, and evaluation. Overpressure effects on personnel have been generally directed to evaluate acceptable or threshold levels of energy for the failure of various types of organs. Overpressure energy characteristics (such as pressure magnitude - time histogram) have a significant effect on injury or damage (See Figure 49).

Additional studies of dynamic pressure (wind) load effects on structures from natural phenomena (hurricanes, tornadoes, etc.) provide valuable information and have generally received a forum through the Civil Engineering societies, such as the ASCE (e.g. Symposium on Tornadoes, ed. R.E. Peterson, et.al., ASCE,

[1976]).

Blast-generated missiles (from overpressure and/or wind effects) present a high risk hazard to personnel. Many of the characteristics of fragments and missiles discussed in the section on source failure (such as dispersion, size-mass, drag/terminal ballistics, and type) are similar and data are generally found in munitions, chemical, and meteorological studies.

Foundation Motion. Foundation motion may be described as that motion through which structures and personnel undergo either directly or indirectly as a consequence of a pressure system explosion or failure. Motions may be imparted indirectly to structures and personnel either through ground motion or floor motion. Similar motions initiated by secondary explosions and impact which cause foundation motion to which structures are supported are considered. Early studies into peak overpressure, impulse, pressure reflection, and soil displacement-velocity-acceleration were motivated by concern for understanding the relationship of quarry/mining blasting and surface/below ground ordnance explosions versus adjacent (surface or below ground) damages. Early studies (USNDRC [1946]) were oriented to semi-empirical formulas; however, more recent advances have included computer based numerical methods (see Richart [1970], Barkan [1962], and Desai [1977]). A considerable amount of study has been devoted to numerical methods, particularly with respect to predicting the seismic response of structures. Studies into the seismic behavior of structures have been primarily motivated by the desire to understand the structural response of buildings and nuclear power plants subjected to earthquake loads. In addition to these areas of study, there has been, in general, broad interest in the field of random vibration and transient response. Although the studies into the response of buildings and structures as a result of foundation motion induced by explosions has occupied a smaller role in this literature, general interest outside of energy release protection provides and has provided a large body of data and a continuing forum for the study of shock, vibration, earthquake, and transient response through numerous technical and professional engineering societies. The problem areas of concern with respect to ground motion are:

1) Cause of catastrophic failure of object, barricade, and/or hazardous pressure systems.
2) Deterioration or weakening of objects, barricade, and/or hazardous pressure systems.

Finally, there is code and standard guidance with respect to foundation motion as provided by such groups as the ASME Boiler and Pressure Vessel Division, the NRC Regulatory Guides, ASCE, and other sources.

Temperature/Heat. Temperature/heat as a hazard may range from supercooled fluids of a cryogenic system to a high temperature release. The high temperature release may be associated with an explosion driving the failure of the containment system or as a consequence of the contained media being ejected during the system failure and subsequently undergoing a detonation or deflagration. High temperature may occur through either conduction, convection or radiation. In the instance of high temperature, areas of concern for injury to personnel and structures are: irreversible damage or ignition, oxygen deprivation, secondary ignitions, and incapacitation or malfunction. A considerable amount of data has been developed over the years through the various chemical societies, chemical engineering societies and technical associations. These efforts have been oriented toward (1) a characterization of the factors influencing ignition, explosions, and thermal hazards and (2) a prediction of the heat flux release by experimental and analytical modeling studies into spatial time energy characteristics of released substances (see Hasegawa [1978] and High [1968]). Some of the factors interrelated with the temperature hazards are pressure, ignition energy, ignition source, flow, vessel geometry and orientation, influence of gravity, oxygen content, catalytic surfaces, dilutant and inhibitors, concentrations and molecular structure of the media, and physical state (liquid, gas, mist, sprays, droplets, foams). Finally, compatability with adjacent chemicals and control agents are a significant part of evaluating this type of hazard (see Benz [1984]).

In some instances in which the contained medium is ejected, the hazard is not associated with force but rather with target (or object) degeneration by such effects as chemical, biological, and radiation toxicity. Important areas of study are: containment, meteorology, biological effects, and neutralization. The study of diffusion, deposition, and resuspension gives some estimate of the consequences of toxic media ejection (see Pruppacher [1983] and Donigian [1984]).

Chemical. Chemical Reaction (non-explosive) hazards studies concern themselves with the degradation of structures and/or injury to personnel through external contact or internal inhalation or digestion of gases vapors, particulates, or liquids, that were released as a consequence of a closed system failure in which the chemical media is ejected. The properties of concern are the toxicity and caustic nature of the chemical. Finally, in the instance of a chemical reaction, heat is associated with the blast; however, it is treated here as a separate hazard.

Biological. Biological hazards are manifest in those substances that are released as a consequence of a closed system failure which fall in the category of microorganism and synthetic chemical substances that effect the micro and cellular biological function of plants, animals, and humans. Work in this area has generally fallen in the domain of chemical and biological research. This area of study is particularly intensive to personnel as opposed to structural damage, with the exception of decontamination procedures.

Radioactive. Radioactive material or radiation hazards studies associated with the rupture or failure of pressure systems has been primarily motivated as a consequence of studies into the nuclear power generation industry and weapons development. Radioactive exposure may take the form of radioactive liquid, gas, vapor and particles. The nuclear power system provides an example of the choice of providing containment about the radioactive pressure system as opposed to the use of a barricading system which would offer little protection in such instances of failure of the primary (radioactive) system. Studies in this area have tended to be oriented toward type of substance, emission levels, dosage exposure, area of exposure (internal or external), and decontamination and treatment. As in the case of biological hazards, the primary concern is injury to plants, animals, and personnel. The problems posed to structures manifest themselves in the form of decontamination, with the exception of material degradation of the pressure structure (this is usually addressed in the area of mechanism failure modes and causes).

1.4 BARRICADE/CONTAINMENT/SHELTER: PROTECTION

The protection of personnel and property against any or all of the seven hazards discussed (missiles, blast, temperature, chemical reaction, biological, radiation, and foundation motion) has led to the design, development and use of barricades and containment structures and devices.

Types. Containment structures may be defined as structures built to contain the source (in the immediate vicinity) of the hazard(s) in order to prevent the hazard(s) from proceeding into the ambient environment. This type of system tends to be oriented toward sources of failure that are relatively small or the consequences of a release unacceptable in its effects on human and property damage. Closed containment systems may be found where radiation, biological, chemical (caustic/toxic) hazards present a high risk (see Scott [1979]). Closed and vented containment systems may be also found as protection against fragmentation, blast, temperature hazards as well. Examples are bunkers used in ordnance storage, enclosures in high pressure autoclave use, layered vessels, explosive chemical handling and storage (see Turkel [1983]). Figure 36 illustrates two major aspects to be considered in containment design against blast: (1) reflected wave and/or quasi-static pressure loads, (2) degree of venting.

In many instances, it is not economically feasible or practical from an engineering point of view to design a containment system about the potential source of failure. In these instances, the mode of protection afforded to personnel and strategic equipment is provided by barricading walls (which are sometimes classified as vented enclosures) or protective shelters (which are enclosures that protect against external hazards) (see TM5-1300 [1969], DoD 5154.4S [1978], Moore [1967] and Bagchi [1982] for an overview of defense and nuclear protective systems design). In instances where the facility is sufficiently removed from residential areas, barricading walls or enclosures may be provided against all of the cited hazards. In some applications such as at nuclear containment buildings, it is designed as both a containment and protective shelter structure.

Types of barricading/containment systems that have received the greatest attention with respect to design, development and use are: excavations, cubicles, safety walls, shielding against jets, tie down systems (primarily used for piping restraints), quench/suppression systems, multiwalled components, and containment of airborne hazardous particles, vapors, and gases

Design. Most studies into the design and analysis of containment/barricade systems has been performed in the area of blast and missile (fragment) impact studies. Blast pressure is usually the governing factor in determining structural response; however, missile (fragment) impact may dictate design because of required personnel or strategic equipment protection requirements (TM5-1300 [1969]). Impact studies have generally been directed to predicting missile penetration, perforation, and residual velocity as a function of missile and target (object) characteristics. Secondary (target) fragments resulting from the impact present a hazard and some study has been devoted to this area. The study of impact phenomena covers a range of disciplines depending upon (1) the material of the missile and target, (2) shape, attitude, etc., and (3) striking velocity. Figure 23 developed by Zukas [1980] illustrates the effects of velocity. Below 500 miles per hour (a regime of many vessel and piping explosions without chemical explosive assistance), local and global dynamic response are usually strongly coupled and are to be considered. Data on impact comes from various sources such as the ordnance industry (manufacturers and users), propellant and missile handling, nuclear industry, gas turbine technology, chemical & process industries, steam turbine and rotating equipment industry, and designers and construction industry of structures to sustain tornado and other mechanisms of meteorologically air-borne missiles. The most frequently used and tested barricade materials are concrete, earth, and steel. Composites have received use and interest in gas turbine blade barricade applications. Most impact studies have been oriented to the development of formulas based upon (empirical) test data for specific material compositions, as discussed by Sliter [1980]. Recently Romander and Florence (see Brown, ed. [1984]) have provided experimental comparisons to theoretical NDRC and CEA-EDF penetration formula. Figure 21 provides a comparison by Kennedy [1976] of various penetration formula developed over the years. Figure 37 illustrates an Army - empirically based nomograph for design guidance of a barrier against missiles. With the development of the high speed computer that can utilize numerical (finite difference and finite element) methods, (1) a better phenomenological understanding of missile (and blast) impact is evolving and (2) the development of performance criteria for barricade design is becomming more cost effectively possible (see Vinson [1980] and Zukas [1982]). Figure 30 provides some examples of computer simulations of missile-target impact that are used to investigate phenomenological and constitutive behavior. Finally, Shaaban (see Brown, ed.[1984]) provides an overview of target/missile performance with respect to various computational methods.

The remaining hazards with respect to protection of personnel and structures have received increased interest and attention since the second world war. With respect to design of structures to withstand hazards, particularly fragments and missiles, the tendency has been to develop <u>empirically based formulae</u> rather than <u>performance criteria.</u> Figure 38 illustrates empirically based design guidance of barriers against blast waves for missile handling (see Jensen [1972]).

1.5 DISTANCE-SITING CRITERIA FOR OBJECT, SOURCE, BARRICADING/CONTAINMENT

The study of distance-siting criteria (which takes into account the interrelationship of object, source of failure, and barricading) has received broad interest and investigation in those affected industries and disciplines for which the hazards that have been discussed present particular concern. This area of study addresses the problem of the siting of personnel and strategic equipment in relationship to a potential source of failure within the context of the severity of the hazards (missiles, blast, temperature, chemical reaction, biological, radiation) (see White [1965] and Clare [1976]) and probability of damage or injury with or without the use of containment and barricading as a variable. Figure 49 illustrates "injury to personnel overpressure" criteria (see Jensen [1972]) for equivalent TNT explosive energy of source versus distance from the explosion source as a result of extensive research and experience.

1.6 SCOPE OF PRESENT STUDY

Of the five categories in which energy release protection of pressure systems may be divided, this report concerns itself principally with the category of distance siting criteria with respect to: source, barricading and object. This investigation and report is divided into two parts: Part one consists of a review of the studies into energy release protection, and part two provides a development and discussion of energy - distance criteria along with numerical examples and a technical evaluation. Part two of this study (that deals with energy-distance criteria) is limited to single phase inert gas systems, that is, the contained medium is non-toxic, non-flammable and non-explosive. The principal hazards of concern in this study are those as a result of blast and fragments. The review part of this investigation provides a literature survey of studies (theoretical, experimental, numerical) in the five categories of energy release protection. Significant milestones are presented in an historical context.

This study, Parts I and II, is important for several reasons:

1) a crucial step in the design of a facility or plant is the arrangement or layout (dimensional plans) for the placement of potentially hazardous high energy pressure systems relative to adjacent structures, equipment, and personnel that may be facility or non facility related. The interrelationship of the hazardous source, barricade-containment, and object with respect to the hazards of concern is crucial in determining a distance-siting criterian.

2) a literature review of the studies into energy release protection provides guidance for present and future engineering investigation based on past experiences with respect to source of failure, hazards, barricading-containment, object classification, and distance siting criteria.

3) Many pressure systems that are potential sources of failure contain media which act as a gaseous system.

4) Because the design, analysis, testing, and prediction of the phenomena related to energy release protection are numerous and interrelated, a treatment of separate effects provides a better understanding of their role in the energy release protection process. This allows a better understanding of phenomena with the intent to give guidance to developing performance criteria.

5) There is need to place greater emphasis on pressure vessel and piping systems in the context of energy release protection. Historically the explosive nature of the contained media received the greatest attention; however, the significance of pressure effects in more recent times with the development of ultra-high-pressure autoclaves (3,000 psi to 250,000 psi) is receiving increased attention and concern.

Although distance siting criteria are based on the interrelationship of source, barricade-containment, and object siting, other factors that are criteria variables are:

1) The characteristics of the source of failure (such as the physical properties of the vessel, energy content, mechanism of failure).

2) The characteristics of the hazards (such as media physical properties and their relationship to the environment during rupture).

3) Barricade-containment characteristics (performance relative to the hazards it is intended to protect against).

Because it is important to understand these effects in the context of distance-siting criteria, some references to these areas of study are provided in the survey part of this study and cited where necessary in the development and discussion part of distance-siting criteria of part two.

2.0 A REVIEW OF STUDIES INTO ENERGY RELEASE PROTECTION

The experimental and theoretical investigation of energy release protection of vessels and piping systems and the means to effectuate protection has received increased attention over the last several decades. The motivation has come from technological advances and an ever increasing awareness that improved safety is good economics. These more recent motivating forces into the studies of energy release protection has come from: the handling of liquid and solid propellant missiles (military and non-military - NASA), ultra high pressure systems (10,000 psi to 250,000 psi used for ceramic, crystal growth, bonding techniques, etc.), nuclear power (with its requirements to contain leaks from the primary radioactive system), chemical process-conveyance-storage (the ever increasing growth of an industrial society has been accompanied by the need to manufacture, process, and/or transport increasingly complex substances that are increasingly hostile to human and environmental contact), and ordnance. There are other areas that have contributed to the understanding of energy release protection that, strictly speaking, do not fall into the category of pressure systems: such as the containment of missiles from turbine and rotating equipment failures (particularly with respect to the development of containment in the aerospace and nuclear power industry), and ballistics and impact of missiles associated with natural phenomena such as tornadoes and hurricanes.

The studies into energy release protection touch many engineering disciplines. For example, civil engineers generally have concerned themselves with the design of structures to withstand blast and fragmentation; mechanical engineers have concerned themselves with the design of the pressure systems, containment structures, and fragmentation from both rotating and non-rotating equipment; chemists have provided characterization of the contained media with respect to its properties and their hazardous implications to the primary and secondary hazards; engineering mechanics has provided studies into blast, impact, and ground motion effects; and chemical engineers have attempted to correlate the implication of these studies within the context of an economical operating system. As shall be discussed, the characteristics of the source of failure play an important role in determining the character of the hazards that are present. Unfortunately, by and large, those engineers and scientists involved in the study of preventing the system failure (particularly studies in the area of fracture mechanics) and those engaged in the study of energy release protection (particularly with respect to blast and fragmentation) have historically represented two distinct camps.

2.1 PRELIMINARIES

Early interest to investigate and remedy the effects of these hazards, particularly blast and missile generation, were motivated as a result of nineteenth century boiler and ordnance handling and storage accidents discussed by Green [1951], Farr [1982], and Assheton [1930].

These developments have their origins in the early studies performed in connection with the storage and handling of ordnance, particularly the work begun by Col. B.W. Dunn in 1909 in developing the American Table of Distances, [Assheton, 1930]. The study initiated by Dunn resulted in a compilation of 117 documented explosions (starting from the early nineteenth century to the early twentieth century), and provided the basis for a theoretical versus empirical physical comparison of the cube root formula for distance versus weight of explosives as shown in the equation in Figure 1. This study resulted in the development of quantity distance tables for inhabited buildings, public railway, and public highway locations.

$$R_1 = K_1 W^{1/3} = 34.75 W^{1/3} \quad \text{(inhabited buildings)} \qquad |1a|$$

$$R_2 = 0.6\, K_1 W^{1/3} = 20.85 W^{1/3} \quad \text{(public railroads)} \qquad |1b|$$

$$R_3 = 0.3\, K_1 W^{1/3} = 10.43 W^{1/3} \quad \text{(public highways)} \qquad |1c|$$

where R_1 = distance in feet
W = lbs of high explosive
K_1 = 34.75

In Dunn's study, the primary hazard or concern is the blast wave since the stored explosive material (fragments) was expected to be contained within barricaded bunkers.

The blast hazard is one of three major classifications associated with the category of Force/Displacement resulting from a pressure system rupture; the other two are missiles from the system, and ground motion. The second of the two categories of hazards is degenerative hazards which are classified by chemical, temperature, biological, radiation effects from the released media.

Hazards have not only been organized by category (Force/displacement and degenerative) but organized by either primary types (resulting directly from the system rupture) or secondary (resulting from the system rupture initiating a secondary rupture, fragmentation, explosion, or release). The studies of receptors (or targets) of the hazardous release have been directed to three areas: 1) personnel, 2) secondary hazards, 3) protective systems (e.g. shelters, barriers, containment). These later areas, particularly missile or fragmentation, were principally investigated from the nineteenth to early twentieth century in connection with ordnance (weapons development and defense). The work developed through the second world war is outlined in the NDRC document EFFECTS OF IMPACT AND EXPLOSIONS [White, 1946]. The study of blast, missile characteristics, and barricading design has and does presently occupy the greater part of energies devoted to research in the study of energy release protection.

Sophisticated explosion measurement methods did not evolve until around 1940. As Kennedy [1946] points out, prior to 1940 a usual measure of blast and fragmentation was to perform a Trauzl Lead Block Dent Test and detonation in an enclosure in order to determine the number and penetrating power of fragments. Post 1940 research development and application of blast techniques were carried on principally at the Roads Research Laboratory (RRL) and the Armament Researh Department (ARD) in the UK and in the United States, at Princton University Station (NDRC), The

Ballistics Research Laboratory (BRL), Aberdeen Proving Ground, The David Taylor Model Basin (DTMB), Harvard University (HU) - operating later at the Underwater Explosives Research Laboratory (UERL) at Woods Hole Oceanographic Institute (WHOI).

System Energy Effects. The system energy (E_S) prior to its explosive failure or rupture is composed in varying degrees of: the contained media expansion energy (E_1), chemical/explosive energy (E_2), and elastic strain energy (E_3) as expressed in Equation 2a:

For Pre System Failure (Static):

$$E_S = E_1 + E_2 + E_3 \qquad |2a|$$

The hazards associated with a pressure system failure or rupture is characterized by the conversion of the system energy to blast energy, missile energy, heat release, and energy dissipation as illustrated in Equation 2b.

For Post System Failure:

$$E_S = E_B^0 + E_M^0 + E_Q^0 + E_d^0 \qquad @t=t_0 \qquad \text{primary} \qquad |2b|$$

or

$$E_S = E_B + E_M + E_F + E_Q + E_d + E_U \qquad \text{secondary} \qquad |2c|$$

where $E_B \equiv$ *Blast Wave Energy*

$E_M \equiv$ *Kinetic Energy of Structure & Media*

$E_F =$ *Foundation Energy (From Blast, System, ect.)*

$E_Q =$ *Thermal Energy*

$E_d =$ *Dissipated Energy*

$E_U =$ *Unreleased Energy*

E_1 = *Media Expansion Energy*

E_2 = *Chemical/Explosive Energy Release*

E_3 ≡ *Elastic Strain Energy*

t = *time*, t_0 = *initial or instantaneous time*

The system failure is a dynamical event in which the primary energy states of Equation 2b may undergo changes to produce secondary hazards. For example, the blast energy (E_B) and missile energy (E_M) in Equation 2b may include foundation energy and unreleased energy of the media as illustrated in Equation 2c. The unreleased energy presents the hazard of a secondary detonation. The missiles themselves may be composed of the structure or media and represent a hazard depending upon the nature of the media: biological, radiation, chemical, etc.

In the NDRC (National Defense Research Committee) summary report of research prior to 1946 on effects of impact and explosions, Kennedy discusses the dissipative effect (E_d) of the vessel or casing on reducing the effects of blast and fragmentation [Kennedy, 1946]. Two empirically-based equations that give some measure of the effects of the casing are presented by Kennedy: 1) an equation (see Equation 3a) developed by the RRL relating explosive weight, vessel weight, and positive impulse and 2) a relationship (see Equation 3b) developed by the BRL, Fano, Mayer, and Sarmousakis [1944] that relates explosive weight, vessel mass, and equivalent blast weight (it is assumed in the limit that twenty percent goes to blast and eighty percent goes to fragmentation).

$$I_1 = e^{-(1-W/W_C)} I_2 \qquad |3a|$$

$$W' = [0.2 + [0.8/1+2(W_c-W)/W]]\,W \qquad |3b|$$

$$W' = W_e = |(1 + M(1-M')/W)/\ 1 + M/W| \quad 1.19W \qquad |3c|$$

where $M' = M/W$ for $M/W < 1$

$M' = 1$ for $M/W \geq 1$

$I_1\ I_2$ = positive impulse with & without case

W_c = Explosive weight with case

W' = Equivalent explosive weight without case

M = Weight of cylindrical metal case

Swisdak [1975] presents another (semi-empirical) formula for steel cylindrical cases based on studies reported by Filler [1970] and Fisher [1953]. With respect to Equation 3c, Dewey [1963] reports studies at BRL that suggest: 1) W' is dependent upon distance (D or R) for a given W, 2) Sach's scaling law does not apply to light frangible casing material, and 3) modified scale distance:

$$(\bar{D}' = D/(W+W_c)^{1/3})$$

Studies at the RRL in the 1940's indicate that the case undergoes considerable plastic flow prior to rupture.

The vessel energy dissipation (E_d) varies as a function of whether the vessel fails in a ductile or brittle manner. Consider the explosion and drop weight test series by Pellini [1969], illustrated in Figure 2. In the instance of identical materials subjected to identical loading at differing temperatures, Figure 2 illustrates: (1) the dramatic increase in fracture toughness as a function of temperature and (2) the transition from the development of fragments during rupture versus a shear tear breaching of the thickness. A vessel rupture as a result of the dynamics of an internal explosion of the media may result in either ductile or brittle failure of the vessel; however, a static type load (pressure/mechanical) induced rupture of the vessel (with catastrophic consequences) is more likely to be associated with a brittle type failure (where initiation is most likely to occur as a result of material defects). As discussed in the Introduction, statistical data supporting this observation may be found in studies by Smith [1974], Phillips [1968], USAEC (WASH 1318) [1974], Kellerman [1966] and [1975]. In addition, some vessel failures that provide illustrative lessons may be found provided by Muzzall [1964], Neck [1966], Srawley, [1966], Miller [1966], Whitman, [1967] SSEB [1967], Pohto [1971], FPLC [1972], EEI [1973], Banks [1973], Vigilance [1974] and Welsh [1982]. Rolfe and Barsoum [1977] suggest in their text on Fracture Mechanics that there are three primary factors that control the suseptibility of structure to brittle fracture: 1) material toughness, 2) crack size, and 3) stress level (factors such as temperature, load rate, stress concentration, residual stress, etc. affect all these three primary factors to some degree). The study of fracture mechanics, while outside the scope of this survey, is very important and has received considerable attention from various industries, particularly the nuclear and aerospace industries. The reader is directed to the survey text by Rolfe and Barsoum for a discussion of the various fracture criteria and applications. Of the approximately ten fracture criteria, each has its supporters and detractors (eg. Dawes [1983], Labbens [1984]).

Chemical Characteristics. The chemical characteristics of the contents or media contained within a bursting pressure system are important with respect to the type of blast and fragmentation that is affected. As indicated by Grelecki [1976]: the explosion may be physical/mechanical or consist of a chemical reaction. The phenomena of combustion (refer to Zeldovich [1960]) and explosion are beyond the scope of this survey; however, a good overview is provided by Greleki [1976] in a report with discussions of gas, condensed phases, dust and physical explosions. Greleki reviews representative papers by Moore [1967], Macek [1962], Ribovich [1968], Watson [1967], Sectchkin [1954], Hilado [1962], Zabetakis [1965], Cubbage [1959], Eichel [1967], Frank-Kamenetsky [1939], Langwell [1968], Diss [1961], and Glasstone [1977]; and he discusses a number of ASTM procedures for testing various properties related to explosive chemical reactions. In another document, Bartknecht [1981] discusses gas and dust explosions in closed vessels and in pipelines. Bartknecht's text provides a three part presentation on explosions, protective measures to prevent them (or control their effects), and practical applications. He emphasizes the effect of vessel dimensional properties, and presents chemical state parameters influence on explosive effects. Baker [1980] presents an overview of combustion and explosive phenomena in his workbook. Benz [1984] has produced a comprehensive survey of over 1,000 references, which is oriented to explosive fluids used in the aerospace industry and relevant research and development. Frequently cited ASTM techniques or procedures to characterize chemical detonation or exlosion properties are ASTM:B2540, D92, D93, D1310, D56, D3243, and D3278. Since the standard for energy release has historically been TNT, the practice has been to calculate the heat of reaction and compare it to the calculated heat of reaction of TNT (see Greleki [1976], Johansson [1970], USAMC [1972], Dobratz [1974], USAMC [1971], Eichler [1977] and Holland [1965]). A discussion is presented in the handbook edited by Jensen [1972] and Baker [1983] (correlating data from Strehlow [1976], Baker [1977], Esparza [1977] and Baker [1973]/reissued [1984]), concerning the limitations of the use of the equivalent TNT weight. The issue of concern (particularly addressed by Baker) is the different characteristic variations of the pressure time histograms for various explosive media of supposed equivalent TNT quantities; this will be discussed in the section on blast.

Secondary Explosions. Finally, another area of concern relative to the combustion of pressure system media as a result of venting or rupture is unconfined cloud explosions (a secondary hazard). The Eichler [1977] data presents a tabulation of heat of combustion of combustible gases involved in vapor cloud accidents. An overview of this area may be found in material by Strehlow [1973], Brown [1973], Munday [1976], Anthony [1977], Davenport [1977], and Baker [1980]. Unconfined vapor cloud explosions can result in explosions or deflagrations that can be very dangerous as is evidenced by numerous documented cases in NTSB (National Transportation Safety Board) documentation. Currently, the Gas Research Institute (GRI) is funding studies oriented to understand LNG vapor cloud ignition, dispersion, and control (Zalosh [1983] and Moussa [1982]).

2.1.1 Blast

The energy components following an explosion (as presented in Equation 2c) are illustrated in Figure 3 [Strehlow, 1975]. The proportions of the components of energy vary in proportion to the type of rupture or explosion. Brinkley [1969, 1970] indicates that there is a relationship between the rate of release and that fraction of energy ascribed to the blast wave. Only about 1/3 of the total chemical energy available in high explosives is released in the detonation process (see Johansson [1970]). In experiments by Esparza [1977] , Boyer [1958] with gas pressurized glass spheres, Pittman [1972], [1976] and Larson [1957] with metal pressure vessels, it was observed that a considerable amount of energy is absorbed in accelerating vessel fragments. Pittman [1976] provides overpressure calculations by the TUTTI and WUNDY computer codes for comparison to experimental data and records fragment velocity up to 350 fps. Huang [1968] and Baker [1975] have reported numerical studies for bursting pressurized spheres. Using the computer program CLOUD, gas pressure ranges from 5 to 37,000 atmospheres (with various temperature and ratio of specific heat values). Baker observes that the overpressure behavior is much like that of a blast wave from a high explosive.

Saville [1977] in the U.K. High Pressure Safety Code, suggests 80% of the available system energy might be ascribed to shock wave energy for a brittle type failure (the remainder goes to fragment kinetic energy). However, for major vessel section ejection, it is suggested that 40% of the system energy is ascribed to shock wave energy (with the remainder given to fragment kinetic energy). It is not customary in air blast technology to report or compute potential or kinetic energy from the blast waves, but rather to use values such as peak overpressure (P_S), impulse (I), and positive phase duration (τ) (as a function of TNT weight illustrated in Figure 4 and reported by Kennedy [1946] as a convention adopted prior to the end of the second world war - (see Equation 4)). Dynamic pressure (q) (Equation 5) is sometimes of interest as discussed by Glasstone [1962] which is associated with the drag effects loading of an object.

$$P = f\left(\frac{r}{W^{1/3}}\right) = f\left(r/W^{1/3}\right) \quad |4a|$$

$$\frac{I}{W^{1/3}} = F\left(\frac{r}{W^{1/3}}\right) \quad |b|$$

$$\frac{t_c}{W^{1/3}} = \phi\left(\frac{r}{W^{1/3}}\right) \quad |c|$$

P = *peak pressure*

I = *positive impulse*

t_c = *positive duration* (*or* τ)

f, F, ϕ *are functions*

r = *distance*

dynamic pressure $(q) = \rho U^2/2$ $\quad |5|$

ρ = *density*
U = *particle velocity*

But before we go further with the discussion of blast wave characteristics, a review of Equation 2a (for system energy prior to rupture) and present practices is in order.

Energy Release. The energy for various chemical states is presented in Table 1. Johansson [1970], USAMC [1972], Greleki [1976] and Baker [1982] suggest the chemical formula of Equation 6.1a (Table 1) for condensed phase detonations. For compressed gases, Brode [1959] suggests Equation 6.2a. For isentropic expansion, Equation 6.2b has been proposed by Brinkly [1969] and suggested by Baker [1975], Greleki [1976], Fryer [1981], and Pohto [1981]. For an isothermal expansion, the energy is shown by Equation 6.2c. Equation 6.2d has been shown to be the lower limit of energy release by constant pressure (Adamczyk [1977]). Hence, the blast energy (for which a blast wave will form) lies between Equations 6.2c and 6.2d. Equation 6.3a presents the specific work (thermodynamic equation) for flash evaporating liquids such as propane, butane, methane (LNG), hydrogen (LH2), ammonia, freon, etc. The calculation of energy depends upon the change of states of the media (i.e. super-heated vapor, super-heated vapor/wet vapor, wet vapor/wet vapor). Some tables of thermodynamic properties for fluid, which can be used to estimate blast yields using Equation 6.3a, are found in: the ASHRAE HANDBOOK OF FUNDAMENTALS FOR REFRIGERANTS [1972], Keenan [1969] for steam, Din [1962] for various fluids and fuels such as propane and ethylene, and Goodwin [1974, 1976] for methane and ethane. During vessel rupture, pressurized high temperature fluids (eg. water) flash evaporate and behave in a manner similar to a gas-filled vessel (consider Tagami [1965], studies of water blow down and Hunt [1961]). Baker [1975, 1978] and Jensen [1972] illustrate the fact that liquid propellants generally yield a considerably lower percentage of their potential total chemical energy available. Baker [1975], in his workbook, discusses the effects of exploding propellant tanks and suggests Equation 6.4a for liquid propellants (hypergolic liquid, oxygen - hydrocarbon, and liquid oxygen - liquid hydrogen). For inert liquids, the estimated confined energy may be calculated from Equation 6.5a as suggested by Fryer [1981] and

Pohto [1981]. Care should be exercised (when calculating the energy of fluid filled pressure systems) that gas pockets are accounted for, since studies by Irvine [1964], Bevitt [1964], and Nichols [1966] in the U.K. indicate that pressurized fluid systems with approximately 20% gas ruptured in a manner similar to a gas-filled system. Saturated water will flash into steam in an explosive manner when the pressure is released rapidly as illustrated in VIGILANCE [1974] and discussed by Brown [1959], Meyer [1966], Moore [1966] [1967], and Hunt [1961] (see Table 8b). Saville [1977] in The High Pressure Safety Code (UK) and Gwaltney [1968] suggest the calculation of stored strain energy for instances of vessel head bolts, tendons, and parts of the cylindrical structure. Saville shows an equation for strain energy in a cylinder and states that E_3 is generally small compared to the other values E_1 and E_2. However, its potential hazard should be evaluated. Care should be exercised in utilizing the estimated elastic strain energy (E_3) throughout the system since compressive and tensile regions may counter-balance each other or be composed of, either singly or in combination, structural moments and axial thrust.

Jensen [1972] provides the equivalent explosive weights of various substances in terms of TNT, also listed are liquid propellant explosive equivalents in this handbook. Baker [1982] in his manual provides an appendix of explosive properties with tables (reported also by him in his manual [1980]) which also includes comparisons of combustion for vapor cloud gases reported by Eichler [1977] versus TNT peak overpressure energy. Additional explosive equivalent weight data is presented in the NSWC (Naval Surface Weapons Center) report by Swisdak [1975] that is an update to NOLTR 65-218. Held [1981] refers to this equivalence as energy equivalence and proposes the calculation of a blast equivalence (to be discussed later). Finally, Bartknecht [1981] provides some tabulation of confined gas and dust measures of violence of explosion, (K_G) and (K_{st}) respectively; and Long [1957] provides some perspective of metal-water explosions.

Scaling Laws. Around the same time that Col. Dunn [1909] began formulating the American Table of Distances

[Assheton,1930], Hopkinson [1915] in the UK, and Cranz [1926] formulated the blast scaling law, referred to as the Hopkinson-Cranz ("Cube-root") law. As suggested by Equation 4 (discussed by White [1946] in regard to the principle of similitude), the scaling law suggests that an observer stationed at a distance will feel the blast wave form with similar pressure, duration, and impulse for similar explosive source characteristics. Owing to the fact that TNT blast characteristics were so broadly studied, it is clear that relating explosive energy of various sources to TNT, was and is of general interest as a reference.

$$(R/R_1) = (t/t_1) = (I/I_1) = (W/W_1)^{1/3} \qquad |7|$$

As mentioned previously (discussed by Baker [1983]), and illustrated by Esparza [1977] - in a series of burst tests on glass spheres), the pressure-time history response can vary significantly with different types of explosions or explosive events at the same energy level. Hence, the interrelationship of the explosive media and vessel can result in unique or characteristic pressure histograms. The implication is that peak pressure (P_S), impulse (I), and duration (τ) will not be identical for equivalent explosive energy levels. Held [1981] suggests a simple procedure for calculating a TNT blast equivalence rather than energy equivalence for gas filled vessels. Using his procedure, he calculates a peak blast pressure and positive phase blast impulse. On the other hand, Swisdak [1975], illustrates that blast waves from high explosives (detonation velocities approximately 25,000 ft. per second and detonation 2.7×10^6 to 4.9×10^6 psi) in general have very similar blast wave characteristics for a great variety of different explosives.

In general, the cube-root scaling laws have been shown to be applicable over a wide range of explosive weights from a fraction of a kilogram up to and including a megaton. While the explosion or rupture of a system may result in characteristic pressure time histogram that may require some adjustments of the scaling laws, there are additional factors that have been investigated that are important in the calculation of the desired effect (eg. peak overpressure, impulse, duration, etc.).

Effects of Height and Ambient Conditions. The investigation of the effect of the placement of the burst or explosion above the ground (The Height of the Burst (HOB)) has its origins in the 1940's as a result of studies at UERL and RRL (see discussion by Kennedy [1946]). These studies were motivated by interest in determining an optimum altitude or height for a burst or explosion to effectuate maximum damage (as a result of using the application of blast wave reflection effects). The scaled height of blast (HOB) is related to the actual height of burst as shown in Equation 8 and illustrated in Figure 5 (see NOLTR 65-218, Swisdak [1975], Jensen [1972]).

$$\text{Scaled HOB} = \lambda_H = (\text{actual HOB})/W^{1/3} \qquad |8|$$

The results of many studies have shown that peak pressure and impulse are enhanced by a burst or explosion at some optimum elevation above the ground, above and below which the effects attenuate. In some instances, either in-air free field (spherical) blast data or ground level (hemispherical) blast data is available (TM-5-1300 provides both spherical and hemispherical). In this case the adjustment of the explosive weight may be used as an approximation by considering $W_H = 1.8\ W_S$ (for cratering) or $W_H = 2.0\ W_S$ (for a perfect reflecting surface), where W_H = explosive weight in free field and W_S = explosive weight at ground level.

For bursts above sea level a further adjustment to the blast parameters is made to account for atmospheric density change. The blast scaling law generally used is that attributed to Sachs [1944]. The Sachs scaling relations for peak overpressure (P_S), distance (D_Z), duration (τ_Z), and impulse (I_Z), are illustrated in Equation 9 and discussed by Swisdak [1975], Jensen [1972], and Baker [1980, 1982, 1983] who suggest the scaled forms of Equation 9.

$$\Delta P_Z = \Delta P_0 (P/P_0)$$

$$D_Z = D_0 \; W^{1/3} \; (P_0/P)^{1/3}$$

$$t_Z = t_0 W^{1/3} (P_0/P)^{1/3} (T_0/T)^{1/2} \qquad |9|$$

$$I_Z = I_0 \; W^{1/3} (P/P_0)^{2/3} (T_0/T)^{1/2}$$

where

Z = at altitude (Z), 0 = at sea level

ΔP = peak overpressure

t = duration

T = temperature

I = impulse

Dimensional Effects. Thus far, most of the studies discussed have been oriented toward point or spherical charges. In some instances, the system rupture or explosion may have dimensions in one direction of failure considerably greater than in the other two directions. This explosive shape effect on blast characteristics for high explosives was investigated by Kirkwood [1945] (OSRD 4814), Brinkley [1945] (OSRD 5653), and is discussed by Kennedy [1946]. Subsequent to the NDRC report (White [1946]), Adams [1949], Zaker [1969], Makino [1956], Reisler [1972], and Tancreto [1974], report experimental programs or studies concerning the effect of explosive shapes on the blast field. In general, it is reported that the largest overpressure always occurred in the direction perpendicular to the largest exposed surface area of the explosive charge. Swisdak [1975] presents peak overpressure data on cylindrical charges versus spherical charges - that is also reported by Jensen [1972] (see Wisotski [1965] and Plooster [1978]). The cube-root scaling law is found to apply in general, except within a region very close to the rupture or blast (near field). Swisdak also reports hemisphere versus sphere overpressure and positive impulse effects based on studies by Kingery [1964, 1966] and Sadwin [1973]. His overpressure and impulse comparisons between hemisphere and spherical explosive shapes versus scaled distance are very similar with the exception of slight variations or deviations in the near field.

Multiple Explosions. In some instances a system explosion or rupture may not occur as a single source nor linear configuration (such as a line or cylindrical explosion). Some studies have been undertaken with respect to multiple high explosive detonations for sequential and simultaneous detonations. Of interest is how do the blast waves interact, i.e. may their effects be treated independently and do they enhance or reduce effects? A summary overview of these is presented by Baker [1982]. For simultaneous detonation, there is little data for unequal simultaneous explosions under controlled conditions. Armendt [1960, 1961, 1962] reports results from the White Tribe Test Program and Resler [1979] reports results from the Dipole West Program and work by Hokanson [1978]. The Dipole West Program included a two-charge test of vertical and horizontal separated charges, the White Tribe experiments used a triangular three-charge array, and the Hokanson experiments consisted of three charges in different grouped horizontal and vertical arrays. Brode [1977] discusses numerical methods for predicting blast wave effects from multiple explosions. It has been shown that there is a blast field enhancement between multiple explosions where the blast waves meet. This results in a blast wave effect equivalent to one large charge instead of separate explosions or ruptures. The enhancement effect of multiple charges (whether grouped horizontally, or vertically) depends on spacing and/or standoff distance. However, at large scaled distances, the blast parameters for multiple explosions approach those of single explosions with the same total source energy.

In the case of sequential explosions, Zaker [1969] provides data on the significant available studies in this area. This test program consisted of two and three sequentially detonated equal and unequal explosions. Included in Zaker's program are numerical studies using a finite difference computer program (BLOWUP). Zaker observes that the blast characteristics of a multiple explosion can be similar to the blast from a single explosion equal to the total of the individual explosion. This type of phenomena of multiple explosions is of concern in instances where an initial system rupture or blast results in subsequently other system secondary explosions which follow as a consequence of the initial failure. Time delays are shown by Zaker to play an important role in whether an additive or neutralizing effect of the peak pressure takes place. The ratio of source to secondary explosion magnitude of 1:1, 2:1 and 1:2 were investigated by Zaker. Baker [1982] discusses and summarizes the conclusions of the simultaneous and sequential detonation data.

Rate. A discussion by Kennedy [1946] concerning burning rates of explosives is of some interest. "It had long been realized that if the energy of complete combustion could somehow be utilized to produce blast, many combustible substances such as parafin, gasoline, aluminum, etc. offered possibilities of greatly improving the blast performance of bombs." Such substances have heats of combustion 2 or 3 times as great as those of ordinary high explosives. The effectiveness of such explosions in the open was found to be practically nil. Good results were obtained when it was realized that the problem lay in dispersing the combustible quickly in an adequate volume of air and igniting it in such a way that rapid combustion would occur.

<u>Reflection</u>. When a blast wave strikes a flat surface such that the velocity of the wave is normal to the surface, the resultant pressure is referred to as <u>reflected pressure</u> (P_r). Very little data exists for reflected peak pressures and impulse for explosive failure sources other than high explosives. A number of studies have addressed the problem of normally reflected blast waves: Kennedy [1946] discusses pre 1945 studies; Glasstone [1977] gives a good overview (see Equation 10 and Figure 7 for the relationship between peak overpressure and side - on overpressure per Doering [1949]); and other high explosive data as presented by Johnson [1957], Goodman [1960], Dewey [1962], Jack [1963, 1965], and Wenzel [1972]. Baker [1980] provides a set of scaled curves for P_r (peak reflected pressure) and i_r (specific reflected impulse) versus a large range of scaled distances.

$$P_r = 2P_S + (\gamma+1)Q$$

where (Good for ≤ 100 psi)

P_S = *"Side-on" or peak pressure*

γ = *ratio of specific heat*

Q = *dynamic pressure* |10|

Q = *(introduce appropriate Rankine-Hugonot equations)*

$$Q = \frac{P_S^2}{(\gamma-1)P_S+2\gamma P_0}$$

P_o = *ambient pressure*

Referring to Equation 10, it would appear that the lower limit of the peak reflected overpressure approaches twice the side on peak incident overpressure (for air) and the upper limit approaches 8 times the peak side-on incident pressure, however, Doering [1949] has suggested that it may be as high as 20 times the peak incident overpressure. Baker [1982] compares results using the perfect gas Equation 10 and Brode's equation (Brode [1977]) and suggests that Equation 10 be used for peak side on pressure less than 100 psi.

As mentioned earlier, interest in the early 1940's in whether the effectiveness of an explosion may be increased as a function of height, led to studies of investigating incident and reflected waves (see Kennedy [1946]). This led, in turn, to studies into the effect of peak reflected waves called "regular" reflection and "irregular" or Mach reflection, which occurs when the reflected front moves faster than the incident wave. Under certain conditions, the reflected wave overtakes the incident wave so that the two wave fronts fuse to form a single front. A phenomenological description of this effect is presented by Baker [1973, 1984] (Explosions In Air), Glasstone [1977], and Harlow [1970]. Additional sources of data are provided by Porzel [1954], Groves [1960], Wenzel [1972], Swisdak [1975], and Hokanson [1978]. The transition between the single fused wave and the separate incident and reflected waves is called the "triple point". Below the path of the triple point the single wave is perpendicular to the surface; above the triple point path two peak pressures occur.

In the instance of regular wave reflection, there appears to be an optimum angle of incidence (39 degrees, 23 minutes) at which peak reflected overpressure occurs for strong incident waves. The height of the burst and yield energy generally define the variation of pressure with distance from ground zero at which the Mach stem or triple point begins to form, and other wave characteristics. Of interest is the discussion by Kennedy [1946] with respect to the horizontal limit for regular reflection versus explosion height.

Dynamic Pressure. Glasstone [1977] points out that the destructive effects of the blast wave are usually related to values of the peak overpressure, however (as mentioned earlier) another important pressure quantity is referred to as the dynamic pressure (see Equation 11).

$Q = \rho_S U_S^2 / 2$ = *peak dynamic pressure*

U_S = *peak particle velocity in blast wave* |11|

ρ_S = *peak density in shock front*

This pressure is associated with the wind effect or flow of air with the passage of the shock wave. For a great variety of structures, the degree of damage depends on the drag force associated with these transient winds accompanying the passage of the blast wave. Glasstone shows that for very strong shocks, dynamic pressure can be larger than the overpressure, but below a maximum wind velocity of approximately 1,000 mph, the peak overpressure is larger than the peak dynamic pressure. For low values of peak dynamic pressure, Glasstone provides an empirical expression for the time variation of the peak dynamic pressure (an exponential decay). Baker [1982, 1980] discusses the use of a modified Friedlander equation to express side on overpressure as a function of time. He develops relations involving peak overpressure, peak reflected pressure, peak dynamic pressure and dynamic pressure.

$f(t) = C_D q(t)$ *time history drag pressure* |12|

where

C_D = *drag coefficient*

$q(t) = Qh(t) = Q(1-t/\tau)^2 \, e^{-bt/\tau}$

$h(t)$ = *modified form of Glasstone (1962) by Baker (1973,1980) for TNT*

b = *see Baker (1982)*
τ = *duration of positive phase*

Once the time-history dynamic pressure is known, an appropriate drag coefficient (dependent upon the configuration) is factored times the dynamic pressure, then the drag force of the wind or dynamic pressure can be calculated (See Equation 12).

Confinement. Thus far, only the effects of blast in a free field or at ground level have been discussed. Of interest is the occurance of an explosion or vessel rupture within an enclosed structure or containment (see Pearce [1966], Pigford [1952], USAEC [1966] (Bulletin #10)). Kennedy [1946] reports studies performed in the 1940's with high explosives in enclosed rooms. It was observed that two effects occur that are distinctive with respect to pressure loading on the enclosed room. As a result of some instrumentation, the pressure time curve reveals oscillations about a mean reference or hump in the curve of pressure versus time. The hump is due to a buildup of pressure inside the structure as a result of heat energy released by the explosion. The peaks or spikes are the initial shock wave and reflections. These two values, the peak reflected pressures and the quasi-static pressure are distinctive. If the walls of the containment are considered perfectly rigid, Kennedy reports the simplified equation attributed to Lu (Equation 13) is used for the calculation for the pressure rise.

$$\Delta P = \frac{8.8H}{V} = \text{pressure rise} \qquad |13|$$

H = heat of combustion

V = volume

$I = H(\text{constant})$ = total impulse

Total impulse is shown to be proportional to the total heat of combustion (H). The relationship between impulse and heat of combustion is of interest as discussed and illustrated by Kennedy, since some explosive material performs very well in open air, but not so in a closed space. For example, the explosive Composition B has a relatively good performance in open air; however, it has very poor performance (for a high explosive) in an enclosed unvented space because of its low relative heat of combustion. Swisdak [1975] and Proctor [1972] provide quasi-static pressure data for a number of high explosive compounds. Baker [1960,1966] and Gregory [1976] discuss the computation of pressure time loads on cylindrical enclosures. Peak and quasi-static pressure - time - histograms are illustrated. As can be surmised, the more complicated the geometry, the more complex the calculation of the peak reflected pressure. Baker [1982] considers several approximations concerning simplified load predictions based on scale blast data for reflected waves: 1) he assumes that the incident reflected blast pulse is triangular (see Equation 14a), 2) the peak and reflected peak pressures are calculated by Equation 14b, and 3) the internal blast loading parameters are the normally reflected parameters.

|14|

$$P_S(t) = P_S(1-t/\tau_S),\ 0 \le t \le \tau_S \qquad |a|$$

$$P_S(t) = 0,\ t \ge \tau_S$$

$$P_S = \frac{2i_S}{\tau_S} \qquad |b|$$

$$P_r = \frac{2i_r}{\tau_r}$$

$$P = k(W/V)^a \qquad |c|$$

$k = \gamma$ = ratio of specific heats
$a = 1.0$
V = chamber volume
W = Charge mass

Turkel [1983] discusses barricade design criteria in which total containment is considered. Design criteria for internal loading of full containment for gas dominant and shock pressure dominant cases are considered.

$$i_g/W^{0.3} = 3.462 \times 10^6 \, (A/W^{0.67})^{-0.78} \ldots$$
$$\ldots (W/V)^{-0.38} \qquad |15|$$

A = Vent Area (m^2)

V = Volume (m^3)

$W \equiv$ yield energy where 4.6×10^6 J/kg of TNT is used (kg)

In instances where the gas pressure from combustion is of greater magnitude and longer duration than the shock pressure (P_r), the use of the Loving formula is suggested,particularly for small changes in large volumes (See Equation 14c); For shock pressure dominated loading of short duration and lower gas pressure the peak reflected pressure is determined by Equation 14b. For partially vented containment enclosures, Turkel suggests the use of the Weibull [1968] equation to calculate the gas which takes the form of Equation 14c where a = 0.72, $(W/V) \equiv \#/ft^3$ charge weight and R = 2410 pressure (P_g); and gas generated impulse (i_g) effects may be estimated from Kennan [1975] relationship (for $(A/V^{2/3})<0.21$) see Equation 15). Anderson et al [1983] have published some similitude data which indicate a correction to TM5-1300, Weibull [1968], and Keenan [1975] estimate of quasi-static pressure and impulse (particularly at a transitional valve). The effects of blast on structures internally and externally will be discussed later in this report in the section on studies into barricade design.

Summary of Blast Effects. To summarize the effects of blast, frequently cited parameters associated with the blast wave from an explosion or vessel rupture are peak pressure, impulse, time-duration, and dynamic pressure. During an explosion process, the energy is divided between the blast wave, missile generation, and unexploded media. The type of explosion depends upon the chemical properties and/or vessel (casing) influences. The media may be condensed, liquid, gas, flash evaporating, and inert. For explosive media, the heat of combustion and rate of detonation are important quantities that influence the blast wave magnitude. Scaling laws have been shown to be effective in relating parameters such as peak pressure, impulse, and time (arrival and duration) for various explosive media to TNT. Other important parameters that should be considered are the shape of the exploding system, its height above ground, and whether there are multi source explosions. In a free field, a blast wave striking a structure will produce a peak reflected pressure. Also of importance is the drag pressure produced by the winds as they pass over the object. For an explosion or rupture within a closed space, reflected pressure as well as a quasi-static pressure should be considered of some importance.

2.1.2 Fragmentation & Missiles

When systems fail, as discussed earlier, fragments or missiles composed of the vessel or media are ejected. These are referred to as the primary missiles or fragments. Secondary missiles may be initiated as a result of secondary effects such as blast, secondary detonations, spalling as a result of missiles striking objects or initiating other vessel or system explosions. The contents of the pre-ruptured system may consist of various substances from solid to gaseous, and explosive to inert. Fragmentation into small pieces is characteristic of high energy explosions, whereas fragmentation into numerous chunky or a few chunky pieces is more characteristic of fracture type ruptures. Most of the non-explosion initiated failures cited in this report (i.e., surveys on pressure vessel statistics and illustrative failures) resulted in large chunky fragments or component separation at such locations as closures, openings (such as manways, handholes, branch connections, etc.), vessel longitudinal seam, welded end caps, interlocking or threaded connections. An example of an analysis of a high pressure gas system is provided by Baker [August, 1963, October, 1963] and

Muzzall [1964]. A similar type analysis was performed by McGuire [1959, 1960] (for the Fermi Reactor) and Horvay [1966]. Even low pressure (ASME considers low pressure < 3000 psi) explosions can have devastating effects: consider the explosion resulting from the separation of the closure from a 90 ton, 6ft. diameter, 200 psig steam autoclave explosion [VIGILANCE, 1974]. In this incident, the 90 ton vessel was propelled approximately 150 ft. while the closure was ejected approximately 600 ft. from ground zero. The blast wave destroyed much of the enclosing building. The estimated equivalent TNT weight was approximately 70 lbs. An example of a steel vessel fragmenting into many pieces is discussed by Strawley [1966] for a 21.7 ft. diameter vessel during a hydrotest at 542 psi. Weck [1966] provides another example of large high velocity missiles generated as a result of pressure vessel rupture. In order to provide protection against missiles or fragments, some estimate of fragment velocity, distribution, size, interaction with the environment, terminal ballistics, etc. should be assessed. One may be compelled to ask how this is possible if the system failure is a result of some unintended design, material or operational defect? As we shall see, some studies into this area have sucessfully predicted fragment characteristics in certain phenomenological regimes. However in many other areas, because of the complexity or lack of data, bounds have been sought as design guidance.

Initial Velocity. One of the earliest and commonly referenced methods for computing fragment velocity is the initial velocity formulas developed by Gurney [1947] for cylindrical and spherical vessel or casing geometries surrounding high explosives (see the Gurney equations (Equation 16) , see also Stern [1947], Holland [1965], Ellwell [1967]).

Gurney Law for Initial Fragment Velocity |16|

The initial velocity of a fragment can be estimated using the Gurney Equation which assumes that the charge consists of an evenly distributed explosive in a metal case:

$$\text{Cylindrical } V_o = (2E)^{1/2} \quad ((C/M)/(1+C/2M)^{1/2})$$

$$\text{Spherical } V_o = (2E)^{1/2} \quad ((C/M)/(1+3C/5M)^{1/2})$$

where:

V_o = Initial fragment velocity (ft./sec.)

$(2E)^{1/2}$ = Gurney's Explosive Energy Constant (ft./sec.)

C = Explosive Weight (Grams)

M = Case Weight (Grams)

$$(1-(\gamma-1)/2)\ V/a^*)^{2\gamma/\gamma-1} \simeq \quad (1+(V/a^*)^2 M_{a^*}{}^2/2P^*\ell)^{-\gamma} \qquad |17|$$

M = mass/unit area of vessel wall

P^* = rupture pressure

a^* = speed of sound in gas

V = peak fragment velocity

γ = isentropic expansion coefficient of compressed gas

ℓ = control distance from surface (taken as R/2 where R≡radius of vessell)

These formulas have been sucessfully verified for high explosives for a wide range of explosive weights. A modification to the Gurney formula has been proposed by Moore [1965] for casing or vessel cylinders and spheres. Comparisions with experimental data at that time and more recently by Baum [1983] [1984] indicate that the Moore equation tends to be conservative. Gwaltney [1968] suggests that the slower explosion rate or rupture rate of non high explosive pressure systems failures may account for disagreement between Moore's equation versus some vessel burst tests and accident data. Henry [1967] developed additional modifications of the Gurney formula for geometries other than cylindrical and spherical. The Gurney energy constant shown in Equation 16 is a constant for a given explosive. Some discussion of the transfer from chemical energy to kinetic (Gurney energy) is presented in ASME [1972], Smith [1964], Kennedy [1970], and Kury [1965].

The HAZARDS OF CHEMICAL ROCKETS AND PROPELLANTS HANDBOOK (Jensen, editor) [1972], compares liquid propellant space vehicle explosion fragmentation to incidents and tests with high explosives. The comparisons lend credence to the point of view that high explosive experimental data may be useful in predicting missile fragmentation. This will be discussed in the next section on fragmentation range and distribution.

Velocities of fragments from the rupture of pressurized vessels containing gas have been investigated by Grodzovskii [1965], Taylor [1971], Bessey [1974], Pittman [1976] and Baum [1983] for spheres. Bessey [1976] and Baum [1973] provide analytical treatment of velocities of fragments for cylindrical vessels. Pittman [1976] reports fragment velocities up to 350 fps for fragmentation of ultra high gas pressurized (15,000 to 50,000 psi) metallic spheres. Baker [1975] developed a computer code based upon the method developed by Taylor [1971] to predict the velocities of fragments from bursting spherical and cylindrical gas filled vessels (referred to as SPHER and CYLIN, for spherical and cylindrical geometries respectively). For the case of gas pressurized cylinders bursting into unequal fragments with a length to diameter ratio of 10, Baker [1978b,c] developed the computer programs UNQL and GASROC to calculate the velocities of the unequal fragments. Also, Baker [1980] provides some comparison of computer code predicted velocities versus experimental data by Boyer [1958] and Pittman [1972]. The results show favorable agreement. In the study by Baum [1983], [1984], a relatively simple theoretical model is developed to describe the velocity of fragments generated when gas pressurized vessels disintegrate. Baum's comparisons include hypothetical upper limit, zero mass upper limit, large mass, and Moore equation data; also included in these comparisons are experimental data from (1) Boyer [1959], Glass [1960], Esparza [1977], Moore [1967], Boyer [1958] - for spherical vessels and (2) Collins [1960], Moskowitz [1965], and Pittman [1972] - for cylindrical vessels. His predictions with new and existing experimental data are shown to be an improvement over the widely used empirical correlations developed by Moore [1967]. For illustrative purposes, the scaled velocity versus scaled energy curves from Baker's and Baum's studies are provided in Figures 8 and 9 respectively. Of some guidance to the designer interested in the determination of depressurization transients in a pipeline are the studies reported by Baum [1981] (for brittle rupture) and [1982] (for a propogating axial rupture), and [1984] (for end cap, vessel rocketing, and pipe-line missile rupture).

In contrast to the fragmentation studies discussed thus far, Jager [1981, J8/5] developed simple formula for a <u>self propelled fragment</u> and a <u>jet propelled fragment</u>. The jet propelled fragment is characterized by a circumferential break of a cylindrical vessel into two parts. The self propelled fragment may be characterized as a plug type or appurtement separating from the vessel wall. Jager [1981, J/6] reports a series of 26 tests to benchmark his derived simplified formula and reports good agreement and improvement over similar estimates by Andren [1977] and Baker, et al [1978b,c]. Gwaltney [1968] discusses jet propelled missiles with respect to compressed fluid, gas, and flash-two-phase expansion based upon fundamental principles. (See Perry [1950], Doolittle [1964], Keenan [1948] and Cottrell [1965]).

<u>Velocity Retardation</u>. In the preceding discussion, the

resistance of the surrounding atmosphere to the movement of the fragment was not considered. This problem is of particular concern in ballistics as cited by Bethe (see White [1946]) in a review of pre 1945 studies. In fact, Bethe cites that there is a distinction between hypervelocity and lower velocity fragment air resistance, i.e. hypervelocity missiles tend to loose energy in flight at a greater rate than do lower velocity fragments. Hence, hypervelocity fragments are viewed as effective only over short range. A frequently used formula called the "retarded velocity" formula, (see Equation 18) provides a measure of the striking velocity at a target some distance away from the explosion as a function of the initial velocity, drag, and properties of the missile or fragment.

$$V_S = V_O e^{-kR} \text{ and } k = K_D A/m\rho_a \qquad |18|$$

where:

V_S = Striking velocity (ft/sec)
V_o = Initial velocity (ft/sec)
R = Distance traveled (CM)
K_D = Drag Coefficient
A = Average presented area (CM^2)
m = Mass (GM)
P_a = Density of Air (CM/CC)

The retardation of fragments is discussed by Braun [1943], Thomas [1944], Healey [1975] and Jensen [1972], (the last provides easy to follow procedures for the use of the formula and nomographs). Baker [1975a] developed a computer program to calculate fragment velocities to Mach 1 as a function of drag and lift coefficients, initial velocity, and physical properties. This program was later revised by Baker [1978c] and curves were generated using the computer code FRISB (see Fig. 10). Baker assumes that the fragment is spinning in order to assure stability. From the FRISB code, the maximum range versus scaled velocity can be plotted (see also Baker [1983]).

Range. For the calculation of initial velocity of fragments versus range as a result of high explosive fragmentation, Smith [1951] provides charts for supersonic and subsonic portions of the fragment trajectory (See Jensen [1972]). In the CHEMICAL ROCKETS AND PROPELLANTS HANDBOOK (Jensen [1972]), fragment data from incidence and full scale test (eg. Flame and Plume Environmental study, project PYRO, and investigation of vehicle explosion: S-IV, Atlas Centaur S-IVB) are used to develop a high explosive envelope for weight versus maximum fragment distance for comparison to liquid propellant missile explosions (see Figure 11). Utilizing some of this data (Baker [1974a],[1975c]) provides a statistical evaluation to develop a number of curves which give guidance with respect to yield of propellant explosions versus fragment range, mass distribution, and initial velocity. Baker [1978] (NASA-CR-3023) reports a statistical analysis of 25 accidental explosions. This study was organized into six groups of data consisting of propane/ammonia, LPG, air, LPG/propylene, argon, and propane. Computations are presented based on fragment range, mass, and energy.

Distribution. An empirically based equation to predict the vessel or casing fragment mass distribution resulting from high energy explosion is discussed in the NWL Handbook by Johnson and Moody [1964] and Healey [1975]. This equation is referred to as the Mott equation.

$$\ln N_X = \ln (C' M_A) - M/M_A \qquad |19|$$

where:

N_X = *the number of fragments with weight greater than* W_f

C' = *fragment distribution constant*

$= W_C/(2M_A^3)$

W_C = *total casing weight (lb)*

$M = (W_f)^{1/2}$

W_f = *fragment weight (lb)*

M_A = *fragment distribution parameter*

$= B\, t_c^{5/6}\, d_i^{1/3}\, (1+t_c/d_i)$

t_c = *average casing thickness (in.)*

d_i = *average inside diameter of casing (in.)*

B = *explosive constant*

The Mott equation assumes that the casing or vessel is cylindrical, of uniform thickness, and contains uniform explosive material. Using the Mott equation and simplifying assumptions, problems involving non-cylindrical, non-idealized fragments and shapes, fragment number by weight, and maximum weight ejected have been addresed by Baker [1982] (see Gurney [1947] and Johnson [1964]). It is observed that the Mott equation predicts that approximately 76% of the fragments have a weight less than the average. Interestingly enough, the fragmented data from the selected liquid propellant space vehicle explosions suggests the same sort of trends with respect to percent number of fragments and weight distribution as the high explosion test.

Blast Generated Fragments. Of some interest to the designer is an evaluation by Baker [1982] with respect to fragment mass and range distribution based on DOD Explosive Safety Board reports on accidents. The fragments were accelerated by the blast wave. For three estimated energy ranges, secondary fragments from the adjacent structure to the explosion source are estimated on a percentage basis of mass and range. Figure 12 illustrates the interaction of the blast wave with an irregular object that might be unrestrained or restrained. A brief discussion of the interaction of the blast wave and the pressure time histogram and assumptions is presented in the section on blast, of this article (see also Baker [1975b,e], Baker [1982a]). Baker [1982] provides a set of curves for the analysis of far field objects (subsonic flow field) in which nondimensional object velocity is plotted as a function of nondimensional pressure and nondimensional impulse. The use of Figure 12 curves are suggested for $R/R_e = D/D_e > 10$ where D_e is the diameter of the charge and D = distance from center of the charge to the object surface.

A series of studies (experimental and analytical) at the BRL and NRL (see Baker [1967], Kineke [1976], Westine [1978]) provide information on the specific impulse imparted to an object adjacent to (near field) a high explosion. Two types of explosive configurations are considered: cylindrical and spherical. The results suggest that for R/R_e between 1 and 10, the specific acquired impulse for a cylindrical charge is similar to a spherical charge for the target objects investigated. See Figure 13. A discussion of scaling relationships is presented by Baker [1982] (see also Baker [1967] and Westine [1978b]).

With respect to constrained objects becomming secondary fragments, Westine [1978] investigated the amount of energy used in freeing a cantilevered beam from its mooring. Toughness and stress level (also defects) are important material properties. A considerable body of studies exist with respect to strain rate effects and toughness as a result of studies into pipe whip (see Chouard [1982], Campbell [1982,1983], Peterson [1982]) and studies directed toward predicting the response of structures due to impactive and impulsive loads. The rate sensitivity characteristics of materials are particularly important with respect to the design of structures that may be subjected to a high rate dynamical load such as blast (Cox [1978]) or possibly fragment impact (see Section 2.1.3). The rate sensitivity, particularly of carbon steels, has been investigated for some time and a considerable amount of data exists. Some example sources of information are: for metals, Manjoine [1944], Nada [1950], Wintlock [1953], Symonds [1967], and Lindholm [1968, 1969]; for concrete rate effects studies are reported by

Watstein [1953], Gupta [1979], McHenry [1955]; for rate effects of wood, Markwardt [1955] and Ferguson [undated]; and for glass, Ritland [1955].

General study into the dispersion of missiles has received little attention except in the application of free field explosions of ordnance. The dispersion depends upon the characteristics of adjacent structures and the types of explosions (e.g. ruptures involving breaching, jetting or the separation of a few fragments can be highly directional). Bergman [1968] ("Model Tests of Explosions in Buildings") and Baker [1982] using the DOD accident data (previously discussed for two energy levels) provide some correlation on fragment density and dispersion. Baker uses a multiple linear regression analysis to develop a relationship between distance as a function of angle and density.

The characteristics of the pressure system (particularly for non-explosive assisted ruptures) play a significant role in the dispersion of missiles. Although there is a relatively large reservoir or data base of pressure system failures (such as those collected in the Federal Republic of Germany, the United Kingdom, and the United States), there exists very little correlation between the dispersion of the missiles resulting from the fragmentation of a pressurized system and the characteristics of the system such as welds, attachments, material properties, fittings, etc. This is attributed to the fact that the data is either collected 1) to determine causality, 2) to document component characteristics, and/or 3) to evaluate the injury or damage caused by the ruptured system. However, rarely is the ballistic missile information correlated with the three items cited. In spite of this lack of coordination, the statistical use of data bases does provide useful information, such as pointed out in this report that certain preferred directions of missiles trajectories are identified by this data to have higher risk (for example, welds, attachments, fittings, etc.). An example of a pressure system rupture associated with failure initiation at a vessel attachment that resulted in highly directional missile generation is reported by Baker [1985]. This article documents a pneumatic rupture test performed at Sandia Labs. The failure of this large vessel and resulting missile generation is similar to that illustrated in Figure 9d. Figure 14a illustrates missile preferred directions, i.e., low missile and high missile density sectors, mapped as a part of a study reported by Moseley [1981]. Figure 14b illustrates fragment by percent number and percent weight versus range as typically reported for a number of studies discussed in Jannaf [1972]. Failure data and statistical data can guide the designer in identifying locations that are susceptible to a high probability of impact. In addition to this, stress analysis of the sytem during the design stage similarly provides information as to high risk locations with respect to increased probability of failure. As is pointed out in Section 3.1 and in Sundararajan [1984], an integrated methodology for the probabilistic assessment of pressure vessel missile generation and damage assessment may be formulated which incorporates failure data, statistical data, and analytical predictive methods to guide the designer with respect to the risk associated with certain parameters. The information and methodology may result in a sample missile-strike-probability contour map (see Figure 60) to guide the designer in site selection and/or protective barrier design; a further discussion of the probabilistic methodology with respect to missile generation, damage potential, and risk assessment will be discussed in a following section.

Further study in this area, particularly with respect to 1) experimental and accidental dispersion data and 2) analytical predictive, methods is necessary before reliable missile mapping predictions can be made. A valuable source of information on wind generated missiles (trajectory, aerodynamic coefficients, and impact effects) is provided in studies with respect to tornado and hurricane research. The Institute for Disaster Research at Texas Tech Univeristy provides a focal point for collection and dissemenation of studies in this area. (See Peterson [1976], session 5, TORNADO GENERATED MISSILES, Part I and Part II) and individual technical papers by Iotti, Stephenson, Marte, Radbill, Costello....individual papers 1976.

Media Ejection. In addition to fragments generated by the rupture or breach of the casing or vessel of the pressure systems, the ejection of the contained media can present a hazardous missile or jet. This type of phenomena is associated more with a breach or attachment separation rather than an explosive fragmentation. Pohto [1981] suggests the use of shielding to protect against fluid pressurized systems in excess of 15,000 psi. McIntyre (see Moody [1983]) discusses some aspects of water slug ejection.

Soil Ejection. When an explosion occurs at or near the surface of the ground, a crater may be formed that results in the ejection of material and a rupture of the original ground surface. Lampson (White [1946]) reports the development of an empirically based formula that predicts the radius of a crater (based upon high explosive detonations) and is shown in Equation 20.

$$R = 1.3\, CE''k^{1/12}\ W^{1/3} \qquad |20|$$

C, E'',k are constants dependent upon depth, explosive, and soil respectively

As an explosive source moves from above ground to below ground the crater diameter proceeds from 0 to some critical optimum size (approximately, D (charge depth)/$W^{1/3}$ (charge weight X 2)). And then the crater size will decrease until depth of burial (DOB) is reached (see also Sauer [1964]). Some studies concerning ejected missiles are provided by Kaplan [undated] who reports ejecta density distribution as a function of fragment size, explosion yield, ground material, and distance from explosion. Some of this data is summarized by Jensen [1972] (see Figure 15). Swisdak [1975] presents data (for a variety of soil characteristics) for apparent crater parameters vs. depth of burial.

2.1.3 Terminal Ballistics (Missile/Target Response)

Once a missile or fragment reaches a potential target with a striking velocity (V_S), it presents three potential hazards:

1) as a primary effect to strike personnel directly,

2) as a structural impact that results in either one or all of three consequences:

   a) spalling on the impact side (that is the ejection of fragments from the target)
   b) scabbing (the ejection of particles from the back of the structure opposite the impact area)
   c) penetration of the structural target with a net residual velocity (V_R) and
   d) (a), (b), and/or (c) consequently (the spall, scab, residual velocity of the missile) may impact personnel or equipment, and

3) global damage will occur as a result of the missile or fragment transferring or dissipating a sufficient amount of kinetic energy into the global force on the structure (see Figure 17).

The study of impact phenomena involves a variety of classical disciplines: material behavior, dynamics, theoretical mechanics, and applied mechanics. Experimental mechanics, which is an invaluable tool in investigating all of these areas, is even more important in impact phenomena because of its complexity. Because of this complexity, we find pre 1945 studies reported by White [1946] primarily oriented to empirically-based formulae.

These studies reported by White, and much of the investigation from 1945 to the present, have been undertaken with respect to the development of ordnance to penetrate protective surfaces, and the development of protective surfaces to inhibit penetration by ordnance. Both ordnance and storage applications have been the focus of these studies. Since private and commercial buildings are not, in general, built to resist fragmentation, little investigation has been devoted to the impact of fragments into non-barricading or containment structures (see White [1946] for military data). Hence, the study of impact phenomena has been closely associated with either barricade/containment or punch, pierce, and forming industrial processes. Because of this relationship between impact and barricade/containment protection, both are generally discussed in the same literature. Summary reviews of different aspects of impact are presented by Zukas [1980,1982], Jonas [1978], Backman [1978], Goldsmith [1960], White [1946], Backman [1976], Recht [1970], and Shockey [1975].

For striking velocity below 500 to 550 mph., there is generally a strong coupling between local impact and the global structural response, and typical response times are in the millisecond regime.

When the striking velocity is approximately 1,000 - 3,000 mph., the local response dominates the global response. Hence, only a small zone within two to three missile diameters of the impact area are affected. Loading and reaction times are on the order of microseconds. Through this regime, strain rate, material constitutive regimes, and wave propagation are usually considered.

At a striking velocity of approximately 4500 - 6500 mph. the impact of the solids is characterized by fluid behavior.

At striking velocity greater than 26500 mph. the high energy resulting from the colliding materials produces an explosive vaporization. Figure 23 from Zukas [1980] gives a "feel" for the relationship between striking velocity, strain rate, and material effects. In this review, Zukas concentrates on numerical methods for velocities from approximately 1,000 mph. to 4,500 mph.

The pre 1945 classification in the NDRC Volume I Part III, (White [1946]) on terminal ballistics, classifies terminal ballistic studies in one of four categories: armor, concrete, plastic protection, and soil. This grouping with its representative material characteristics has been used since that time to the present. <u>Material failure modes</u> may be characterized in several different ways. Curtis (White [1946]), in discussing steel as a protective metallic material, refers to three modes illustrated in Figure 17:

1) ductile hole growth
2) petaling in the case of thin plates
3) plugging

If a very thick plate is impacted, ductile hole growth occurs. The target material is forced aside by the projectile, much in a fashion similar to a punch being pushed into it. The pressure on the projectile has been interpreted as the hydrodynamic static pressure necessary to expand a hole in the plate.

Petaling is produced by high radial and circumferential tensile stresses adjacent to the high stress fields near the tip of the projectile. As radial cracks develop from the point of the missile, bending moments created by the forward motion of the missile push the material.

Plugging is different from spalling which consists (Spalling) of the ejection of flakes from the back face of the plate. Shockey [1975] refers to the mechanism of plug formation as adiabatic shear bending. In general, plugging failure is generally thought to be characterized by the occurance of plastic shear instability at the site of stress. The deformation is confined to a narrow region in the neighborhood of the surface because the rapid rate in the increase of the stress does not allow time for heat conduction. The large temperature rise in the region of maximum shear further facilitates deformation. Plugging failure is sensitive to impact angle and projectile shape.

Materials that behave ductilely at a certain temperature, may behave quite brittlely at another temperature as shown in Figure 2. Some materials such as concrete exhibit very little ductility over most temperature ranges.

During impact, spalling occurs when tensile forces are induced by the reflection of the initial compression wave from the rear surface of the plate (see Figure 17). Fracture results from an initial stress wave exceeding the material's ultimate strength on the face opposite the impact area.

Scabbing which occurs on the side opposite the impact is produced by large deformation tensile stresses.

Structural targets may be classified (Backman [1978]) into one of the following four categories:

1) semi-infinite if there is no influence of the distal boundary on the penetration process,

2) thick if there is influence of the distal boundary only after substantial travel of the projectile into the target,

3) intermediate if the rear surface exerts considerable influence on the deformation process during nearly all of the penetrator motion and

4) thin if stress and deformation gradients throughout its thickness do not exist.

The principal impact conditions are:

1) the striking velocity (V_S),
2) the striking obliquity or angle of incidence of the trajectory and the yaw,
3 the missile properties such as dimensions, mass, material properties,
4) changes of deformation of the missile and target due to impact and
5) mass, velocities, and trajectories of fragments generated by the impact process.

Analytical approaches to predict or evaluate target missile impact phenomena are categorized into three areas of study:

1) empirical or quasi-analytical methods that consist of algebraic equations that are based on correlations with a large number of experimental data. These formulations are closely related to certain types of material characterizations and impact regimes. In general, these formulae do not provide a phenomenological description of the process involved, but rather give a global effect over some parametric ranges. Owing to the complexity of the impact process, their value should not be underestimated. A variety of such models for penetration, ricochet, and perforation have been discussed by a number of authors such as Recht [1973], Kennedy [1976], Baker [1973], Sliter [1980], and Florence [1984] (see Brown [1984]).

2) approximate analytical methods which attempt to solve some phenomenological regime by simplifying some constitutive or governing equations. Generally, the missile or target is treated as rigid and momentum or energy balance is used. In most cases, these methods require experimental parameters as input,

3) numerical methods which offer the possibility of complete characterization of the impact phenomena. Since the 1960's the finite element and finite difference capabilities have evolved with the ever increasing computer speed and storage capabilities. Two of the major limitations of these methods are economic availability of large high speed scientific computers and adequate or sufficiently sophisticated pre and post processing capabilities necessary to interpret the data and insure meaningful results.

The study into the prediction of target missile performance or terminal ballistics has occupied interests of man since the development of a projectile as a weapon. One of the earliest publications of terminal ballistics is reported by Robins [1742]. A number of experimental studies during the 1800's are reported by Holie [1950]. These early experiments set the pattern for the reliance on experimental programs to define semi-empirical formula to predict missile - target responses (such as penetration, perforation, spalling, and scabbing) into the twentieth century. This is due to the fact that theoretically derived equations to predict missile target performance has enjoyed only limited success because of the complexity of the problems to be solved. Numerical methods essentially had to wait for the development of the high speed digital computers in the early 1960's.

Historically the finite difference methods have received the earliest use in simulating impact. They tend to be more computationally cost effective than finite element programs. However, because of the generality of the finite element method to idealize structures geometrically for a considerable range of mechanics problems, it has received the greater attention of research and development over the last two decades and is capable of solving wave propagation, nonlinear material, and nonlinear large deformation problems. The computer codes developed to solve impact problems are generally characterized as either Lagrangian or Eulerian. Zukas [1980] provides an excellent review of the assessments of the numerical methods available for impact, particularly in the regime of 0.5 - 2 km/sec. Some discussions are provided on two dimensional Lagrangian code such as HEMP, TOODY/TOOREZ, PISCES/CRAM and SHEP, and EPIC - II; two dimensional Eulerian Codes: HELP, HULL, DORF and CSQ; three dimensional codes: HEMP 3D, TRIOIL, TRIDORF, METRIC, EPIC - III, NIKE 3D, and DYNA 3D.

In the following section, a brief discussion will be provided covering the development of target/missile formulas, numerical methods, and associated experimental programs.

<u>Target-Missile</u> <u>Impact</u> <u>Formulas</u>. A number of excellent surveys over the past several decades have appeared reviewing the state of the art in missile penetration formula. Most notable of these is that by White [1946], Gwaltney [1968], Recht [1970], Kennedy [1975], Sliter [1980], Pohto [1981], Shaaban [1984] and Baker [1984]. The pre-1945 studies reported by White [1946] show that missile striking velocities (V_S) were investigated generally between the range of 500 fps to 5,000 fps. Interest in

velocities below 600 fps were motivated since that time as a result of protection against fragments from rotating equipment (such as turbine blade release), pressure vessel rupture and/or explosion, and dynamic pressure (wind) generated missiles from meteorological phenomena and blast. Until the 1960's the parametric range of available test data was limited to $t/d \geq 3$; $d \leq 16$ in.; 0.2 lb./in.^{3} $\leq D \leq 0.8$ lb./in.^{3}; 500 ft./sec. $\leq V_S \leq$ 3000 ft./sec.; $3 \leq e/d \leq 18$; and $3 \leq s/d \leq 18$

where d is the projectile diameter in inches

$D = W/d^3$ is the caliber density of the projectile (lbs/in^3)

t = target thickness (inches)

V_S = is the striking velocities (ft per second)

e = perforation thickness (inches)

S = scabbing thickness (inches)

Impact on concrete targets. The history of terminal ballistics in concrete beginning with Robins [1742] through 1939 is discussed by Robinson [1941] (see H.P. Robinson, TERMINAL BALLISTICS, C.P.P.A/B, NRC, 1941, and refer also to NDRC Survey, White (ed.) [1946]), who reports that prior to the preparation of the NDRC survey, no significant experimental work on terminal ballistics of concrete had been documented since 1835. The principal authors cited in the survey from 1742 through 1939 include Robins, Euler, Morin, Poncelet, Piobert, Didion, Martin DeBrettes, v. Wuich, Resal, Levi-Civita, Petry, deGiorgi, Cranz, Tompson, Scott, Peres, Milota, Gaede, Vieser, Heidinger, Skramtjew, Montigny, Speth, Bazant, Gailer, Harosy, and Hayes. The chapter (5) on terminal ballistics of concrete in the NDRC, 1946 survey reports investigations limited to ranges of missile weights from 45 caliber to 1000 lb. Some detailed data on 1.7 lb. missiles with striking velocities of approximately 700 to 3100 ft. per second are presented for penetration, ricochet, obliquity (see Figures 18 and 19). Other areas reported are front cratering, spalling, sticking, ricochet, back crater (scabbing), perforation, concrete thickness and quality, reinforcement, scab plates and meshes, layers and laminations, spaced slabs, and composite slabs. Ballistic limits for perforation, scabbing, sticking and ricochet are provided by way of several graphical summaries.

In the last decade, the nuclear power industry (internationally) has been quite active in investigating low velocity impact of missiles into concrete and steel barriers. Much of this work has been oriented toward reinforced concrete impact due to vessel rupture, missiles from turbines and other rotating equipment, and external impact to the containment building from airborne meteorological (tornado and manmade (airplane)). Recent results reported by EPRI Woodfin [1983] (EPRI Np-2745), Romander [1983] (EPRI NP-2747), McHugh [1983] (ERPI NP-2746) illustrate a wide scope EPRI program studying the effects of turbine missiles on concrete targets. Tests are conducted on full scale (prototype missiles) as large as 4600 lbs. at velocities as great as 300 mph impacting 4.5 ft. thick full scale model targets. A series of scale tests are also performed to evaluate the use of scale models as a predictive technique to the full-scale testing of large missiles. The evaluation of penetration and perforation formulas is part of this program and is discussed by Romander, Sliter and Florence (as mentioned previously, see Woodfin [1981] - SMiRT J8/1, J8/2, and Sliter [1983], SMiRT J8/5).

Sage and Pheiffer [1979] (SMIRT J8/4) report a joint UK (AEA) and German (GRS) experimental program to investigate the feasibility of small scale modeling of soft crushable missiles impacting on reinforced concrete targets. The German test program at Meppen used large scale targets and soft tube shape missiles. The British program at Foulness conducted scale model tests. In a manner similar to the EPRI test program of scale model testing, relatively good results were obtained. And, it was concluded that scale model experiments are an effective tool to investigate quantitative and qualitative orders of magnitude. However it was observed that the damage in small scale tests was slightly less than those of the large tests. Additional results from the Meppen slab tests are reported by Nachtsheim [1983] (SMiRT J8/1).

The French have had a project underway since 1974 to develop a computational method reliable enough to describe the behavior of reinforced concrete walls under rigid missile impact. One of the results of this program is the development of the homogeneous perforation formula called the CEA-EDF formula (discussed later with respect to compiled data by Sliter [1980]). Discussions of the French program are provided by Berriaud [1979] (J7/1), Dulac [1981] (J7/1), and Berriaud [1983] (J8/2). A discussion of some of the ranges of application for the CEA-EDF is also provided by Berriaud [1978-1977]. The tests reported by Dulac [1981] are oriented toward short term impact loads of blunt, non-penetrating loads with the objective to develop predictive methods for non-linear slab response due to missile impact loads. Finally, a series of theoretical and experimental investigations with respect to the impact of deformable missiles into reinforced concrete slabs is presented by Rudiger [1983] and penetration and spallation depth estimates for concrete structures is presented by Haldar [1983] at the 7th International SMiRT. The SMiRT conference (Structural Mechanics in Reactor Technology) through its division J has provided an international focal point of studies into missile impact phenomena related to the nuclear industry. The American Society of Civil Engineers (ASCE) - particularly, Nuclear Structures and Materials Committee - and the American Society of Mechanical Engineers (ASME) - particularly, PVP/OAC & High Pressure Committee and Code Subcommittee on Energy Release Protection has addressed some of the concerns of impact phenomena through its technical forum and the potential code and regulatory issues.

An analysis of the experimental data presented in the NDRC survey (Chapter 5, TERMINAL BALLISTICS OF CONCRETE by Beth) leads to the empirical penetration formula (1) shown in Table 11. A discussion of the theory of concrete penetration is briefly outlined along with the importance or need for developing an equation based on a phenomenological description of missiles impacting concrete barriers.

Assuming that the penetrability factor K in Equation 1 of

Table 11 is proportional to the reciprocal of the ultimate concrete tensile strength (which is taken to be proportional to the square root of the ultimate concrete compressive strength f_c'), Kennedy [1966] proposes a modified NDRC formula (see Equation 2, Table 11) for penetration in combination with Equation 1. Another modification of the NDRC formula was suggested by Beth [1945], Chelapati [1970, 1972] and Kennedy [1966] for slab thickness/projectile diameter ratios (t/d) <3 and x/d < (1.35) (see Equation 3 of Table 11); for a larger t/d (>3) and x/d ratios, Equations 4a and 4b (Table 11) are to be used. Equations 1 and 2 along with Equations 4 (Table 11) are known as the modified NDRC formula for perforation and scabbing. The perforation and scabbing thickness relationships were obtained as a result of regression analysis on tests reported by Beth [1943].

Kar [1977] provides a similar formula for the barrier thickness required to prevent perforation but includes a parameter (a) called the minimum aggregate size in the concrete (see Equations 5a and 5b (Table 11)).

One of the most commonly used formulas is the modified Petry formula that was developed in 1910 (see Samuely [1939], Amirikian [1950], Russell [1962], and Kennedy [1976]). A formula developed for a hard missile impacting a massive target is given by Equation 6 in Table 11. Kennedy [1976] refers to this form of the formula as the modified Petry formula I. Amirikian suggested that the K_p coefficient be revised to account for the effect of concrete strength. The revised K_p value as a function of concrete strength is shown in Figure 20. Kennedy [1976] refers to the use of the Amirikian value of K_p as the modified Petry formula II. The suggested Petry perforation thickness and scabbing thickness are given in Equations 7a and 7b (Table 11) respectively.

The U.S. Army Corps of Engineers [1946] report the development of a formula referred to as the Army Corps of Engineers formula shown as Equation 8 in Table 11. Gwaltney [1968] provides a discussion of this formula along with comparisons to the NDRC, Petry, and BRL (Ballistics Research Lab) formula for small and large missiles. The Ballistics

Research Laboratory formula (Equation 9 Table 11) directly predicts the perforation thickness. If Equation 9 is modified for other values of ultimate compressive strength (where it is assumed that the perforation thickness is inversely proportional to the square root of f_c'), this leads to what is referred to as the modified BRL formula for perforation shown as Equation 10a in Table 11; and the scabbing thickness has been suggested by Linderman [1973] to be assumed as Equation 10b (Table 11). Another formula used to predict the perforation of small fragments traveling over 1000 ft. per sec. is referred to as the Ammann - Whitney formula (Equation 11, Table 11), (see TM5-1300 [1969]). Kennedy [1976] provides an excellent comparison of concrete perforation and penetration by the various formulas discussed thus far (see Figures 21a and 21b).

In Equation 12, of Table 11, the CEA-EDF formula is presented for low velocity perforation production. This formula was developed in France as a part of an experimental program for a large series of steel missile tests (see Berriaud [1977]). CEA refers to Commissiart al l'Energie Atomique, EDF is Electricite de France. Romander and Sliter [1984] (ASME/PVPD symposia on Impact, Fragmentation & Blast) report good comparison between the CEA-EDF formula and experimental data for 25 scaled impact tests of missiles ranging from 2.4 lbs. to 6.3 lbs. and velocities between 110 and 660 ft/sec. This study is part of a program sponsored by EPRI (Electric Power Research Institute) to investigate the effect of low velocity (< 600 fps) of large missiles impacting concrete. They also provide comparisons to the NDRC formula which appear to be overly conservative. Sliter [1980] (at an ASCE symposium on impactive and impulsive loads) presents a comparison of the calculated residual velocity of missiles subsequent to perforation of reinforced concrete targets: 1) used by the NRC and developed by Rotz [1974], 2) the Recht [1963] residual velocity formula and 3) CEA-EDF residual velocity formula (see Berriaud [1977]). These three formulas (Equation 21) are compared to 28 experimentally determined test data on residual velocities. The Recht and CEA-EDF residual velocity calculations give relatively good comparison. The NRC calculations were considerably conservative.

$$V_r = |V_S^2 - V_p^2|^{1/2} \qquad \text{NRC} \qquad |21a|$$

$$V_r = |M/(M+M_t)| \; |V_S^2 - V_p^2|^{1/2} \qquad \text{Recht} \qquad |21b|$$

M = Missile Mass M_t = target fragment mass

$$V_r = |M/(M+M_t)|^{1/2} \; |V_S^2 - V_p^2|^{1/2} \qquad \text{CEA-EDF} \qquad |21c|$$

V_s = Eqn. 12 Table 11

Sliter [May, 1980] provides an overview examination of both U.S. (Jankov [1976], Stephenson [1977] and Vassallo [1975]) and European tests (Berriaud [1977], Langheim [1976 & 1977]). Of 145 data points: 103 are for solid missiles, and 42 are for pipe. The emphasis was on the use of the NDRC formula for low impact velocities and target thickness to missile diameter less than 3. Perforation by solid missiles was observed to be predicted better by the CEA-EDF formula vs. the NDRC. For pipe missiles, the NDRC formula predicted relatively good results when the pipe outer diameter is used in penetration calculations and an equivalent solid missile used in the scabbing calculations. For effects of obliquity refer to studies reported by Proctor [1972] and Stephenson [1977]. For highly deformable missiles such as wooden poles, the penetration results are shown to be significantly less than those predicted by the formula (see Stephenson [1975, 1977] and Vassallo [1975]). This will be discussed further. Sliter [May, 1980] also provides an assessment of the scabbing formulas: NDRC, Bechtel (developed by Rotz [Dec. 1975, June, 1976]), and

Stone and Webster (Jankov [June 1976]). In addition to the 145 studies of solid and pipe missile impact into concrete targets (V_S below 1000 ft/sec) reported by Sliter [May 1980], Baker [May 1976] reports 7 tests of steel pipe missile impact on concrete targets and Ting [1975], Fiquet [1977], and Goldstein [1977] provides data on approximately 50 rod missile impact tests on concrete targets.

A number of tests were performed with wooden projectiles against concrete barriers (utility pole missiles) for low velocities (below 1000 ft/sec) by Vassallo [1975], Stephenson [1975, 1977], Ting [1975], Jankof [1976], and Baker [May 1976]. Of some interest is the development by Jankov [1976] of the scabbing threshold for pipe and slug missiles based upon his reported data (see Figure 22). Healey (see Peterson [1976]) provides charts for concrete penetration by armor piercing steel fragments. Goldstein [1977] illustrates a scabbing threshold for solid rod missiles impacting reinforced concrete panels in a manner similar to Jankov, i.e. scaled missile kinetic energy vs. scaled target thickness. Westine [1978] presents a model to predict insipient spalling from targets which are struck by fragments whose cross sectional width at impact is less than the lateral dimensions of the target. A cylindrical fragment is assumed and the formulas are obtained in terms of nondimensional impulse and nondimensional pressures.

The question of missile and target deformability effects on target-missile performance has been of some concern over the years (White [1946] refers to the reduced penetrating power of deformable missiles). Kennedy [1976] discusses the effects of target and missile deformability with respect to missile concrete impact and concludes that target deformability is generally insufficient to influence local missile impact and missile deformability has to be at least 40% of the calculated penetration depth of a non deformable missile before missile deformation has significant influence on the perforation and scabbing thickness. Ettouney [1979] discusses Kennedy's method and conclusions and shows that target missile coupling must be considered when evaluating the effects of missile and target deformability. Ettouney [1981] (SMiRT J8/7) provides a discussion of rebound of missiles impacting targets. He developes an analytical method that takes into account the energy loss due to missile impact and penetration with resulting rebound residual velocity. The reader is directed to a recent discussion of industrial missile impact formulas by Baker, Shabaan, and Florence (see Brown, [1984]).

Impact on metal barriers. In spite of the attempts to develop theoretical formulae based upon rigorous field and constitutive equation descriptions for penetration of missiles into targets, particularly metal, there has been only marginal or limited success. Generally,impact studies of metal targets have been motivated by military applications of projectiles to penetrate metal armor or the development of armor to defeat missile penetration. Most of these studies have been oriented to velocities (missile striking velocities) of 2,000 ft/sec. to 4800 ft/sec as discussed by White [1946] for pre-1940 studies. In fact, the NDRC study (White [1946]) has as its theme the trend toward hypervelocities, and such studies have continued since that time as reported by Kornhauser [1960]. One of the concerns discussed by Curtis (Chapter 6 editor of the NDRC report, White [1946]) was the problem of projectile breakup with increased velocities, hence, a reduction of the penetrating capability. The projectile velocity is usually classified into one of three regimes: low, transition, and hypervelocity. Hertzian or contact velocity (<100 fps) represents a fourth regime of non-penetration. The transition regime corresponds to threshold of missile breakup at the end of low speed impact. Some of the mechanisms of target failure (illustrated in Figure 17) are: plugging, ductile hole growth, and petaling. Until the emergence of the Nuclear power industry in the 1960's, little research was undertaken to investigate missile impact into steel targets for missile striking velocities below 500 ft./sec., Seth [1977]). Studies that were underway throughout this time, and until today that addressed some of the constitutive and phenomenological characteristics of low velocity impact, are: the punch, perforation, and pierce techniques used in manufacturing. An example is reported by Johnson [1981] for velocities of piercing of tubes at 165 meters/sec.

While the NDRC (White [1946]) and subsequent military studies have generally evaluated parametric ranges (particularly velocities above 1000 ft./sec.) that do not include impact into steel targets into the ranges of parameters of concern to pressure system designers, they have provided the basis for the development of semi-empirical formulas that have been used in various commercial applications. A number of perforation formulas (1 parameter, 2 parameter, and hardness effect) are reported by Curtis. A number of other areas of interest, discussed by Curtis, are: projectile deformation, effect on perforation ability, projectile parameter effects, and obliquity. An interesting observation is the effect of projectile shatter (not to be confused with deformation) where the increase in perforation energy is observed to be as great as 100% for missile shatter versus non missile shatter. Since the time of completion of the 1946 NDRC report on effects of impact and explosions (White, ed.), a number of test programs and theoretical formulae have appeared in the literature on the impact of missiles into metal targets.

The Ballistic Research Laboratory formula for steel is illustrated by Equation 1 in Table 12 and is reported in several reference documents such as by Russell [1962], DOA [1965] (TM5-855-1), Gwaltney [1968], and Pohto [1981]. No restriction is placed on the shape of the fragment.

A formula reported by Recht [1970] for blunt fragments, with velocities below 2,000 ft./sec., with a Brinell Hardness Number (BHN) 200-300, is shown in Table 12, Equation (3). This modified DeMarre Equation is based upon the DeMarre equation reported by the USNOL [1955] (for blunt fragments) and higher Brinell hardness numbers. Recht also compares several other equations for blunt fragments such as the Thor equation (BAL [1961], see Table 12, Equation (4)) and the Recht - Ipson equation discussed by Recht [1963] (not shown). The Thor equation(s) are empirical and based on a large series of tests for impact resistance of various metallic materials (BAL [1961]) and resistance of various non-metallic materials (BRL [1963]). Greenspon [1976] more recently has summarized the results of the Thor project. Recht [1970] presents a formula for perforation of steel plates by sharp fragments in which plate hardnesses lie between 250 and 350 BHN. This equation is illustrated in Table 12, Equation 5. In some instances in the design of a steel barrier against fragments, it may not be necessary to fully stop fragments from penetrating. In this instance, the residual velocity of the fragments as they leave the barrier must be determined by the design, and the characteristics of residual effects of the missile should be understood. Comparisons by Recht [1970] of residual velocity vs. impact velocity (Figure 24) for blunt and armor piercing projectiles illustrate the rate of residual velocity increase as a function of a number of parameters that were tested. Table 12 illustrates the residual velocity formulas for blunt and sharp fragments: discussed by Recht [1963, 1971] (blunt penetrator), Recht [1967] and Brooks [1964] (sharp penetrator). Quasi-analytical penetration and ricochet models are reviewed by Recht [1973]. A simplified formula for the ballistic limit for fragment trajectories other than normal is also illustrated in Table 12, Equation 6c. It is worthy to mention here, an interesting discussion by Recht [1970] on the use of ricochet traps and shielding blankets. It has been shown that small fragments at velocities less than 1,000 ft./sec. can be stopped effectively by combed and needle nylon fiber felt material. However, they are not effective against sharp penetrators.

A formula suggested for use in the design of containment of a runaway nuclear reactor is the Stanford Research Institute formula reported by White [1963], (see Equation 7 Table 12). This formula is limited to fragments that weigh between 10 and approximately 110 lbs., striking velocities between 70 and 400 ft./sec., fragment diameter between 2 and 10 in., and ultimate tensile strength between 60 to 70 ksi. Gwaltney [1968] provides a discussion and some of the parametric limits of application for the Stanford, BRL, and Recht (blunt equation) formulas.

A recent experimental program sponsored by Japanese Electric Power Companies (Tokyo Chubu and Chugoku) in cooperation with Toshiba and Hitachi is summarized in a paper by Masuda [1983]. Masuda et al. [1983] discuss studies in Japan with respect to low velocity missile impact concerned with fracture or plate thickness breaching. In this instance, the application is nuclear containment steel structures and the design interest is to insure that no breaching of the containment structure occurs. Breaching refers to any size opening or crack that goes through the wall of the steel plate target. In contrast to previous studies oriented to the definition of the perforation limit for missiles impacting steel targets, the Japanese study emphasized the critical fracture energy and the occurence of cracks in the target. In nuclear reactor containment vessels which require leak tightness against possible radioactive air or gasses, no failure of the containment shell is allowed. In this research project, the effects of missile nose shapes and the mechanical properties of the steel plates were analyzed. A formula was developed that defines the critical failure energy on steel plate targets. An example of experimental results for <u>missile energy</u> versus <u>target thickness</u> for a 90 degree conical missile are illustrated in Figure 25. The critical fracture energy formula is illustrated in Table 12, Equation 8, and is referred to as the Toshiba - Hitachi formula. Additional data and information regarding the Toshiba-Hitachi test program is reported by Miyamoto [1979] SMiRT J8/9 and Ohte [1981] SMiRT J7/10.

Baker [1976] (SwRI 02-9153-001) has conducted a number of experiments and performed a correlation with an energy balance equation to develop an equation (illustrated in Table 12, Equation 9) for the limit velocity for solid wooden cylinders (length to diameter ratio of 31:1 impacting into thin mild steel sheet targets). Utilizing data of fragment and hailstone impact on metal sheets and plates from Weals [1968], Bergman [1968] and McNaughtan [1969], Baker [1977] (NASA CR-134906) investigates low velocity impact of rigid non deforming fragments and crushable fragments. For the impact of high strength spheres which do not deform while perforating, he provides a nomograph as a function of:

ρ_p = *density of projectile material*

V_{50} = *limit velocity*

σ_t = *yield stress target material*

ρ_t = *density of target material*

h = *plate thickness*

a = *sphere radius*

Figure 26 illustrates this relationship between limit velocity and target thickness.

For design guidance with respect to low velocity crushable fragments impacting on steel targets, Baker [1977] provides a nomograph (see Figure 27) of scaled denting of metal plates vs. velocity. In this analysis, plastic deformation occurs. The parameters illustrated in Figure 27 are defined as follows:

δ = *plate depth*

a = *radius of spherical missile*

E_S = *impact velocity*

h = *plate thickness*

σ_t = *plate yield stress*

ρ_t = *plate density*

ρ_p = *missile density*

For metal plates under impulse loading, the reader is directed to Goldsmith [1960] and surveys by Baker [1975,1979,1982] (Shock & Vibration Digest).

Courant [1983] reports tests and analysis of steel missiles impacting mild steel barrier plates for velocities below 200 meters per second. In this study, cylindrical steel missiles with a length to diameter ratio of 4:1 (missile diameter of 12.5 mm) were used to obtain the perforation velocity vs. plate thickness curve shown in Figure 28.

In addition to a considerable interest with respect to missile impact on <u>concrete targets</u> by the nuclear power industry throughout the world, additional experimental and theoretical programs are underway to examine the effect of missile impact on <u>steel barricades</u>. For example, the Toshiba-Hitachi formula for energy fracture of steel barriers (which has already been discussed) comes from an active program by the nuclear industry in Japan. These studies are oriented toward the investigation of fragments from vessel ruptures and turbine missile fragments for parametric ranges similar to those for missile impact into concrete targets (as previously discussed). Nakagami [1981] and Yamamoto [1983] provide data on additional studies in Japan with respect to missile impact into steel targets. The studies reported by Nakagami [1981] provide interesting data for <u>perforation</u> and <u>tensile failure</u> of steel cylindrical shells impacted by turbine missiles.

A number of full scale and reduced scale model tests were performed by EPRI to investigate the effects of turbine rotor impact on steel casing. The full scale testing is reported by Yoshimura [1979] (SMiRT J8/12) and [1983] (EPRI NP-2741). In the full scale test Yoshimura describes two full scale impact tests of a turbine disk (in the piercing position and the blunt position) weighing 3366 lbs. with a striking velocity of 492 fps into a steel target. Scale model tests are reported by Romander [1983, 1984] (EPRI NP-2742 and ASME Volume Brown (ed.) [1984] respectively). Romander reports reasonably good results from the scale tests in duplicating the full scale tests. Some differences in ductility with respect to energy absorption between the full scale and the 1/5 scale tests are observed, however, the agreement is generally favorable. In this same EPRI project, Wilbeck [1983] (EPRI NP-2743) reports the results from ten 1/11 scale model turbine missile impact test to determine the effects of missile spin and blade crush on energy absorbed by a steel target or turbine casing impacted by the disk metal fragment. These 1/11 scale models are scaled from the test models reported by Yoshimura. The results of these tests indicate that the neglect of spin on the fragments should yield conservative results with respect to residual energy of escaped fragments through the metal barrier. Finally, an interesting feature of the EPRI full scale tests report is the inclusion of comparisons of some of the full scale test data with finite element data for computed impact displacement, strain, and velocity using the ADINA program (see Bathe [1976] and the ADINA reference manual). Good correlation is reported for the piercing test; however correlation for the blunt missile impact with the experimental data was not as favorable. A further discussion of some of the numerical methods emerging to predict missile target impact will be discussed in one of the following sections of this report.

Fragment penetration into soil. Stipe (editor chapter 9, NDRC report - White [1946]) reports that most of the work on penetration into soil prior to 1945 consists of the determination of parameters in empirical equations that have been developed for other materials with no systematic attempt to find out if the assumptions applied or not. Six types of projectiles are used in a test program reported by Stipe that determine projectile penetration into three types of soil: sand, loam, and clay. The velocities evaluated ranged from 500 to 3000 ft/sec. The results of this program are illustrated in Figure 29 for penetration versus striking velocity. Several characteristics are identified in this test program for fragments penetrating into soil: 1) blunt fragments penetrated further into clay and loam than sharp projectiles, 2) all nose shapes (blunt and sharp) tended to perform about the same with respect to penetration into sand, 3) actual trajectory paths (which tended to be highly nonlinear) for projectiles into the soil from entry point to resting point traveled from 10% to 30% more than a straight path from entry point to resting point, and 4) of the three types of soil tested, the order of greatest penetration to least is observed to go from clay, to loam, and sand. Sand offered the greatest resistance to missile penetration. An empirical equation to be used with Figure 29 is provided by Stipe in the NDRC report (see Equation 22).

$$x = W^{1/3} f(v)$$

or

$$(x/d) = (W/d^3)^{1/3} f(v) \qquad |22|$$

x = penetration path (straight)
d = projectile diameter
W = projectile weight
$f(v)$ = penetration functional dependent upon velocity (v)

for

$$0.15 \leq (W/d^3) \leq 0.65$$

Figure 29 also compares the penetrating capabilities of concrete versus soil. When sand is used as a barrier, it should be tightly packed and protection is enhanced if it is moist. Roddy [1977] reports a study of high velocity impact and cratering mechanisms.

A formula for predicting the maximum penetration in sand is reported by Allen [1957] and illustrated in Table 13. A number of other reports describing the relationship between the depth of penetration into sand and the missile striking velocity may be found in studies reported by Butler [1975], Healey [1975], and TM5-1300. Baker [1982] suggests the use of the penetration equation reported in Healey [1975] (illustrated in Equation 23).

$$x = 19D \ln (1 + 2160 V_S^2) \qquad |23|$$

x = depth of penetration in projectile diameter
D = fragment caliber density (#/in³)
V_S = (fps)

In instances when sand is used in a layer (for example: such as a roof or wall covering), the residual velocity may be calculated by Equation 24.

$$V_r/V_S = (1 + t/t_s)^{0.555} \qquad |24|$$

t = depth of penetration (Eqn.23)(in)
t_s = sand layer thickness (in)

A 1/3 root formula similar to that reported in the NDRC document [1946] by Stipe is presented in a study reported by Christman [1966]. This formula is illustrated in Table 13 and is used for different types of soils.

Another empirically based formula that provides an estimate of maximum penetration into soil as a function of a number of coefficients relating penetration resistance to missile characteristics has been presented by Wang [1971] for low velocity projectile penetration (see Table 13 for an illustration of this formula).

Seth [1977] provides a discussion of these soil penetration formulas that may be used to establish the minimum depth of burial for protection against missile impact and reviews a number of other formulas that predict penetration of missiles into concrete and steel (these are reported in this survey).

A formula reported by Backman [1976] and attributed to Petry is listed in Table 13 as the Petry - Backman formula.

Young [1967] reports the development of empirical equations as a result of a test program within the low velocity impact regime for earth penetrators into soil. This equation is illustrated in Table 13 and a discussion of this formula is presented by Baker [1982, 1984]. Baker suggests that supplemental and more detailed information may be obtained by using some of the methodology discussed by Westine [1975], particularly for long slender projectiles impacting earth.

Miscellaneous target material. Although the predominant materials for containment/barricading protection are concrete, metal, soil (or earth works). A number of other materials have been investigated in concert with these traditional containment/barricade materials. A material reported by Stipe (White [1946]) is referred to as plastic protection. This material consists of stone embedded in a mastik of asphalt: 60% stone, 30% limestone dust filler and 10% asphalt. This material is sometimes placed between a sandwich of metal plates or an expanded metal exterior and a sheet metal interior sandwich. Its desirable features are that it inhibits ricochet,and on an equal weight basis, has good stopping performance of small fragments (outperforming mild steel or armor) in certain velocity ranges.

Stotler [1979] (NASA CR-159544) reports a series of 20 tests investigating missile impact on 10 different containment structures. Missile velocities range from 193 meters/sec to 287 meters/sec. and missile weights varied from 0.07 lbs. to 0.13 lbs. The types of containment structures are: steel, aluminum/kevlar, honeycomb, titanium finned, kevlar finned-long, aluminum finned, kevlar finned-short, steel kevlar-thick, steel kevlar-thin. One of the conclusions of this program was that the thin steel faced containment backed by dry kevlar cloth (similar to some of the lightweight armor concepts developed by the U.S. Army) proved to be the most weight-effective concept for containing fragments. This study was geared toward containment of fragments in turbo fan blades on aircraft. However, this data provides valuable guidance for barricade designers of non turbine blade applications (but certainly for improving turbine engine containment barrier design when combined with failure data such as reported by Delucia [1978]). Refer to HEXCEL [1964, 1979] and Matonis [1964] on honeycomb materials and NASA [1964] CR-93 on cellular aluminum.

An extensive program that developed a data base from a large series of tests on metallic and non-metallic materials is reported in the Thor project [1961] (report #47) and BRL report [1963] and summarized by Greenspon [1976]. Some of the materials investigated with respect to ballistic limit velocity, residual velocity, and residual mass are: magnesium alloys, aluminimum, titanium, cast iron, face hardened steel, homogeneous steel, copper, lead, tuballoy, unbonded nylon, bonded nylon, lexan, plexiglass, duron, and bullet resistant glass. The Thor equations with empirical constants are found in BRL [1963](TR 51), Greenspon [1976], and Beal [1961] (Report 47).

BRL [1956] (TR25) presents data for target materials such as strawboard (specific weight of about 45 lbs. per cubic foot, and fiberboard (specific weight from 16 to 28 lbs. per cubic foot, such as Celotex) impacted by steel fragments whose ballistic limit velocity may be empirically described by Equation 25.

$$V_S = c(tA_c)^{\alpha} W^{\beta} \qquad (25)$$

c, α, β = coefficients of material
t = thickness (in)
W = (lbs) missile wt.
A_c = fragment area

As mentioned previously, relatively small blunt fragments having velocities of less than 1,000 ft. per second can be stopped by combed and needled nylon fiber felt material (see ASTM [1963 (STP336)); reported impact data may be found in Ipson [1966] and Alesi [1969]. Recht [1970] provides a discussion of the ballistic limit formula for the response of nylon felt to 17-gr cylindrical fragment impact. Responses above the ballistic limit are also presented.

Finally, refer to Healey [1975], Schlosser [1974], and Elias

[1978] for studies on composite barriers of soil and other material.

Experimental Measurements (trajectories and dynamic material behavior). Missile trajectories may be determined in a number of ways: high speed photography, yaw card measurements, and radiography. Ballistic tests are designed to obtain the following information: 1) the velocity and trajectory prior to impact, 2) changing the configuration of the missile and target due to impact and,3) mass, velocity, and trajectory of the fragments generated by the impact process (secondary missiles). During the testing program, fragment recovery and examination may be required. A variety of methods from the use of fiberboard and plywood to earthworks (such as is used in the large missile program by EPRI) is necessary. Discussion of testing and data evaluation is presented by Lambert and Ringers [1978], Herr [1978], Arbuckle [1973], Wenzel [1975], Lambert [1978], and Ringers [1980]. A number of recent advances in high speed radiography, photography, and photonics are discussed by Bracher [1976, 1979], Hadland [1978], Swift [1978], and Venable [1965].Instrumented impact tests provide information about target response during the missile penetration process, which gives insight into mechanisms in order to formulate a theoretical approach or benchmark numerical methods such as discussed by Yoshimura [1983], Gupta [1980], Netherwood [1980], Hauver [1978, 1980], and Backman [1976].

In addition to an evaluation of the missile-target displacement interaction throughout the penetration process, it is also important to properly characterize the dynamic material behavior in order to develop a more accurate formula or computational numerical methods (Bertholf [1975]). Improper material characterization not only leads to incorrect results, but to descriptions of the phenomena that are even qualitatively incorrect. An imperfect understanding of material characteristics can lead to (as observed by Mescall [1974] and Zukas [1980]) "an undesirable iterative process of matching imperfectly understood experiments with theoretical computations based on incomplete models". Because the ranges of missile velocities and masses that impact targets result in a range of material characteristics (as illustrated in Figure 23), no one dynamic material property test can provide information over the range of stresses, strains, strain rates, and temperatures encountered in impact. Some discussion on strain rate effects up to $10s^{-1}$ has been presented previously in this text.

Lindholm [1971] reviews methods for dynamic characterization of materials for high strain rate testing. A discussion of inelastic material behavior at large strains, very high strain rates, and elevated temperatures, with respect to the current state of the art for dynamic constitutive modeling and experimental property determination in this regime is presented by Lindholm and Vinson [1980].

A discussion of the use of the split Hopkinson bar which may be used in tension, torsion, and compression at strain rates from 10^2 to 10^4 - s^{-1} is given by Lindholm [1964, 1971] with additional discussions provided by Duffy [1971], Nicholas [1975], Bertholf [1975], and Bushan [1978]. A method employing a free flight impact with a measurement of surface strain by optical techniques is employed by Bell [1965, 1967, 1968] (see also Von Karman [1950], and Nolle [1974]). A technique discussed by Taylor [1948] on the use of flat ended projectiles for determining dynamic yield stress, consists of firing a short circular cylindrical bar against a rigid surface in contrast to the free flight impact of identical bars used by Bell. The struck end of the bar is subjected to large plastic strains. The average dynamic yield stress in terms of the impact velocity and the residual length of the bar may be determined in a straight forward manner. Further discussion of this method is provided by Whiffen [1948], Hawkyard [1969], and Wilkins [1973].

For measurements of higher strain rates, Karnes [1968] and Davidson [1979] discuss the use of impact of a flat projectile on a flat target plate which produces plane stress waves in which the strain is one-dimensional until the arrival of the reflected wave from the plate edges. Strain rates varying from 10^4 to 10^6. s^{-1} have been evaluated.

For solid impacts in the striking velocity range of 500 to

2000 meters/sec., only moderate pressures are generated, hence the equations of state and impact is of secondary importance. The von Mises yield criteria and Prandtl - Reuss incremental theory are generally used to describe plastic behavior. For a review of shock wave behavior refer to the reviews by Van Thiel [1977] and Kohn [1969], and for a review of plasticity models see Armen [1979] and Brown [1980]. In many instances, theoretical and numerical models employ the elastic, perfectly plastic descriptions of Wilkins [1964]. Some further discussions of plastic modeling is provided by Lee [1970], Green [1965], Johnson [1978], Hermann [1978], Wilkins [1973], and Norris [1977].

Misey [1980] (see Vinson [1980]) reports an experimental numerical simulation of high velocity impact (striking velocity of 1000 meters/sec) of a steel rod impacting a steel target. Comparisons are provided for two-dimensional Eulerian finite difference (HELP), a two-dimensional Lagrangian code (EPIC-2), and a beam bending version of the finite difference code REPSIL. The results with all three methods show good agreement in the elastic phase of deformation. However, within the plastic regime, numerical correlation with test results is dependent upon failure criteria incorporated into the numerical solution. The Lagrangian method used in EPIC seems to offer a better treatment for strain hardening and history dependent failure than is possible with Eulerian methods. The results indicate the need to determine the dynamic material properties through experimental investigation in order to provide appropriate material modeling in the numerical codes within the prescribed parametric ranges of field and material parameters.

Numerical methods. The bulk of computer codes capable of evaluating or performing impact studies falls into two categories: Lagrangian and Eulerian. In the numerical discretization process, the two most commonly used techniques are the finite element and finite difference methods. With respect to dynamic impact, the finite difference was the first developed computational technique. The finite difference method has enjoyed a relatively longer history of success than the finite element method but the finite element method is presently receiving greater attention and enjoying increasing success in predicting impact response. In general, it has been found that the finite difference method is usually computationally more cost effective than the finite element method. The finite element method has the advantage of being able to handle complex geometry and boundary conditions as well as material regions or zones throughout the structure. Another advantage of the finite element method is its ability to solve a variety of boundary value problems with the same mesh or idealized structure, e.g. thermal, elastic, nonlinear material, nonlinear strain, etc. Finite element may be simply described as basically utilizing a stiffness formulation in which the displacement functions or polynomials within each element are assumed; and the stiffness is determined by a variational approach. Finite difference is generally well known and employs a representation of the governing differential equation in terms of a variety of difference equations. Because of the greater flexibility and generality of the finite element method, it has enjoyed great popularity over the last two decades, particularly with the introduction of high speed computers such as the CDC 7600 and CRAY.

The appeal of numerical methods are their ability to supplement the researcher with detailed information on the internal response of the target and projectile.....more so than can be observed generally in an experimental test program.

In the Eulerian approach to modeling a target missile impact, the grid is assumed fixed in space while the continuum moves through the discretized zone or elements. In the Lagrangian approach, the zones or mesh of elements (and mass) move with the motion of the continuum (material - node points). For large displacements, the Lagrangian formulation undergoes significant distortion and potential computational difficulties. A variety of techniques have evolved to overcome this difficulty. Some are discussed by Hermann [1975]. Integration of the discretized equations have been discussed in a number of papers:

Chang [1977], Belytchko [1977], Hermann [1973,1975, 1977], Courant [1928] (instability in the explicit integration), Argyris [1979] and Walsh [1972].

A recent review of computer code capabilities is provided by Zukas [1980] and is summarized here.

The most popular two dimensional Lagrangian codes are:

1) finite difference codes HEMP (developed by Wilkens [1969]) and TOODY/TOOREZ (developed by Bertholf [1969], (see also Giroux [1973], Thorn [1974], and Swegle [1978]). Swegle [1979] presents a discussion of the anisotropic features of TOODY. Derivatives of HEMP are CRAM and SHEP which are two dimensional members of the PISCES family.

2) finite element codes such as: EPIC II (developed at the BRL (Johnson [1978])), in which the equations of motion are integrated directly rather than through the traditional stiffness approach, and CIVM-JET & CIVM-PLATE (Stagliano [1979] and Spilker [1980]), in which rings, beams, and panels subjected to impulsive or impactive loads may be solved.

Two dimensional Eulerian codes that are currently popular for impact studies are HELP (developed by Hageman and Walsh [1975]), a finite difference code, and HULL (developed by Matuska and Durrett [1978]), also a finite difference code.

A failure criteria based on maximum plastic work hardening for plugging failure is available (see Hageman [1972]) and a version for ductile and brittle failures in metals has been incorporated in HELP and is discussed by Hageman [1978]. Smith [1979] reports the revision in the internal energy algorithm and its implication to conical shape charge simulations; and Sedgewick [1978] reports the use of the HELP code to solve a variety of impact problems in the high and hypervelocity regimes. Sedgewick [1976] provides a discussion and evaluation of the anisotropic features available in HELP.

An interesting feature of the HULL program is the development of a zone of failed material in which a void is inserted into the zone such that the spall may be simulated. Documentation is provided in the reports by Durrett [1978] and

Gabby [1978]. Other two dimensional codes cited by Johnson [1971] and Thompson [1975] are the DORF and CSQ codes. DORF is similar to HELP and example problems may be found in a report by Bertholf [1979].

A 3-D Lagrangian finite difference code that is generally used is HEMP3D (Wilkins [1977]), which was designed to solve problems in soil mechanics involving dynamic plasticity and time dependent material behavior. HEMP has been applied to a number of static and dynamic problems as reported by Wilkins [1977] and Chen [1976, 1978]. TRIOIL and TRIDORF are Eulerian three dimensional finite difference codes developed by Johnson [1967, 1977]. Similar to TRIOIL and TRIDORF is METRIC by Hageman [1976] (SS-R-76-2973 and BRL-CR-305). The methodology of METRIC is similar to that of HELP upon which it was based.

A coupled 3-D Eulerian-Lagrangian finite element program for analyzing high velocity impact is CELFE reported by Lee [1975] which provides a coupling of the Eulerian impact model with the Lagrangian structural response codes such as NASTRAN (see Reddy [1975,1976]). The users manual and interim report are outlined by Lee [1975] (parts I & II) and Chan [1975] respectively. EPIC-3 is a three dimensional finite element Lagrangian formulation code developed by Johnson [1976] (Journal of Applied Mechanics), [1977] (Journal of Applied Mechanics), [1977] (Symposium on Ballistics), [1978] (BRL, AFATL-TR-78-81), and [1980] (BRL). In a manner similar to the EPIC II, the equations of motion are integrated directly. The sliding surface capability includes frictional effects, provisions are provided for elasto-plastic analysis of orthotropic materials, and impact into concrete and other similar materials may be treated. An example of an EPIC-3 simulation of a steel sphere impacting an aluminum target with a ricochet trajectory is illustrated in Figure 30. This problem was first solved by Johnson [1977] (Symposium on Ballistics), based on experimental data by Backman [1976]. In light of results by Ghosh [1977], the EPIC-3 predictions of residual velocity and target deformed shape appeared to be quite good.

Hallquist [1979] reports a discussion of the NIKE 2D code: an implicit finite-deformation finite element code for analyzing static and dynamic response of two dimensional solids. In DYNA II, Hallquist [1978] (UCRL-52429) provides an explicit finite element and finite difference code for axisymmetric and plane strain calculations. DYNA3D and DYNAP by Hallquist [1979] provide nonlinear dynamic analysis of solids in three dimensions for the solution of problems involving large strains and deformation. A further discussion of the development of these programs is provided by Hallquist [1976] (UCRL-52066), [1977] (ASCE), [1978] (AMD/ASME). For a cursory review of the capabilities of some of the computer programs mentioned here, refer to the survey articles by Zukas [1980], Hermann [1975], and von Riesmann [1974].

As Zukas [1980] observes, one of the most serious limitations to the use of numerical computational techniques such as finite element and finite difference codes to predict target missile performance is the inadequacy of the models to describe material failure. A number of experimentally-based general features are observed and discussed concerning the time dependent nature of material failure by Seaman [1975]. Computational failure models for impact loading situations are also discussed in Jonas [1978] and NMAB [1979]. Tuler [1968] is one of the earliest to apply the time dependent initiation criteria which offers a greater level of sophistication over the pressure cutoff model (which assumes that when the hydrostatic pressure reaches a critical tensile value, then failures occur). In the NMAB [1979] report, Seaman [1975,1976], and Erhich [1980] outline the development of models for ductile, brittle, and shear failure in an attempt to include micromechanical behavior in a continuum damage model. Davidson [1977] reports the development of a criterian in which the damage accumulation is a function of the extent of damage as well as field variables. The damage accumulation function is then taken to be dependent upon strain, temperature, and the current damage level (the post failure description includes weakening of the material as the damage increases). Hicks [1979] reports the development of a two-dimensional wave propagation code using a shock fitting technique which shows cost effective computation.

Hsieh [1980] provides an assessment of co-rotational finite element method for small and large deformation analysis of impact/penetration. A number of constitutive laws are compared and the endochronic theory is found to have some numerical advantage (approximately 30% reduction in computation costs) over that of the elasto-plastic theory for the impact/penetration problems (a comparison of deformation of impact for various consitutive laws and time steps are illustrated in Figure 30). Such studies or investigations into numerical techniques, constitutive equations, and field equation variables when coupled with experimental programs play a vital role in defining: 1) permissible simplifying assumptions in different phenomenological regimes of impact for performance analysis and 2) code and standard criteria development for the design of containment/barricading.

As an increasing number of experimental - computer numerical simulations, (finite element and finite difference computations) are compiled, greater confidence will evolve to perform cost effective computer design and analysis simulations of large containment/barricade systems. Further examples of computer impact studies are provided for the reader: Bless [1978] (Zukas [1980]) for experimental-numerical (EPIC III) study of a yawed rod striking a steel target at 550 meters/sec.; Neilson [1979] (SMiRT -J8/8) for a comparison of EURDYN and CADROS missile impact on metal targets with missile velocities from 21 to 122 meters/sec.; Kinsey [1981] for an experimental - theoretical (EPIC II) study of the impact of a steel rod at 909 meters/sec. into a metal target. The reader is also directed to studies reported by Jamet [1983], Kanto [1983], Yamamoto [1983], and Dubois [1983].

Pipe Whip Impact. The design against and analysis of pipe rupture and impact (referred to as "pipe whip") has received particular attention over the last 15 years from the nuclear power industry. The U.S. Nuclear Regulartory Commission standard review plan section 3.6.2 requires the determination of the break locations and dynamic effects associated with the postulated rupture of piping (see also ANS-58.2, American Nuclear Society, [1978]). The consequences of such a rupture can result in (1) the ruptured pipe "whipping" as a consequence of the thrust generated during blow down and available strain energy and (2) fragments being generated from the initial break (primary) and/or those that separate as a result of the "whipping" action (secondary) - refer to Gibbons [1964].

Two types of pipe breaks are generally considered: circumferential (guillotine) and longitudanal (split). The protection against such impact resulting from pipe whip are: 1) pipe restraint or 2) barriers. A number of pipe whip analyses have been reported that have compared experimental tests to numerical computer simulations (see Peterson [1982] and D. Peterson "Pipe Whip Dynamics - An Experimental and Analytical Investigation" Doctoral Dissertation, Univeristy of Akron [1982]) using such computer codes as ABAQUS, ADINA, ETC (see Zeinkewicz and Bathe for discussion of nonlinear finite element computer codes): Gesswein [1977] provides a discussion of pipe whip restraint design and analysis and testing and an overview of pipe whip dynamics and restraint is provided in the Welding Research Council Bulletin #269, 1981.

A large test and analytical program has been underway since 1976 in France and is sponsored by the CEA, EDF, Westinghouse, and EPRI. Presently the Aquatine II program (a part of the French study) has investigated 10 test configurations which are designed to provide data on jet impingement, support, and a number of other parameters (see Figure 31). Some of the results of this program have been published through SMiRT by Cauquelin [1979], Martin [1979], Caumette [1981], Garcia [1981], and the ASME Symposium on Pressure Vessel and Piping Impact (see Brown [1984]). Additional studies are reported by Shimizu [1977], Pirotin [1977], and Silva [1977].

Although the evaluation of the motion of ruptured pipes and their resulting impact with structures have been traditionally limited to highly sophisticated computer simulations, a number of papers have appeared more recently that have addressed the need for simple techniques to predict pipe-barrier impact analysis.

Roemer [1980] (ASCE [1980]) presents a method for pipe-barrier impact analysis and design in which the whipping pipe is characterized as an equivalent missile. The barrier is evaluated for local damage and overall structural response. Another paper (at this same symposium) by Enis [1980] (see ASCE [1980]) presents of method for considering local effects in the analysis of reinforced concrete barriers subjected to impact by a whipping pipe. The method accounts for the deformability of the impacting pipe, thus reducing the inherent conservatism.

2.1.4 Foundation Motion

Ground or foundation motion and shock can result in structural damage or injury to personnel. Ground or foundation motion may be induced by: (1) above-ground blast or fragment forces at the surface or (2) as a result of an underground explosion transmitted through the soil. A considerable number of applications of underground storage for high energy systems have evolved, particularly since the 1940's. Some examples of these applications are: underground storage of munitions, missile systems, high pressure technology (above 10,000 psi), and chemical and nuclear process equipment. Prior to 1939, Lampson [1946] (see White [1946]) indicates that the only systematic investigations of the effects of underground explosions had been the study undertaken by the U.S. Bureau of Mines and explosive manufacturers with respect to adequate limits of distance from dwellings to underground blasting. A survey of pre-1940 knowledge concerning underground explosions is provided by Christopherson [1941]. The hazards associated with ground motion and shock are: (1) damage to above-ground buildings, equipment, and personnel due to surface motions, (2) damage to underground structures, equipment, and personnel due to pressure loads and motion, (3) blast wave transmission from below-ground explosion to above ground, and (4) damage or injury due to potential cratering due to below-ground or above-ground explosions. Considerable guidance, particularly with respect to surface building and equipment design (as well as below-ground equipment) is available from a wealth of data on earthquake (seismic) studies: however, care should be exercised in distinguishing the characteristics of earthquake acceleration time histories (and spectra) vs. near-ground and above-ground explosions. A major source of publications discussing research into this area is provided by: the ASME (the American Society of Mechanical Engineers) through such publications as Ariman [1983] (by the Life Line Earthquake Engineering Committee) and Lin [1983] & Yan [1983] (by the OAC Committee of the Pressure Vessel and Piping Division); The American Society of Civil Engineers, ("Civil Engineering and Nuclear Power, Vol. VI, Seismic Analysis,"), ASCE [1980]; and Structural Mechanics and Reactor Technology (SMIRT), through its division K. "Design by analysis" dynamic and seismic criteria is provided in the USNRC standards review plan and ASME Pressure Vessel and Boiler Code, sections III and VIII.

References frequently cited that describe the mechanics and properties of wave propagation and seismic response are Richart, [1970], Thompson [1948], Lamb [1904], and Barkan [1962]. Types of waves that propagate through the ground as a result of an explosion or disturbance are referred to as: P (compression), S (shear), R (Rayleigh surface waves), and L (Love stratification waves). R waves are found to predominate for explosions near the surface (approximately 500 ft.) whereas P and S waves are associated with deeply-buried explosions in the near field (with P,S, and R in the far field). R waves travel predominantly along the surface, most energy goes into the R waves, and they are the cause of major tremors. When the shear modulus of an underlying strata is greater than that of the overlying layer, an L wave is developed which causes transverse horizontal motions.

Blast waves can be generated from underground explosions. For relatively small depth to explosive weight ratios (λ_{Depth} = Depth/ $W^{1/3} \leq$ 2ft.), Swisdak [1975] presents data for peak overpressure in air from underground explosion. Conversely, ground motions can be caused by air disturbances (shock or sonic). Merit [1964] reports experimental measurements of ground motion from high energy explosions in air and suggests a close correlation between ground motion and the peak overpressure (or sonic pressure) velocity. Similar observations are reported for rocket noise induced ground motion (see Mickey [1962, 1963] for Saturn SA 1, 2,3, and 4). Newmark [1962] and Cook [1962] suggest a simple model that provides a relation between peak side-on overpressure (P_S) versus vertical ground velocity (V) that is initiated by a compressive P wave (see Equation 26). Integrating Equation 26a, impulse versus displacement may be obtained as shown in Equation 26b.

$$P_S = \rho_S C_P V_P \qquad |26a|$$

$$i_S = \rho_S C_P X_P \qquad |26b|$$

where ρ_S = density of undisturbed soil

C_P = seismic velocity

V_P, X_P = velocity and displacement of soil

Lampson (White [1946]) presents a relationship for peak pressure in free earth as a function of TNT explosive weight (see Equation 27).

$$P_S = FEk(W^{1/3}/R)^n \qquad |27|$$

where F = coupling coefficient determined by depth of explosion
E = energy factor per type of explosive
n = factor a function of depth of explosion
k = constant characteristic of soil
r = standoff distance

Although the R wave is more likely to be the major cause of motion, the velocity of the R wave can be estimated through the use of Equations 26 and 27 (both for the P wave). Lampson also provides empirically based formulas for impulse and particle velocity. Baker [1982] in his discussion of this topic compares the two forms of the velocity and displacement equation: the Munitions/Mining vs. Atomic Energy Commission formulation (see

Equation 28).

$$U = K(W^{N_W})(R^{N_R}) \quad \text{(Geol.)} \qquad |28a|$$

$$U = K(W^{1/3}/R)^{N_U} \quad \text{(NRC)} \qquad |28b|$$

where K, N_W, N_R, *and* N_U *are constants*
U = *peak velocity (similar expressions for displacement)*
W = *explosive energy, TNT*
R = *standoff distance*

Both have their origins in the form of Equation 27. Westine [1978] provides a more generalized form of the velocity and displacement equations for R waves from buried explosions. For a further review of the empirically based shock propagation and peak velocity or displacement amplitude formula, refer to Richert [1940], Thoenen [1942], Habberjan [1952], Ichiro [1953], Morris [1957], Teichmann [1957], Carder [1959], Willis [1960], Crandell [1960], Hudson [1961], and Murphey [1961].

The effects of voids and soil characteristics can have significant effect upon the transmission of underground waves. This is of interest, both from a design and preventative point of view. The studies presented by Murphy [1961] that contain experimental results indicate that velocity and displacement are reduced significantly for explosions in cavities vs. those from a fully submerged explosion. The uses and significance of foundation isolation are discussed in Barkan [1962], Woods [1968], Kennedy [1979] and Smith [1979]. The use of trenching, foundation preparation, and supports are discussed. It is important for the designer of protective measures for surface buildup (or structures) from subsurface blasts to consider that subsurface natural or "man-made" topology and soil characteristics may enhance (or magnify) the blast effects on the object or possibly reduce the blast effects on the object. "Ideal," "homogeneous," and "free field" assumptions cannot be generally assumed.

Pre 1945 tests (16 targets) to determine the effects of pressure, accelerations, velocities, and displacements on a target in free earth are reported by Lampson (White [1946]). It is observed that the pressure on the front face was approximately twice that measured in free earth without the target, and the impulse per unit area is approximately 2.8 times (see Equation 29 for the reflected peak pressure).

$$P_r = 2kE\lambda^{-3} \qquad \text{(reflected pressure)} \qquad [29a]$$

where $\lambda = R/W^{1/3}$
k = soil constant
E = explosion factor

$$P_r = 2\rho_S C_P V \qquad \text{(see Eqn. 26)} \qquad [29b]$$

Impulse and deflection are also recorded in these tests. Westine [1978] provides a study on the analysis and testing of buried pipe response to buried explosive detonations. The peak frontal pressure is shown to be twice the side-on, free-field pressure. Westine also presents the estimation of pipe line stresses due to underground shocks.

Finally, a number of numerical techniques such as finite element and finite difference have been applied to predict the response of buried and surface structures subjected to explosive energy release excitation (see Desai [1977]). Most numerical studies and applications have tended to be oriented toward seismic type response generally in the range of between 2 and 33 Hertz.

2.1.5 Target Degeneration

Heat Flux. Explosions can produce a tremendous amount of heat flux. The liberation of high heat flux is associated with thermonuclear, condensed high explosive, liquid propellant, and gas explosions that are characterized by the generation of "fireballs". Studies into the release of thermal energy and explosions have generally focused on two areas: 1) Heat flux (Figure 16 c,d) propagation by radiation of thermal energy from the "fireball" and, 2) The dimensional versus time-history characteristics "fireball" growth and/or movement (see Figure 16a,b, High [1968] and Baker [1982]). Injury to personnel, buildings, and strategic equipment can occur (as mentioned in the Introduction) as a result of ignition, oxygen.deprivation, and/or incapacitation. The serious hazards posed by thermal effects, particularly to humans, were recognized in a number of studies, for example: (1) some investigations with respect to exposure to radient energy may be found in Buettner [1950], Glasstone [1962, 1977], (2) surveying injuries Settles [1968], and (3) developing criteria, Jarrett [1968] (see the table on radiant energy exposure from Glasstone, Tables 9 & 10 also found in Baker [1982]. A number of studies that have been performed with respect to "fireball" effects are reported by Gayle [1965, 1975], High [1968], Bader [1971], and Hasegawa [1978] with respect to liquid fuel explosion and Rakaczky [1975] with respect to munitions. Some further discussion and illustration of fire hazards associated with vessel rupture and explosion are presented by Pigford [1952], Pierce [1966], and USAEC [1966] for Nuclear facilities; Strehlow [1976] for LPG transportation; Scott [1979] for toxic chemical and explosive facilities; and Jensen [1972] and Baker [1980] for a general overview.

Gayle [1965] developed empirically based formulas for predicting (1) the "fireball" dimensions in terms of chemical weight and "fireball" duration also as a function of chemical weight (as shown in Equations 30a and 30b respectively) for liquid propellants: LO_2/RP-1, LO_2/LH_2, LO_2/RP-1 and LH_2, and N_2O_4/N_2H_4 - UDMH (50:50).

$$D = \alpha W^{\beta} \qquad |30a|$$

$$\tau = C W^{\delta} \qquad |30b|$$

W = # propellant

where D = diameter (feet)
τ = duration of fireball (sec)
Constants:
$\alpha = 9.56$
$\beta = 0.325$
$C = 0.196$
$\delta = 0.349$

Willoughby [1968] reports the eleven 25,000 lb. LO_2/RP-1 and LO_2/LH_2 "fireball" tests; and heat flux density versus time are measured and shown in Figure 14. The estimated time duration constants are C = 0.113 and δ = 0.333. Ellwell [1967] (in project SOPHY) reports 16 "fireball" tests in which a number of "fireball" dimensional parameters and time durations are recorded (see Jensen [1972] for an overview). High [1968] obtained similar results (with β = δ = 0.32, α = 9.84, and C = 0.232) for liquid propellant "fireball" calculation, and Rakaczky [1975] also suggests similar relationships to those developed by Gayle (Equation 30) for "fireball" diameter and duration.

Baker [1982] suggests that Equation 30 may be written as shown in Equation 31.

$$D = \alpha |E/\theta|^{1/3} \text{ (feet)} \qquad |31a|$$

and

$$\tau = C|E/\theta^{10}|^{1/3} \text{ (seconds)} \qquad |31b|$$

where θ = temp
E = energy release

C-2

His equation suggests that the "fireball" diameter and duration is dependent upon the energy content (E) and the temperature (θ) which is a function of the nature of the chemical. For example, he indicates that temperatures on the order of 1350K are associated with gas, 2500K are associated with propellants, and 5000K are associated with chemical explosives. Similar relationships for diameter and time are used by Bader [1971] and Hasegawa [1978], for liquid propellant and propane, pentane, and octane respectively. Baker [1982] develops a mathematical model to predict heat flux (q) and thermal energy per unit area (Q) based upon some simplifying assumptions. Utilizing data reported by High [1968], Baker obtains good agreement between calculated and measured results for several cases.

Toxic Substance. An area that has been receiving increasing attention is the design of systems that contain toxic substances, the investigation of ways to contain the toxic products of the system failure, and the consequences if such containment is not realized. Since it is not within the scope of this study to address the hazards associated with toxic chemical release, only a brief or cursory review will be provided. In general the type of toxic media usually fall into one of three major categories: 1) Radioactive, 2) Biological, and 3) Chemical (caustic). The earlier studies into this area were motivated by the handling of military and non-military chemical substances of a toxic nature. Post 1945 studies were given impetus as a result of military and commercial studies into the handling and use of fissionable material. In the last 2 decades, the tremendous growth of the number of new and widely used chemical products has created an ever-increasing awareness of the need to understand the properties of the substances in order to more effectively and safely process them. More recently, research and commercialization into new biological substances has added another aspect of consideration in the design of operating systems and containment. A number of industry and governmental organizations have provided a focal point or a forum to promote research and share experiences; the American Chemical Society, the American Institute for Chemical Engineers, the U.S.

Environmental Protection Agency, and the USNRC. Some example symposia are: Scott [1978] (American Chemical Society) and ERDA [1974].

The hazards associated with toxic substances are generally divided into two categories: meteorological and biological. The biological hazards are manifest in the effects on humans, plants, and animals. The meteorological studies are concerned with the atmospheric diffusion, deposition, and resuspension, (see Amato [1971] (USAEC WASH 1187), Chamberlain [1955], Stewart [1965], "Proceedings of Atmosphere/Surface Exchange of Particulate and Gaseous Pollutants", ERDA [1974], Pruppacher [1983], and NOAA [1984]).

2.2 BARRICADING/CONTAINMENT/SHELTER: PROTECTION

Protection against hazards resulting from a system failure may vary from (1) containment structures which are designed to contain the hazardous effects from ambient conditions, to (2) protective shelters (enclosures) that are designed to prevent hazardous effects from entering a maintained ambient enclosure. In between these two concepts are partial protective structures or devices such as barricades, safety walls, restraints, and quench suppression systems.

Protective shelters and barricades have been designed and built probably as long man has been able to propel rocks, spears, arrows, and other missiles. The art of barricading against missiles was refined as a deterrent with the development of the catapult and later, the cannon.

Blast effects became a consideration in protective design with the development of high explosives: with respect to manufacturing, transport, storage, and military applications.

The design of the protective structure: (containment, barricade, shelter) is dictated by the type of hazard for which it is to be designed, either singly or in concert with numerous hazards (blast, fragments, foundation motion, temperature transient, chemical, radioactive, or biological effects). Some protective systems may be designed for all, or nearly all, of these hazards and act as a containment, barrier, and shelter. An example is a nuclear power plant containment building (which excludes design against biological effects).

Hazards may be grouped into two categories with respect to protective device design: 1) force-dominated hazards, such as blast, fragment impact, and foundation motion and 2) degenerative hazards such as thermal, chemical, radioactive, and biological.

Force-dominated hazards may be categorized into either 1) local effects and/or 2) global effects.

TM5-1300 characterizes blast wave pressure loads into three ranges: high, intermediate, and low. High pressure levels are considered much greater than 200 psi, intermediate < 200 psi but > 10 psi, and low pressure < 10 psi. In the high pressure range, the design load is generally guided by impulse; in the intermediate pressure range by pressure vs. time; and in the low pressure range pressure is considered time independent.

The design of protective measures against degenerative type hazards generally addresses itself to containment. However, protective barriers and shelters have been designed (usually for control rooms) for protection against degenerative type hazards such as thermal radiation.

2.2.1 Containment Structures.

A containment structure may be characterized as (Jensen [1972]) ductile (a metal), brittle (concrete), and/or special load carrying (aggregate, etc.) or other material singly or in combination that fully encloses a space and is used for the storage of hazardous material subjected to accidental release. It may also function as a test chamber. When only partial protection is offered against a hazard, the containment structure is called a barricade. When considering the containment of blast pressure, a containment structure or fully enclosed space is defined by the ratio of vented area to volume (see Equation 32) equal to zero. Turkel [1983] refers to full venting by $(A/V^{2/3}) \geq 0.6$.

$$(A/V^{2/3}) = 0 \quad \textit{containment} \qquad |32a|$$

$$0 < (A/V^{2/3}) \leq 0.60 \quad \textit{partial venting} \qquad |32b|$$

$$(A/V^{2/3}) \geq 0.60 \quad \textit{fully vented} \qquad |32c|$$

A = Vent area
V = Volume of containment/barricade

The motivating forces behind the research and development into containment structures has generally come from needs for safe munitions handling and storage, chemical research and development, and nuclear reactor containment design. More recently high pressure technology has been an increasing motivating factor to explore new concepts such as those reported by Penninger [1980] and Boomer [1983].

The optimum configuration for a containment structure subjected to an internal blast (overpressure and quasi-static pressure) is a spherical shape. However, usually the next best configurational choice is a cylinder. The poorest configuration is a rectangular shaped containment structure. Dobbs [1970] and, more recently, Penninger [1980] discuss the advantages of cylindrical shaped metal containment structures for use in (explosive-toxic and high pressure respectively) facilities design. Both cite cost effectiveness, facility flexibility, and reliability of metal containment (see Figure 32) versus the more traditional reinforced concrete cubicles. The Penninger [1980] study investigates various concepts for total confinement of blast and fragmentation hazards. The JANNAF (Jensen [1972]) Handbook suggests the use of the <u>peak reflected shock pressure as a static load</u> and limit the metal vessel to material yield strength as a conservative estimate of containment vessel design adequacy. If this conservative approach cannot be used, then the approximate transient analysis discussed in section 2.1.1 (on confinement by Baker [1959], [1975], [1982]) is suggested. A number of blast tests for fully contained vessels are provided by

Baker [1956], Wise [1964], Hoffman [1956], and the USAF [1962] (U.S.Air Force Design Manual).

Based on data by Machenzie [1963] and Wise [1965], empirically determined containable blast (charge) versus vessel diameter for aluminum and 304 stainless steel cylinders is presented in Figure 33 as a function of vessel thickness. An interesting result of this study was that the safe explosive weight to prevent vessel failure is twice as high for a gas filled vessel versus a fluid filled vessel. The NOL study (Wise [1965]) presents a semi-empirical formula to predict the safe containable charge weight for vessels filled with water.

The UK high pressure safety code (Seville [1977]) states that the preferred method of protection against shock waves is a completely enclosed containment and it also recommends the use of equivalent static pressure for the reflected shock pressure calculated by the Weibull [1968] formula. Ventilation in accordance with a study by Leich [1973] is suggested. A safety factor of 3 to 4 is recommended. Other areas discussed are thickness, doors, windows, and external fittings. It is recommended that the containment structure should withstand shock wave and fragmentation; doors should be mounted on the inside and be made larger than the opening; viewports should utilize mirror arrangements (to avoid fragment penetration); and valve stems should not protrude directly into the operating area.

Browne [1961], National Safety Congress and Industrial and Engineering Chemistry presents a discussion of the design and testing of a high pressure cell to prevent the spread of gasses, fragments, to contain explosions, and to confine fires; and Bowen [1957] presents the design of an eight cubicle laboratory.

A brief overview article is presented by Pressure Products Industries (Bulletin 307.1) that discusses some general features of laboratory test cells. In addition to basic design philosophy, barricade layout is discussed with respect to ceiling height, cell size, vent lines, services, viewing devices, ventilation, drainage and vent systems, valve handle extensions, reserve wall penetration, and cell wall blowout. Sixty percent of the calculated available explosive energy is assumed to be by isentropic expansion to ambient conditions and cell size is suggested to be 1000 to 10000 times greater than the volume of the largest vessel within the cell.

TM5-1300, "Structures to Resist the Effects of Accidental Explosion" is a comprehensive design manual that represents the results of a broad program of analysis, testing, and evaluation of structural design to afford protection against the effects of accidental explosions. This effort was supported by the U.S. Army, Navy, and Air Force. The manual contains procedures, charts, and tables required to establish the environment of an explosion and its output in terms of blast and fragments (see Rindner [1979] for a discussion of the TM5-1300 program, presented in the symposium Scott [1979]). Methods are given in TM5-1300 for predicting pressure loadings on walls and roofs for various chamber sizes, ratios of length to height, numbers of enclosing walls and roofs, standoff from the nearest reflected surface, and for central and offcenter explosions in an enclosure. Some of the other areas discussed in TM5-1300 are: explosion protective systems, basis for structural design, effects of explosions, structural behavior of reinforced concrete, structural analysis and design for ductile mode response, structural analysis and design for brittle mode response, structural behavior to primary fragment impact, construction details and procedures (laced reinforced and unlaced reinforced concrete construction), and other factors considered in explosive facility design (site planning, closure systems, structure motions, and earth covered steel arch magazines).

Gupta [1984] (see Brown 1984) reports the study of a computer method for modeling of blast response of hemispherical enclosures subjected to boundary condition effects. A comparison between the experimental data and computer data is provided. See Anderson [1983] for the study of response of structures subject to deflagration type blast loading.

As mentioned earlier, an industry that has motivated the use of advanced design and analysis techniques in the development of containment design has been the nuclear power industry. Some of the early studies into the design of the nuclear containment structure with respect to available energy as a result of an accident, blast, and fragments are provided by Wood [1954], Alco [1955], Brown [1956], Porter [1956], Alvy [1957], Porzel [1957], Asire [1958], McGuire [1959, 1960], Kato [1963], Wise [1963], and Proctor [1966]. In addition, recent studies of interest are reported by Levy [1970], Ferritto [1977], Kulesz [1980], and Bacigalupi [1980]. A review of nuclear containment vessel design is provided by Bagchi [1982] (ASME Decade of Progress).

Nuclear containment vessel material is usually either metal (first constructed in the U.S. in 1953), or concrete (first commercial containment vessel in 1968). Nuclear containment design load requirements essentially cover all hazards except biological. A discussion is presented by Bagchi concerning the internal energy release following a postulated design basis accident and methods of maintaining pressure and temperature below design limits within the containment structure. The latter is accomplished by the use of dry pressure suppression systems (ice condensor systems and water suppression systems) (see ANS 58.2-ANSI N176).

Recent studies for jet loading and internal explosions within the nuclear containment structure during blowdown or hypothetical core meltdown accidents are reported by Mohammadian [1983], Peretz [1983], and Bracht [1983]. The U.S. Nuclear Regulatory Commission through its standard review plan outlines areas of review in the construction of nuclear containment to provide protection against internal loads (examples: Reg. Guide 1.115 for protection against turbine missiles and Reg. Guide 3.5.1.2-3). Herzog [1981] reports the results of a test program in Germany that was undertaken to evaluate the use of a metal containment shield to minimize shock wave, jet forces, and reaction forces (and retain vessel fragments). The shield is designed to be used to enclose nuclear power plant pressure components.

Scott [1978] has brought together an American Chemical Society symposium on toxic chemical and explosive facilities which gives a good overview of safety and engineering design through a number of excellent articles on hazardous protection in the following areas: safety design considerations in munitions plant layout by Rindner, shielding of facilities for work with explosive materials by Katsanis, newly developed technology for ecological demilitarization of munitions by Crist, a discussion of modern propellant and propulsion research and development facility by Wharton, prevention of propellant flame propagation through conveyers using sprinkler systems by Ewig, design criteria for mobile ammunition and surveillance shop by Huddleston, explosion suppression by Crosley, suppression of explosion in incendiary fires by Elkins, laboratory design and operations procedures for chemical carcinogen use by Barbito, concepts and methodology for toxicological testing by MacNamara, DOD chemical ammunitions safety program by Scott, and designing a safe academic chemistry building by Houser.

Finally, Bartknecht [1981], in his excellent book on EXPLOSIONS (course, prevention, protection) concerning flammable gases and combustible dust, offers considerable discussion with respect to safety measures within enclosures or rooms. Information is provided with respect to relief venting, burst disks, self closing relief devices, explosion plates, explosion doors, spring loaded relief devices, flame barriers, detonation barriers, automatic extinguishing barriers, and pipeline venting devices.

2.2.2 Suppressive Shields.

Suppressive shields are containment structures designed to fully contain fragments from an explosion while providing a controlled venting of the product gases from the detonation. The design of suppressive shields is a relatively new technology that has received particular attention in the munitions area. An extensive handbook (SSSDA) titled "Suppressive Shields Structural Design and Analysis Handbook," has been recently issued by the U.S Army Corps of Engineers, (USACE) [1977]. In addition to containing fragments and the attenuation of blast pressure, a suppressive shield can significantly reduce the diameter of a resulting fireball. Desired features are ease in construction and maintenance and they have been found to be cost effective. This Army handbook is a result of extensive testing of both scale model and prototype structures and the participation by the BRL, NASA, NSWC, SwRI, the Corps of Engineers (Huntsville division), and the AAI Corp. Concepts similar to suppressive shields have been used in the past through the use of blast mats in concert with partially vented cubicles. The usual design procedure cited by the SSSDA Handbook is: 1) the suppressive shield is designed with the maximum allowable venting which will meet blast overpressure suppression requirements, 2) once this is done, the structure is designed to sufficient strength to withstand pressure and fragmentation loads. An interesting observation in the handbook is that the strength of welds and concrete components is often the determining factor in the overall strength of the shield. Table 14 lists the eight suppressive shield design groups that have been developed by the U.S. Army. Figure 34 illustrates vent area ratios for various structural configurations and Figure 35 illustrates the general configuration of suppressive shield groups.

The first significant work into the design and development of the suppressive shield concept has its origins at the Edgewood Arsenal in 1968. A number of studies that have laid the groundwork for the investigation of suppressive shield design are Weibull [1968], Keenan [1975], Zilliacus [1974], Kenney [1974], Baker [1975], and Owczarak [1964]. Several reports that provide data in support of the suppressive structures program are by Kingery [1978], Schumacher [1976], and Esparza [1975]. Comparisons are provided by Kingery with his experimental determination of internal gas pressure as a function of time for the suppression structure versus two theoretical predictive methods: by Proctor (NSWC/WOL TR 75-183 (to be published)) and by Kinney [1974]. Kingery reports that: 1) these two methods appear to be adequate for predicting internal gas pressure versus time 2) the method devised by SwRI and used by BRL to calculate effective vent area does not apply to effective vent area and 3) there is a need for more basic data on decay rate of internal pressure versus known vent area. Esparza [1975] discusses the specific formulas and methods for predicting the vent area ratio for suppressive structures studied by SwRI.

A directionally vented suppressive structure may be thought of as partially vented barricades as discussed in TM5-1300 and reviewed by Tunkel (see Figure 36) in which the open areas are enclosed by a suppressive panel or a blast mat. Fragments or missiles are fully contained, however the blast wave causes directional pressure effects. Keenan [1975] investigates six directionally-vented chambers. He provides comparisons of peak sidewall pressure versus scaled distance. These results along with further comparisons are provided by Tunkel [1983].

<u>2.2.3</u> <u>Barricades</u>.

Barricades may be described as protective structures that provide directional protection against missiles and heat. They generally offer limited or no protection against blast and other degenerative hazards (chemical, radiation, and biological). Barricades may consist of <u>natural</u> <u>or</u> <u>artificial</u> <u>terrain</u> and <u>man made</u> structures.

The U.K. High Pressure Safety Code (Seville [1977]) suggests that safety walls used adjacent to high pressure systems should be designed to resist blast and fragmentation. A factor of 3 is to be used for designing the wall thickness based on impulse load and a factor of 2 based on fragment penetration. Spalling effects should be considered.

Anderson [1954] provides one of the early discussions of the construction and erection of barricades, the problem of barricading equipment, protection from burns in connection with the design and operation of high pressure vessels and hazards connected with hydraulic systems. In addition to a discussion of shielding of pressure vessels, Anderson also provides quidance for shielding of high pressure piping and tubing (in excess of 200,000 psi), pressure indicating instruments, valves, fittings, and intensifiers. Shielding is not recommended against shock waves in instances where the high pressure systems contains non combustible liquids. With respect to barricading against high pressure systems, frequently cited references that give barricade design guidance are Moore [1966], Fryer [1981], and Pohto [1981].

Moore [1966] provides a good survey of design practices for barricades prior to 1966 with respect to: missile effects, blast effects, laboratory test cells, transparent barricades, and numerous other general reference material. An interesting aspect of barricade design raised by Moore is the possibility of a simultaneous blast and missile impact of structures and the need for consideration of these simultaneous effects by the designer.

In the high pressure systems manual edited by Pohto [1981], many areas are covered with respect to design practices. A frequently overlooked potential problem area with respect to shielding for jets is addressed. In instances of designing shielding for jets alone, mild steel sheet is suggested in two ranges: systems up to 15,000 psi and for systems greater than 15,000 psi. Other areas of interest to the barricade designer are: maze barriers, blowout panel, and heating and ventilating systems. A frequently cited nomograph in the literature for barricade design against penetration is shown in Figure 37 (see also Muzzall [1964]). Anonymous [1968] discusses fragment containing barriers for pressure systems up to 1,000 psi and cites some precautions worthy of mentioning: avoid nuts and bolts in shielded structures, use wood (only where splintering will not be a hazard), use auxiliary shields where appropriate to reduce the speed of fragments (effectiveness is increased when hung like curtains), and minimize fire hazards by fireproofing.

In a symposium on safety in high pressure polyethylene plants, presented in 1972 by the American Institute of Chemical Engineers, a number of high pressure safety problems were discussed and practical design approaches reviewed. In that symposium, Guill [1972] emphasized the importance of ventilation to minimize explosions in addition to barricading and shielding design for reactor, compressor, and high pressure piping. Protection against fragments, blast, and heat were discussed (using water walls, plastic sheet, canvas curtains, concrete, masonry, rope mats, wire mats, sheet metal, etc.) but emphasis was placed on insuring that the designer understands the nature of the hazards and the ability of the barricade to perform its intended function. Ziefel [1972], Royalty [1972] and Ford [1972] (in this AIChE symposium) discussed design approaches for high pressure vessel and piping systems. They emphasize design considerations, inspection, and maintenance procedures (for a reference see API Pressure Vessel Inspection Code, API 510, [1980]).

Boomer [1983] presents a pit type barrier design configuration for a two kilo bar pressure vessel. This configuration provides for the high pressure vessel to be accessible in the lab through an opening in the floor which is covered by a movable sand-filled cover that is mounted on tracks for protection against missiles generated as a result of a potential vessel failure. This design allows for easy access. Pit type barriers for protection against potential high energy release generally require an evaluation of ground shock in order to prevent possible hazardous damage to adjacent laboratory buildings and equipment.

The most common <u>earthwork type barricades</u> are mound and single-revetted. An example of <u>mound type barricades</u> are shown in Figure 39 (from DOD 5154.4S [1978]). A <u>revetted barricade</u> utilizes a retaining wall in place of one of the slopes on a mound type barricade. In general, earthwork type barricades are used to provide safety at explosives facilities for military applications. A number of manuals provide guidelines for building spacing relative to explosives and barricading such as the DOD 5154.4S manual, AMCR 385-24 [1961], AFM 127-100 [1964], Department of the Navy OP5 [1963], and Saffian [1963].

The report by Wenzel & Bessey [1969] provides most of the significant studies with respect to blast effects on earthen barricades. Both mound type and single revetted earthen barricades were studied with respect to peak pressure versus scaled distance for both near field and far field proximity of blast to mound distances. Some key points of the reported results of these tests by Wenzel [1969] are: earthwork barricades do reduce the peak pressure and impulse immediately behind the barricades, single revetted barricades are more efficient in reducing peak pressure and impulse than mound barricades, blast attenuation caused by mound barriers can be considered negligible, single revetted barricades are shown to be effective in the near field (but far field effects are difficult to predict). Jensen [1972] reports that the primary purpose of these types of structures is the containment of fragments or to prevent the propagation of detonation to a second explosive site. Hence, there is no data that supports the idea that earthwork type barricades near an explosion will reduce damage to structures or personnel in the far field by reducing shock pressure levels.

2.2.4 Protective Shelters.

TM5-1300 defines protective shelters as structures which provide protection for personnel, valuable equipment, and/or extremely sensitive explosives. This protection is effectuated by minimizing pressure leakage into a shelter, providing adequate protection for the contents of the structure, preventing penetration into the interior of the structure by primary fragment, or formation of fragments from the structure itself (scabbing). Protection against the uncontrolled spread of hazardous material (eg. chemical, radioactive and biological) is provided by confining material within the structure to where the explosion takes place or by permitting the spread of the hazardous material to controlled safe areas. This workbook presents, as mentioned previously, extensive guidance with respect to the design and construction of concrete shelters with respect to blast and fragmentation protection. Design curves are provided for force-motion-loading considerations. Earth covered steel arch magazines, earth mounded igloo, and devices (such as isolation systems, blast valves, arch tension doors, steel plate doors, air tight doors, etc.) are discussed. The spacing and orientation of igloos is also discussed in DOD 5154.4S [1978] (a further review of this manual with respect to energy distance evaluation will be presented in the next section).

White [1946] presents data on a number of studies during the 1940's (as was previously mentioned) that addresses protective structural response. Some guidance with respect to spall plate construction and reinforced concrete rebar arrangement is presented. Of some interest in this manual is the experimental, theoretical investigation of the response of columns and panels above and below ground (see White 1946, sheets 6A1A, 6A1B, 6A5, 6A6) which are found useful today as first approximate estimates in conceptual design of protective structures. A significant amount of data is also available with respect to the response of buildings from blast effects, damage to underground piping from above ground explosions, and earth displacements from underground explosions (see sheets 3B2 and 6E1, and as examples, see Chapter 6 for reinforced panel and scab plate construction). Figure 38 provides a partial illustration of 6A6 from White [1946].

A more recent motivating force in the improvement of the design of protective shelters is nuclear reactor containment vessel design which may be composed of metal, concrete, and mixed composition. As discussed earlier, Bagchi [1982], the containment structure is required to act as a containment building as well as a protective shelter. It also must be capable of withstanding prescribed ground motions. Typically a nuclear containment structure must be designed to withstand external blast forces and missile penetration. The missiles may range from small projectiles to a C5A military air transport craft carrying two M60 tanks, Kennedy [1966]. The U.S. Nuclear Regulatory Commission standard review plan provides guidance with respect to the types of loadings that are to be evaluated (some examples are found in 3.5.1, 3.6.1 and 3.6.2 - all [1975]).

Thus far in this report, a number of experimental and theoretical investigatory programs have been discussed concerning missile impact within the nuclear containment structure. Most studies regarding blast and large missile impact on the <u>exterior</u> of the containment (shelter) structure have been oriented to computational techniques such as finite element and finite difference methods. Drittler [1976] presents a numerical method to calculate the forces acting on a containment building during the impact of a projectile. Utilizing his finite difference method, a parametric study on impact force from a military aircraft is presented. Hammel [1976] provides a discussion of aircraft impact on a spherical shell. The projectile is modeled by a mass, spring, dash pot or damper by Hammel, and he concludes that the transient force from impact by a deformable aircraft upon an elastic shell is more influenced by the considered aircraft model than the elastic displacements of the vessel. Degen [1976] attempted the evaluation of the carrying capacity of the containment structure with respect to impact load (aircraft). A number of methods such as yield line theory, linear elastic shell theory, plastic shell theory, and 3D finite element with nonlinear capabilities are compared and evaluated with the possibility of simplification and recommendation for practical design. This ambitious study met with limited success but provides valuable information. Kiedrzynksi [1981] reports an experimental and numerical investigation of impact damping effects as a result of local material and structural vibration damping. This study was oriented toward the investigation of steel bumper and tie bar anchors that are exposed to impact loads due to the presence of gaps. It is shown that, when developed in a simplified model of an impact problem (where inertial damping is present), forces are recommended in serving as an equivalence criteria versus the popular restitution coefficient criteria which is of value when the missile energy is mostly transformed or converted to energy dissipated by viscous material damping.

Jonas [1979] provides an analytical and experimental comparison of missile impact onto reinforced concrete containment structures. A number of examples are provided by Crutzen [1979] who compares a program SLOOFDYN to NONSAP, EURDYN and HUMPHREYS for a number of dynamic pressure loads including snap buckling. Reynan [1981] reports the use of the SLOOFDYN program with SEMILOOF in order to investigate the development of cracks in a containment structure due to dynamic loading. Bangash [1981] illustrates a 3-dimensional finite element analysis of concrete containment vessels under impact loads in which nonlinear behavior of the concrete, structural damping, and cracking is included. The finite element program DYCONT is used.

The computational results are compared to experimental studies reported by Barr in NUCLEAR ENERGY [1980]. Nonlinear effects are found to vanish approximately 2 diameters from the impact point. Puttonen [1981] uses the PISCES-2DELK computer code to evaluate local deformations caused by impact of aircraft on a building. A number of interesting observations are made: the energy absorbing ability of the reinforcement is found to be nonessential, the main task of the reinforcement is to keep the concrete together, the energy absorbed by the structure is mainly distortional energy from which the energy taken by the concrete is over 15 times that of the reinforcement. Hence the impact phenemona is quite local.

Finally, a number of studies on missile impact that have been recently presented at the 1983 SMiRT conference are provided by Krutzen, Henkel, Andersen, Chedmal, Bauer, Brandes, Buchhardt, Marti, and Kamil are all geared toward the evaluation of impactive loads (primarily oriented to the assessment of airplane crash) into the containment building.

A subject that has received only cursory treatment until recently is the evaluation of the response of the nuclear containment structure to blast effects. Kot [1979] presents a method which provides general and scalable estimates of the structural response utilizing the ultimate strength or yield line analysis. The method is applicable for blast loading, however it cannot be extended to missile impact since the impulse is dependent upon the dimensions. Strangenberg [1981] provides a report of a test program in the Federal Republic of Germany with respect to external blast loads applied to reinforced concrete containment structures. Two important aspects of this ongoing program are reported: 1) when the underpressure or reverse phase of the blast wave is neglected (which is usually the case) along with the higher available material strengths, this leads to conservative results and 2) the highly nonlinear pressure versus time on the containment structure may be "filtered" for use as input loads to parametric computer models. Thor [1981] reports scale model testing of a nuclear containment structure subjected to explodierenden gaswolken'. Varpasuo [1981] and Zinn [1981] report the effect of gas explosion shock wave load on a nuclear containment building and reports that overall displacements caused by the gas explosion load are comparable to earthquake loads.

Recently reported studies at the 7th SMiRT conference in 1983 for a nuclear containment building subjected to external explosions are provided by: Alliaud, Thor, Werkle, Huber, and Hendrickx.

Kot [1978] (see also Kot [1979]) provides a set of scaled curves which compare maximum spall and wall displacement velocities with standoff distance and scaled concrete wall velocities due to impulsive air blast loading. He suggests that the most severe spalling from blast loads may be due to coupling of spall formation and gross wall or containment motion. Additional information is provided by Lysmer [1983] with respect to underground shelters in his study on the dynamic behavior of tunnels subjected to impact loads.

Baker [1982] provides an overview of the Pantex facilities. The arrangement of numerous shelter designs and equipment are reviewed, including the new high explosive machining facility (see Booker [1979], Vol. I,II, III). Steps cited to be followed in designing buildings subjected to high explosives are: 1) develop conceptual building design, 2) define the hazardous environment, 3) predict building, equipment, and personnel response and 4) perform an iterative design to provide hazardous resistance.

A number of manuals utilized for design quidance at the Pantex facility and worthy of review by the designer of protective structures are: TM5-1300 [1969] (in revision), DOD 5154.4S [1978], Pantex plant design criteria manual (PCDM), AMCR385-100 [1977], ERDA (Division of Construction, Planning & Support) [1977], DOE (6430), URS [1976], Texas Tech. (for AEC) [1975], and Texas Tech. (for AEC) [1974].

2.2.5 Structural Dynamic Analysis (Global-Force-Motion Hazards)

An important part in the development of a design of a protective structure to resist the force - motion induced hazards resulting from an energy release or explosion is the dynamic response analysis of the structure and its components or parts. The force - motion hazards are: blast (pressure waves), missiles, and foundation motion. TM5-1300 divides structural response into two parts:

1) structural members which respond to: (a) pressure only (low-pressure) and (b) pressure - time relationships intermediate - pressure design range and
2) structural members which respond to the impulse (high pressure design range).

If the duration of the pressure pulse is short compared to the period of a structure (1/30 or less), the pressure pulse may be referred to impulsive. On the other hand, if the period of the component is short compared to the pressure pulse, then all loads may be considered quasi-static (refer to MacDuff [1968], Gwaltney [1964] and [1968]). Some of the characteristics associated with blast, missile, and foundation motion hazards have been discussed previously in this section. The designer or analyst may be required to consider that the structure (containment, barricade, shelter) may be subjected to any combination or all hazards simultaneously (of blast, missile impact, and foundation motion). As we have seen in the previous section, most analytical predictive methods of structural response (as well as hazard dynamics) for force-dominated hazards have followed similar paths of development and investigation: first classical theoretical approaches in their early stages, then followed by numerical techniques in the late 1950's and early 1960's with the introduction of the digital computer.

Structural analysis and design has probably received the greatest attention (to a greater extent in the last several decades) with respect to the evaluation of <u>foundation motion</u> because of the interest in the seismic analysis of many commercial structures (particularly in nuclear power plant design). <u>Impact phenomena</u> (as discussed in section 2.1.3 on terminal ballistics) has received considerable attention also, as is evident by the number of programs utilizing computer-aided design and analysis methods such as the finite difference and finite element methods. <u>Blast wave propagation</u> has not received as much attention with respect to numerical computer programs to solve overpressure, reflection, and dynamic pressure effects (by such codes as PISCES). This is probably attributable to the fact that blast effects are fairly well understood in a theoretical sense (Glasstone [1962]) and there is little coupling between blast in air and barricade or protective structures. Pressure-time-history prediction from a blast loading can be complex (as has been discussed) when it occurs within a confined or partially confined enclosure. The modeling of the influence of internal equipment, baffles, etc. have been attempted with some success with finite difference codes such as PISCES.

When considering <u>missile impact dynamics</u>, structural response problems may be categorized as:

1) high local nonlinear dynamics and low global coupling => high (above 5000 fps) velocity and
2) linear to nonlinear local effects and high global coupling => intermediate (1000 to 5000 fps), low (100 to 1000 fps), Hertz or contact (<100 fps) velocity.

A considerable amount of computer numerical simulation development has been devoted to impact phenomena.In the section on terminal ballistics (2.1.3), it was shown that many finite difference and finite element codes have been developed to investigate the local missile - target impact response. Finite difference codes have predominated in this application. In contrast to this, finite element has become the predominant tool for a numerical computer simulation of the global structural response due to the dynamics from impactive and impulsive loads. This is evident in the number of publications presently appearing in the literature.

<u>Foundation motion</u> induced by a system rupture or explosion utilizes essentially the same analytical predictive techniques as those for seismic analysis of structures. The analysis of structures due to foundation motion have their origins in classical solution of simple elastic members or structures, but have evolved to the numerical computer based methods of the present.

An important part of structural analysis is a proper description of the material behavior. This has been emphasized in several sections of this report, for example in sections: 2.1.2, the subsection on Blast Generated Fragments, and 2.1.3 the subsection, Experimental Measurements (trajectories and dynamic material behavior). Additional guidance with respect to material testing and characterization may be found at the end of the list of references under design guides. The reader is also directed to Smith [1977], ANSI/ASTM [1975], ASTM [1978] (annual book of ASTM standards), and MSH [1976] (military standardization handbook of metallic materials).

Protective structures subjected to extreme loading such as missile impact or blast wave effects from pressure loads are usually permitted to respond inelastically. The theoretical response of a structure and hence its distributed stress and strains may be significantly different from the actual structure if, for instance, it were assumed that only elastic behavior prevailed. Figure 40 (Bathe [1976]) illustrates the comparison between the linear elastic and elastic plastic solution for a step pressure load applied to a spherical cap. The use of the additional load carrying capability beyond the yield limit is recognized in TM5-1300 in terms of a ductility ratio or ratio of maximum deflection to the equivalent maximum elastic deflection (at yield). An early discussion of inelastic effects in blast-loaded structures is presented by Biggs [1964]. More recently Campbell [1983] discusses the advantage of utilizing the Dynamic/Static ratio in order to examine the conservatism in the ASME code rules for the design of metal piping systems subjected to earthquake and impulsive loads. Campbell recommends the revision of the current ASME criteria which utilizes a constant factor of safety for dynamic and static loads.

Amann [1981] reports an experimental and numerical investigation of reinforced and prestressed concrete beams subjected to shock loading. This study in Switzerland is oriented to investigating energy-absorbing capacity in the plastic range for the design of nuclear containment structures. Using 25 ft. beams, a number of parametric influences are investigated such as: damping, influence of pre-existing plastic deformation, etc.

As mentioned earlier, different types of explosions with the same energy content (involving, for example, condensed high explosives, liquids, gas, or material characteristics) can result in blast waves whose pressure-time histogram that are applied to the structure vary significantly. Baker [1980] (see Figure 41) compares the effects of a typical triangular pressure time histogram versus structural loading characteristics of gas-type explosions. The effect of blast wave characteristics from an argon blast wave pressure time-histogram on structural loading is illustrated in Figure 42. The comparisons clearly show that the characteristics of the blast wave can play an important part of predicting the response of a structure. In fact, Baker observes that the negative phase of the blast wave (under certain conditions) can be the most important factor.

In some instances <u>specified pressure characteristics</u> must be considered in the design of a protective structure. An example is the IAEA (International Atomic Energy Agency) standards for siting of nuclear power plants for pressure waves resulting from deflagration of saturated hydrocarbons.

A number of other effects that can influence the dynamic response of a structure are damping, coupling, and local flexibility (or boundary conditions). Damping can significantly reduce the amplitude response of elastic structures. In general structural material damping may be considered to range from 2 to 5% for most structures. ASME Non Mandatory Appendix N assigns damping values by earthquake magnitude, components, and material (eg. bolted structures, reinforced concrete, etc. and Operational Basis Earthquake (OBE) & Safe Shutdown Earthquake (SSE) events).

Two very important questions that confront the designer of a structural system for dynamic loading are: how much of the overall system must be included in his theoretical model to perform a reasonable analysis, that is, do the adjacent components of the structure influence the dynamic response of the component in question; and can the boundary conditions of an isolated component be idealized. Prior to the development of high- speed digital computers and resulting numerical methods, this question was more urgent. However, even today with the ability of the analyst to idealize most of the details for the structure to be evaluated, the question is still relevant. It has been demonstrated through numerous papers, that coupling effects can be indeed quite important. A few examples are : discussion by Brown [1977], on the influence of boundary conditions upon the axisymmetric vibration of a spherical shell, and Scavuzzo [1980] on the seismic analysis of multisupported components.

Dynamic Analysis Methods.

Dynamic analysis methods may be classified into two broad categories: Classical methods and numerical methods (using computer solutions).

Classical solutions have their strength in being able to perform economical parametric studies. Their disadvantage is that they are usually solved for particular boundary conditions and relatively simplified structural geometries.

A discussion of classical solutions may be found in such reference texts as Biggs [1964], Norris [1959], DenHartog [1947], Thompson [1948], and Harris [1961] (Vol. I & II). Baker [1980] provides a cursory review of a variety of classical and numerical methods of calculating structural response due to dynamic impactive and impulsive loads.

In general, classical solutions are usually reduced to graphical form or a simplified procedure for the use of the designer. Solution approaches are generally categorized as modal (response spectrum or step-by-step integration) or direct integration. The modal method utilizing the response spectrum techniques has received broad acceptance in seismic analysis. However, some concern remains with respect to the appropriate summing techniques of the modes (see Brown [1980] and ASME Non Mandatory Appendix N). This cost-efficient method yields only maximum response (displacements, stress, etc.). A step-by-step integration time - history modal solution (for an illustrative example, see Brown [1983]) is less expensive than direct integration and yields response versus time solutions. Modal one-degree-of-freedom methods of determining the peak displacement of a structural element is presented in TM5-1300 [1969], Biggs [1964], Norris [1959], U.S. Army [1965] (TM5-856), DCPA [1972], Crawford [1974], Healey [1975] and Tseng [1975]. This approach provides relatively good accuracy when the duration of the loading is greater than the fundamental period of the structure. For transient solutions with one-degree-of-freedom elastic equivalent systems, numerical or closed-form integration is straightforward.

Another theoretical approach, that is similar to the response spectrum method for base excitation, is called the P-I (Pressure - Impulse) Method. A P-I diagram for the structural component defines the pressure and impulsive asymptotes between impulsive loading and quasi-static loading. Abrahammson [1976] illustrates the effect of pulse shape for a linear spring-mass system. Baker [1978], [1980] discusses the use of energy solutions to determine P-I diagrams for beams and plates: (1) subjected to a variety of boundary conditions, (2) elastic-plastic, and (3) axial and transverse loading. Using the P-I approach, no displacement time history is obtained but rather only the peak displacement is computed, similar to the response spectrum method for computing ground motion. Additional references that provide dynamic structural equations and graphs for an estimation of the blast load are provided by Greenspon [1976] and Westine [1974, 1975 (reports #4, & #6), and 1972]. Rotz (see Peterson, [1976]) in his paper on the Evaluation of Tornado Missile Impact Effects on Structures discusses different aspects of: the spring-mass model, force-time solution, energy balance solution and elastic/elasto-plastic/nonlinear resistance-displacement functions.

Finally, a number of survey papers that are suggested for a review of approximate methods for plastic influences in dynamically impulsively loaded structures: Baker [1975, 1979 (Shock & Vibration Digest), 1975 (EM-CR-76043)], Lee [1970], Kaliszky [1970], Symonds [1973, 1974, 1975], and Neil [1977].

Computer-aided numerical solutions have the advantage of representing the idealized structure as close to actual conditions as computer capacity will allow. This translates into an advantage over laboratory tests by being able to look in detail at all the effecting variables. The disadvantage is that numerical solutions may be classified as "one-of-a-kind," hence parametric studies (for example, with finite element or finite difference idealization) may require many models and solutions. Costs are comparatively much greater for numerical methods than with classical solutions. In many instances (based on cost studies of the computer simulation vs. experimental test) numerical simulations are cost effective, particularly when the designer is evaluating a large expensive structure that cannot be cost-effectively tested by an experimental program.

Of the numerical methods utilized to perform dynamic structural analysis, the finite difference and finite element methods are the most frequently cited. The finite element method has its origins in the development of numerical structural computer analysis. The difference solutions tend to historically come from those areas investigating transient response such as thermal and fluid dynamics. The finite element method is currently the most popular method for performing computer aided design (CAD) and analysis of structural components. This popularity traces its roots to the fact that the finite element method is basically a stiffness formulation which has been familiar to the structural analyst as a method of employing a variety of solution strategies. Another reason for the finite element method's appeal is its simplicity: the independent variables are expressed in terms of a polynomial that are assumed within a finite region called an element, local constitutive conditions are assigned within the element, and the overall component matrix is assembled from the elemental calculations. A comparison between the finite element and finite difference method is provided in the text edited by Fenves [1973]. There are many similarities between the finite element and finite difference methods, but procedurally they are different. A number of excellent review texts of the finite element method are available by authors such as: Gallagher [1975], Bathe [1976], Zienkiewicz [1977], Cook [1981], and Connor [1976]. Excellent surveys or reviews of computer codes and methodology are provided in the volumes edited by Pilkey [1974], Perrone [1977,1978], and ASME Decade of Progress (Chapter 8, Computer Technology) [1976, 1982].

While the finite element method is conceptually quite simple, its efficient utilization is dependent upon the digital computer to solve large matrices, perform extensive bookkeeping, and be assisted by a variety of pre-and post-processors. Hence the finite element technique must be looked at from the view of a total system of hardware and software. Pre-processors usually consist of mesh generators, geometry plots, and diagnostics. Post-processor programs usually consist of data reduction, data plotting, and data interpretation. Figure 43 illustrates the impact response of a containment structure predicted by the finite element method. Figure 44 illustrates the dynamic pressure response of a concrete cooling tower. An overview of the total finite element system is presented by Brown [1983]. Refer to Figures 45 and 46 for illustrations of a CAD finite element procedure.

Tables 15a and 15b list 18 programs that have received some use and discussion in the public forum, are available under various arrangements, and have been used to perform dynamic analyses for either one or all (blast, impact, or foundation) motion analysis. As can be seen, not all programs have the same solution features built in. The user must evaluate the type of problem to be solved and examine the capabilities of the computer code. Design and analysis code and standard criteria may dictate also the necessary features, for example if the structural adequacy is based upon elastic strain or stress limits, then inelasticity is not necessary. This is characteristic of seismic analysis of components and structures per ASME codes and standards. On the other hand, as has been cited, some criteria permit plastic deformation (and strains) when designing a structure. Many of the cited computer codes in Tables 15a & 15b have their origins in the development of Wilson's SAP code.

There are a number of excellent finite element and finite difference computer codes that have been developed to solve dynamic impulse, impact, and foundation motion problems for which limited space here does not permit a development of various computational characteristics or strategies. However a reference of public domain computer codes and their capabilities is available from COSMIC and other similar sources. Finally, a few additional computer dynamic analysis programs of interest are: DYNFA (STEA [1977]), PETROS IV (Piroten [1976]), DEPROSS (Wu [1972]), and AGGIE I (Haisler [1977, 1978]).

2.2.6 <u>Structural Degeneration Hazards: Design and Analysis</u>

Degenerative type hazards are: temperature, chemical, biological, and radioactive effects. A protective system may be required to interdict the effects of one or all of these hazards. The types of facilities associated with these types of hazards are: explosives handling (temperature), chemical research and processing (chemical toxicity), biological research (carcinogen), and nuclear power and processing (radioactive). It is not within the scope of this present study to go into the detail that is required with respect to the design of structures and systems oriented to specific degenerative type hazards that must be considered; however, some salient points will be reviewed. Protective measures against degenerative type hazards may be classified into two categories: <u>active</u> and <u>passive</u> systems. Material characteristics of containment structures, barricades, and shelters are examples of passive design. Examples of active protective systems are: monitoring devices, reactive systems (such as fire suppression systems), pressure control, filtration, disposal, and decontamination. These are important areas of consideration in designing a protective system.

Jensen [1972] provides a good cursory review of: <u>fire prevention and protection</u> (Chapter 3) and disposal and decontamination (Chapter 4). When considering facilities designed for fire prevention and protection, building design, electrical equipment, ventilation, heating, location, and extinguishing (or suppression systems) are important considerations.

In the symposium (Scott, ed. [1979]) on toxic chemical and explosive facilities, Rindner, Ewig, Carroll, Crosley, and Elkins discuss the use of infrared and ultraviolet detectors, and the use of quench - suppression systems (with extinguishing agents such as water, Halon 2402, Halon 1211, Halon 1301, Purple K, dry chemical) against flame explosion propagation. Jensen [1972] provides an extensive list of solid and liquid explosive material along with fire control methods and measures.

Barbeito [1979] describes laboratory design and operation procedures for chemical carcinogenic use. The main facility design features are oriented to address the concerns associated with controlling the air in the primary containment devices (such as fume hoods, safety cabinets, and containment systems). U.S. Dept. of Health, Education and Welfare guidelines (USDHEW [1978]) provide design criteria with respect to containment cabinets. In addition to facility design, emphasis is placed on medical surveillance, personnel practices, operational practices, control practices, and emergency procedures.

Scott [1979] discusses total containment and vapor containment in the Department of Defense safety program with respect to minimizing risk to personnel and property from chemical toxicity. Vapor containment can be achieved through negative pressure, controlled air flow, and walled or multiple walled enclosures in concert with detection devices. Hendrickson [1979] outlines a new design concept for a chemical maintenance facility of toxic munitions. Behringer [1979] gives some insight into the development of monitors to detect toxic compounds in a military processing facility. Additional references, such as Sax [1962], Fawcett [1980], National Board of Fire Underwriters, DDESB [1975], and USDHEW [1975] provide design guidance with respect to degenerative hazards.

2.3 SAFETY SITING CRITERIA (ENERGY DISTANCE CRITERIA)

Safety Siting Criteria (energy distance hazards criteria) may be divided into two areas of study: force/ motion hazards criteria and degenerative hazards criteria. The focus of this survey is force/motion hazards criteria, however a brief overview of degenerative hazards criteria is presented with some pertinent references (as has been done in the previous sections). A criterion must consider the effect on both personnel and structures (and equipment), where applicable. In an ideal design of a facility, the location of the potential hazardous source relative to personnel - structures - equipment requires an estimate of the characteristics of the hazard, distance, and the effects of various containment/barricade/shelter concepts. Most of the present criteria are oriented toward free field effects, ie., unimpeded hazards.

2.3.1 *Force/Motion Hazards Criteria*

Personnel. Personnel injury has been divided into three categories (Jensen [1972]): *primary blast* criteria, *missiles* (penetrating and nonpenetrating), and *displacement* (differential displacement of body parts and/or displacement of the entire body).

The *eardrums*, the *sinuses*, the *lungs*, and soft tissue are sensitive to blast damage. Lung damage which results in air bubbles reaching the general circulation is most dangerous and is usually fatal. Suffocation from lung hemorrhage and edema, and heart failure can occur. Some of the factors influencing the severity of blast injury to pressure are the *rate of rise* and *duration* of the pressure wave (White [1965, 1968, 1971]). Table 16 outlines blast hazard criteria taken from Jensen [1972] based on studies by White [1959, 1965] and Richmond [1962]. This data includes blast, missiles, and impact criteria for body translation as a consequence of blast effects. In general, bodily displacement injuries tend to be of greater concern as a result of blast effects than ground motion. The hazards associated with ground motion (as has been discussed and will be discussed further in the next section) are related to structural failure. These criteria are considered to be tentative based on the state of the technology at that time. Investigators have taken two basic approaches in studying force/motion from blast effects on human subjects: White [1959, 1965, 1971], Richmond [1962,1968], and Bowden [1968] have extrapolated their results from experiments on laboratory animals and VonGierke [1967, 1971, 1973], Kaleps [1971], Carmicheal [1973] and Fletcher [1971] have utilized simulated human body response by way of laboratory models. Baker [1975] reviews the studies of White [1971], Richmond [1978], and Bowen [1968] with respect to pressure versus duration lethality on humans for lung damage and presents lethality criteria curves for scaled overpressure versus scaled impulse shown in Figure 47. Additional data is presented by Danon [1970] and [1974] for blast effects on the respiratory system. Generally, these studies indicate that the threshold of lung damage is an incident pressure of about 5 psi incident overpressure or 12 psi reflected pressure. The eardrum rupture threshold has been cited as approximately 2.5 psi incident overpressure or approximately 5 psi for reflected pressure as a threshold. Figure 48 illustrates the relationship of ruptured eardrum criteria versus maximum overpressure based on studies by Vadala [1930], Henry [1945], Reider [1968] and Hirsch [1968]. The threshold and 50 percentile of exposed eardrums rupture (5 psi and 15 psi respectively) corresponds to the reflected pressure utilized in the JANNAF Handbook (Jensen [1972]). Not as much data has been collected for eardrum damage as has been collected for lung damage from blast, hence a good definition of incident overpressure versus specific impulse criteria is not cited.

Noise as a result of shock overpressure has been cited by Fryer [1981] as 170 db for eardrums and 165 db for windows (1 psi and 0.5 psi respectively) based on Swisdak [1975].

Nonpenetrating missile impact, penetrating missile impact, skull fracture, and total body impact criteria are illustrated in Table 16 from Jensen [1972]. These studies are oriented toward consequences of human body displacement during blast overpressures and impulse such that the body is picked up and translated. Since much of this data was developed by missile impact, it also provides some criteria guidance with respect to total missile impact on humans. Figure 49 provides an illustration of overpressure injury criteria versus equivalent TNT weight. Studies reported by White [1959, 1965, 1968, 1971], Hirsh [1968], Clemendson [1968], Ahlers [1969], VonGierke [1971], and Baker [1975] (NASA CR-134906) form the basis for the development of criteria in this area. Baker's studies have been oriented toward development of a method to predict blast incident overpressure and specific impulse combination that correlates with the critical velocities for human bodies (illustrated in Table 16). The results are provided in readily usable curves for skull fracture and bodily translation. Baker, 1984 (see Brown [1984]) reviews the effects of fragment impact on humans. For high speed bullet and fragment impacts, Baker suggests the use of Equation 33 to calculate skin penetration (Refer also to Baker [1975, 1980]).

$$V_{50} = 1247\ (A/M) + 22.03\ m/s \qquad |33|$$

$$\text{for } A/M \leq 0.09\ m^2/kg, \quad M \leq 0.015\ kg$$

where A = cross-sectional area of fragment
M = fragment mass, kg
V_{50} = ballistic limit velocity, m/s

This equation is based upon studies by Sperrazza [1967], and Kokinakis [1974]. Sperrazza's data is based on the impact of steel cubes, spheres, and cylinders into thick isolated skin and Kokinakis utilizes plastic sabots fired into gelatin to simulate skin. Masses up to .033 lbs were used. Baker correlates data from Glasstone [1962] (for glass fragments up to 2×10^{-2} lbs), White [1961] (for spherical bullets with weight of 0.0191 lbs), and Custard [1970] (for glass with weight up to 0.033 lbs) which indicates the relative consistency of Equation 33.

For nonpenetrating effects, the "personnel response to fragment impact" curves, Baker [1983] (Explosion Hazards and Evaluation) set a criteria for large, low-velocity, industrial missiles. Figure 50 illustrates criteria curves for the velocity versus personnel response to fragment impact for abdomen and limbs. Figure 51 illustrates threshold criteria curves for serious injury to the head and thorax based upon fragment velocity versus fragment weight for personnel response to fragment impact. Clare [1976] presents a probability function of lethality which has as variables: personnel mass, fragment mass, impact velocity of fragment, diameter of equivalent sphere of fragment, and curve fit parameters. Equation 34 illustrates this probability function by Clare.

$$P_L = \frac{1}{1 + \exp |a+\beta \ln (MV^2/WD)|} \qquad |34|$$

where P_L = probability of lethality for person of mass W

a, β = curve fitting parameters determined by least squares
M = mass of fragment (g)
V = impact velocity of fragment (m/sec)
W = mass of person (kg)
D = diameter of equivalent sphere for a chunky fragment (cm)

Steffens [1952] arrived at the human threshold criteria for ground vibrations as: just perceptible, clearly perceptible, annoying (defined by 0.03, 0.1 and > 0.1 velocities in in/sec ranges respectively). This result correlates with those of Rieher [1931]. A good cursory review of the development of criteria for ground motion effects is provided by Baker [1982]. In this review a spectra diagram for vibration-induced noise criteria is provided that compares criteria from studies by Reiher [1931], Steffens [1952], Rausch [1943] and Thoenen [1942]. Duvall [1962] of the Bureau of Mines provides a review of acceleration criteria as a method to estimate damage to residences by vibration based on data from Thoenen [1942].

Structures. Force motion criteria for structures provide estimates of levels (or orders) of magnitude for some parameters related to the amount of structural damage.The criteria provide a basis for measuring reusability and safety to personnel. Curves providing estimates of damage to structures (single story, multistory, igloo, and a variety of load bearing material) are provided in the JANNAF Handbook which defines severe blast structural damage and moderate structural damage criteria in terms of TNT yield versus overpressure blast. The JANNAF handbook (Jensen [1972]) categorizes damage to reinforced concrete wall panels as follows:

Description of Damage	Type of Damage	Average Deflection Span, in./ft.
Slight	Slight Cracking & Bending	0.1
Moderate	Light Punching & Cracking with Possibly Some Spalling	0.5
Heavy	Heavy Punching, Shattering, or Possible Perforation	1.2
Breaching	Perforation with Extensive Scabbing Bars May be Bent or Bulged	- -

For metal walls, a suggested conservative estimate is to limit stresses to the elastic range. The ASME boiler code specifies elastically derived stress intensity factors on the metal wall surface to prevent plastic collapse (in membrane and/or bending).

The U.K. AEA High Pressure Safety Code suggests the following limiting values:

Unreinforced brick work	0.3 bar
Corrogated asbestos panels	0.15 bar
Glass windows	0.03 bar
Eardrum	0.07 bar
Reinforced concrete (safety walls)	10.0 m/s (limit impulse velocity)

TM5-1300 defines four protection categories: Category 1 (applies to personnel and is the most stringent), Category 2 (applies to shelters used for protection of equipment and stores of hazardous material), Category 3 (applies to barriers used for partial containment of explosives to protect other structures and explosives), and Category 4 (is similar to category 3 except limited communication of detonation is permitted). The structural response is limited by deflection or support rotations, for example: limit rotation is defined by $\theta_m \leq 5^{\circ}$ (maximum support rotation angle) and is cited for protection of category 1. Large rotation is considered for $\theta_m > 5^{\circ}$ but < incipient failure rotation. Category 2 may operate in this range (from $\theta_m = 0$). Categories 3 and 4 may operate between $\theta_m = 0$ to total destruction. A number of design parameters cited by TM5-1300 that influence the designers decision are: the protective structure type, pressure design range, structure load sensitivity, design method, deflection criteria (ductility factor, maximum support rotation), cross section type, design stress f_{dy} and f_{du} (dynamic yield stress and dynamic ultimate stress), brittle mode (crushing, scabbing, spalling).

The USDOD Ammunition and Explosive Safety Standards (5154.4S) utilizes the blast standoff criteria similar to those first developed in the American Table of Distances (see Equation 1):

$$R/W^{1/3} = K \text{ (constant)} \qquad |35|$$

Note: DOD 5154.4S uses
D = R ≡ (distance from NEW (net explosion weight))

The DOD hazards classification system is based on the United Nations (UNO) which consists of nine classes of dangerous goods. Explosive material is included in UNO Class 1, "Explosives"; and toxic chemical, agents, and containers of toxic chemical agents are included in UNO Class 6, "Poisonous Toxic and Infectious Substances". A comparison of hazardous classification/compatibility groups between DOD class 1, and the Department of Transportation (DOT) classifications are shown in Table 17 (with storage compatibility mix chart). Distance criteria applied to the DOD class 1 division 1 hazards are divided into the following ranges:

1) igloo magazines
2) above ground magazines
3) underground chambers
4) exposure levels of 10 to 11 psi (K=9)
5) exposure level 3.5 psi (K=18)
6) exposure level 2.3 psi (K=24)
7) exposure level 1.7 psi (K=30)
8) exposure level 1.2 - 0.85 (K=40 to 50)

As an example, item 4 indicates unstrengthened buildings will suffer severe structural damage approaching total destruction and personnel are expected to suffer severe injury or death in the exposed sites from direct blast, building collapse or translation. Item 8 indicates that unstrengthened buildings are expected to sustain damage up to about 5% of replacement cost and personnel are provided a high degree of protection from death or serious injury, but injury is possible by glass breakage and building debris. Factors are incorporated into Equation 35 to account for different effects such as: f_c (earth cover factor), f_d (chamber loading function), and f_g (a decoupling factor, a function of loading density). The use of TM5-1300, AFM 88-22, and NAVFAC P-397 for the design of protective structures may be used with DOD 5154.4S.

When considering the design of containment structures subjected to internal blast loading, Tunkel [1983] presents an estimate of the blast pressure criteria (see Figure 36). Structural criteria that are used for external loading are considered applicable for internal loading.

Healey [1975] recommends deformation criteria for steel framed buildings based on the following parameters: ductility ratio (μ = (max. allowable deformation)/(elastic limit deformation), maximum permanent rotation (θ_{max}), and relative deflection (H /1) for deflection per beam length between floors).

	θ max		μ	
	reusable	non-reusable	reusable	nonreusable
Beam	1°	2°	3	6
Plate	2°	4°	5	10
Open-web joist	1°	2°	2	4
floor and wall panels (cold formed)	0.9°	1.8°	1.25	1.75
			H/1	
Frame structures	1°	2°	1/50	1/25

Wilton [1972] provides an evaluation of a number of test dwellings that were exposed to high explosives and nuclear blast waves. The test structures were organized into four groups based on the type of construction. Estimates are provided for dwelling item damage based on an assessment of percent to repair each area or item as a function of the total repair cost.

A number of U.K. papers providing guidance with respect to building response to explosions is provided by Mainstone [1971, 1973, 1974, 1976]. Criteria for glass breakage (Mainstone [1971]) is provided as a function of glass area thickness and pressure. The blast standoff criteria generally used in the U.K. is based on the studies reported by Jarrett [1968] entitled "Derivation of British Explosive Safety Distances" (See Equation 36 and Figure 52).

$$R/W^{1/3} = \frac{K \text{ (constant)}}{|1 + (7000/W)^2|^{1/6}} \qquad |36|$$

Additional criteria have been suggested by Brasie [1968], Glasstone [1962], and O. Johnson [1967] with respect to blast effects.

With respect to blast generated ground shock, the greatest hazard is to the structures rather than directly to personnel. Personnel are in danger of injury through structural failure. Nicholls [1971] has correlated data developed by the Bureau of Mines, Thoenen [1942], Langefors [1958], Edwards [1960] to provide a "displacement amplitude versus frequency" derived criteria for three levels of structural damage (see Figure 53). These three criteria relate particle velocity of the foundation as a criteria for structural damage. This is consistent with the studies reported by Dvorak [1962] who investigated the effect of explosive charges on brick buildings. It is interesting to note that the safe-damage zone of 2 in/sec. is very close to that of Crandall [1949] of 3 in/sec. The U.S. Department of Interior has used a charge weight and standoff distance criteria ($W=(D/60^2)$) that is cited by Morris [1957] which is based upon a ground particle velocity of 3 in/sec. A number of references citing information on ground shock induced equipment damage are Eubanks [1963], Odello [1976], Meireis [1973], Batchelder [1974], USACE [1975] (HNDDSP-72-156-ED-r) Vol. I and II.

Finally, a number of references for design criteria not discussed, but worthy of review are the safety standards for high pressure systems facilities (Pohto [1981]), ERDA (Manual 6301) [1977], DOE (Manual 6430) [1983], URS [1976] (Design Basis

Tornados and Design Manual for the Pantex Plant Site), AMCR (385-100) [1977] (Dept. of Army Safety Manual), Pantex Plant Design Criteria Manual (Current Edition), and Saville [1977] (U.K. High Pressure Safety Code).

2.3.2 Degenerative Hazards Criteria

Degenerative hazards have been categorized as temperature, chemical, biological, and radioactive criteria for buildings and personnel. Since the primary emphasis of this study is blast and fragmentation, only a cursory review of degenerative criteria is presented here, however, this in no way is intended to diminish the importance of this area of study to develop criteria.

Personnel & Structures. Criteria for skin burns have generally been defined either by thermal energy per unit area (Q) or heat flux (q) versus time (t). A number of studies in this area have been mentioned in section 2.1.5. In one of these, Jarrett [1968] provides criteria of first, second, and third degree burns as a function of Q versus t (see Figure 54). In contrast to this criteria Buettner [1950] provides criteria based on heat flux versus time illustrated in Figure 55. Glasstone [1962, 1977], provides threshold radiant energy criteria based on nuclear radiant energy (as is Jarrett's data). Glasstone also provides approximate radiant exposure for ignition of household materials, dry forest fuels, and fabrics. If the source explosion and fireball is a consequence of a vapor cloud, Baker [1980] suggests that for an unconfined vapor cloud, a maximum of 10% of the total available vapor is considered to be involved in the explosion estimate for blast yield (or energy content), however 100% of the fuel is assumed to be consumed in generating a fireball. When considering damage to the eye (rods and cones) as a result of exposure to thermal energy, Miller provides a set of curves for various exposure times as a function of thermal energy versus image diameter. This data was obtained as a result of experimental studies on primates.

The National Fire Protection Association provides guidance with respect to compounds relative to fire hazards, toxicity, and reactivity. As mentioned earlier the DOT (Department of

Transportation), UNO (The United Nations Organization), DOD 5154S, and JANNAF (Jensen [1972]) provide guidance with respect to handling, storage, transportation, disposal, and decontamination of various toxic and explosive substances. A listing of applicable government documents are provided in the JANNAF chapter 6 manual (Jensen [1972]). Katsanis [1979] reports work on heat flux and pressure suppression shields and demonstrates a substantial reduction in radiant heat flux versus time. He reports a need for predictive methods (see Rakaczky [1975]) to develop criteria for heat flux suppression.

A number of laws and guidelines regulate the type and toxicity of chemical hazards to which personnel are exposed (for short term and long term). The major governmental regulatory philosophies are outlined by McNamara [1978]. The National Environmental Policy Act (PL 91-90) states that nothing will be put into the environment which will have short and/or long term adverse effects on: man, domestic animals, wild life, property, recreational values, or cultural values. The Clean Air Act of 1970 (PL 91-6604) cites that short term and long term effects on health include: toxicological, behavioral, biochemical, immunological, physiological, teratogenic, mutagenic, and carcinogenic effects. The Occupational Safety and Health Act of 1970 (Pl 91-596) cites that no employee will suffer diminished health, functional capacity or life expectancy as a result of the work experience. The Toxic Substance Control Act of 1976 states that chemicals will be tested for safety to man and the environment by the producer. A number of guidelines to toxicological testing are cited by McNamara. The reader is directed to this article for FDA, EPA, NIOSH, DOT, CPSC, NIC, NAS, CFR and FR guidelines; however the emphasis of this study is oriented to systems, structural, and facilities preventative and protective methods.

A number of standards are cited by Barbeito [1979] with respect to laboratory design and operation procedures for chemical carcinogen use, such as USDHEW [1978] and USDHEW [1975]. Barbeito provides a discussion with respect to laboratory containment cabinets, filtration systems, and permeability of laboratory equipment. Scott [1979] discusses the role of the DOD Explosives Safety Board in setting safety criteria with respect to chemical agents. The personnel are protected from the unexpected release of agents using the DDESB-quantity distance standards based upon hazard radii from the source which is outlined in DDESB technical paper #10 entitled "Methodology for Chemical Hazard Predictions" [1975]. Of the two types of containment available, vapor containment and total containment facilities, the containment structure of either facility is equipped with a means of attracting or detoxifying the evaporated or aerosolized chemical agents by filters, scrubbers, incinerators or other appropriate means. Total containment consists of two designs. One is capable of retaining all fragments and explosion effects while preventing release of detectable quantities of agents. The second type (under study) is a suppressive shield concepts capable of retaining fragments and sufficiently attenuating blast forces while a chamber retains the combustion gasses and prevents release of toxic chemicals. The vapor containment concept is under study to provide negative pressure, controlled air flow, and walled or multiple walled enclosures which will contain any detectable quantities of agent release. The use of detectors and monitors (as mentioned earlier) play an important role in leak detection. Hendrickson [1979] outlines design criteria for standard chemical maintenance facility at DARCOM with respect to safety manual and regulations cited in AMCR 385-100 [1977], DARCOM - R385-102 [1977], AMCR 385-31 [1975], and AR 50-6 [1976]. These standards cover respectively: explosives, toxic agents, disposal, and maintenance. Whelen [1979] provides some insights into the disposal process, procedures, and equipment in the demilitarization of chemical munitions by the Army. The safety design criteria cited are: total containment, ventilation, monitoring/detection, and safety/medical. Total containment is identified by four areas: toxic material control, accidental explosion control, remote control equipment, and operating and maintenance procedures. Ventilation is identified or classified by four areas: volume flow/face velocity, air lock/buffer zones, localized ventilation, and filters/afterburners/scrubbers. Hendrickson [1979] illustrates personnel protective clothing from level A to level F. Barbeito [1979] illustrates facility code compliance with respect to medical surveillance, personnel practices, operational practices, control practices and emergency procedures.

2.3.3 Probabilistic/Risk Analysis

An area that is receiving greater attention with respect to eliminating unnecessary conservatism in overall system performance from design to safety and incorporating operating experience from well organized data bases is the area of probabilistic and risk analysis. Some recent studies in the area of vessel and components evaluation and energy release protection are provided by Sundararajan [1978], Sundararajan [1984] (see Brown, ed. [1984]), Fong [1978], Gangadharan [1977], ASCE [1980] (Vol. V - see Haldar), Haldar [1979, 1981, 1983].

Haldar presents a probabilistic analysis into the damage predicting equations for spallation and penetration in concrete. The probabilistic approach shows, for example, (Haldar [1981]) that the NDRC equations with a safety factor of 1.2 are unjustifiable in a probabilistic sense. Sundararajan [1984] outlines a procedure to consider fragment ejection and impact as a part of the probabilistic methodology. As pointed out by Haldar, the probabilistic characteristics of all the parameters involved should be considered.

A number of excellent articles are provided in the volume edited by Gangadharan and Brown [1977] on probabilistic methods, failure data, and risk assessment. A number of methods or techniques such as the Fault Tree, Monte Carlo simulation, equation rating techniques, testing and use data, and the Go methodology are presented. A list of some of the topics discussed in this volume are: current programs on power plant availability and reliability data systems; failure data collection and analysis in the Federal Republic of Germany; failure analysis and failure data collection in the ERDA coal conversion system; review of the liability in piping and lightwater reactors; a solution of the failure data problem in the processing industries; failure data and risk analysis; a workable approach to extending the life of expensive life-limited components; a method for generation of fault tree; and systems reliability analysis using the Go methodology.

Eichler [1977] provides an example of a risk evaluation of the effects of an accidental vapor cloud explosion on nuclear plants located near transportation routes.

Baker [1975] (NASA CR-134906) provides a limited development of a risk assessment and integrated effects with respect to predicting pressure wave and fragment effects from exploding propellant tanks and gas storage vessel hazards. The three basic systematic methods cited are employed either singly or in combination: an event tree, fault tree, FMECA (failure mode effects and criticality analysis). Five different scenarios are considered: building and personnel damage are considered, as well as blast, fragment, and barricade effects.

The prospect of performing an evaluation of criteria and utilizing large data bases from operational and accident data seems formidable, however the benefits when considered in light of the potential cost savings and safety offer great prospects.

3.0 ENERGY DISTANCE CRITERIA (FOR GAS FILLED VESSELS & BLAST & FRAGMENTATION HAZARDS)

Part 1 of this report consists of a review of the studies into energy release protection. The purpose is to provide a survey of the relevant technical research that has been performed in various industries and engineering disciplines with respect to energy release protection of concern to the pressure vessel and piping designer. Three areas reviewed in Part 1 of this report are: hazards, containment/barricading/shelter protection, and safety siting criteria. Hazards have been classified into two categories: 1) force/motion and 2) degenerative. Hence, all hazards are not energetic.

In this part of this report, guidelines are provided with respect to energy-distance criteria based upon existing data reported in Part 1. Part 2 provides a development and discussion of energy distance criteria, along with examples, and a technical evaluation. This part of this report is limited to single-phase, inert gas systems,that is,the contained medium is non-toxic, non-flammable, and non-explosive. The principal hazards of concern in this part are those as a result of blast and fragments.

Two methods for identifying (1) the source of potential vessel, piping, or system failure; (2) blast and fragmentation hazards; and (3) the necessary siting or protective systems are outlined in this section. The first, and preferred method, is a probabilistic approach. The second, and more generally used approach, is the deterministic or "worst case" methodology structured in a performance criteria. Here the designer is expected to check each hazard and system characteristic to assure that the integrity (or performance) of personnel are not exceeded. Probabilistic methods provide a rational alternative to the current deterministic procedure by recognizing that stacking "worst case" methods on top of each other (with respect to system failure, hazards, and protective systems) can lead to very conservative estimates and in some instances unconservative and unsafe designs. On the other hand, "worst case" scenarios provide a starting point in the estimate of system safety from blast and fragmentation.

3.1 PROBABILISTIC METHODOLOGY

3.1.1 Introduction

If a gas-pressurized vessel bursts, the fragments (missiles) ejected during the burst have the potential to damage equipment and structures located in the vicinity of the vessel. Currently a deterministic, "worst-case methodology" is used to determine safe areas where equipment can be located or to determine the wall thickness of barriers necessary to protect equipment located in unsafe areas. However there are considerable uncertainties involved in the determination of the minimum distance to safe areas and in the determination of barrier thickness. The uncertainties are in the methods of determining the size, shape, velocity and ejection orientation of fragments, as well as in the damage-prediction formulas. Because of these uncertainties, no rigorous theoretical solutions are available and the deterministic procedures are based on limited test data. Paucity of sufficient data base and the wide scatter in the available data, not only make the worst-case, deterministic design procedures very conservative in most cases but the resulting design may also be unconservative and unsafe in a few cases.

Probabilistic methods provide a rational alternative to the current deterministic procedures. The probabilistic approach, instead of ignoring and conservatively upper-bounding the scatter in the basic test data, considers this scatter explicitly and propagates the uncertainties through the various steps of the evaluation to the final results. A rational design, set to an achievable and accountable safety goal, for example, say, 10^{-6} incidences of equipment damage per year, can be accomplished from the final probabilistic results. Also, depending on the importance of a piece of equipment, the safety goal (probability of equipment damage) can be increased or decreased; and a design consistent with this safety goal can be achieved. Such means of tying the design to specified safety goals (damage probability) are not available in the deterministic approach.

This section presents an integrated probabilistic approach for the evaluation of pressure vessel missile generation and damage potential. (Only damage due to fragments is discussed here; however, damage due to blast waves can be considered in a similar manner). First, an overview of the probabilistic approach is given, which briefly introduces the three phases of the approach, namely, (1) generation of missiles, (2) missile trajectory, and (3) missile induced damage. Next, each of the three phases is described in detail. Then a flow-diagram of the integrated method is given, and a discussion on how a fully probabilistic analysis or a hybrid deterministic-cum-probabilistic analysis can be carried out is presented. Research and development needs are discussed next, and finally benefits of the probabilistic approach over the deterministic approach are enumerated.

3.1.2 Overview of the Probabilistic Approach

The physical phenomena of pressure vessel missile generation and damage to equipment/structures involves three distinct phases:

1) generation of missiles
2) missile trajectory
3) missile induced damage

Probabilistic analysis of each of the three phases is discussed in Sections 3.1.3, 3.1.4, and 3.1.5. A brief overview is given here.

Weight, velocity and orientation of the missiles (pressure vessel burst generated fragments) depend on the energy stored by the vessel, the geometry and structural details of the vessel, and the failure mode. In the deterministic approach, a conservative estimation of the stored energy, upper bound relationships for the missile weight and velocity as a function of the energy, and worst-case shape and orientation are used. The probabilistic approach, on the other hand, estimates the energy in the form of a probability density function, develops the energy versus weight and velocity relationships in a statistical form, and also uses a suitable probability distribution for the orientation. Results of the probabilistic assessment of missile generation are probability density functions for the missile weight, velocity, and orientation.

The missile flight evaluation is rather straightforward. In the deterministic analysis, the trajectory, the strike location, velocity and orientation are determined using worst-case initial conditions (ejection velocity and orientation). In the probabilistic evaluation, the flight model (trajectory) is deterministic, but the initial conditions are random numbers, and so the strike location, velocity, and orientation are also random in nature.

Considerable amounts of data are available on barrier damage due to missile strikes. However, most data are for high-velocity, rigid, cylindrical missiles typical of ordnance applications and a limited amount of recent data for low-velocity, flexible missiles typical of nuclear power industry applications. In the deterministic approach, empirical damage-prediction equations developed using upper bound values of test data are utilized. However, even a cursory examination of the test data would indicate considerable scatter, and so a statistical description of the test data is most appropriate. The probability density functions of the strike velocity, orientation and weight shall be input to the statistical damage-prediction equations and the final result is the probability of potential damage to a barrier.

Thus the three-phase probabilistic analysis provides the following information:

1) missile strike probabilities for specified target areas
2) damage probabilities for specified barriers

These results can be used in decision making on locating critical equipment, and to determine the thickness of barriers to provide required levels of safety.

3.1.3 Missile Generation

The first phase of the analysis involves the determination of the pressure vessel failure probabilities, and given a pressure vessel failure the probability distribution of missile weight, velocity and orientation of ejection. We shall discuss these under two headings: 1) determination of pressure vessel failure probabilities, and 2) determination of the probability distributions of missile parameters.

Pressure Vessel Failure Probability. In its simplest form, the pressure vessel failure probability or failure frequency is equal to the number of vessel failures divided by the total number of years of operation. Sources for pressure vessel failure data in the U.S. include the Edison Electric Institute, the American Boiler Manufacturers Association and the National Board of Boiler and Pressure Vessel Inspectors (see U.S. Atomic Energy Commission [1974], National Board of Pressure Vessel Inspectors [1982] and Bush [1975]). Failure experience in the United Kingdom has been examined by Smith and Warwick [1981]. IRS-TUV of the Federal Republic of Germany has accumulated a large amount of pressure vessel failure data from worldwide sources (see Oberender [1978]). Marshall's second report [1982] summarizes the available failure statistics. According to this report, the upper 95% confidence limit for pressure vessel failure probability is in the range of 4.2×10^{-6} to 3×10^{-4} failures per operating year.

It should be noted that the above failure probability is based on a pressure vessel population covering a wide range of vessels in size, pressure rating, manufacturing, inservice inspection, quality assurance, etc. For a given vessel of specific characteristics, it is impossible to obtain failure statistics directly from the historical data, since the population of a specific pedigree of vessels is too small to provide any meaningful statistical estimates. It is a common practice to use the generic failure probability since these estimates, in any case, are accurate only in an order-of-magnitude sense. If the failure probability of a specific pedigree is required because it is determined to be too different from the generic population, the consideration should be given to the effects the differences in rating, manufacture, inservice inspection, etc. may have on the failure probability, and the generic probability shall be upgraded or downgraded on the basis of expert judgement. Formal methods for obtaining and assessing expert opinion have been developed by applied statisticians (see Linstone [1975]).

Pressure vessel failures may be categorized into two groups on the basis of failure mode:

Mode 1 normal operating condition failures, and

Mode 2 abnormal over-pressurization failures

The former failure occurs at about the normal operating pressure, due to the inherent weaknesses in the vessel; and the latter failure occurs at severe overpressures due to operator errors, system malfunction, etc. (abnormal conditions). This categorization is important in missile generation assessment, since the mode of failure determines the weight and velocity of the missiles generated due to vessel burst. (This is discussed further in the section on Probability Distributions of Missile Parameters). Again, the generic failure probabilities found in literature include both types of failures. Information on the type of failure are available in some of the data sources, and a categorized statistical evaluation will provide separate estimates of failure probabilities for both types of failures. Alternatively, or to complement this approach, one can estimate probabilities of system malfunctions and operator errors leading to abnormal conditions by rigorous systems engineering techniques such as reliability block diagram analysis or fault tree analysis.

Some of the pressure vessel failure scenarios of interest to NASA are unique. For example, one such hypothetical scenario is described in Baker [1975] as:

> "The space shuttle falls back just after lift-off due to failure of thrust. The shuttle falls back on the launch pad with sufficient impact velocity to rupture the pressure vessel".

Such scenarios are so rare that the probability of such failures cannot be estimated from historical data, except for making very conservative estimates using rare-event-statistic methodologies. If a more reasonable failure estimate is needed, a bottom-up deductive logic may be used to derive the failure probability. Noting that the pressure vessel failure occurs, not because of any inherent weakness in the vessel, but because the vessel is grossly overstressed because of an accident caused by control system malfunction, the vessel failure probability can be equated to the control system failure probability. The system failure probability can be derived considering (1) the reliability of the various system elements (basic electronic, electrical, and mechanical components) and (2) how these element failures propagate to system malfunction. Reliability analysis techniques such as reliability block diagram analysis or fault tree analysis can be used for this purpose. In fact, the reliability (hence, the failure probability) of many of the control systems in space applications are routinely determined by systems engineers as part of systems design, and such available results may be used to determine the pressure vessel failure probabilities due to accidental ruptures.

Probability Distributions of Missile Parameters. Missile generation parameters that are of interest in a damage assessment are: 1) number of fragments and weight of each fragment, 2) size and shape of the fragments, 3) ejection velocity and 4) orientation of ejection.

In the deterministic analysis, conservative values of these parameters are chosen such that the damage-prediction is the worst-possible case. What are required in a probabilistic analysis are the probability density functions for the weight of fragments, the ejection velocity and orientation (ejection angles).

Number of Fragments and Weight Distribution. The number of fragments generated and the weight distribution depend on a multitude of factors including the internal size and energy (or energy content), working media in the system, failure mode, size and geometry of the vessel, welds, attachments, dents, grooves, and flaws. One can assume that the nozzles, valves, flanges, reinforced openings, etc. may each be ejected as a single fragment, with the weight of these fragments more or less known. These types of fragments shall be classified as "Group A" fragments. As for the numerous other fragments from the body of the vessel, one has to make some statistical estimates on the basis of available test data. These types of fragments shall be classified as "Group B" fragments.

The number and weight of fragments depend on the mode of failure, whether it is a normal operating condition failure or an abnormal operating condition (over-pressurization) failure. In the former case the vessel failure is due to inherent weaknesses of the vessel, and such failures are usually due to brittle fracture, fatigue crack growth, stress corrosion cracking, etc. This kind of failure leads to smaller and numerous Group B fragments with a wide range of shapes and weights (in addition to the Group A fragments). In the case of abnormal operating condition failures, the failure is ductile in nature and is due to the overstressing of the vessel and/or piping material beyond yield stress. The resulting Group B fragments are larger and less numerous. Because of the differing nature of fragments generated in the two modes of failures, determination of the weight distribution shall be considered separately.

Normal Operating Condition Failures (Mode-1): A literature search for an expression for the weight distribution leads to Mott's equations (see Healey [1975]). These equations were developed for fragments generated by a high-order detonation of evenly distributed explosive within a uniform cylinder. Though this is not representative of most pressure vessel bursts, Mott's equation may be used as a starting point for the development of more appropriate equations. Mott's equations are given below (These equations are for Group B fragments. As noted earlier, Group A fragments are better understood). Total number of fragments is given by:

Total number of fragments is given by,

$$N_T = W_C / 2M_A^2 \qquad |37|$$

Where, W_C = total weight of the cylinder (lb),

M_A = fragment distribution parameter

$= B\ t^{5/6} d^{1/3} \quad (1+t/d)$

d = average inside diameter of casing,

t = average cylinder thickness, and

B = explosive constant (values for different types of explosives is provided by Mott. An applicable value for pressure vessel failures has to be determined by fitting test data to Equation 37.

The average fragment weight is given by,

$$\bar{W} = W_C / N_T + 2M_A^2 \qquad |38|$$

The weight distribution is given by,

$$(N_x / N_T) = e^{-\sqrt{W}/M_A} \qquad |39|$$

Where N_x is the number of fragments with weight greater than W.

In probabilistic form, Equation 39 can be written as,

$$F(W) = 1 - e^{-\sqrt{W}/M_A} \qquad |40|$$

Where F(W) is the cumulative distribution function of fragment weight W. The probability density function P(W) is obtained by differentiating the cumulative distribution functions with respect to W.

The probability density function derived from Mott's equation may not necessarily be applicable to pressure vessel bursts. Available fragment weight data from tests and accidents should be compiled and checked as to whether the data conform to Mott's equations. Either the λ^2 goodness-of-fit test or the Kolmogorov-Smirnov goodness-of-fit test may be used for this conformity check. If the tests disqualify Mott's equations as a suitable basis, then a suitable weight distribution should be developed from standard probability density functions such as the Gaussian, gamma, exponential, or lognormal distributions. Bayes method provides a suitable approach for selecting an appropriate distribution on the basis of judgement, and then updating the distribution using actual data. If the actual data available is sparse, opinions of experts can also be incorporated, assigning suitable weight for each expert's opinion. The Bayes method also provides a basis for updating the distribution when new test data become available in the future.

Abnormal Operating Conditions (Over-pressurization) Failures (Mode-2): As noted earlier, fragments generated by abnormal failures are larger in size, and so a weight distribution different from one developed for normal operating condition failures has to be developed.

Available information indicates that very large fragments can be generated (see Oil & Gas Journal [1956]). Holmes and Narver Company has recommended that 10% of the vessel weight be considered as the upper bound value (see Williamson [1973]). A probability density function with 10% of the vessel weight as the upper bound value (say, 99% probability of non-exceedance) may be constructed with the test and accident data. As with the normal operating condition failures, Bayes method provides a suitable vehicle for developing the probability density function. An urgent need in this area is to collect and statistically analyze available data on abnormal over-pressurization failures, followed by a carefully defined test program to generate additional data in parameter ranges where there is a void in the present data base.

Shape and Size of Distribution. Group A Fragments: The size and shape of these fragments are more or less known, and need no further discussion here.

Group B Fragments from Mode 1 Failures: The size and shape of these fragments are truly random, and for all practical purposes these fragments can be treated to have "standard military fragment shapes" (see Fig. 56, and Baker [1978]). (Most test data on missile induced barrier damage is for these types of fragments and so using these fragment shapes is prudent.) For these standard shapes, the equivalent cylinder diameter is a known function of the fragment weight. Since we have the probability density function for fragment weight, deriving the probability density function for the diameter, P(d), is straightforward.

Group B Fragments from Mode 2 Failures: There is no data base for the size and shape of these fragments.

Velocity Distribution. Fragment velocity is a function of the fragment weight and the energy of the pressure system. In deterministic analyses, semi-empirical formulas based on test data and analytical derivations have been employed to determine the fragment weight and system energy. The probabilistic approach utilizes the semi-empirical formulas and the limited amount of available data to develop the probability density function for fragment velocity.

Since fragment velocities are functions of system energy, we shall first discuss Baum's expression for system energy (see Baum [1983]). The energy is given by,

$$E = (P_o \phi_o / \gamma - 1) k \qquad |41|$$

Where

$$k = \left| 1 - (P_e/P_o)^{\gamma - 1/\gamma} \right| + (\gamma - 1)(P_e/P_o) \left| 1 - (P_e/P_o)^{-1/\gamma} \right| \qquad |42|$$

in which, P_o = *rupture pressure,*

P_e = *pressure of external atmosphere,*

ϕ_o = *volume of vessel, and*

γ = *isentropic expansion coefficient of compressed gas.*

Of the parameters entering the equation for E, P_o is an uncertain quantity since the exact value of the rupture pressure is not known. In the case of normal operating condition failures, P_o may be assigned a suitable probability distribution around the design pressure. Available rupture pressure data can be fitted to a candidate distribution such as the clipped Gaussian distribution, shifted gamma distribution, shifted lognormal distribution or a skewed triangular distribution. Alternatively, or to complement historical data, probabilistic fracture mechanics analysis can be conducted to determine the distribution of rupture pressure. Input to such an analysis includes the vessel geometry, initial flow distribution, inservice inspection data and the probability distribution of material fracture toughness. Detailed discussion of probabilistic fracture mechanics analysis is beyond the scope of this section.

In the case of abnormal over-pressurization failure, the rupture pressure is much higher than the design pressure. The probability distribution can be determined on the basis of a probabilistic ultimate load analysis of the vessel. The input required for such an analysis includes the vessel geometry and the statistical stress-strain relationship of the vessel material.

Once the probability density function of the rupture pressure, $P(P_o)$, is determined, the probability density function of the energy, P(E), can be determined from Equation 41, using standard probabilistic analysis methods.

Moore [1967] provides an empirical expressions for fragment velocity from cylindrical and spherical vessels.

$$V = 1.092(EG/M)^{1/2} \qquad |43|$$

Where,

$G = 1/(1 + (3C/5M))$ (for spherical vessels),

$G = 1/(1 + (C/2M))$ (for cylindrical vessels),

C = mass of gas,

M = mass of vessel

E = Eqn. 41

Baum [1983] presented theoretically derived equations for fragment velocity; two equations were presented, one for zero-mass fragments and the second for large-mass fragments. (It should be clarified that both these equations are for small fragments. The zero-mass equation provides an upperbound formula and the large-mass formula falls within test data points). These equations are rather complicated and readers are referred to the development by Baum [1983]. Moore's equation, Baum's equation, and test data points are plotted in Figure 57 for spherical and cylindrical vessels. Both the Moore's equation and Baum's equations are for brittle fracture failures and may not be applicable to ductile failures or for Group A fragments. Moore's equations are shown to be conservative estimates of fragment velocity. Refer to Figures 9a-9f for illustration of fragment, end-cap, rocket, and pipeline missile data by Baum (see Brown [1984]).

Developing a probabilistic form of the above equations, or in other words, developing a probability density function for fragment velocity is a rather difficult task. If a large amount of test data is available for a range of rupture pressures and fragment weights, developing probability density functions for the velocity for different pressures and weights, [P(V/p,W)], should be straightforward. However, as seen in Figure 57, only a few data points are available, and so a practical, indirect approach which utilizes the few available data points (the theoretical and empirical equations such as those by Moore or Baum, and expert opinion) shall be developed for this purpose.

Instead of the Moore or Baum expressions, a more rigorous approach using the deterministic computer programs SPHER, CYLIN (see Baker [1975]) or UNQL (GASROC, see Baker [1978], is also possible). A probabilistic counterpart of these programs can be developed using uncertainty propagation techniques. Two methods are available. The first is the Monte Carlo simulation technique. Though the approach provides good results, the method is very expensive computationally. The second method is the moment generation technique. This method is much cheaper than the simulation method, but provides acceptable results only for certain types of problems. The validity of this method for deriving velocity probability distributions has to be investigated.

Results of the derived probability distributions, whether using Moore's methods, Baum's method, or one of the computer programs noted above, should be compared with the limited amount of available data to assure the correctness of the derived distributions.

Distribution of Ejection Angles. The origin of the missiles is assumed at the center of the pressure vessel. Two orthogonal, horizontal axes X and Y are defined in any arbitrary orientation, and the Z-axis is vertical (Figure 58). The direction of missile ejection is defined by two angles, ϕ and ψ . The angle ψ subtends the Y-axis and the projection of the ejection vector on the Y-Z plane, and ψ is the angle from the Y-Z plane to the ejection vector.

Probability density functions of the angles ϕ and ψ for Group A and B fragments shall be determined separately. Angle ψ for Group A missiles such as nozzles, valves, and reinforced openings can be determined rather accurately (deterministically) depending on their orientation with respect to the reference X-axis. From test observations and theoretical models, the bounding limits for $\underline{\phi}$ can be established, and a uniform probability density function (pdf), a triangular pdf or a clipped Gaussian pdf between these limits can be assumed.

For Group B fragments, if the vessel can be considered as axisymmetric, ψ can be assumed to be uniformly distributed between zero and 360 degrees. From test observations and theoretical models, upper and lower bound values for ϕ can be established and a suitable probability density function can be assumed between these limits.

3.1.4 <u>Missile Trajectory</u>

Given the initial conditions of a missile (ejection velocity and orientation), determination of the missile trajectory, and thus the location velocity and orientation of missile strike is straightforward. The missile trajectory analysis may employ either a simple parabolic trajectory which neglects the drag and lift forces acting on the fragment during its flight, or a more rigorous trajectory which accounts for the drag and lift forces. The parabolic trajectory analysis is simple in its deterministic form and a corresponding probabilistic evaluation is also inexpensive. The second approach is more complex, and an expensive Monte Carlo simulation is necessary for the corresponding probabilistic analysis.

<u>Parabolic Trajectory</u>. The trajectory is given by a parabola defined by Equation 44 and lying in the vertical plane containing

the ejection vector.

$$Z = r \tan \phi' - (gr^2/2(V \cos \phi')^2) \qquad |44|$$

Where,

$\phi' = \sin^{-1} (\sin \phi \cos\psi)$

$\psi' = \tan^{-1} (\tan\psi/\cos\phi)$

Z = *elevation of the trajectory at a horizontal distance r from the origin, and*

V = *ejection velocity*

These trajectories can be classified into high-trajectories and low-trajectories (Figure 59). High-trajectories are those trajectories that rise above the elevation of the strike point and then fall back on it. Low-trajectories are those trajectories that never rise above the elevation of the strike point. The significance of this classification will become obvious later in this section.

The trajectory defined by Equation 44 is a deterministic trajectory, in the sense that given deterministic initial conditions, the flight path and the end conditions are also deterministic. However, in the pressure vessel missile analysis the initial conditions are random and so the resulting end conditions are also random in nature. A number of methods for random missile-trajectory-analysis have been developed in the nuclear industry for turbine missile analysis (see Swan [1975], Haldar [1978], Seamanders [1972], Downs [1973], and Squire [1983]). Each of these methods can be adapted for the pressure vessel missile trajectory analysis. Two promising methods are discussed in this section.

Monte Carlo Simulation Method. The Monte Carlo simulation method (see Brown [1958]) consists of performing a series of deterministic trajectory analyses (each deterministic analysis is called a "trial"), each analysis being carried out for a specific set of deterministic input parameters (V, ϕ , ψ). Each set of input parameters is sampled according to the specified probability density functions of these parameters as determined in Section 3.1.3. Each trial analysis consists of the deterministic calculation of the strike location using Equation 44.

If the purpose of the analysis is to draw a strike probability contour map of the area surrounding the vessel, the area is divided into a uniform grid and the total number of strikes into each grid is counted. Total number of strikes within a grid divided by the total number of trials gives the probability of strike for that grid, conditional that a vessel burst has occured. This analysis is carried out for both Mode 1 and Mode 2 failures. The absolute strike probability for a grid is given by,

$$P_S = P_1 \cdot (N_{1,s}/N_{1,t}) + P_2 \cdot (N_{2,s}/N_{2,t}) \qquad |45|$$

where,

P_1 = *probability of Mode 1 failure of the vessel,*

P_2 = *probability of Mode 2 failure of the vessel,*

$N_{1,t};N_{2,t}$ = *number of trials in the Mode 1 and Mode 2 simulations, respectively, and*

$N_{1,s};N_{2,s}$ = *number of strikes within the grid in the Mode 1 and Mode 2 simulations, respectively*

Knowing the strike probability for each grid, a strike probability contour map of the area surrounding the vessel can be drawn. A sample contour map is given in Figure 60. Setting safety goals for the different equipment, safe areas and unsafe areas can be demarcated. (For example, in the nuclear power industry, a safety goal of 10^{-7} strikes/year has been considered as the design goal for critical equipment. A higher probability may be acceptable for other industries, depending on the consequences of a missile strike on a critical piece of equipment.) If a piece of equipment has to be located in an unsafe area, protective barriers may have to be built around the equipment. Probabilistic methods of barrier design will be discussed in Section 3.1.5.

In addition to computing the strike probability, the probability density functions of striking missile weight, strike velocity, and strike orientation can also be determined for each of the grids. However, since a very large number of trials are required for a statistically meaningful analysis, (up to millions of trials in certain cases), computation of these parameters in each of the trials is very costly. Also, it is not necessary to have this information for each grid; this information is required only for those locations where critical pieces of equipment are to be placed.

The second approach to be discussed, namely, the semi-analytical method, is better suited when not only the strike probability but also the weight, velocity, and orientation pdf's are required for a limited number of grids.

Semi-Analytical Method. Though the Semi-Analytical method can be used to generate strike probability contour maps, it is best suited for calculating the probability density funcitons of strike velocity, orientation and weight for selected targets. The target may be a flat surface where a piece of equipment is to be placed or an enclosure (protective barrier) with vertical, horizontal and inclined surfaces. In either case, the target is divided into a number of small elemental areas. For the midpoint of each elemental area, there only two possible trajectories, one high-trajectory and one low-trajectory, that can hit that point for a given ejection velocity. These two trajectories can be defined by three angles, ψ, ϕ_H, and ϕ_L where ψ is the horizontal angle for both the trajectories, and ϕ_H and ϕ_L are the vertical angles for the high- and low-trajectories, respectively (see Figure 58 for definition of ψ and ϕ). These angles are defined by Squire [1983],

$$\phi = tan^{-1} | (V^2 \pm (V^4 - R^2 g^2 - 2V^2 Zg)^{1/2}) / X \cdot g | \qquad |46|$$

$$\psi = tan^{-1} | (R^2 - X^2 / X^2)^{1/2} \cdot Cos\ \phi | \qquad |47|$$

Since the elemental area is not just a point but a two dimensional area, trajectories within a small angular range around the ψ and ϕ values (defined above) can strike the area. Squire [1983] provides expressions for $\Delta\psi$ and $\Delta\phi$ which define this range. The conditional probability of strike within the i-th elemental area, for a given velocity V is,

$$P_{si(V)} = P_\psi(\psi) \cdot P_\phi(\phi_H) \cdot \Delta\psi \cdot \Delta\phi_H + P_\psi(\psi) \cdot P_\phi(\phi_L) \cdot \Delta\psi \cdot \Delta\phi_L \qquad |48|$$

Where $P_\psi(\psi)$, $P_\phi(\phi_H)$ and $P_\phi(\phi_L)$ are the probability density functions of the ejection angles at the specified values computed using Equations 46 and 47. The conditional probability of strike within the i-th elemental area for all possible velocities is

$$P_{si} = \iiint P_{si(V)} \cdot P(V/W,p) \cdot P(W) \cdot P(p) \cdot dV \cdot dW \cdot dp. \qquad |49|$$

The conditional probability of strike on the target is obtained by summing P_{si} over all the elemental areas, and for both Group A and Group B missiles. This computation is carried out for both Mode 1 and Mode 2 failures. The absolute probability of missile strike on the target is given by,

$$P_s = P_1 \cdot P_{1,s} + P_2 \cdot P_{2,s} \qquad |50|$$

where,

P_1 = *probability of Mode 1 failure of the vessel,*

P_2 = *probability of Mode 2 failure of the vessel,*

$P_{1,s}$ = *conditional strike probability for Mode 1 failures,*

$P_{2,s}$ = *conditional strike probability for Mode 2 failures*

In addition to the strike probability, the probability density functions of strike weight, $P(W_s)$, striking velocity, $P(V_s/W_s)$, and the strike angle, $P(\Theta_s/W_s,V_s)$, can also be computed in a similar fashion.

<u>"Exact" Trajectory</u>. An "exact" trajectory analysis which considers the influence of drag and lift forces involves numerical integration of the equation of rigid body dynamics. Baker [1978] has developed a deterministic computer program called FRISB for this purpose. This program can be modified to provide the probability density functions of the final conditions of the missile (strike probability, strike velocity, etc.), given the probability density functions of the initial conditions (initial velocity, ejection angle, etc.).

<u>Use of Fragment Terminal Data</u>. In the preceeding subsections, methods of computing the statistics of fragment terminal conditions (also called "missile final conditions") using the missile initial conditions as data and a probabilistic trajectory analysis are described. An alternate approach is to establish the statistics directly from the fragment terminal conditions data collected from tests and post-accident investigations. Though it is possible technically to draw strike

probability contours and probability density functions of strike velocity, mass, etc., as a function of burst pressure (or energy), there is not sufficient data available to obtain the above results with any confidence. So the best use for the fragment terminal data is to utilize it to complement the results of the trajectory analysis. Two sets of probabilities and probability distributions can be derived from initial conditions data/trajectory analysis and terminal conditions data, respectively. The two sets of statistics can then be combined with a suitable weight assigned to each. Bayes method may be used for combining the two sets of statistics.

3.1.5 Damage Potential

If a piece of equipment has to be located in an unsafe area (that is, in an area where the probability of missile strike is higher than acceptable), then barriers or shelters (usually reinforced concrete enclosures), are considered to protect the equipment. Alternately, a containment structure may be considered for the source of the hazard. The missiles have the potential to damage the protective wall and then the equipment inside. There are two modes of unacceptable barrier damage:

1) Perforation - the missile passes through the wall. Thickness of a barrier just sufficient to prevent perforation by a specified missile is called the perforation thickness, t_p.

2) Scabbing - ejection of pieces of concrete from the back face of the barrier. Thickness of a barrier just sufficient to prevent scabbing by a specified missile is called the scabbing thickness, t_s.

The determination of the perforation and scabbing thicknesses using theoretical methods is rather difficult because of the complex local failure mechanism involving crushing, cratering, shear failure, and tensile fracture of a highly nonhomogeneous material. In the deterministic approach, the current practice is to use empirical formulas that have been developed from test data on specific materials and dimensional characteristics (refer to section 2.1.3 and Tables 11,12, and 13). Available empirical formulas include the National Defense Research Committee (NDRC) formula, the Petry formula, the

Ballistic Research Laboratory (BRL) formula, Amman and Whitney formula, the Bechtel formula, the Stone and Webster formula, the CEA-EDF formula and the Haldar formula. Sliter [1980] has presented an excellent comparison of a number of these formulas with test data. The first four formulas noted above are based on ordnance test data where the missiles are high velocity (>500 fps), nondeformable cylinders. The remaining four formulas are derived for application in the nuclear power industry which have used both the ordnance data and a limited amount of test data for low velocity (80 fps to 1,000 fps), deformable solids.

All the available formulas are deterministic in nature; that is, given deterministic values of missile diameter, weight, and velocity, the formulas predict deterministic values of perforation thickness and scabbing thickness. Comparison of the different formulas and their applicability to pressure vessel missiles are beyond the scope of this paper. However, before discussing how a probabilistic damage-prediction formula can be developed from deterministic formulas, a few remarks on the need for additional test data are in order.

Most of the test data and formulas are for "standard fragment shapes" used in ordnance tests (Figure 56), which are applicable to Group B type fragments generated by Mode 1 failures. A well-planned test program to assess the damage potential of these types of missiles is needed. The test data can be used to modify the current formulas for application to Group A fragments, and Group B fragments generated by Mode 2 failures.

Consider the applicable deterministic formula to predict the perforation thickness as follows:

$$t_p = f(W, V, \theta, d) \qquad |51|$$

where,

W = missile weight,
V = strike velocity,
θ = strike angle (orientation), and
d = equivalent diameter of missile.

We may have different formulas for Group A and Group B fragments and for Mode 1 and Mode 2 failures. A probabilistic form of the above equation can be expressed as,

$$T_p = A \cdot f(W, V, \theta, d) + B \qquad (52)$$

Where T_p is the perforation thickness (a random variable), W, V, θ, and d are deterministic parameters as defined before, and A and B are two random variables with specified probability density function P(A) and P(B) respectively. Fitting exact probability density functions for A and B from the scatter in the test data would require considerably more test data than what is available now or what could become available in the near future. The type of density function has to be chosen from standard probability distributions. Available data are not sufficient to favor a single distribution as the most appropriate, and a choice has to be made on the basis of qualitative judgement. Once the type of distribution is chosen, the parameters defining the probability density function are determined from test data points. Because of the very limited amount of test data available for pressure vessel generated missiles, information from tests may have to be supplemented by expert opinion; Bayes method provides a formal procedure to combine expert opinion with actual data.

Thus we have the probabilistic damage-prediction model in the form of Equation 52. Input to this damage model are the missile weight, W, strike velocity, V, strike angle, θ, and the equivalent diameter, d. The probability density functions of these parameters are obtained from the missile trajectory analysis, as discussed in Section 3.1.4. The Monte Carlo simulation technique is used to compute the probability density function of T_s. In each trial of the simulation, the random input parameters (W, V, θ, d, A, B) are sampled from their probability density functions and the value of T_s is computed using Equation 52. A sufficiently large number of trials are carried out, and the ensemble of T_s values thus obtained is fitted to a suitable cumulative distribution function. These computations are carried out for Group A and Group B fragments, and for each of Mode 1 and Mode 2 failures. The absolute probability of perforation for a given barrier thickness, T, is computed as follows:

$$P_p(T) + P_1 \cdot (F_{1A} + F_{1B}) + P_2 \cdot (F_{2A} + F_{2B}) \qquad |53|$$

where,

P_1 = *probability of Mode 1 failure of the vessel,*

P_2 = *probability of Mode 2 failure of the vessel,*

F_{1A}, F_{1B},

F_{2A}, F_{2B} = *value of cumulative distribution function of perforation thickness at T_s = T; the subscripts 1 and 2 refer to the Mode 1 and Mode 2 failures, and A and B refer to Group A and Group B fragments.*

From Equation 53, a graph of barrier thickness versus perforation probability can be plotted as in Figure 61. Starting with an equation for scabbing thickness, similar to Equation 51, a graph of barrier thickness versus scabbing probability can also be developed.

The designer can choose a barrier thickness depending on the level of safety required for the particular equipment protected by the barrier. For example, if 10^{-6} failures per year is the acceptable safety goal, the barrier thickness corresponding to this probability is read off from Figure 61. Thus starting from pressure vessel failure probabilities, we have developed a methodology for designing protective barriers to specified levels of safety.

3.1.6 Flow-Diagram of Methodology

A flow-diagram of the integrated probabilistic assessment methodology is given in Figure 62. As seen from a number of "ANR/OR circles" in the diagram, there is more than one approach to determine the statistics of the various quantities. In general, the two possible approaches are:

1) Direct statistical evaluation of test/post-accident data, and
2) Detailed probabilistic analysis using physical/mathematical models.

If the analyst believes that there is sufficient, relevant data available, he may choose the first approach; and if there is very little data, he may choose the second approach. If a limited amount of data is available, a combination of the two approaches is the best choice.

Another important aspect of the probabilistic approach described here is that a variety of hybrid probabilistic-cum-deterministic approaches can be developed by selectively using certain steps of the probabilistic approach and employing deterministic procedures for the other steps. For example, a deterministic analysis may be carried out to determine the worst-case strike velocity and mass; and then a probabilistic damage analysis may be conducted to compute the damage probability and/or barrier thickness. Though this hybrid approach provides more conservative results than a fully probabilistic analysis, the results are less conservative than a worst-case deterministic analysis.

3.1.7 Illustrative Example

This is the first time an integrated probabilistic assessment approach is developed for pressure vessel missile generation and damage potential evaluation. The necessary statistical data and computer programs are yet to be developed. Hence, it is not possible to solve an actual problem as an illustrative example.

3.1.8 Summary of R&D Needs

Four distinct needs have been identified (and will be discussed in more detail in Section 5.0). The first two tasks, (1) compilation of available data, and (2) expert opinion surveys should be carried out before embarking on a major test program (the third task). Cooperation with other groups carrying out pressure vessel tests to failure (for purposes other than generating fragment data) is recommended; at relatively low additional cost, useful data on fragment generation can then be obtained. The fourth task (development of methodology and computer software) may be carried out parallel to or prior to the first two tasks.

3.2 PERFORMANCE (DETERMINISTIC) GUIDELINES

The purpose of this section is to provide performance guidelines to protect personnel and property against the effects of a possible failure of a high energy gas pressurized system. A high energy pressure system is a pressurized vessel, piping system and/or components that contain a working medium with a total energy content of sufficient magnitude and a possibility of failure which is sufficiently high to warrant the specification of a safe working distance for personnel and/or the use of a protective wall such as containment, barricading, or sheltering structures.

By performance criteria is meant, the citation or specification of acceptable limits of response of personnel or structures to external conditions such as force, displacement, or other parameter(s). An example of performance variables as a function of hazards and receptors (of these hazards) is illustrated in Table 18. Only the hazards, fragmentation and blast, will be considered in this section. When a high energy pressure system fails, the system energy becomes available to do external work. In the scope of this section, the working fluid or pressurized media is limited to inert gas; and we have eliminated ground motion and group B type hazards shown in Table 18 as primary hazards. In this section, for the case of a catastrophic failure of the high energy pressure system, the energy available to do external work is divided between the kinetic energy of the system fragments (structural and internal medium) and the energy of the blast wave. This section covers the determination of: (1) system energy, (2) the siting of personnel & structures, and (3) protective systems to interdict hazards that may cause injury or damage to personnel and property.

3.2.1 Receptor (Object) Classification

There are three classes of receptors: 1) primary, 2) secondary, and 3) protective.

Primary receptors refer to personnel who may be injured by the failure of the pressurized gas system or source of the hazard.

For the purpose of safe siting of personnel against hazards from high energy pressure system failure, personnel location or siting are classified into two categories: 1) work and dwelling areas and 2) travel ways.

Secondary receptors refer to equipment, structures, or material that may undergo damage from a failure of the source system and thus become a secondary hazard to personnel by their failure.

Secondary receptors are divided into three categories: 1) strategic equipment, 2) hazardous material, and 3) buildings.

Strategic equipment refers to: (1) regulating equipment, controlling equipment, and operating system components which are necessary for the safe operation and shutdown of the high energy pressure system that presents a potential hazard and (2) adjacent independently operated high energy pressure system. Strategic equipment may include: electronic, electrical, hydraulic, pneumatic, mechanical, pressure vessels, and piping type equipment.

Hazardous material refers to stored substances which (if they are released as a result of missile impact or blast wave pressure from the failure of a high energy pressure system) result in secondary hazards; i.e. in the possibility of secondary: blast, fragmentation, foundation motion, heat propagation, chemical reaction, radiation, and biological effects.

Buildings and structures are categorized into two groups: 1) inhabited and 2) uninhabitated. This group of receptors provide no protection against blast and fragmentation, and are intended to provide a controlled environment, storage, or support.

The third class of receptors, protective structures or protective systems, are classified into three type categories: 1) containment, 2) barriers, and 3) shelters. A Containment protective structure is designed to contain in its interior, all effects from specified hazards. The hazards are contained from entering the environment. In this section, the hazard types would be either blast, fragments, or both.

Protective barriers refer to protective systems that offer limited protection for primary and secondary receptors from hazards such as blast and fragmentation. Examples of limited protection by protective barricades are: (1) directional placement of a protective wall to limit fragments from a certain direction, (2) a suppression shield to control the pressure - time loading, or (3) a restraint that inhibits motion (usually piping).

A protective shelter encloses primary and secondary receptors and is designed to protect them from exterior hazards (outside of the shelter) such as blast and fragmentation from a distant high energy pressure system.

A probabilistic assessment of the high pressure energy pressure system facility or source receptor locations relative to the receptors is preferred (see Section 3.1). However, it is suggested that a four class population index system (similar to ANSI B31.8 for gas transmission and distribution piping systems) be utilized for source receptor (facility) class locations:

Class 1 Locations

> Class 1 locations include waste lands, deserts, rugged mountains, grazing land, farm land, and combinations of these; provided however, that (a) the ten mile density index for any section of the pressure system (vessel, pipeline, component) length is $\leq$ an average of 12 dwelling units per linear mile or alternately 300 persons within a 5 square mile radius of a high energy pressurized system considered as a single source (the area is calculated assuming a constant radius); and (b) the one mile density index for any one mile of length is $\leq$ 20 dwellings or alternately 100 persons per square mile (of constant radius of the source).

Class 2 locations

> Class 2 locations refer to those areas about a high energy pressure system with population density indexes greater than class one.

Class 3 locations

Class 3 locations consist of occupied residential or commercial buildings in which the prevalent height of the buildings is three stories or less.

Class 4 locations

Class 4 locations include areas where occupied multistory (four or more floors above ground) are prevalent, where traffic is heavy or dense, or where there may be other high energy pressure system facilities.

3.2.2 Source of Potential Failure

A high energy pressure system source consists of a closed boundary that is designed to sustain internal pressure to some design pressure above the external or ambient pressure. Temperature may be at or other than ambient. Pressure systems consist of: vessels, pipes, fittings (such as elbows, Tee's, etc.), and/or equipment (such as valves, pumps, compressors, etc.). The energy content of the pressured system shall be computed on a component by component and/or on a node to node basis. The total system energy content shall be the sum of the component and/or node to node computed energies. A component is defined as: pressure vessels, valves, pumps, heat exchangers, (i.e. a pressure boundary in which some process or operation is performed between node points - attachments). The energy content of piping shall be computed between fittings (such as elbows, T's, flanges, or components, or supports which are refered to as node points (end points) for a continuous length of pipe).

The potential sources of high energy pressure system failure shall be determined from specification and design data and evaluated for the following four areas: 1) contained media classification, 2) pressure system characteristics, 3) energy release content, and 4) mechanism of failure.

It is the purpose of this section to characterize the high energy pressure system as a source of hazards to personnel and property. In this section, the hazards have been limited to blast and fragmentation. It is not the intent of this section to provide guidance for the design of the pressure system itself or to determine or quantify its reliability or degree of safety.

However, the risk of failure must be considered in determining the need for additional protection in accordance with this section.

Contained Medium Classification. Contained medium shall be classified by state variable which will influence the estimation of available energy of the system. For example, given the ambient and operating conditions to which the system is to be exposed, the medium may be classified as changing state (gas, liquid, or solid); also chemical characteristics such as inert explosive (propagating reaction, uniform reaction, thermal explosion), or degenerative shall be identified and assessed with respect to energy content and contribution to type of hazard. This report is limited to pressure systems with inert gas that present a hazard by blast and fragmentation effects.

Energy Release Content. Energy release content is calculated from equation 2a which reduces to:

$$E_s = E_1 + E_3 \qquad [54]$$

Where

E_1 (media expansion energy) = Equation 6.2

E_3 (elastic strain energy) = Equation 6.6

The available energy from the expansion of the gas has been shown to be calculated in most instances, by Equation 6.2b wherein isentropic expansion has been assumed.

The instantaneous rupture energy may be redefined as (from Equation 2b)

$$E_S = E_B + E_M + E_Q + E_d$$

where E_B is the blast energy and E_M is fragment energy (kinetic energy of structure and media). E_1 contributes or is converted to E_B and E_M whereas E_3 contributes energy only to E_M. In many instances E_3 may be neglected, except in those cases where the length of the fragment is much greater that the pressure system thickness, such as Group A fragments (see Section 3.2.3). In this section thermal energy E_Q may be considered negligible for inert media.

The dissipated energy (E_d) may be included by the designer when it is felt that the design of the pressure system is such that the energy driving a catastrophic failure is significantly dissipated.

The computed dissipated energy shall be verified by existing test data or a test performed in support of the calculated E_d.

In the absence of experimental verification, the designer may neglect the dissipated energy in the estimation of available energy (E_B) and kinetic energy (E_M) of the structure and media.

The rupture energy within the high pressure energy system shall be converted to pounds TNT of equivalent energy where the energy yield of 1 lb of TNT is 1.426 X 10^6 foot-pounds.

In determining TNT - equivalent energy within the pressure system containing argon gas, the curve in Table 8A may be used. For other gases, the applicable monatomic or diatomic ideal - gas values in Table 8A may be used with the all "temperatures curve" or by computation using Equation 6.2b (with the specific heat value such as listed in Table 19).

Additional Media Expansion Effects. In instances where the designer finds that in addition to gas within the pressurized system, there are also: liquids, liquids that become gases at ambient conditions, or gases that become liquid at ambient conditions, then they should be evaluated for their contribution to expansion energy. Alternatively, the designer may substitute the volume of liquid by an equal volume of compressed gas. For water or water based liquids at ambient temperatures, assume the compressibility (pressure/bulk modulus, or P/B) to be 7% at 30,000 psig with a linear variation below this pressure (down to 3,000 psig). For oil at ambient temperatures, assume its compressibility (P/B) to be 14% at 30,000 psig with a linear variation above and below the pressure.

As an example of the energy content contribution of liquid in a pressurized gas system, consider the calculation of the TNT equivalent energy within a circular vessel illustrated in Figure 64. In this example, the TNT equivalent energy is a function of the internal pressure, volume of the fluid, and bulk modulus.

In the case in which the fluid contained within the pressure system is flash evaporating, the available energy contributed by the fluid may be estimated by calculating the change in internal energy, Δu, via an isentropic expansion of the fluid from the bursting pressure and specific volume to the outside ambient pressure. The internal energy, Δu, is usually available from thermodynamic tables, charts, formula where

$$\Delta U = \Delta H - \Delta (PV) \qquad |55|$$

ΔH is the change in enthalpy

In a pressure system rupture, the process from a highly pressurized gas takes place rapidly such that it is unlikely that any condensation would take place (ie. the gas would supercool). In instances where the internal pressure is substantially above 100 bar, the assumption that the expansion process follows the path [$(PV)^n$ = a constant] and to calculate the U as $\int PdV$ can lead to gross errors (whether n is treated as a polytropic exponent or the specific heat ratio).

Alternatively, the flash evaporating fluid volume may be replaced by an equal volume of compressed gas (at pressure and temperatures in the system that are to be evaluated). This option is permitted because the stored energy in compressed gas is much greater than compressed flash evaporating liquids and for compressed liquids, hence this assumption leads to a conservative estimate of the available energy from a ruptured vessel.

Two areas that influence the characteristics of the energy rate of release (particularly the relationship between fragment kinetic energy, shock wave energy, and dissipation energy) are 1) pressure systems characteristics, and 2) the mechanism of the pressure system failure.

Pressure Systems Characteristics. Pressure systems characteristics shall be evaluated with respect to: (a) material properties of the system, (b) geometrical considerations (thickness, discontinuities, reinforcements, shape of shells, etc.), (c) components (such as valves, T's, nozzles, access closures, etc.), (d) fabrication (location of welds), and (e) operating conditions (pressure, temperature, normal and upset conditions).

Pressure system rupture into missiles or fragmention is divided into two groups:

Group A consists of entire systems, subsystems, or components (large fragments) and Group B consists of numerous small fragments resulting from a pressure system shattering (small or "zero mass" fragments). This will be discussed further in Section 3.2.3, however, it is mentioned here in the context of pressure system characteristics since the designer may use the system design and analysis data to evaluate likely areas of fragmentation.

The Mechanism of Failure. The mechanism of failure is classified into two categories (as noted in Section 3.1): Mode 1 failures refer to normal operating conditions and Mode 2 failures refers to abnormal failures under abnormal operating conditions. In Mode 1 type failures, the pressure system failure is due to inherent weakness of the vessel and such failures are usually due to brittle fractures, fatigue crack growth, stress corrosion cracking, creep, etc. Abnormal failures (Mode 2) result from operating overpressurization, impact, blast loads from adjacent system rupture, and/or unexpected external sources, etc.

Mode 2 type failures can only be approached realistically by a probabilistic methodology. Specified unusual (non operating) loadings and failures of systems resulting from adjacent system failures will be considered as Mode 2 failures in this report.

Having documentation for pressure system design against brittle fracture, for example, by specifying system design at NDT + 60°F, the safety siting designer may exclude group B (small fragments) in the fragment calculations. This may not be the case for mode 2 type failures.

3.2.3 RECEPTOR PERFORMANCE

In this study, the principal medium (content) of the pressure system is inert gas. Liquid or solid is not considered as a primary medium, but shall be considered for its contribution to energy content or hazard (missile, slug, jet, etc.). Degenerative hazards are not present except within secondary receptors. Primary and secondary type hazards are considered, where the effects on the receptors (objects or targets) are force/motion. The two primary hazards considered in this study are blast and fragmentation resulting from the energy release pressure system.

The cause of failure, (including catastrophic failure) may be ascribed to the six following categories: 1) deficiency in design, 2) material use and selection, 3) defects in materials, 4) manufacturing and processing, 5) improper or unusual operating conditions, and 6) maintenance and inspection.

> Studies show that most failures of pressure systems occur as a result of the presence of defects or flaws in the material. These have been found to occur anywhere in the system or in the component production process from the mill to the fabrication process (defects in welds are particularly responsible for a high incidence of failure of pressure vessel systems). Fatigue crack growth is another important area. Improper or unusual operating conditions account for a number of catastrophic failures as well as improper maintenance and inspection (resulting in the failure to detect or remedy structural defects or structural degradation).

In this section (3.0), it is assumed that the high energy pressure system is adequately designed, hence, items 1 & 2 ("deficiency in design" and "material use and selection" respectively) are not considered as a potential contributory cause of failure and hence need for protection. Item 3, "defects in materials" and item, 4, "manufacture and process" are considered <u>Mode 1 type failure</u>. Item 5, <u>improper or unusual operating conditions</u> and item 6, "maintenance and inspection" are considered mode 2 type failures. Mode 2 failures can only be assessed realistically by probabilistic methodology. However, prescribed abnormal loads or those resulting from the failure of adjacent pressure systems are to be assessed.

Hazards that are to be considered that may result from high energy pressurized gas systems failures are: a) missiles from the pressure system, b) ejection of the media, c) blast wave pressure, d) missiles initiated by the blast wave, d) secondary missiles and blast resulting from initiation by the primary missiles and/or blast wave, and e) secondary missiles from damaged structures (spalling and scabbing).

Areas in the pressure system that are likely sources of failure and hence blast and fragmention hazards are: 1) vessels with intersecting attachments (such as nozzles, lugs, closures, etc.), 2) pipe intersections (such as T's, elbows, Y's, etc.), 3) Weld areas, (particularly welded reinforcements), 4) high tensile stress areas, 5) geometrical discontinuities (such as transition of a thin cross sectional shell to a thick cross sectional shell), 6) poor fracture toughness material properties at specified normal and abnormal load conditions, 7) vessel closures (such as bolted, breach lock, threaded, etc. type attachments), and 8) areas susceptible to flow induced vibration.

Risk Assessment. Risk assessment is a means of providing quantitative and qualitative measures of the potential severity and probability of injury or damage in order to guide decision making in the siting of receptors and identifying the need for protection. The preferable method for performing a risk assessment is by probabilistic methodology. However, until such a methodology can be incorporated into this section, the following qualitative assessments are cited:

A) Probability estimate - the likelihood that a identified hazard will result in a mishap based on an assessment of such factors as: location, exposure in terms of cycles or hours of operation, and population density and distribution. The probability may be estimated as follows:

1) estimate A - likely to occur - source-receptor class 4 locations.

2) estimate B - probably will occur in time - source - receptor class 3 locations.

3) estimate C - may occur in time - source-receptor class 2 locations.

4) estimate D - unlikely to occur - sourece-receptor class 1 locations.

B) Severity Class. An estimate of the worst consequences defined by the degree of personnel injury, or property damage that could occur for each hazard (blast and fragmentation) severity classification is identified as follows:

1) class I catastrophic - may cause death or system destruction.
2) class II - critical - may cause severe injury, (severe occupational illness) or major property damage.
3) class III - marginal - may cause minor injury (occupational illness) or minor property damage.
4) class IV - negligible - probably would not affect personal safety or health, and negligible property damage.

For example, it is suggested that severity classes be mapped on a pressure system or facility layout for blast effects and fragment effects on personnel (severity classification is cited in the performance criteria section of this report) for both, cases of without protection and with protection.

A single number Severity - Probability Code (SPC) will be assigned to each combination of severity class and probability estimates as shown in Table 20. This does not preclude the use of locally developed systems for risk assessment for special application. SPC's 1 will be considered eminent danger and require immediate attention by way of resiting or providing protective systems. SPC's 2 will be considered serious and require priority attention. All SPC's 3 through 6 may be serious, probably require local rather than global protection, and they establish a scheme for prioritizing for corrective action.

In addition to the SPC code, a further measure of risk is provided by evaluating siting-protective system effectiveness. A qualitative measure is provided by way of: 1) Protection Effectiveness Coefficient (PEC) which is determined as the exponent (n) obtained from the ratio of estimated cost for the repair, compensation, and restitution incurred as a result of a postulated severity class I (catastrophic event) divided by the cost to put in place a protective system against a catastrophic system failure, and 2) the Protection - Source Coefficient (PSC) which is defined as the exponent (n) from the ratio of the estimated purchase cost for the facility, system, component (that is the source of a potential failure) divided by the cost for the protective system (both total system and local source ratios will be calculated for the pressure system loop). The ratios are expressed $K(10)^n$ where $1.0 > K \geq 0.1$.

For example, consider the ratio from a $10 M cost for a facility repair divided by $0.1 M for a protective system = 10^3. Hence, the PEC value is 3. Similarly, if $5 M is the estimated cost for the system divided by $0.1 M for the protective system, the ratio is 0.5 $(10)^2$, then the PFC = 2.

Ratios of 3 or greater are considered high effectiveness and values of 0 or less are considered low effectiveness. This is, of course, a qualitative assessment and may require additional considerations with respect to production need and economics.

Distribution of System Energy. The determination of the distribution of energy between primary missiles, blast, and energy dissipation is discussed in sections 3.2.3.1 and 3.2.3.2.

3.2.3.1 Fragmentation and Missiles

A) Personnel/Primary Receptors. The acceptable limit for missile impact into personnel, F^p, shall be severity class IV. If personnel are located within severity class I through III, protection shall be provided in the form of containment, barricading, or protective shelter; and the zone of protection shall be reclassified accordingly. $F^p = F^p(m,u,t) = F^p(m,v)$, where m = missile mass, u = displacement, t = time, and v = velocity.

Impact missiles or fragments from a system rupture or secondary fragments are grouped into two categories: 1) non-penetrating (or blunt), and 2) penetrating. Penetrating objects are generally described as sharp (may cut skin such as broken glass) or pointy (with a minimum tangent of adjacent surfaces as 70^o or less). Blunt surfaces or non-penetrating surfaces are not sharp or pointy.

Referring to Figure 65, the F^p limit that personnel shall be subjected to is the fragment mass-velocity combinations defined by the region below curve F, except in instances where it can be demonstrated that all fragments or missiles may be considered classified as non-penetrating or blunt. The limit mass-velocity parameter, F^p, for non-penetrating or blunt missiles and fragments shall be limited to those combinations of mass and velocity defined by the area in Figure 65 below curve C (minor injury threshold for non-penetrating fragments).

Missile and Fragment Initial Velocity. Primary (fragments from the failed pressure system, system structure, and media) and secondary (parts from structures failed by blast or impacted by primary fragments) missile and fragment initial velocity shall be estimated based on any or all of the following methods: experimental test data, theoretical solutions, numerical methods; provided that the method(s) are demonstrated to cover the parameters of the missile's generating mechanism such as 1) the contained medium, 2) the gas pressure system characteristics (material, geometry, and specified operating and postulated unusual conditions) are accounted for within reasonable engineering certainty (approximately 10% or is a conservative bound).

Example data are presented for gas pressurized (1) cylinders and spheres in Figure 8 and (2) end cap, rocket, ductile pipeline, and brittle formed missiles (limited data in Figure 9a through 9f).

Alternatively, in the event that experimental, theoretical, and numerical predictive methods (that have been documented) are not applicable to the high energy gas pressure systems or components to be evaluated, then three alternative methods of evaluation are cited in the order of preference: 1) the performance of a test program of at least 5 tests that cover the range of parameters with respect to system characteristics, 2) an estimation of fragment velocity based upon the zero mass formulation (see paper by Martin Baum, reference Brown [1984]) or upper limit formulation, and 3) use of the Gurney law (or Moore equation) for initial fragment velocity for which the available energy E_s is converted to an equivalent explosive weight of TNT (see Jensen [1972]).

Fragment Distribution. Since pressure system characteristics (particularly geometrical, restraint, boundary conditions, and component characteristics) frequently define axes, planes, or regions to which fragments will be limited, it is permissible to consider only these directions (demonstrated as permissible) as defining potential areas of missile impact. Any permanent structure which it has been shown to completely stop or prevent fragments through a certain area (refer to section 3.2.4 on protective systems) shall be considered as protective barriers.

Missile or Fragment Size. It has been shown that controlled fragment size can be incorporated into a design by way of restraint, geometry, and material (see Figure 9d - Brown [1984]). As discussed earlier, operating conditions such as temperature can (refer to Figure 2b) influence whether numerous small fragments are generated or only a few large ones. Some components have relatively predictable directions and masses such as valve bonnets, closures, intersections, and pressure systems designed by leak before break criteria (where component jetting and tearing predominate).

The determination of the size distribution (mass and geometry (sharp and blunt)) of the fragments developed from the pressure system's rupture; may be based upon existing experimental, theoretical, or numerical methods that have been verified for the range of parameters to be covered in the evaluation. Alternatively, (1) five tests may be performed to cover the range of parameters to be evaluated or (2) both small mass and large mass (single component between node points) shall be evaluated for both mass and geometry.

Velocity Retardation. The inclusion of drag (and lift) effects shall be considered in the calculation of fragment trajectory or terminal velocity based on either or all of the following: experimental data, theoretical formula, numerical methods that have been documented for the range of parameters for the range of fragmentation of the pressure system or secondary fragments that are to be evaluated (refer to Figure 10 of Part I). In the event that no methodology exists for the range of parameters to be considered, then alternate considerations shall be: 1) perform five tests on the known missile configuration (such as a valve bonnet), or 2) neglect drag and lift effects in instances where missile or fragment consideration cannot be deterministically described.

Blast Generated Fragments. Refer to Section 3.2.3.2

Media Ejection. Jets of gas or liquid resulting from the pressure system failure (as well as water slug ejection) shall be considered with respect to siting or protection for personnel and structures. Generally liquid or gas jets have a limited range when compared to solid missiles, hence shielding for fragments or projectiles are sufficient protection against liquid or gas jets (protection against jets will be discussed further in Section 3.2.4).

B) Secondary Receptors

Although the specification of the safety performance of secondary receptors is not within the scope of this report, secondary receptors shall be located or protection provided for them against missiles only inasmuch as they exceed a hazard greater than Class IV severity hazard to personnel (primary receptors); hence protection shall be provided for secondary receptors that present severity levels I through III to personnel. The threshold level for minor damage to: (1) the strategic equipment (F^E) and/or hazardous material (F^H) (serious damage to the equipment or material refers to its threshold of missile impact to initiate a hazardous release by blast, missile, foundation motion, heat, radiation, biological, chemical agents, or (2) buildings/structures (F^B) shall be provided by the manufacturer/designer (serious building structural damage indicates the threshold for reduced structural load carrying capacity by missile impact, major support beams or walls undergo sectional average yield (S_Y) stress intensity).

Both fragmentation (missile) and blast loads are assumed to occur both singly and simultaneously to secondary receptors unless they are protected against one or both hazards. Consider an example of a high energy pressure system with an automatically controlled or self actuated valve within the range of fragment impact. An estimate of the missile mass and velocity that could strike the actuator (and thus damage the valve actuator) is found to be above the threshold for minor damage; and in fact, will render the actuator inoperable which will result in a catastrophic failure of another piece of equipment. If personnel are located sufficiently beyond the range of this secondary failure or are sufficiently protected, no further protection is needed. Hence it is the discretion of the facility owner or operator to determine the risks of whether or not protection will be implemented to avoid loss of the equipment due to the potential failure of the actuator.

Hazardous material shall be stored against missile impact in accordance with storage combatibility mixing criteria and hazard classifications as outlined by the Department of Transportation, the Department of Defense, and the United Nations Organization (UNO) specifications (when not in conflict with DOD and DOT criteria).

Buildings or structures shall be considered as offering no protection against fragments unless evaluated as a protective structure, hence inhabited buildings shall be located or protected by the guidelines or procedures outlined for personnel and severity criteria specified in Figure 65. No restrictions are placed on the location of uninhabited buildings or structures with respect to specified siting or protection from missiles except that structural collapse or secondary fragments shall present no risk of injury to personnel greater than Class IV severity. In general, the siting or protection of personnel against primary missiles (fragments) is usually sufficient to insure that secondary missiles are not presented as a result of primary fragments striking adjacent structures. However, it is recommended that adjacent structures or uninhabited buildings that pose a threat to personnel by collapse should be evaluated with respect to its major support columns, walls, and beams where $B^B{}_p$ (cross-sectional primary membrane stress intensity) is less than S_Y for both normal membrane stress intensity and shear stress intensity and $B^B{}_S$ (primary membrane plus bending stress is stress intensity) at the outer fiber is less than 1.5 S_Y, where S_Y is the yield stress. Conservatively, the impact should be assumed plastic (i.e. no rebound). Of particular concern is the ejection of a large mass of fragments.

C) <u>Protection Against Missiles and Fragments</u>

Protective systems used against missiles that result from a pressure system failure shall be designed to protect primary and secondary receptors against severity class I through III missile velocity and masses. There is no protection requirement for severity class IV. A protective system shall be designed to resist both estimated missile and blast load simultaneously and singly, unless it can be demonstrated that these effects cannot occur simultaneously or the system is designed for only one hazard.

Because of the irregular nature of missile geometry, and hence uncertainty in predicting penetration or perforation, protective barriers shall not be designed to permit missile velocity retardation, and hence permit some residual velocity (V_r) once the missile perforates the wall (see Figure 17). There are numerous mechanisms in which a missile may penetrate into a protective structural wall as illustrated in Figure 17, and these mechanisms are dependent upon the wall material(s) and dimensions.

A protective system design against missile impact shall be evaluated for design adequacy with respect to the three following criteria: 1) missile penetration (F^S_p), 2) structural adequacy of the overall structure (global effect) to withstand impact (F^S_G), and 3) resistance to fracturing (spalling and scabbing) - F^S_S.

In the case where it has been determined that a pressure system rupture may result in a range of fragment masses, weights, and geometry, then an evaluation of the design adequacy of the protective system shall be performed with respect to both the blunt and piercing configuration at the optimum weight and velocity. For deterministic shapes such as postulated ejection of closures, valve bonnets, intersections, etc., both blunt and penetrating orientations shall be used to evaluate the design adequacy of the protective system. A protective system (containment, barrier, shelter) may be designed and classified according to the four severity classifications (see Section 3.2.3.2(C)):

Class IV - is applicable to personnel and is the most stringent of the four classes. The full integrity of a shelter in this classification must be maintained. The percent missile perforation limit F^S_{P4} shall require the protective wall to stop missile perforation by a factor of two times the worst terminal missile energy at the wall (where a 50% probability penetration velocity or > is used). The global linear membrane and bending stress intensity (excluding the local perforation or impact stresses) F^S_{G4} shall be limited to a maximum allowable stress intensity not to exceed $S_Y + 1/4\ (S_U - S_Y)$ where S_Y and S_U are the dynamic yield and dynamic ultimate stress intensity of the wall material. The formation of fragments from failure of the shelter or barricade (brittle mode behavior) shall not be permitted and appropriate limits for F^S_{S4} with respect to fracture stresses or adequate shielding shall be employed.

Severity Class III applies to protective systems that are used to protect secondary receptors. The formation of post-failure fragments due to the collapse of the protective system is prohibited here. Penetration of primary fragments and the formation of secondary fragments are allowed, but shielding is required if their severity classification exceeds those which can result in the damage to the secondary receptors which would present a severity Class I through III threat to personnel. As discussed in the sections on secondary receptors, the levels governing the sensitivity of secondary receptors (such as strategic equipment, hazardous material, and structures can only be defined depending upon the nature of the secondary receptors as specified by the manufacturer/designer of the secondary receptors). F^S_{P3} is approximately equal to the 50 percentile probability of missile perforating the wall with a residual velocity equal to 0. F^S_{G3} stress intensity (for linear membrane and bending stresses) through the protector wall shall not exceed the stress intensity limit of $0.5\ (S_U + S_Y)$.

Severity Class II pertains to protective systems used for partial containment of explosive material and pressure components to protect secondary receptors and pressure systems (rupture sources). Controlled failure (deflections exceeding the insipient failure deflection) of the structural elements is allowed, thereby permitting post-failure fragment formation. The velocities of primary, spalled, and scabbed fragments must be limited to values such that secondary explosions or ruptures from the source failure are prevented. Barriers providing the protection of Class II can be designed for both ductile and brittle behavior. Where communication of an explosion by fragments must be prevented, the response criteria used for the donor barrier design will vary from limited deflections for protection of sensitive secondary receptors whose protective systems are designed to withstand the additive effects of more than one impulsive load to total failure for protection of less sensitive secondary receptors, $F^{P}_{G3} < S_{U}$.

Severity Class I is similar to II except that limited primary and secondary fragmentation is permitted. A total failure criteria is used for the design of the protective system in this category where F^{S}_{G1}, the stress intensity (for membrane and bending stresses through the protective wall) may exceed S_{U} (local impact stresses are excluded from this limit). F^{S}_{P1} and F^{S}_{S1} shall be specified or limited according to the sensitivities of the secondary receptors.

Documentation for protective systems shall be maintained in accordance with section 3.2.4.0 in order to provide tracability of the historic events and predict the remaining load carrying capability of the protective systems. Recertification or evaluation of remaining performance shall be determined for protection severity Classes II through IV.

The performance evaluation of protective systems shall be estimated based on any or all of the following methods: experimental test data, theoretical solutions, numerical methods; provided that the method(s): (A) are demonstrated to cover the parameters of the initial and protective structure's dynamic response mechanism such as 1) material properties, 2) geometry, 3) boundary conditions, & 4)coupling effects; (B)are accounted for within reasonable engineering certainty (approximately 10% or is a conservative bound).

An example of a computational method used to determine the response of a shelter is provided in Figure 43. Finite element time-history response and deformation plots permit the designer to locate regions of the structure which will develop the most critical stresses in the wall as a result of a postulated impact in the worst location. The computer simulation provides the designer the ability to test the response of the structure due to a specified impact at a great variety of locations. In this example, the missile, was considered an aircraft impacting a protective barrier around a nuclear reactor. The example illustrates the economy of computer simulations to assess what might be prohibitively expensive to simulate in an experimental test program (unless scale modeling could be shown to be reliable).

In another example (illustrated in Figure 30), two separate test programs are computer simulated for missiles impacting a protective barrier. One computer simulation evaluates the effect of material properties (or constitutive laws), the other provides an evaluation of the effects of oblique impacting. These numerical computer simulations were benchmarked against experimental tests.

On the other hand, Romander [1984] provides an example of the search to develop penetration and perforation formula. In Florence's study, comparisons are made to experimental tests of scaled missiles impacting concrete targets. Formulae such as these are generally developed for specific materials, geometry, velocity ranges, and mass of the missile, hence, they are limited although very useful.

Alternatively, in the event that experimental, theoretical, and numerical predictive methods (that have been documented) are not applicable to predict the missile impact and protective structural response, then the following alternative methods of evaluation are cited: 1) the performance of a test program with at least 5 tests that cover the range of parameters with respect to the protective system and missile characteristics for worst case impact, 2) perform an estimation of structural response based upon simplified modeling assumptions which may be demonstrated to provide a conservative or upper bound estimate, and 3) limit the allowable stress intensity values for membrane and bending stress intensity in the protective structural wall to the elastic range.

As an example of item 2 (alternate methods) consider Figure 68 for an illustration of pressure loading of structural response parametric ranges in which impulse, pressure-time, or static load predominate. Similar relations have been developed for missile impact.

3.2.3.2 <u>Blast</u> <u>Waves</u>

<u>A).</u> <u>Personnel/Primary</u> <u>Receptors.</u> Severity classifications for overpressure applied to personnel are specified as follows: Class I - 20 psi or greater, Class II - 2.5 psi to 20 psi, Class III - 0.2 psi to 2.5 psi, Class IV - 0 to 0.2 psi. The acceptable limit B^p, for blast wave loading (a pressure - time - distance load) on personnel shall be those values specified by

severity Class IV. If personnel are located within severity Classes I through III, protection shall be provided in the form of containment, barricading, or protective shelter and the protected zone reclassified accordingly. Blast generated missiles shall be limited by the value of the functional, $F^p = F^p (m,u,t) = F^p (m,v)$ as described in section 3.2.3.1.

It has been shown through studies that higher levels of pressure may be sustained by personnel for short duration pressure pulses, hence, pressure impulse (I) may be considered as a variable in defining the upper limit of severity classfication IV, provided that this can be demonstrated for specific pressure-time-distance histograms to which personnel will be exposed.

The pressure-time-distance histogram from the failed pressure system shall be estimated based on any or all of the following methods: experimental test data, theoretical solutions, numerical methods; provided that the method(s) are demonstrated to cover the parameters of the blasts (pressure-time-distance histogram) generating mechanism such that: 1) the contained medium, 2) the pressure system characteristics (material, geometry, and specified operating and postulated unusual conditions), and 3) environmental effects (such as ambient conditions, reflecting surfaces, multiple source, etc.) are accounted for within reasonable engineering certainty (approximately 10% error is a conservative bound).

Pressure-time-distance histograms refers to the blast pressure being a function of time and distance from the blast source. Peak overpressure and impulse for a pressure-time histogram at some distance R from the source of gas pressure vessel rupture are illustrated in Figure 4b.

Alternatively, in the event that experimental, theoretical, and numerical predictive methods (that have been documented) are not applicable to the high energy gas pressure systems or components to be evaluated, then three other methods of evaluation are cited in the order of preference: 1) the performance of a test program of at least five tests that cover the range of parameters with respect to the system characteristics, 2) an estimatation of pressure-time-distance history based upon an upper bound limit formulation, and 3) convert the blast energy into equivalent TNT energy and use existing high explosive (HE) data. A number of pressure-time histogram parameters may be estimated (such as peak pressure (P_s), impulse (I), time of arrival (TOA), and duration) using data for TNT (as illustrated in Fig.4a for scaled distance) based on the Hopkinson - Cranz cube root law. Since it has been demonstrated that pressure-time histograms for gas may differ greatly from condensed high explosives of equivalent energy, (refer to Figure 4b) it shall be demonstrated that when using this procedure that the calculated values such as peak overpressure (or positive impulse) shall be equivalent to or conservatively estimate (bound) the pressure response produced by the gas pressure system rupture.

As an example of experimentally derived burst or blast data for scaled distances versus peak side-on overpressure and impulse from spheres pressurized with various gases (air, argon, and Freon), refer to data by Baker [1984] (or refer to Brown [1984]).

As an example of alternative #3, blast energy (E_B) may be obtained by subtracting the missile kinetic energy (E_M) from the available energy (E_S). Another approach is to convert the available energy (E_S) into an equivalent TNT weight; then the reduction in available blast energy caused by the shell may be calculated by Equation 3 in part I of this report.

An example of a numerical computer code that has been used to calculate blast effects is the PISCES computer code. Computer solutions such as these (which can be cost effective when compared to experimental tests) require the use of a high speed large mainframe computer. Such computer solutions are typically benchmarked against experimental data to demonstrate verification.

Effects of Ambient Conditions. Ambient pressure, temperature, and density are known to affect the pressure-time-distance histogram from a blast wave. In general, these influences are not great, however these effects shall be assessed particularly for facilities located in extreme environments such as: high altitude mountain locations, arid sea level locations, and arctic conditions.

Dimensional Effects. The manner in which a pressure system fractures influences the directionality of the blast wave. A single propogating crack in which a component or system separates (for example, pressurized spheres fracturing in half, an end cap release, a longitudinal crack in a cylinder (which turns into circumferential cracks at the supports - see Figure 9d)) will have definite increased energy along the planes of separation of the component parts or along the initiation site of the crack where breaching has occured. In pressure systems which fragment into many pieces, the blast wave has greatest strength occuring in the direction perpendicular to the greatest length of breaching or fracturing surface area (similar to high explosive bursts). This directional characteristic is limited to the near field (a scaled distance of approximately 10), beyond which the blast wave is assumed spherical and the scaling laws apply.

Sequential Explosions. Multiple ruptures or explosions shall be considered to be additive. Multiple pressure system ruptures are likely to occur when failure is communicated from an initiating primary failure source to adjacent separate (secondary) pressure sytems or pressure systems that are a part of the initiating loop which do not have sufficient time to (or cannot) depressurize before being impacted. Sequential explosions can either cancel or enhance the effect of blast pressure, depending upon the timing and distance between the sources; however this phase relation cannot usually be predicted in accidental explosions, hence are assumed additive.

Reflection. When a blast wave strikes a flat surface such that the velocity of the wave is normal to the surface, the pressure is referred to as a reflected pressure (P_r). The severity classification for personnel subjected to blast has been cited in terms of overpressure. The approximate values in terms of reflected pressure, which accounts for the presence of the personnel may be listed as follows: Class I - 60 psi or greater, Class II - 5.4 psi to 60 psi, Class III - 0.3 psi to 5.4 psi, and Class IV - 0 to .3 psi.

The effect of reflection of pressure waves off of surfaces such as the ground, floors, walls, and equipment shall be evaluated with respect to the acceptable severity specified in this section. In instances where the reflected pressure exceeds the severity over-pressure criteria, an evaluation of the reflecting surface shall be made to determine its ability to sustain blast load (this will be discussed in the next section). This type of reflection is referred to as a regular reflection. An irregular or Mach reflection occurs when the reflected front moves faster than the incident wave. Under certain conditions, the irregular reflected wave overtakes the incident wave so that the two fronts fuse to form a single front. The position between the single fused wave and the separate incident in reflected wave is called the triple point. Below the path of the triple point, the single wave is perpendicular to the surface; above the triple point path two peak pressures occur. The greatest concern associated with the formation of irregular Mach waves is associated with explosions located some distance above the earth (or rigid floor, surface).

The effects of regular reflected blast pressure and irregular blast pressure shall be evaluated for personnel by either or all of the following: experimental test data, theoretical solutions, numerical methods; provided that the method(s) are demonstrated to cover the parameters of the reflection generating mechanisms that the effecting variables are accounted for within reasonable engineering certainty (approximately 10% error is a conservative bound). The location of the triple point relative to siting of personnel shall be determined. Secondary receptors designated as buildings and structures shall be considered to offer no protection or wave reflection capability.

Alternatively, in the event that verified data does not exist for the high energy pressure gas systems rupture, then it is permissible to convert the equivalent blast energy of the system to TNT equivalent energy, and then estimate the effects of regular and irregular reflective wave pressure resulting from the source explosion. For explosions at ground level, the explosive source energy for a half space is twice the source energy of an infinite space about the explosion; and usually a ratio of 1.8 is assumed when the half space surface or ground is earth.

As an example, consider the location of an explosive source (or charge) some distance from personnel as illustrated in Figure 66. The effects of the height of the blast with respect to overpressure to pressure and the path of the triple point may be obtained from data provided in Swisdak [1975] and Jensen [1972]. An example of a height of burst curve versus peak overpressure along the surface is provided in Figure 5. In the region below the triple point, the overpressure takes the form as illustrated in Figure 7b, however above the triple point, the reflected and incident wave takes the form as illustrated in Figure 7a (whose peak pressures are of lower order magnitude than the peak overpressure below the triple point). Hence, personnel located at elevation A illustrated in Figure 66 would experience a different pressure load than those at elevation B. The reflected pressure coefficient ($C_{r\alpha} = P_{r\alpha}/P_{so}$, reflected pressure/overpressure) versus angle of incidence (α) has been computed for explosives generated blast waves and is illustrated in Figure 67 (reference TM5-1300 - a revision is in progress).

Relative high pressure buildup can be achieved in closed spaces that can adversely effect personnel even at relatively low blast energies. Confined areas in which personnel are located with pressure systems shall be evaluated with respect to reflected and quasi-static pressure. An enclosed area that is normally occupied by personnel is not considered a protective containment enclosure. A fully vented area is considered as $A / V^{0.67} \geq 0.6$ where A is the vent area and V is the enclosure volume (refer to Figure 36). Blowout panels, blast mats, etc. may be considered if necessary to increase the effective vent area of the room. Confinement with respect to protective containment structures is discussed in section 3.2.3.2 (C).

Dynamic Pressure. Dynamic pressure is associated with the wind effects or flow of air with the passage of the shock waves. The peak dynamic pressure is defined by Equation 11. The hazards posed to personnel by the dynamic pressure ($\mathcal{Q}$) are considered to be less severe than the peak overpressure of the wave generating the dynamic pressure effects. Hazards to personnel from dynamic pressure are manifest in the form of fragments, structural collapse, or body translation, all of which are influenced by the drag coefficient (a function of the structure, object, person configuration).

The severity classification IV from a blast overpressure of 0.2 psi for personnel shall be considered a sufficient limit for protection against dynamic pressure (wind born) fragments from debris such as glass and objects under 10 lbs. For pressures above 0.2 psi, objects larger than 10 lbs., and/or structures classified as non protective shall be evaluated with respect to mass-velocity severity criteria for personnel and appropriate building structural criteria to resist the risk of injury to personnel (either occupying the building or structure or adjacent to the building or structure).

Ground Shock. Ground shock from high energy pressure systems above or below ground pose a hazard to personnel via building/structure collapse and/or initiating a damaging release of secondary receptors. Although the design criteria for secondary receptors is beyond the scope of this report, they shall be evaluated to insure that they do not pose a severity Class I - III threat to personnel. A displacement time-history (or response spectrum) analysis is recommended and ground particle velocity versus structural frequency limited according to the criteria of Figure 53 (negligible damage - $0 \leq V \leq 2$ in/sec., minor - $2.0 \leq V \leq 5.4$ in/sec., major - 5.4 in/sec. $\leq V \leq$ 7.6 in/sec., destruction - $V > 7.6$ in/sec.

B) Secondary Receptors. Although the specification for the safety components of secondary receptors is not within the scope of this report, secondary receptors shall be located or protection provided for them against blast only in as much as they present a hazard greater than Class IV severity to personnel (primary receptors); hence protection shall be provided for secondary receptors that present severity levels I through III to personnel. The threshold level for minor damage shall be provided by the manufacturer/designer for: 1) the strategic equipment (B^E) and/or hazardous material (B^H) (serious damage to the equipment or material refers to its blast wave (B^E and B^H) threshold to initiate a hazardous release by blast, missiles, foundation motion, radiation, biological agents, chemical agents) or 2) building/structures (B^B). Serious damage indicates the threshold for reduced structural load carrying capacity by blast wave impact, major support beams undergo sectional average yield

(S_y) stress intensity. Both fragmentation (missile) and blast load are assumed to occur both singly and simultaneously to secondary receptors unless they are protected against one or both hazards.

Hazardous material shall be stored against missiles in accordance with storage combatibility criteria and hazard classifications as outlined by the Department of Transportation (DOT), the Department of Defense (DOD), the United Nations Organization (UNO) specification (when not in conflict with DOT and DOD criteria).

Buildings or structures shall be considered as offering no protection against blast unless evaluated as a protective structure, hence inhabited buildings shall be located (sited) or protected by the guidelines or procedures outlined for personnel in severity criteria cited in section 3.2.3.2(A). No restrictions are placed on the location of uninhabited buildings or structures with respect to specified siting and protection from blast waves except that structural collapse or secondary fragments shall present no risk to personnel greater than class IV severity.

For reference purposes the following four severity classes may be obtained from DOD 5154.4S for unstrengthened buildings (in terms of peak overpressure): Class I total destruction - 10.3 psi, Class II - serious damage of approximately 50% destruction - 3.5 psi, Class III - 20% damage - 2.3 psi, and negligible damage - 5% or less from 0 to 0.85 psi.

In general, the siting or protection of personnel against blast pressure is usually sufficient to insure that secondary missiles will not present a serious hazard.

C) <u>Protective Systems Against Blast</u>. Protective systems used against blast pressures that result from a pressure system failure shall be designed to protect primary and secondary receptors against severity Class I through III pressures. Effects of ambient conditions, dimensional effects (eg.long running crack type rupture versus point or source rupture), multiple explosions, reflection, dynamic pressure, confinement, and blast generated missiles shall be considered. There is no protection requirement for severity Class IV. A protective system shall be designed to resist both estimated missile and blast loads simultaneously and singly, unless it can be demonstrated that these effects cannot occur simultaneously or the system is designed only for one hazard. A protective system design against blast impact shall be evaluated for design adequacy with respect to the pressure-time histogram loading. The pressure-time histogram loading of a structure has been associated with three parameters (singly or in combination) that are a measure of structural performance, these are: impulse (I), pressure-time (P(t)), and peak pressure (static) - (P_S).

A protective system (containment, barrier, shelter) may be designed and classified according to the four following severity classifications (see also 3.2.3.1 (C)):

Class IV is applicable to personnel and is the most stringent of the four classes. The full integrity of a shelter must be maintained. Blast generated missiles shall be limited $B^S{}_4$ in accordance with the requirements in section 3.2.3.1 (C). Personnel must be protected against blast pressures, and excessive structural motions. The global stress intensities (linear membrane and bending stress) $B^B{}_{G4}$ shall be limited to a maximum allowable stress intensity not to exceed $S_Y + 1/4\ (S_U - S_Y)$ where S_U and S_Y are the dynamic yield and dynamic ultimate stress intensities of the wall material. The formation of fragments (brittle mode behavior) shall not be permitted and appropriate limits for $B^S{}_{S4}$ with respect to fracture stresses or adequate shielding shall be employed.

Class III applies to protective systems that are used to protect secondary receptors. The formation of post-failure fragments due to collapse of the protective system is prohibited here. The formation of secondary fragments are allowed, but shielding is required if their severity classification exceeds those which can result in damage to the secondary receptors which would present a severity Class I through III threat to personnel. As outlined in the sections on secondary receptors, the levels governing the sensitivity of secondary receptors (such as strategic equipment, hazardous material, and structures) can only be defined depending on the nature of the secondary receptors as specified by the manufacturer/designer of the secondary receptors . B^S_{P3} for blast generated missiles is equivalent to the limits of F^S_{P3}. B^S_{G3} stress intensity (for linear membrane and bending stress intensities through the protection wall) shall not exceed the stress intensity limit of 0.5 $(S_U + S_Y)$.

Severity Class II pertains to the protective systems used for partial containment to protect secondary receptors, protect other protective structures, and pressure systems from the loading effects of both blast generated fragments and from high pressures. Controlled failures (deflections exceeding the incipient failure deflection of the structural elements is allowed where $B^S_{P2} < S_U$, thereby permitting post-failure fragment formation). The velocities of spalled and scabbed fragments must be limited to values such that secondary explosions or ruptures from the source are prevented. Barriers providing the protection of Category II can be designed for both ductile and brittle behavior where communication of a secondary rupture or explosion by fragments must be prevented. The response criteria used for the donor barrier design varies for limited protection of sensitivity.

Severity Class I is similar to II except that limited communication of system rupture or detonation of hazardous material is permitted. Total failure criteria are used for the design of the protective system in this category where B^S_{G1} (the stress intensity limit) for membrane and bending stress through the protective wall may exceed S_U where S_U is the ultimate stress intensity for the wall material. B^S_{P1} and B^S_{S1} shall be specified or limited according to the sensitivities of the secondary receptors.

Documentation for the protective system shall be maintained in accordance with section 3.2.4.0 in order to provide tracability of historic events and predict the remaining load carrying capability of the protective system. Recertification or evaluation of the remaining performance shall be determined for protection severity Classes II through IV.

The performance evaluation of blast pressure protective systems shall be estimated based on any or all of the following methods: experimental test data, theoretical solution, numerical solutions; provided that the methods are demonstrated to cover the parameters of the initial protective structures dynamic response mechanism such that: 1) material properties, 2) geometries, 3) boundary conditions, 4) coupling effects, and 5) blast pressure-time-distance histogram are accounted for within reasonable engineering certainty (approximately 10% or is a conservative bound).

An example of a computational method used to determine the response of a structure subjected to dynamic pressure is provided in Figure 44. A finite element solution provides deformation and stress plot data which permit the designer to locate regions in which the structure will undergo its most severe stressing.

Alternatively, in the event that experimental, theoretical, and numerical predictive methods (that have been documented) are not applicable to predict the blast wave and protective structural response, the following alternative methods of evaluation are cited:

1) the performance of a test program with at least five tests that cover the range of the parameters with respect to the protective system and blast pressure characteristics for worst case loading.

2) Perform an estimation of structural response based on simplified modeling assumptions which may be demonstrated to provide a conservative or upper bound estimate.

3) Limit the allowable stress intensity values for membrane and bending stress intensity in the protective structural wall to the elastic range.

As an example to item 2 (alternate methods), consider Figure 68 for an illustration of pressure-loading/structural-response parametric ranges in which impulse, pressure-time, and static pressure loads may be assumed to predominate over certain pressure ranges depending upon the relationship of the duration of pressure pulse (t_o) to structural response time (t_m).

Containment Protective Structures. Containment structures may be classified as: a) fully confined, b) partially vented, c) fully vented. All enclosures shall be evaluated with respect to pressure-time history loading as outlined for protective structures in this section 3.2.3.2. The classification of containment structures are based on the following ratio of $A/V^{0.67}$ (area to volume ratio), where: for fully contained blast, $A/V^{0.67} = 0$; $A/V^{0.67} \leq 0.60$ for partially vented; and $A/V^{0.67} \geq 0.60$ is fully vented (or is referred to as a barricade). For fully confined containment, both gas pressure dominant loading and shock pressure dominant loading are to be evaluated. An alternate design load criteria is illustrated in Figure 36.

For partially vented containment structures, it is found that they have short duration shock pressures and long duration gas pressure, hence the mean pressure has been found to affect a similar response as the combined short duration plus long duration time histogram. A formula cited for maximum mean pressure P_{mo} versus charge - volume ratio (W/P_oV, energy release (in-lbs)/ambient pressure (psi)$\cdot$ volume (inches^3)) is provided

for $W/P_oV \leq 350$

$$\bar{P} = 1.336\ (W/P_oV)0.6717 \qquad [56]$$

$W/P_oV > 700$

$$\bar{P} = 0.1388\ (W/P_oV)$$

where, $\bar{P}_{mo} = (P_{mo} + P_o)/P_o$ (see Anderson [1983] which replaces the TM5-1300 formula $P_{mo} = 2410(W/V)^{0.72}$ (where $(W/V) \equiv$ (lbs TNT/ft^3 and $P_{mo} \equiv$ psi)

The design load takes the form as graphically shown in Figure 36b, for the line $P_R - 0 - T_0$ where $P_R = P_{mo}$ and $T_0 = 2\ I_{mo}/P_{mo}$.

A fully vented enclosure will experience a reflected pressure in a manner of a barricade in an open space, hence, the design load will take the approximate form illustrated in Figure 36b by the line $P_R - 0 - T_0$.

When providing containment for a gas filled system, it is often desirable to provide a blow out panel or wall so that the sustained overpressure or shock wave from a pressure system failure will be minimized, thereby reducing the resulting damage to a secondary containment facility. External to the blow-out feature, protection must be provided for personnel and nearby secondary receptors against both potential fragmentation and blast effects. A secondary barricade must be provided, such as: a wall, maze, seal-off unoccupied area, blast mat(s), or suppression screen, with appropriate approximate access limitations.

In the use of a kinetic - energy (missile) absorbing pendulum shield, movable wall, or cover, the energy absorbing system shall be so secure that it cannot become a missile itself (blast generated secondary hazard).

Suppressive Shields. Suppressive shields provide a mechanism to contain fragments while providing controlled venting (such as discussed in containment) or control the combustion process (detonation/deflagration). Suppresive shields may fully enclose the high energy gas pressure system (examples are illustrated in Figure 35). Illustrations of several suppressive shield lattice arrangements are shown in Figure 34 and definitions of vent area ratios for various lattice or structural configurations are provided. The ability of the suppression shield to sustain fragmentation (if specified) shall be evaluated in accordance with section 3.2.3.1 on fragmentation. The pressure-time history response within and on the exterior of the pressure system shall be determined and specified (or rated for specific loads) in accordance with the section on blast 3.2.3.2.

Restraint Devices. Restraint devices designed specifically as hazard reducing structures shall be evaluated in accordance with the limit specified for protective structures.

Layered Vessels, Pipes, and Components. Layered pressure systems shall be considered protective walls or structures if: 1) the layer is not considered for its added safety or structural support in estimating the design adequacy of the pressure boundary and 2) the layer is adequately vented or ventilated to ambient conditions.

Shielding for Jets. For protection against gas and fluid jets for systems up to 15,000 psi, a mild steel sheet thickness of 16 gauge (0.059 in.) minimum is required. Where jets are used in continuous high pressure cleaning-type applications, where the shielding is also to flying debris as a result of a jet cleaning, or where the system pressure exceeds 15000 psi., shielding for jets shall have a minimum mild steel thickness of 12 gauge (0.104 in.).

3.2.4.0 Documentation

The objective of this section is to provide guidance to the designer/constructor/owner/operator of high pressure facilities or portions thereof as to the type of documentation which is necessary to provide tracability of the historic events and predicted remaining capability of the protection systems defined in 3.2.

The retention requirements for these documents are established in section 3.2.4.8.

This section is applicable to protective systems as defined in section 3.2.

3.2.4.1 Design Documentation

Design Documentation includes all system/component calculations which are required by section 3.2 for the design of blast and missile energy release protection. Such documents include, but are not limited to, the system/component specification, criteria, references such as computer program manuals.

Design documentation should also include specified material properties or actual measurements available to the designer prior to the development of the calculations as a result of controlled material supply such as mill test reports, and concrete strength test results.

Design drawings which incorporate design criteria, establish the fabrication or installation requirements or dimensions are also classified as design documents and should be retained by the system owner in accordance with section 3.2.4.8.

3.2.4.2 Fabrication Documentation

Fabrication documentation which should be maintained includes process control records indicating that quality assurance/control programs were functioning during the manufacturing process. These documents include, but are not limited to weld traveler reports, mill certification reports and other material property reports which may be required by the design process. These records may at the end of the fabrication cycle be substituted by a certificaton of compliance with the design/purchase specification. It should be noted, however, that it very often becomes beneficial in analysis of system changes to have the actual material properties rather than an enveloping certification. The actual test documents should be obtained by the owner in all cases.

3.2.4.3 <u>Installation Documents</u>

Installation documents are typically comprised of welding records, welder certification records, and material process records including heat treating records, slump tests, soil compaction records, and core borings. Obviously the type of record which is obtained depends on the type of protective system that is being utilized.

For critical systems where the protective system is of such a design that close tolerances must be maintained during installation, good practice dictates that the allowable tolerances be established by analysis prior to installation. Additionally, after installation is completed the as-built dimensions should be checked and compared against the designer dimensions. Any discrepancies must then be resolved by analysis and a statement or documentation of the acceptability of the discrepancy must be issued by the analyst for retention by the owner.

3.2.4.4 <u>Pre-Service/In-Service Inspection Documentation</u>

Pre-Service inspection documents include those records of testing which good practice would dictate be performed to insure construction fabrication and operational integrity. These records may include the results of ultrasonic testing, radiographs, and hydrostatic testing at operating temperature if applicable.

In-service inspection documents should be developed and maintained to allow the requalification and recertification of equipment. As such, these documents must include complete operational logs of the equipment indicating all temperature and pressure cycles. In the absence of such information the burden of proof of the acceptability of the protection device to perform its intended function lies with the owner of the equipment.

3.2.4.5 Repair

Repair documentation includes documents which relate to the analysis, fabrication, and inspection phases of the protection device's rehabilitation. Examples of the documents which are included in this category are: the design specification (if different from the original); the analysis calculations showing the acceptability of the repair scheme, the material test properties used in the analysis and any actual test results; and the results of pre-service inspections and comparisons against the original or supplemental design documents to which the repair work was to be performed.

The documentation should include any information which must be provided to demonstrate that good engineering practices were followed and good engineering judgement was used to assure personnel and property safety prior to putting a repaired protection system back into service.

3.2.4.6 Post Accident

Post accident documentation includes records of the performance of a protection system following an accident within a high energy system. Such records may include photographs of any residual deformation of the protective device, records or estimates of peak temperatures and pressures reached during the accident and any information pertaining to cyclical loading on the system as a result of pressure wave reflection. Analytical calculations to assure the suitability of the protection system to again perform its intended function following an accident should also be included in the retained documentation.

3.2.4.7 Derating/Decommissioning/Recertification/Requalification

The documentation described in sections 3.2.4.1 through 3.2.4.6 should be sufficient to allow analysis for determining the need or ability for derating, decommissioning, recertifying or requalifying equipment or facilities at any point during their useful life. The owner or user may be aware of additional information required to allow such analysis for their particular facility or equipment and should make provisions to retain any records of this nature.

3.2.4.8 Document Storage and Retention

The storage of documents should be such that the documents are reasonably protected from loss due to fire, water damage and theft. There are several methods that can be used to provide such protection:

1) Remote duplicate storage of either hard copy or microform.
2) Protection enclosures with proper firerating water tightness and access control.

The suggested types of records which should be retained over the life of the facility are listed in Table 21. This list provides general record types whose retention should insure maximum flexibility for equipment or facility use over its lifetime.

3.2.5.1 Testing

Within the scope of the certification of protective structures to provide protection for primary and secondary receptors at rated missile impact and/or blast pressure loads, three types of testing are required: a) material testing, b) performance testing, and c) acceptance testing.

Material Testing. Protective structural material may be metallic, mineral (masonry), and/or organic. Material specifications and testing shall be provided for the applicable dynamic loads (global and local impact) in accordance with the appropriate ASME, ACI, and ASTM standards. For example, see ASME Section II.

Performance Testing. Performance testing may be destructive and/or nondestructive, that is, performed to verify the design adequacy of the protective structure against missiles and blast in accordance with sections 3.2.3.1 and 3.2.3.2 of this report. Performance testing may consist of scale model tests as well as full size components.

Acceptance Testing. Acceptance testing refers to insitu nondestructive testing of protective structures against blast and impact. Sub-assemblies, parts or components may be destructively tested within the insitu system provided all affected damaged areas are removed or repaired; and replacement or repaired parts are shown to meet or exceed performance requirements.

Testing Criteria. While testing criteria are a very important part of a protective system certification, the development of relevant guidelines is not within the scope of this report. This will be provided in more detail in the next phase of this study.

3.3 PROBABILISTIC VS DETERMINISTIC APPROACHES

An assessment or comparison of the proposed probabilistic approach over the current deterministic procedures are as follows:

1) Because of the inherent uncertainties in many input parameters, worst-case assumptions and data are used in the deterministic analysis. The probabilistic method considers the uncertainties explicitly and thus provides more rational, usually less conservative, and thus economical designs.

2) A deterministic analysis does not provide any indication of the damage probability or strike probability to equipment and work areas. A probabilistic analysis provides these probabilities, which are useful in comparing alternate barrier design and alternate locations of equipment/work areas.

3) Depending on the importance of the different equipment, the barrier design and/or location can be set to different damage probabilities. Thus the more critical equipment can be given additional protection while the less critical equipment is given moderate levels of protection. This aids in allocating funds economically and effectively. Such a quantitative approach is not possible with the deterministic method.

4) The damage/strike probabilities obtained from probabilistic analyses can be used to arrive at optional designs; that is, relationships between increase in barrier strength versus decreases in the probable cost of equipment damage can be established. Then an optimum barrier design can be sought. Cost-savings can be significant.

5) Current probabilistic design criteria are based on judgement and experience. Generic probabilistic studies can be used to arrive at more rational, reliable, and economical deterministic design criteria.

6) Some of the results generated from the development of probabilistic methodology, for example, compilation, and statistical analysis of data, are directly useful in developing better, and less conservative input parameters

for current deterministic analyses. Thus the development of the probabilistic methodology advances the state-of-the-practice of the deterministic procedures also.

7) Deterministic methods generally have their origins in the solution of manageable equations or formulae for many aspects of the phenomena from explosion hazards resulting from system explosions or rupture, hence once the characteristics of the system, hazard, receptors, and protection is known,the designer can select the formulations that are applicable to his problem. In many instances these solutions may consist of solving a series of simple formulae. Hence, the designer lacks the ability to easily determine the effects of certain parameters that are propagated through the calculations.

8) Deterministic methodology tends to limit the view of the researcher to a narrow view rather than the larger picture that a unified probabilistic approach tends to encourage. This is particularly evident in the studies undertaken in the areas of blast and fragmentation in which duplicating efforts are found to exist by divergent industrial or government studies addressing their perceived special application.

9) There is a need for a formal mechanism for inputting the "lessons learned" not only from controlled burst test but also from accidental pressure system failures. Probabilistic methodology provides this mechanism.

10) Deterministic methodologies are percieved as easier in allowing more judgement input into the design cycle. This can be both good and bad, however probabilistic methods allow considerable latitude in judgement.

11) As more and more sophisticated computer numerical solutions become available, there is a perception that this will lead to a lack of need for probabilistic methodology or a conflict of these methods. In fact, probabilistic methodologies are compatible with these numerical methods and are being explored only recently with respect to their promising potential.

12) It has been observed that some conservatism may be eliminated in fragment (distribution of mass and geometry) prediction by controlling the permissible fragment mass and size distribution through design. A probabilistic approach is best suited to evaluate the practicality and possibilities of such methodology.

4.0 SUMMARY - CONCLUSIONS - COMMENTS

The purpose of this report was two-fold. One to provide an overview of the studies that have been performed in the area of energy release protection that may be relevant in providing guidance with respect to the safe location or the provision of protection for personnel located adjacent to a high energy pressure system. The second part of this study outlines a procedure or course of action from a probabilistic point of view and a performance point of view as to how one might proceed in providing protection to personnel by proper distance and/or protective systems. In part two, the medium of the pressure systems was assumed to be limited to inert gas.

Upon reviewing the available literature, one comes to several conclusions:

1) High energy pressure systems are utilized in many diverse industries or technologies and their use is increasing with the demands of technological advances.

2) There is a tremendous wealth of data on energy release which should more appropriately be called hazardous release protection. Because the mechanisms of (1) explosions, (2) fragmentation, and (3) degenerative release hazards are complex, much investigation remains to be done.

3) Most blast and fragmentation data have developed with respect to explosive materials, much of this test data are gathered for defense and military applications. This information provides a tremendous starting point.

4) Different media within a pressurized system produce characteristic blast waves that are different from vessel failures initiated by high explosives. Not much blast data are available for non high explosive media.

5) The blast wave and fragmentation characteristics of a ruptured pressure system are dependent upon the material properties, geometry, and ambient (or operating) conditions. A mechanistic assessment of the influence of vessel characteristics on missile (fragment) number, mass, geometry, and distribution from a system rupture is needed; but compounding this problem is the reality that many pressure system failures are initiated by the presence of unknown flaws or defects.

6) The pressure-time-distance histograms for most gases are not well known. This is important since the loading of a structure can be highly dependent upon the characteristic

pressure-time histogram of the blast wave.

7) The direction and range of missiles from pressure system failures are not easily predicted since the shapes are not known and are usually irregular. It is possible that this irregularity contributes to a spinning or frisbe mode as suggested by Baker, however these effects are not well documented. The general practice is to assume worst case sizes.

8) Although a considerable amount of data exists for the blast and fragmentation effects on people and structures, more data is needed in terms of performance criteria, particularly with respect to human response. There is a lack of data that relates human response to missiles in terms of force or pressure.

9) Considering the worst case scenario from vessel rupture, fragment size, fragment shape, fragment orientation, optimum impact on a structure or person, results in a summation of worst case effects, which intuitively, most people would agree are highly improbable. Hence, a considerable amount of conservatism or error can be built into an analysis to protect against a hazardous release of a pressure system.

10) Probabilistic methodology offer a means to reduce some of the overconservatism built into the analysis of protection against pressure vessel ruptures.

11) A mechanism to incorporate failure histories and statistics is needed in the design cycle. A probabilistic methodology provides a means to accomplish this as well as providing a decision making tool with respect the influences of various parameters on the probability that an event will occur.

12) Although there are some differences between data developed from high explosive tests and that data needed for gas pressurized (and other media) systems, these high explosive studies represent a vast resource of information to be incorporated in developing future data.

13) The prediction of missile penetration and perforation has become increasingly more accurate with the introduction of the high speed digital computer and numerical methods. However

these methods as of yet are not cost effective which is necessary if advanced and exotic materials and/or designs are to be considered for protective systems. Such materials may prove to be light and cost effective versus traditional materials.

14) Protection concepts have taken on traditional industry related characteristics unchanged for years. Alternate protection concepts other than those traditionally used in pressure systems should be explored, such as those used in the aerospace industry for protection against turbine blade generation.

15) This study was but a modest overview and beginning to the larger issue of developing design guidance for systems that contain blast, missile, chemical, biological, radioactive, heat, and shock effects. With diverse industries using the technology of high energy pressure systems throughout the United States, there is clearly a need to develop a code and standard consensus document to provide design guidance such as provided through the ASME Pressure Vessel and Boiler Code.

Section 5.0 lists a number of recommendations for future research needs with respect to high energy pressure systems, design, analysis and criteria development.

5.0 RECOMMENDATIONS FOR FUTURE RESEARCH

The development of general design practices and criteria, code and standard guidance, and reliable analytical predictive methods for siting and barricading/containment of hazardous pressure systems presents a formidable challenge. To accomplish this objective, it is necessary to correlate the valuable but diverse data that exists and to define those studies which are necessary to undertake that will provide a common service to the various designers, developers, manufacturers, owners, and operators of such systems. The following is a list of recommended initial studies. They are not prioritized. Because of the expense of test programs, the need to evaluate many phenomena, and the vast number of topics and problem areas, test programs should be designed (where possible) to evaluate as many of the interrelating effects as possible.

5.1 A) <u>Source (Location) of Rupture or Failure</u>

1) Perform an updated study on vessel and pipe rupture. Collect data on failures from Europe (such as those underway in Germany and the U.K.), Japan, and various sources in the U.S. (such as EEI, ABMA, NRC, ASME, Boiler Inspectors, etc.), and published cases in the open literature with respect to identifying mechanism of failure, characterization of the system, and an assessment of energy content where possible. An assessment of the types of hazards posed would be evaluated. The resulting data base and report would be used as an aid to identify needs for research with respect to high energy systems, the hazards they present, the need of barricading/containment and energy distance criteria.

2) Undertake studies to determine the improved criteria for establishing types and location of vessel, pipe, and component breaks. Such improved criteria should include fracture mechanics, crack stability, and crack propagation mode considerations in addition to current simple fatigue basis. Further material considerations such as stress corrosion cracking should be included.

3) Perform analytical parametric studies to determine effects of gap, strain rate, geometry changes, damping, and realistic break opening modes on system response.

4) Develop and benchmark reasonable criteria for (1) estimate of system energy (E) content, (2) prediction of percent E contribution to blast wave, fragment, and/or post failure explosion generation, and (3) rupture rates and blast wave characteristics for ranges of explosives (HE to inert), state (solid, liquid, gas), and FLT (pressure, dimensions, temperature).

5) Investigate the practicality of controlling pressure vessel fragmentation with respect to size and mass at the design stage.

6) Investigate the relationship between the failure mechanism and the prediction of sharp versus blunt fragments. And, correlate this relationship of sharp versus blunt fragments with penetration data for regular missiles.

5.2 B) <u>Hazards Produced by the Failure Source</u>

1) Missiles and fragments (solid or liquid) generated by non high explosive (HE) vessel explosions or ruptures pose a hazard to equipment and personnel that is complex to predict because of its interrelationship with the type of failure. However, there is a a need to assess the initial velocity, dispersion, size, environmental effects, etc., to adequately design and develop containment, restraint or siting strategies. A testing program is needed to evaluate the parameters influencing missile generation. Such a test program would also provide an opportunity to investigate other areas such as <u>blast effects</u>.

2) Perform a study on media ejection during vessel and piping rupture. This study is oriented toward the interrelationship of media vs rupture characteristics; and dispersion characteristics of the media as a function of media properties such as vapor, gas, flash evaporation, liquid, particulates, etc.

3) Evaluate literature and benchmark effects of physical versus/and chemical energy on fragmentation characteristics.

4) Develop experimental, analytical, and developmental program to (1) predict the characteristics of fireball hazards (size, duration, heat flux) for various gas, liquid, solid substances and (2) investigate suppression (or containment) and protective techniques.

5.3 C) <u>Barricade/Containment:</u> <u>Protection</u>

1) Develop performance criteria for code and standard development with respect to barricade/containment design. The design adequacy of barricade and containment walls against missile impact is usually guided by empirically based formula. The intent of this study is to develop performance type criteria that are used in ASME vessel design practices. The result would provide more freedom in innovative design of barricade/containment structures and material selection.

2) As a complement to or support of item C-1, provide for a continued testing, research, and development program to:

(a) model or characterize the dynamic material behavior by numerical computer solutions and

(b) evaluate permissible parametric ranges of material model and numerical simplifications.

3) Collect and critically correlate existing test data for various barricade, containment, shelter, suppression, and pipe restraint design configurations and publish handbooks on barricade, containment, shelter, suppression and whip restraint design that could serve as a standard for this newly developed discipline.

4) Continue the research that has been initiated to characterize static and dynamic local resistance curves for carbon and stainless steel pipes as a function of diameter/thickness ratio, diameter/length ratio, and target stiffness.

5) Collect and critically correlate data on barricade containment concepts to protect against various combinations of hazards (missiles, blast, heat, chemical, radiation, biological, secondary ignition).

6) Investigate the effectiveness of various types of protective systems (material and geometric effects) such as multilayer vessels, composite material, fiber, etc.

5.4 D) <u>Distance Siting Criteria for Object, Target, Source, Barricade/Containment</u>

1) There exists a need to develop siting criteria which takes into account, the interrelationship of source and target as a function of distance and barricade/containment. Such a study would provide guidance for code and standard development. In the broadest sense, such an undertaking would consist of several studies that would address each type of hazard (fragments/missiles, blast, temperature/heat, chemical, biological, radiation, foundation motion).

2) An experimental program is needed to assess the siting criteria established in item D-1. This test program may be correlated with the suggested B-1 test to evaluate missile characteristics as related to failure characteristics cited in A above.

3) A more technically precise method consistent with structural analysis methods are needed to determine what are acceptable stress or force limits for the impact of missiles into personnel. For example, it is not clear from the available data what is considered a sharp or pointy or blunt fragment.

5.5 <u>Probabilistic Methodology Research and Development Needs</u>

The R&D needs may be categorized into four major groups:

1) <u>Compilations and Statistical Analysis of Available Data</u>. In any probabilistic analysis of engineering problems, a reliable data base is the key to success. The data that are of interest in a pressure vessel missile generation and damage assessment are:

A) Pressure vessel failure statistics (categorized according to size, operating pressure, internal medium, failure mode, etc.)

B) Fragment parameters
- Initial conditions
  - *Velocity
  - *Ejection angle
  - *Mass
  - *Size
  - *Shape
- Final conditions
  - *Strike Location
  - *Strike Angle
  - *Strike Velocity

C) Barrier damage due to missile strike (categorized according to velocity range, shape/size of missile strike angle, etc.)
- *Concrete barriers
- *Steel barriers

Data shall be gathered from all available sources including the aerospace industry, defense industry, chemical industry and the power industry. Both test data and post-accident investigation data shall be included. Data from European and Japanese tests may also be used.

The data thus gathered has usefulness, not only in the probabilistic anslysis, but also in deterministic analysis. The data can be used to better estimate the worst case values of input parameters (for example, missile velocity and mass) to the deterministic analysis thus leading to less conservative and more economical designs.

2) Expert Opinion Survey. In cases where there is paucity of data, expert opinion shall be sought to provide "soft" data. Industry experts are in a position to provide estimates of the statistics of many of the parameters of interest, on the basis of their experience and judgement. Statistical methods for assessing such expert opinion have been developed for applications, particularly in social sciences. These methods can be adapted for engineering problems also. For example, one such technique - the Delphi method - has been successfully utilized to develop failure statistics of electronic components (see IEEE [1977]).

Once independent statistical distributions of the expert opinion are developed, they can be combined with the data-fitted distributions (Task 1) to arrive at combined, more reliable distributions.

An alternate method of utilizing expert opinion is to provide the experts with the data-fitted distributions or histograms and let them each upgrade (modify) these distributions on the basis of their experience and judgement. The expert opinion thus obtained is used to formally modify the original distributions, using statistical techniques such as the Bayes method.

3) Test Program. Purpose of the test program is to obtain new data to complement the data already available from past tests and post-accident investigations. Details of the test set-ups (geometry, pressure, energy of the pressure vessels) shall be decided only after Task 1 (compilation of available data) is completed, because Task 1 will point to specific areas where there is no or very little data available.

It shall be noted that pressure vessel failure tests are conducted in the aerospace, defense, petrochemical and power industries, for purposes other than obtaining fragment characteristics. However, these tests do generate data on fragments; and every attempt shall be made to work with these groups and obtain fragment data. Joint programs with European and Japanese agencies conducting destructive pressure vessel tests are also recommended.

Data obtained from the test program shall be used to update the probabilities and probability distributions derived in Task 1.

4) Methodology and Computer Software Development. An integrated probabilistic assessment approach has been developed in this report. Development of the detailed mathematics of the methodology for the various steps, and their implementation in a computer program shall be carried out in parallel with Tasks 1 and 2 discussed above or prior to those tasks. It is recommended

that the computer program be modular in structure. The modular structure has the following advantages:

A) Alternate probabilistic models and/or updated models as the state-of-the-art advances can be easily "plugged-in".

B) Deterministic-cum-probabilistic analyses can be carried out easily, by accessing only those modules required for the probabilistic parts of the analysis.

C) Different modules of the program can be developed independently and plugged into the main program.

A suggested modular structure of the program is given in Figure 63.

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TABLE 1

Energy: Post Rupture

Chemical |6.1|

$E_2 = W \cdot \Delta H$

ΔH = heat of reaction/unit weight |a|

Compressed Gas |6.2|

$E_1 = [(P_1 - P_a)/(\gamma_1 - 1)]\ V_1$ |a|

P_1 = initial absolute pressure in vessel

V_1 = volume of vessel

P_a = outside pressure

γ_1 = ratio of specific heat of gas

isentropic expansion |b|
or quasi steady process

$E_1 = [P_1 V_1 (\gamma_1 - 1)] \left\{ [1-(P_a/P)^{\gamma_1 - 1/\gamma_1}] + (\gamma - 1) P_a/P_1\ [1-(P_a/P_1)^{-1/\gamma_1}] \right\}$

$E_1 = P_1 V_1/(\gamma_1 - 1)\quad [1-(P_a/P_1)^{\gamma_1 - 1/\gamma_1}]$

or

$E_1 = [P_a V_1/(\gamma_1 - 1)]\quad [(P_1/P_a) - (P_1/P_a)^{1/\gamma_1}]$

isothermal expansion |c|

$E_1 = nRT\ \ell n(P_1/P_2)$

or

$E_1 = 1.26\ V[P_1/P_0]\ [T_0/T_1]\ \ RT_1 \ell n\ [P_1/P_2]$

P_0 = standard condition (one atmosphere)

T_0 = standard temperature (273 K)

R = gas constant 1.987 cal/gm - ml - ^{0}K

adiabatic expansion

$E_1 = (P_1 V_1 - P_a V_a)/(\gamma - 1)$

Table 1 Continued

constant pressure |d|

$$E_1 = P_a (V_f - V_1)$$

V_f = final volume of gas

Flash Evaporation |6.3|

$$E_1 = m(u_1 - u_2) = m\int_1^2 p\,dv$$ |a|

u = internal energy = $h - pv$
m = total mass of fluid
h = enthalpy
v = specific volume

Liquid Propellants |6.4|

$$E_2 = (4.18 \times 10^6\ J/kg)\ W_T\ Y/100$$ |a|

W_T = total mass of propellant and oxidizer

Y = terminal blast yield

INERT LIQUIDS |6.5|

$$E_1 = PV\gamma$$ |a|

V = vessel volume
P = internal pressure
γ = compressibility

Vessel Elastic Strain Energy |6.6|

$$E_3 = \int_V \sigma_{ij}\varepsilon_{ij}\,dV$$ |a|

Table 2

ASME SAFETY STANDARDS FOR HIGH PRESSURE SYSTEMS
Subcommittee 6000: Energy Release Protection

Table of Contents

Table 2 (cont'd)

6332 Reflected Wave Characteristics
6333 Scale Factors
6334 Source Effects
6335 Media Effects
6336 Target Effects
6340 Fragment
6341 Velocity
6342 Distribution
6343 Size
6344 Terminal Ballistics
6345 Secondary
6346 Type
6347 Relationship to 6241
6350 Foundation Motion
6360 Heat propogation
6370 Chemical Reaction
6380 Radiation/atomic
6390 Biological

6400 <u>CONTAINMENT/BARRICADING: ACTIVE & PASSIVE SYSTEMS</u>
6410 Types
6411 Safety Walls
6412 Shielding for Jets
6413 Shielding for Airborne Hazardous Particles
6414 Excavations
6415 Tie-Down Systems
6416 Quench/Suppression Systems
6417 Multi Wall Components
6418 Cubicles
6420 Performance per Hazard
6430 Test Certification
6440 System or Equipment Secondary Hazards (see also other sections)

6500 <u>DISTANCE SITING CRITERIA OF SOURCE, OBJECT, BARRICADING</u>
6510 Personnel Siting Criteria
6520 Structural Siting Criteria
6530 Adjacent Hazardous Material Siting Criteria

6600 <u>DOCUMENTATION</u>
6610 Installation
6620 Service/Modification
6630 Failure
6640 Repair
6650 Operation Cycles
6660 Inspection
6670 Decommission
6680 Supporting Analysis

Table 3

Conversion Factors (TNT Equivalance)
For Some High Explosives

Explosive	Weight Specific Energy, E/W, kJ/kg	TNT Equivalent $(E/W)_x/(E/W)_{TNT}$
Amatol 60/40 (60% ammonium nitrate, 40% TNT)	2650	0.586
Baronal (50% barium nitrate, 35% TNT, 15% aluminum)	4750	1.051
Comp B (60% RDX, 40% TNT)	5190	1.148
RDX (Cyclonite)	5360	1.185
Explosive D (ammonium pictrate)	3350	0.740
H-6 (45% RDX, 30% TNT, 20%Al, 5% D-2 wax)	3863	0.854
HBX-1 (40% RDX, 38% TNT, 17% Al, 5% D-2 wax)	3850	0.851
HMX	5680	1.256
Lead Azide	1540	0.340
Lead Styphnate	1910	0.423
Mercury Fulminate	1790	0.395
Nitroglycerin (liquid)	6700	1.481
Nitroguanidine	3020	0.668
Octol, 70/30 (70% HMX, 30% TNT	4500	0.994
PETN	5800	1.282
Pentolite, 50/50 (50% PETN, 50% TNT)	5110	1.129
Picric Acid	4180	0.926
Silver Azide	1890	0.419
Tetryl	4520	1.00
TNT	4520	1.00
Torpex (42% RDX, 40% TNT, 18% Al)	7540	1.667
Tritonal (80% TNT, 20% Al)	7410	1.639
C-4 (91% RDX, 9% plasticizer)	4870	1.078
PBX 9404 (94% HMX, 3% Nitrocellulose, 3% plastic binder)	5770	1.277
Blasting Gelatin (91% Nitroglycerin, 7.9% Nitro-cellulose, 0.9% Antacid, 0.2% water)	4520	1.00
60 Percent Straight Nitroglycerin Dynamite	2710	0.60

Table 4

Equivalent Weights for Free Air Effects[1]

Material[2]	Peak Pressure $(P)_{TNT}$	Impulse $(I)_{TNT}$	Composition or Formula
TNT	1.00	1.00	$C_7H_5N_3O_6$
Explosive D	0.85	0.81	$C_6H_6N_4O_7$
Cyclotol 70/30	1.14	1.09	RDX/TNT, 70/30
RDX/5 Wax	1.19	1.16	RDX/Wax, 95/5
Comp B	1.13	1.06	RDX/TNT/Wax, 59.4/39.6/1.0
Comp A-3	1.09	1.07	RDX/Wax, 91/9
Picratol	0.90	0.93	Explosive D/TNT, 52/48
Minol II	1.24	1.22	NH_4NO_3/TNT/Al, 40/40/20
Tritonal 80/20	1.07	1.11	TNT/Al, 80/20
HBX-1	1.21	1.21	RDX/TNT/Al/Wax, 40/38/17/5
Torpex II	1.23	1.28	RDX/TNT/Al, 42/40/18
H-6	1.27	1.38	RDX/TNT/Al/Wax, 45.1/29.2, 21.0/4.7
Pentolite	1.17	1.15	PETN/TNT, 50/50
HBX-3	1.16	1.25	RDX/TNT/Al/Wax, 31/29/35/5
TNETB	1.13	0.96	$C_6H_6N_6O_{14}$
Comp B/TiH_2, 70/30	1.13	1.13	RDX/TNT/TiH_2, 42/28/30

[1]Data are obtained in 2-50 psi range for shock overpressure and converted to EW

[2]To calculate equivalent weights not on this table, see Chemical Reviews, Vol. 59, No. 5, 801-825, October 1959.

Table 5

Liquid Propellant Explosive Equivalent (%) TNT

Propellant Combination	Other Than Range Launch Pads	Range Launch Pads
LO_2/LH_2	60%	60%
LO_2/LH_2 - LO_2/RP-1	Sum of (60% for LO_2/LH_2) (10% for LO_2/RP-1)	Sum of (60% for LO_2/LH_2) (20% for LO_2/RP-1)
LO_2/RP-1 or LO_2/NH_3	10%	20% up to 500,000 lbs plus 10% over 500,000 lbs
IRFNA/Aniline*	10%	10%
IRFNA/UDMH*	10%	10%
IRFNA/UDMH - JP-4*	10%	10%
N_2O_4/UDMH - N_2H_4*	5%	10%
N_2O_4/UDMH - N_2H_4 - Solid*	5% plus the explosive equivalent of the solid propellant	10% plus the explosive equivalent of the solid propellant
Tetranitromethane (alone or in combination)	100%	100%
Nitromethane (alone or in combination)	100%	100%

*These are hypergolic combinations.

Basis: Recommendations of the ASESB Work Group. Tetranitromethane and nitromethane are known to be detonable.

NOTES:

1. The percentage factors to be used to determine the explosive equivalencies of propellant mixtures at launch pads and static test stands when such propellants are unconfined except for their tankage. Any configurations other than stated above should be considered on an individual basis to determine the equivalencies.

Table 6

HEAT OF COMBUSTION OF COMBUSTIBLE GASES

Material	Formula	Low Heat ΔHc Value (Btu/lb)	e_{HC}/e_{TNT}*
Paraffins	(C_nH_{2n+2})	(18,857-21,502)	(10.48-11.95)
Methane	CH_4	21,502	11.95
Ethane	C_2H_6	20,416	11.34
Propane	C_3H_8	19,929	11.07
n-Butane	C_4H_{10}	19,665	10.93
Isobutane	C_4H_{10}	19,614	10.90
Alkylbenzenes	(-)	(17,259-17,984)	(9.59-9.99)
Benzene	C_6H_6	17,446	9.69
Alkylcyclohexanes	(C_nH_{2n})	(18,642-18,846)	(10.36-10.47)
Cyclohexane	C_6H_{12}	18,846	10.47
Mono-olefins	(C_nH_{2n})	(19,214-20,276)	(10.67-11.26)
Ethylene	C_2H_4	20,276	11.26
Propylene	C_3H_6	19,683	10.94
Isobutylene	C_4H_8	19,367	10.76
Miscellaneous			
Hydrogen	H_2	51,571	28.65
Ammonia	NH_3	8,001	4.45
Ethylene Oxide	C_2H_4O	11,482	6.38
Vinyl Chloride	C_2H_3Cl	8,239	4.58
Ethyl Chloride	C_2H_5Cl	8,246	4.58
Chlorobenzene	C_6H_5Cl	11,754	6.53
Acrolein	C_3H_4O	11,830	6.57
Butadiene	C_4H_6	20,200	11.22
HC Groups (est)	-	19,000	10.56

*Ratio of Specific Energies for Equivalent Weights of 'Fuels' and TNT.

(i.e., $e_{HC}/e_{TNT} = \frac{\Delta Hc}{1832.4}$ [BTU, lb] $= \frac{\Delta Hc}{4.274(10^6)}$ [joules, kg]

Table 7

K_G - value of gases, ignited at zero turbulence[a]

Ignition energy $E \approx 10J$, $P_{max} = 7.4$ bar

Flammable gas	K_G-value ($bar \cdot m \cdot s^{-1}$)
Methane	55
Propane	75
Hydrogen	550

[a] average values

K_{St} - values of technical fine dusts - high ignition energy

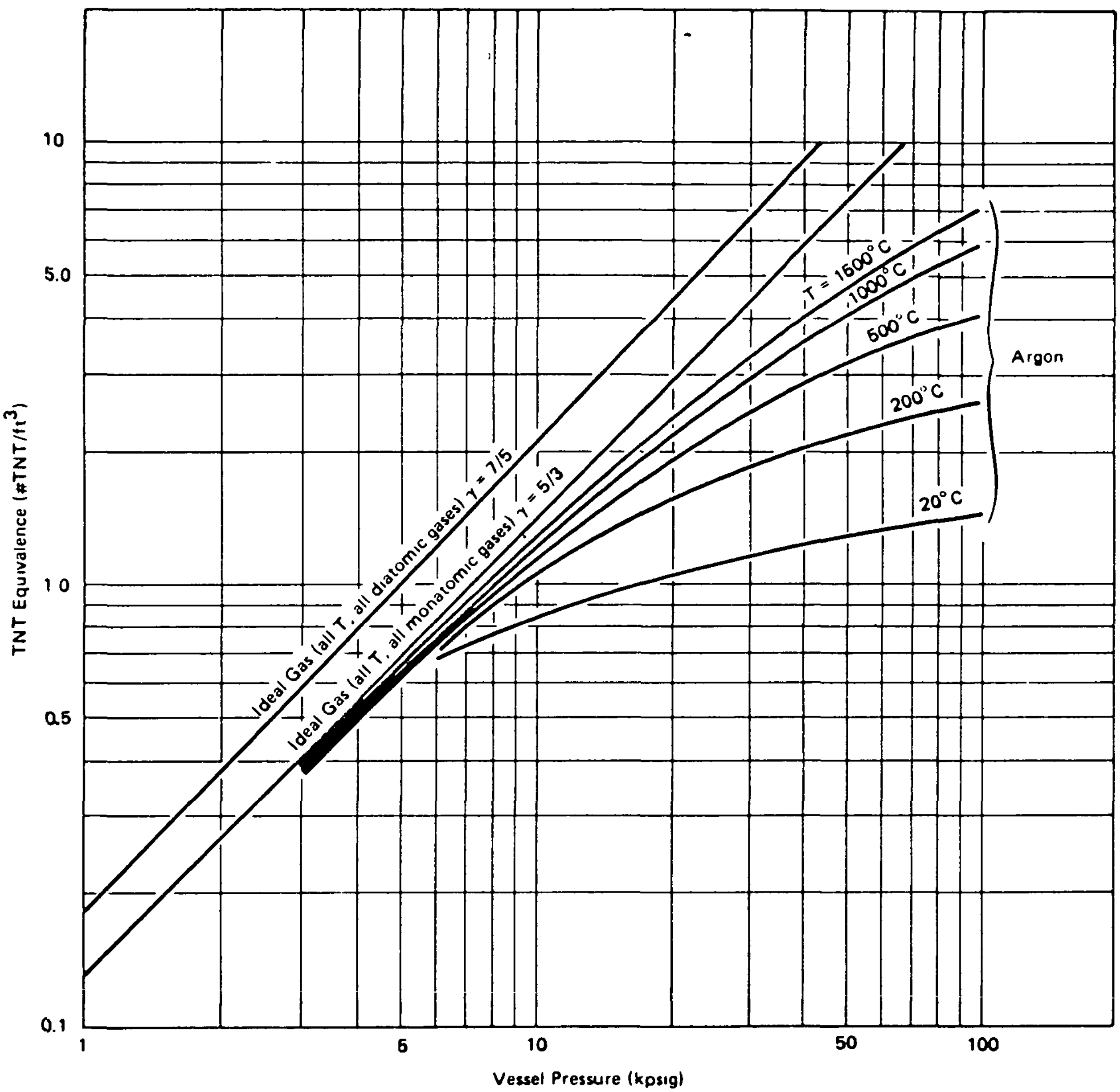
Type of dust	P_{max} (bar)	K_{St}-value ($bar \cdot m \cdot s^{-1}$)
PVC	6.7- 8.5	27- 98
Milk Powder	8.1- 9.7	58-130
Polyethylene	7.4- 8.8	54-131
Sugar	8.2- 9.4	59-165
Resin Dust	7.8- 8.9	108-174
Brown Coal	8.1-10.0	93-176
Wood Dusts	7.7-10.5	83-211
Cellulose	8.0- 9.8	56-229
Pigments	6.5-10.7	28-344
Aluminum	5.4-12.9	16-750

$$(dp/dt)_{max} \, V^{1/3} = \text{Const.} = K_G \text{ or } K_{St}$$

$$(\text{rate of pressure}) \, (\text{volume})^{1/3} = \text{Const.}$$

Table 8a

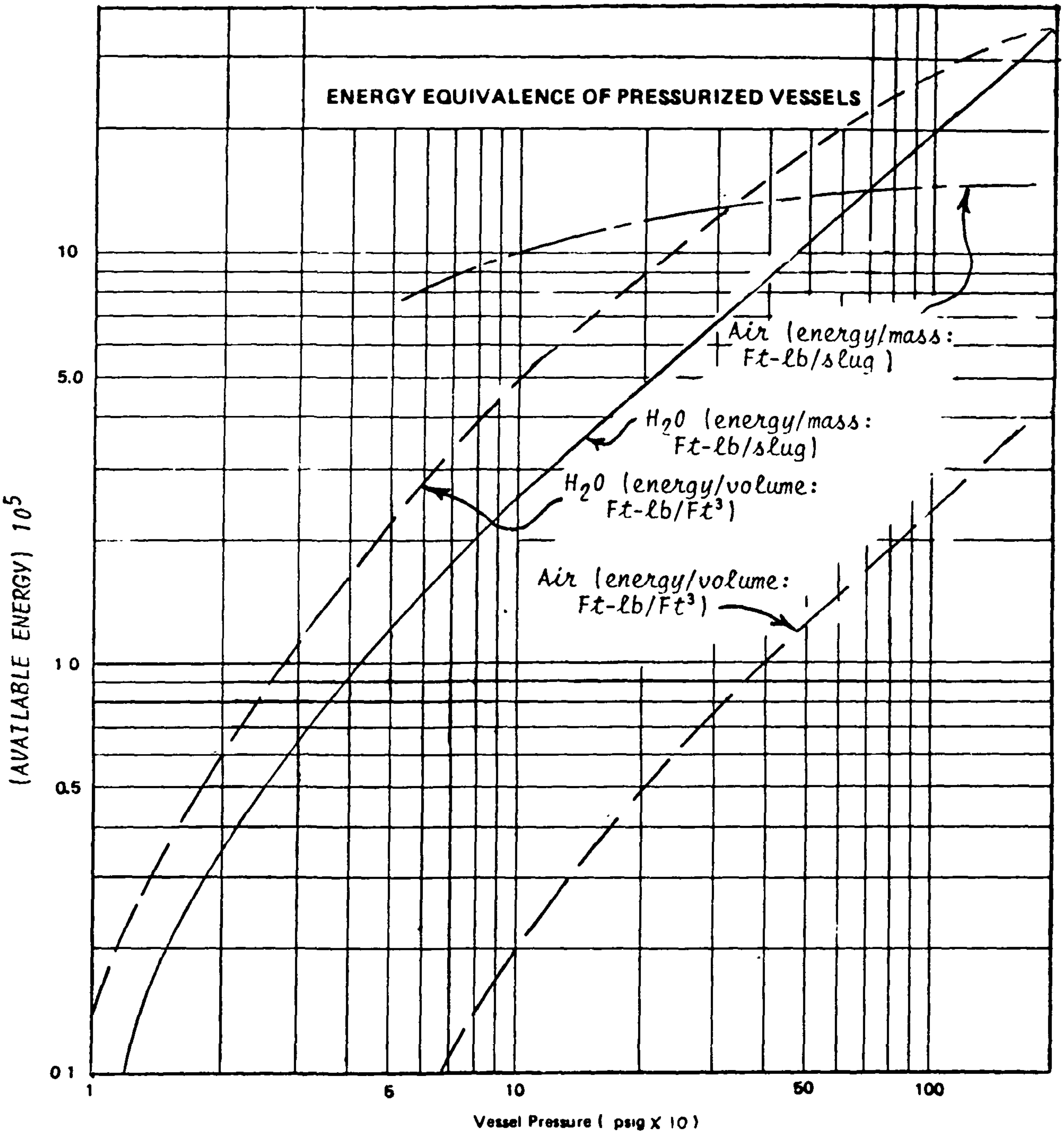
TNT ENERGY EQUIVALENCE OF PRESSURIZED VESSELS (POHTO)



NOTES:

1. 1 #TNT = 1832 4 BTU
2. Argon Data Based on Redlich-Kwong Equation of State.
3. These Curves Should Only be Used as a Guide. Variation of Temperature within a Vessel must be Considered with Their Respective Percentage Volume Relationship These Curves Represent a 100% Volume/Temperature Relationship.

Table 8b



Energy Release on Isentropic Expansion
(Air and Saturated Water) - (Moore)

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Table 9

APPROXIMATE RADIANT EXPOSURE FOR IGNITION OF HOUSE-HOLD MATERIALS AND DRY FOREST FUELS

Material	Weight g/m^2	Ignition Exposure $(J/m^2) \times 10^{-4}$ ** 20 kilotons	** 10 megatons
Dust mop (oily gray)	---	13	21
Newspaper, shredded	68	8	17
Paper, crepe (green)	34	17	33
Newspaper, single sheet	68	13	25
Newspaper piled flat, surface exposed	---	13	25
Newspapers, weathered, crumpled	34	13	25
Newspaper, crumpled	68	17	33
Cotton waste (oily gray)	---	21	33
Paper, bond typing, new (white)	68	63	126
Paper, Kraft, single sheet (tan)	68	29	59
Matches, paper book, blue heads exposed	---	21	38
Cotton string scrubbing mop, used (gray)	---	25	42
Cellulose sponge, new (pink)	1322	25	42
Cotton string mop, weathered (cream)	---	29	54
Paper bristol board, 3 ply (dark)	339	33	63
Paper bristol board, 3 ply (white)	339	50	105
Kraft paper carton, flat side, used (brown)	543	33	63
Kraft paper carton, corrugated edges exposed, used (brown)	---	50	105
Straw broom (yellow)	---	33	71
Excelsior, Ponderosa pine (light yellow)	2976 g/m^3	21	50
Tampico fiber scrub brush, used (dirty yellow)	---	42	84
Palmetto fiber scrub brush, used (rust)	---	50	105
Twisted paper, auto seat cover, used (multicolor)	440	50	105
Leather, thin (brown)	203	63*	126*
Vinyl plastic auto seat cover	339	67*	113*
Woven straw, old (yellow)	440	67*	138*
Dry rotted wood (punk)	---	17	38
Fine grass	---	21	42
Deciduous leaves	---	25	50
White-pine needles	---	25	59
Coarse grass	---	29	67
Spruce needles	---	33	71
Ponderosa pine needles, brown	---	33	75

* Indicates material was not ignited to sustained burning by the incident thermal energy indicated.

g=grams J=Joules
m=meters

** Approximately a 4-second duration with a 20 kiloton fireball and a 40-second duration with a 10-megaton fireball.

Table 10

APPROXIMATE RADIANT EXPOSURES FOR IGNITION OF FABRICS

	Weight	Ignition Exposure $(J/m^2) \times 10^{-4}$	
Material	g/m^2	20 kilotons	10 megatons
Rayon-acetate taffeta (wine)	102	8	13
Cotton chenille bedspread (light blue)	---	16	33
Doped fabric, aluminized cellulose acetate	---	75	147
Cotton muslin, oiled window shade (green)	271	21	46
Cotton awning canvas (green)	407	21	38
Cotton corduroy (brown)	271	25	46
Rayon twill lining (black)	102	4	8
Cotton venetian blind tape, dirty (white)	---	29	50
Cotton sheeting, unbleached, washed (cream)	102	63	126
Rayon twill lining (beige)	102	33	67
Rayon gabardine (black)	203	13	25
Cotton shirting (tan)	170	29	54
Cotton denim, used (blue)	339	33	54
Cotton and rayon auto seat cover (dark blue)	305	33	54
Acetate shantung (black)	102	38	63
Rayon-acetate drapery (wine)	170	38	67
Rayon marquisette curtain (ivory)	68	38	59
Cotton denim, new washed (blue)	339	38	59
Cotton auto seat upholstery (green, brown, white)	339	38	67
Rayon gabardine (gold)	237	38	84
Cotton venetian blind strap (white)	---	67	126
Wool flannel, new washed (black)	237	33	67
Cotton tapestry, tight weave (brown shades)	407	67	126
Wool surface, cotton base, auto seat upholstery (gray)	440	67*	147*
Wool, broadloom rug (gray)	237	67*	147*
Wool pile chair upholstery (wine)	543	67*	147*
Wool pile frieze chair upholstery (light brown)	475	67*	147*
Nylon hosiery (tan)	---	21*	42*
Cotton mattress stuffing (gray)	---	33	67
Burlap, heavy, woven (brown)	610	33	67
Rubberized canvas auto top (gray)	678	67*	117*

* In these cases the material was not ignited to sustained burning by the radiant exposure indicated.

g=grams
m=meters
J=Joules

TABLE 11

Impact Formulas For Concrete

<u>NDRC Formula</u>

$$G(x/d) = KNd^{0.20}D(V/1000)^{1.80} \qquad |1|$$

where

$$G(x/d) = \begin{cases} (x/2d)^2, & \text{for } x/d<2.0 \\ |(x/d) - 1|, & \text{for } x/d>2.0 \end{cases}$$

<u>Modified NDRC Formula</u> for Penetration, Eqns. (1) and (2)

$$K = 180/(f_c')^{1/2} \qquad |2|$$

where f_c' = ultimate concrete compression strength, the modified formula for penetration. (Equations 1 and 2)

<u>Perforation & scabbing</u> for t/d<3 thicknesses

$$e/d = 3.19\ (x/d) - 0.718\ (x/d)^2,$$

for $x/d<1.35$ |3a |

$$s/d = 7.91\ (x/d) - 5.06\ (x/d)^2,$$

for $x/d<0.65$

s = scabbing thickness |3b|

N is a missile shape factor equal to: 0.72 for flat nosed bodies; 0.84 for blunt nosed bodies; 1.00 for average bullet nose (spherical end)· and 1.14 for very sharp nose. K is a concrete penetrability factor which is a function of concrete strength.

Perforation and scabbing thicknesses for $t/d>3$

$$e/d = 1.32 + 1.24\ (x/d),\ \text{for}\ (3<e/d<18), \qquad |4a|$$

$$s/d = 2.12 + 1.36\ (x/d),\ \text{for}\ (3<s/d<18) \qquad |4b|$$

<u>Kar formula for perforation</u>

$$(e-a)/d = 3.19x/d - 0.718(x/d)^2,\ x/d \leq 1.35 \qquad |5a|$$

$$(e-a)/d = 1.32 + 1.24(x/d),\ \ x/d>1.35\ \text{and}\ 3\leq(e/d)\leq 18 \qquad |5b|$$

a = min. aggregate size of concrete

<u>Modified Petry formula I</u>

$$x = 12K_pA_p\log_{10}(1 + V_S^2/215000), \qquad |6|$$

where K_p is a coefficient depending on the nature of the concrete; and A_p is the weight of missile per unit projected area (lb/ft^2). Originally K_p was defined as: 0.00799 for massive concrete: 0.00284 for specially reinforced concrete.

<u>Petry perforation thickness</u>

$$e = 2x \qquad |7a|$$

Scabbing thickness

$$s = (2.2)x \qquad |7b|$$

(Table 11 Cont'd)

The Army Corps of Engineers formula

$$(x/d) = (282Dd^{0.215})/(f_c')^{1/2} \quad (V_S/1000)^{1.5} + 0.5 \qquad |8|$$

The Ballistic Research Laboratory (BRL) formula
(directly predicts the perforation thickness)

$$e/d = 7.8Dd^{0.2} \; (V_S/1000)^{1.33} \qquad |9|$$

$$e/d = (427Dd^{0.2})/(f_c')^{1/2} \quad (V_S/1000)^{1.33} \qquad |10a|$$

modified BRL formula for perforation and the scabbing thickness

$$s = 2e \qquad |10b|$$

The Ammann and Whitney formula
(fragments traveling over 1000 ft/sec)

$$(x/d) = (282NDd^{0.2})/(f_c')^{1/2} \quad (V_S/1000)^{1.8} \qquad |11|$$

CEA - EDF formula for perforation

$$V_S = 1.43 \; |f_c'(e^2/Dd^2)|^{1/2} \qquad |12|$$

Bechtel Scabbing Formula

$$S = (15.5/f_c^{1/2})(W^{0.4}V_S^{0.5}/d^{0.2}) \qquad |13|$$

Stone and Webster Scabbing Formula

$$S = (WV^2/C)^{1/3} \qquad |14|$$

where $C = f(t/d)$ tested for $1.5 \leq t/d \leq 3$

TABLE 12

Impact Formulas for Steel

<u>*Ballistic Research Laboratory*</u>

$$e^{3/2} = 0.5\ V_S{}^2 W K_\rho^2 / 8.975 \times 10^{-2} D^{3/2}$$ |1|

Thickness of steel plate to be just perforated by fragment of any shape.

$$t = 1.25\ e$$ |2|

suggested thickness of plate required to prevent perforation

<u>*Modified DeMarre Equation*</u>

$$V_{50} = 2.05 \times 10^4\ (e/M^{1/3})^{3/4}$$ |3|

<u>*Thor Equation*</u>

$$V_{50} = 4.05 \times 10^4 (e^{.906}/M^{.359})$$ |4|

(Table 12 cont'd)

Recht Equation

$$e = (6.25 \times 10^{-5}/K\rho^{1/2})\ (M_1/d^2)\ \{V_{50} - 1.19 \left|\tau \ln(2Z)/K\rho^{1/2}\right| \ln \left|1.0 + (0.84\ V_{50}\ (K\rho)^{1/2}/\tau \ln(2Z))\right|\}$$ |5|

Thickness to be just perforated by an armor-piercing projectile of any caliber for steel plate with $250 \leq$ BHN plate ≤ 350.

Recht Residual Velocity

$V_r = M/(M+M_t)\ (V_S^2 - V_{50}^2)^{1/2}$	Blast fragments (See Eqn. 21b)	|6a|
$V_r = (V_S^2 - V_{50}^2)^{1/2}$	Sharp Penetrators	|6b|

Recht Obliquity Velocity

$(V_{50})_\theta = (V_{50})_n \sec\theta$	Blunt & Sharp @ angle θ n ≡ normal	|6c|

Stanford Research Institute

$$(KE)/d = (S/46,500)\ (16,000e^2 + 1,500\ (W_L/W_S)\ e)$$ |7|

for $2 \leq d \leq 10$ inches
$10 \leq W \leq 110$ lbs.
$S = 60$ ksi to 70 ksi

(Table 12 cont'd)

<u>Toshiba-Hitachi</u>

$E_f = 2.9t^{1.5}\ D_e^{\ 1.5}$ Limit of Through Surface Break |8|

where E_f = critical fracture energy

$D_e = t(1+2.9\ \tan\ (\theta/2)^{2.1})$ for conical tip missile angle (θ)

D_e = d for cylindrical or hemisphere missile

d = diameter of missile

<u>Southwest Research Institute</u>

$\rho_p V_{50}^{\ 2}/\sigma_y = 1.751\ (e/d)(\ell/d)^{-1} + 144.2\ (e/d)^2(\ell/d)^{-1}$ for wood poles |9|

for $5 \leq \ell/d \leq 31$
$0.05 \leq e/d \leq 0.10$
$0.01 \leq \rho_p V_{50}^{\ 2}/\sigma_y \leq 0.05$

<u>NDRC Formula For Mild Steel</u>

$(e/d)^2 + 3/128\ (W_L/d)\ (e/d) = (0.452\ DV_S^{\ 2}/S)$

Valid for: $2'' \leq W_L \leq 12''$, $0.062'' \leq d \leq 3.5''$ |10a|

$(e/d)^2 + (3/16)\ (e/d) = (0.0537\ NDV_S^{\ 2}/S_s)$

for $e/d > 0.1$ and $W_L = 8\ \ d$ |10b|

$(e/d)^2 = (0.0187\ NDV_S^{\ 2}/S)$

for $e/d < 0.1$ and $W_L - 80\ e$ |10c|

NOMENCLATURE FOR TABLE 12

A_p = Missile Weight/Projected Frontal Area of Missile (psf)

d = Diameter of Missile (in.)

D = Core Caliber (ins) for armor-piercing projectiles (For 0.30 and 0.50 caliber APM2, d = 0.246 and 0.424 in. respectively)

E = Elastic modulus of shield material (psi)

f_c' = compressive strength of concrete (psi)

K = Bulk modulus of shield material = $E/(1-2\upsilon)$ (psi)
where: υ = Poisson's Ratio

K_p = Material coefficient for penetration - as follows:

Material	K_p (ft^3/lb)
1. Alloy Steel	0.00026
2. Steel	0.00040
3. Lexan Sheet	0.00200
4. Limestone	0.00538
5. Reinforced Concrete	See Figure 20
6. Stone Masonry	0.01172
7. Brickwork	0.02048
8. Sandy Soil	0.03670
9. Soil with Vegetation	0.04820

M = Weight of projectile - grams

M_1 = Armor-piercing core weight - grams. (For 0.30 and 0.50 caliber APM; M_1 = 82 and 410 grams respectively).

ρ = Mass density of shield material - $lb\text{-}sec^2/in.^4$ (For steel and aluminum plates, $\sqrt{K\rho}$ = 130 and 51 $lb\text{-}sec/in.^3$ respectively).

t = plate thickness (in.)

e = max rate thickness (in.) of target at a given velocity

τ = Compressive shear strength (static) of plate material (psi)

V_{50} = Ballistic limit of protection (ft./sec.) with 50% probability of perforation of target.

S = Ultimate tensile strength of target metal

W_L = Length (in.) of plate between supports.

(Nomenclature for Table 12 cont'd)

W_S = length (in.) of standard width (4in.)

ℓ = length of the missile (in)

ρ_p = density of the projectile

(KE) = Kinetic energy of missile

V_S = Projectile striking velocity (ft/sec)

W = Weight of projectile (lb)

Z = $E/\sigma_y \quad \sqrt{T/(T+2E/\sigma_y)}$ where σ_y = Shield material static yield stress (psi)

N = Projectile shape factor

TABLE 13

Penetration Formulas for Soil Media

W. Wang Formula

$$V_S^2 = \{ (M/2B)((C/B)-(2A/M)) + |(C/B)x - (M/2B)((C/B)-(2A/M))| e^{(2B/M)x} \} \qquad |1|$$

where A = Coefficient of constant static penetration resistance

= $0.6\pi r^3 \nu N_\nu$ (see Terzaghi (1948) bearing capacity formula for A, B & C)

B = Coefficient of v^2 term = $(\nu/g)\, a f$

C = $\pi r^2 \nu N_q$ = Coefficient of static penetration resistance per unit penetration

M = Mass of Missile — V_S = Impact Velocity

x = Maximum Penetration — W = Weight of Projectile

Allen, Mayfield & Morrison Formula

$$x = x_c + (1/2\beta)\ \ln\ (\beta V_c^2 f_\nu/\nu) \text{ where } \beta = (\rho A_c C_D/2M) \qquad |2|$$

where x = Maximum penetration in C_m

x_c = Critical penetration @ V_c = critical speed (Velocity of sound - sand)

ρ = density of sand gm/cm^3

A_c = Cross sectional area of missile in cm^2

M = Mass in gm and C_D = 2.61

(Table 13 cont'd)

Christman & Gehring Formula

$x = 0.13\ (\rho_p/\rho)^{1/3}\ \ (KE_1/\beta max)^{1/3}$

where $KE_1 = (MV_S^2\ /2)$ |3|

KE_1 = Kinetic energy of missile in joules

βmax = Maximum target hardness in Kg/mm^2

ρ_p & ρ = Projectile/Missile and Target material density respectively in gm/cm^3

Petry - Backman

$x = (W/A_C)K_1 log_{10}\ (1+(V_S^2/215{,}000))$ |4|

where x = penetration depth, ft.

W = projectile weight, lb.

A_C = projectile cross-section area, $in.^2$

K_1 = a factor dependent on soil properties ranging from 2.5 - 55.

V_S = striking velocity, fps.

(Table 13 cont'd)

Young

$$x = 0.53\ SN(W/A_C)^{1/2}\ \ell n\ (1 + 2V_S^2/10^5)$$

$V_S < 200$ fps |5|

and

$$x = 0.0031\ SN(W/A_C)^{1/2}\ (V_S - 100),\ V_S > 200 \text{ fps}$$

where x = penetration depth, ft.

W = projectile weight, lb.

A_C = frontal area of the projectile, in^2

V_S = striking velocity, fps.

N = nose shape factor (0.56 for a blunt-nosed penetrator)

S_1 = soil coefficient (~6 for moist loose sand).

Table 14

SUMMARY OF SUPPRESSIVE SHIELD GROUPS

Shield Group	Hazard Parameter		Representative Applications	Level of Protection*
	Blast	Fragmentation		
1	High	Severe	Porcupine Melter (2000 lbs) plus 2 pour units 250 lbs each	Reduce blast pressure at intraline distance** by 50%
2	High	Severe	HE bulk (750 lbs) Minute Melter	Reduce blast pressure at intraline distance** by 50%
3	High	Moderate	HE bulk (37 lbs) Detonators, fuzes	Category I hazard*** at 6.2 feet from shield
4	Medium	Severe	HE bulk (9 lbs) Processing rounds	Category I hazard*** at 19 feet from shield
5	Low	Light	30 lbs Illuminant Igniter slurry mixing HE processing (1.84 lbs)	Category I hazard*** at 3.7 feet from shield
6	Very High	Light	Laboratory, handling, and transportation	Category I hazard*** at 1 foot from shield
7	Medium	Moderate	Flame/fireball attenuation	Category I hazard*** at 5 feet from shield
81 mm	High	Moderate	81 mm mortar drill-and-face and/or cast-finishing operation	Category I hazard*** at 3 feet from shield

*All shield groups contain all fragments.

**Unbarricaded intraline distance

***Category I hazard (2.3 psi level)

Table 15a

COMPARISON OF CAPABILITIES OF GENERAL PURPOSE COMPUTER CODES

Capabilities \ Program		ANSYS	ASKA III-1,2	MARC	NASTRAN*	NEPSAP	NONSAP	STARDYNE	SUPERB	SAP IV
Static		x	x	x	x	x	x	x	x	x
Dynamic		x	x	x	x	x	x	x	x	x
Elements	1-D	x	x	x	x	x	x	x	x	x
	2-D	x	x	x	x	x	x	x	x	x
	3-D	x	x	x	x	x	x	x	x	x
Shells	Shells of Revolution	x	x	x	x	x	x	x	x	x
	Arbitrary	x	x	x	x	x	x	x	x	x
Thermal Loadings		x	x	x	x	x	0	x	x	x
Creep		x	x	Creep & Relaxation	0	x	0	0	0	0
Temp.Dependent Mat'l Prop.		x	x	x	0	x	0	0	0	x
Geometric Nonlinearities		x	x	x	x	x	x	0	0	0
Large Strains		x	0	x	0	x	x	0	0	0
Material Model	Metal Plasticity	x	x	x	x	x	x		0	0
	Soil/Rocks	0	0	x	0	0	0	0	0	0
Material Symmetry	Isotropic	x	x	x	x	x	x	x	x	x
	Anisotropic	x	x	x	x	x	x	0	0	x
Crack 3-D		x	0	x	0	0	0	0	0	0
Geometry Plottings		x	0	x	x	0	0	x	x	0
		DeSalvo 1979	Argyris or Parisch	Marc 1975	cCormic 1976	Sharifi 1973	NISEE or Cosmic	SDC	SDRC	NISEE or Cosmic

* Commercial Version
x = yes 0 = no

Table 15b

COMPARISON OF CAPABILITIES OF GENERAL PURPOSE COMPUTER PROGRAMS

Capabilities \ Program	NISA	DANUTA	SERC	STRUDL II	NFAP	ABAQUS	ADINA	SAP 6 SAP 7	COSMOS 6 COSMOS 7
Static	x	x	x	x	x	x	x	x	x
Dynamic	x	x	x	x	x	x	x	x	x
Elements: 1-D	x	x	x	x	x	x	x	x	x
Elements: 2-D	x	x	x	x	x	x	x	x	x
Elements: 3-D	x	x	x	0	x	x	x	x	x
Shells: Shells of Revolution	x	x	x	x	x	x	x	x	x
Shells: Arbitrary	x	x	x	x	x	x	x	x	x
Thermal Loadings	x		x	x	x	x	x	x	x
Creep	0	0	0	0	x	x	x	0	0
Temp. Dependent Mat'l Prop.	0	0	x	0	x	x	x	x	x
Geometric Nonlinearities	0	0	x	x	x	x	x	x	x
Large Strains	0	0	x	x	x	x	x	x	x
Material Model: Metal Plasticity	0	0	0	0	x	x	x	x	x
Material Model: Soil/Rocks	0	0	0	0	0	0	0	0	0
Material Symmetry: Isotropic	x	x	x	x	x	x	x	x	x
Material Symmetry: Anisotropic	0	0	0	x	x	x	x	x	x
Crack 3-D	0	0	0	0	x (2-D)	x	0	0	0
Geometry Plottings	x	x	x	0	x	x	0	x	x
	EMRC	Charcour Allis-Chalmers	SDRC	MIT/GIT Mass/Ga. Tech.	Chang 1980	HIBBITT 1980	Bathe 1976	Univ. So. Cal.	SRAC Santa Monica

x = yes, 0 = no

Table 16

Personnel Blast Hazard Criteria

Blast (Long Duration)

a. Eardrum Failure

Threshold	5 psi (2.3 psi)*
50 percent	15-20 psi (6.2-8.0)*

b. Lung Damage,

Threshold	10-12 psi (4.4-5.1 psi)*

c. Lethality

Threshold	30-42 psi (11-15 psi)*
50 percent	42-57 psi (15-18 psi)*
Near 100 percent	57-80 psi (19-24 psi)*

Nonpenetrating Missiles (10-lb Object)

a. Cerebral Concussion

Mostly "safe"	10 ft/sec impact velocity
Threshold	15 ft/sec impact velocity

b. Skull Fracture

Mostly "safe"	10 ft/sec impact velocity
Threshold	15 ft/sec impact velocity
Near 100 percent	23 ft/sec impact velocity

Penetrating Missiles (10-gm Glass Fragments)

a. Skin Lacerations,

Threshold	50 ft/sec impact velocity

b. Serious Wounds

Threshold	100 ft/sec impact velocity
50 percent	180 ft/sec impact velocity
Near 100 percent	300 ft/sec impact velocity

Skull Fracture from Head Impact

Mostly "safe"	10 ft/sec impact velocity
Threshold	13 ft/sec impact velocity
50 percent	18 ft/sec impact velocity
Near 100 percent	23 ft/sec impact velocity

Total Body Impact

Mostly "safe"	10 ft/sec impact velocity
Lethality threshold	21 ft/sec impact velocity
Lethality 50 percent	54 ft/sec impact velocity
Lethality near 100 percent	138 ft/sec impact velocity

Impact, Standing Stiff-Legged

a. Mostly "Safe"

No significant effect	8( ) ft/sec impact velocity
Severe discomfort	8-10 ft/sec impact velocity

b. Injury

Threshold	10-12 ft/sec impact velocity
Fracture threshold	13-16 ft/sec impact velocity

Impact, Seated

a. Mostly "Safe"

No effect	8( ) ft/sec impact velocity
Severe discomfort	8-14 ft/sec impact velocity

b. Injury, Threshold 15-26 ft/sec impact velocity

*The figures in parentheses represent overpressures that on normal reflection will give the maximal value of pressure noted before the parenthesis.

Table 17

ORIGINAL PAGE IS OF POOR QUALITY

Hazards Classifications/Compatibility Groups

	Items	SCG	Q-D Class 1 Division	Dot Class
1.	Initiating explosives	A	1	A
2.	Detonators and similar initiating devices	B	1, 2, or 4	A or C
3.	Bulk propellants, propellant propelling charges, and devices containing propellant with or without means of ignition	C	1, 2, 3 or 4	A, B, or C
4.	Black powder, high explosives, and HE ammunition without its own means of initiation and without a propelling charge	D	1 or 2	A
5.	HE ammunition without its own means of initiation, with a propelling charge	E	1 or 2	A
6.	HE ammunition with its own means of initiation, with or without a propelling charge	F	1 or 2	A
7.	Fireworks and illuminating, incendiary, smoke, or tear producing ammunition other than ammunition that is activated by exposure to water or the atmosphere	G	1, 2, 3, or 4	A, B, or C
8.	Ammunition containing both explosives and white phosphorus or other pyrophoric material	H	2 or 3	A or B
9.	Ammunition containing both explosives and flammable liquid or gel filler	J	3	B
10.	Ammunition containing both explosives and toxic chemical agent	K	2	A
11.	Ammunition, not included in other groups, requiring separate storage	L	1, 2, 3, or 4	A, B, or C
12.	Ammunition which presents no significant hazards	S	4 or None	C or exempt

Storage Compatability Mixing Chart

GROUPS	A	B	C	D	E	F	G	H	J	K	L	S
A	X	Z										Z
B	Z	X										X
C			X	Z	Z		Z					X
D			Z	X	X							X
E			Z	X	X							X
F						X						X
G			Z				X					X
H								X				X
J									X			X
K										Z		
L												
S	Z	X	X	X	X	X	X	X	X			X

X = groups may be combined

Z = special conditions warrant limited mixing (see DOD 5154.4S)

TABLE 18

PERFORMANCE VALUE (FUNCTIONALS)

HAZARDS		RECEPTORS					AFFECTING VARIABLE
Group	Type	Personnel (P)	Strategic Equip. (E)	Hazardous Mat'l. (H)	Buildings (B)	Protective	
A: Force/Motion	Fragment	F^P_{ij}	F^E_{ij}	F^H_{ij}	F^B_{ij}	F^S_{ij}	M,U(t),R
	Blast	B^P_{ij}	B^E_{ij}	B^H_{ij}	B^B_{ij}	B^S_{ij}	P(t),R
	Ground Motion						
B: Degenerative	Heat						
	Chemical						
	Radiation						
	Biological						

PROTECTIVE(III)	SECONDARY(II)	PRIMARY(I)
Protective Structures	Buildings	Personnel
1) containment	1) inhabited	1) work & dwelling areas
2) barricades	2) uninhabited	2) travel ways
3) shelters		

i (missile hazard) = p,g,s
p = perforation
g = global
s = shatter

j (protection design category = 1,2,3,4
1 = Class I
2 = Class II
3 = Class III
4 = Class IV

M = mass, U = displacement, P = pressure, R = distance, t = time

TABLE 19

RATIO OF SPECIFIC HEAT (γ_1) FOR VARIOUS GASES

SUBSTANCE	$\gamma_1 = C_p/C_v$
Argon, A	1.67
Helium, He	1.66
Hydrogen, H_2	1.41
Nitrogen, N_2	1.40
Oxygen, O_2	1.40
Carbon Monoxide, CO	1.40
Air	1.40
Water Vapor, H_2O	1.33
Methane, CH_4	1.32
Carbon Dioxide, CO_2	1.30
Sulfur Dioxide, SO_2	1.26
Acetylene, C_2H_2	1.23
Ethylene, C_2H_4	1.23
Ethane, C_2H_6	1.18
Propane, C_3H_8	1.12
Isobutane, C_4H_{10}	1.09

TABLE 20

SEVERITY - PROBABILITY CODE

		Probability Estimate			
		A	B	C	D
Severity Class	I	1	1	2	3
	II	1	2	3	4
	III	2	3	4	5
	IV	3	4	5	6

SECTION 6000 ENERGY RELEASE PROTECTION

DOCUMENT STORAGE AND RETENTION (Cont'd)

RECORD TYPES

DESIGN RECORDS

Applicable Codes and Standards Used In Design
As-Constructed Drawings
Design Calculations and Record of Checks
Design Deviations
Design Reports
Design Review Reports
Purchase and Design Specifications and Amendments
Stress Reports
Systems Descriptions
Systems Process and Instrumentation Diagrams
Technical Analysis, Evaluations, and Reports

PROCUREMENT RECORDS

Procurement Specifications

MANUFACTURING RECORDS

As-Built Drawings and Records
Certificate of Inspection and Test Personnel Qualification
Certificate of Compliance
Ferrite Test Results
Heat Treatment Records
Liquid Penetrant Examination Final Results
Location of Weld Filler Material
Magnetic Particle Examination Final Results
Major Defect Repair Records
Material Properties Records
Nonconformance Reports
Performance of Test Procedure and Results Records
Pipe Fitting Location Report
Pressure Test Results
Radiographic Procedures
Radiographic Review Forms and Radiographs
Ultrasonic Examination Final Results
Welding Procedures

INSTALLATION-CONSTRUCTION RECORDS

Civil

Check-Off Sheets for Tendon Installation
Concrete Cylinder Test Reports and Charts
Concrete Design Mix Reports
Concrete Placement Records
Material Property Reports on Containment Liner and Accessories
Material Property Reports on Metal Containment Shell and Accessories
Material Property Reports on Reinforcing Steel
Material Property Reports on Reinforcing Steel Splice Sleeve Material
Material Property Reports on Steel Embedments in Concrete

TABLE 21
(continued)

DOCUMENT STORAGE AND RETENTION

RECORD TYPES

INSTALLATION-CONSTRUCTION RECORDS (Cont'd)

Civil (Cont'd)

Material Property Reports on Steel Piling
Material Property Reports on Structural Steel and Bolting
Material Property Reports on Tendon Fabrication Material
Pile Drive Log
Pile Loading Test Reports
Procedure for Containment Vessel Pressure-Proof Test and Leak Rate Tests and Results
Reports for Periodic Tendon Inspection
Soil Compaction Test Reports

Welding

Ferrite Test Results
Heat Treatment Records
Liquid Penetrant Test Final Results
Magnetic Particle Test Final Results
Major Weld Repair Procedures and Results
Radiographic Test Procedures
Radiographic Test Final Results
Ultrasonic Test Final Results
Weld Procedures
Welding Filler Metal Material Reports

Mechanical

Hydro-Test Procedures and Results
Installed Lifting and Handling Equipment Procedures, Inspection and Test Data
Material Property Records
Material Property Test Reports for Thermal Insulation
Pipe and Fitting Location Reports
Pipe and Fittings Material Property Reports
Pipe Hanger and Restraint Data
Safety Valve Response Test Procedures
Safety Valve Response Test Results

Electrical and I&C

Documentation of Testing Performed After Installation and Prior to Systems Conditional Acceptance
Field Workmanship Checklist or Equivalent Logs
Instrument Calibration Results
Relay Test Procedures and Results
Reports of Pre-Installation Tests
Voltage Breakdown Tests on Liquid Insulation

TABLE 21
(continued)

DOCUMENT STORAGE AND RETENTION (Cont'd)

RECORD TYPES

INSTALLATION-CONSTRUCTION RECORDS (Cont'd)

General

"As-Built" Drawings and Records
Final Inspection Reports and Releases
Nonconformance Reports
Specifications and Drawings

PREOPERATIONAL AND STARTUP TEST RECORDS

Automatic Emergency Power Source Transfer Procedures and Results
Final Systems Adjustment Data
Flushing Procedures and Results
Hydrostatic Pressure Test Procedures and Results

OPERATION PHASE ACTIVITY RECORDS

Operation, Maintenance and Testing

Records and Drawing Changes Reflecting Plant Design Modifications Made to Systems and Equipment
Transient or Operational Cycling Records for Those Plant Components That Have Been Designed to Operate Safely for a limited Number of Transients or Operational Cycles
Abnormal Occurrence Records
Periodic Checks, Inspections and Calibrations Performed to Verify that Surveillance Requirements are Being Met
Changes Made in the Operating Procedures

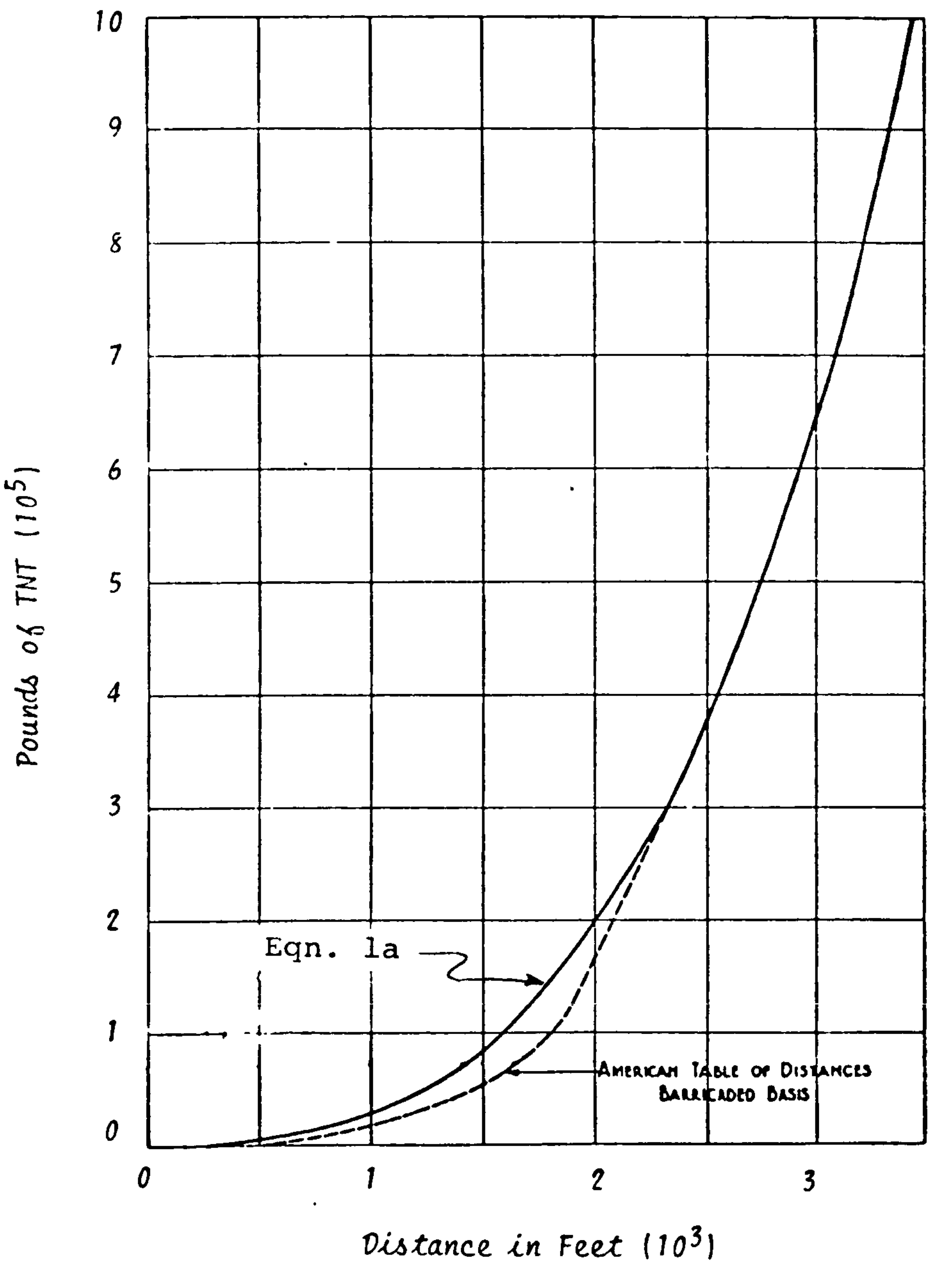
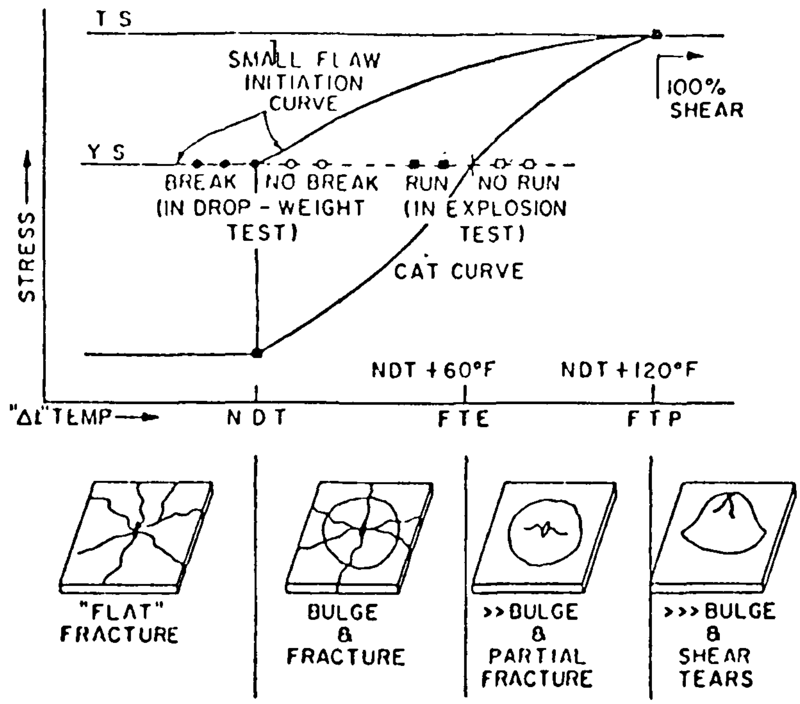


Figure 1 Safe Distance for Inhabited Buildings (eqn. 1a & data) vs TNT Explosive Weight



Drop weight and explosion bulge test criteria related to the fracture analysis diagram.

Figure 2a

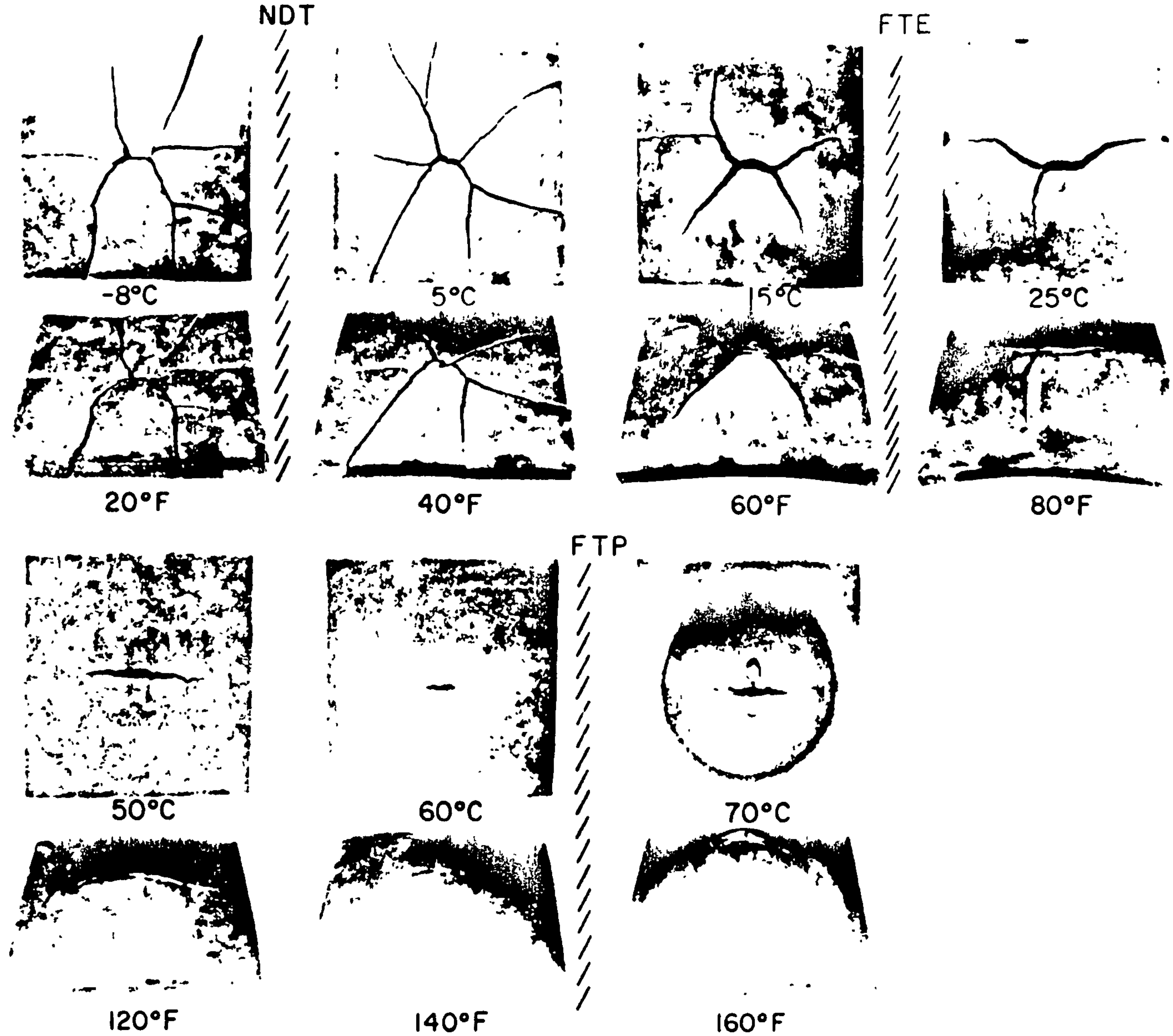


Figure 2b **Features of Explosion Crack Starter Tests of ship plate steels. The steel illustrated features a 15 ft-lb C_v transition of approximately 30°F (0°C) and is representative of best quality Ship plates of relatively poor quality develop similar transition features at higher temperatures.**

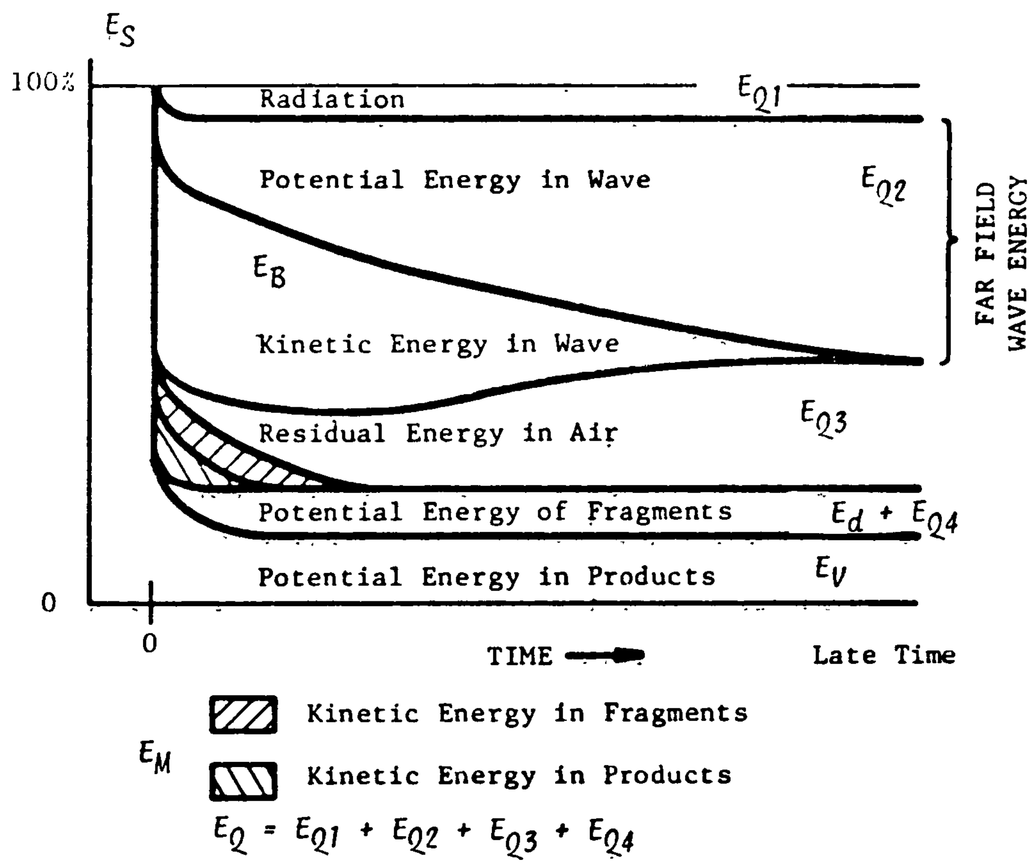
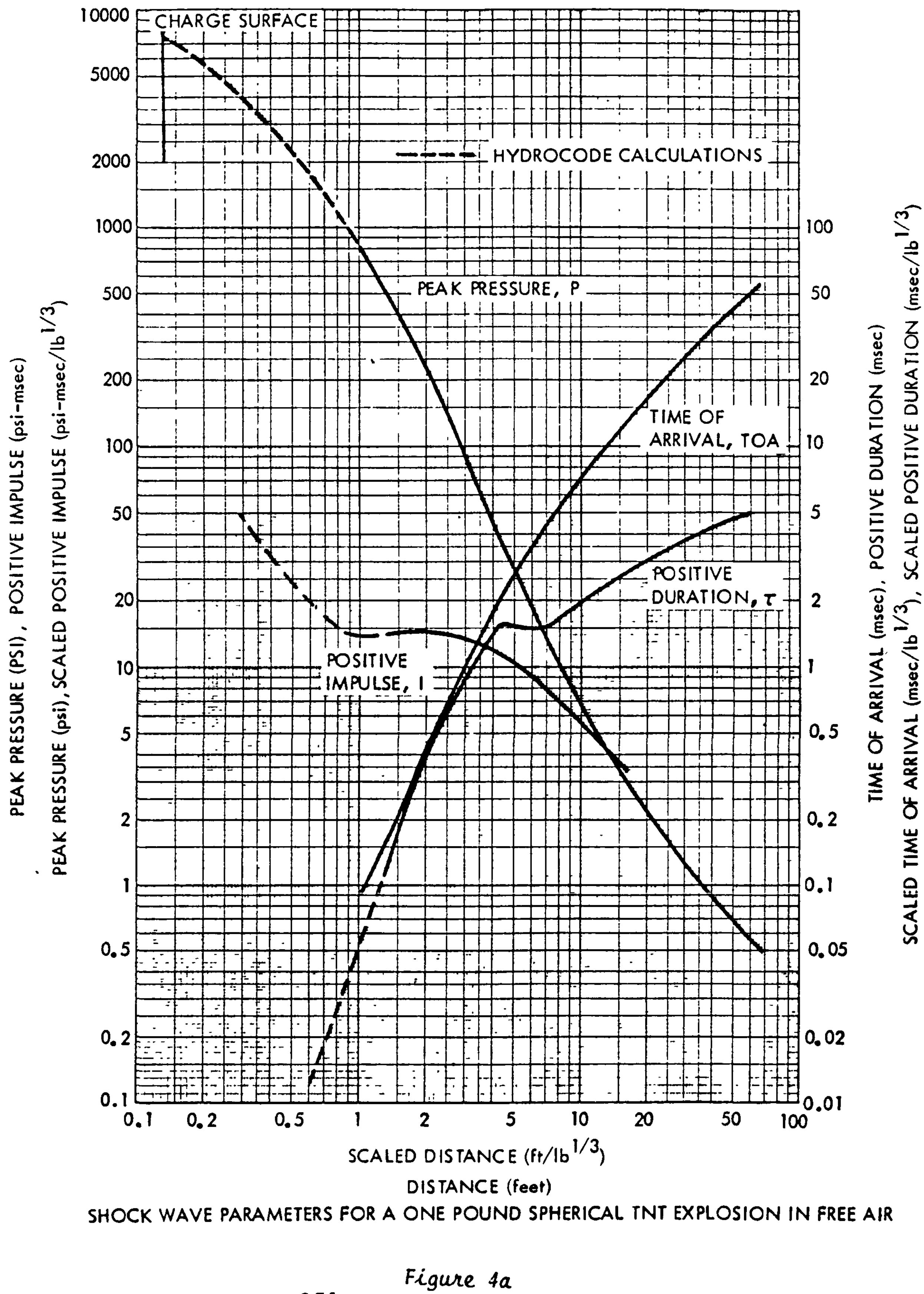
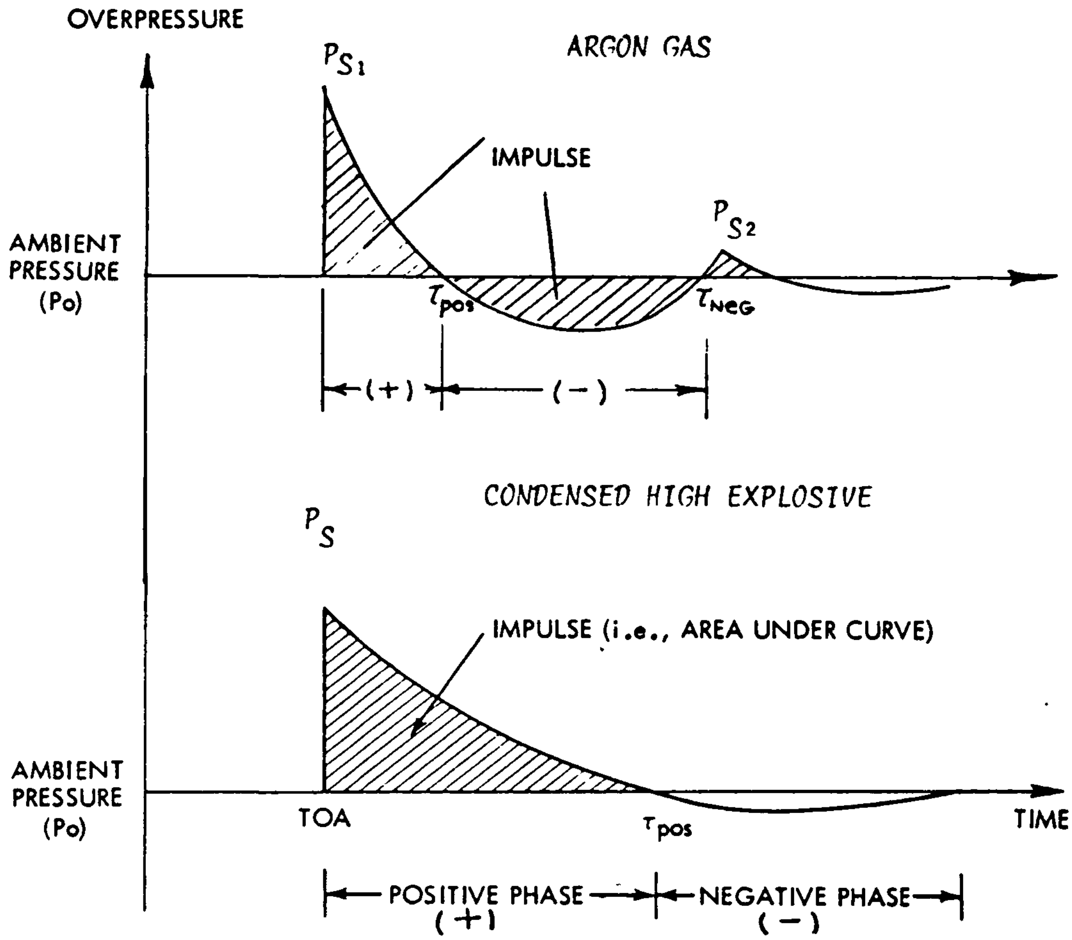


Figure 3. Energy Distribution in a Blast Wave as a Function of Time After the Explosion (Schematic) (Strehlow & Baker (1975)).



SHOCK WAVE PARAMETERS FOR A ONE POUND SPHERICAL TNT EXPLOSION IN FREE AIR

Figure 4a



(1) TOA (TIME-OF-ARRIVAL) ≡ THE TIME REQUIRED FOR THE SHOCK WAVE TO TRANSIT THE DISTANCE FROM THE CENTER OF THE EXPLOSION TO THE POINT AT WHICH THE MEASUREMENT IS TO BE MADE.

(2) P (OVERPRESSURE) ≡ PEAK PRESSURE ABOVE AMBIENT CONDITIONS.

(3) τ ≡ POSITIVE PHASE DURATION - THE LENGTH OF TIME (MEASURED FROM THE FIRST PRESSURE RISE) NECESSARY FOR THE OVERPRESSURE TO RETURN TO THE AMBIENT PRESSURE.

(4) POSITIVE PHASE IMPULSE ≡ $\int_0^{\tau} P(t)\, dt$

Figure 4b Shock Wave Parameters For HE And Argon Explosion

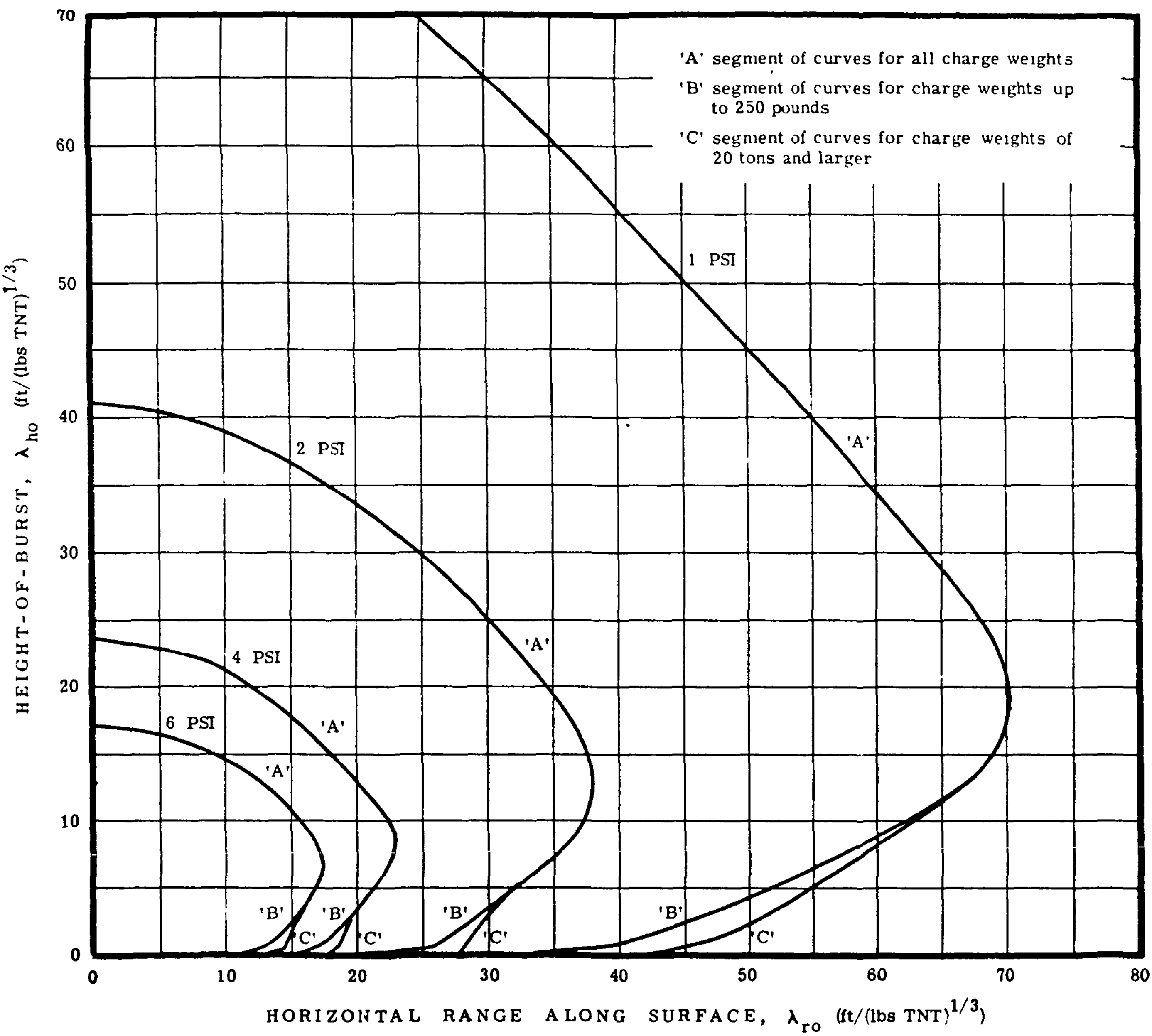
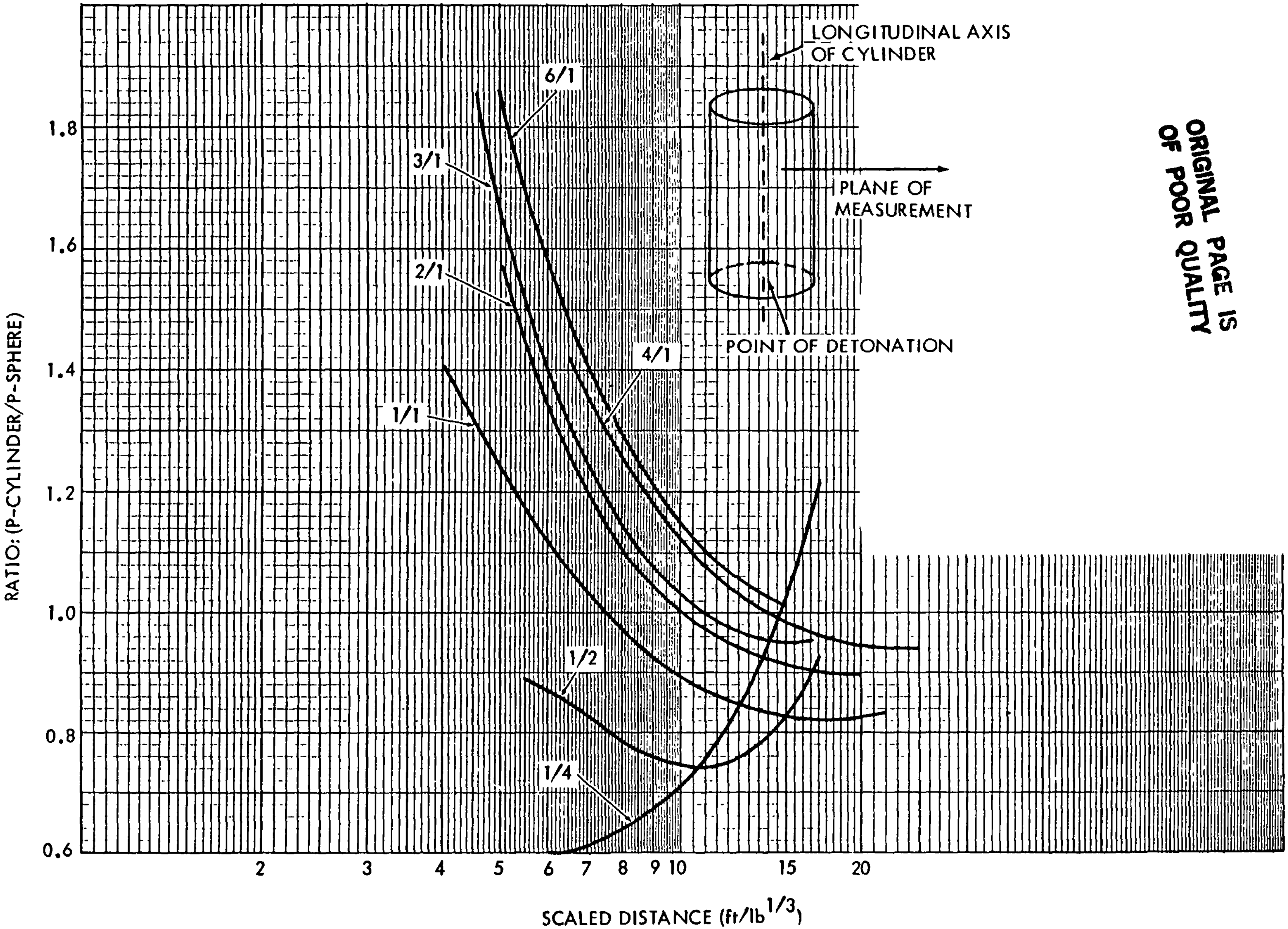


Figure 5 Height-of-Burst Curves-Peak Overpressure



RATIO OF FREE AIR PEAK OVERPRESSURE (P-CYLINDER/P-SPHERE) VS DISTANCE FOR CYLINDERS WITH DIFFERING ASPECT RATIOS (ℓ/d)

Figure 6

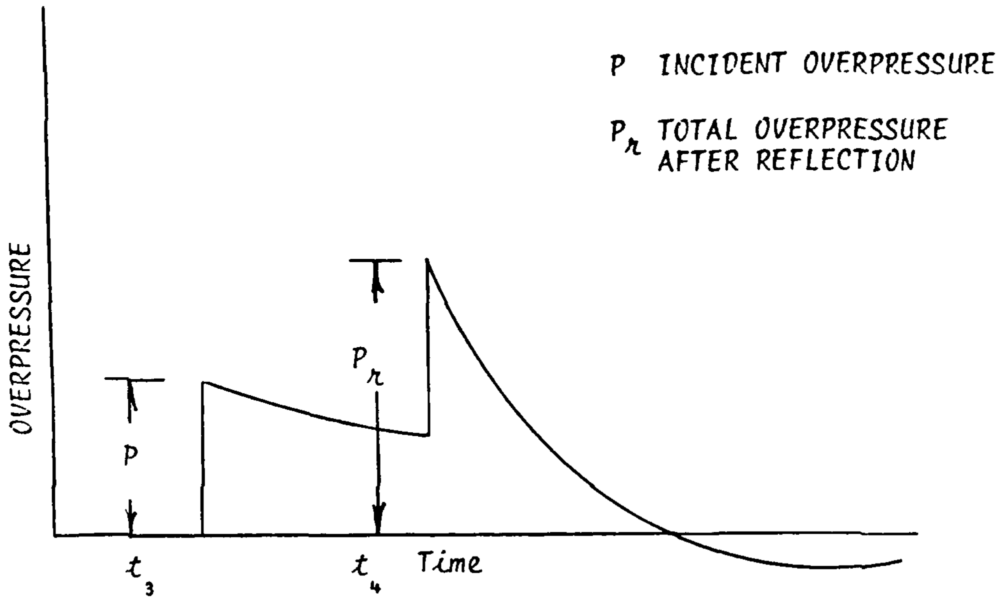


Figure 7a. Variation of overpressure with time at a point above the surface in the region of regular reflection

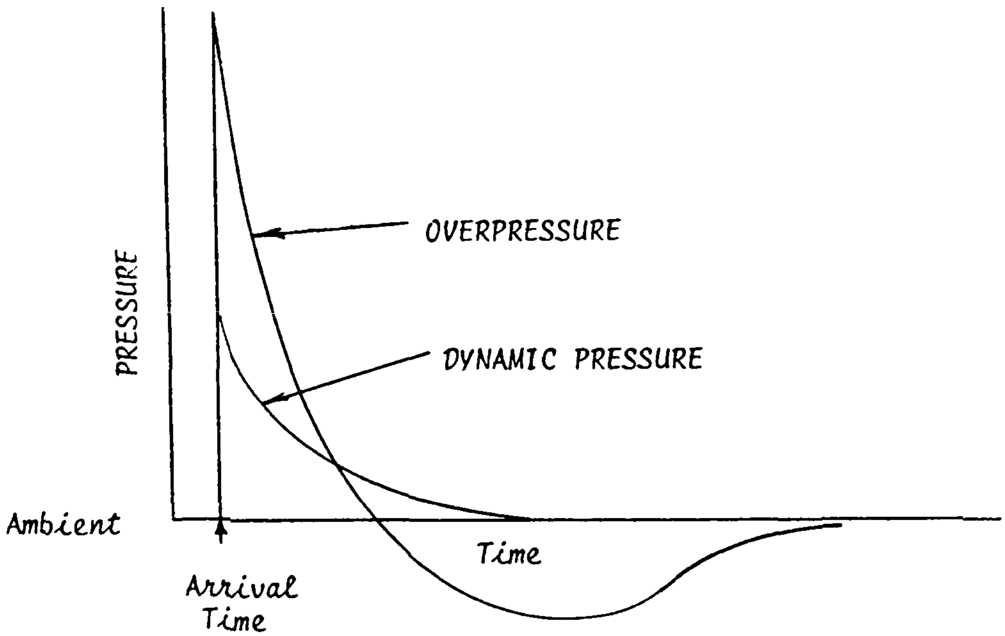


Figure 7b. Variation of overpressure and dynamic pressure with time at a fixed location in the low-pressure region.

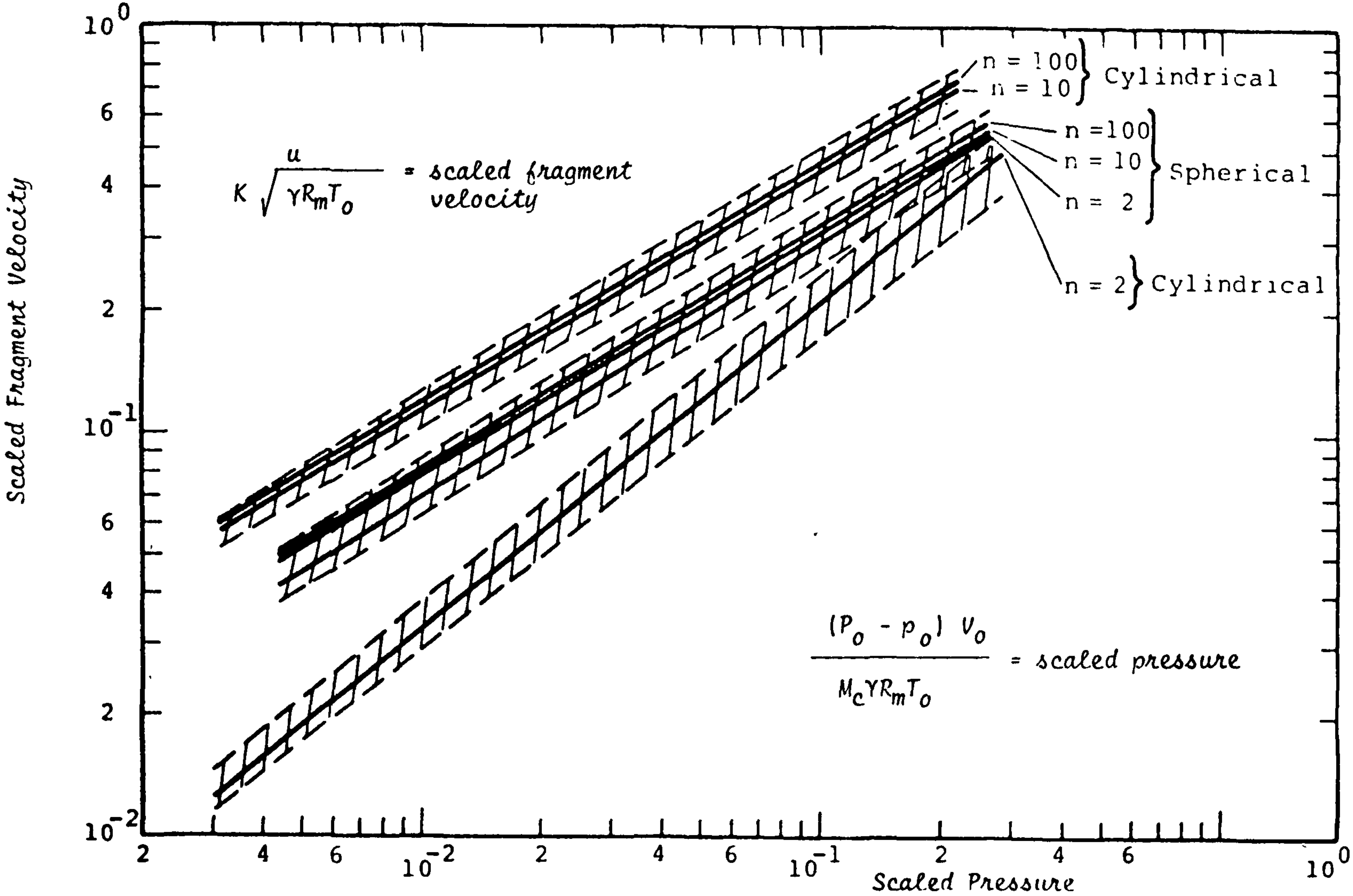
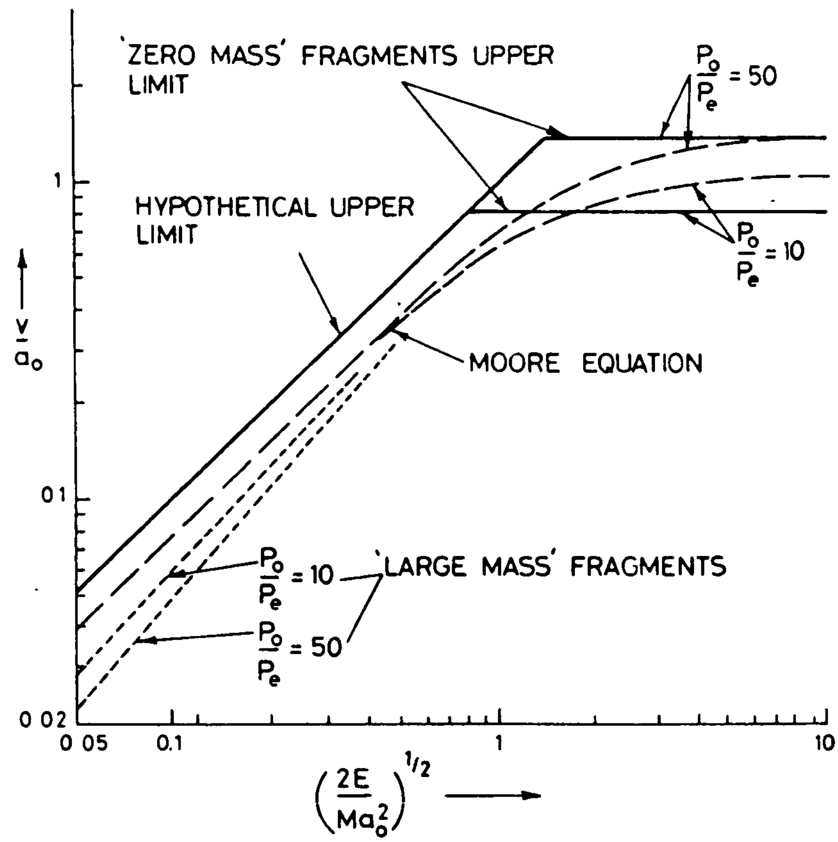


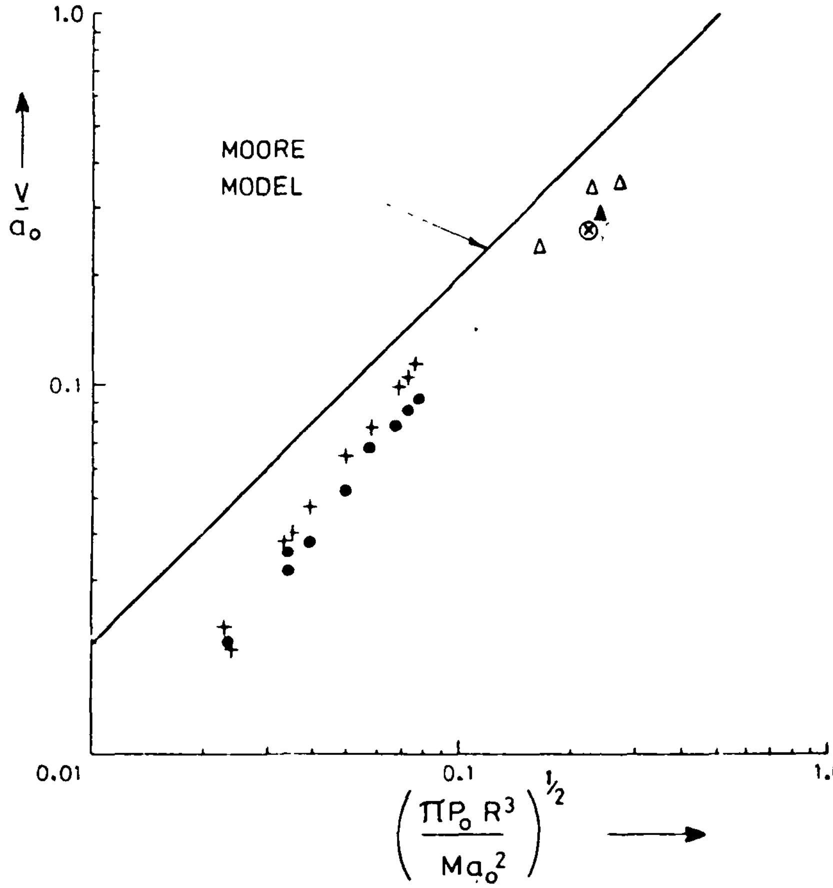
Figure 8. Scaled Fragment Velocity Versus Scaled Pressure



Fragment Velocities (Sphere With γ = 1.4)

Figure 9a

KEY				
SYMBOL	SOURCE of DATA	L/R	γ	P_o / P_e
●	BNL.	5	1·4	10 - 30
+	BNL	8·3	1·4	10 - 30
▲	BNL	10	1·4	20
△	HELD & JAGER	13·5	1·4	100 - 285
⊗	HERTZOG et al	5·3	1·4	25·6

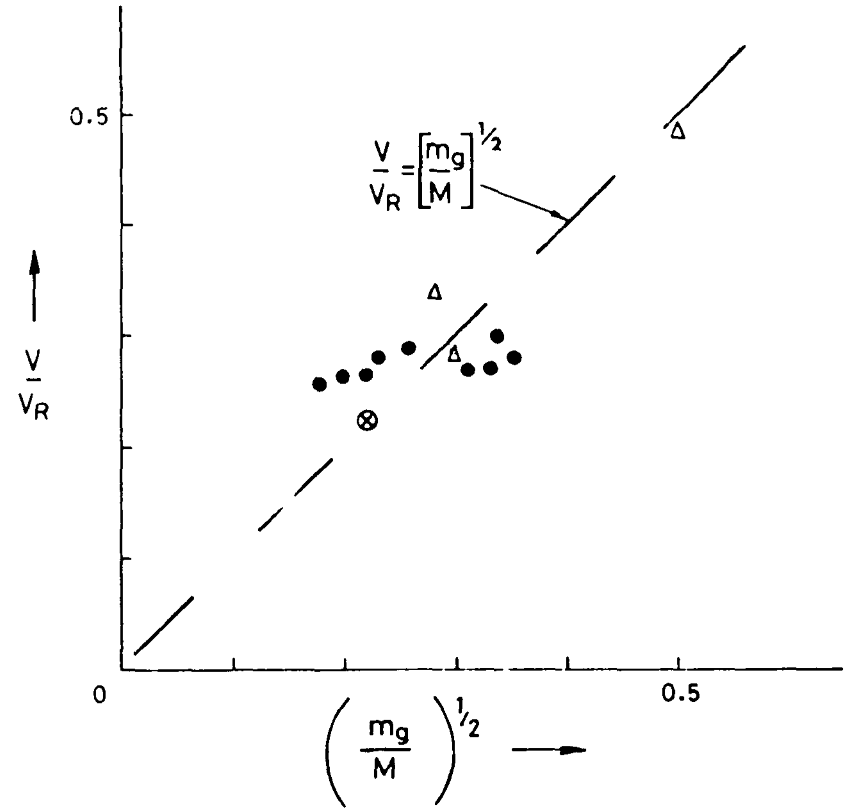


END-CAP MISSILE DATA.

Figure 9b

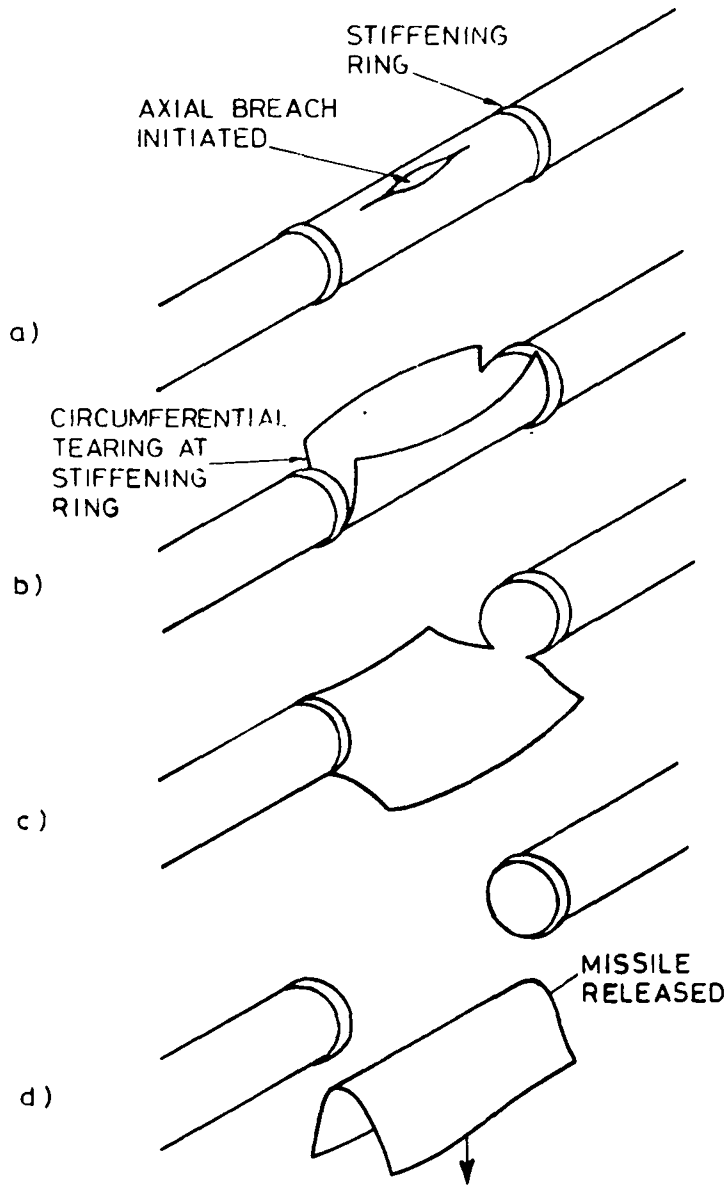
KEY

SYMBOL	SOURCE of DATA	L/R	γ	P_o/P_e	m_g/M
●	B.N.L.	6·25-18·75	1·4	10−30	0·03−0·13
Δ	HELD & JAGER	6·75	1·4	100-294	0·08−0·25
⊗	HERTZOG et al.	5·3	1·4	25·6	0·05



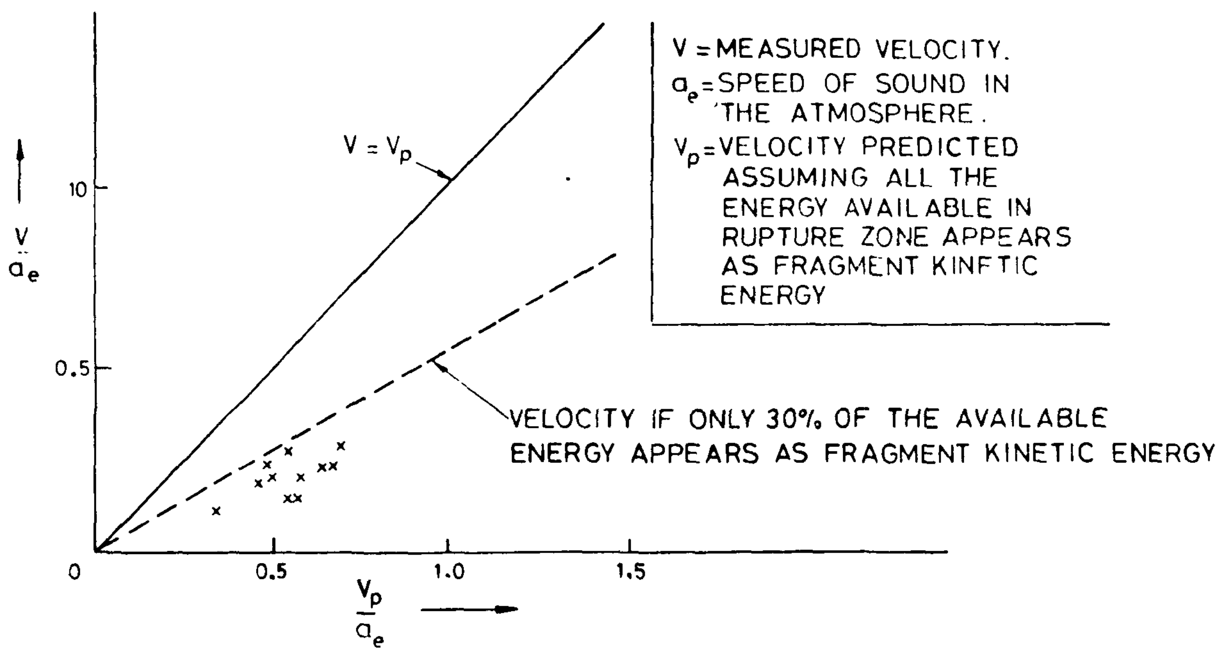
ROCKET MISSILE DATA.

Figure 9c



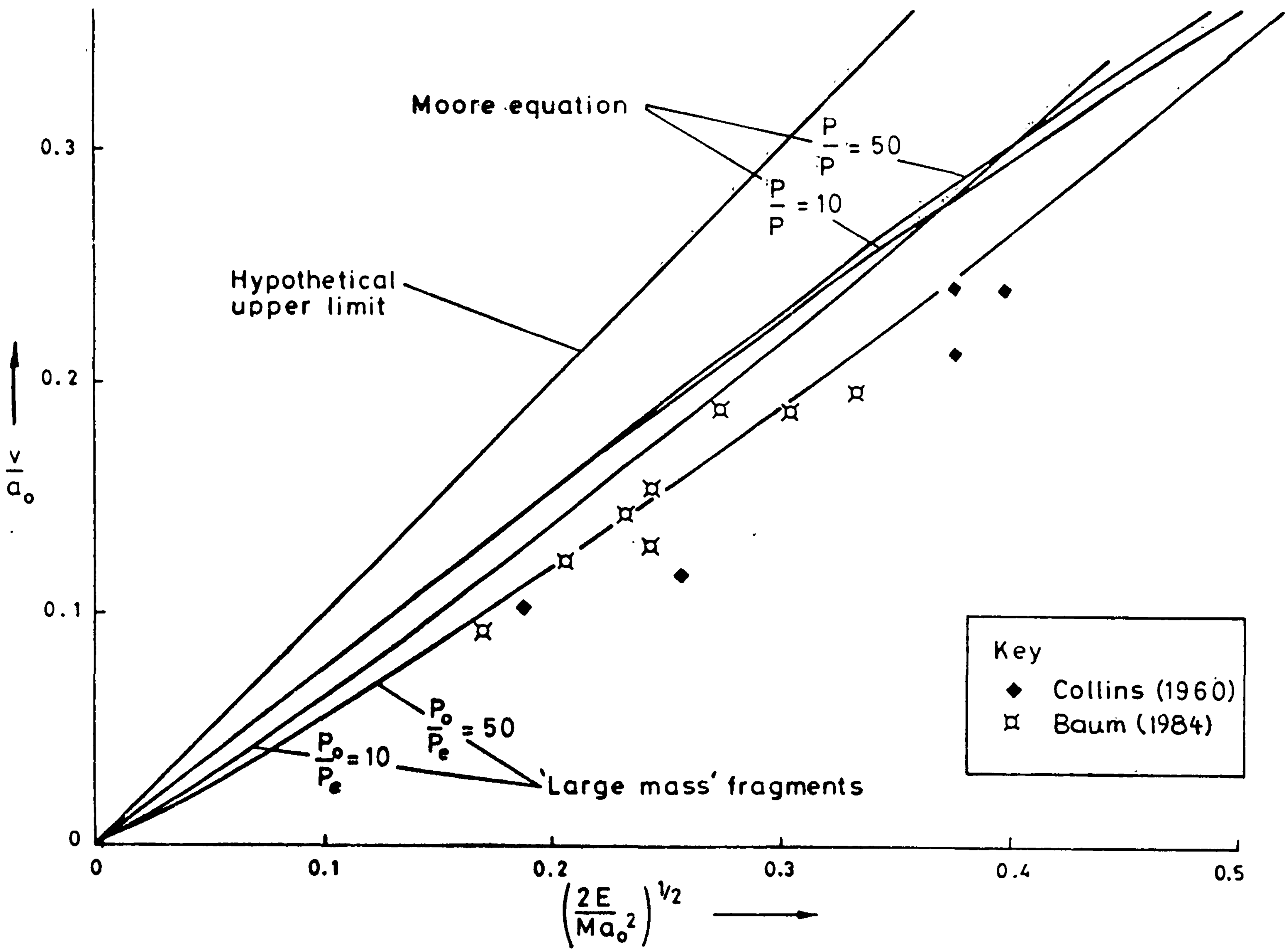
FORMATION OF PIPE-LINE MISSILE.

Figure 9d



THE VELOCITY OF MISSILES GENERATED BY PIPELINE RUPTURE.

Figure 9e



Cylindrical Vessel Data (γ =1.4) --BRITTLE RUPTURE

Figure 9b

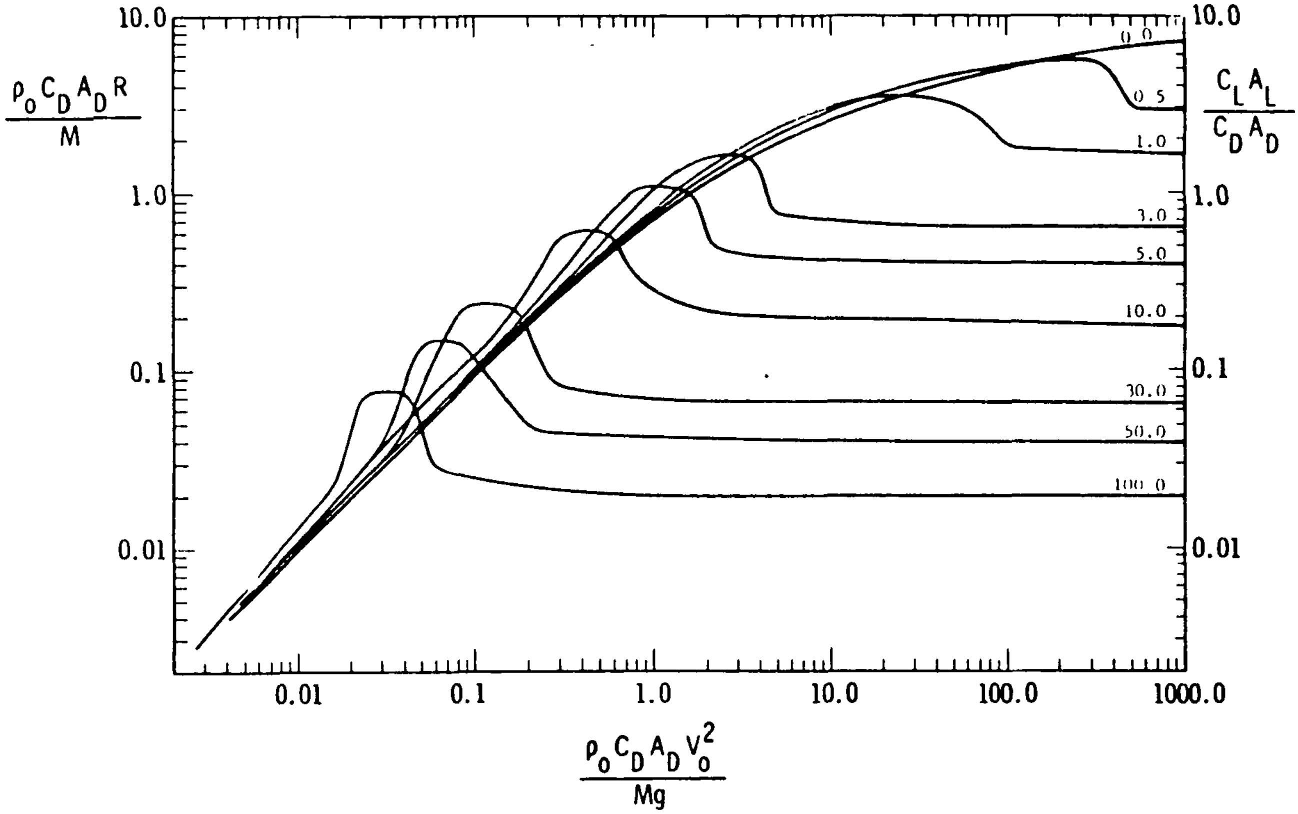
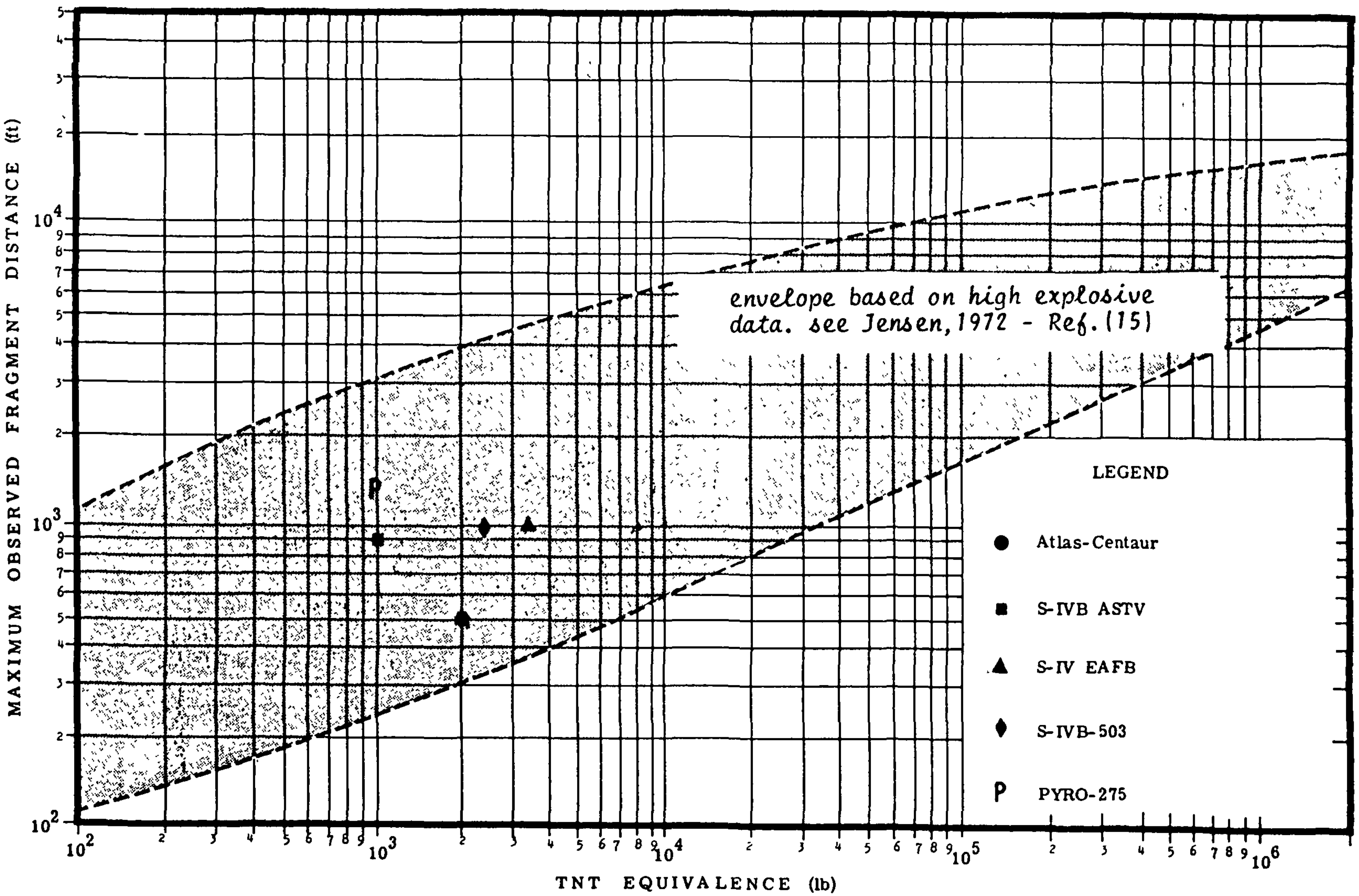


Figure 10. Scaled Fragment Range Versus Scaled Force



Estimated TNT Equivalence versus Maximum Fragment Distance for Actual Space Vehicle Explosions

Figure 11

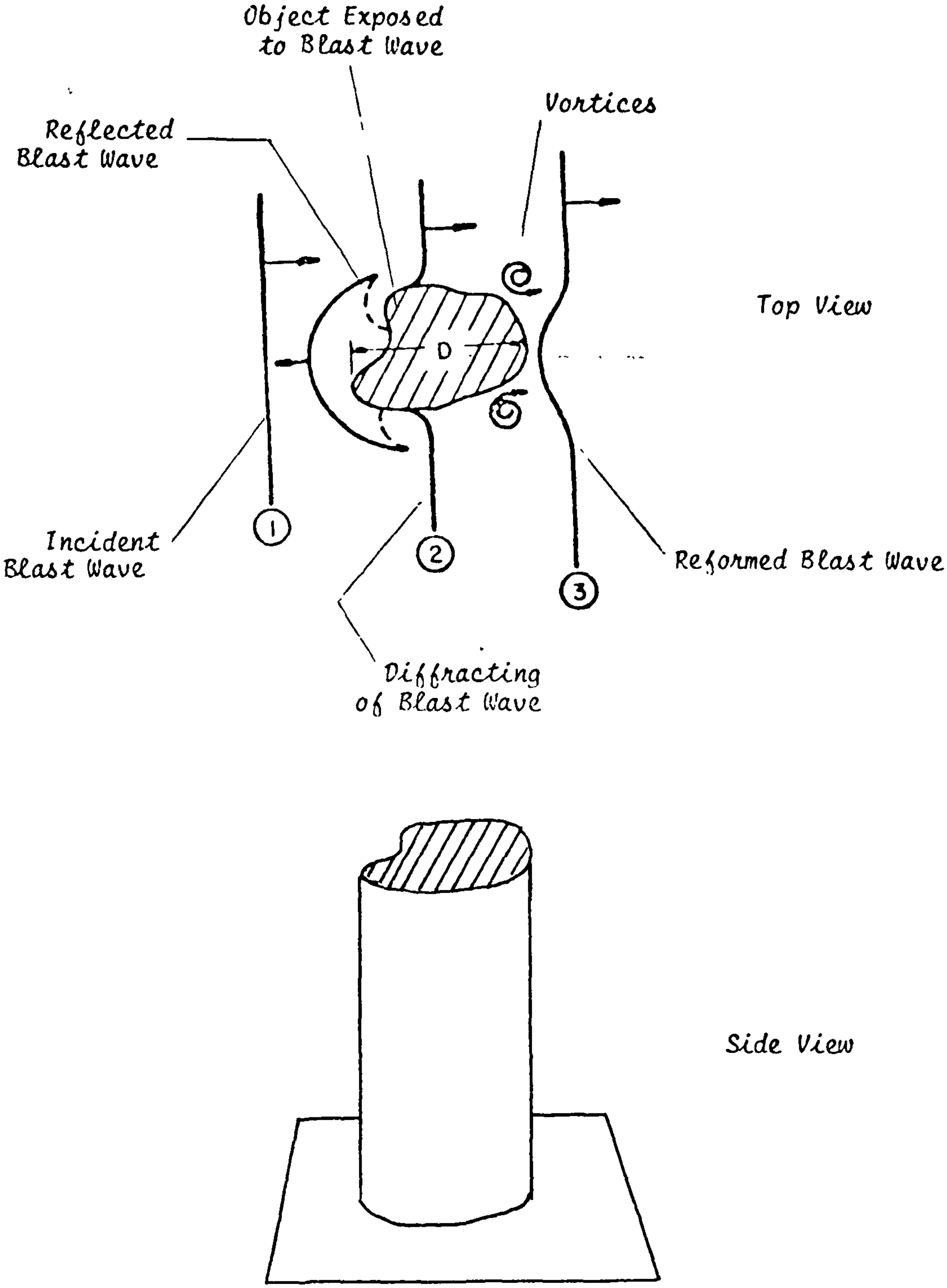


Figure 12a Interaction of Blast Wave with Irregular Object

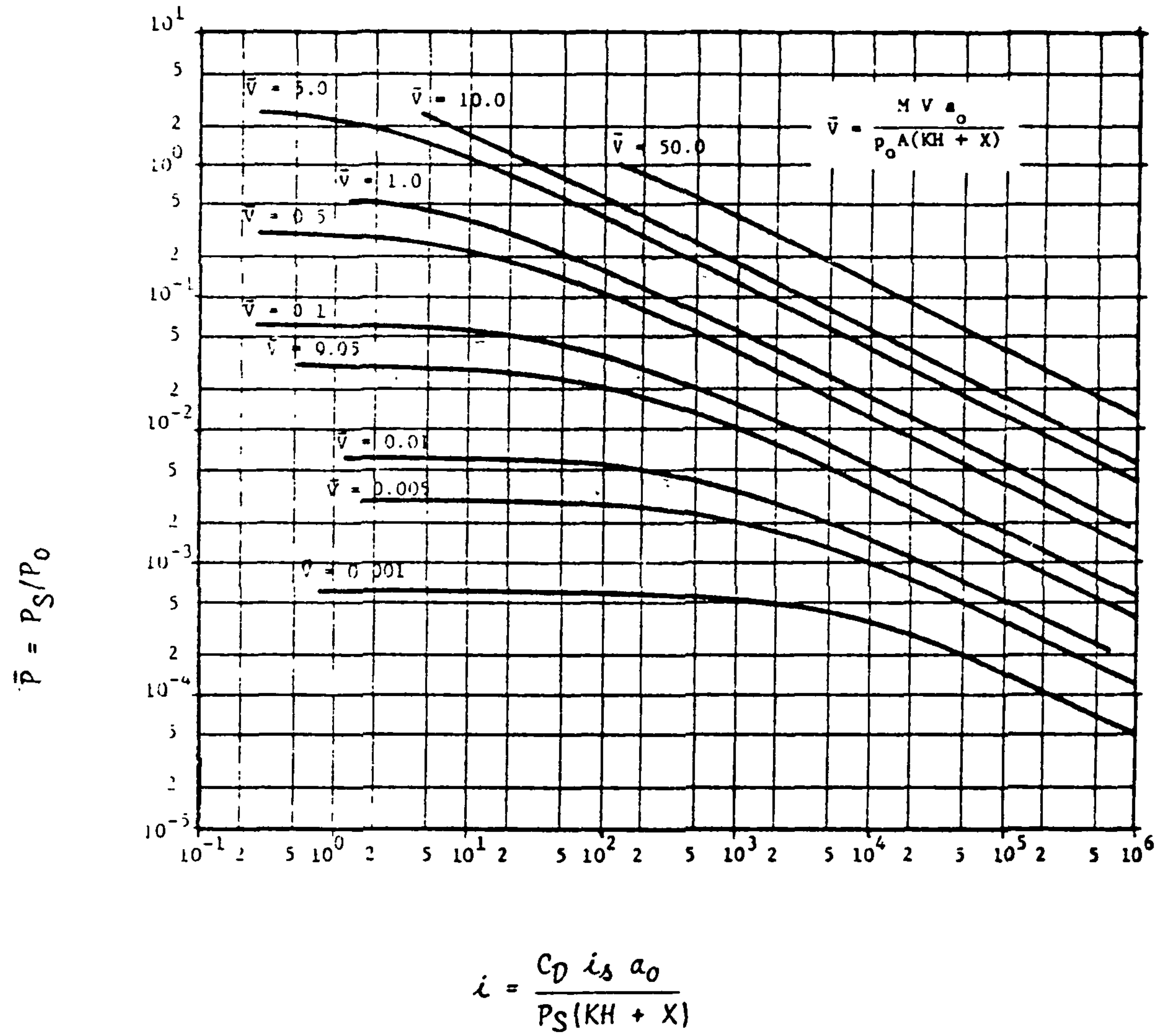


Figure 12b. Nondimensional Object Velocity $\bar{V}$ as a Function of Nondimensional Pressure $\bar{P}$ and Nondimensional Impulse I

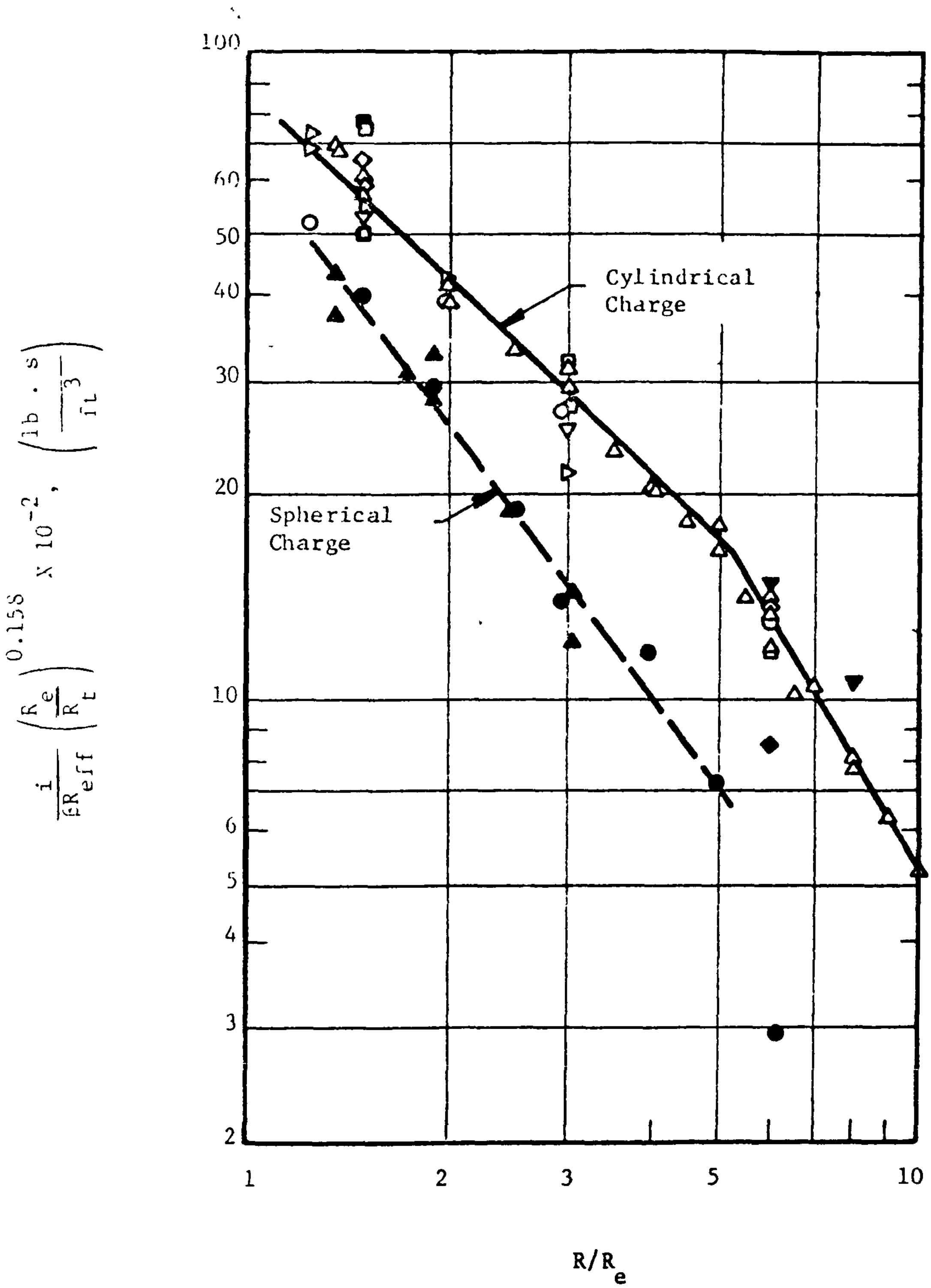


Figure 13. Specific Acquired Impulse (Explanation of Symbols Appear on Following Page)

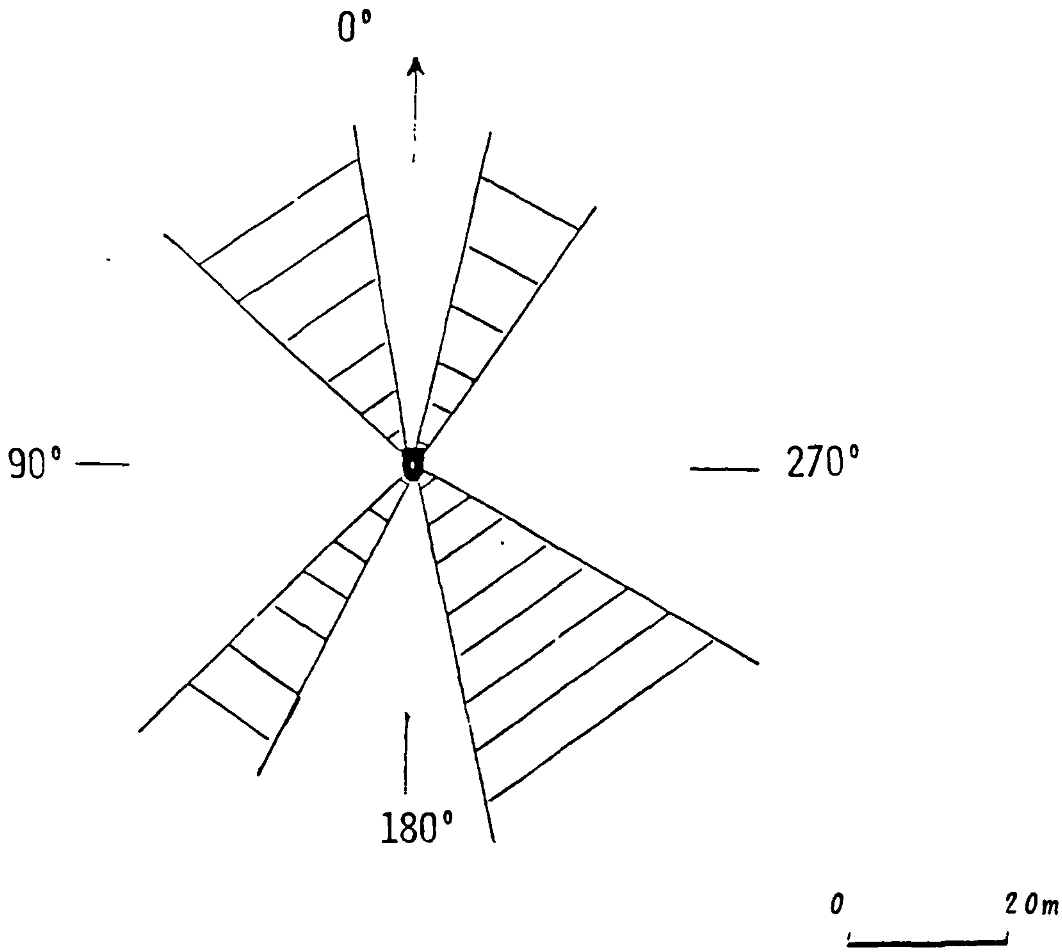


Figure 14a Sectors With Very Low Missile Density (Shaded).

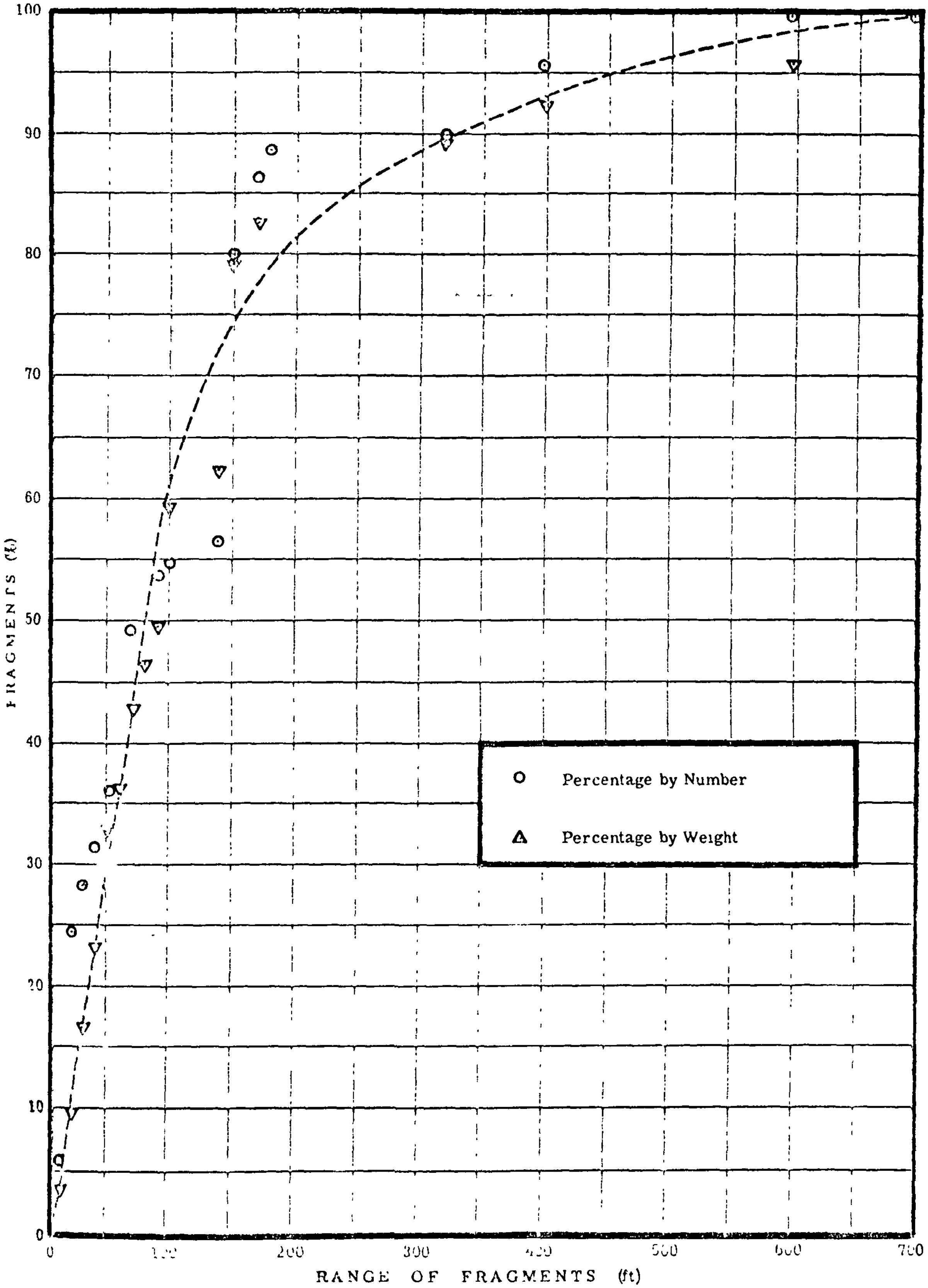


Figure 14b Fragment Distribution

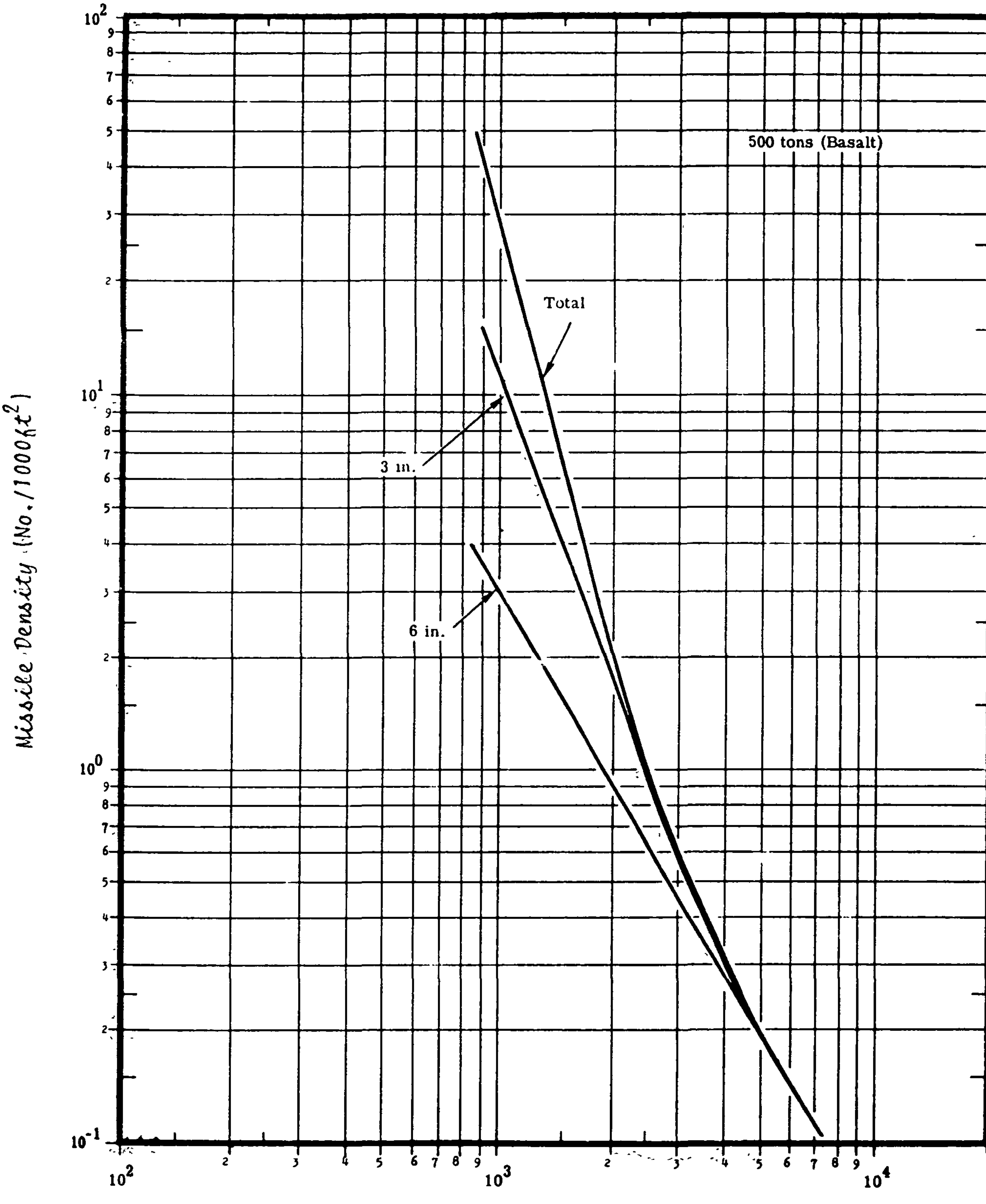


Figure 15. Missile Population Density versus Distance for a 500-Ton Surface Burst.

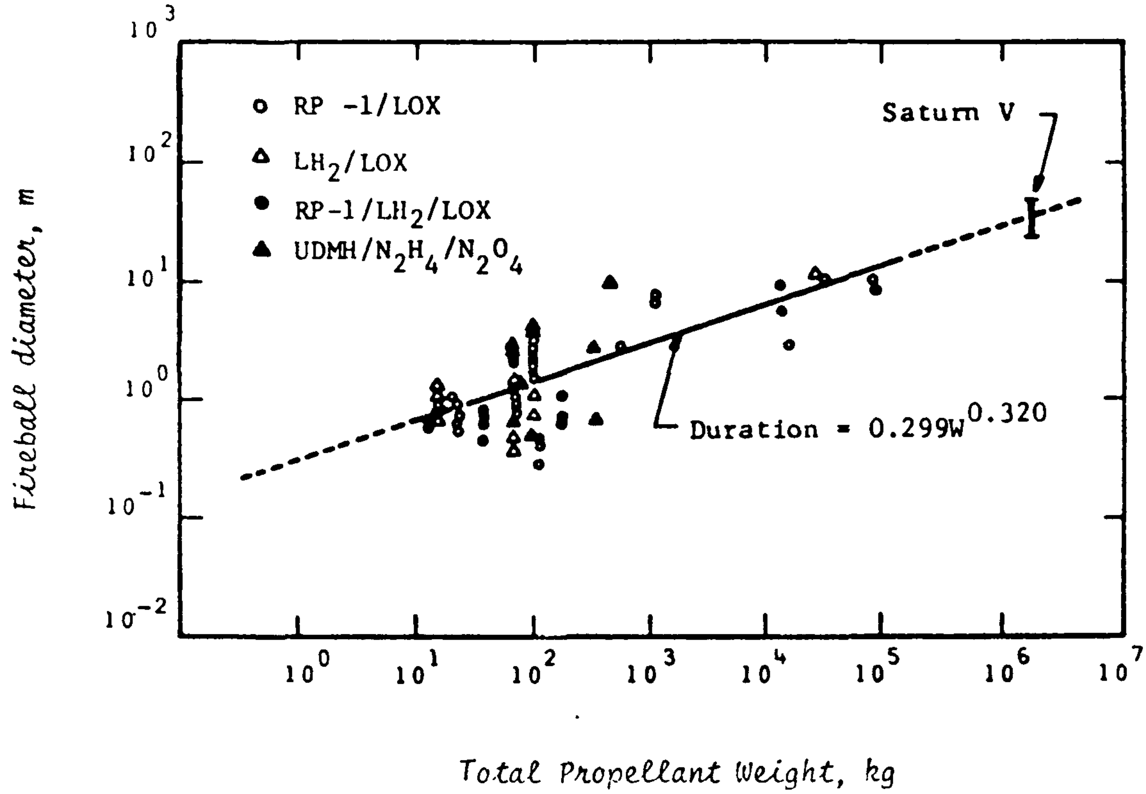


Figure 16a

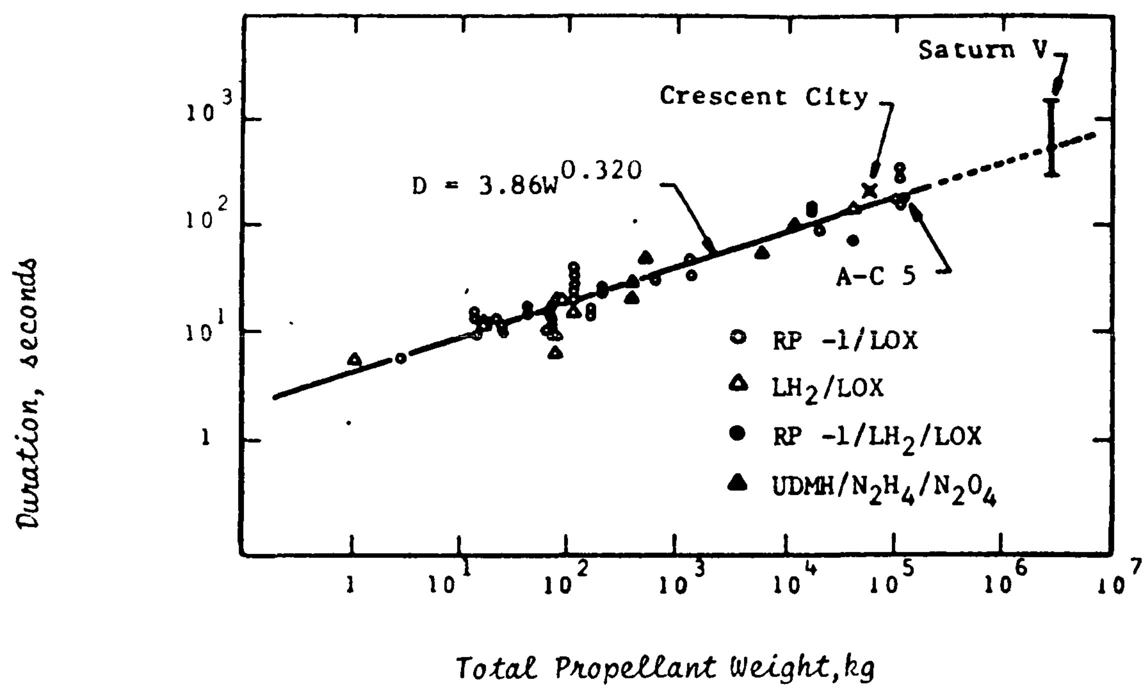
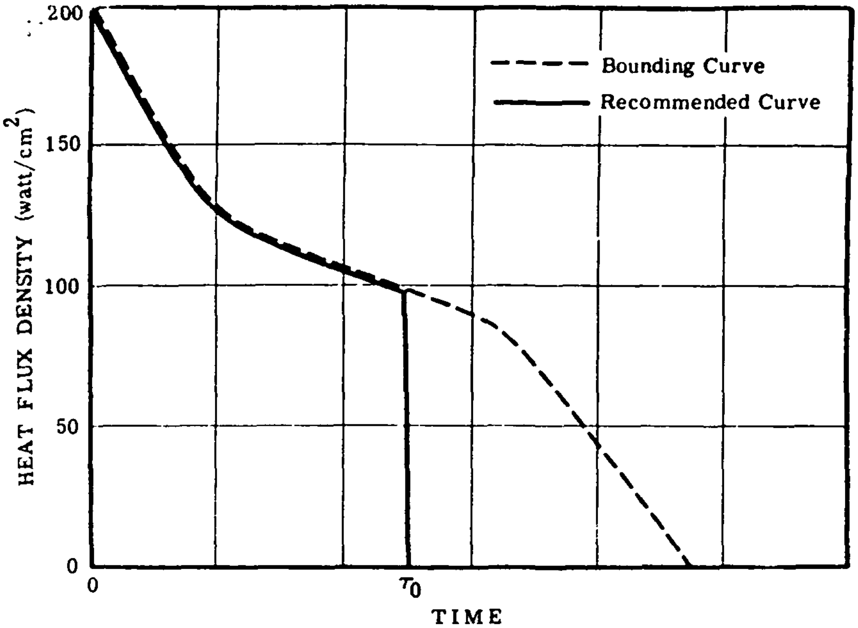
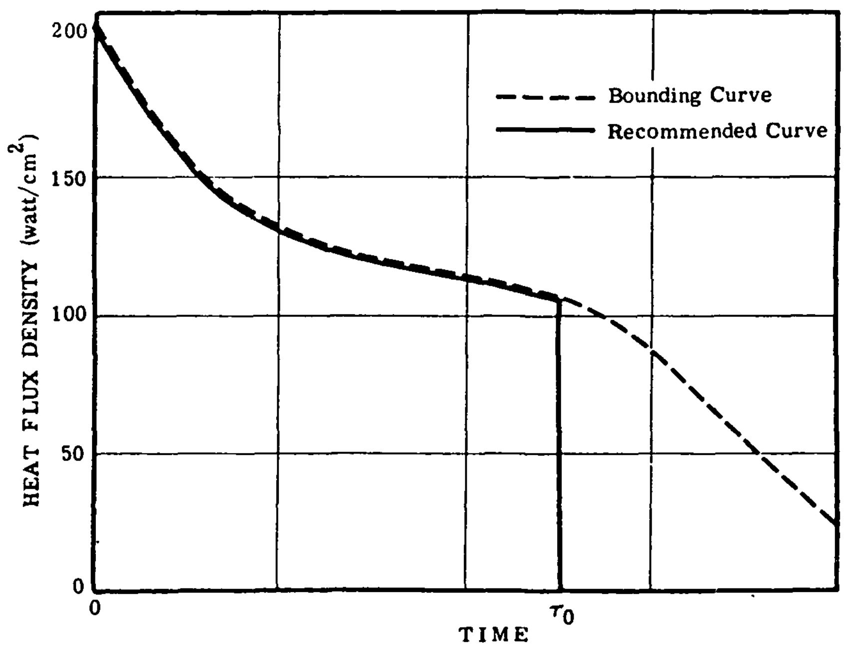


Figure 16b Fireball Duration for Various Weights and Types of Propellants (High (1968) & Baker (1980)).



Bounding and Recommended Heat Flux Density Curves for the LO_2/RP-1 Propellant Combination

Figure 16c



Bounding and Recommended Heat Flux Density Curves for the LO_2/LH_2 Propellant Combination

Figure 16d

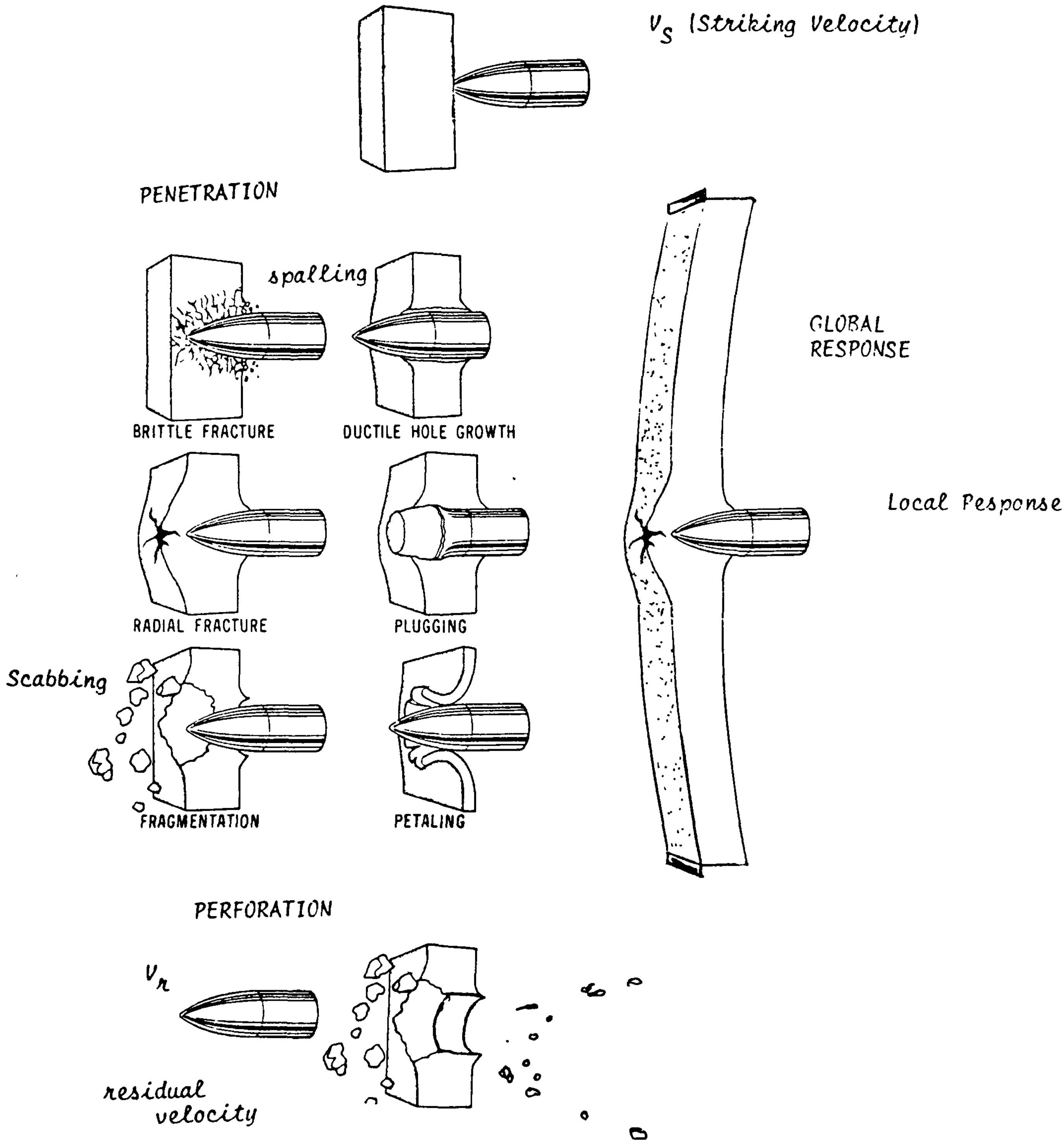


Figure 17. Failure Modes for Impacted Plates (Backman)

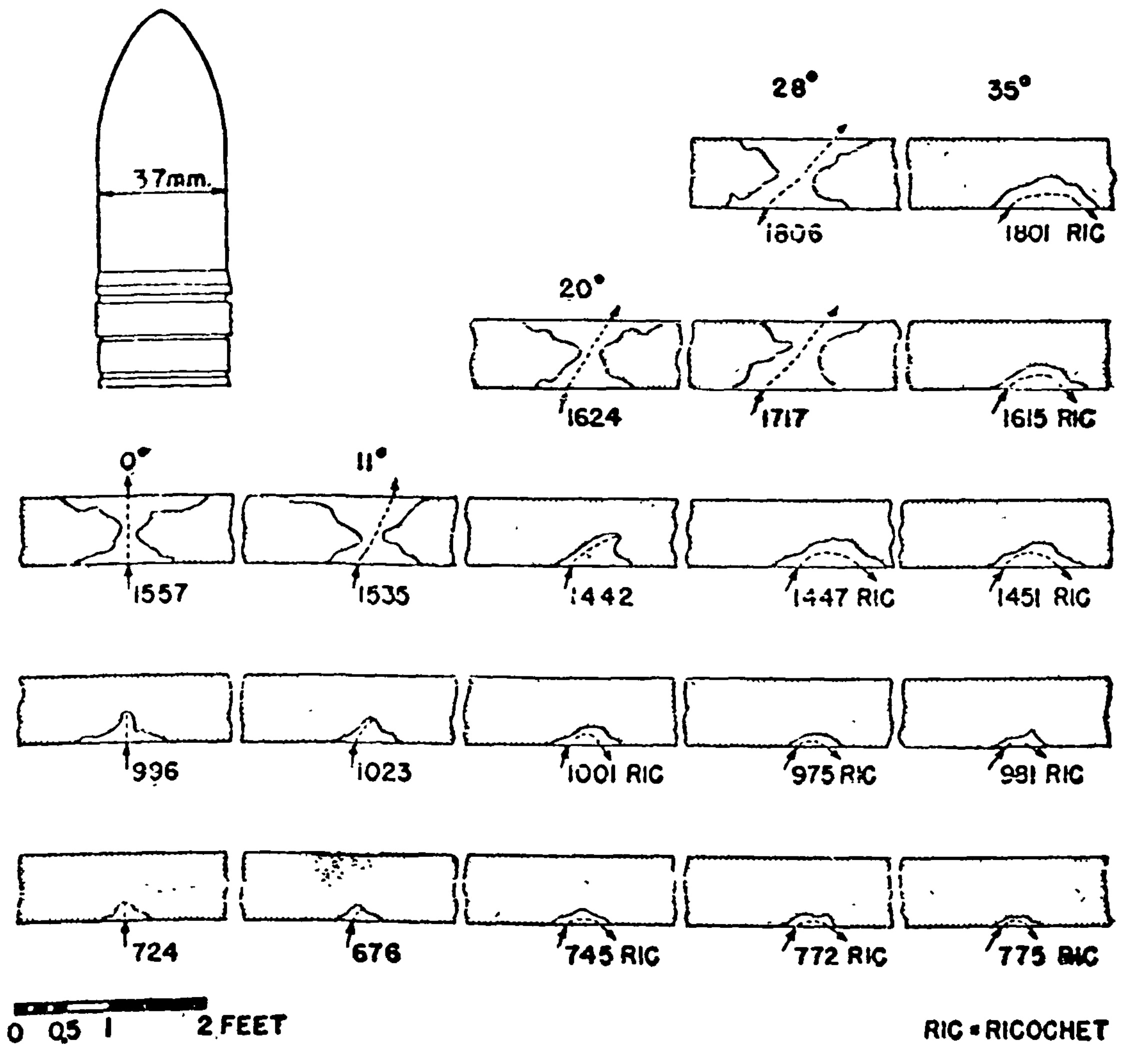


Figure 18. Thin slab. Profiles of actual craters. Slab: thickness, 8.9 in.; compressive strength, 5,700 psi. Projectile: 37-mm M80; weight, 1.70 lb; cap and windshield removed. Striking velocity (fps) shown for each impact.

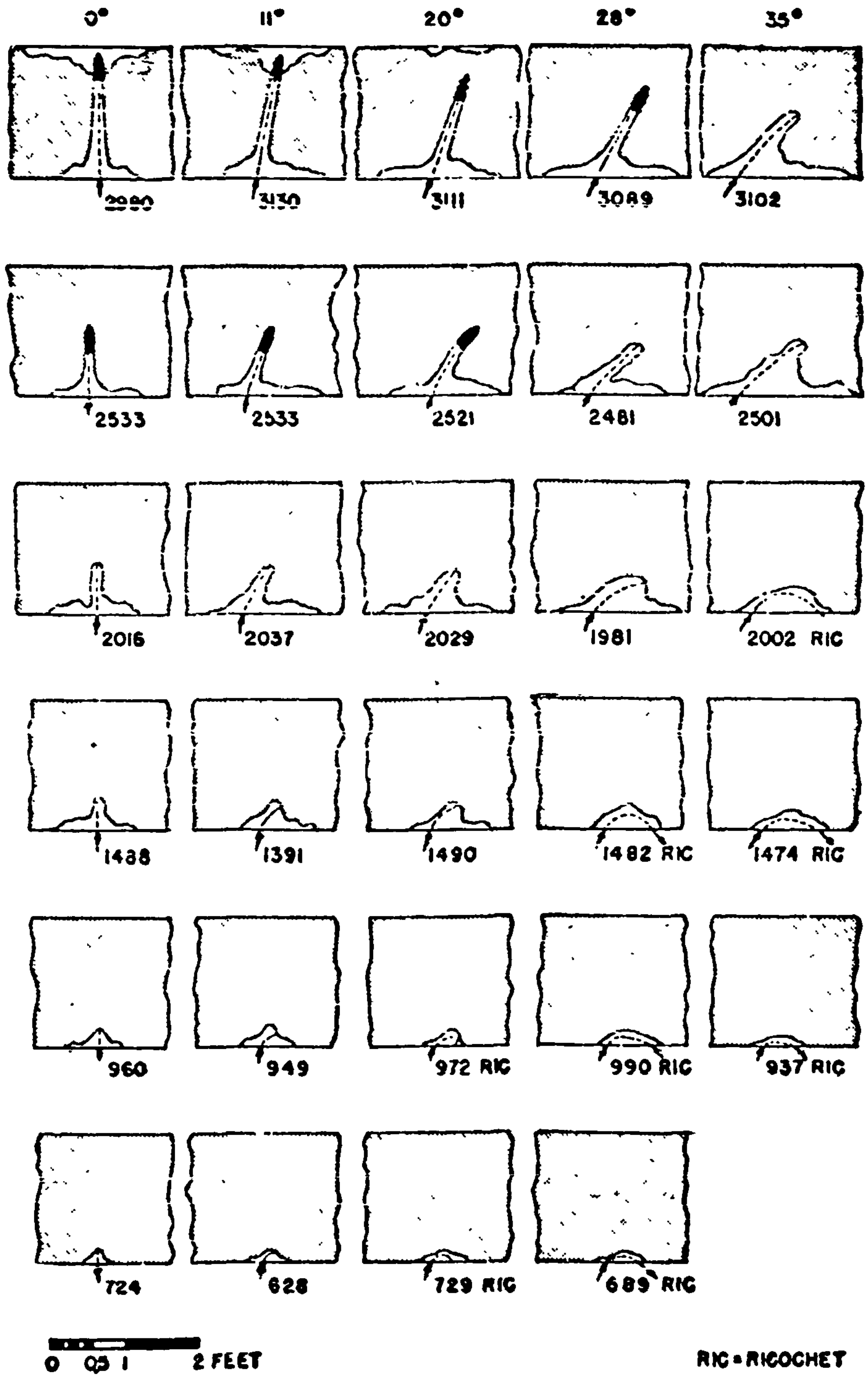
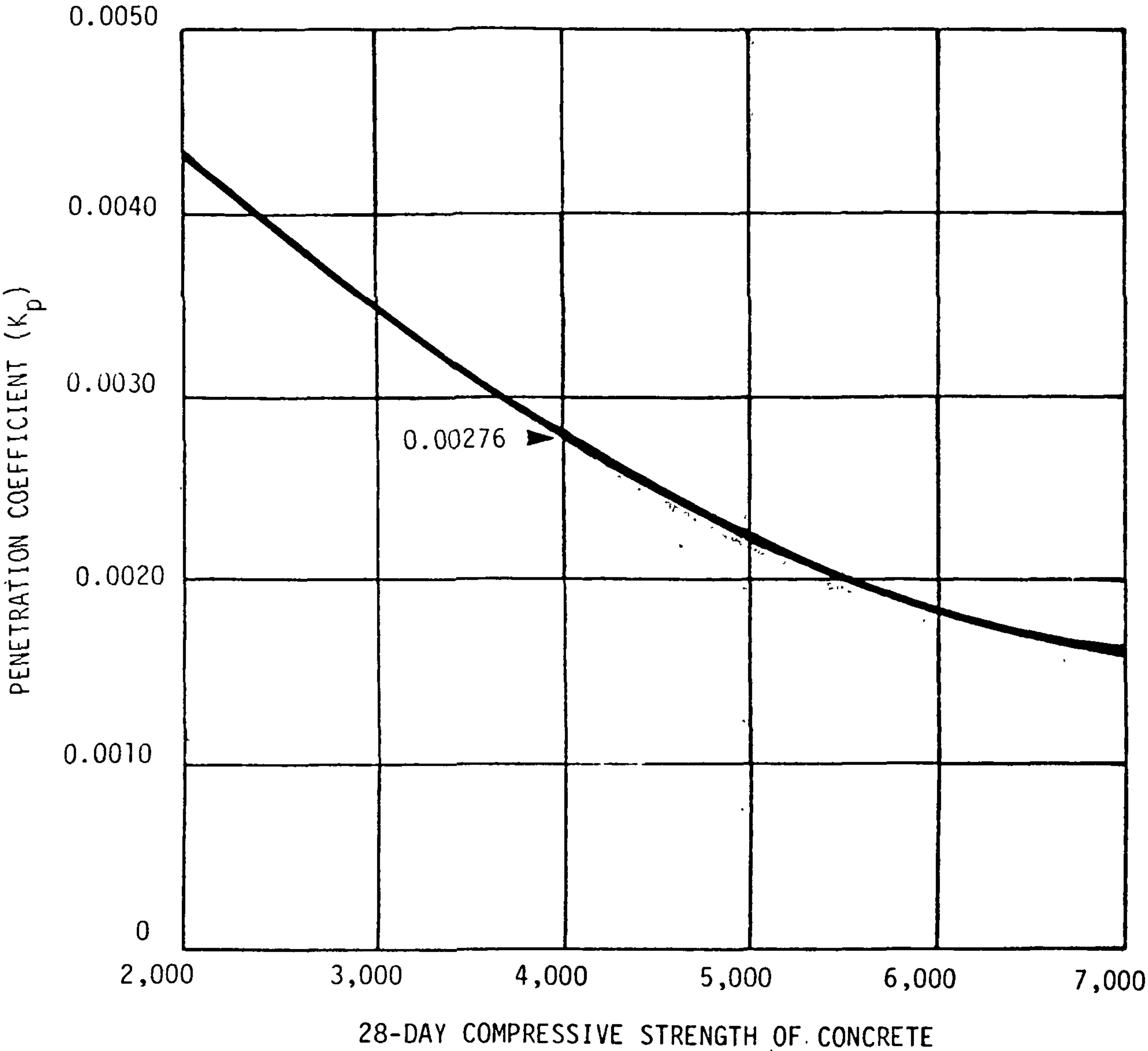
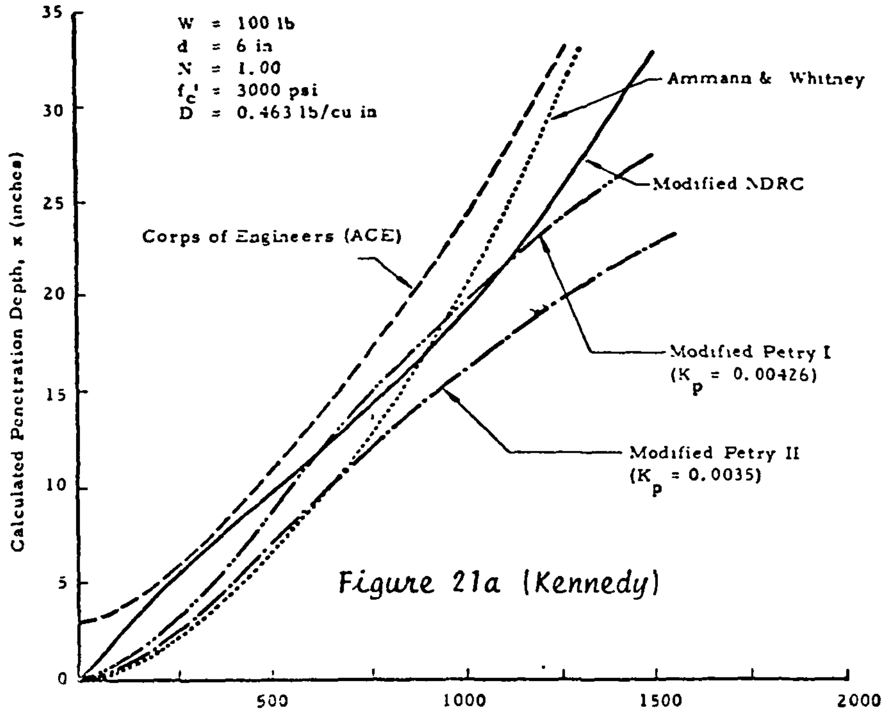


Figure 19. Thick slab. Profiles of actual craters. Slab: thickness 22 in.; compressive strength, 5,700 psi. Projectile: 37-mm M80; weight, 1.70 lb; cap and windshield removed. Striking velocity (fps) shown for each impact. Stuck projectiles actually shown.

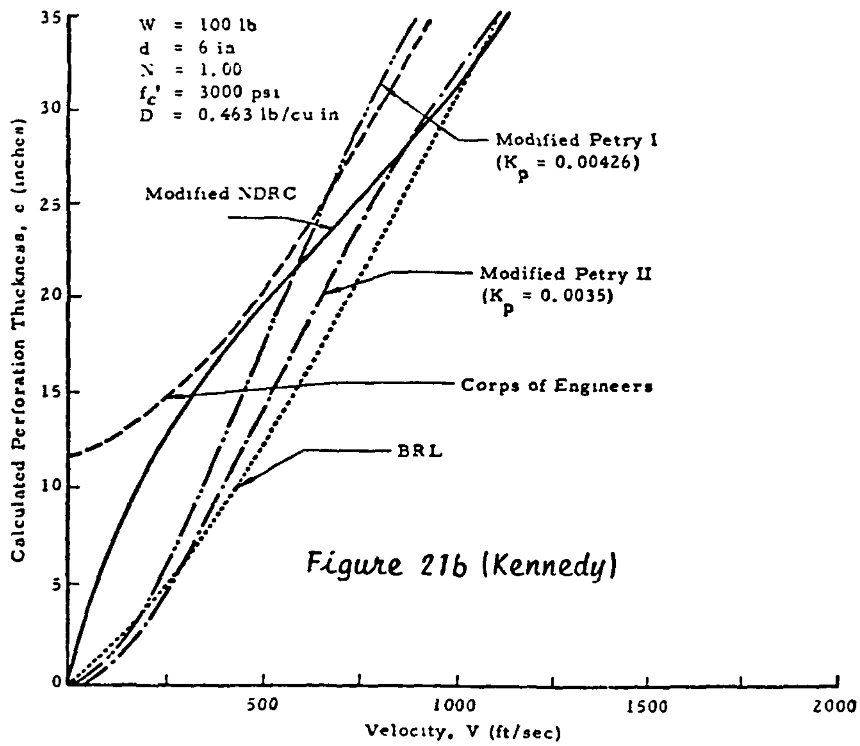


VALUES OF PENETRATION COEFFICIENT (K_p) FOR REINFORCED CONCRETE

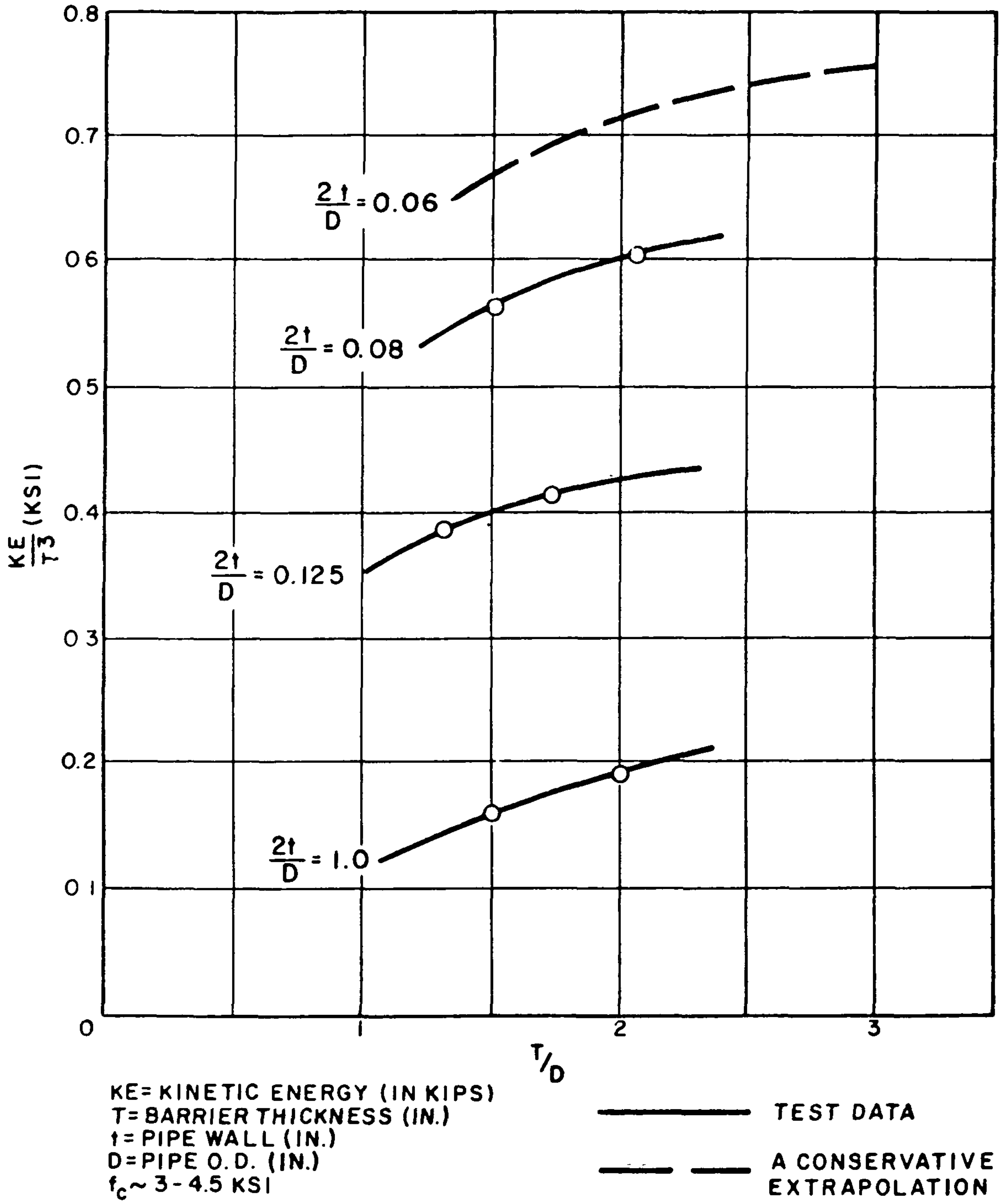
Figure 20



Comparison of concrete penetration depths calculated by various formulae for the case of a typical missile.



Comparison of concrete perforation thickness calculated by various formulae for the case of a typical missile.



SCABBING LIMIT STEEL PIPES OR SLUGS ON REINFORCED CONCRETE BARRIERS

Figure 22

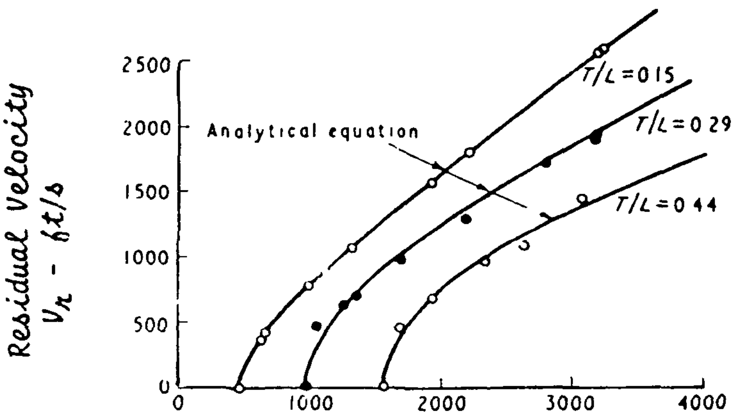
Strain Rate

$\dot{\epsilon}$	V_S	EFFECT	METHOD OF LOADING
10^8	> 12 kms^{-1} *26.8 Kmph*	EXPLOSIVE IMPACT-COLLIDING SOLIDS VAPORIZED	—
10^6	3-12 kms^{-1} *3.4-26 Kmph*	HYDRODYNAMIC-MATERIAL COMPRESSIBILITY NOT IGNORABLE	EXPLOSIVE ACCELERATION
	1-3 kms^{-1} *2.3-6 Kmph*	FLUID BEHAVIOR IN MATERIALS; PRESSURES APPROACH OR EXCEED MATERIAL STRENGTH; DENSITY A DOMINANT PARAMETER	POWDER GUNS, GAS GUNS
10^4	500-1000 ms^{-1} *1.1-2.3 Kmph*	VISCOUS-MATERIAL STRENGTH STILL SIGNIFICANT	POWDER GUNS
10^2	50-500 ms^{-1} *0.1-1.1 Kmph*	PRIMARILY PLASTIC	MECHANICAL DEVICES, COMPRESSED AIR GUN
10^0	< 50 ms^{-1} *0.1 Kmph* *112 mph*	PRIMARILY ELASTIC SOME LOCAL PLASTICITY	MECHANICAL DEVICES, COMPRESSED AIR GUN
0			

1 Kms^{-1} = 1000 meters/sec

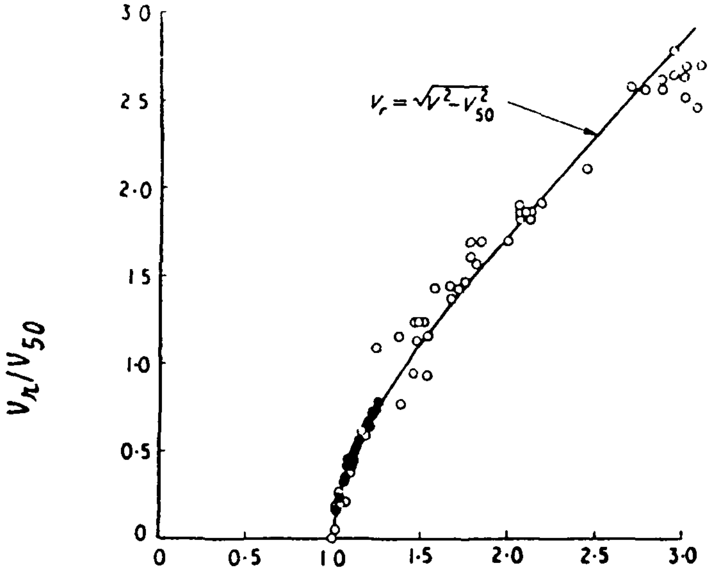
1 Kmph ≡ 1000 miles/hour

Figure 23



Steel cylinders
(R_c30)
Mild Steel Plate
(190 B.h.n.)
Ratio of plate thickness to projectile length T/L

Cylindrical fragments after perforating 1/8, 1/4, or 3/8 in mild steel plate (190 B.h.n.)



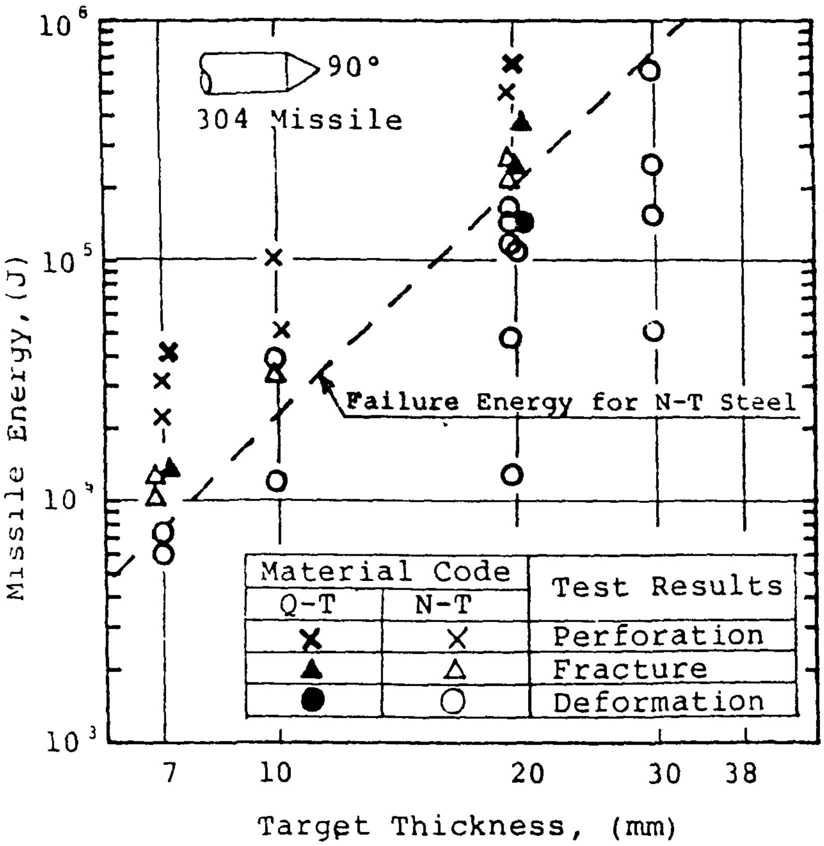
● Brooks

O Recht

Armor-piercing projectiles as a function of impact velocity (normalized with respect to ballistic limit velocity)

Figure 24. Residual Velocity

By 90° Conical Missile



Test Results on Q-T Steel Target Plate by Conical Missiles

Figure 25

C-5

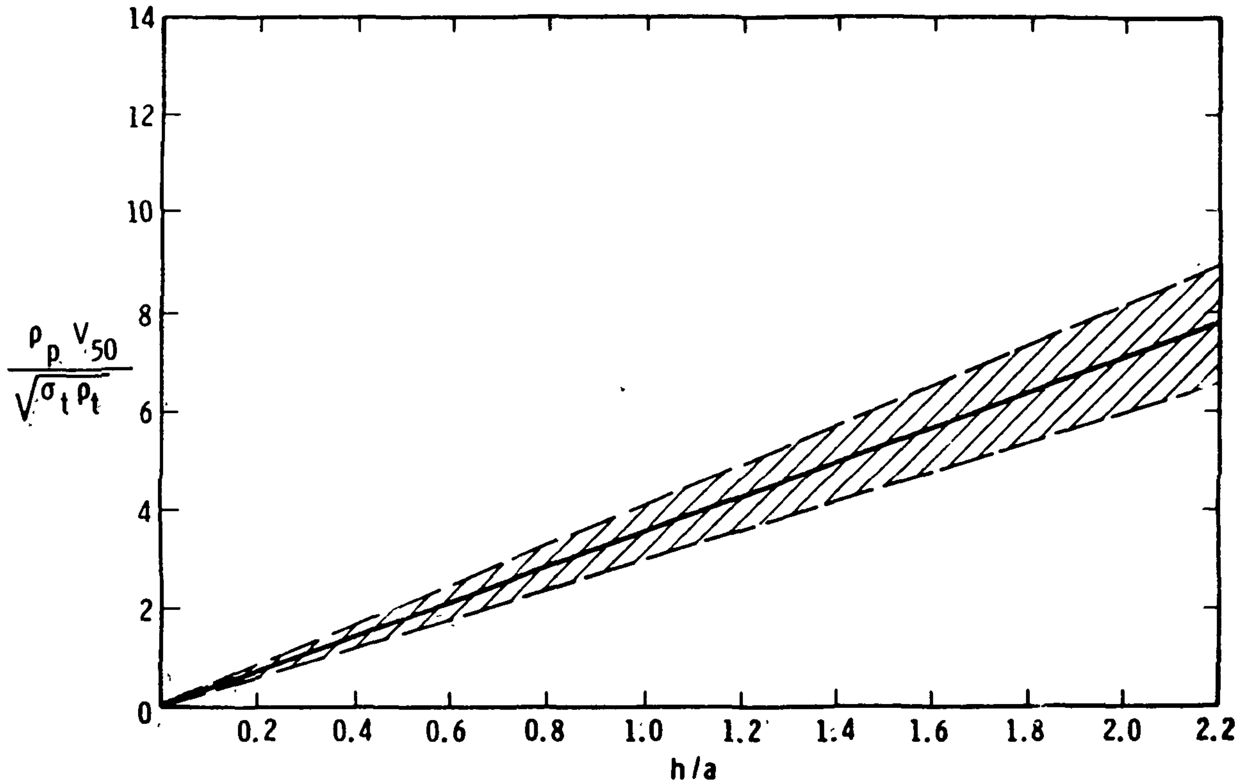


Figure 26. Limit Velocities for Perforation of Thin Metal Plates by Nondeforming Spheres

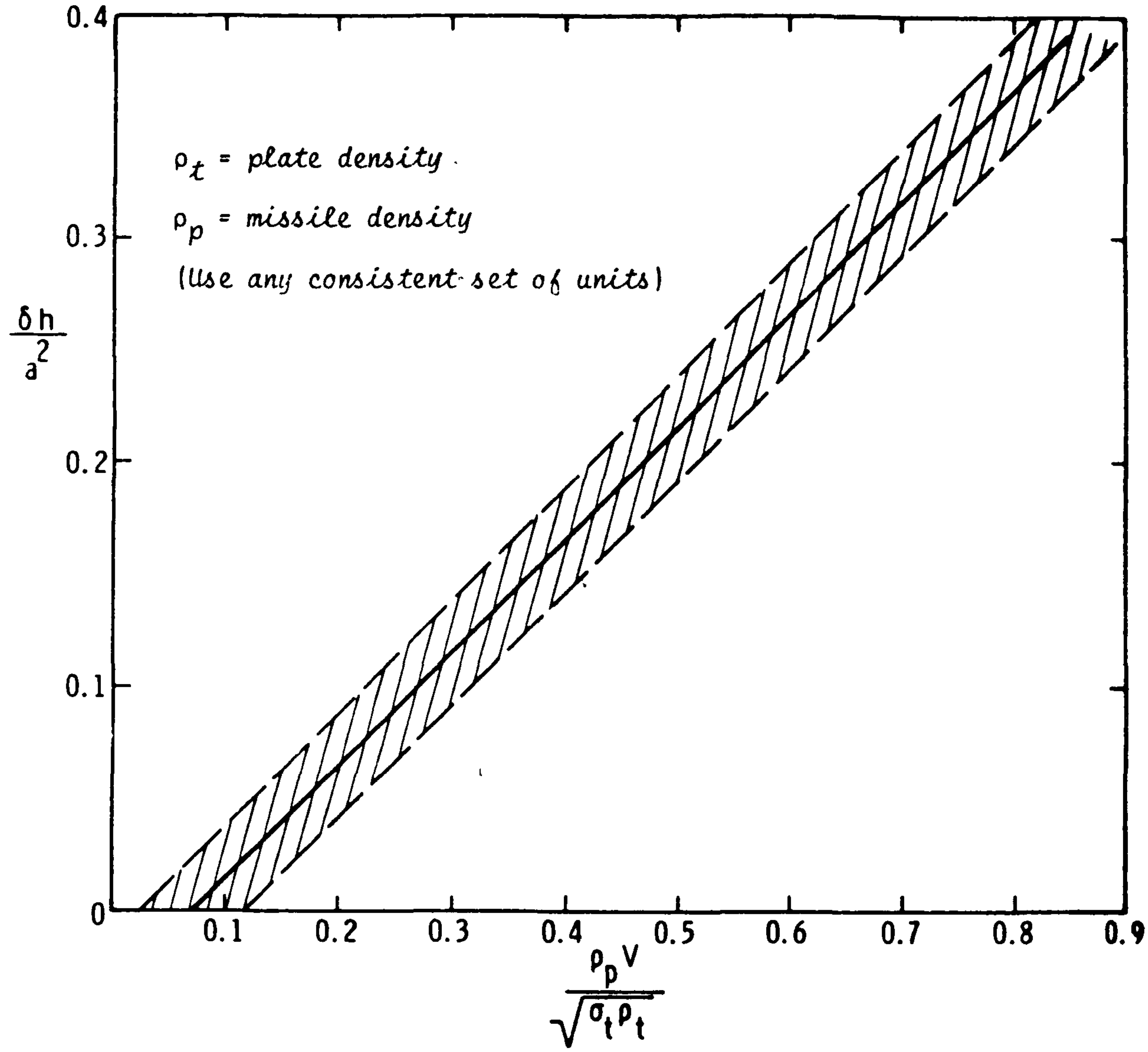


Figure 27 Scaled Denting of Metal Plates by Chunky, Crushable Missiles

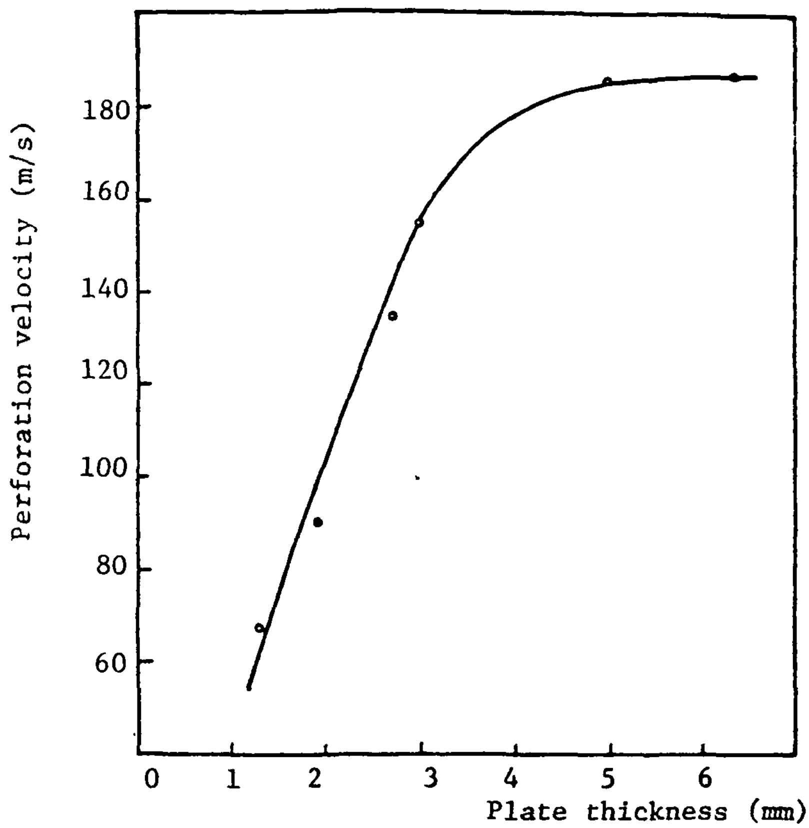
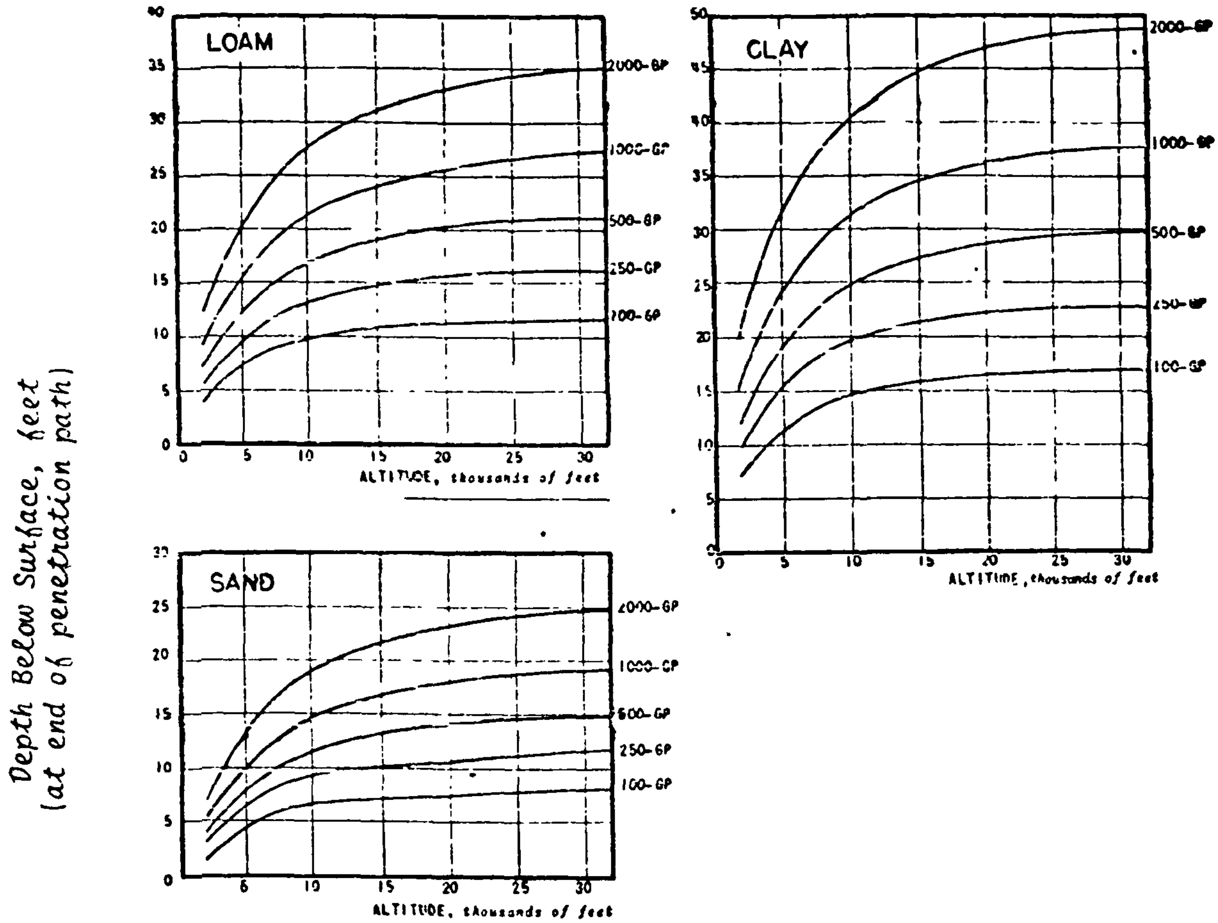


Figure 28 Variation of Perforation Velocity with Plate Thickness for Mild Steel Plate Targets

A - BOMB PENETRATION *for U.S. GP Bombs.*



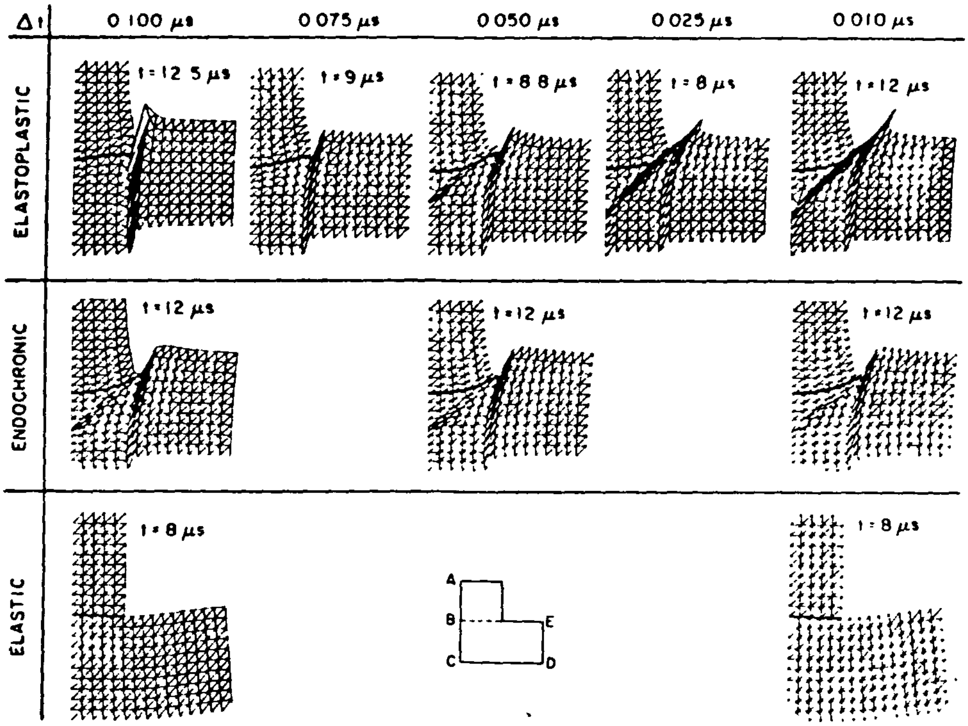
B - SMALL CALIBER BULLETS

SOIL	U.S. CALIBER .30 AP				U.S. CALIBER .50 AP			
	Maximum Expected Penetration	Average Penetration, Short Range	Parapet Thickness Perforated	Parapet Thickness for Protection	Maximum Expected Penetration	Average Penetration, Short Range	Parapet Thickness Perforated	Parapet Thickness for Protection
LOOSE SAND	12 in	10 in	13 in	40 in	20 in	16 in	21 in	64 in
COMPACT SAND	9½ in	7½ in	12 in	30 in	15 in	12 in	19 in	46 in
LOAM	16 in	12 in	16 in	44 in	24 in	20 in	28 in	72 in
PLASTIC CLAY	23 in	20 in	23 in	65 in	40 in	30 in	36 in	100 in

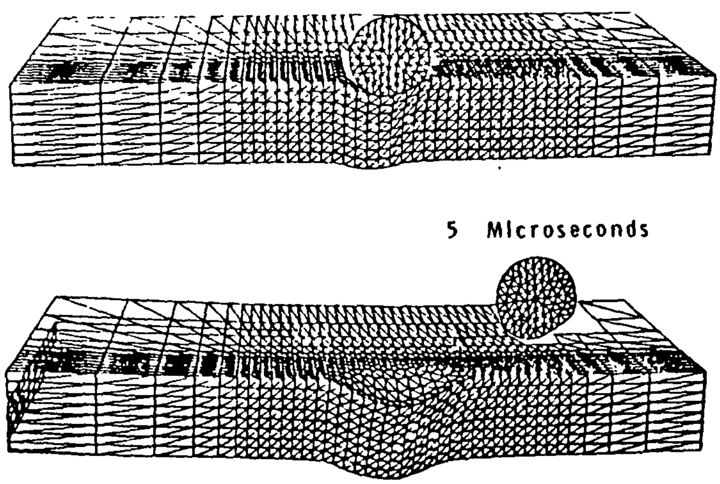
SOURCE: The Bomb Penetration Curves are based on British and American tests with bombs and large caliber projectiles. The Small Caliber Bullet Tabulation is based on tests for the Corps. of Engineers, U.S.A.

Figure 29

ORIGINAL PAGE IS
OF POOR QUALITY



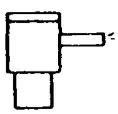
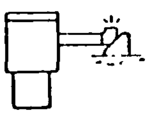
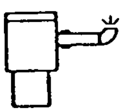
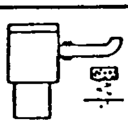
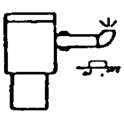
Comparison of Constitutive Laws and Time Steps (Hsieh)



Steel Sphere Impacting Aluminum Obliquely (Zukas)

Figure 30. Computer Simulation of Impact System

AQUITAINE 2 - Program

Test configuration	Number of tests	Main measurements and observations
A 	14	Pressure and temperature of the fluid in the vessel and in the pipe. Forces exerted on the vessel supports.
B 	4	Vertical component of the jet force on the elbow.
	3	Pipe whip.
C 	6	Pipe whip and impact on the concrete mass.
	2	Pipe whip and impact on the rigid structure.

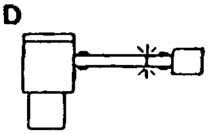
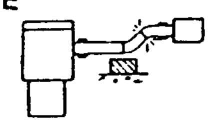
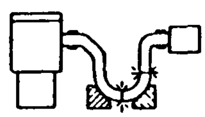
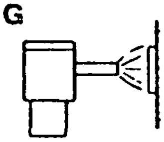
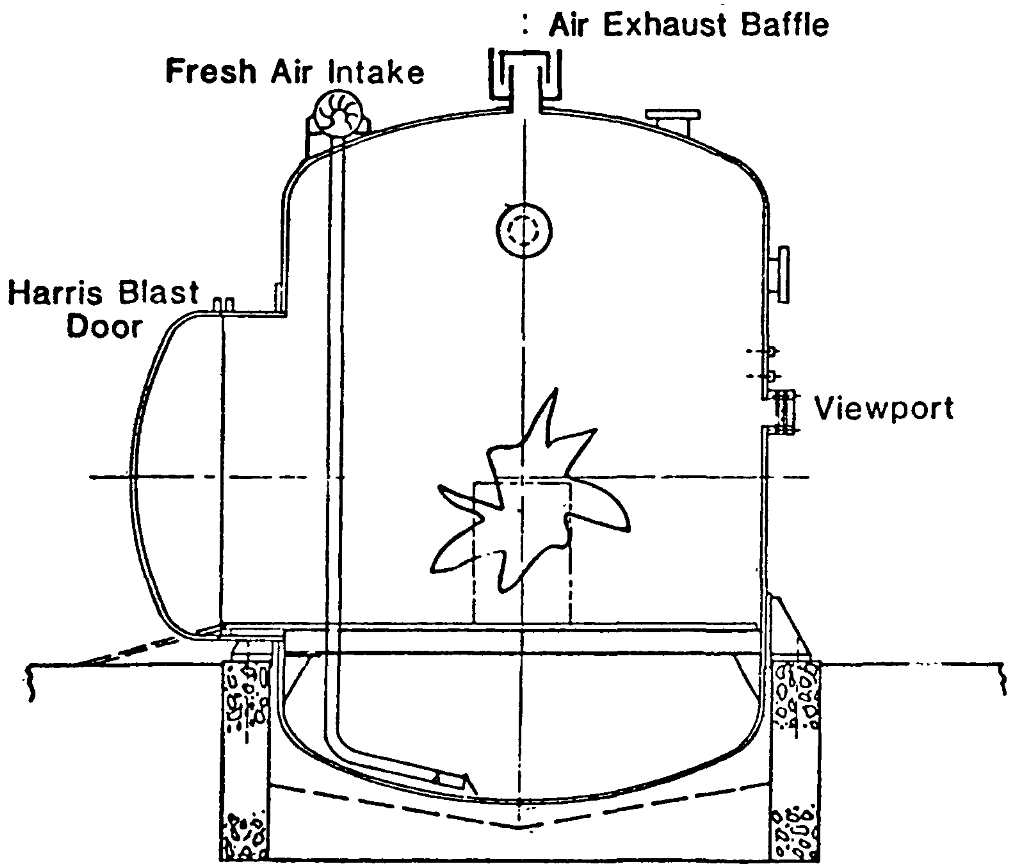
Test configuration	Number of tests	Main measurements and observations
D 	8	Behavior of the straight pipe (stability or not).
E 	4	Efficiency of the bumper.
F 	2	Behavior of the pipe. Efficiency of supports.
G 	2	Jet impingement load.

Figure 31



Occidental's Steel Containment for High-Pressure Reactions

Figure 32

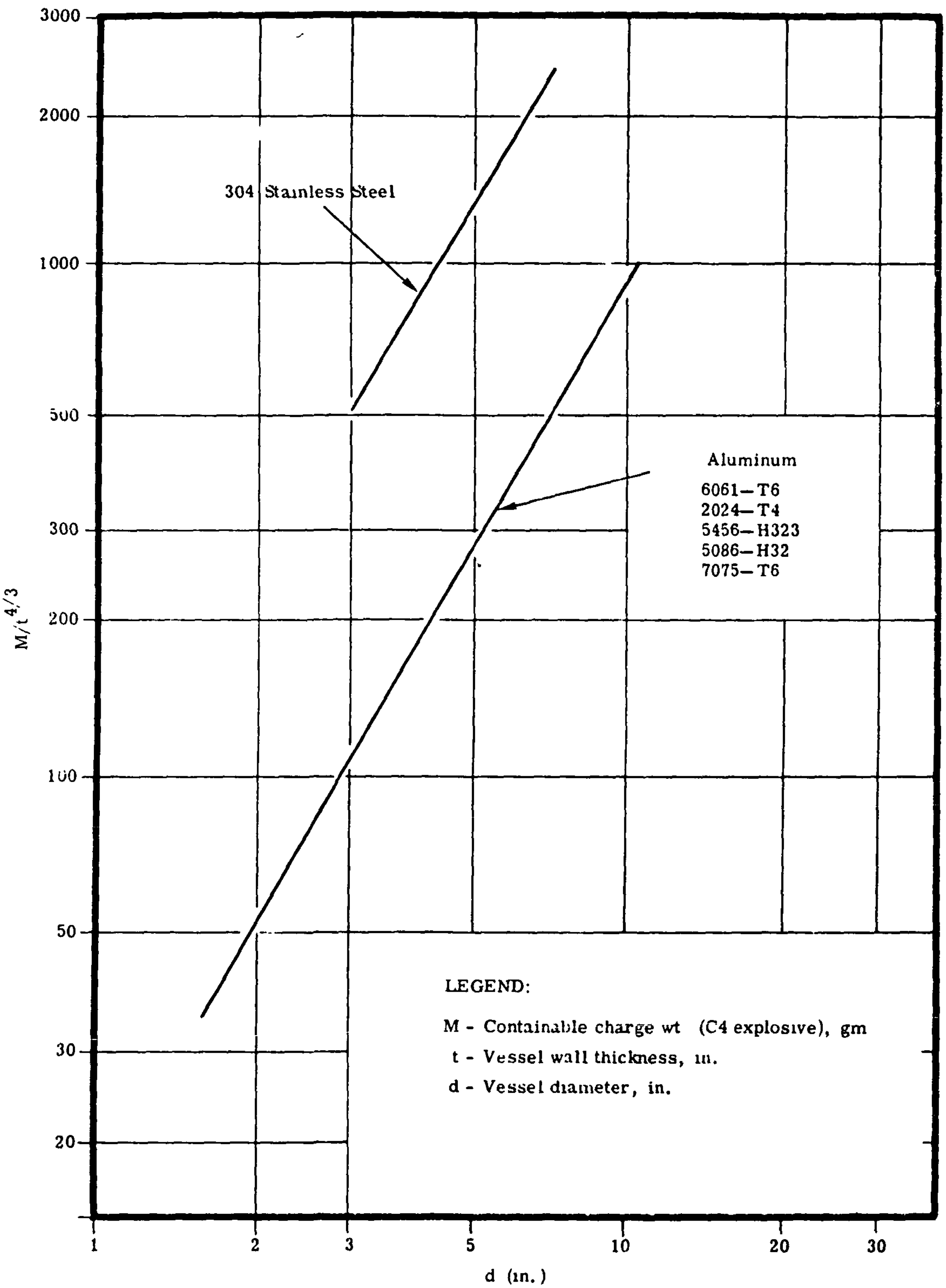
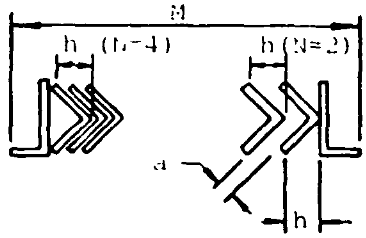

3000
2000
1000
500
300
200
100
50
30
20
$M/t^{4/3}$
304 Stainless Steel
Aluminum
6061—T6
2024—T4
5456—H323
5086—H32
7075—T6
LEGEND:
M - Containable charge wt (C4 explosive), gm
t - Vessel wall thickness, in.
d - Vessel diameter, in.
1
2
3
5
10
20
30
d (in.)

Figure 33



A_v = $n\ell a/N$

n = number of openings

ℓ = length of exposed element

h = projected width of angle

N = 2 for one opening per projected width h of angle; = 4 for two or more openings per width h

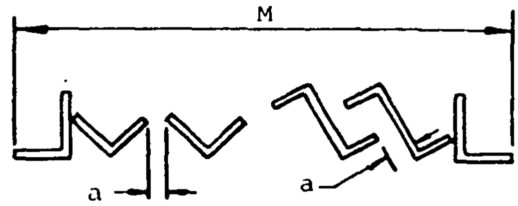
A_w = LM

L = length of wall

α_1 = A_v/A_w

M = panel width

(a) Nested Angles



A_v = $n\ell a$

n = number of openings

ℓ = length of exposed element

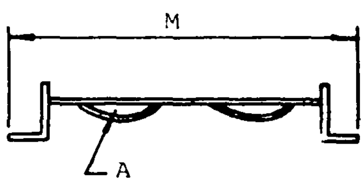
A_w = LM

L = length of wall

α_1 = A_v/A_w

M = panel width

(b) Side-by-Side Angles or Zees



A_v = nA/2

n = number of louvres

A = open area of louvre

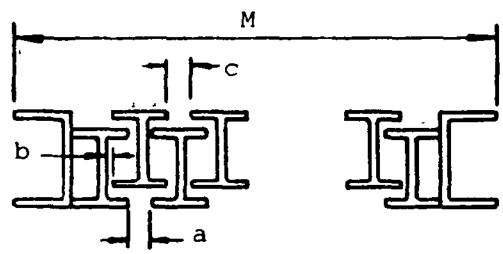
A_w = LM

L = Length of wall

α_1 = A_v/A_w

M = panel width

(c) Louvres



M = panel width

A_{v_1} = $2\ell n_a a$

A_{v_2} = A_{v_3} = $2\ell n_b b$

A_{v_4} = $2\ell n_c c$

n_a, n_b, n_c = number of openings a, b, c

ℓ = length of element

A_w = LM

L = length of wall

α_1 = A_{v_1}/A_w, α_2 = A_{v_2}/A_w, . . .

(d) Interlocked I-Beams

Definition of Vent Area Ratios for Various Structural Configurations

Figure 34

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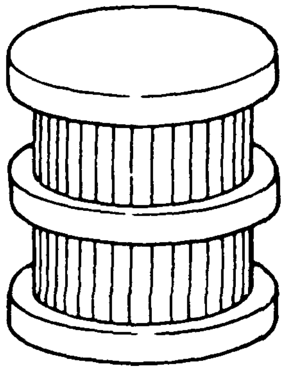
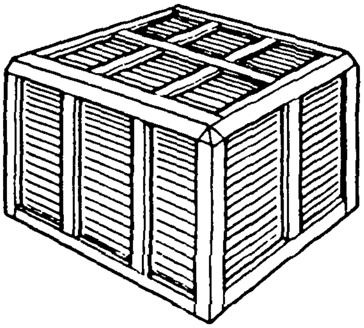
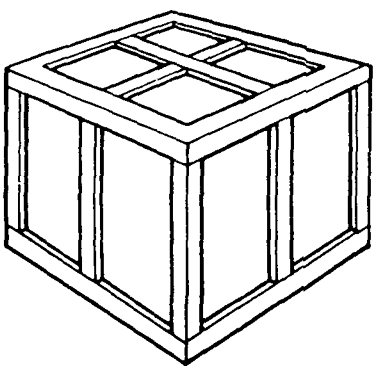


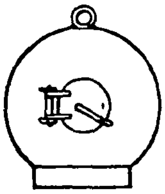
a. *Suppressive Shield Groups 1,2, and 3*



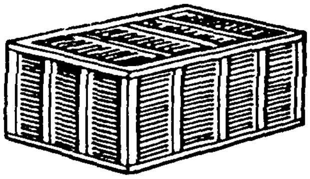
b. *Suppressive Shield Group 4*



c. *Suppressive Shield Group 5*



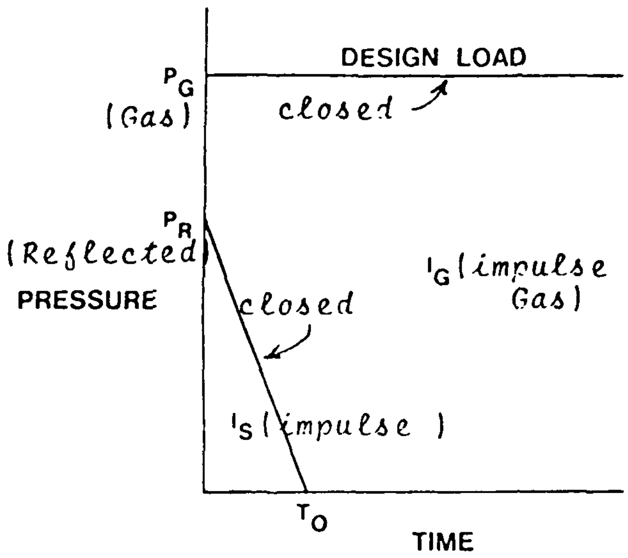
d. *Suppressive Shield Group 6*



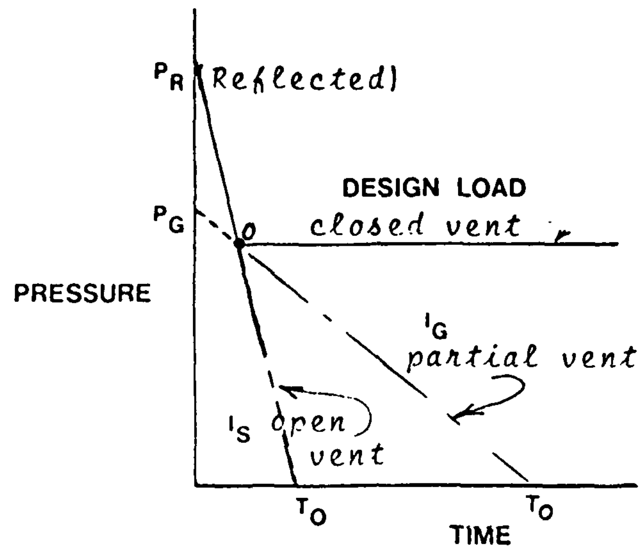
e. *Suppressive Shield Group 81 mm.*

General Configuration of Suppressive Shield Groups

Figure 35

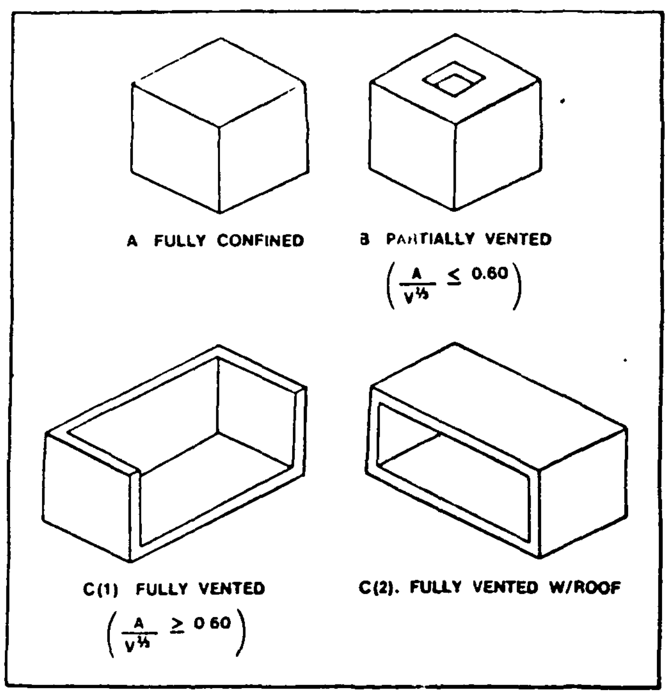


A GAS PRESSURE DOMINANT



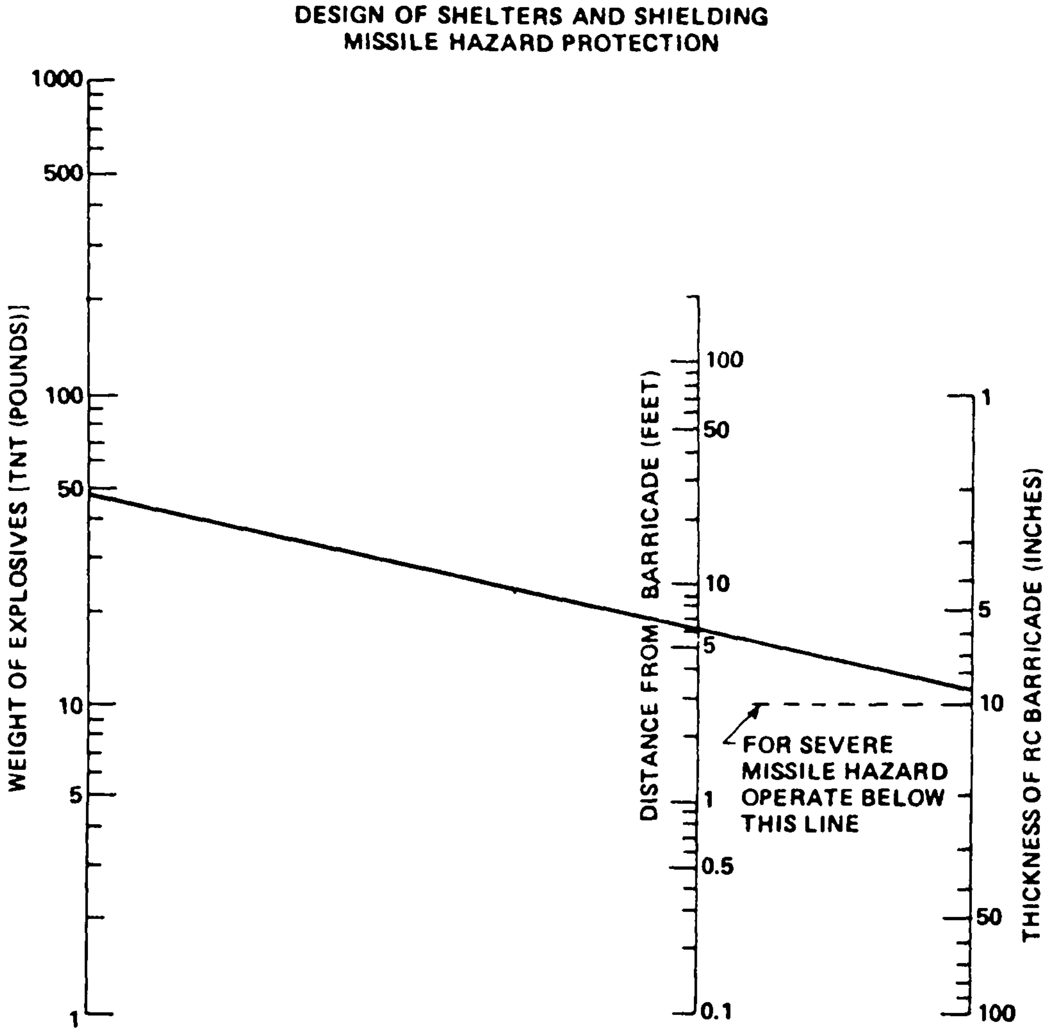
B SHOCK PRESSURE DOMINANT

CRITERIA FOR INTERNAL LOADING OF CONTAINMENT



C **Barricade configurations.**

Figure 36

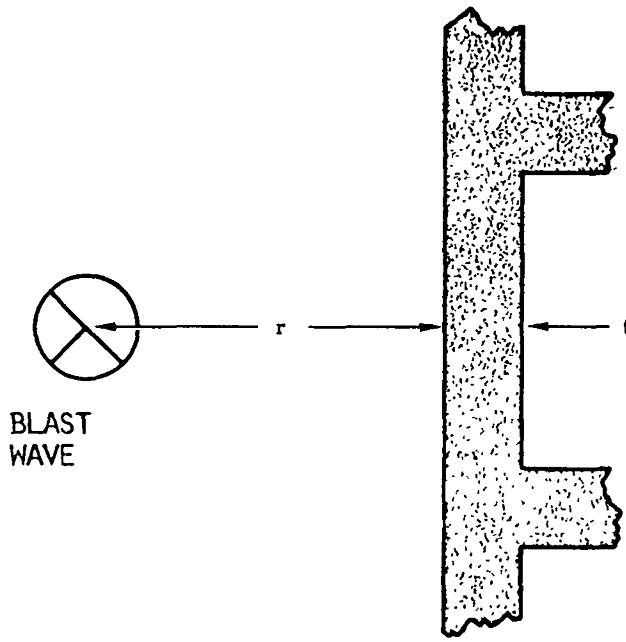


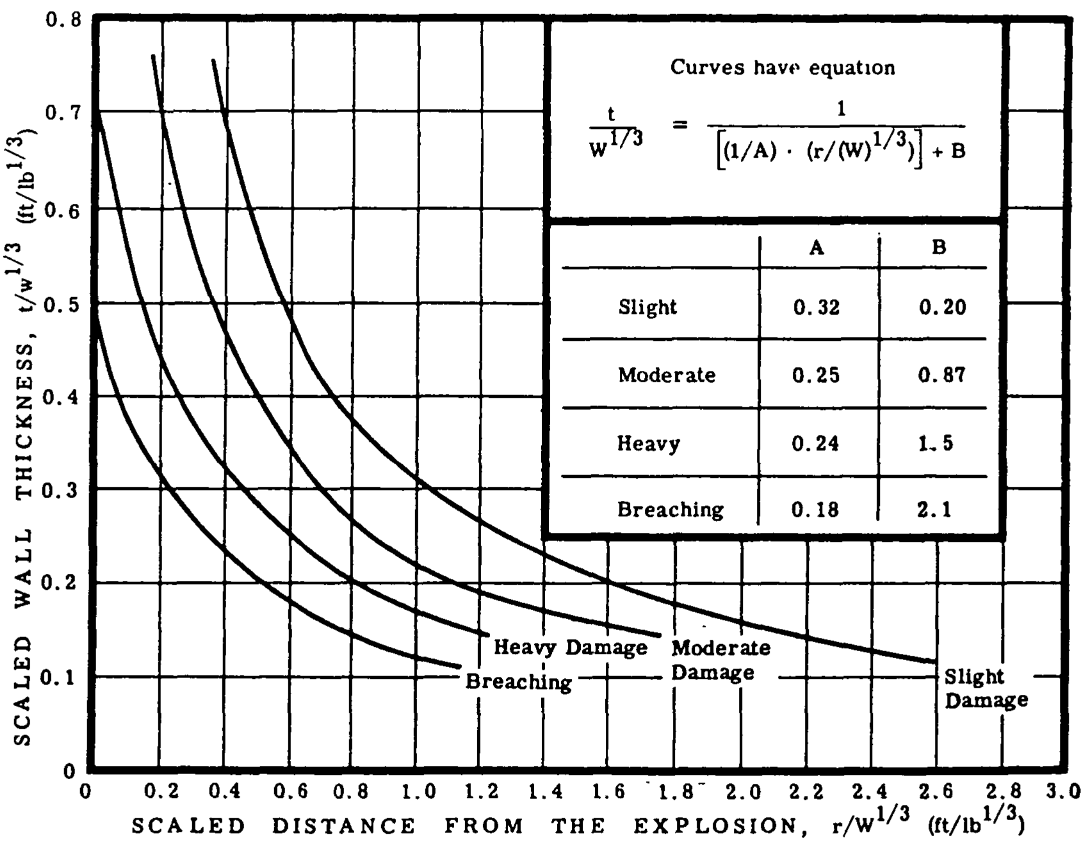
NOTE:

1. IN A CONFINED SPACE (AS IN A THREE-WALL CUBICLE WITH ONE OPEN SIDE AND OPEN ROOF), THE THICKNESS OBTAINED FOR A ONE-WALL BARRICADE SHOULD BE INCREASED BY 1/3.
2. IF THE STEEL BARRICADE IS TO BE USED, THE THICKNESS OF THE PLATE SHOULD BE TAKEN AS 1/5 THAT OF THE RC (REINFORCED CONCRETE) WALL.
3. IF SAND BAGS OR BOXES FILLED WITH SAND ARE TO BE USED, THE THICKNESS OF THE WALL SHOULD BE SEVERAL TIMES THE THICKNESS OF THE RC WALL.
4. FLEXURAL DESIGN REQUIREMENTS ARE ADDITIVE.

Prepared by US Army Ballistics Research Laboratories, Aberdeen Proving Ground, Maryland.

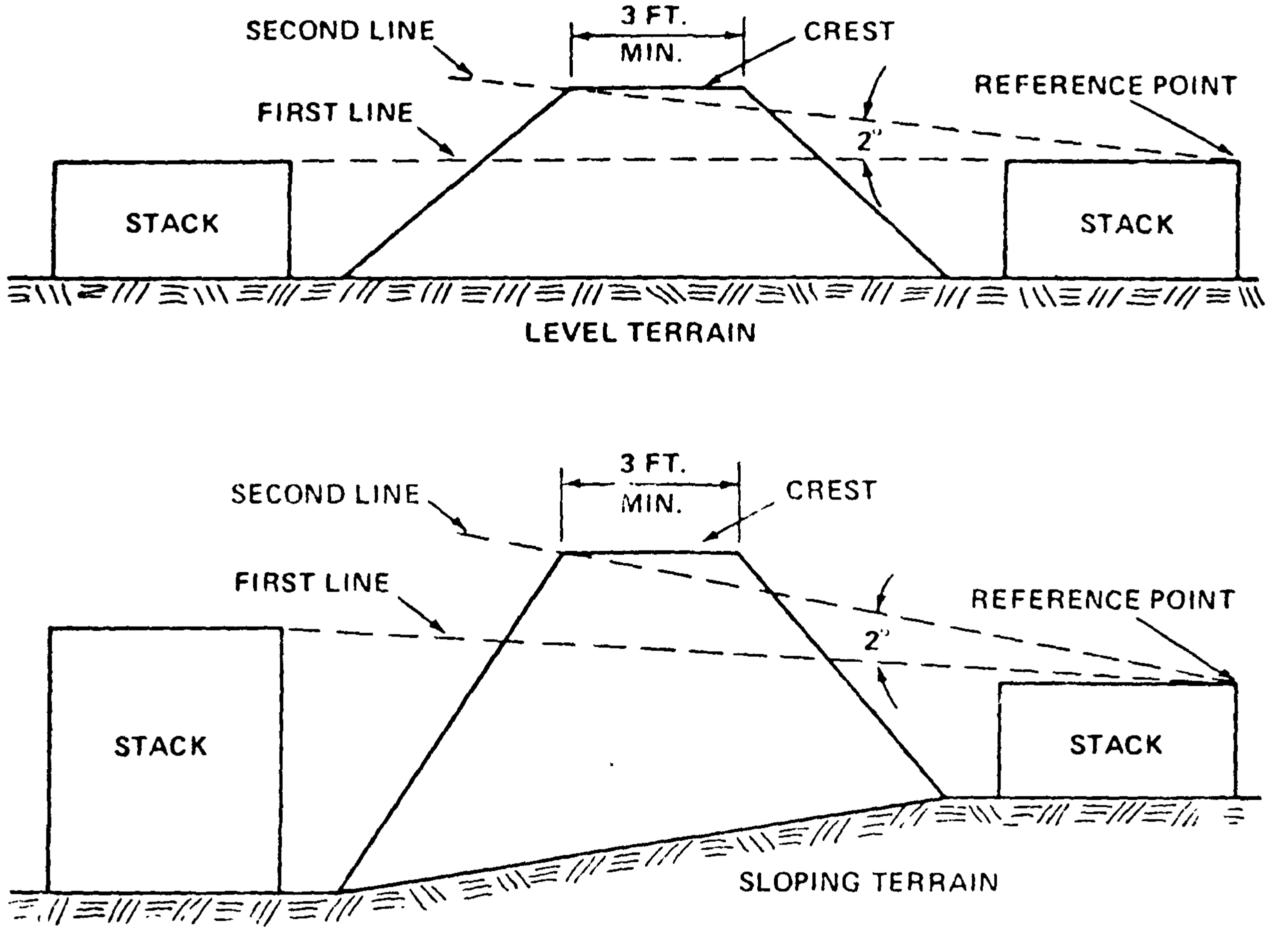
Figure 37



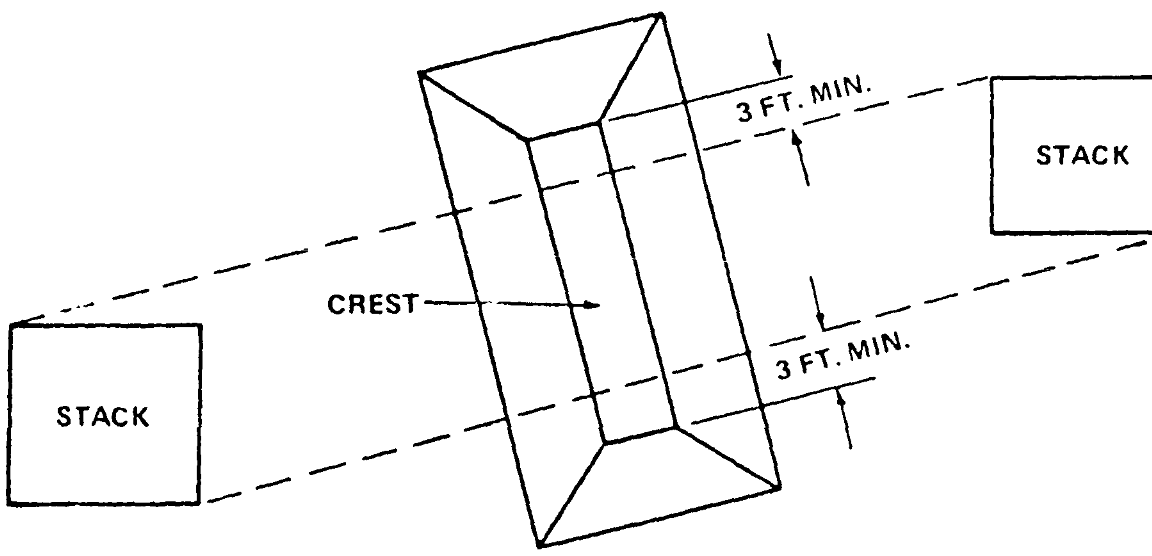


Damage to Reinforced Concrete Wall Panels from TNT Explosions in Air

Figure 38

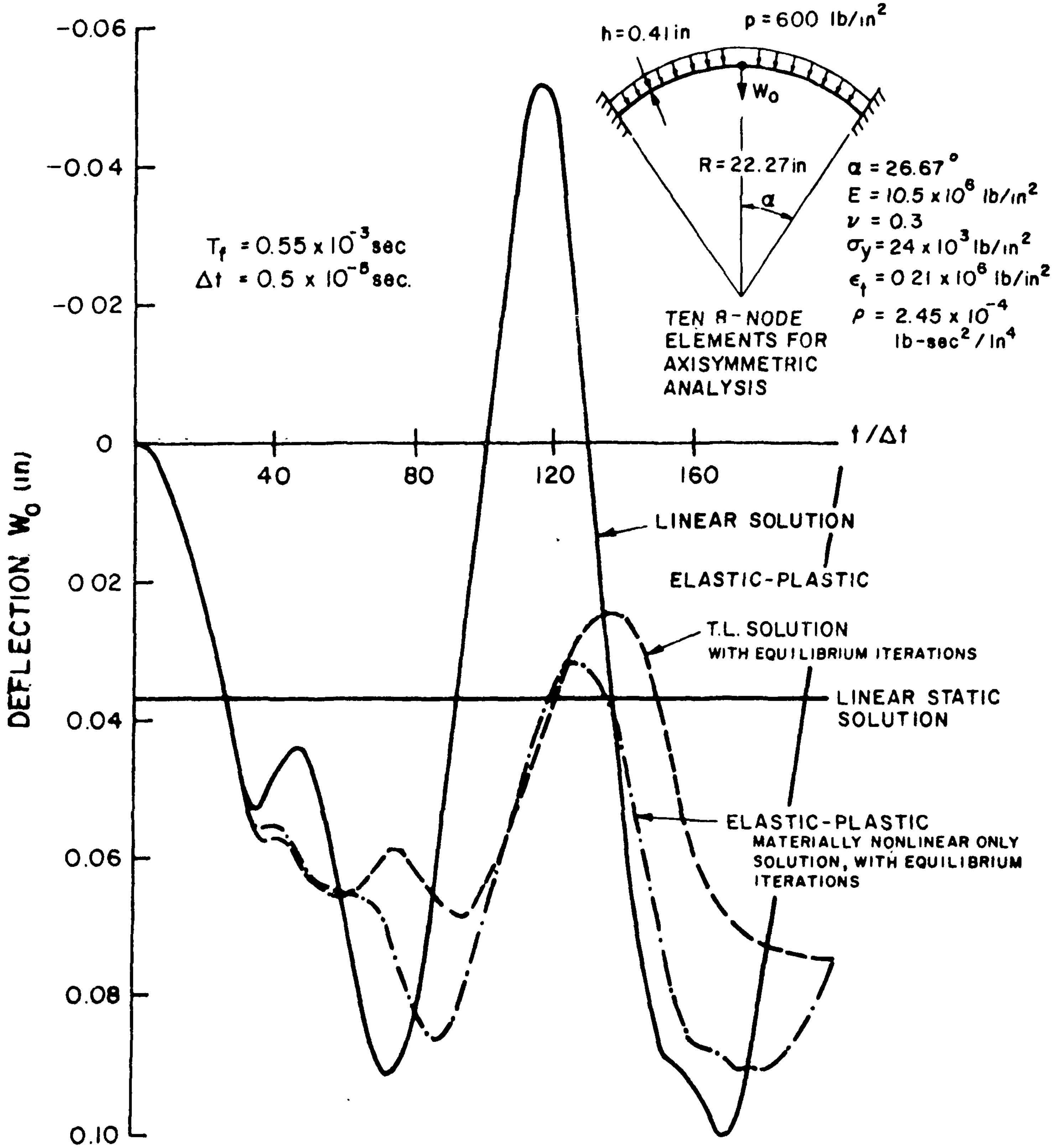


-DETERMINATION OF BARRICADE HEIGHT



–DETERMINATION OF BARRICADE LENGTH

Figure 39



LARGE DISPLACEMENT DYNAMIC ELASTIC-PLASTIC ANALYSIS OF SPHERICAL CAP, NEWMARK METHOD, δ=0.50, α=0.25

Figure 40

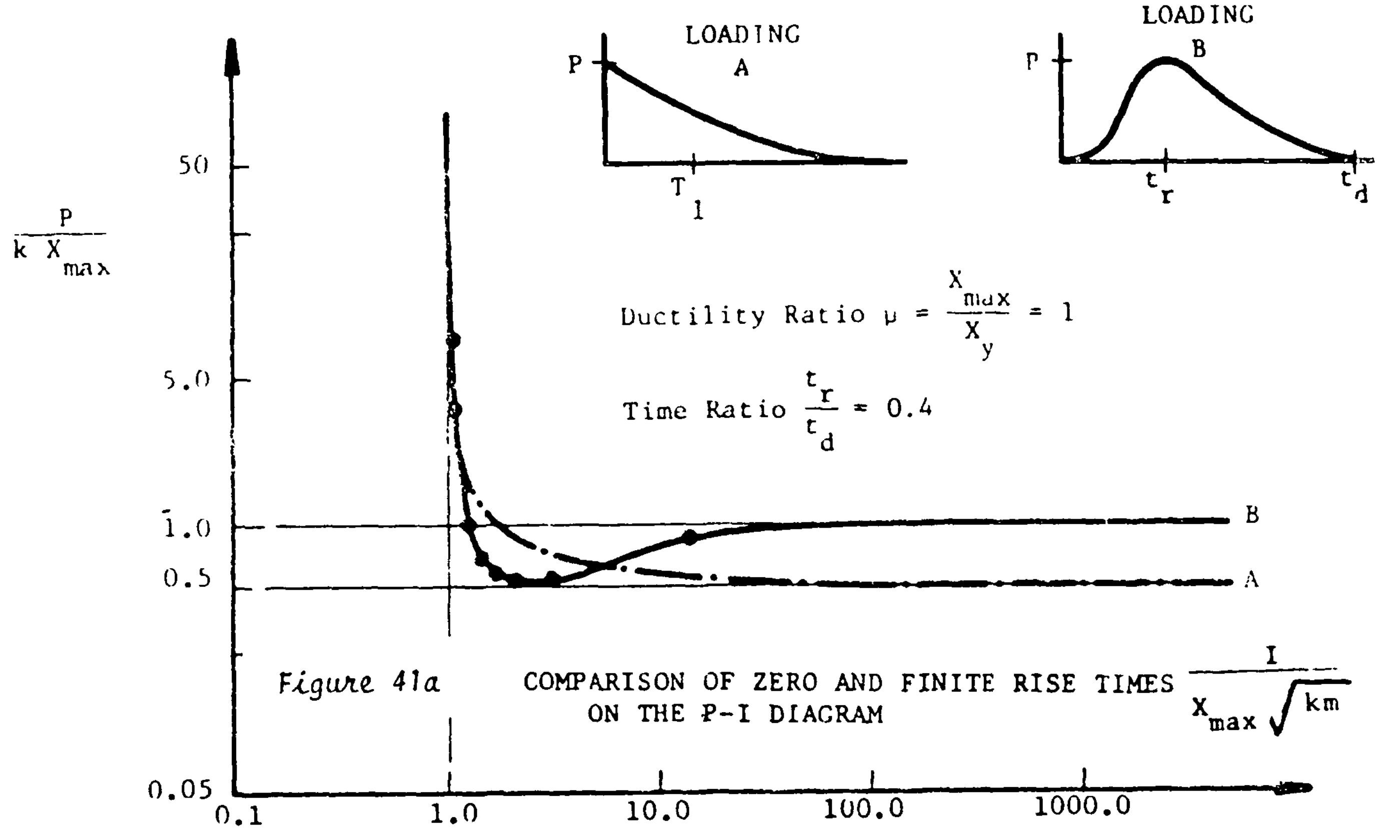


Figure 41a COMPARISON OF ZERO AND FINITE RISE TIMES ON THE P-I DIAGRAM

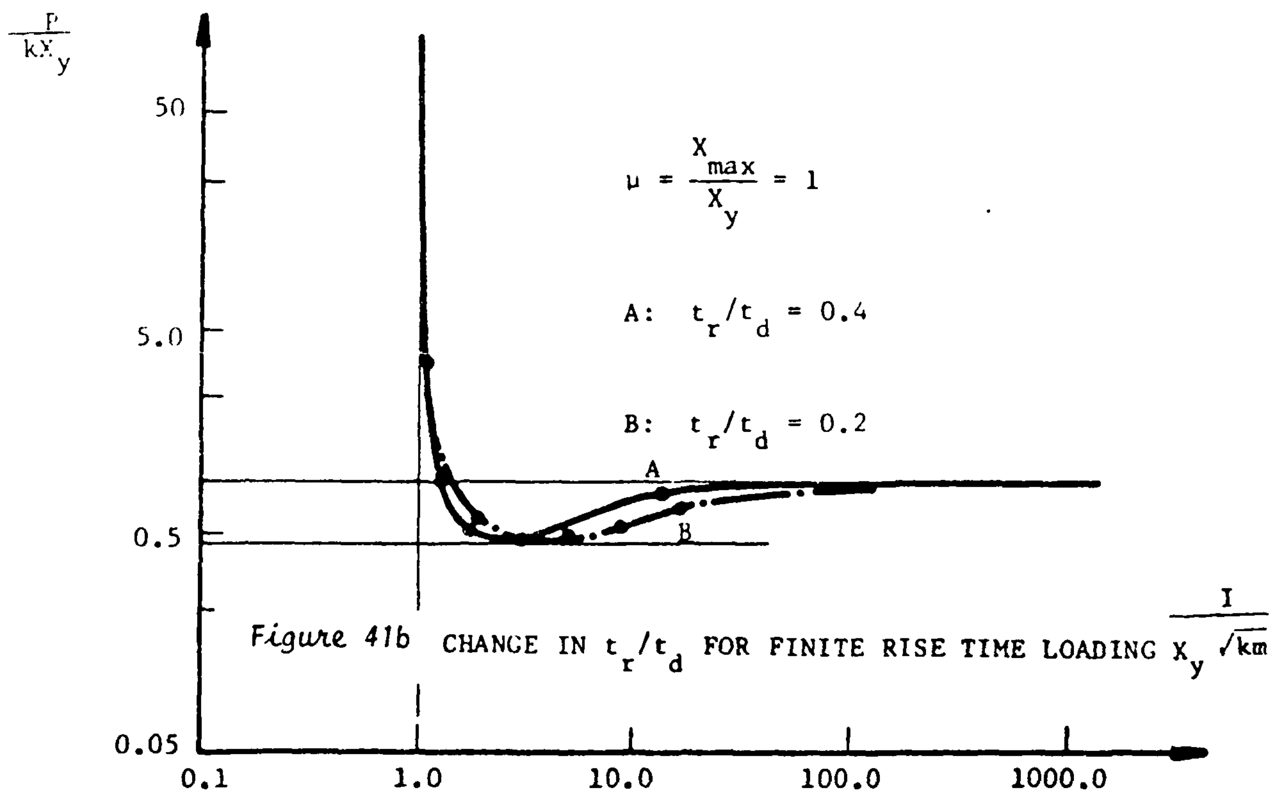
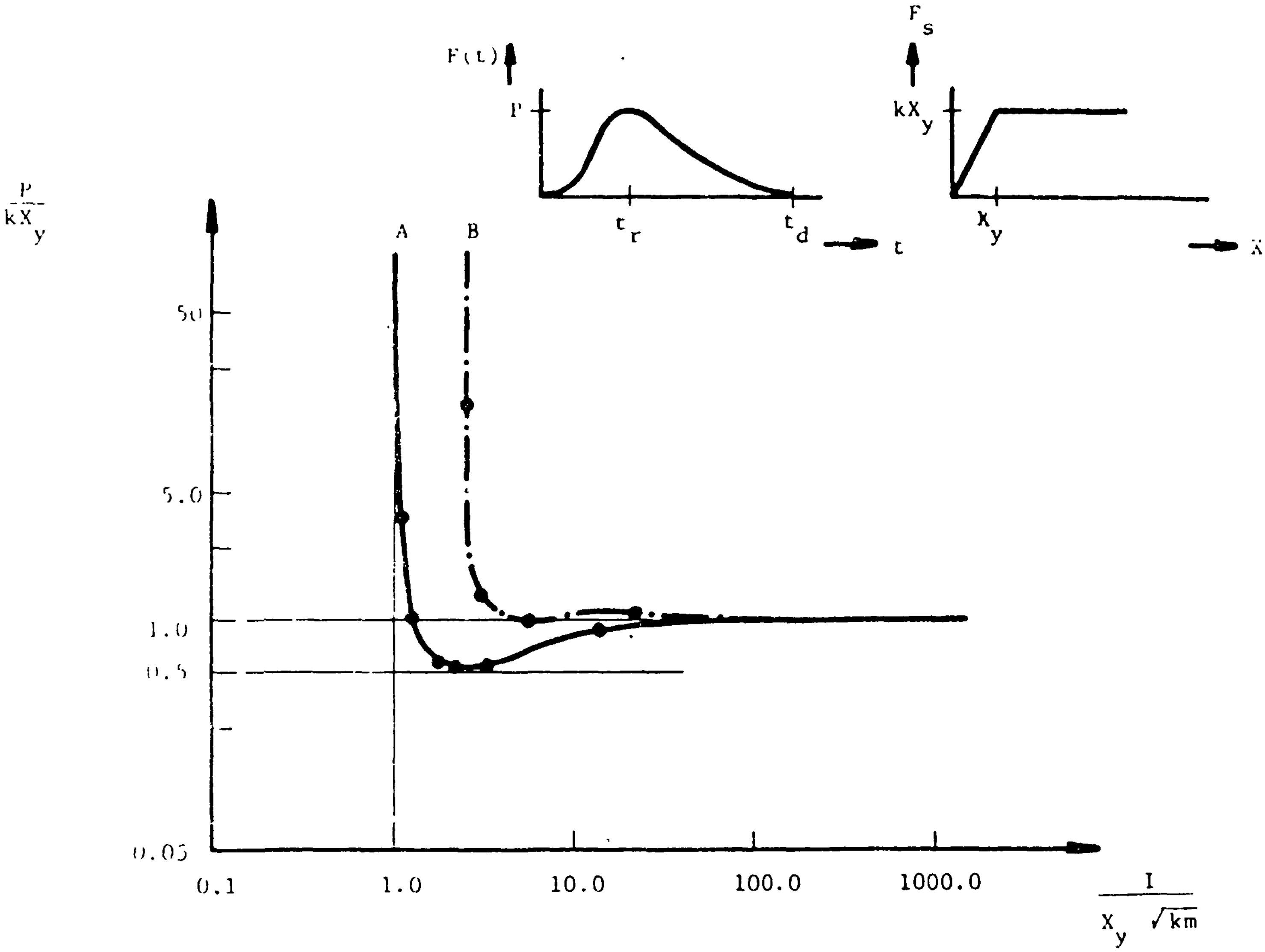


Figure 41b CHANGE IN t_r/t_d FOR FINITE RISE TIME LOADING



A: $(t_r/t_d) = 0.4, \ \mu = 1$

B: $(t_r/t_d) = 0.4, \ \mu = 3$

Figure 41c EFFECT OF PLASTICITY

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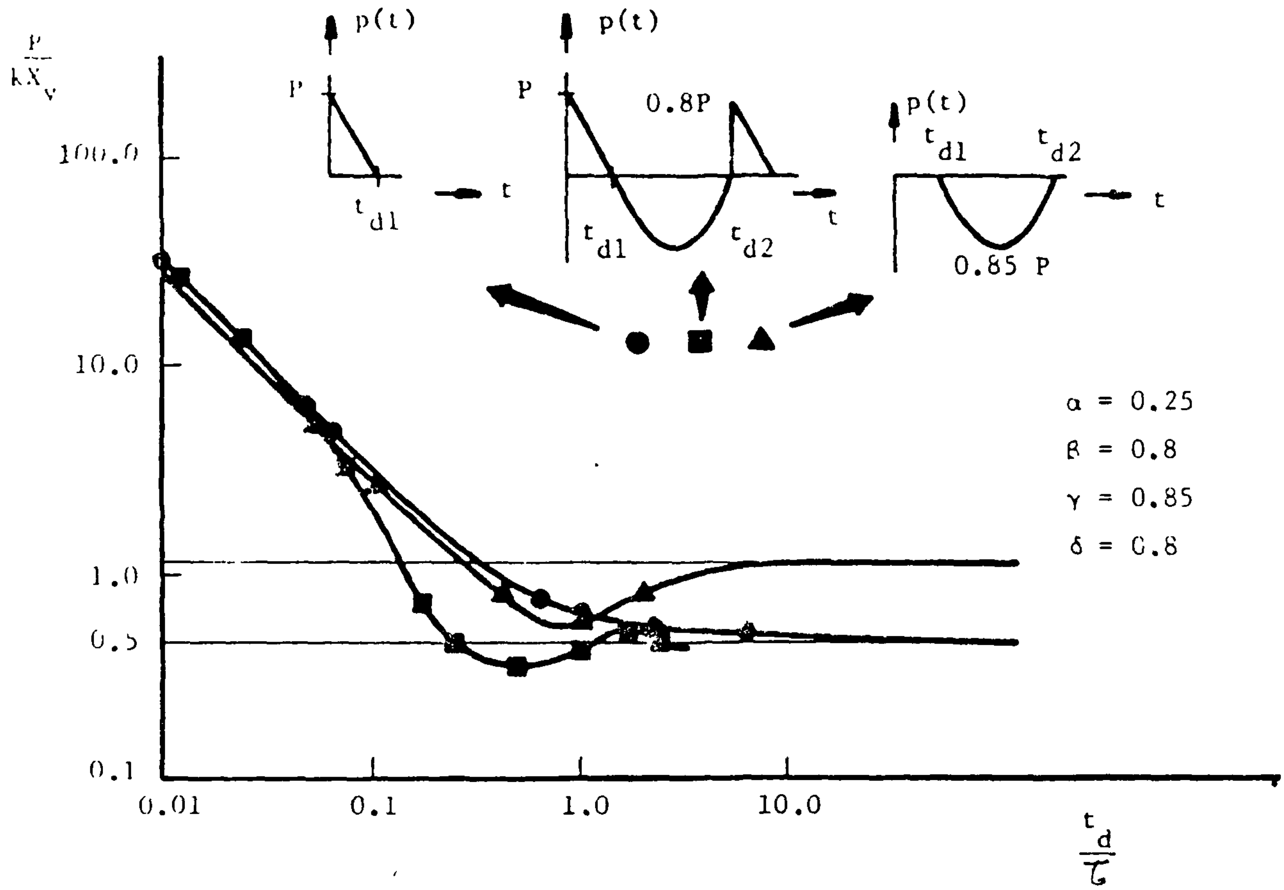
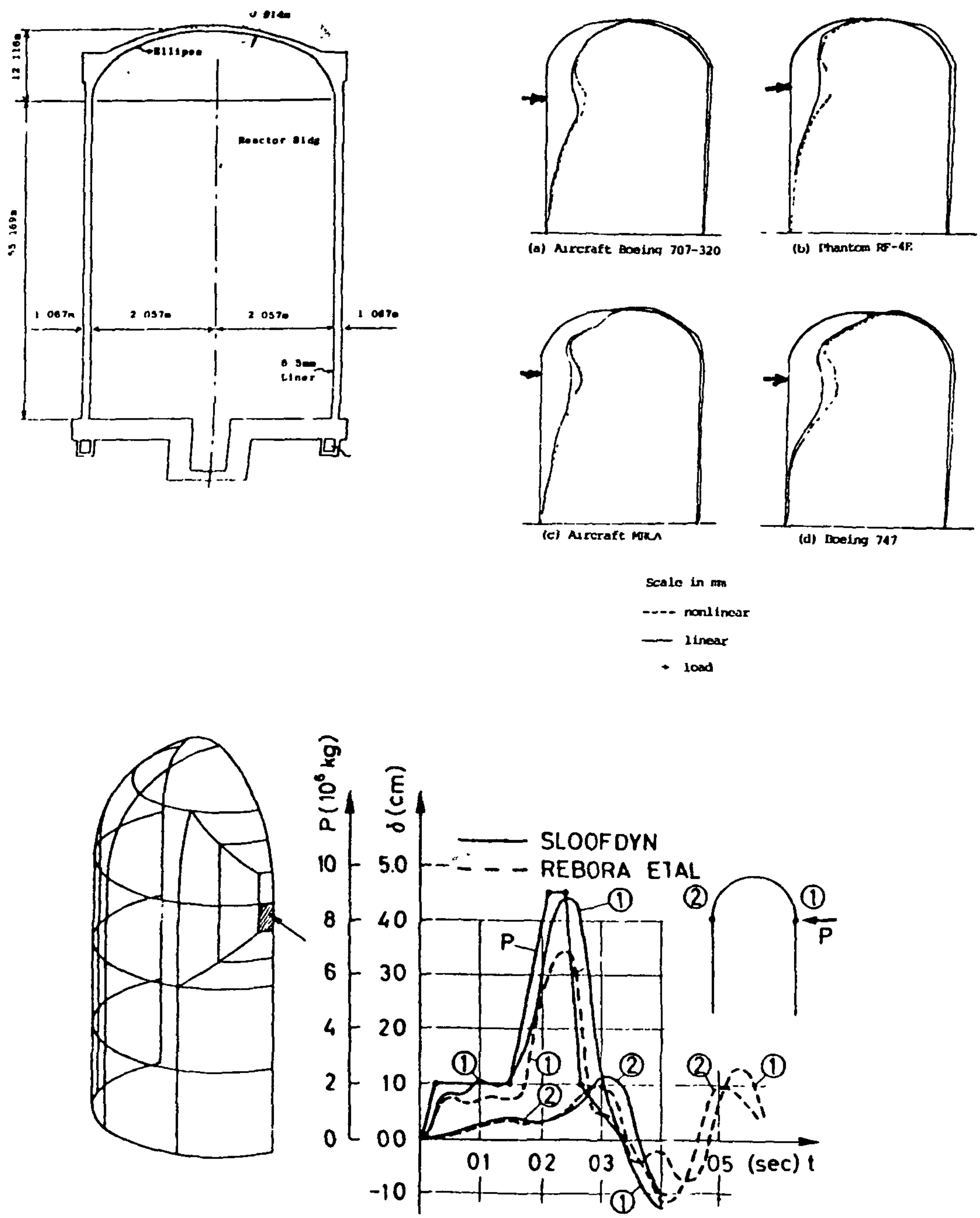


EFFECTS OF LOADING WHICH CHARACTERIZES A BURSTING VESSEL

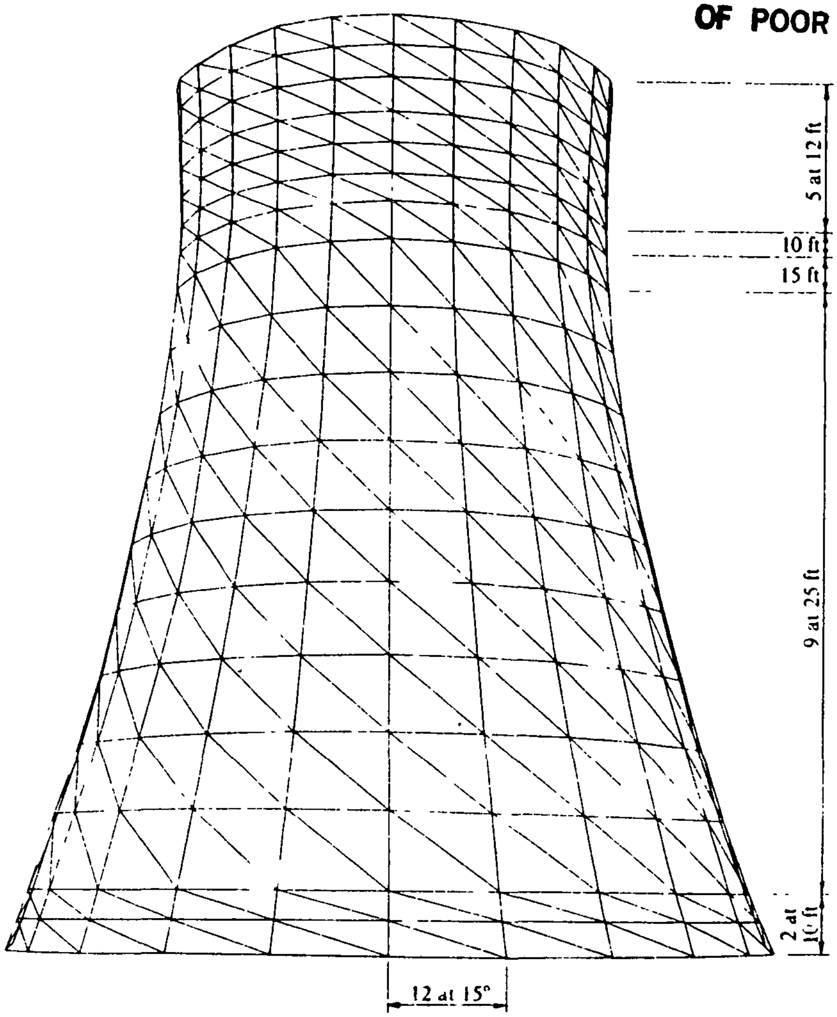
Figure 42



Mesh and Dynamic (Linear) Response of Reactor Containment Due to Aircraft Crash

Figure 43

(a)



(b)

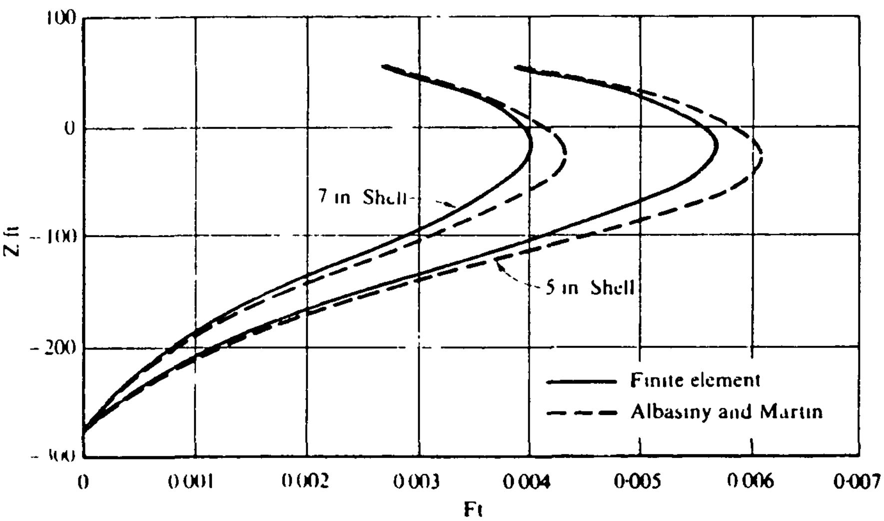


Figure 44 (a) Structural idealization by FE mesh
(b) Displacements from dynamic pressure

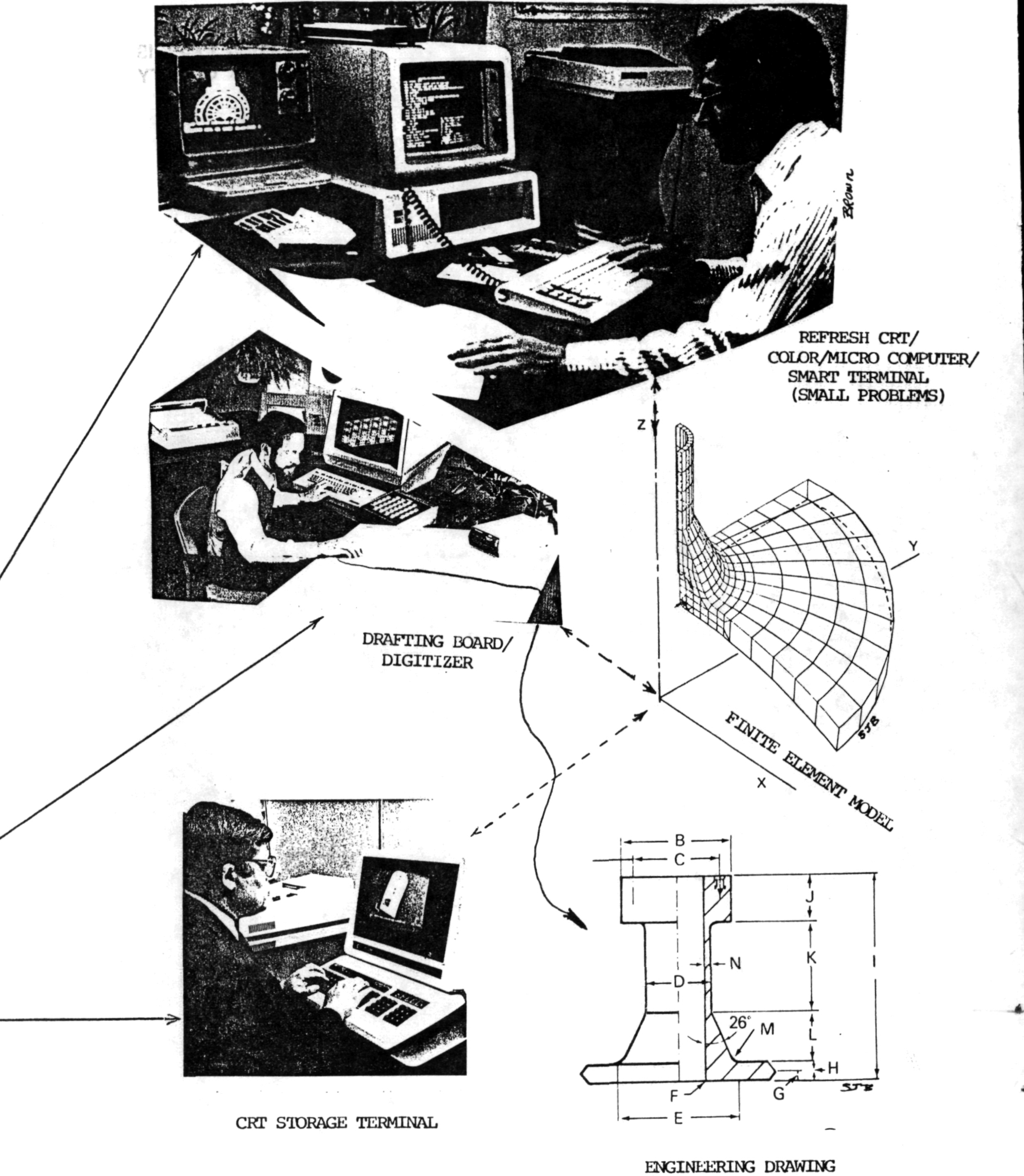
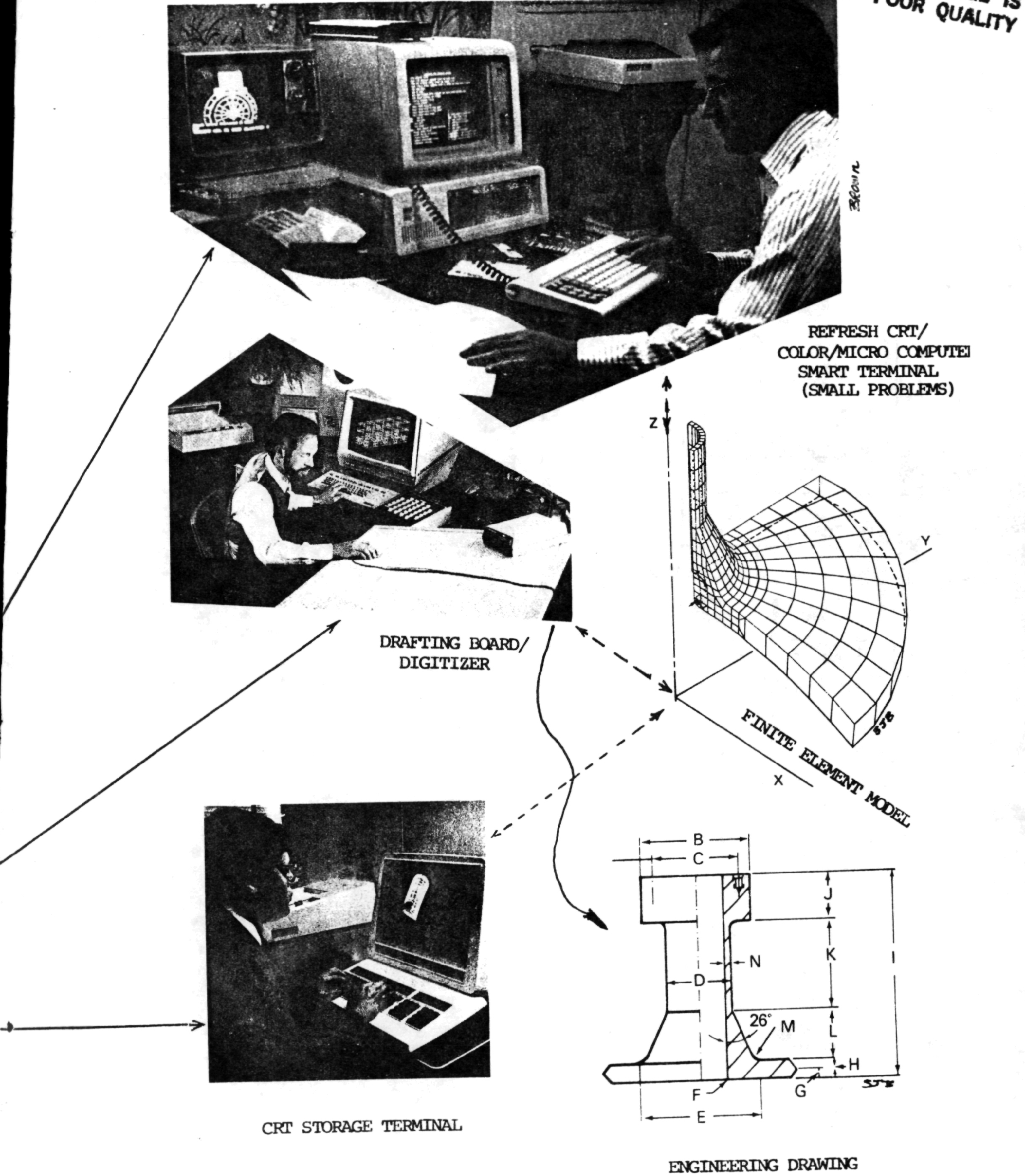

REFRESH CRT/
COLOR/MICRO COMPUTER/
SMART TERMINAL
(SMALL PROBLEMS)
DRAFTING BOARD/
DIGITIZER
Z
Y
X
FINITE ELEMENT MODEL
CRT STORAGE TERMINAL
B
C
J
K
N
D
I
26°
M
L
H
F
G
E
ENGINEERING DRAWING

Figure 45


REFRESH CRT/
COLOR/MICRO COMPUTE
SMART TERMINAL
(SMALL PROBLEMS)
DRAFTING BOARD/
DIGITIZER
FINITE ELEMENT MODEL
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CRT STORAGE TERMINAL
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ENGINEERING DRAWING

Figure 45

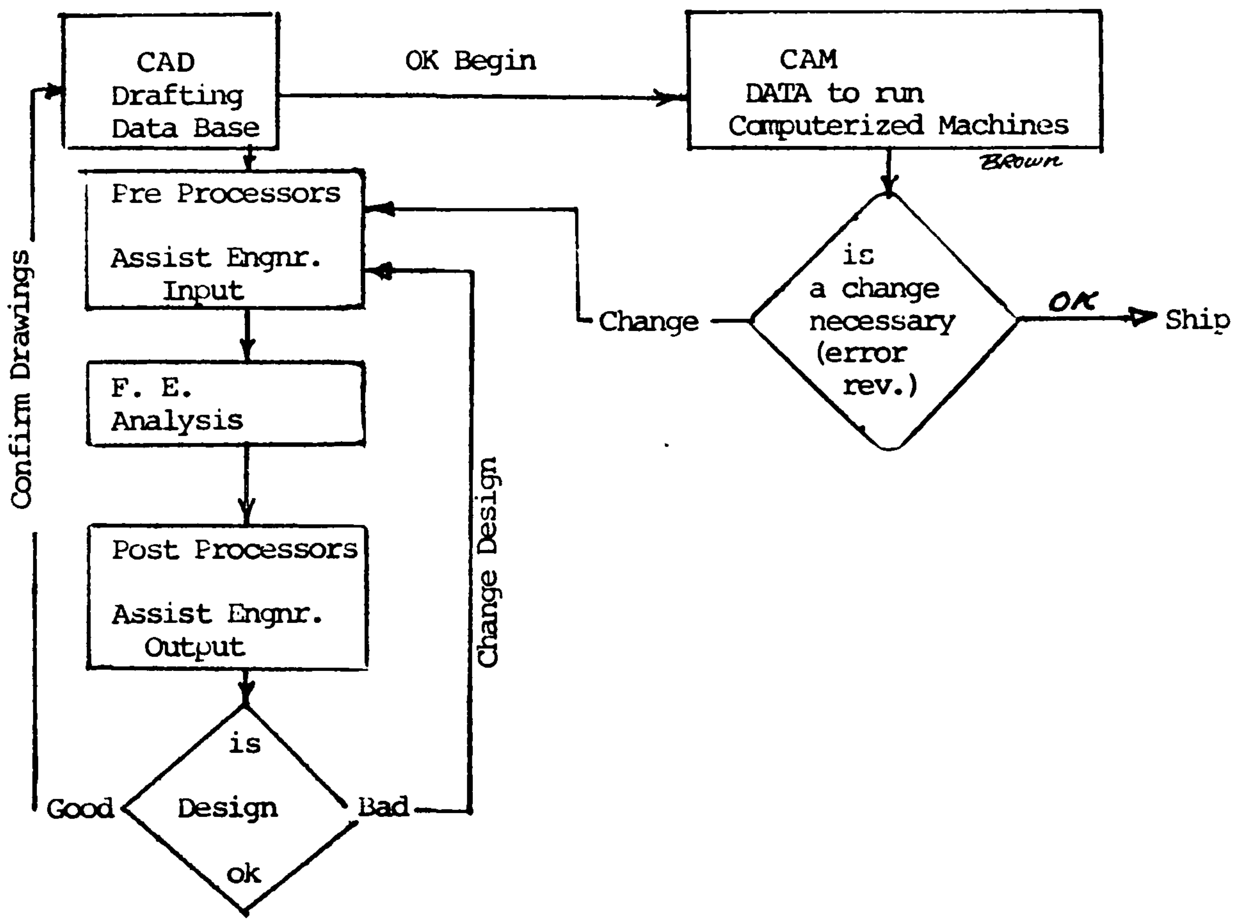

CAD
Drafting
Data Base
OK Begin
CAM
DATA to run
Computerized Machines
Brown
Pre Processors
Assist Engnr.
Input
F. E.
Analysis
Post Processors
Assist Engnr.
Output
is
Design
ok
Good
Bad
Confirm Drawings
Change Design
Change
is
a change
necessary
(error
rev.)
OK
Ship

Figure 46

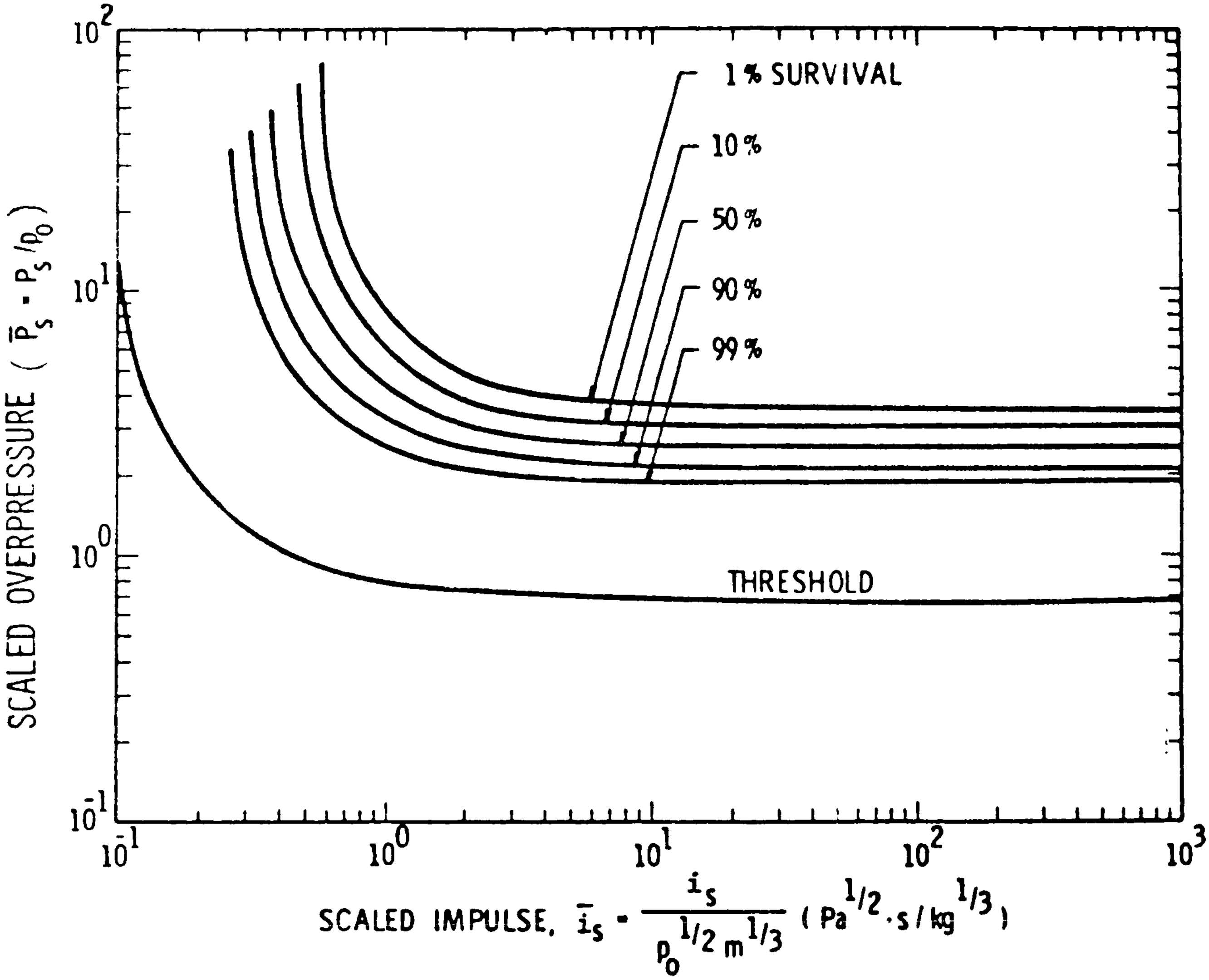


Figure 47. Survival Criteria Lung Damage to Man

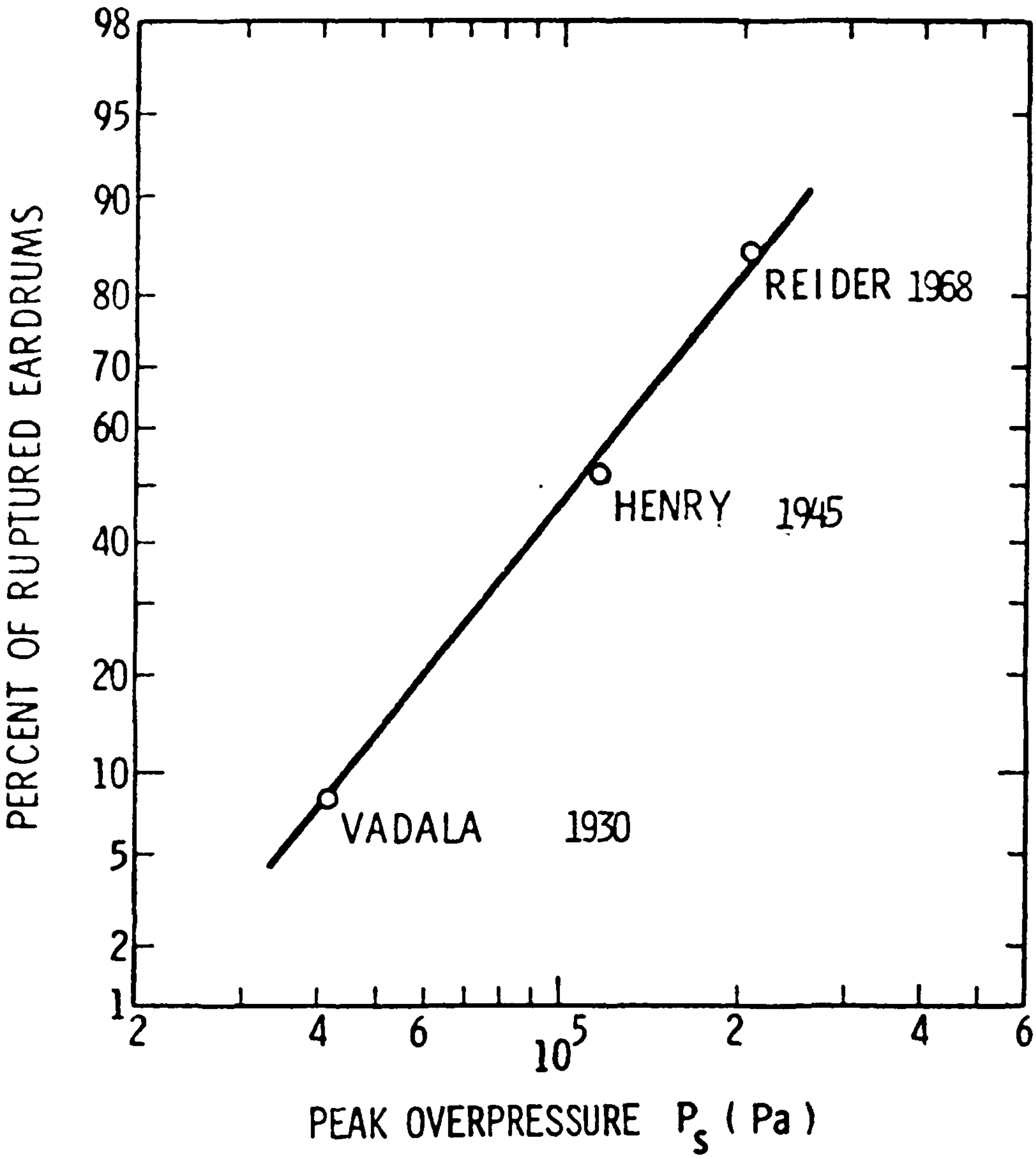


Figure 48. Percent Eardrum Rupture VS Overpressure

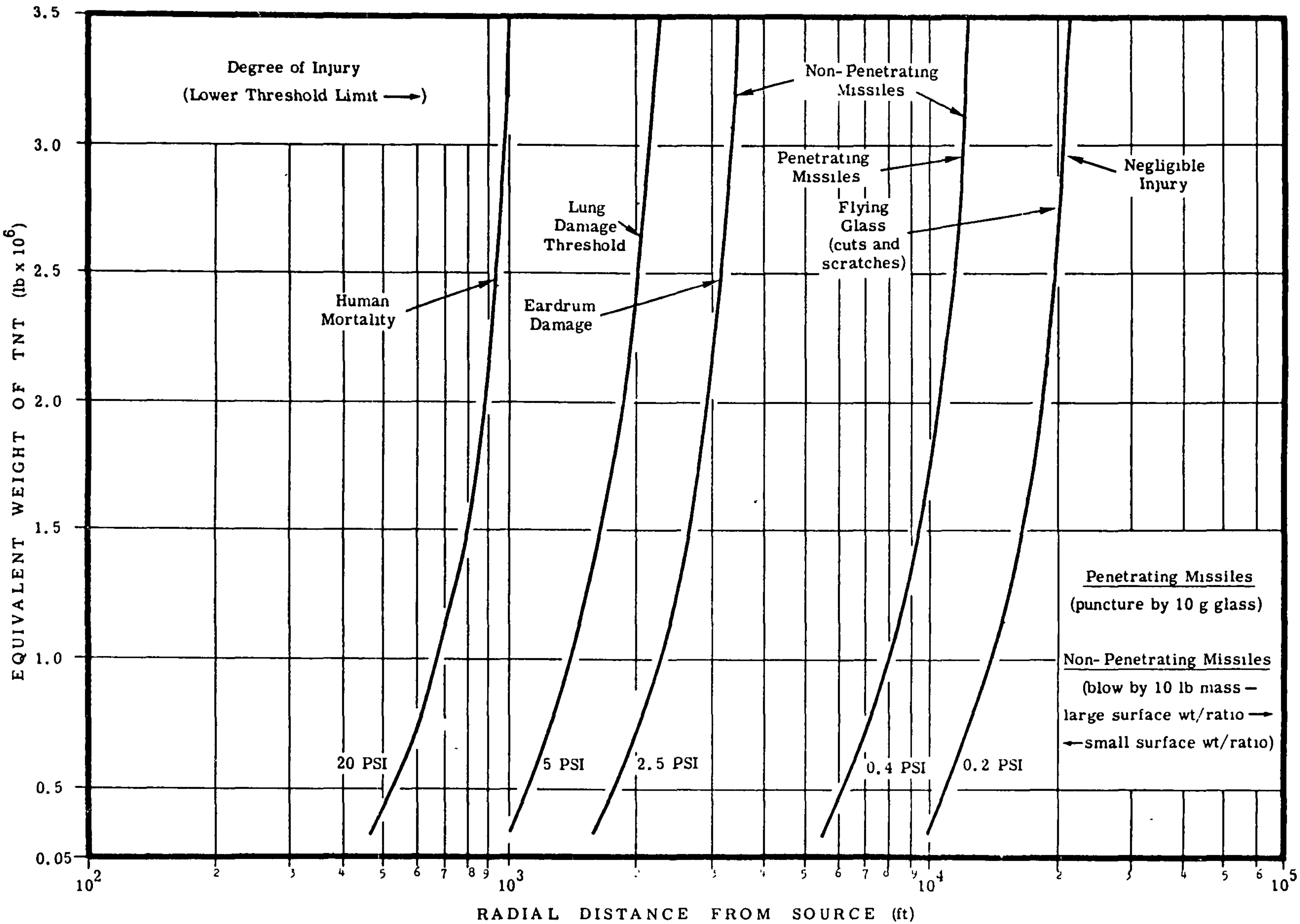


Figure 49. Overpressure Injury Criteria

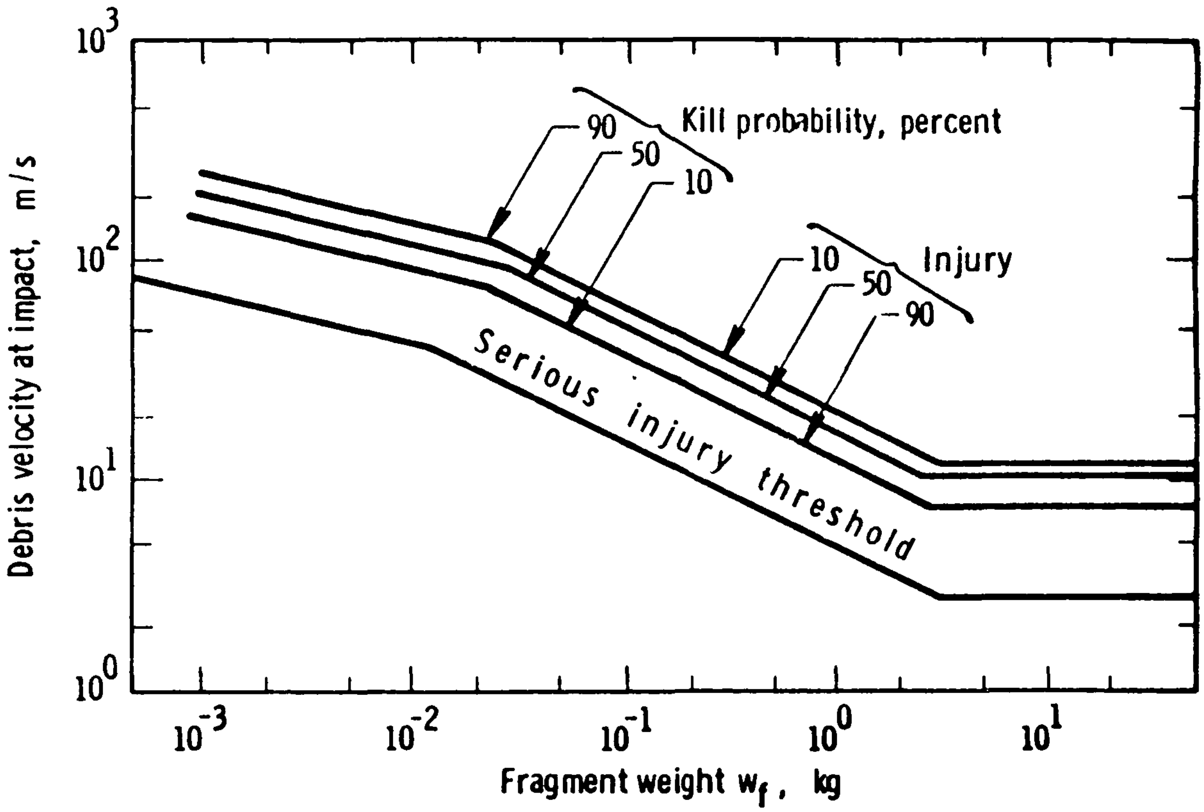


Figure 50. Personnel Response to Fragment Impact (abdomen & limbs)

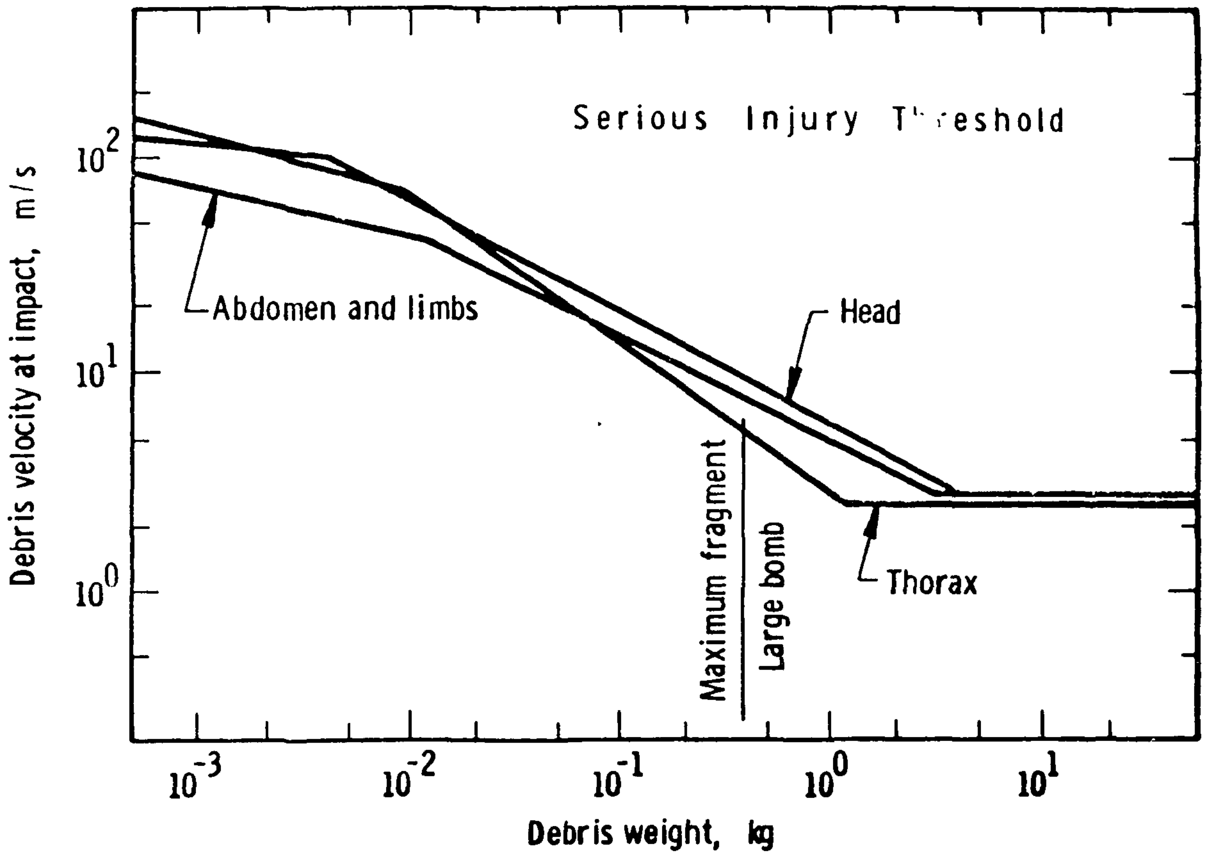


Figure 51. Personnel Response to Fragment Impact (Serious Injury Threshold)

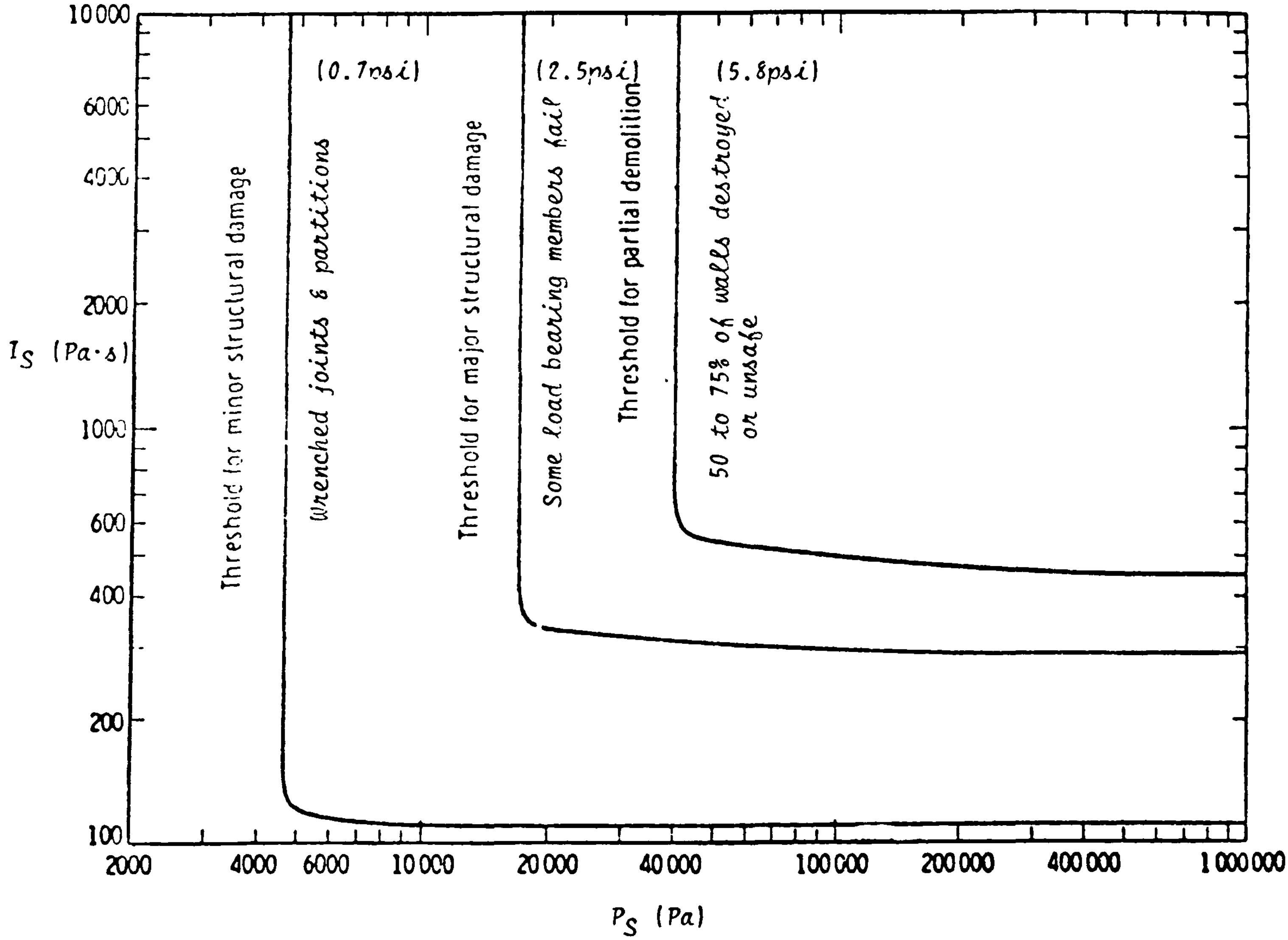
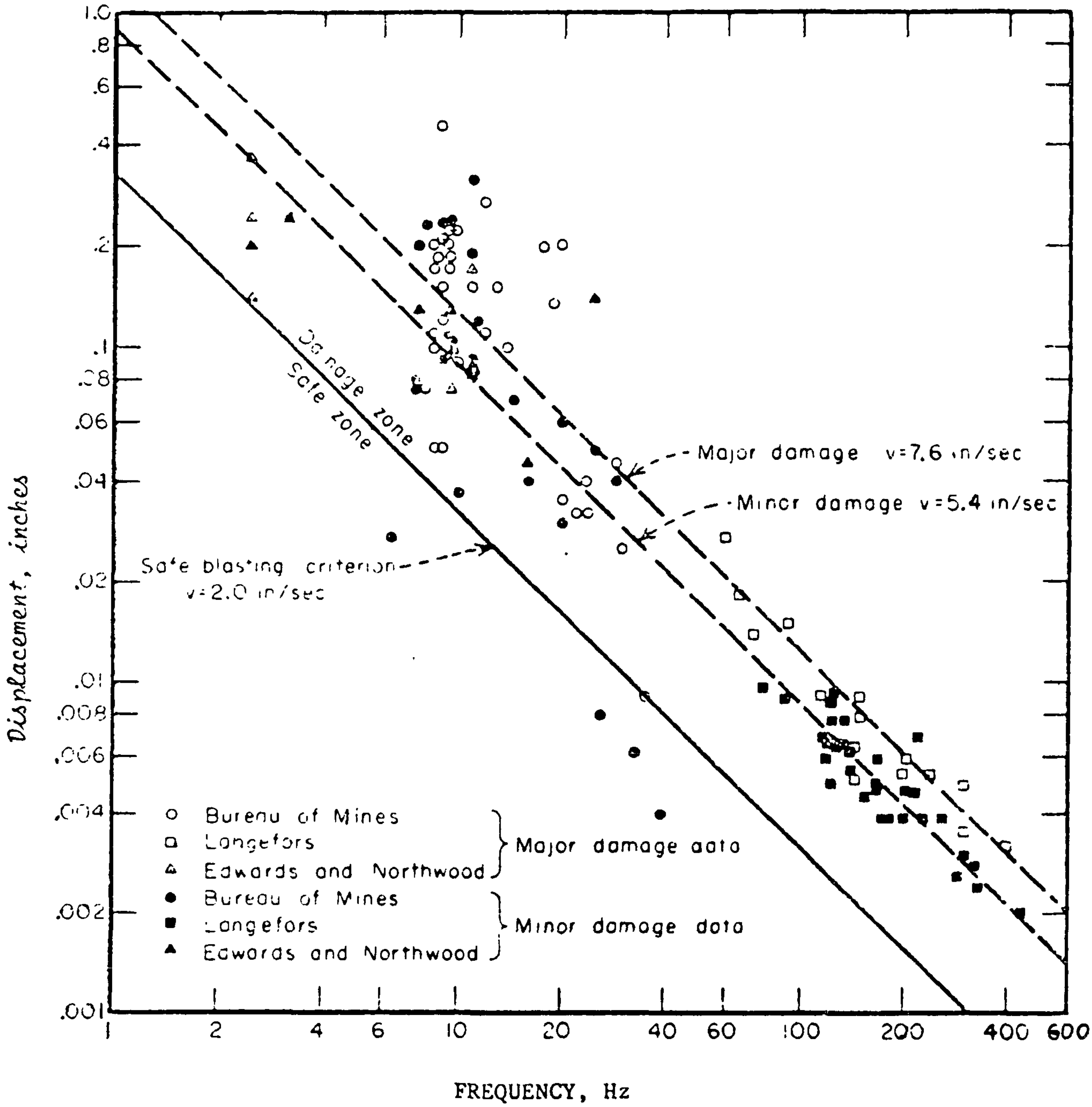
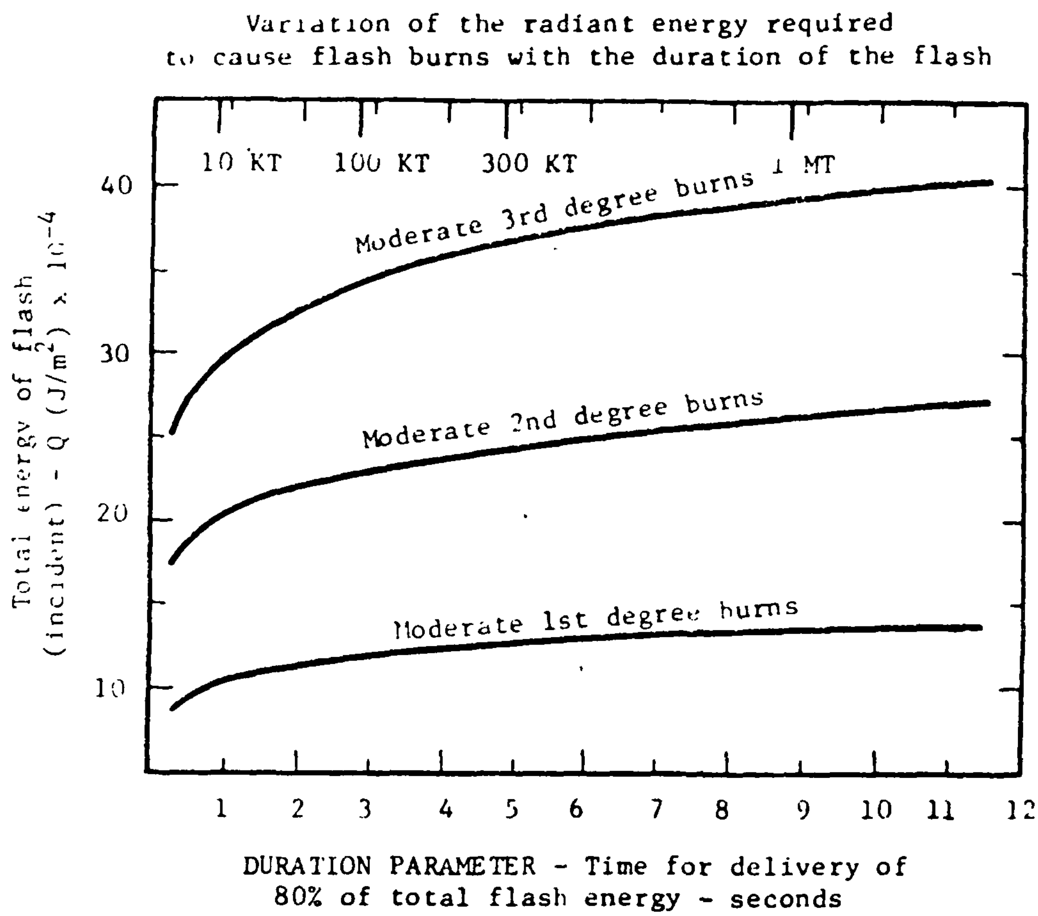


Figure 52. Pressure VS Impulse Diagram for Building Damage



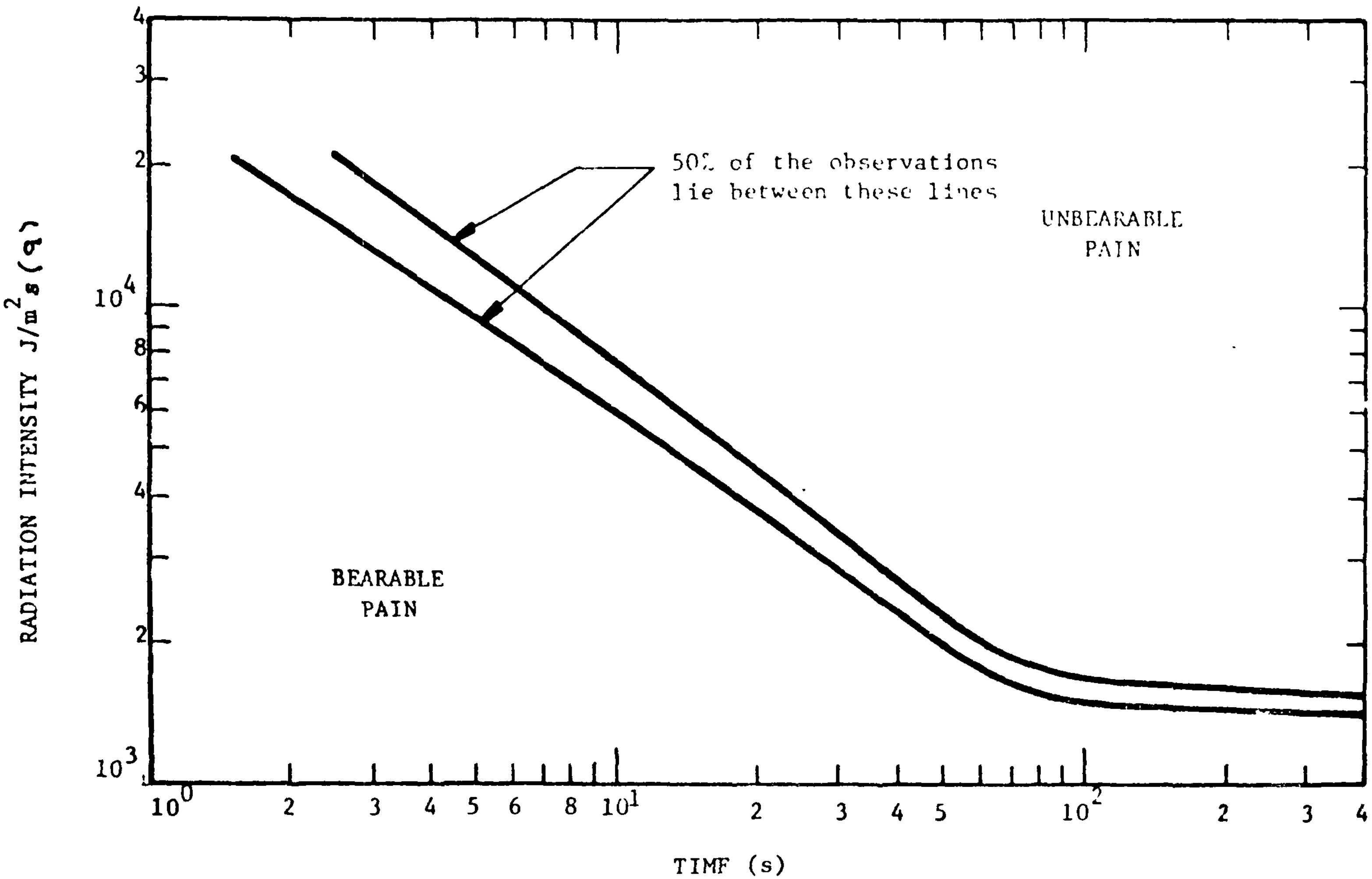
Displacement versus Frequency, Combined Data with Recommended Safe Blasting Criterion

Figure 53



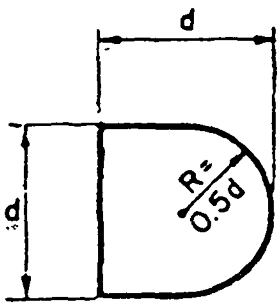
RADIANT ENERGY EXPOSURES FOR BURNS
[Jarrett (1968)]

Figure 54



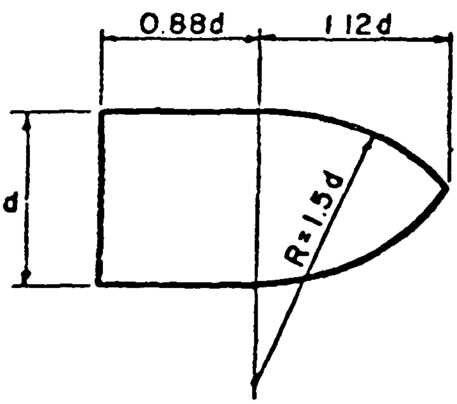
THRESHOLD OF PAIN FROM THERMAL RADIATION ON BARE SKIN
[Buettner (1950)]

Figure 55



$n = 0.5$
$N = 0.845$
$\text{Volume} = 0.654d^3$
$W_f = 0.186d^3$
$D = 0.186\ \text{lb/in.}^3$
$A = \pi d^2/4$

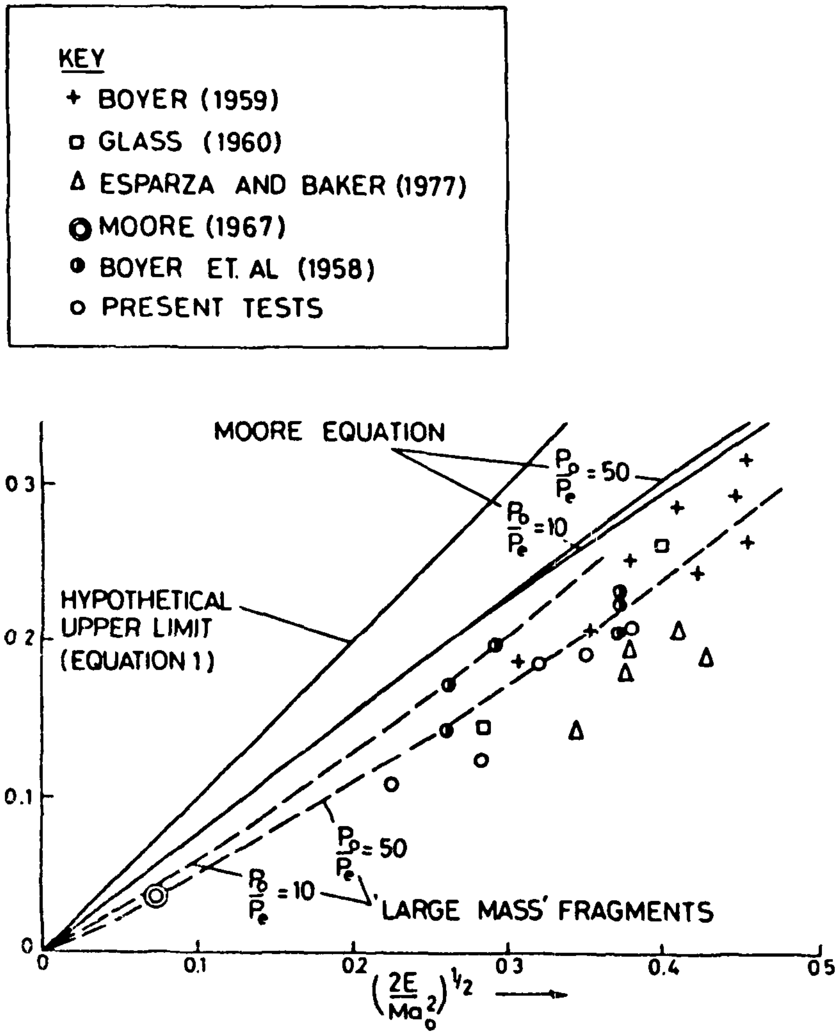
(a) Standard Fragment Shape



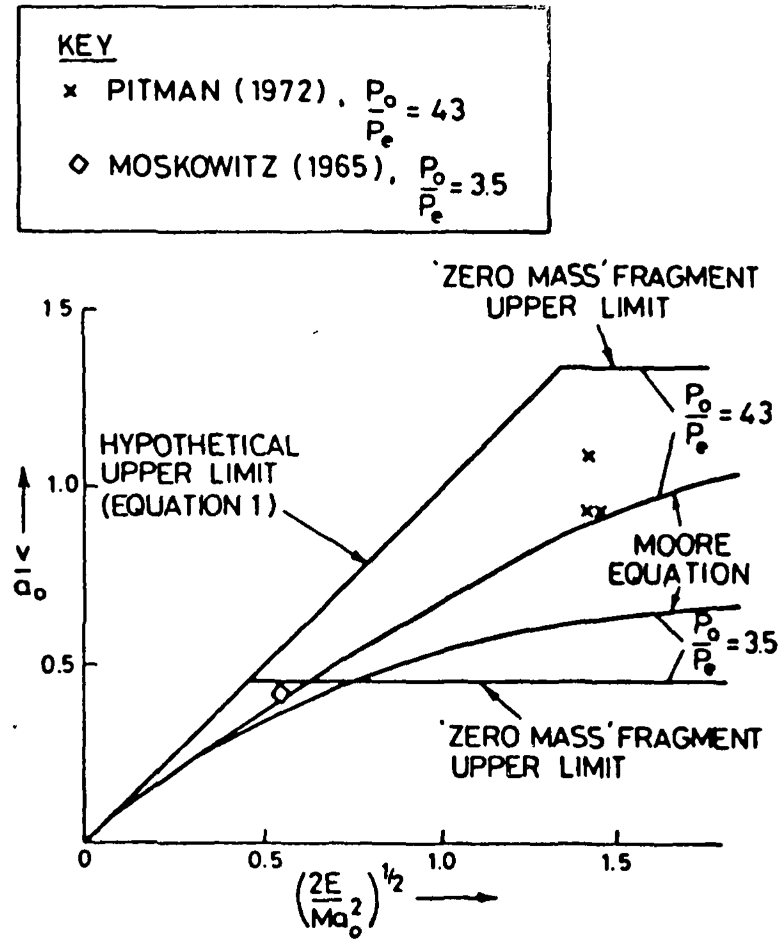
$n = 1.5$
$N = 1.00$
$\text{Volume} = 1.2d^3$
$W_f = 0.34d^3$
$D = 0.34\ \text{lb/in.}^3$
$A = \pi d^2/4$

(b) Alternate Fragment Shape

FIGURE 56 *Standard Military Fragment Shapes (From Baker (1978))*



SPHERICAL VESSEL DATA ($\gamma = 1.4$).



CYLINDRICAL VESSEL ($\gamma = 1.4$) BEYOND THE DESIGN RANGE.

FIGURE 57 *Fragment Velocity Plots for Spherical and Cylindrical Vessels (From Baum (1983))*

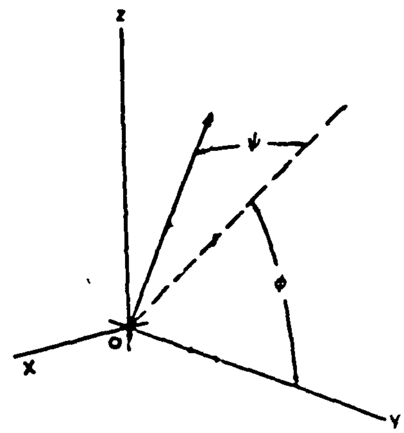


FIGURE 58 Definition of Ejection Angles

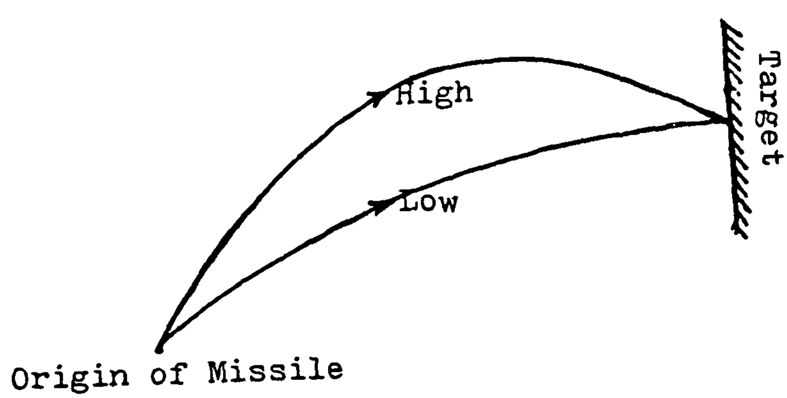
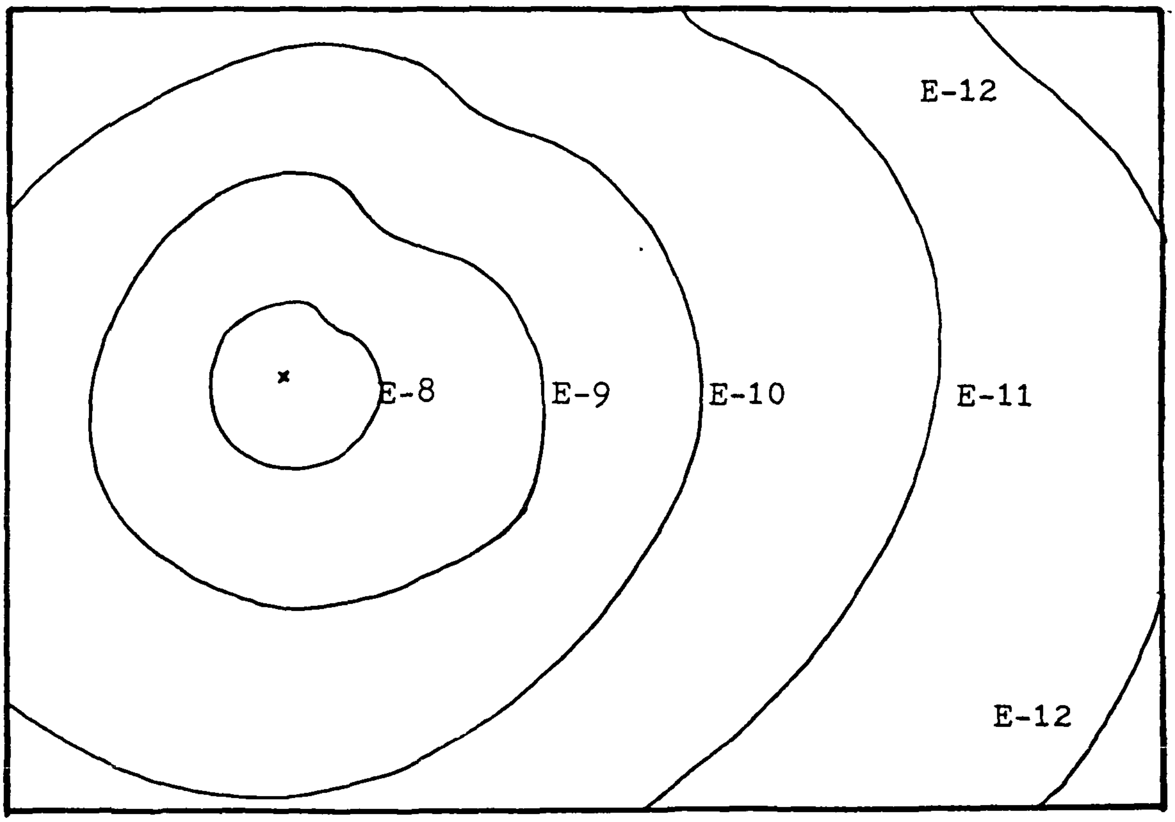


FIGURE 59 Low- and High-Trajectory Missiles



NOTE: E-8 means a strike-probability of 10^{-8} strikes per operating year per square foot.

FIGURE 60 Sample Missile-Strike-Probability Contour Map

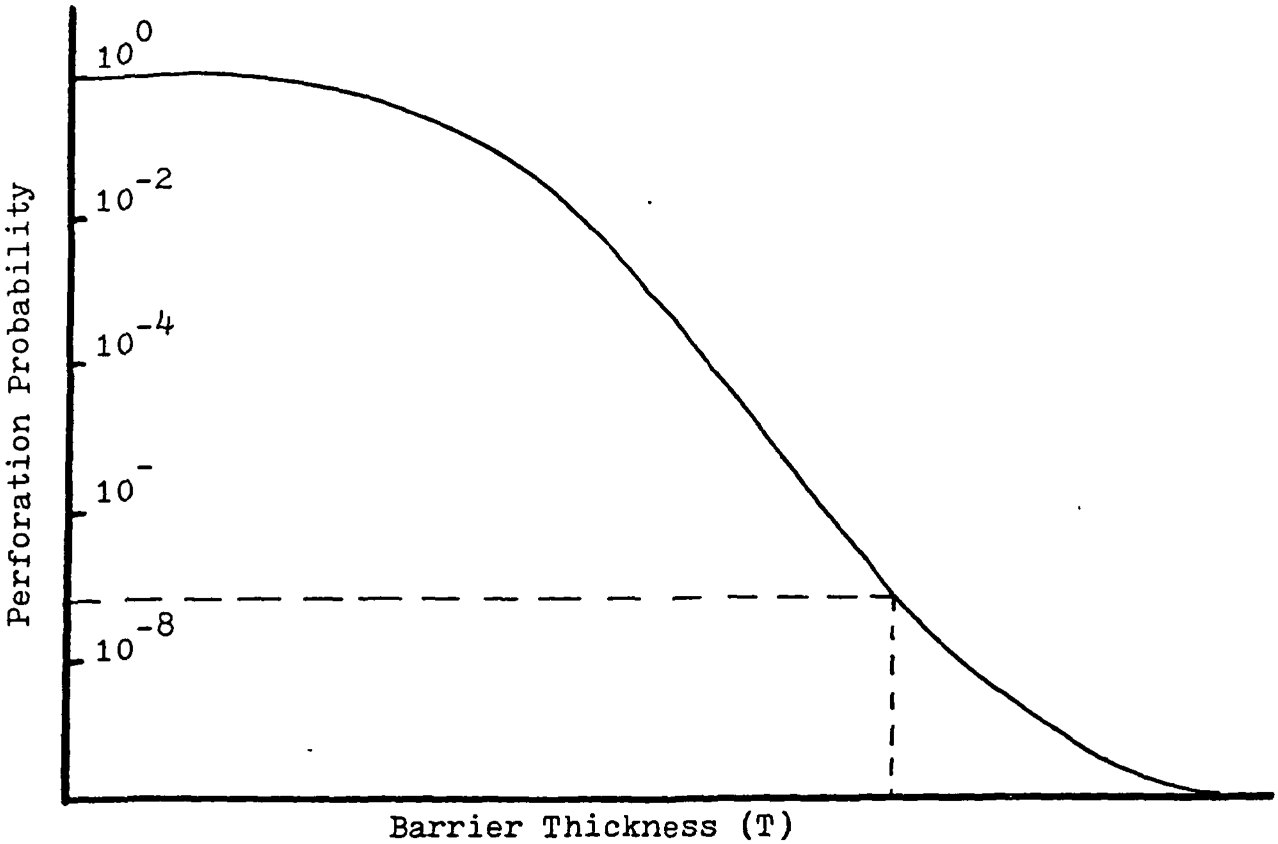


FIGURE 61 *Probability of Perforation vs. Barrier Thickness*

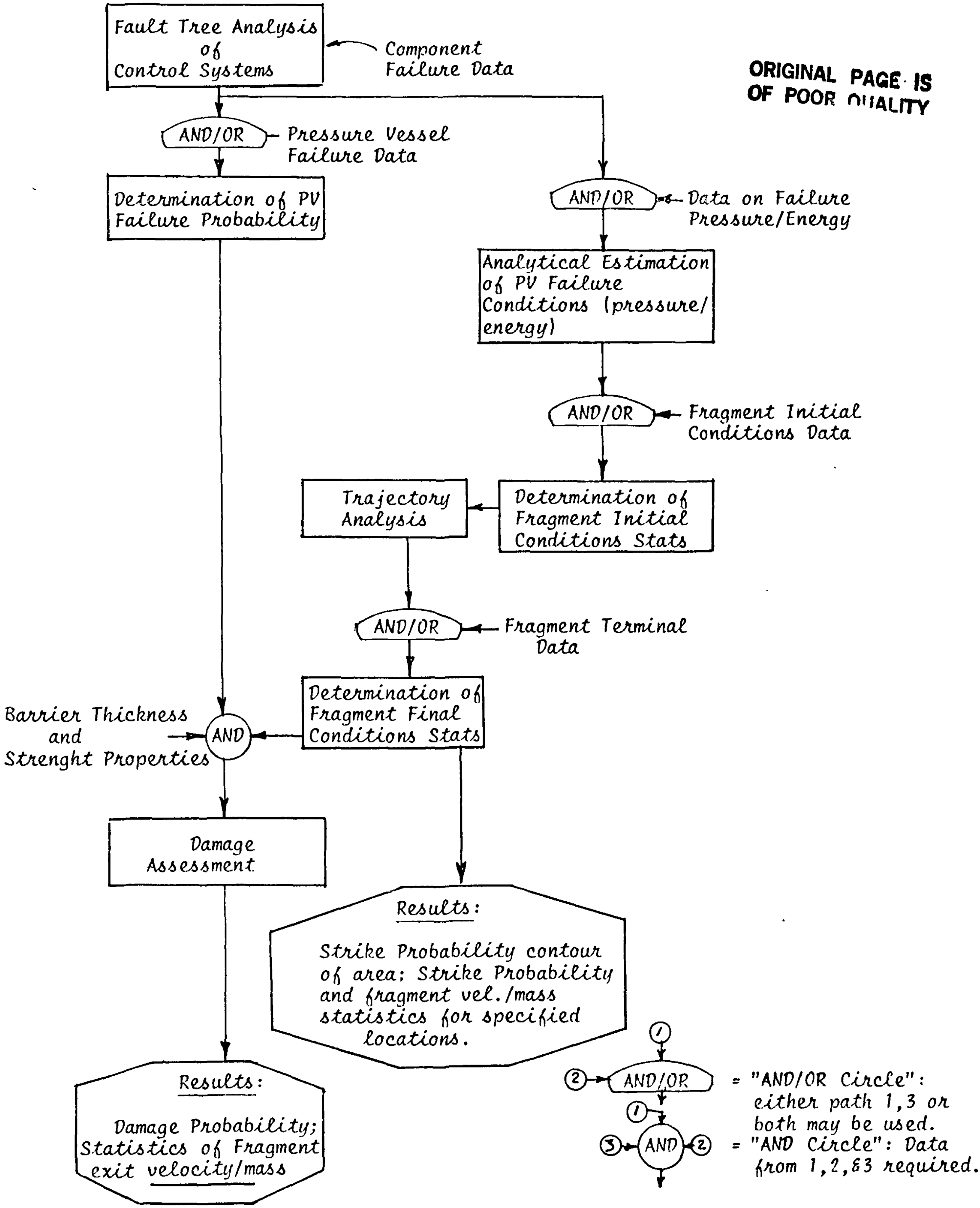


FIGURE 62 Flow-Diagram of Probabilistic Methodology

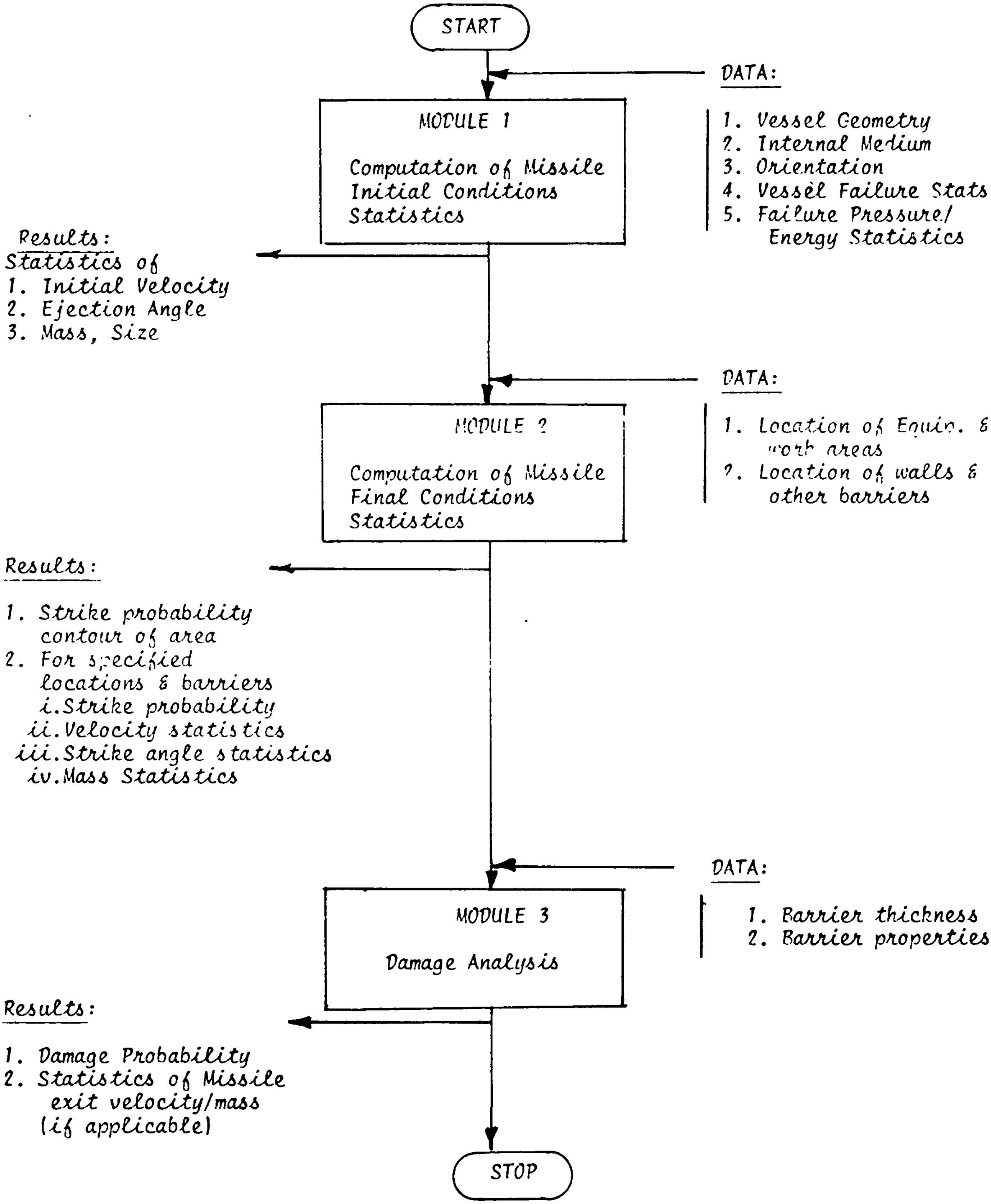
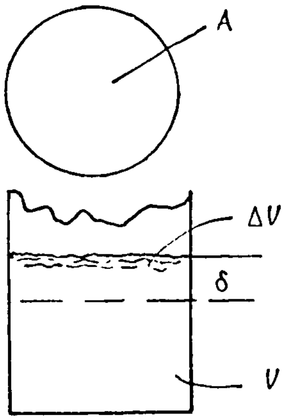


FIGURE 63 Modular Structure of Computer Program for the Probabilistic Approach



A = area (in.^{2}) of cylinder cross section

P = pressure (psi)

F - force = PA (lb)

V = volume of fluid (in.^{3})

ΔV = compressibility x volume = δA

δ = compression (in)

$K = \dfrac{F}{\delta}$: $P = \dfrac{\Delta V}{V} B$

E = energy in ft-lb.

B = bulk modulus

$$E = 1/2 \; P\Delta V \text{ in-\#} \qquad |a|$$

$$\text{TNT Equivalent} = \frac{P\Delta V}{24\ (1.426 \times 10^6)} \text{ lb of TNT} \qquad |b|$$

$$= \frac{P^2 V}{B\ 24\ (1.426 \times 10^6)} \text{ lb of TNT} \qquad |c|$$

Figure 64

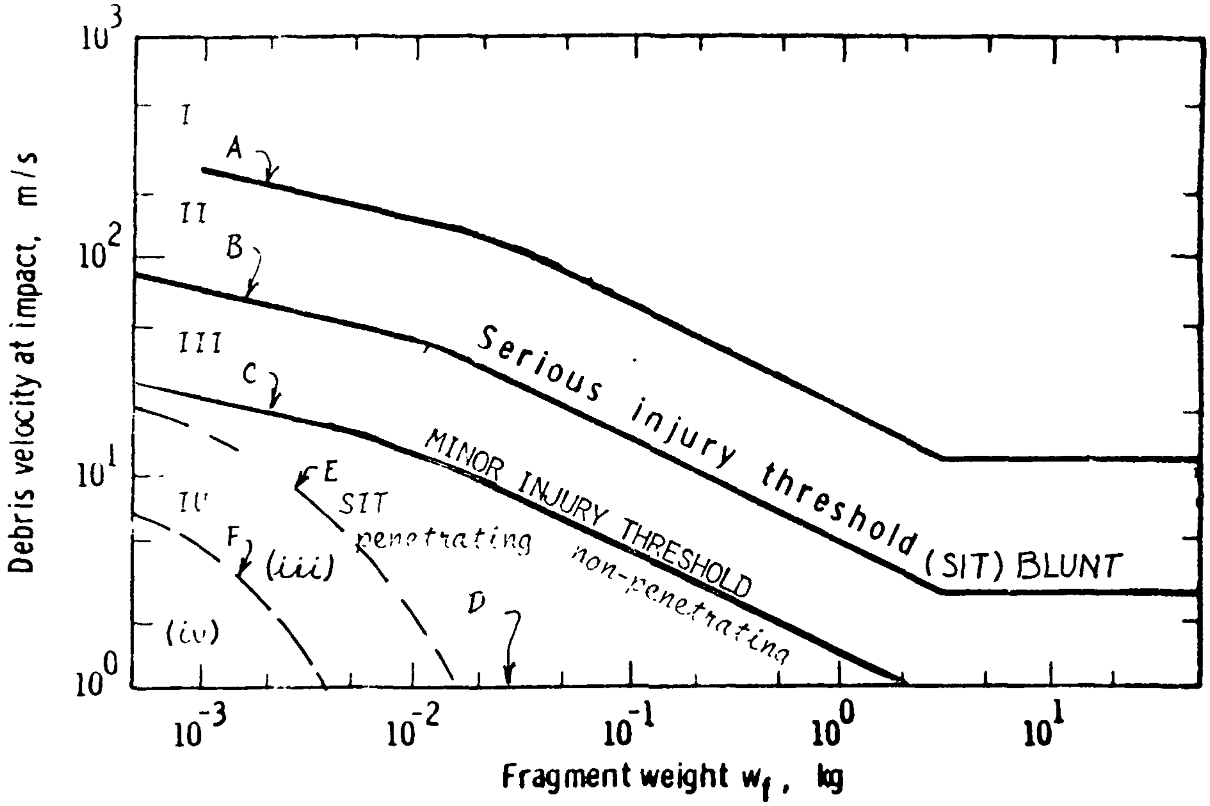


Figure 65 Personnel Response to Fragment Impact

Non-penetrating (—) & penetrating (---)

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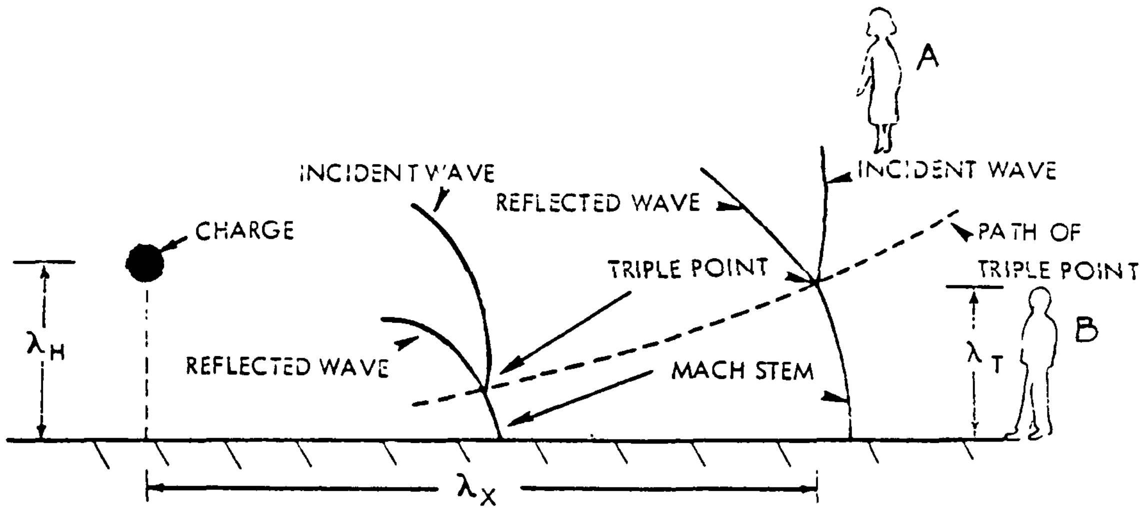

λ_X ≡ SCALED HORIZONTAL DISTANCE TO TRIPLE POINT (FT/(LBS TNT)$^{1/3}$)

λ_H ≡ SCALED CHARGE HEIGHT (FT/(LBS TNT)$^{1/3}$)

λ_T ≡ SCALED HEIGHT OF TRIPLE POINT (FT/(LBS TNT)$^{1/3}$)

Figure 66 TRIPLE POINT LOCI FOR A TNT CHARGE AT SEA LEVEL

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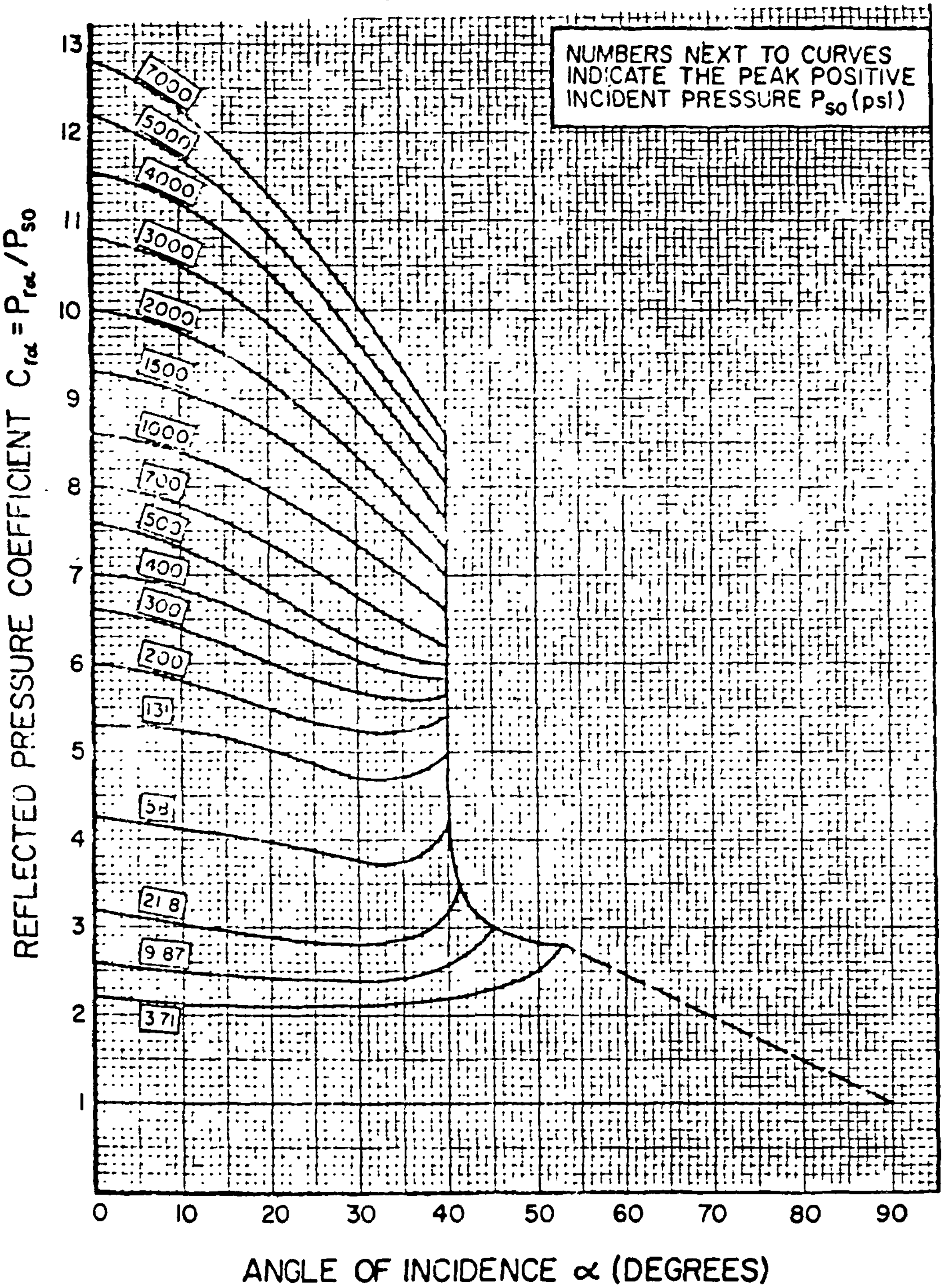
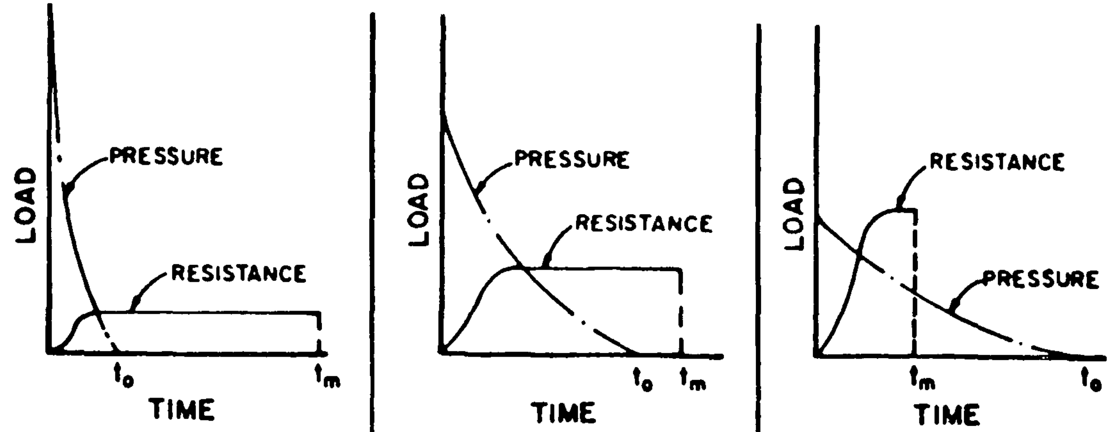


Figure 67 REFLECTED PRESSURE COEFFICIENT
VS ANGLE OF INCIDENCE



PRESSURE DESIGN RANGE	HIGH	INTERMEDIATE	LOW
DESIGN LOAD	IMPULSE	PRESSURE-TIME	PRESSURE
PRESSURE LEVEL	$\gg$ 200 psi	$<$200psi	$<$ 10 psi
PRESSURE DURATION	SHORT	INTERMEDIATE	LONG
RESPONSE TIME	LONG	INTERMEDIATE	SHORT
RELATIONSHIP OF t_m/t_o	$t_m/t_o > 3$	$3 > t_m/t_o > 0.1$	$t_m/t_o < 0.1$

FIGURE 68. Parameters Defining Pressure Design Ranges

Standard Bibliographic Page

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7. Author(s) Samuel J. Brown		8. Performing Organization Report No. J114
9. Performing Organization Name and Address QED (Quest Engineering Development) Corp. P. O. Box 1275 Crosby, TX 77532		10. Work Unit No.
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12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, DC 20546		13. Type of Report and Period Covered Contractor Report
		14. Sponsoring Agency Code 323-53-03
15. Supplementary Notes Langley Technical Monitor: Dr. J. R. (Randy) Rooker Final Report		

16. Abstract

This report provides (1) a survey of studies into hazards associated with closed or pressurized system rupture and (2) preliminary guidelines for the performance design of primary, secondary, and protective receptors of these hazards. The hazards discussed in the survey are: blast, fragments, ground motion, heat, radiation, biological, & chemical. The part of the report that addresses performance guidelines for receptors is limited to pressurized systems that contain inert gas. The performance guidelines for protection against the remaining unaddressed degenerative hazards are to be covered in another study.

17. Key Words (Suggested by Authors(s))	18. Distribution Statement
Hazards Protection, Blast, Missiles, Barricading	Unclassified - Unlimited Subject Category 37

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