SPECIAL PUBLICATION ARLCD-SP-84001

STRUCTURES TO RESIST THE EFFECTS OF ACCIDENTAL EXPLOSIONS
VOLUME 1 - INTRODUCTION

NORVAL DOBBS

AMMANN & WHITNEY
96 MORTON STREET
NEW YORK, NY 10014

JOSEPH P. CALTAGIRONE
PROJECT ENGINEER
ARDEC

DECEMBER 1987

U. S. ARMY ARMAMENT RESEARCH, DEVELOPMENT AND ENGINEERING CENTER

ARMAMENT ENGINEERING DIRECTORATE

PICATINNY ARSENAL, NEW JERSEY

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION UNCLASSIFIED	1b. RESTRICTIVE MARKINGS
2a. SECURITY CLASSIFICATION AUTHORITY	3. DISTRIBUTION/AVAILABILITY OF REPORT Approved for public release; distribution unlimited.
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE	
4. PERFORMING ORGANIZATION REPORT NUMBER(S)	5. MONITORING ORGANIZATION REPORT NUMBER(S) Special Publication ARLCD-SP-84001
6a. NAME OF PERFORMING ORGANIZATION Ammann & Whitney; 6b. OFFICE SYMBOL (If applicable)	7a. NAME OF MONITORING ORGANIZATION ARDEC, AED Energetic Systems Process Div (SMCAR-AES-M)
6c. ADDRESS (City, State, and ZIP Code) 96 Morton Street New York, NY 10014	7b. ADDRESS (City, State, and ZIP Code) Picatinny Arsenal, NJ 07806-5000
8a. NAME OF FUNDING/SPONSORING ORGANIZATION ARDEC, IMD STINFO Br; 8b. OFFICE SYMBOL (If applicable) SMCAR-IMI-I	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER DAAK10-82-C-0112
8c. ADDRESS (City, State, and ZIP Code) Picatinny Arsenal, NJ 07806-5000	10. SOURCE OF FUNDING NUMBERS: PROGRAM ELEMENT NO. / PROJECT NO. / TASK NO. / WORK UNIT ACCESSION NO.

11. TITLE (Include Security Classification) Structures to Resist the Effects of Accidental Explosions, Volume I - Introduction

12. PERSONAL AUTHOR(S) Norval Dobbs, Ammann & Whitney; Joseph P. Caltagirone, ARDEC, Project Engineer

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Year, Month, Day)	15. PAGE COUNT
	FROM Dec 86 TO Oct 87	December 1987	55

16. SUPPLEMENTARY NOTATION

17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB-GROUP	Blast-resistant design; Explosion effects; Protective structures; Donor/acceptor structures

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

This report serves as an introductory manual to previously published reports which present methods of design for protective construction used in facilities for development, testing, production, maintenance, modification, inspection, disposal and storage of explosive materials. This volume contains the safety factor and accuracy to be used with the various design procedures presented in the manual. Also presented is the qualitative description of an explosion protection system, acceptor system tolerance, and the basis for structural design.

DTIC COPY INSPECTED

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT ☐ UNCLASSIFIED/UNLIMITED ☒ SAME AS RPT. ☐ DTIC USERS	21. ABSTRACT SECURITY CLASSIFICATION UNCLASSIFIED
22a. NAME OF RESPONSIBLE INDIVIDUAL I. HAZNEDARI	22b. TELEPHONE (Include Area Code) (201)724-3316; 22c. OFFICE SYMBOL SMCAR-IMI-I

DD FORM 1473, 84 MAR — 83 APR edition may be used until exhausted. All other editions are obsolete.

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE

Availability Codes

Dist	Avail and/or Special
A-1	

18. SUBJECT TERMS (cont)

Blast pressures
Human tolerance
Fragments
Safe separation distance
Shelters
Barriers
Barriers
Blast environments
Blast effects

TABLE OF CONTENTS

INTRODUCTION

VOLUME CONTENTS

SAFETY FACTOR

EXPLOSION PROTECTION SYSTEM

ACCEPTOR SYSTEMS TOLERANCE

TABLE OF CONTENTS (Continued)

LIST OF FIGURES

LIST OF TABLES

TABLES

VOLUME I
INTRODUCTION

INTRODUCTION

1-1 Purpose

The purpose of this six volume manual is to present methods of design for protective construction used in facilities for development, testing, production, maintenance, modification, inspection, disposal and storage of explosive materials.

1-2 Objective

The primary objectives are to establish design procedures and construction techniques whereby propagation of explosion (from one building or part of a building to another) or mass detonation can be prevented and protection for personnel and valuable equipment will be provided.

The secondary objectives are:

(1) Establish the blast load parameters required for design of protective structures;

(2) Provide methods for calculating the dynamic response of structural elements including reinforced concrete, structural steel, etc.;

(3) Establish construction details and procedures necessary to afford the required strength to resist the applied blast loads;

(4) Establish guidelines for siting explosive facilities to obtain maximum cost effectiveness in both the planning and structural arrangements; providing closures, and preventing damage to interior portions of structures due to structural motion, shock, and fragment perforation.

1-3 Background

For the first 60 years of the 20th Century, criteria and methods based upon the results of the catastrophic events have been used for the design of explosive facilities. The criteria and methods did not include a detailed or reliable quantitative basis for assessing the degree of protection afforded by the protective facility. In the late 1960's quantitative procedures were set forth in the first edition of the present manual, "Structures to Resist the Effects of Accidental Explosions". This manual was based on extensive research and development programs which permitted a more reliable approach to current and future design requirements. Since the original publication of this manual, more extensive testing and development programs have taken place. This additional research was directed primarily towards materials other than reinforced concrete which was the principal construction material referenced in the initial version of the manual.
Many exotic chemicals, fuels, propellants, etc., required less space for a given quantity of explosive material than was previously needed. Such concentration of explosives increases the possibility of the propagation of accidental explosions (one accidental explosion causing the detonation of other explosive materials). It is evident that a

requirement for more accurate design techniques has become essential. This manual describes rational design methods to provide the required structural protection.

These design methods account for the close-in effects of a detonation including associated high pressures and nonuniformity of the blast loading on protective structures or barriers as well as intermediate and far-range effects which are encountered in the design of structures which are positioned away from the explosion. The dynamic response of structures, constructed of various materials, or combination of materials, can be calculated, and details have been developed to provide the properties necessary to supply the required strength and ductility specified by the design. Development of these procedures has been directed primarily towards analyses of protective structures subjected to the effects of high explosive detonation. However, this approach is general and can be applicable to the design of other explosive environments as well as other explosive materials as enumerated above.

The design techniques set forth in this manual are based upon the results of numerous full- and small-scale structural response and explosive effects tests of various materials conducted in conjunction with the development of this manual and/or related projects.

1-4 Scope of Manual

This manual is limited only by variety and range of the assumed design situation. An effort has been made to cover the more probable situations. However, sufficient general information on protective design techniques has been included in order that application of the basic theory can be made to situations other than those which were fully considered.

This manual is generally applicable to the design of protective structures subjected to the effects associated with high explosive detonations. For these design situations, this manual will generally apply for explosive quantities less than 25,000 pounds for close-in effects. However, this manual is also applicable to other situations such as far or intermediate range effects. For these latter cases the design procedures as presented are applicable for explosive quantities in the order of 500,000 pounds which is the maximum quantity of high explosive approved for storage facilities in the Department of Defense manual, "Ammunition and Explosives Safety Standards", DOD 6055.9-STD.

Because the tests conducted so far in connection with this manual have been directed primarily towards the response of structural steel and reinforced concrete elements to blast overpressures, this manual concentrates on design procedures and techniques for these materials. However, this does not imply that concrete and steel are the only useful materials for protective construction. Tests to establish the response of wood, brick blocks, plastics, etc. as well as the blast attenuating and mass effects of soil are contemplated. The results of these tests may require, at a later date, the supplementation of these design methods for these and other materials.

Other manuals are available which enable one to design protective structures against the effects of high explosive or nuclear detonations. The procedures in these manuals will quite often complement this manual and should be consulted for specific applications.

Computer programs, which are consistent with the procedures and techniques contained in the manual, have been approved by the appropriate representative of the U.S. Army, the U.S. Navy, the U.S. Air Force and the Department of Defense Explosive Safety Board

(DDESB). These programs are available through the following repositories:

1. Department of the Army

   Commander and Director
   U.S. Army Engineer
   Waterways Experiment Station
   Post Office Box 631
   Vicksburg, Mississippi 39180

   Attn: WESKA

2. Department of the Navy

   Officer-in-Charge
   Civil Engineering Laboratory
   Naval Battalion Construction Center
   Port Hueneme, California 93043

   Attn: Code L51

3. Department of the Air Force

   Aerospace Structures
   Information and Analysis Center
   Wright Paterson Air Force Base
   Ohio 45433

   Attn: AFFDL/FBR

The individual programs are identical at each repository. If any modifications and/or additions to these programs are required, they will be submitted by the organization for review by DDESB and the above services. Upon concurrence of the revisions, the necessary changes will be made and notification of these changes will be made by the individual repositories.

1-5 Format of Manual

This manual is subdivided into six specific volumes dealing with various aspects of design. The titles of these volumes are as follows:

Volume	I	-	Introduction
Volume	II	-	Blast, Fragment and Shock Loads
Volume	III	-	Principles of Dynamic Analysis
Volume	IV	-	Reinforced Concrete Design
Volume	V	-	Structural Steel Design
Volume	VI	-	Special Considerations in Explosive Facility Design

Appendix A pertinent to a particular volume and containing illustrative examples of the explosive effects and structural response problems appear at the end of each volume.

Commonly accepted symbols have been used as much as possible. However, protective design involves many different scientific and engineering fields, and, therefore, no attempt has been made to standardize completely all the symbols used. Each symbol has been defined where it is first introduced, and a list of the symbols, with their definitions and units, is contained in Appendix B of each volume.

VOLUME CONTENTS

1-6 General

This volume contains the safety factor and accuracy to be used with the various design procedures presented in this manual. Also presented is the qualitative description of an explosive protective system, acceptor system tolerance, and the basis for structural design.

SAFETY FACTOR

1-7 Safety Factor and Accuracy

Certain simplifications have been made in the development of the design procedures presented in this manual. An analysis of a protective structure using these procedures will generally result in a conservative estimate of the structure's capacity. Consequently, protective structures designed according to these procedures will generally be adequate for a blast load in excess of the assumed loading conditions.

Certain unknown factors, however, can result in an underestimation of the protective structure's capability to resist the effects of an explosion. These factors, including unanticipated reflections of the shock waves, overestimate of the structural response, inadequate construction methods, including type and quality of construction materials, workmanship, etc., vary for each facility design. To compensate for these uncertainties resulting from these factors, it is recommended that the weight of the explosive be increased by 20 percent for design purposes. This increased weight of explosive will be the "effective charge weight" or the charge weight used for a particular design case or cases. Modification of this increased "effective charge weight" must be approved by the cognizant military construction agency. Proposed modifications may require testing to verify the change(s).

All charts pertaining to explosive output in this manual are for readings at sea level.

EXPLOSION PROTECTION SYSTEM

1-8 System Components

1-8.1 *General*

Explosive manufacturing and storage facilities are constructed so that they provide a predetermined level of protection against the hazards of accidental explosions. The design of these facilities may be thought of as a problem consisting of three broad components: (1) the donor system (amount, type and location of the potentially detonating explosive) which produces the damaging output, (2) the acceptor system (personnel, equipment, and "acceptor" explosives) which requires protection, and (3) the protection system (protective structure, structural components or distance) necessary to shield against or attenuate the hazardous effects to levels which are tolerable to the acceptor system. The flow chart in figure 1-1 briefly summarizes the protective system and relates the individual components to each other.

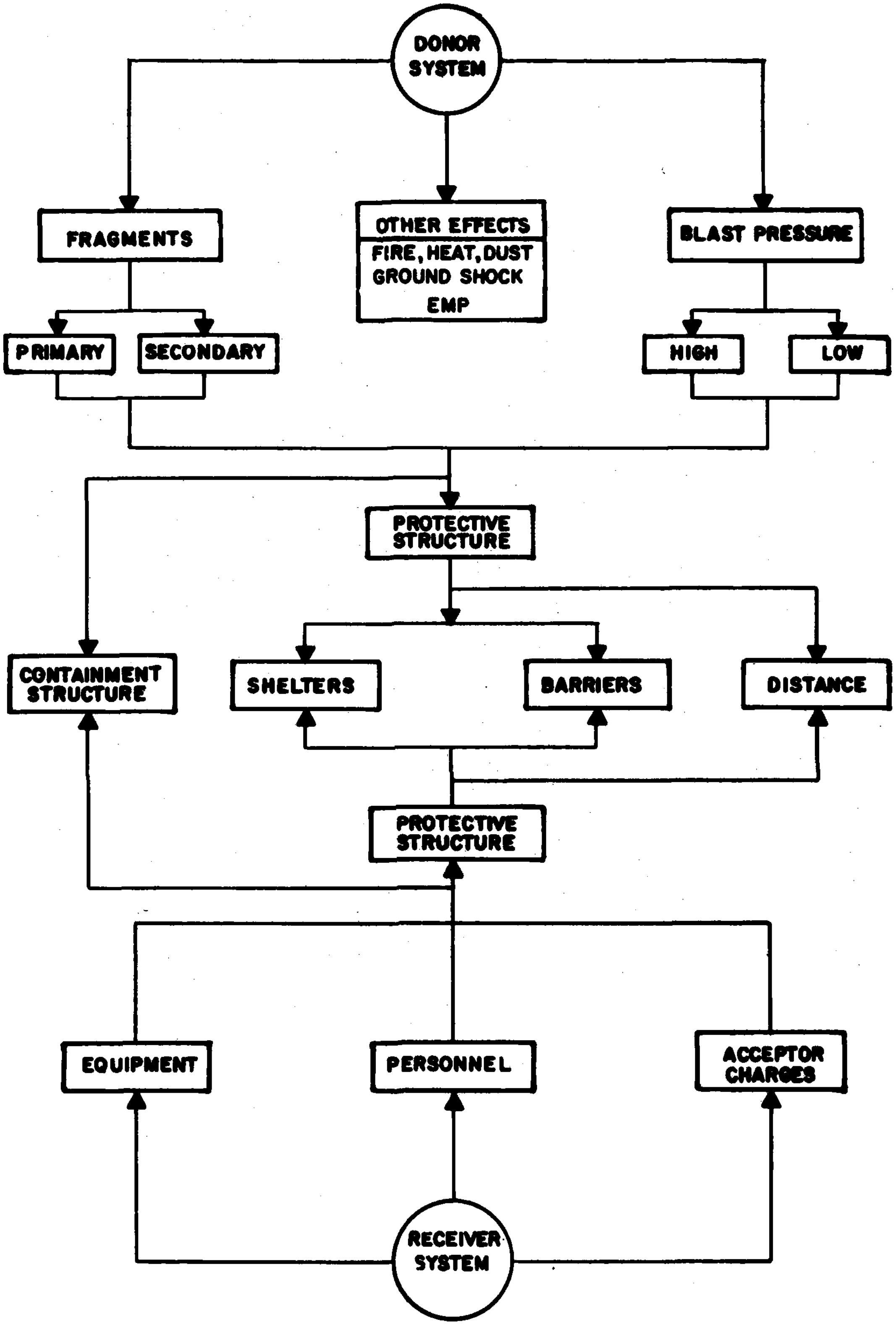


Figure I-I Explosive protective system

1-8.2 *Donor System*

The donor system includes the type and amount of the potentially detonating explosive as well as materials which, due to their proximity to the explosive, become part of the damaging output. The output of the donor explosive includes blast overpressures (hereafter referred to as blast pressures or pressures), primary fragments resulting from cased explosives and secondary fragments resulting from materials in the immediate vicinity of the donor explosive. Other effects from the donor include ground shock, fire, heat, dust, electromagnetic pulse, etc. For the quantities of explosives considered in this manual, blast pressures constitute the principal parameter governing the design of protective structures. However, in some situations, primary and/or secondary fragments and ground shock may assume equal importance in the planning of the protection system. The other effects enumerated are usually of concern in specific types of facilities, and their influence on the overall design can usually be met with the use of standard engineering design procedures. Except for very large quantities of explosives, ground shock effects will usually be small and, in most cases, will be of concern when dislodging of components within the protective structure is possible.

The chemical and physical properties of the donor explosive determine the magnitude of the blast pressures whereas the distribution of the pressure patterns is primarily a function of the location of the donor explosive relative to the components of the protective facility. The mass-velocity properties of the primary fragments depend upon the properties of the donor explosive and the explosive casing, while, for secondary fragments, their mass-velocity properties are functions of the type of fragment materials (equipment, frangible portions of the structure, etc.), their relative position to the donor explosive, and the explosive itself.

The explosive properties, including the molecular structure (monomolecular, bimolecular, etc.) of the explosive, shape and dimensional characteristics, and the physical makeup (solid, liquid, gas) of the charge, determine the limitation of the detonation process. These limitations result in either a high- or low-order detonation. With a high-order detonation, the process is generally complete and results in the maximum pressure output for the given type and amount of material. On the other hand, if the detonation is incomplete with the initial reaction not proceeding through the material mass, then a large quantity of the explosive is consumed by deflagration and the blast pressure is reduced.

Primary fragments are produced by the explosion of a cased donor charge. They result from the shattering of a container which is in direct contact with the explosive material. The container may be the casing of conventional munitions, the kettles, hoppers, and other metal containers used in the manufacture of explosives, the metal housing of rocket engines, etc. Primary fragments are characterized by very high initial velocities (in the order of thousands of feet per second), large numbers of fragments, and relatively small sizes. The heavier fragments may penetrate a protective element depending upon its composition and thickness. The lighter fragments seldom achieve perforation. However, in certain cases, primary fragments may ricochet into the protected area and cause injury to personnel, damage to equipment, or propagation of acceptor explosives. For protection against primary fragments, sufficient structural mass must be provided to prevent full penetration, and the configuration of the components of the protective facility must prevent fragments from ricocheting into protected areas.

Secondary fragments are produced by the blast wave impacting objects located in the vicinity of the explosive source. At these close distances, the magnitude of the shock load is very high and objects can be broken up and/or torn loose from their supports.

Pieces of machinery, tools, materials such as pipes and lumber, parts of the structure (donor structure) enclosing the donor explosive, large pieces of equipment, etc. may be propelled by the blast. Secondary fragments are characterized by large sizes (up to hundreds of pounds) and comparatively low velocities (hundreds of feet per second). These fragments may cause the same damage as primary fragments, that is, injury to personnel, damage to equipment or detonation of acceptor explosives. However, protection against secondary fragments is slightly different than for primary fragments. While preventing perforation by primary fragments is important, secondary fragments pose additional problems due to their increased weight. The protective structure must be capable of resisting the large impact force (momentum) associated with a large mass traveling at a relatively high velocity.

1-8.3 *Acceptor System*

The acceptor system is composed of the personnel, equipment, or explosives that require protection. Acceptable injury to personnel or damage to equipment, and sensitivity of the acceptor explosive(s), establishes the degree of protection which must be provided by the protective structure. The type and capacity of the protective structure are selected to produce a balanced design with respect to the degree of protection required by the acceptor and the hazardous output of the donor.

Full protection is usually required for personnel. People must be protected from the direct effects of both blast pressure and fragment impact as well as from the effects of ground shock. It must be realized that personnel located in the immediate vicinity of a donor explosive are difficult to protect from the high blast pressures, fire, heat and high speed fragments associated with a detonation. Protection can be afforded through the use of distance and/or protective structures. Personnel may be subjected to low blast pressures and/ or small ground motions without direct injury. However, injury can be sustained by falling and impacting hard surfaces.

In most explosive processing facilities, equipment is expendable and does not require protection. Equipment which is very expensive, difficult to replace in a reasonable period of time, and/or must remain functional to insure the continuous operation of a vital service may require protection. The degree of protection will vary depending upon the type and inherent strength of the equipment. In general, equipment and personnel are protected in a similar manner. However, equipment can usually sustain higher pressures than personnel, certain types of equipment may be able to withstand fragment impact whereas personnel can not, and lastly, equipment can sustain larger shock loads since it can be shock isolated and/or secured to the protective structure.

The degree of protection for acceptor explosives range from full protection to allowable partial or total collapse of the protective structure. In order to prevent detonation, sensitive acceptor explosives must be protected from blast pressures, fragment impact, and ground shock whereas "insensitive" explosives may be subjected to these effects in amounts consistent with their tolerance. The tolerances of explosives to initial blast pressures, structural motions, and impact differ for each type of explosive material with pressure being the lesser cause of initiation. Impact loads are the primary causes of initiation of acceptor explosives. They include primary and secondary fragment impact as well as impact of the explosive against a hard surface in which the explosive is dislodged from its support by pressure or ground shock and/or propelled by blast pressures.

1-8.4 *Protective Structures*

Personnel, equipment or explosives are protected from the effects of an accidental explosion by the following means: (1) sufficient distance between the donor and acceptor systems to attenuate the hazardous effects of the donor to a level tolerable to the acceptor, (2) a structure to directly protect the acceptor system from the hazardous output of the donor system, (3) a structure to fully contain or confine the hazardous output of the donor system, and (4) a combination of the above means. While large distances may be used to protect acceptor systems, a protective facility is the most common method employed when limited area is available. In general, separation distances are used as a means of attenuating the hazardous effects of the donor to a level which makes the design of a protective facility feasible, practical and cost effective.

Protective structures can be classified as shelters, barriers or containment structures. Protection is provided by each structure in three distinct manners. Shelters are structures that fully enclose the acceptor system with hardened elements. These elements provide direct protection against the effects of blast pressures, primary and secondary fragments and ground shock. On the other hand, containment structures are buildings which fully or near fully enclose the donor system with hardened elements. They protect the acceptor system by confining or limiting the damaging output of the donor system. Lastly, a barrier acts as a shield between the donor and acceptor systems. They attenuate the damaging output of the donor system to a level which is tolerable to the acceptor system.

Shelters are fully enclosed structures and are used to protect personnel from injury, prevent damage to valuable equipment, and prevent detonation of sensitive explosives. The exterior of the structure is composed of hardened elements which must be designed to resist the effects of blast pressures and both primary and secondary fragment impact and the interior must be arranged to shock isolate the acceptor system. Entrances must be sealed by blast doors, and depending upon the amount of usage and/or the potential explosive hazard, may also require blast locks (an entrance containing a blast door followed by a second blast door; one of which is always closed). Other openings required for facility operations, such as ventilation passages, equipment access openings, etc., may be sealed by blast valves or blast shields. Design criteria for these protective closures are governed by their size and location and the magnitude of the blast pressures and fragment effects acting on them. Small openings may be permitted if the magnitude and rate of pressure buildup within the structure is tolerable to the occupants and contents of the shelter. Special provisions may also be necessary to insure that partitions, hung ceilings, lighting fixtures, equipment, mechanical and electrical fixtures, piping, conduits, etc., are not dislodged as a result of structure motions or leakage pressures and become a hazard to the building's occupants and contents.

Barriers are generally used to prevent propagation of explosions. They act as a shield between two or more potentially detonating explosives. Their main purpose is to stop high speed fragments from impacting acceptor explosives. In addition, they reduce secondary fragments striking the acceptor. They can also reduce blast pressures in the near range (at a distance of two to ten times barrier height) but have little or no effect on the far range. Barriers can be either barricades (revetted or unrevetted earth barricades), simple cantilever walls, etc., or cubicle-type structures where one or more sides and/or the roof are open to the atmosphere or enclosed by frangible elements. Igloos (earth covered magazines), below ground silos, and other similar structures with open or frangible surfaces can also be classified as barriers. They are usually used in storage, manufacturing, or processing of explosives or explosive materials. The explosives are usually located close to the protective element. Consequently, the barrier is subjected to high intensity blast loads and the acceptor explosive is subjected to comparatively high leakage pressures.

Containment structures are fully (or near fully) enclosed structures in which the donor explosive is located. In the event of a detonation, the structure fully confines the explosive output or reduces the output to a tolerable level. Blast pressures and primary and secondary fragments are confined within the structure. Personnel and/or equipment located within the structure cannot be protected. Containment structures are generally used for high hazard operations and/or operations involving toxic materials. These operations must be remotely controlled since operating personnel should not be located within the structure during hazardous operation. All entrances must be sealed with blast doors. Other openings required for facility operations such as ventilation passages, equipment and/or product access openings, etc., must be sealed by blast valves or blast shields. For operations not involving toxic materials, blast pressures may be released to the atmosphere. However, this pressure release must be controlled both in magnitude and direction either by mechanical means (through blast valves or shields) or by limiting the size of the openings and/or directing the leakage pressures to areas where personnel, equipment and acceptor explosives will be protected.

The various components of a protective facility must be designed to resist the effects of an explosion. The exterior walls and roof are the primary protective elements. These elements are said to be "hardened" if they are designed to resist all the effects associated with an explosion (blast pressures, primary and secondary fragments, structure motions). On the other hand, a blast resistant element is designed to resist blast pressures only. While a blast resistant element is not designed specifically to resist fragments, the element has inherent fragment resistance properties which increases with increasing blast resistant capabilities. In many parts of this manual, the term "blast resistant" is used synonymously with "hardened."

ACCEPTOR SYSTEMS TOLERANCES

1-9 Protection Categories

For the purpose of analysis, the protection afforded by a facility or its components can be subdivided into four protection categories as described below:

1. Protection Category 1 - Protect personnel against the uncontrolled release of hazardous materials, including toxic chemicals, active radiological and/or biological materials; attenuate blast pressures and structural motion to a level consistent with personnel tolerances; and shield personnel from primary and secondary fragments and falling portions of the structure and/or equipment;

2. Protection Category 2 - Protect equipment, supplies and stored explosives from fragment impact, blast pressures and structural motions;

3. Protection Category 3 - Prevent communication of detonation by fragments and high-blast pressures; and

4. Protection Category 4 - Prevent mass detonation of explosives as a result of subsequent detonations produced by communication of detonation between two adjoining areas and/or structures.

1-10 Protective Structures

1-10.1 *Containment Type Structures*

The first three categories can apply to structures classified as containment structures when these structures are designed to prevent or limit the release of toxic or other hazardous materials to a level consistent with the tolerance of personnel. These structures generally are designed as donor structures and can resist the effects of "close-in" detonations (detonations occurring close to the protective structures). Added protection is accomplished by minimizing the pressure leakage to the structure's exteriors, by preventing penetration to the exterior of the structure by primary fragments and/or formation of fragments from the structure itself. Quite often, containment structures may serve as a shelter as described below. Procedures for designing reinforced concrete containment structures are contained in Volume IV. A design ratio of weight to volume of $.05 < W/V < .15 \ lb/ft^3$ is a practical range for reinforced concrete containment structures.

1-10.2 *Shelters*

The first three categories apply to shelters which provide protection for personnel, valuable equipment, and/or extremely sensitive explosives. Shelters, which are usually located away from the explosion, accomplish this protection by minimizing the pressure leakage into a structure, providing adequate support for the contents of the structure, and preventing penetration to the interior of the structure by high-speed primary fragments, and/or by the impact of fragments formed by the breakup of the donor structure. Protection against the uncontrolled spread of hazardous material is provided by limiting the flow of the dangerous materials into the shelter using blast values, filters and other means. Procedures for designing concrete and structural steel buildings are contained in Volumes IV and V, respectively.

1-10.3 *Barriers*

Although the three categories of protection can be achieved with the use of a shelter, the last two protection categories (para. 1-9) pertain to the design of barriers where protection of explosives from the effects of blast pressures and impact by fragments must be provided. For the third protection category, the explosion must be confined to a donor cell, whereas in the fourth protection category, propagation between two adjoining areas is permitted. However, the communication of detonation must not extend to other areas of the facility. This situation may arise in the event of the dissimilarity of construction and/or explosive contents of adjacent areas. Procedures for designing reinforced concrete barriers are contained in Volume IV.

1-11 Human Tolerance

1-11.1 *Blast Pressures*

Human tolerance to the blast output of an explosion is relatively high. However, the orientation of a person (standing, sitting, prone, face-on or side-on to the pressure front), relative to the blast front, as well as the shape of the pressure front (fast or slow rise, stepped loading), are significant factors in determining the amount of injury sustained. Shock tube and explosive tests have indicated that human blast tolerance varies with both the magnitude of the shock pressure as well as the shock duration, i.e., the pressure tolerance for short-duration blast loads is significantly higher than that for long-duration blast loads.

Tests have indicated that the air-containing tissues of the lungs can be considered as the critical target organ in blast pressure injuries. The release of air bubbles from disrupted alveoli of the lungs into the vascular system probably accounts for most deaths. Based on present data, a tentative estimate of man's response to fast rise pressures of short duration (3 to 5 ms.) is presented in figure 1-2. The threshold and severe lung-hemorrhage pressure levels are 30 to 40 psi and above 80 psi, respectively, while the threshold for lethality due to lung damage is approximately 100 to 120 psi (Table 1-1). On the other hand, the threshold pressure level for petechial hemorrhage resulting from long-duration loads may be as low as 10 to 15 psi, or approximately one-third that for short duration blast loads. Since survival is dependent on the mass of the human, the survival for babies will be different than the survival for small children which will be different from that for women and men. These differences have been depicted in figure 1-2 which indicates that the survival scaled impulse depends on the weight of the human. It is recommended that 11 lb. be used for babies, 55 lb. for small children, 121 lb. for adult women and 154 lb. for adult males.

A direct relationship has been established between the percentage of ruptured eardrums and maximum pressure, i.e., 50 percent of exposed eardrums rupture at a pressure of 15 psi for fast rising pressures while the threshold of eardrums rupture for fast rising pressure is 5 psi. Temporary hearing loss can occur at pressure levels less than that which will produce onset of eardrum rupture. This temporary hearing loss is a function of the pressure and impulse of a blast wave advancing normal to the eardrum. The curve which represents the case where 90 percent of those exposed are not likely to suffer an excessive degree of hearing loss, is referred to as the temporary threshold shift (figure 1-3).

The pressures referred to above are the maximal effective pressures, that is, the highest of either the incident pressure, the pressure plus the dynamic pressures, or the reflected pressure. The type of pressure which will be the maximal effective depends upon the orientation of the individual relative to the blast as well as the proximity of reflecting surfaces and the occurrence of jetting effects which will cause pressure amplification as the blast wave passes through openings. As an example, consider the pressure level which will cause the onset of lung injury to personnel in various positions and locations. The threshold would be 30 to 40 psi reflected pressure for personnel against a reflector (any position), 30 to 40 psi incident plus dynamic pressure; 20 to 25 psi would be the incident pressure plus 10 to 15 psi dynamic pressure for personnel in the open, either standing or prone-side-on, and 30 to 40 psi incident pressure for personnel in the open in a prone-end-on position.

However, the above pressure level assumes that an individual is supported and will not be injured due to being thrown off balance and impacting a hard and relatively non-yielding surface. In this case, pressure levels which humans can withstand is generally much lower than those causing eardrum or lung damage. For this case, one publication has recommended that tolerable pressure level of humans not exceed 2.3 psi which is higher than temporary threshold shift of temporary hearing loss (figure 1-3) and probably will cause personnel, which are located in the open, to be thrown off balance. Therefore, for individuals which are located exterior of a shelter structure and subjected to the transient effects of the blast wave, it is recommended that exposure pressure be limited in the order of one psi or less.

Since shelters can be designed to protect personnel from the impact effects of the blast wave, the higher pressure tolerance of 2.3 psi may be permitted for shelter contained personnel. This higher tolerance, however, is dependent on whether the build-up in pressure is controlled both in intensity and duration and that the leakage pressure into the structure does not produce internal damage to the structure or its contents. Direct

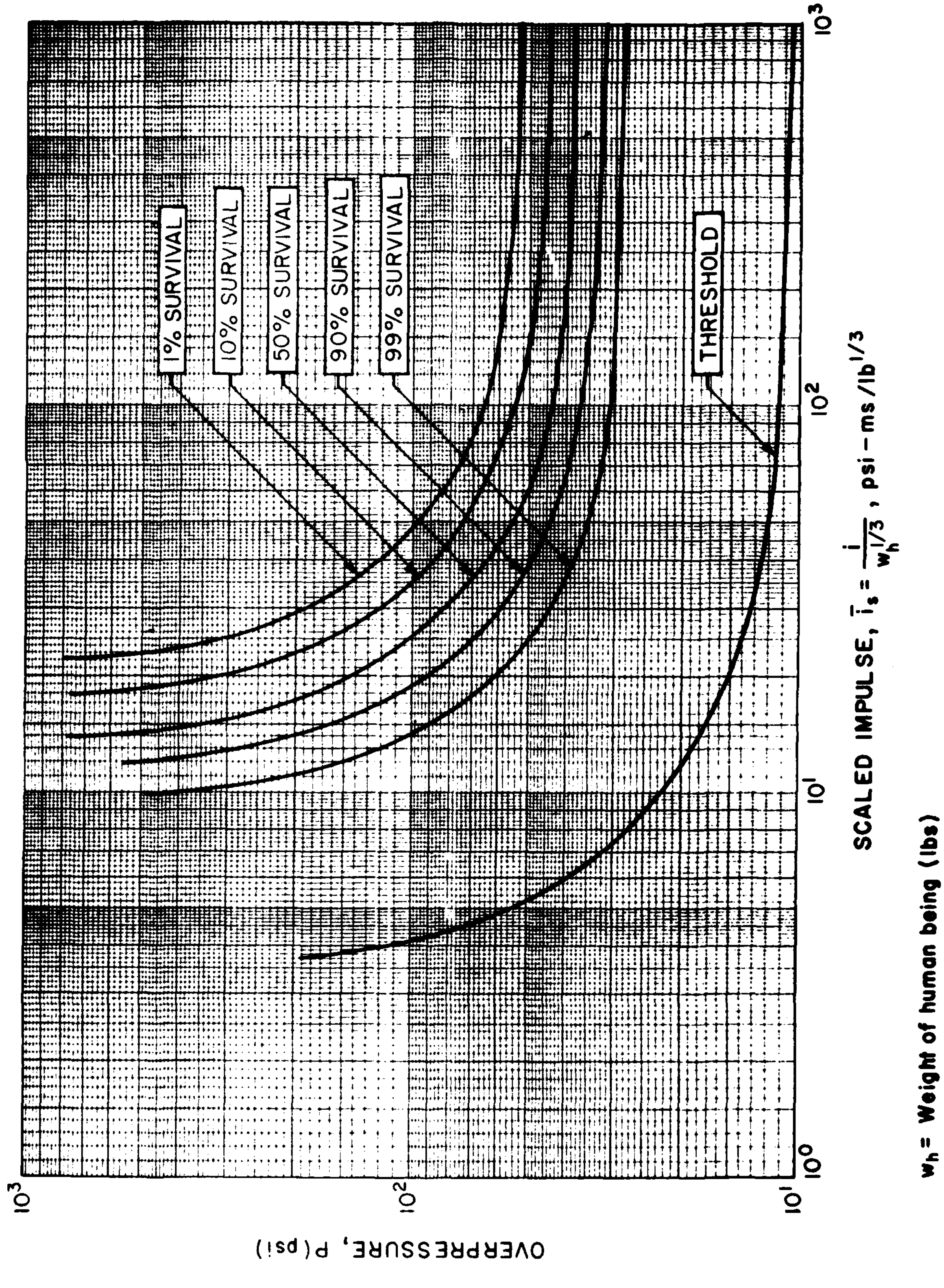


Figure I-2 Survival curves for lung damage

Table 1-1 Criteria for Primary-Blast Effects in Man Applicable to Fast-Rising Air Blasts of Short Duration (3-5 ms.)

Critical Organ or Event	Maximal Effective Pressure (psi)
Eardrum Rupture	
Threshold	5
50 percent	15
Lung Damage:	
Threshold	30-40
50 percent	80 and above
Lethality	
Threshold	100-120
50 percent	130-180
Near 100 percent	200-250

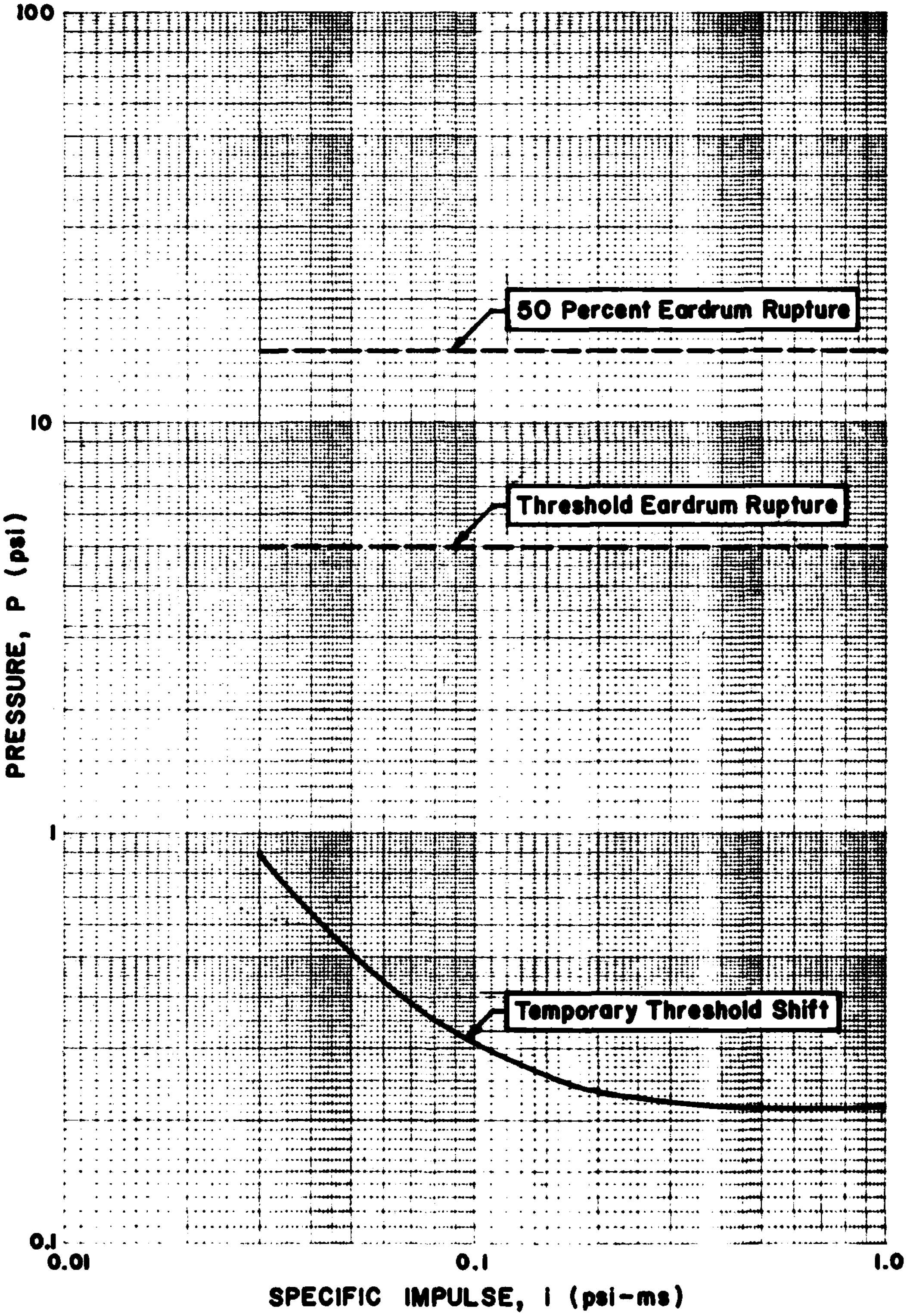


Figure 1-3 Human ear damage due to blast pressures

exposure to the pressures entering the structure should be minimized. The jetting effects produced by the pressure passing through an opening can result in amplification of the pressures at the interior side of the opening. The magnitude of this increased pressure can be several times as large as the maximum average pressure acting on the interior of the structure during the passage of the shock wave. Therefore, openings where jetting will occur should not be directed into areas where personnel and valuable equipment will be situated.

1-11.2 *Structural Motion*

Because the structural motions associated with high-explosive detonations are transient in nature and can possibly impact an abrupt velocity change to the body either in stopping or starting, in addition to shaking or vibrating of the body, it is necessary that human tolerance to two types of shock exposure be considered:

1. Impacts involving velocity-shock causing body acceleration and/or deceleration, and

2. Body vibration as a result of the vibratory motion of the structure.

If a subject is not attached to the structure, he may be vulnerable to impact resulting from collision with the floor due to the structure dropping out beneath him and/or the structure rebounding upward towards him. However, the more plausible means of impact injury results from the subject being thrown off balance because of the horizontal motions of the structure, causing him to be thrown bodily against other persons, equipment, walls and other hard surfaces.

Studies have indicated that a probable safe impact tolerance velocity is 10 fps. At 18 fps there is a 50 percent probability of skull fracture and at 23 fps, the probability is nearly 100 percent. This applies to impact with hard, flat surfaces in various body postures. However, if the line of thrust for head impact with a hard surface is directly along the longitudinal axis of the body (a subject falling head first), the above velocity tolerance does not apply since the head would receive the total kinetic energy of the entire body mass. Impacts with corners or edges are also extremely critical, even at velocities less than 10 fps. An impact velocity of 10 fps is considered to be generally safe for personnel who are in a fairly rigid posture; therefore, greater impact velocities can be tolerated if the body is in a more flexible position or if the area of impact is large.

The effect of horizontal motion on the stability of personnel (throwing them off balance or hurling them laterally) depends on the body stance and position, the acceleration intensity and duration, and the rate of onset of the acceleration (jolt). An investigation of data concerning sudden stops in automobiles and passenger trains indicates that personnel can (depending on stance and jolt) sustain horizontal accelerations less than 0.44 g without being thrown off balance. These accelerations have durations of several seconds; hence, the accelerations considered in this manual required to throw personnel off balance are probably greater because of their shorter durations and associated jolts. Therefore, the tolerable horizontal acceleration of 0.50 g required to provide protection against ground-shock effects resulting from nuclear detonations is recommended for non-restrained personnel (standing, sitting or reclining).

If the vertical downward acceleration of the structure is greater than 1 g, relative movement between the subject and the structure is produced. As the structure drops beneath him, the subject begins to fall until such time that the structure slows down and the free falling subject overtakes and impacts with the structure. The impact velocity is equal to the relative velocity between the structure and the subject at the time of impact, and to assure safety, it should not exceed 10 fps.

To illustrate this vertical impact, a body which free falls for a distance equal to 1½ feet has a terminal or impact velocity of approximately 10 fps against another stationary body. If the impacted body has a downward velocity of 2 fps at the time of impact, then the impact velocity between the two bodies would be 8 fps.

Because of the general activity required in most explosive manufacturing and testing facilities, attaching personnel to a structure to prevent displacement is not usually practical. However, in certain testing and other facilities operations, this method of protection against structural motion may be useful. Although the possibility of the occurrence of impact associated with nonrestrained personnel is not a factor in protecting restrained subjects, the harmful effects associated with restraining can, in certain situations, be more severe than for non-attached personnel. In addition to the direct interference with physical activity, discomfort, pain, trauma and, depending on the severity of the motion and the physical condition of the subject, mortality can occur. Other effects associated with long-duration vibrations, such as irritation and fatigue, are not likely because of the transient nature of the motions.

Based on the available personnel vibration data, the following vibrational tolerances for restrained personnel were considered: 2g for less than 10 Hz, 5g for 10-20 Hz, 7g for 20-40 Hz, and 10g above 40 Hz. However, the use of acceleration tolerances greater than 2g usually requires restraining devices too elaborate for most explosive manufacturing and testing facilities.

1-11.3 *Fragments*

Overall, human tolerance to fragment impact is very low; however, certain protection can be provided with shelter type structures. Fragments can be classified based on their size, velocity, material and source, i.e.:

1. Primary fragments, which are small, high-speed missiles usually formed from casings and/or equipment located immediately adjacent to the explosion, and

2. Secondary fragments, which are generated from the breakup of the donor building, equipment contained within the donor structure and/or acceptor buildings which are severely damaged by an explosion.

Discussion of human tolerance of both of these types of fragments overlap, since the basic differences between these fragments are their size and velocity. Impact of primary fragments can be related to an impact by bullets where the fragment is generally small, usually of metal and traveling at high velocities. A great deal of research has been conducted for the military; however, most of the data from these tests is not available. Some fragment-velocity penetration data of humans has been developed for fragment weights equal to or less than 0.033 pounds, and indicates that, as the ratio of the fragment area to weight increases, the velocity which corresponds to a 50 percent probability of penetrating human skin will increase. This trend is illustrated in Table 1-2 where the increase in velocity coincides with the increase of area of the fragment. In order to protect personnel in the open from the potential fragment hazard created by an accidental explosion, the Safety Manual defines a hazardous density as at least one fragment having an impact energy of 58 ft.-lbs. impacting in an area of 600 square feet or less.

Secondary fragments, because they have a large mass, will cause more serious injuries at velocities significantly less than caused by primary fragments. Table 1-3 indicates the

Table 1-2 50 Percent Probability of Penetrating Human Skin

Ratio of Fragment area/weight (ft^2/lb.)	Fragment Area Based on 0.033 lb. fragment weight (ft^2)	Velocity (fps)	Threshold Energy (ft-lb.)
0.03	.00099	100	5
0.10	.00330	165	14
0.20	.00660	250	32
0.30	.00990	335	58
0.40	.01320	425	93

velocity which corresponds to the threshold of serious human injury. As mentioned in 1-11.2 above, the impact of a relatively large mass with a velocity less than 10 fps against a human can result in serious bodily injury. Also, the impact of smaller masses (Table 1-3) with higher velocities can result in injuries as severe as those produced by larger masses. In general, complete protection must be afforded personnel from all falling and/or flying objects.

1-12 Equipment Tolerance

1-12.1 *Blast Pressures*

Unless the equipment is of the heavy-duty type (motor, generators, air handlers, etc.), equipment to be protected from blast pressures must be housed in shelter-type structures similar to those required for the protection of personnel. Under these circumstances, the equipment will be subjected to blast pressures which are permitted to leak into the shelter through small openings. If the magnitude of these leakage pressures is minimized to a level consistent with that required for personnel protection, then in most cases protection from the direct effects of the pressures is afforded to the equipment. However, in some instances, damage to the equipment supports may occur which, in turn, can result in damage to the equipment as a result of falling. Also, if the equipment is located immediately adjacent to the shelter openings, the jetting effects of the pressures entering the structure can have adverse effects on the equipment. In general, equipment should be positioned away from openings and securely supported. However, in some cases, equipment such as air handling units must be positioned close to the exterior openings. In this event, the equipment must be strong enough to sustain the leakage pressures (pressures leaking in or out of openings) or protective units such as blast valves must be installed.

1-12.2 *Structural Motion and Shock*

Damage to equipment can result in failures which can be divided into two classes; temporary and permanent. Temporary failures, often called "malfunctions," are characterized by temporary disruption of normal operation, whereas permanent failures are associated with breakage, resulting in damage so severe that the ability of the equipment to perform its intended function is impaired permanently or at least over a period of time.

The capacity of an item of equipment to withstand shock and vibration is conventionally expressed in terms of its "fragility level" which is defined as the magnitude of shock (acceleration) that the equipment can tolerate and still remain operational. The fragility level for a particular equipment item is dependent upon the strength of the item (frame, housing, and components) and, to some extent, the nature of the excitation to which it is subjected. An equipment item may sustain a single peak acceleration due to a transient input load, but may fail under a vibration-type input having the same peak acceleration amplitude. Also the effects of the occurence of resonance may be detrimental to the item functioning. For these reasons, fragility data should be considered in conjunction with such factors as the natural frequencies and damping characteristics of the equipment and its components, as well as the characteristics of the input used to determine the tolerance as compared to the motion of the structure which will house the equipment.

The maximum shock tolerances for equipment vary considerably more than those for personnel. To establish the maximum shock tolerance for a particular item, it is

Table 1-3 Threshold of Serious Injury to Personnel Due to Fragment Impact

Critical Organ	Weight (lbs.)	Fragment Velocity (fps)	Energy (ft-lb.)
Thorax	>2.5	10	4
	0.1	80	10
	0.001	400	2.5
Abdomen and limbs	>6.0	10	9
	0.1	75	9
	0.001	550	5
Head	>8.0	10	12
	0.1	100	16
	0.001	450	3

necessary to perform tests and/or analyses. Only selected items of equipment have been tested to determine shock tolerances applicable for protection from the damage which may be caused by structural motions. Most of this data resulted from tests to sustain ground-shock motions due to a nuclear environment, which will have a duration considerably longer than that associated with a HE explosion. However, the data which are available concerning shock effects indicate strength and ruggedness or sensitivity of equipment. These data, which are based primarily on transportation and conventional operational shock requirements, indicate that most commercially available mechanical and electrical equipment are able to sustain at least 3g's, while fragile equipment (such as electronic components) can sustain approximately 1.5g's.

The above tolerances are safe values, and actual tolerances are, in many cases, higher than 3g's, as indicated in Table 1-4. However, the use of such acceleration values for particular equipment require verification by shock testing with the induced motions (input) consistent with expected structural motions.

The above tolerances are applicable to equipment which is mounted directly to the sheltering structure. For the equipment to sustain shock accelerations in the order of magnitude of their tolerances, the equipment item must be "tied" down to the structure, that is, the equipment stays attached to the structure and does not impact due to its separation. In most cases, shock isolation systems will be needed to protect the equipment items. The shock isolation systems will consist of platforms which are supported by a spring assembly for large motion and/or cushioning material when the motions are small. These systems should be designed to attenuate the input accelerations to less than 1g in order that separation between the equipment and support system does not occur. If the spring systems are designed to be "soft" (less than 1/2 g) then, depending on the mass of the equipment, vibratory action of the system could occur due to individuals walking on the platforms.

1-12.3 *Fragments*

Susceptibility of an item of equipment to damage from fragment impact depends upon the ruggedness of its components, its container, if any, and upon the size and velocity of the fragment at the time of impact.

Some heavy equipment (motors, generators, etc.) may sustain malfunctions as a result of the severing of electrical or mechanical connections, but seldom are destroyed by the impact of primary fragments. On the other hand, this heavy equipment can be rendered useless by secondary fragment impact. Fragile equipment (electronic equipment, etc.) will generally be inoperable after the impact of either primary or secondary fragments. In some cases, the impact force and penetration capability of light fragments may be such as to cause perforation of the container of sensitive portions of heavy equipment (fuel tank of generators, etc.) which can render the items unusable. Low-velocity light fragments seldom result in severe damage. These fragments usually ricochet beyond the equipment unless the component part of the equipment it strikes is glass or other fragile material, in which case, some damage may be inflicted.

Although the damage to the equipment of a structure can be great as a result of falling or flying debris, the increased cost of strengthening walls and other portions of the protective shelter is usually not warranted unless personnel or acceptor charge protection is also required and/or the cost of the equipment item lost exceeds the increased construction costs. Even in this latter situation, a probability analysis of the occurrence of an incident should be made prior to incurring additional construction costs.

Table 1-4 Examples of Equipment Shock Tolerances

Equipment	Peak Accelerations
Flourescent light fixtures (with lamps)	20 to 30g
Heavy machinery (motor, generators, transformers, etc. > 4,000 lbs.)	10 to 30g
Medium-weight machinery (pumps, condensers, AC equipment, 1,000 to 4,000 lbs.	15 to 45g
Light machinery (small motors <1,000 lbs.)	30 to 70g

1-13 Tolerance of Explosives

1-13.1 *General*

The tolerances of explosives to blast pressure, structural motion, and impact by fragments differ for each type of explosive material and/or item. Generally, fragment impact is the predominant cause of detonation propagation.

1-13.2 *Blast Pressures*

Except in regions of extremely high pressure, most explosive materials are insensitive to the effects of blast pressures. In many instances, however, the secondary effects, such as dislodgement of the explosive from its support and propulsion of the explosive against hard surfaces, can result in a possible detonation depending upon the tolerance of the explosive to impact. Results of several different types of sensitivity tests (drop tests, card gap tests, friction tests, etc.) are presently available which will aid in the establishment of the tolerances of most explosive materials to impact.

1-13.3 *Structural Motions*

Structural motion effects on explosives are similar to the impact effects produced by blast pressures. The movement of the structure tends to dislodge the explosive from its support, resulting in an impact of the explosive with the floor or other parts of the structure. The distance the explosive falls and its sensitivity to impact and friction determine whether or not propagation occurs.

1-13.4 *Fragments*

Although blast pressures and structural motions can produce explosive propagation, the main source of communication of explosions is by fragments, principally primary fragments from the breakup of the donor charge casing, fragments produced by the fracture of equipment close to the explosion, disengagement of interior portions of the structure, and/or failure of the structure proper.

In recent years, an extensive test program has been performed which has provided a significant amount of information regarding explosive propagation by primary fragment impact. This program was conducted primarily to determine safe separation criteria for bulk explosives and munitions, mainly for the design and operation of conveyance systems. The individual test programs were predicated upon given manufacturing operations where improved safety criteria would lessen the probability of a catastrophic event. Individual test programs were performed in two stages, exploratory and confirmatory, where the safe separation was determined during the exploratory phase and confirmation was established on a 95 percent confidence level.

A typical test set-up is illustrated in figure 1-4, while the results of the various test programs are listed in Table 1-5 for bulk explosives and in Table 1-6 for munitions. These Tables list the bulk explosives and munition types, the configurations examined and the established safe separation distances. For all items/configurations examined, unless specified, the test conditions were: 1) in free air (without tunnels), 2) open spaced (no shields), 3) in a vertical orientation, and 4) measured edge-to-edge. Inspection of Tables 1-5 and 1-6 reveals that minimum safe separation distances have not been established for some of the items listed. If specific safe separation distances are required, as will be for other items not listed, further tests will be required. A detailed compilation of the items and test procedures and methods are listed in the bibliography.

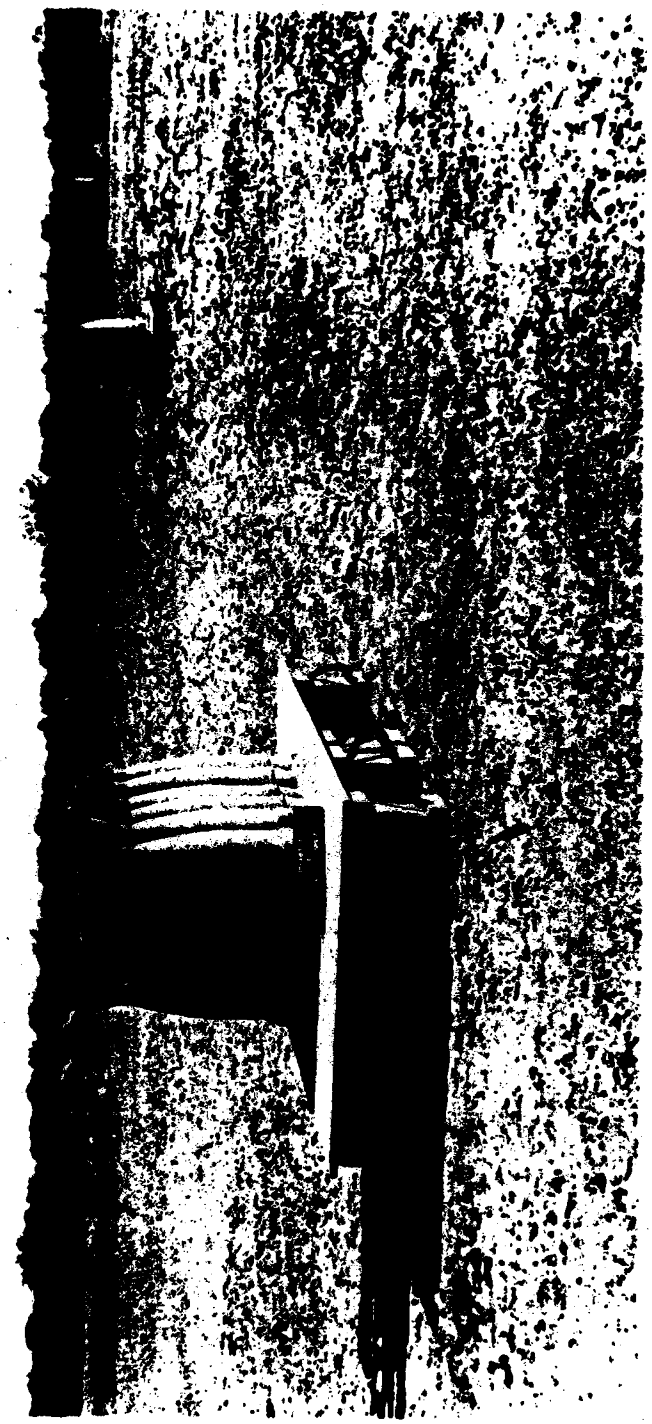


Figure I-4 Example of safe separation tests

Table 1-5 Safe Separation Distance (bulk explosives)

Bulk Explosive	Explosive Weight (lbs)	Test Configuration	Safe Separation (ft)
Composition A-5	10	Rubber buckets in tunnel	6.0
	15	Aluminum buckets in tunnel	20.0
Composition A-7	168	Steel tote bins in tunnel.	130.0[(1)]
Composition B	---	Flake, depth on 15 inch Serpentix conveyor	.17[(2)]
	2.5	Riser scrap: 2 pieces	1.5
	2.5	4 pieces	3.0
	2.5	2 pieces within funnels	2.0
	2.5	4 pieces within funnels	3.0
	60	Cardboard container in tunnel	12.0
	60	Plastic buckets	12.0[(3)]
Composition C-4	35	Aluminum buckets in tunnel	20.0[(3)]
	50	Aluminum buckets in tunnel	25.0[(3)]
Cyclotol (75/25)	60	Aluminum box in tunnel & 0.38-in Kevlar shield.	24.0
	60	Cardboard box in tunnel.	18.0
Guanidine Nitrate	20	DOT-21C-60 Containers with tops on	3.8
	40	DOT-21C-60 Containers with tops on	4.8
	80	DOT-21C-60 Containers with tops on	5.5
Nitro-Guanidine (Powder)	25	DOT-21C-60 Containers with tops on	5.5
	50	DOT-21C-60 Containers with tops on	7.0
	450	DOT-21C-60 Containers with tops on	16.0[(1)]
TNT, Type 1, Flake	---	Depth on 2-foot Serpentix conveyor	.08[(2)]
	55	Cardboard box	12.0
	168	Aluminum tote bin, w/steel fiberglass in tunnel	60.0
	168	Aluminum tote bin in wooden tunnel	50.0

(1) Safe separation distance is greater than distance shown. These are maximum distances tested. Further tests required to establish minimum safe separation distance.

(2) Depth of material at which propagation is prevented is less than or equal to the value shown.

(3) Minimum distance tested. Actual safe separation distance less than or equal to that indicated. Further tests required to establish minimum safe separation distance.

Table 1-6 Safe Separation Distance (munitions)

Munition	Test Configuration	Safe Separation (ft)
8-Inch M106 HE Projectile	Single round	10.0 (1)
	Single round with 3-inch diameter aluminum bar shield	1.0
8 inch M509 HE Projectile	Single round with one-inch thick steel plate shield	5.0 (1)
	Single round with "VEE" shield (Figure 1-5a)	2.7
155mm M107 HE Projectile	Single round	7.0 (1)
	Single round with one-inch thick aluminum or 1/2-inch thick steel plate shield	1.5
	Single round, horizontal	5.0 (1)
	24 per pallet	110.0
	24 per pallet with funnels	140.0 (1)
	24 per pallet with funnels and 3/4-inch thick steel plate shield	110.0 (1)
155mm M483 HE Projectile	Single round	5.0 (1)
	Single round with empty 155mm M483 projectile body shield	3.0 (1)
	Single round with MS shield (Figure 1-5b)	0
155mm M549 HERA Projectile	Single round	5.0
	Single round with 3-inch diameter aluminum bar shield	0.29
	8 per pallet	30.0 (1)
	8 per pallet with 3-inch diameter aluminum bar shield	10.0
155mm M795 HE Projectile	Single round	15.0

Table 1-6 (Cont'd.)

Munition	Test Configuration	Safe Separation (ft)
105mm M1 HE Projectile	16 per pallet	30.0
	16 per pallet, with funnel	40.0 (1)
	16 per pallet, with funnel and 3/4-inch thick steel plate shield	20.0
105mm M456 HEAT-T Projectile	Primed cartridge cases	0
	Single round with 3-inch diameter aluminum bar shield	1.6
	Single round, horizontal with 3-inch diameter aluminum bar shield	0.91
81mm M374A2E1 HE Cartridge	Single round with 1/4-inch thick Lexan plate extension to 2-inch thick aluminum brick shield	0.73 (2)
81mm M374 HE Projectile	Single round	2.0
	Single round with 2-inch thick aluminum brick shield	0.73 (2)
	72 per pallet	30.0
30mm XM789 HEDP Projectile	2 each. PBXN-5 pellets	0.08
	Shell body with 2 pellets	0.08
	Loaded body assembly	0.08
	Heated loaded body assembly	0.25
	Fuzed projectile	0.25
	Heated fuzed projectile	1.3 (1)
25mm XM792 HEI-T Cartridge	Type I pellets	0.08
	Type II pellets	0.04
	Loaded body assembly	0.17
	Fuzed projectile	0.17
	Complete cartridge	0.17

Table 1-6 (Cont'd.)

Munition	Test Configuration	Safe Separation (ft)
BLU-63 A/B Bomblet	Hemispheres	0.04
	Hemispheres in fixtures	0
	Hemispheres, 16 per tray	0
	Bomblet	0.17
BLU-97/B Submunition	16 per pallet	15.0 (1)
	16 per pallet with 1/2-inch thick aluminum plate shield	4.0
	16 per pallet with "airflow" shield (1/2-inch thick aluminum plates, cut in open "picket fence" design with one plate's spaces covered by the second plate's columns).	5.0
	Single bomblet with either 100% or 75% shield (1/2-inch thick aluminum plate).	0.75
M42/M46 GP Grenades (w/o fuzes)	Single grenade	0.17
	64 per tray	7.0
	768 per carrier, in tunnel	40.0
	8 per M483 Ring Pack	1.0
	15 per M509 Ring Pack	1.5
	32/64 per single/dual cluster tray	0
M56 Mine	Single mine	0.50 (2)
	2-mine cannister	0.50 (2)
M74AP and M75 ATAV mines (w/o fuzes)	Single mine	8.5 (1)
	Single mine with 3-inch thick aluminum brick shield	0.25

(1) Safe separation distance is greater than distance shown. These are maximum distances tested. Further tests required to establish minimum safe separation distance.

(2) Minimum distance tested. Actual safe separation distance less than or equal to that indicated. Further tests required to establish minimum safe separation distance.

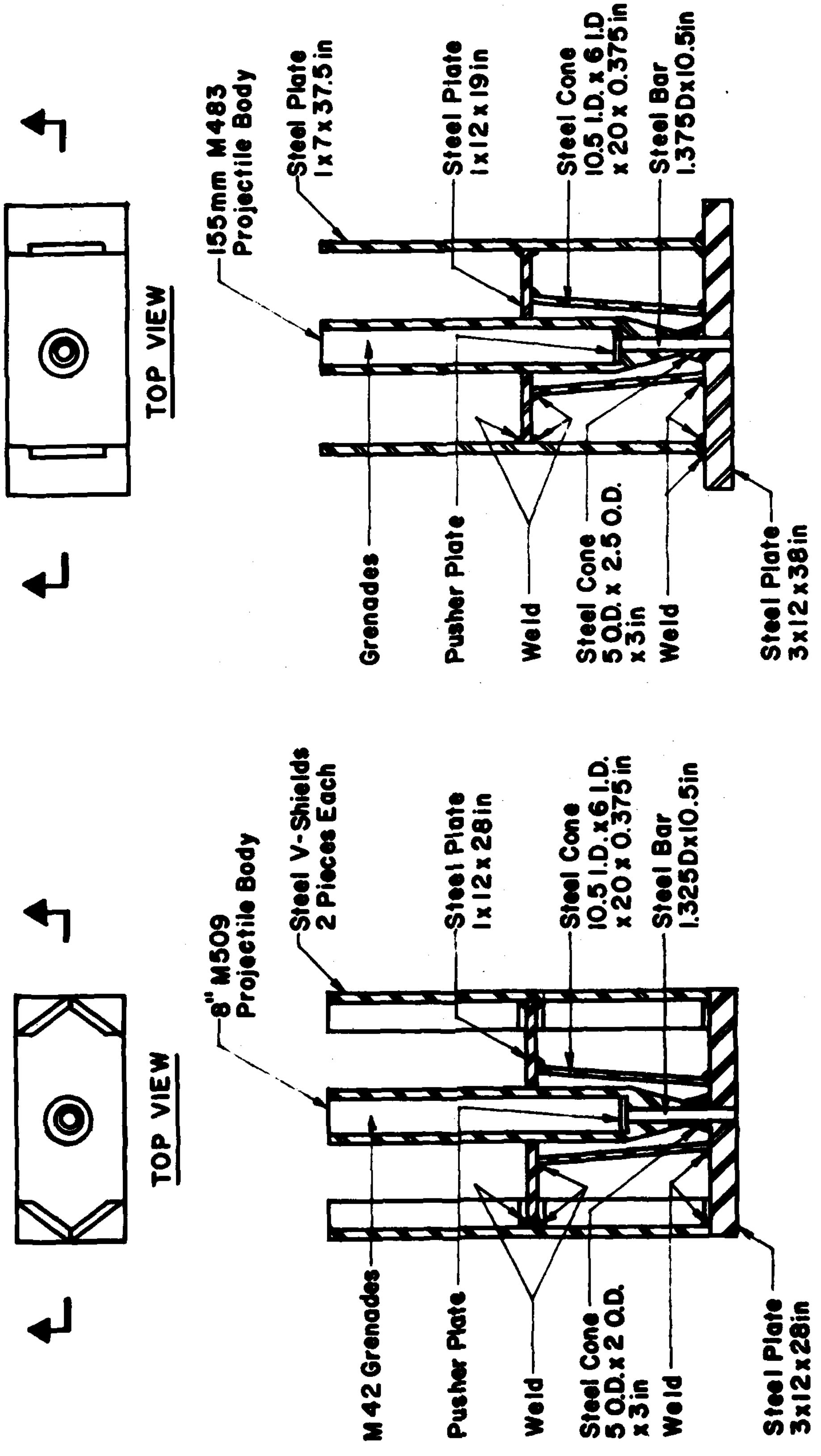


Figure I-5 Safe separation test shields

Several testing methods have been developed to determine the sensitivity of explosives to impact by secondary fragments. In one series of tests which utilized a catapult method for propelling approximately 70 pounds of concrete fragments, sand and gravel rubble, against lightly cased Composition B acceptor explosives indicated a boundary velocity on the order of approximately 400 fps. A second series of tests, which propelled concrete fragments as large as 1000 pounds against 155mm projectiles (thick steel wall projectile), indicated that the projectile would not detonate with striking velocities of 500 fps. This latter test series also included acceptor items consisting of 155 projectiles with thin wall riser funnels, which detonated upon impact with the concrete. Another series of fragment testing included the propelling of large concrete fragments against thin wall containers with molten explosive simulating typical melt-pour kettles in a loading plant. In all cases, the contents of the simulated kettle detonated. Although the results of these test series indicated that thick wall containers of explosive will prevent propagation, while thin wall containers will not, the number of tests performed in each series was relatively few. Additional tests are required to determine the extent that the variation of container thickness has on the magnitude of the mass/velocity boundary established to date.

BASIS FOR STRUCTURAL DESIGN

1-14 Structural Response

1-14.1 *General*

The selection of the dynamic response for use in the design of a protective structure and its elements to the output of an explosion is governed by: (1) the properties (type, weight, shape, casing, etc.) and location of the donor explosive, (2) the sensitivity (tolerance) of the acceptor system, and (3) the physical properties and configuration of the protective structure. The response of the selected protective structure usually depends upon the donor system and the properties of the structure itself. However, in many situations, the acceptor system will control the overall required structural response.

1-14.2 *Pressure Design Ranges*

1-14.2.1 *General*

An engineering analysis of the blast pressures and fragments associated with high explosive detonations acting on protective structures must be made to describe the response of the protective structures to donor output. The response to the blast output is expressed in terms of design ranges according to the pressure intensity, namely, (1) high pressure, and (2) low pressure. As subsequently shown, these design ranges are related to the relative location of the protective structure to the explosion.

1-14.2.2 *High-Pressure Design Range*

At the high-pressure design range, the initial pressures acting on the protective structure are extremely high and further amplified by their reflections on the structure. Also the durations of the applied loads are short, particularly where complete venting of the explosion products of the detonation occurs. These durations are also short in comparison to the response time (time to reach maximum deflection) of the individual elements of the structures. Therefore, structures subjected to blast effects in the high-pressure range can, in certain cases, be designed for the impulse (area under the pressure-time curve, Volume II) rather than the peak pressure associated with longer duration blast pressures. This type of design is usually referred to as incipient failure design where the protective structure is on the verge of collapse. Further, if the acceptor system is comprised exclusively of explosives, the protective donor structure may be permitted to exceed incipient failure and produce "post failure" fragments provided that the fragment velocities are less than that which will initiate detonation of acceptor charges. This latter range of response is referred to as the "brittle mode of failure."

In the event personnel and/or expensive equipment is being protected or where containment type structures are providing the protection, then incipient failure design is not permitted. Here, the effects of the high pressures and the long duration pressures associated with contained products of the explosion must be accounted for in determining the protective structure response.

Fragments associated with the high-pressure range usually consist of high velocity missiles associated with casing breakup or acceleration of equipment positioned close to the explosion. For acceptors containing explosives, the velocities of primary fragments which penetrate the protective structure must be reduced to a level below the velocity which will cause detonation of the acceptor charges. For personnel or expensive equipment, the possibility of fragment impact on the acceptor must be completely eliminated. Also associated with the "close-in" effects of a high-pressure design range is the possible occurrence of spalling of concrete elements. Spalling is generally associated with the disengagement of the concrete cover over reinforcement at the acceptor side of a protective element. Spalling can be a hazard to personnel and sometimes to equipment but seldom will result in propagation of explosion of an acceptor system.

1-14.2.3 *Low-Pressure Design Range*

Structures subjected to blast pressures associated with the low-pressure range sustain peak pressures of smaller intensity than those associated with the high-pressure range. However, depending on the explosion, location and intensity, the peak pressures which can occur in the low-pressure design range may be in the order of magnitude of the response time of the structure. The structural elements designed for the low-pressure range respond to the combined effects of both the pressure and impulse associated with the blast output.

In a few cases where the peak pressure is relatively low and the explosive charge is very large (several hundred thousand pounds of explosive) the duration of blast pressures will be extremely long in comparison to those of smaller explosive weights. Here the structure responds primarily to the peak pressure in a manner similar to those structures designed to resist the effects of nuclear detonations. This latter case, although seldomly encountered, is sometimes referred to as the "very low-pressure range."

Since the low-pressure design range is involved in the design of shelter type structures, donor fragmentation is of concern. Secondary fragments formed from the break-up of donor structures can produce major damage to a shelter. These fragments generally have a large mass but their velocity is highly reduced in comparison to those of primary fragments.

1-14.3 *Analyzing Blast Environment*

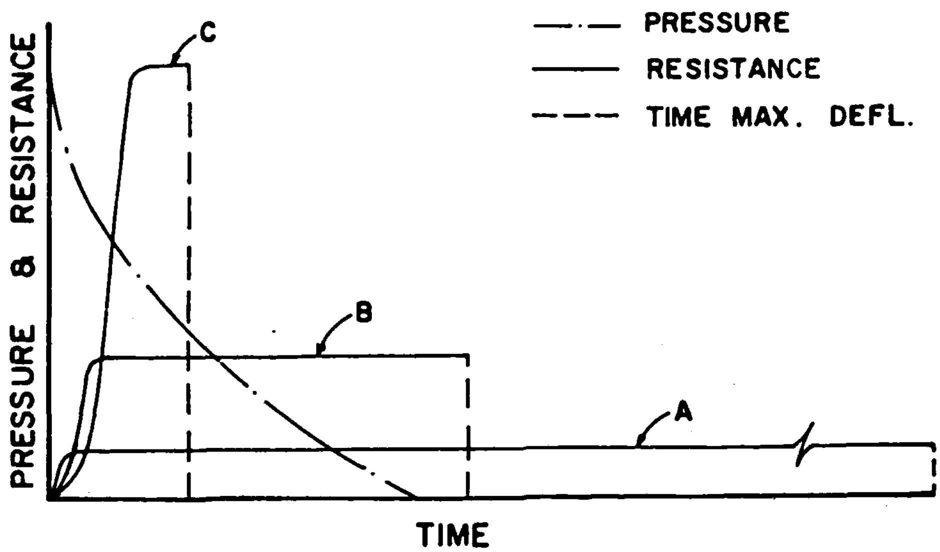
Although each design pressure range is distinct in itself, no clear-cut divisions between the ranges exist; therefore, each protective structure must be analyzed for its own blast environment to determine its response.

Depending on the type of protective structure being considered and its location relative to the explosion, multiple solutions of the structural response can exist, particularly near the fringe areas between the design ranges. To illustrate these fringe areas, consider the three theoretically possible response (resistance-time) curves of an element subjected to a given pressure-time loading (a. figure 1-6a). Curve A represents the resistance-time function of an element which responds to the impulse (high-pressure range where near incipient failure, incipient failure or post failure fragments are tolerated); the time to reach maximum deflection or exceed maximum deflection is very long in comparison to the load duration. The low-pressure range is represented by Curve B where the duration of the load is in the order of magnitude of the response time which is the case of shelter or containment type structures which are designed to sustain small deflections. In other design cases, the response time of an element subjected to low-pressure range can be less than, equal to, or greater than the load duration (figure 1-6a). This variation depends upon the parameters of the blast (pressure and duration), the physical properties (strength and period of vibration) of the elements, and the maximum deflection permitted. Curve C illustrates the very low-pressure design range of an element. The required peak resistance is in the order of magnitude of the peak pressure, while the duration of the load is extremely long compared to the time to reach maximum deflection. Although the required maximum resistance will vary in comparison to the peak pressure, the variation will be slight and, in general, the required maximum resistance of an element to resist long duration loads will be only slightly larger (5 to 10 percent) than the peak pressure.

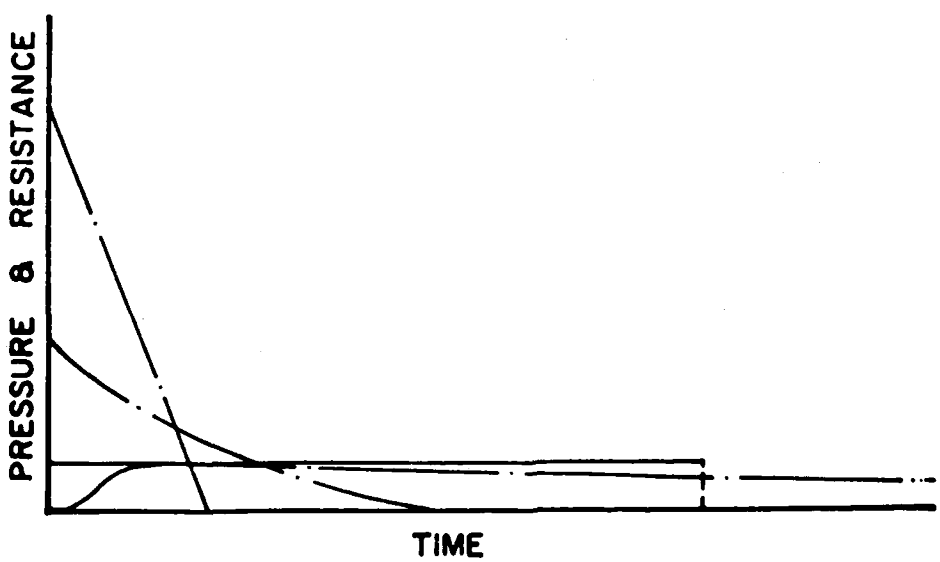
Multiple solutions of the structure response near the fringe areas are illustrated in figure 1-6b. The magnitude of both the peak pressure and duration of each curve has been selected so that the areas under the individual curves are equal to one another. Also, the area under the resistance-time curve is equal to the area under each pressure-time curve, resulting in a situation where the response of the element can be resolved by any one of the design range methods (Volume III), thereby obtaining the same response for all three conditions. Figure 1-7 indicates semi-quantitatively the parameters which define the design ranges (including the very low range) of an element, along with the approximate relationship between the time to reach maximum deflection and the load duration.

It was indicated earlier that the design range of an element is related to the location of the element relative to the explosion. For the quantity of explosives considered in this manual, an element designed for the high-pressure range is usually situated immediately adjacent to the explosion, and its exposed surfaces facing the explosion are oriented normal or nearly normal to the propagation of the initial pressure wave (figure 1-8, cases I through IV). On the other hand, elements which are located close to the explosion and are positions parallel to the path of the wave propagation may respond to the blast effects associated with the low pressure design range. Elements located close to a detonation seldom respond solely to a peak pressure.

Certain elements of a protective structure located a distance from the explosion may respond to the impulse (high-pressure range) even though they are located at the low-pressure range while other structures located near the explosion will respond to the low-pressure design range. In the former case, the structure will not contain personnel or expensive equipment and will primarily serve as a barrier structure. In the latter case, the structure will serve as a shelter (Case I, figure 1-8).

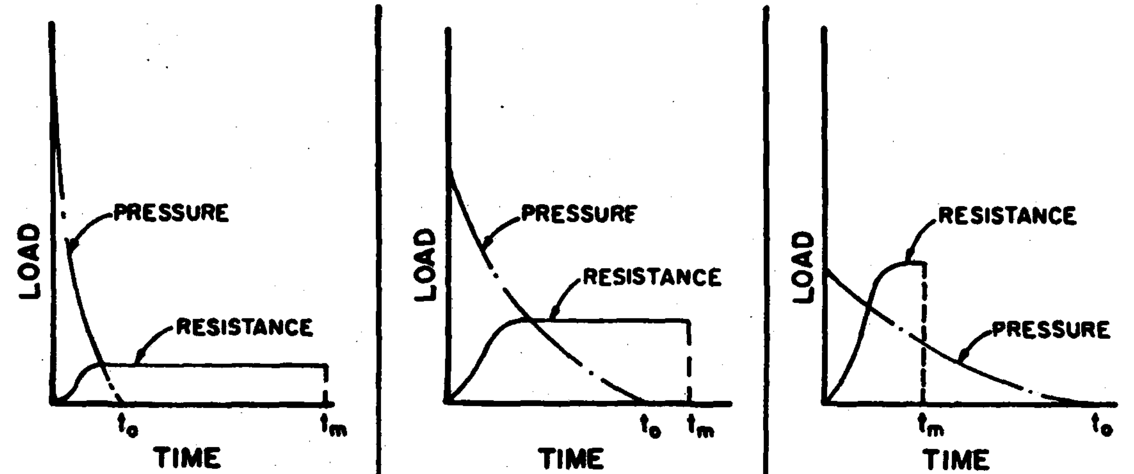


a) VARIABLE RESISTANCE – TIME CURVES



b) VARIABLE PRESSURE – TIME CURVES

Figure 1-6 Variation of structural response and blast loads



PRESSURE DESIGN RANGE	HIGH	LOW	VERY LOW
DESIGN LOAD	IMPULSE	PRESSURE - TIME	PRESSURE
INCIDENT PRESSURE	$\gg$ 100 psi	$<$ 100psi	$<$ 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 1-7 Parameters defining pressure design ranges

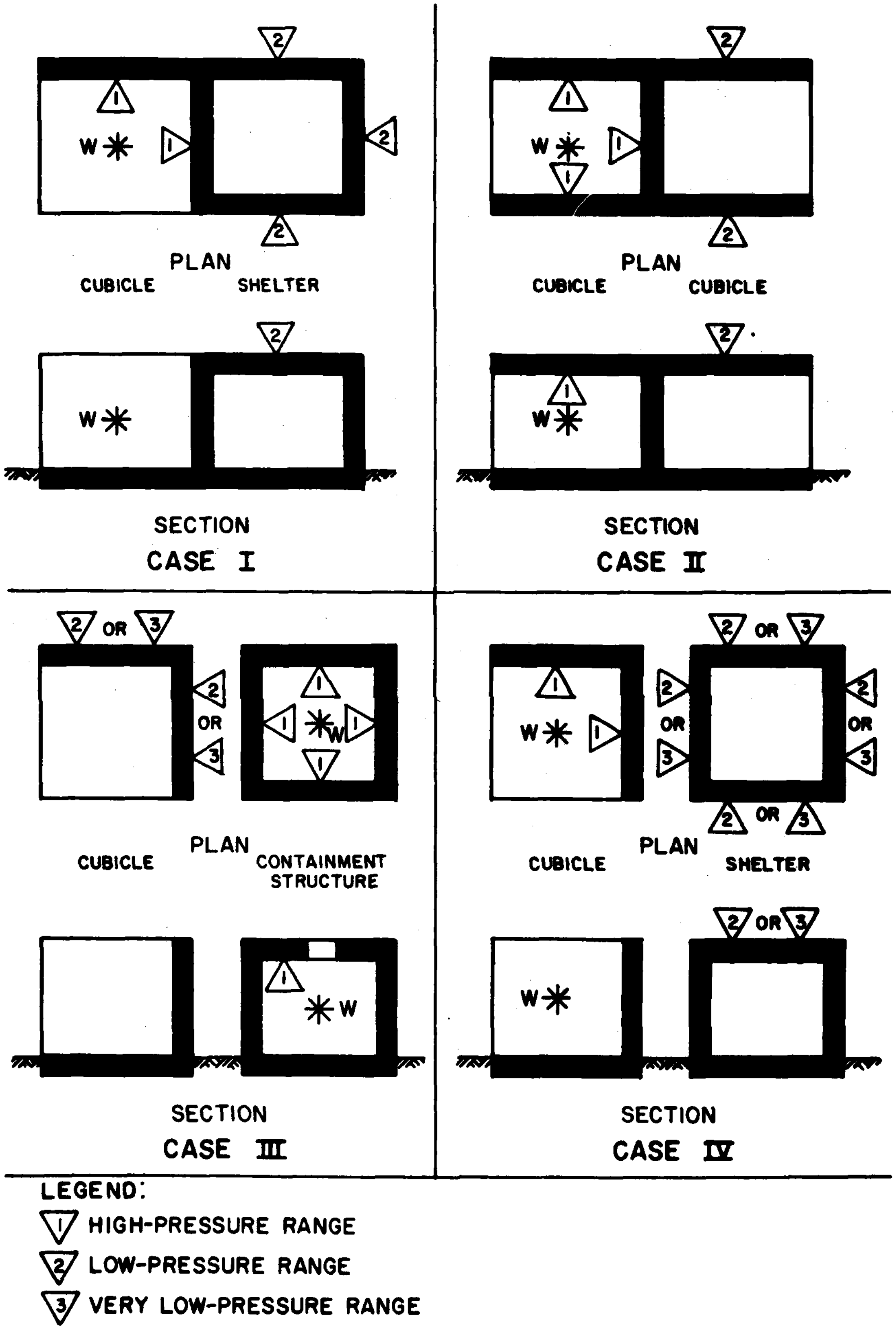


Figure 1-8 Design ranges corresponding to location of the structural elements relative to an explosion

APPENDIX 1A
LIST OF SYMBOLS

LIST OF SYMBOLS

g	acceleration due to gravity (ft/sec^2)
i	unit positive impulse (psi-ms)
i_s	unit scaled impulse for use in figure 1-2 ($psi\text{-}ms/lb^{1/3}$)
p	pressure (psi)
t_m	time at which maximum deflection occurs (ms)
t_o	duration of positive phase of blast pressure (ms)
V	volume of containment structure (ft^3)
w_h	weight of human being (lbs)
W	charge weight (lbs)

APPENDIX 1B
BIBLIOGRAPHY

BIBLIOGRAPHY

1. Structures to Resist the Effects of Accidental Explosions (with Addenda), Department of the Army Technical Manual (TM5-1300), Department of the Navy Publication (NAVFAC P-397), Department of the Air Force Manual (AFM 88-22), Washington, D.C., June 1969.

2. Dobbs, N., Structures to Resist the Effects of Accidental Explosions, Volume I, Introduction, Special Publication ARLCD-SP-84001, Prepared by Ammann & Whitney Consulting Engineers, New York, N.Y., for U.S. Army Armanent Research, Development and Engineering Center, Armament Engineering Directorate, Picatinny Arsenal, Dover, New Jersey, December 1987.

3. Ayvazyan, H., et al., Structures to Resist the Effects of Accidental Explosions, Volume II, Blast, Fragment, and Shock Loads, Special Publication ARLCD-SP-84001, Prepared by Ammann & Whitney Consulting Engineers, New York, N.Y., in association with Southwest Research Institute, San Antonio, TX, for U.S. Army Armament Engineering Directorate, Picatinny Arsenal, Dover, New Jersey, December 1986.

4. Dede, M., et al., Structures to Resist the Effects of Accidental Explosions, Volume III, Principles of Dynamic Analysis, Special Publication ARLCD-SP-84001, Prepared by Ammann & Whitney Consulting Engineers, New York, N.Y., for U.S. Army Armament Research and Development Center, Large Caliber Weapon systems Laboratory, Dover, New Jersey, June 1984.

5. Dede, M., and Dobbs, N., Structures to Resist the Effects of Accidental Explosions, Volume IV, Reinforced Concrete Design, Special Publication ARLCD-SP-84001, Prepared by Ammann & Whitney Consulting Engineers, New York, N.Y., for U.S. Army Armament Research, Development and Engineering Center, Armament Engineering, Directorate, Picatinny Arsenal, Dover, New Jersey, April 1987.

6. Kossover, D., and Dobbs, N., Structures to Resist the Effects of Accidental Explosions, Volume V, Structural Steel Design, Special Publication ARLCD-SP-84001, Prepared by Ammann & Whitney Consulting Engineers, New York, N.Y., for U.S. Army Armament Research, Development and Engineering Center, Armament Engineering Directorate, Picatinny Arsenal, Dover, New Jersey, May 1987.

7. Dede, M., Lipvin-Schramm, S., and Dobbs, N. Structures to Resist the Effects of Accidental Explosions, Volume VI, Special Conditions in Explosive Facility Design, Special Publication ARLCD-SP-84001, Prepared by Ammann & Whitney Consulting Engineers, New York, N.Y. for U.S. Army Armament Research and Development Center, Large Caliber Weapon System Laboratory, Dover, New Jersey, April 1985.

8. Safety Manual, AMC-R 385-100, Department of the Army, Headquarters U.S. Army Materiel Command, Alexandria, Virginia, August 1985.

9. A Manual for the Prediction of Blast and Fragment Loadings on Structures, DOE/TIC-11268, Prepared by Southwest Research Institute, San Antonio, TX, for U.S. Department of Energy, Albuquerque Operations Office, Amarillo Area Office, Pantex Plant, Amarillo, Texas, November 1980.

10. White, C.S., The Scope of Blast and Shock Biology and Problem Areas in Relating Physical and Biological Parameters, Lovelace Foundation for Medical Education and Research, Albuquerque, New Mexico, 1968.

11. Richmond, D.R., et al., The Relationship Between Selected Blast Wave Parameters and the Response of Mammals Exposed to Air Blast, Lovelace Foundation for Medical Education and Research, Albuquerque, New Mexico 1968.

12. Hirsch, F.G., Effects of Overpressure on the Ear - A Review, Lovelace Foundation for Medical Education and Research, Albuquerque, New Mexico, 1968.

13. Clemedson, C., Hellstrom, G. and Lingren, S., The Relative Tolerance of the Head, Thorax and Abdomen to Blunt Trauma, Defense Medical Board, Stockholm and Research Institute of National Defense, Sundbyberg, Sweden; Department of Surgery, University of Uppsala, Uppsala, Sweden; Department of Neurosurgery, University of Gothenburg, Gothenburg, Sweden, 1968.

14. Zaker, T.A., Fragment and Debris Hazards, Technical Paper No. 12, Department of Defense Explosives Safety Board, July 1975.

15. Zaker, T.A., Computer Program for Predicting Casualties and Damage from Accidental Explosions, Technical Paper No. 11, Department of Defense Explosives Safety Board, May 1975.

16. Cohen, E., and Dobbs, N., Prevention of and Protection Against Accidental Explosion of Munitions, Fuels and Other Hazardous Mixtures, Annals of the New York Academy of Science, October 1968.

17. Stirrat W., Compilation of Safe Separation Data on Bulk Explosives and Munitions, Technical Report ARAED-TR-87033, U.S. Army Armament Research, Development and Engineering Center, Dover, N.J., October, 1987.

DISTRIBUTION LIST

Commander
Armament Research. Development and
Engineering Center
U.S. Army Armament, Munitions and
Chemical Command
ATTN: SMCAR-MSI (5)
SMCAR-AE
SMCAR-AEE
SMCAR-AEC
SMCAR-AES
SMCAR-AES-M (10)
SMCAR-TDA
SMCAR-FS
SMCAR-CC
SMCAR-SF
Picatinny Arsenal, NJ 07806-5000

Commander
U.S. Army Armament, Munitions
and Chemical Command
ATTN: AMSMC-GCL(D)
Picatinny Arsenal, NJ 07806-5000

Administrator
Defense Technical Information Center
ATTN: Accessions Division (12)
Cameron Station
Alexandria, VA 22304-6145

Director
Ballistic Research Laboratory
ATTN: AMXBR-OD-ST
Aberdeen Proving Ground, MD 21005-5066

Commander
U.S. Army Armament Munitions and
Chemical Command
ATTN: SMCAR-ESP-L
SMCAR-SF (R) (2)
SMCAR-IR (R)
SMCAR-EN (R)
Rock Island, IL 61299-6000

Commander
Chemical Research, Development and
Engineering Center
U.S. Army Armament, Munitions and
Chemical Command
ATTN: SMCCR-MSI
Aberdeen Proving Ground, MD 21010-5423

Commander
Chemical Research, Development and
Engineering Center
U.S. Army Armament, Munitions and
Chemical Command
ATTN: SMCCR-RSP-A
Aberdeen Proving Ground, MD 21010-5423

CRDC Resident Operations Office
ATTN: SMCCR-TSE-OA
National Space Technology Laboratories
NSTL, MS 39529

Commander
Iowa Army Ammunition Plant
ATTN: SMCIO-SF
Middletown, IA 52638-5000

Commander
Kansas Army Ammunition Plant
ATTN: SMCKA-SF
Parsons, KS 67357-5000

Commander
Radford Army Ammunition Plant
ATTN: SMCRA-SF
Radford, VA 24141-0298

Commander
Lone Star Army Ammunition Plant
ATTN: SMCLS-SF
Texarkana, TX 75505-9101

Commander
Longhorn Army Ammunition Plant
ATTN: SMCLO-SF
Marshall, TX 75670-1059

Commander
Lake City Army Ammunition Plant
ATTN: SMCLC-SF
Independence, MO 64051-0330

Commander
Sunflower Army Ammunition Plant
ATTN: SMCSU-SF
DeSoto, KS 66018-0640

Commander
Badger Army Ammunition Plant
ATTN: SMCEA-SF
Baraboo, WI 53913-5000

Commander
Holston Army Ammunition Plant
ATTN: SMCHO-SF
Kingsport, TN 37662-9982

Commander
Indiana Army Ammunition Plant
ATTN: SMCIN-SF
Charlestown, IN 47111-9667

Commander
U.S. Army Production Base
Modernization Agency
ATTN: AMSMC-PBL-A (D)
Picatinny Arsenal, NJ 07806-5000

Commander
Pine Bluff Arsenal
ATTN: AMCPB-SF
Pine Bluff, AR 71602-9500

Commander
Crane Army Ammunition Activity
ATTN: SMCCN-SF
Crane, IN 47522-5099

Commander
U.S. Army Materiel Command
ATTN: AMCSF
5001 Eisenhower Avenue
Alexandria, VA 22333

Director
AMC Field Safety Activity
ATTN: AMCOS
Charleston, IN 47111

Chief
Benet Weapons Laboratory, CCAC
Armament Research, Development,
and Engineering Center
U.S. Army Armament, Munitions
and Chemical Command
ATTN: SMCAR-CCB-TL
Watervliet, NY 12189-5000

Director
U.S. Army Materiel Systems
Analysis Activity
ATTN: AMXSY-MP
Aberdeen Proving Ground, MD 21005-5066

Chairman
Department of Defense Explosives
Safety Board
ATTN: J. Ward (3)
Hoffman Building 1, Room 856C
2461 Eisenhower Avenue
Alexandria, VA 22331

HQUSACE
ATTN: DAEN-ECE-T (10)
DAEN-RDM
Washington, DC 20314

Commander
U.S. Army Engineering Division
ATTN: HNDED-CS (R. Lein) (10)
P.O. Box 1600
Huntsville, AL 35807

Commander
U.S. Army Construction Engineering
Research Laboratory
ATTN: P.O. Box 4005 (2)
Dr. James Prendergast
Champaign, IL 61820

Commander
U.S. Army Cold Regions REsearch
and Engineering Laboratory
P.O. Box 282 (2)
Hanover, NH 03755

Commander
U.S. Army Engineer Waterways
Experiment Station
ATTN: Library, Helen Ingram (3)
P.O. Box 631
Vicksburg, MS 39180-0631

Commander
Naval Facilities Engineering Command
ATTN: Code FPO-3A, Room 12N57 (20)
200 Stovall Street
Alexandria, VA 22332

Commanding Officer
Naval Civil Engineering Laboratory
ATTN: Code L51, W. Keenan (15)
Port Hueneme, CA 93043

Chief of Naval Operations
Department of the Navy
ATTN: NOP-411F
Washington, DC 20350

Commander
Naval Sea Systems Command
ATTN: SEA-06H1
Naval Sea Systems Command Headquarters
Washington, DC 20362

Commander
David W. Taylor Naval Ship Research
and Development Center
Bethesda, MD 20084

Commander
Naval Surface Weapons Center
ATTN: G10 (J. Proctor)
R12 (W. Filler)
R15 (J. Connor)
R15 (M. Swisdak)
White Oak Laboratory
Silver Spring, MD 20910

Facilities and Maintenance Branch
Department of Energy
Albuquerque Operations
Amarillo Area Office
ATTN: Mr. L.M. Paradee, Chief (5)
P.O. Box 30030
Amarillo, TX 79120

Department of Energy
Facilities and Construction
Maintenance Division
Albuquerque Operations
ATTN: Mr. Manuel G. Martinez (5)
P.O. Box 5400
Albuquerque, NM 87115

AFESC/RDC
ATTN: W.C. Buchholtz (5)
Tyndall AFB, FL 30403

Ammann & Whitney Consulting Engineers
ATTN: N. Dobbs (3)
96 Morton Street
New York, NY 10014

Southwest Research Institute
ATTN: Mark G. Whitney (5)
P.O. Drawer 28510
6220 Culebra Road
San Antonio, TX 78284

Wilfred Baker Engineering
218 E. Edgewood Place (3)
San Antonio, TX 78209

Illinois Institute of Technology
Research Institute
ATTN: H.S. Napadensky
10 West 35th Street
Chicago, IL 60616

Defense Contract Administration Service
Management Area, Dayton (DCASR-CLE-GDQ)
c/o Defense Electronics Supply Center
ATTN: Bill Loser
Dayton, OH 45444

AFATL/DLYV
ATTN: Mr. Ralph McGuire
Eglin AFB, FL 32542

USAED, Europe
EUDAD-TA
ATTN: Roger Crowson (2)
APO New York 09757

DCSAR, Cleveland
ATTN: DCSAR-CEL-QS (4)
1240 East 9th Street
Cleveland, OH 44135

Officer in Charge
White Oak Laboratory
Naval Surface Weapons Center Detachment
ATTN: Robert Hutcheson, Code 12
10901 New Hampshire Avenue
Silver Springs, MD 20903-5000

HQ USAF/LEEE
ATTN: Satish Abrol (5)
Building 516
Bolling AFB
Washington, DC 20332-5000

Department of the Navy
Atlantic Division
Naval Facilities Engineering Command
Code 402, Owen Hewitt
Norfolk, VA 23511-6287

DCSAR N-1-QSS
ATTN; Richard Castell
201 Varick Street
New York, NY 10014-4811

Commander
U.S. Army Engineer District/Fort Worth
ATTN: SWFED-M, Mr. Jose Munoz (2)
P.O. Box 17300
Fort Worth, TX 76102-0300

BMO/AWS
ATTN: Mr. J. Campbell
Building 624/420
Norton AFB, CA 92402

Commander
U.S. Army Engineer District/Sacramento
ATTN: SPKED-M, Mr. Thomas Rudd (2)
650 Capitol Mall
Sacramento, CA 95814-4794