Best
Available
Copy

STUDY OF SHOCK ISOLATION METHODS FOR CIVIL DEFENSE SHELTERS

Prepared for
Department of the Army
Office of the Chief of Engineers
Washington, D. C.
Contract No. DA 49-129-Eng-506

for

The Office of Civil Defense
Department of Defense

Work Order No. OCD-OS-62-159
OCD Research Sub-task 1152C

November 1963

AMMANN & WHITNEY
Consulting Engineers—New York

QUALIFIED REQUESTORS MAY OBTAIN COPIES
OF THIS REPORT FROM:

DEFENSE DOCUMENTATION CENTER
CAMERON STATION
ALEXANDRIA, VIRGINIA 22314

STUDY OF SHOCK ISOLATION METHODS FOR CIVIL DEFENSE SHELTERS

Prepared for
Department of the Army
Office of the Chief of Engineers
Washington, D. C.
Contract No. DA 49-129-Eng-506

for

The Office of Civil Defense
Department of Defense

Work Order No. OCD-OS-62-159
OCD Research Sub-task 1152C

November 1963

AMMANN & WHITNEY
Consulting Engineers—New York

PREFACE

This report was prepared by Ammann & Whitney, Consulting Engineers, New York, under Contract No. DA 49-129-Eng-506 with the Office of the Chief of Engineers, Department of the Army.

This project is part of the FY 1962 research and development program of the Office of Civil Defense, Department of Defense. It was assigned to the Office of the Chief of Engineers, Department of the Army by the Office of Civil Defense in April 1962 because of its relation to previous and current investigational programs and studies in this field being accomplished under the technical guidance of that agency.

ACKNOWLEDGEMENTS

The successful completion of this project is the result of efforts of the staff of the Special Structures Department of the firm of AMMANN & WHITNEY. The work was accomplished under the general direction of Mr. Edward Cohen, Partner-in-Charge, and the immediate supervision of Mr. Edward Laing and Mr. Samuel Weissman. Technical assistance was received from Messrs. Pat DiNapoli, Norval Dobbs, and John Fernandez and Drs. Gerald Goldstein, Wen Liang Chen and Joseph Vellozzi. Other staff members, including Mr. Albert Bayruns and Messrs. Roy LaRose and Frank Wendling, contributed to the editing and the preparation of illustrations.

This project was performed under the supervision of the Missiles and Protective Structures Branch of the Engineering Division, Military Construction, Office of the Chief of Engineers, Department of the Army. Valuable assistance throughout the study was afforded by Mr. George Crowe, of OCE, who monitored the project.

ABSTRACT

Presented are the results of a study devoted to the establishment of basic criteria and shock isolation techniques applicable to hardened civil defense shelters for protection of personnel and equipment against ground shock effects from nuclear weapons. The report includes a comprehensive review of the state of the art covering background information from which are established ground-shock input data and shock spectra, personnel and equipment shock tolerance criteria, and appropriate shock-isolation methods. General shock isolation schemes, including spring systems and cushioning materials, are evaluated. Design examples and cost estimates of specific shock isolation systems are presented and discussed for shallow-buried structures with populations of 10, 100 and 250 persons at the 25-, 100-, and 300-p.s.i. blast overpressure levels for a 20-MT surface burst. Recommendations for further study are given.

* * *

Outlined below are brief summaries of the scope of work of the contract and the Contractor's approach, findings, and recommendations. This summary is intended to enable the recipient of the report to determine quickly whether the report will be of interest to him or to a member of his staff. For a comprehensive technical summary and detailed conclusions and recommendations, the reader is referred to Chapter VIII of this report.

Scope of Work

1. Compilation, review, and summarization of available pertinent publications and sources of data obtained through a research of literature and from meetings with agencies and ex-

perts. Consideration of blast overpressures up to 300 p. s. i. and a single weapon yield up to 20 MT.

2. Establishment of ground shock input data. Development of free-field ground-shock spectra and design spectra for a 20-MT surface burst at 25-, 100-, and 300-p. s. i. overpressure levels applicable to various types of shallow-buried structures at an average site.

3. Establishment of shock tolerance criteria for personnel, equipment, and interior fixtures.

4. Evaluation and summarization of the most promising general types of shock isolation techniques for shallow-buried structures at overpressure levels up to 300 p. s. i. and a 20-MT weapon yield.

5. Development of specific shock isolation systems which provide protection of personnel and equipment housed in shallow-buried personnel shelters having populations of 10, 100, and 250 persons at the 25-, 100-, and 300-p. s. i. blast overpressure levels for a 20-MT surface burst.

6. Determination of approximate estimates of quantities and costs for the design studies of Item 5.

7. Establishment of recommendations for further study.

Approach

1. Review and evaluation of pertinent publications.

2. Establishment of preliminary shock environment and shock tolerance criteria.

3. Meetings with agencies and experts to discuss preliminary criteria and establish the most applicable sources of data.

4. Re-evaluation of preliminary criteria in conjunction with additional information.

5. Establishment of final shock environment and shock tolerance criteria.

6. Evaluation of general shock isolation techniques.

7. Development of design examples and cost estimates for specific shock isolation systems.

8. Establishment of conclusions and recommendations for further study.

Findings

1. Shock-isolation systems can be effectively and economically accomplished for the protection of personnel and equipment against the effects of ground shock.

2. The design shock environment can be adequately described in terms of shock response spectra.

3. Shock tolerances for personnel, as established in the study, can be designated effectively in terms of either vibration or impact. Equipment shock tolerances are designated effectively in terms of vibration.

4. Effective methods of protection for personnel can be achieved by the use of spring-mounted platforms or by protective cushioning materials. Protective clothing and restraining and bracing devices can be used to provide supplementary protection.

5. Shock protection for equipment can be provided by the use of spring-support systems.

6. Appropriate shock-isolation systems for the shelters in the design examples can be accomplished at additional construction costs which vary from 4 to 65 percent of the cost of corresponding non-shock-isolated shelters.

Recommendations

It is recommended that personnel be subjected to simulated ground shock motions so as to substantiate the vibration and impact tolerances established in this study.

TABLE OF CONTENTS

TABLE OF CONTENTS

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

Figure Number	Title	Page

LIST OF TABLES

CHAPTER I

INTRODUCTION

1-1 Objective

Upon the detonation of a nuclear weapon, pressure waves of tremendous intensity are transmitted into the air and into the ground. These waves, which decrease in peak intensity with distance from ground zero, propagate radially outward from the vicinity of the explosion. The resulting forces imposed on the ground and on structures buried within the earth, cause the motions termed "ground shock". Personnel and equipment housed in shelters subjected to ground shock motions require protection against possible injuries or damage which may result from vibration or impact forces. Such protection can be achieved by providing an energy-absorbing system (shock isolation) between the structure shell and the personnel and equipment.

The purpose of this study is to develop effective, economical shock isolation techniques applicable to hardened civil defense shelters for protection of personnel and equipment against the effects of ground shock from nuclear weapons. Blast overpressure levels up to 300 p. s. i. for a 20-MT surface burst are considered.

1-2 Description of Report

The body of the report comprises three groups, namely, (1) Chapters II to VI which contain basic criteria and general shock isolation methods, (2) Chapter VII which contains design studies, and (3) Chapter VIII which summarizes the information and data presented in the preceding groups and also presents conclusions and recommendations. In the appendixes will be found the detailed background information and data from which were developed the contents of Chapters II to VI.

Chapter II describes the procedure for calculating shock spectra and includes a discussion of measured ground motions and structure motions and shock spectra concepts.

Chapters III and IV cover the topic of shock tolerances for personnel and for equipment. The results of the research are summarized and recommended tolerance design criteria are presented.

Chapters V and VI are devoted to general shock isolation techniques, including shock-isolated platforms, protective cushioning materials, protective clothing, and restraining devices.

Design studies of specific shock-isolation systems are developed and illustrated in Chapter VII.

The appendixes contain a detailed compilation of the basic information utilized in the body of the report. To facilitate the use of the appendixes, the references prefixed by the letters A, B, C, or D throughout the discussions in Chapters II to VI indicate the corresponding sections of the appendixes which are pertinent.

CHAPTER II

GROUND MOTION AND SHOCK SPECTRA

2-1 Measured Ground Motions and Structure Motions

Ground motions resulting from a nuclear weapon burst may be transmitted through the ground in a variety of ways. At any particular ground range, the actual ground shock environment is a complex combination of many effects, including air-induced shock, direct-transmitted ground shock, surface waves, reflected and refracted waves, and coupled effects. These effects are further complicated by the interaction of the ground and a buried structure during ground shock.

For design purposes, ground motions associated with nuclear surface bursts (surface bursts produce more severe ground shock effects than air bursts) are considered to be induced by two distinct processes, namely, (1) air-induced shock, and (2) direct-transmitted ground shock. The direct-transmitted ground shock is a transmission of energy into the ground in the immediate vicinity of the explosion and is usually of major importance only in very high-pressure regions. Test data have indicated that the air-induced effects are substantially larger than the direct-transmitted effects for the peak overpressures and type of site conditions involved in this study. Therefore, only the air-induced effects need be considered.

The air-induced shock is caused by the blast wave traveling over the ground surface and generating stress waves into the ground which create ground motions. The characteristics of the air-blast wave (Reference 2.1) are a function of weapon yield, height of burst, and distance from ground zero. This blast wave becomes the impulse loading on the ground surface, inducing the ground shock effects. For a particular impulse loading, the resulting ground motions are dependent upon geological conditions, type of soil, and depth below the surface.

Field measurements have been recorded during nuclear weapon tests. These data have served only as a guide when estimating ground motions for design inasmuch as the scope of the test data was limited to specific weapon sizes and overpressure ranges, and to site conditions which are not necessarily typical. However, these test data, in conjunction with theoretical investigations, have been used as a basis for establishing ground shock criteria for design purposes.

Figures A-1 to A-3 (Appendix A, Pages A-4, A-5, & A-6) include typical curves depicting free-field vertical acceleration, velocity, and displacement versus time as recorded at the Nevada Test Site for a 40-KT weapon yield (burst height of approximately 700 feet) at 229 p.s.i. peak overpressure as presented in Reference 2.2 (Section A-2.2b). Free-field refers to the condition of the ground for which there are no buried structures. Ground motions are shown for various depths below the ground surface down to 50 feet. These data were recorded at a ground range (distance from ground zero) where the air-blast wave arrived prior to the ground wave, at the various depths. The acceleration data were recorded in the field, whereas the velocity and displacement curves were obtained by integration of the acceleration curves.

It is seen in Figure A-1 that the acceleration-time curves are characterized by a single, sharp, downward peak (pulse duration of approximately 10 msec.) preceded and followed by lower amplitude disturbances which become less pronounced with depth because of modification of the wave during its travel through the earth. The surface air-blast arrival time is designated by the vertical line labeled AB, and the arrival time of the motion is indicated. In this case, the early minor disturbances correspond to the precursor (an auxiliary air-blast wave that precedes the main incident wave), and the peak acceleration is produced by the larger peak of the main incident air-blast wave. The time of onset of motion at the surface is the same as the blast arrival time, and the delay time with respect to AB at various depths is the time required for the pressure wave to travel from the surface. The accelerations following the peak pulse are associated with the pressure decay of the air blast, the elastic rebound of the soil, and the arrival of ground waves from sources closer to ground zero. As shown in Figure A-1, a rapid attenuation of the peak surface acceleration and a decrease of frequency with depth occurred, both of which are typical of free-field accelerations in both the vertical and horizontal directions. The peak acceleration at the surface (one-foot depth) was 188.3 g., and the peak acceleration at the 50-foot depth was 12.8 g. (One g. is the acceleration of gravity.)

For larger weapon yields, such as the 20-MT surface burst considered in this study, the general characteristics of the acceleration curve would be similar to the data plotted in Figure A-1 except that the sharp peak would be followed by disturbances of longer duration due to the longer positive-phase duration of the air blast. The occurrence of early disturbances depends on whether or not a precursor forms and also on the relative velocity of the air-blast shock front and the ground-wave propagation. If the ground-wave propagation velocity (seismic velocity) is greater than the velocity of the air-blast shock front, ground motions will arrive prior to the air blast. These motions are generated (air induced) at locations closer to ground zero than the ground range being considered. If the seismic velocity is less than the velocity of the air-blast shock front, the onset of the ground motions is associated with the arrival of the air-blast wave, as is the case for the test records shown above.

The peak incident pressure and the shock-front velocity of the air-blast wave decrease with distance from ground zero. The seismic velocity is nearly the same value (for particular geological conditions) regardless of the magnitude of the ground waves. Thus, as the air-blast wave travels away from ground zero, a point is reached beyond which ground motions will arrive prior to the air-blast wave. Such ground motions may cause an initial upward motion; however, it is expected that these early disturbances will be of minor magnitude compared to the amplitudes associated with the main air-blast shock. For typical soil sites, the ground motions will arrive prior to the air-blast wave at ground ranges where the peak incident overpressures are less than approximately 100 p.s.i. The delay time between the onset of ground motion and the arrival of the air-blast wave will, naturally, increase as the distance from ground zero increases.

As the peak incident overpressure decreases (i.e., increasing distance from ground zero), the upward peak acceleration following the sharp downward peak tends to increase with respect to the downward peak (Reference 2.2). As examples, for the overpressures considered in this study, at the 100-p.s.i. ground range the ratio of peak downward to upward acceleration would be lower than at 300 p.s.i.; and at 25 p.s.i. the upward peak may be equal to the downward peak.

The accelerations occurring prior to, and following, the sharp downward peak depend on the ground-wave contributions at the particular site and on the precursor effects. These can combine to cause a random-type motion of various frequencies. The ground-wave contributions from points closer to ground zero tend to extend the duration of the disturbances since they may arrive after the duration of the positive phase of the air blast (Reference 2.2).

A somewhat clearer understanding of this ground motion over its entire duration can be obtained from study of the free-field ground velocity and displacement wave forms.

Velocity-time curves, obtained from a numerical integration of the acceleration-time curves, are plotted in Figure A-2. The shapes of the velocity curves are similar to that of the air-blast wave but fall off somewhat more rapidly than the air-blast wave and become zero before the end of the positive phase of the air-blast. The rebound of the ground motion results in a peak upward velocity which is expected to be much smaller than the downward velocity (Reference 2.2), although the rebound portion of the plotted curves is not complete. As may be expected, attenuation of the velocity with depth below the ground surface is considerably less than that of acceleration since the duration of the acceleration pulse increases with depth. The peak velocities vary from 15.9 to 4.66 ft./sec.

Displacement-time curves, obtained from a double integration of the acceleration records, are plotted in Figure A-3. It is seen that the wave forms exhibit a gradual time of rise to the peak value which occurs approximately at the end of the positive phase of the air blast; however, for other site conditions the peak displacement value may occur at an earlier time. Actually, a near-peak value occurs considerably before the end of the positive phase inasmuch as most of the impulse is expended in the early portion of the air-blast wave because of the rapid decay. These displacement curves obtained by integration of the acceleration records are not valid beyond the peak displacement value. Other data of direct displacement measurements, as presented in Reference 2.3 (Section A-2.2c) and Reference 2.4 (Section A-2.2d), indicate that, after the peak downward displacement, the displacement rebounds because of elastic action and quickly damps out, leaving a residual permanent displacement due to plastic action. As shown in Figure A-3, the attenuation of the peak displacement with depth is gradual. The peak displacements vary from 9 to 3.5 inches.

It is to be noted that the displacement and velocity ground motions are characterized by a predominant single downward pulse followed by an upward pulse of lesser amplitude and then by a quick damping out of the motion. In the case of the displacement, the rebound may recover only a portion of the peak downward motion and not result in any net upward value. The duration of the downward velocity pulse is in the order of the positive-phase duration of the air blast, and the duration of the corresponding downward displacement pulse would be in the order of twice the positive-phase duration. As previously indicated, the acceleration wave form is characterized by a single, sharp, downward peak followed by an upward peak and then by a high-frequency random-type acceleration of lower amplitude. The sharp downward acceleration pulse results in the peak ground velocity, and the subsequent accelerations correspond to the decay and rebound of the velocity pulse which, of course, signifies that the net area under the acceleration-time curve, following the downward pulse, is in the upward direction.

Generally, the horizontal free-field ground motions have characteristics similar to those of vertical motions in which case the initial peak motion is outward from ground zero and is followed by a rebound in the opposite direction.

The recorded free-field ground motions illustrate general ground-shock phenomena associated with a nuclear explosion. Actual ground shock motions for different site conditions and other shock levels are uncertain. However, the parameters affecting variations with regard to peak intensity can be discussed. It is generally expected that the peak accelerations and the peak velocities increase proportionally to the peak incident overpressure of the air-blast wave and are essentially independent of the weapon yield. The peak displacement is proportional to the impulse of the air-blast wave and is, therefore, dependent upon both the weapon yield and the peak incident overpressure. Thus, for weapon yields in the megaton range, the peak displacement values, at a 229 p. s. i. ground range, would be higher than those recorded for the 40-KT nuclear burst plotted in Figure A-3, assuming that such a test were conducted at a site similar to the Nevada Test Site. The strength and stiffness of the ground also affect the peak intensity of the ground shock motions. The peak intensities of the motions are assumed to be proportional to the seismic velocity of the ground as will be explained in Section 2-3. The seismic velocities of the soil layers down to 650 feet below the ground surface at the Nevada Test Site are lower than those usually encountered at many construction sites.

It is important to note that the ground motions described above are free-field motions inasmuch as there were no structures or other large discontinuities of mass present in the ground in the area of the test measurements. The motion of a buried structure, compared to the free-field ground motions, would depend on the dimensions and mass of the structure. Generally, a small light structure would tend to move with the surrounding soil in accordance with free-field motions, whereas the motions of a larger structure would not be the same as the free-field motions.

Except for an extremely long structure parallel to the direction of the blast wave, the latter will completely engulf the structure and surrounding soil. The loading lasting several seconds (for megaton weapon yields), would cause the structure to experience a peak displacement of the same order of magnitude as that of the peak free-field displacement since the soil beneath the structure receives a total impulse, transmitted through the structure foundation, similar to that in the case of the free-field impulse loading. However, the peak acceleration of the structure (considered as a rigid body) would be less than the peak ground acceleration in the free field because of the longer rise time of the loading on the structure.

Theoretically, in order to determine the motions of an underground shelter, it is necessary to evaluate the interaction of the structure and surrounding soil during the transient ground shock motions. The phenomena associated with these interaction effects are extremely complex and difficult to analyze, and it is necessary that simplified conditions be assumed to obtain even an approximate solution. For design purposes, one such solution is obtained by means of ground-shock response spectra in which case the shock effects of estimated peak ground motions are represented in terms of the peak dynamic response of the structure and its contents to the shock environment. Shock spectra concepts and the procedure for calculation of shock spectra will be described in the following sections.

2-2 Shock Spectra Concepts

When structural systems or equipment are subjected to a base disturbance, as for example that arising from the ground motion associated with a nuclear blast, the response of the system is governed by the distribution and magnitude of the masses and the resistance elements. A knowledge of the response of systems subjected to such loadings is extremely important from the standpoint of design in order to protect the structure, equipment, and personnel from shock damage. It is necessary to consider the transmission of shock and vibration to only the interior structural components and contents of the structure, since for exterior portions of the structure, it is generally sufficient to consider the predominant effect of the direct pressure only when analyzing and designing individual exterior portions of the structure.

For purposes of assessing the relative effects on components of a structure, or the effects on items mounted within the structure, one of the simplest interpretations of ground motion data involves the concept of the response spectrum, which is a plot of frequency versus maximum response of a simple linear oscillator subjected to a given input motion. Studies of shock spectra that have been determined from ground motion measurements, from both blast and earthquake sources, suggest that response spectra can be described in a relatively simple manner in terms of the maximum values of ground displacement, velocity, and acceleration.

As discussed in the previous section, the time history of the actual ground motions caused by the passage of a shock wave over the surface is very complex and subject to considerable uncertainty for site conditions and shock levels different from those of the full-scale nuclear tests. However, the principal effects on equipment and structural components can be described quite readily by use of the concept of the shock response spectrum.

An item of equipment or an internal element of a structure supported at a point in an underground structure subjected to ground shock motions can be represented as a simple oscillator as shown in Figure 2-1. This oscillator represents a single-degree-of-freedom system which signifies that only one generalized coordinate, u, is necessary to specify the relative motion of the mass m. The oscillator shown is an undamped system.

The absolute motion of the mass m is designated y, the ground motion or support motion by x, and the motion of the mass relative to the support by u. The resistance (force developed) of the supporting spring connecting the mass to the ground is r in which $r = ku$, where k is the spring constant for the spring.

The natural circular frequency (radians per second) of the oscillator is given by the equation:

$$\omega = \sqrt{\frac{k}{m}}$$

and the natural frequency (c. p. s.) by:

$$f = \frac{1}{2\pi}\sqrt{\frac{k}{m}}$$

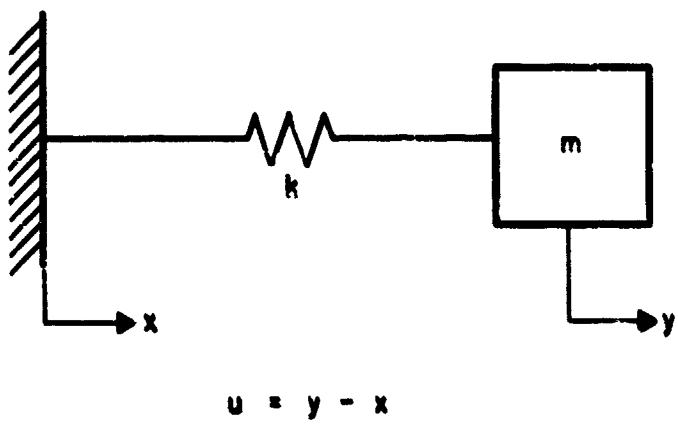


Fig. 2-1 SINGLE DEGREE OF FREEDOM SYSTEM

For a given transient ground motion $x(t)$, the mass m will be set into motion. Considering the ground acceleration $\ddot{x}(t)$, the governing differential equation of motion in terms of the motion of the mass relative to the ground motion is:

$$\ddot{u} + \omega^2 u = -\ddot{x}$$

The solution of this equation (Reference 2.5) is the response of the oscillator to the ground motion. This response is the displacement u relative to the ground motion or support motion. The maximum value of u is called the displacement response spectrum, denoted herein by the symbol D. The maximum value of the absolute acceleration of the mass m is called the acceleration response spectrum, and is denoted here by the symbol A. The maximum value of the mass m relative to the support is approximately equal to a quantity called the "pseudo-velocity" response spectrum V. The maximum responses for the case of a small amount of damping would be approximately the same as those calculated for the undamped oscillator.

The relations between D, V, and A are:

D = Displacement Spectrum
V = ωD = Velocity Spectrum
A = ω^2D = Acceleration Spectrum

For a given input motion the values of D, V, and A are functions only of the frequency f of the oscillator (or system) considered. A single plot of the values of D, V, and A can be drawn, as functions of frequency, by use of the type of chart shown in Figure 2-2. Spectrum values derived from test measurements generally form a curve of the shape indicated by the dashed line. As will be discussed in the following section, design spectra curves can be calculated on the basis of peak ground motions. Such spectra are represented by a straight-line plot as shown by the solid line in Figure 2-2. This straight-line plot constitutes an approximate spectra "envelope".

The spectra grid is a log-log plot determined by multiplication of the displacement spectrum values by the circular frequency ω and the circular frequency squared ω^2.

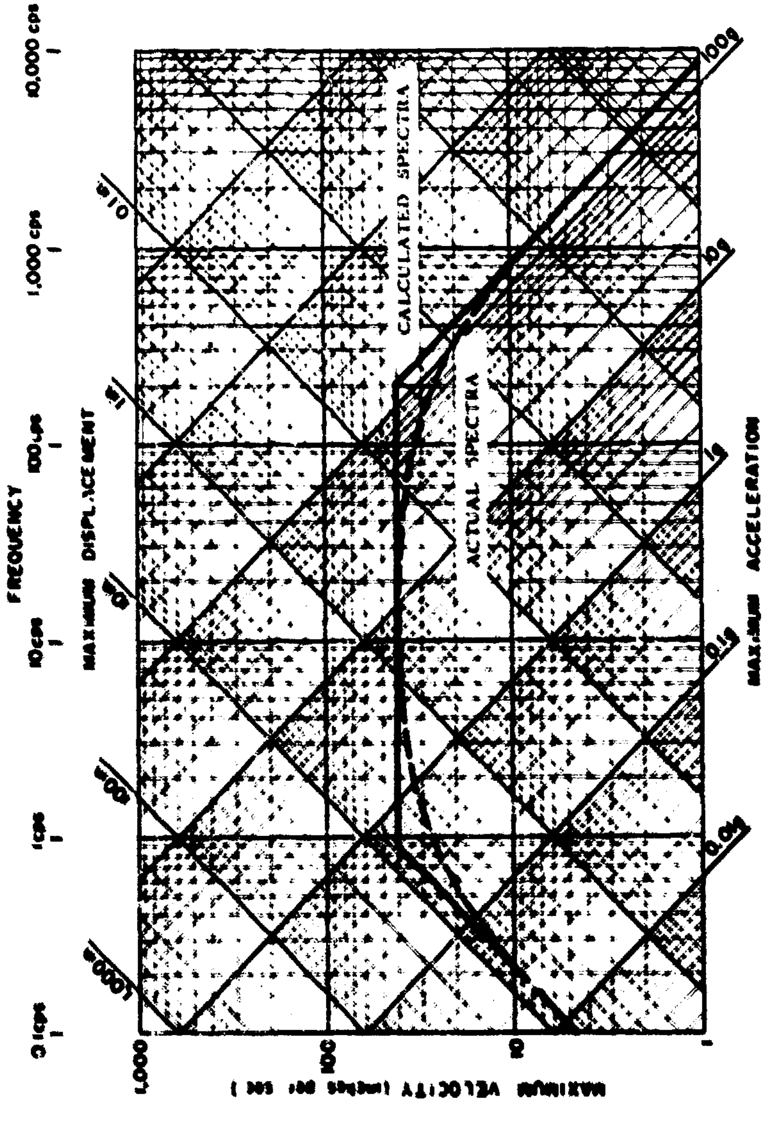


Fig. 2-2 TYPICAL SHOCK SPECTRA PLOT

thereby giving the velocity spectrum and the acceleration spectrum, respectively.

It is shown in Figure 2-2 that the shape of the spectra is such that the highest displacement response (7 inches) occurs in the low frequency range and decreases as the frequency increases, whereas the acceleration response increases as the frequency increases. The highest acceleration response is 125 g. The solid line is the calculated free-field ground-shock spectra at the ground surface for a 20-MT weapon yield at 100 p. s. i. peak overpressure level. For example, an oscillator with a natural frequency equal to 5 c. p. s. would have the following peak response to the ground motions: displacement D equal to 1. 3 inches and acceleration A equal to 3. 2 g. With reference to Figure 2-1, this means that the deflection u of the spring is 1. 3 inches causing a force r equal to ku. The peak acceleration of the mass is 3. 2 g. This acceleration can also be determined by dividing ku by m.

Free-field ground shock spectra have been measured in the field by recording the response of reed gages (oscillators) of various frequencies, to the free-field ground motions. These reed gages are mounted in a container which is buried in the ground. Spectra were also recorded within a buried shelter by mounting reed gages to the interior of the structure. Examples of test measurements recorded at the Nevada Test are presented in Section A-3. 2c. The designer is usually confronted with the task of establishing free-field ground-shock spectra and design spectra for a proposed hardened structure at a site and a protection level for which there are no directly applicable test data available. The next section describes a current procedure used for estimating such spectra. This procedure for calculating shock spectra is used in this study.

2-3 Procedure for Calculation of Shock Spectra

From studies of many earth-shock response spectra, it has been found that the general characteristics and approximate magnitudes of spectra values can be plotted if the maximum values of ground displacement, ground velocity, and ground acceleration are known. Fortunately, it is not necessary that the time history of the ground or support motion be known to estimate response spectra, within the accuracy of other weapon effects data.

Equations for calculating the maximum values of air-induced free-field ground displacements, velocities, and accelerations as presented in Reference 2-6 (Section A-2.?a) are summarized in Appendix C. According to these equations (and as discussed in Section 2-1), peak ground motions are a function of the weapon yield, peak incident overpressure, geological conditions, and depth below the ground surface. The geological conditions are represented by the seismic velocity profile at the site.

When applying the equations, it is found that the peak ground motions are approximately proportional to the seismic velocity profile as follows. The peak displacement is dependent on the seismic profile down to the lower depths (thousands of feet) and is also dependent on the near surface layer. The elastic component of displacement consists of strains down to great depths, whereas the plastic component occurs primarily in the upper layer. Small variations in the depth of the various seismic (ground) layers do not affect the computed peak displacement. The peak velocity and the peak acceleration are dependent on the seismic velocity in the vicinity of the depth being considered and are, therefore, sensitive to thickness of the seismic layers.

Free-field ground shock spectra at each depth depend on the peak free-field ground motions at that depth. The low-frequency range of the spectra depends on the peak ground displacement, the high-frequency range on the peak displacement, and the intermediate frequency range on the peak ground velocity. The spectra envelope (refer to solid line in Figure 2-2) is determined as described below (Reference 2.6):

1. A line parallel to the lines of constant displacement, drawn with magnitude equal to the maximum ground displacement D.

2. A line of constant velocity drawn with a magnitude of 1.5 times the maximum ground velocity V.

3. A line parallel to the lines of constant acceleration, drawn with a magnitude equal to the maximum acceleration.

It is generally felt that spectra measured within a structure would have lower values at certain frequencies than the free-field shock spectra. As discussed in Section 2-1, a buried structure would tend to experience a peak displacement of the same order of magnitude as the peak free-field displacement. This means that the low-frequency portion of the structure spectra would be similar to that of the free-field spectra. It is expected that the peak acceleration of the structure (as a rigid body) would be less than the peak ground acceleration. This corresponds to lower responses in the higher frequency range of the structure spectra compared to that of the free-field spectra. Depending on the flexibility of an actual structure, peak accelerations of the roof slab may be higher than the rigid-body acceleration of the structure if the roof is near the ground surface. In addition, it may be possible to transmit high-frequency ground accelerations directly through the structure roof or walls although these accelerations would also be reduced because of the structure flexibility and structure damping.

Although it is expected that the peak acceleration (and thereby the acceleration bound of the spectra) for a buried structure may be considerably less than that of the free-field, the extent of this reduction and its exact dependence on the parameters involved (size of structure and geology, etc.) is not known. The recommendations presented in Section A-3.1b will be followed. These recommendations are based on a review of the scant test data available and on other information. This study includes shallow-buried structures with an earth cover in the order of several feet. In addition, both short (less than 30 feet) and tall structures are considered. Geological conditions are based on a soil site.

For short, shallow-buried structures, the design shock spectra for the structures shall be the same as the free-field spectra at a depth approximately equal to the mid-height of the structure.

For establishing design shock specra for tall, shallow-buried structures, it is advisable that the free-field spectra at a depth above the mid-height of structure be used. This accounts for the added induced motions of the structure due to the larger frictional forces acting on the exterior surface of the shell of a tall structure. In addition, because of the rapid attenuation of the peak free-field acceleration with depth, the application of the free-field spectra at the mid-height of a tall structure would not properly account for the acceleration of the structure, due to the impact of the blast loading on the roof. Also, the displacement at the base of a tall structure will be larger than the free field at the same depth because of the direct transmission of the virtually unattenuated roof loads to the soil below the foundation compared to a considerable attenuation in the free field as the blast wave propagates down through the soil. For the case of a short structure this effect would be small.

It is important to note that these recommendations are based on a soil site, and judgment must be exercised in their application with regard to the changes in soil layering adjacent to the structure. For a structure located on a dense or rock-like material compared to the soil above, application of the free-field spectra at the mid-height or above may result in peak displacements which are too high.

2-4 References

2.1 Glasstone, S. (Editor), The Effects of Nuclear Weapons, Revised Edition, U.S. Atomic Energy Commission, April 1962. Available from the U.S. Government Printing Office.

2.2 Swift, L. M. et al, Ground Acceleration, Stress, and Strain at High Incident Overpressures, Operation Plumbbob, Project 1.4, WT-1404, May 1960. Prepared by Stanford Research Institute for the Defense Atomic Support Agency. (Secret - Formerly Restricted Data).

2.3 Perret, W. R., Ground Motion Studies at High Incident Overpressures, Operation Plumbbob, Project 1.5, WT-1405, June 1960. Prepared by Sandia Corporation for the Defense Atomic Support Agency.

2.4 Cohen, E. and Weissman, S., "Underground Shock Environment Data and Application to the Design of Underground Structures", Shock, Vibration and Associated Environments, Part III, Bulletin No. 28, September 1960, pp. 269-322. Prepared by Ammann & Whitney, Consulting Engineers, for the Office of the Secretary of Defense (Research & Engineering). Available from the Defense Documentation Center (AD No. 244 784).

2.5 Fung, Y. C., "Shock Loading and Response Spectra", Shock and Structural Response, August 1960. The American Society of Mechanical Engineers, New York City, pp. 1-17.

2.6 Protective Construction Review Guide (Hardening), Volume I, June 1961. Prepared by Newmark, Hansen & Associates for the Office of the Assistant Secretary of Defense (Installations & Logistics).

CHAPTER III

SHOCK TOLERANCES FOR PERSONNEL

3-1 Basic Concepts

The purpose of a civil defense shelter is to provide personnel and emergency equipment with a level of protection against the weapon effects associated with a nuclear burst. For blast shelters, this protection level is generally specified in terms of a particular peak incident overpressure level (equivalent to a particular ground range) for a particular weapon yield and height of burst. The structure is designed to carry the blast pressure loads without interior pressure buildup. It is also designed to reduce the thermal radiation, nuclear radiation, and ground shock motions to tolerable levels. The blast-load structural design requirements will, in almost every case, provide more than enough thermal radiation shielding. At very low overpressures (5-10 p.s.i. and below) additional shielding is generally required to obtain the necessary fallout-radiation protection. This shielding is achieved by increasing the roof slab thickness or by providing additional earth cover. For higher overpressures, initial nuclear-radiation shielding requirements may control the roof thickness or depth of earth cover.

Ground shock motions cannot be completely prevented from affecting the shelter interior in the manner that the blast pressure loading is resisted by the shelter and ambient pressures are maintained. Shock effects can be attenuated but not eliminated. The structure provides only nominal protection against the ground motions, depending upon the flexibility of the structural members. For additional shock protection, an energy-absorbing system must be provided between the structure shell and the personnel. The extent of this shock isolation depends upon the personnel tolerance levels.

For personnel housed in a hardened, underground structure, the principal biological effects of ground shock encompass pain or injuries that might occur as a consequence of the motions of the shelter. Proper assessment of this hazard requires knowledge in at least two areas; namely,

(a) information concerning the motions of the structure, and (b) man's tolerance to the environment as a function of the motions.

The structure motions, which are a function of the free-field motions discussed in Chapter II, are transient (several seconds duration) in nature and are characterized by (1) a low-frequency downward displacement which reaches a maximum value generally near the end of the positive phase of the air blast wave, then rebounds and damps out quickly, and (2) a high-frequency random acceleration which reaches a peak value in the extreme early stages of the motion. In some cases, the initial motion may be upward but of less magnitude than the following downward movements. In addition, there is horizontal motion of the structure of similar character.

Although exact magnitudes of the structure motions are not necessary for estimating shock and vibration tolerances for personnel housed within the structure, the nature of the motions and their duration are considered pertinent since tolerance has meaning only in terms of a particular type of environment or exposure.

Because the motions in a ground shock environment are transient in nature and could possibly result in imparting an abrupt velocity change to the body, either in stopping or starting, in addition to a shaking or vibrating of the body, it is necessary that human tolerance to two types of shock exposures be considered; namely, (1) impacts involving velocity shocks causing body acceleration or deceleration, and (2) body vibrations.

In a structure subject to ground shock, a person may experience various types of motions depending upon his location and posture within the structure and upon the flexibility of the supporting system. The latter is a function of the degree of isolation of the seat and/or floor which supports the subject, and of whether or not he is attached to his seat by straps or seat belts.

If the floor is not shock isolated, its motions are approximately the same as those of the structure as in the case of a floor slab which is monolithic with the structure shell. Therefore, a subject not attached to the floor is vulnerable to impacts resulting from collision with the floor due to the structure dropping out from beneath him and/or the structure rebounding upward beneath him. Impacts may also result as a consequence of the subject being thrown off balance because of the horizontal motions of the structure resulting in his being thrown bodily against other persons, furniture, walls, or other hard surfaces.

If a subject is attached to a structure, he will experience the actual motions of the structure. In some cases, the resulting effect could be more severe than that for non-attached personnel.

The floor system may be shock isolated by either being mounted on springs or being suspended from the ceiling. In this case, the motions of the floor differ from the structure motion. Peak structure accelerations will be reduced and the floor response will be a vibration in accordance with the frequency of the system. This vibration will, in general, be somewhat longer in duration than the transient structure motions, depending upon the amount of damping in the spring system. It is expected that most systems will stop vibrating in less than 30 seconds. Although the floor motion is modified, separation from non-attached personnel may still result depending on the degree of shock isolation. If the isolation limits the peak acceleration response to less than one g., separation will be prevented. Personnel attached to a shock-isolated floor by means of seat belts or other strapping, will experience the vibratory response of the floor. A subject may also be isolated by individual isolation of his support, such as a spring-mounted chair or cot. In this case, he will be subjected to the vibratory response of the individual support.

The motions of a structure in a ground-shock environment may have several possible effects on personnel housed within such a structure. The motion may interfere directly with physical activity and/or it may result in discomfort, pain, trauma, or mortality. Other effects associated with long-duration vibrations, such as irritation and fatigue, are not likely due to the transient nature of the motions.

3-2 Summary of Results of Research

3-2.1 General

Pertinent information concerning impact and vibration effects on personnel was obtained from a review of literature and at meetings with various organizations in this field. Data compiled from pertinent publications are presented and discussed in detail in Section A-4 of Appendix A. Minutes of the meetings are presented in Appendix B. This section summarizes the significant results of this research.

To date, personnel tests conceived specifically for the ground shock environment have not been performed. However, based on tests and studies of human and animal response to vibration and impact associated with other types of shock environments, it is possible to prepare estimates of tolerances for the ground shock environment. Naturally, a degree of uncertainty will subsist with such estimates until appropriate tests have been conducted.

Impact and vibration tests have been conducted to establish personnel tolerances for such shock environments as aircraft ejection, high-speed air and space travel, shipboard explosions, impact due to falls, and miscellaneous industrial shock environments, etc. Even in these cases where test results are available, only approximate tolerance limits have been established since the exact physical mode of action of any exposure varies with respect to individual physical, physiological, and psychological reactions. Very often, test results can be evaluated only on a statistical basis.

3-2.2 Vibration Tolerances

Reference 3.1 (Section A-4.2a) reports on tests performed to determine whole-body response and tolerance to sinusoidal vibrations in the frequency range from 1 to 70 c.p.s. In these tests, subjects were placed (non-attached) in a standing, sitting, or prone position on a horizontally or vertically vibrating platform. At various selected frequencies and amplitudes subjective responses ranging from the threshold of perception to the threshold of pain were recorded. The latter threshold was considered as a tolerance limit and the motions were discontinued beyond this level. Exposure times ranged from 5 to 20 minutes. In analyzing the results of several such investigations in terms of willingness of a subject to tolerate various levels of vibration exposure (Reference 3.1), it was shown that the variability among different studies is very great; the results were averaged and simplified as plotted in Curve a of Figure A-4 (Appendix A, Page A-26). In this figure, subjective reactions indicating tolerance are plotted as a function of frequency and acceleration.

In considering this data relevant to the ground shock problem, it should be noted that Curve a represents a summary of tolerances for relatively long exposure times (on the order of 5-20 minutes) probably rendering the values of tolerance necessarily conservative for the considerably shorter exposure times resulting from ground shock. According to Curve a, the lower level of tolerance for these relatively long exposures is about 0.25 g. From Curve a it is also seen that the average tolerable limit is about 0.3 g. in the low-frequency range, then gradually increases after 30 c.p.s., reaching one g. at about 80 c.p.s., and sharply increasing after 100 c.p.s.

A source of information on shorter time vibration tolerance for supported (attached) subjects resulted from the experimental work reported in Reference 3.2 (Section A-4.2b). In these tests, each of 10 male subjects was supported in a seat with a standard seat belt and shoulder harness and was exposed to an increasing sinusoidal acceleration at selected frequencies in the range from 1 to 15 c.p.s. At each frequency, the amplitude was increased to the point where the subject stopped the run because he thought that further increase might cause bodily harm. This amplitude was considered as a tolerance limit. Exposure times ranged from 18 to 208 seconds.

The average results of these tests are presented in Curve b of Figure A-4 which shows the tolerance for each frequency.

It is to be noted from the curve that the lower level of tolerance is between 1 and 2 g. at 3-4 c.p.s. and 7-8 c.p.s., and the higher level is 7-8 g. at 15 c.p.s. These levels are considerably higher than the results of other tests reported in Reference 3.3 (Section A-4.2c) for similar support conditions but for somewhat longer exposures. Tolerance levels obtained in the tests are shown on Curve c of Figure A-4. Relatively high acceleration sensitivity was indicated at 1, 4 to 10 and above 20 c.p.s. The lowest level was 0.25 g. and occurred at one c.p.s. It then increased to 0.8 g. at 2-3 c.p.s., decreased to 0.65 g. at 4-8 c.p.s., and then gradually increased to the maximum tolerance of 1.4 g. at 17-20 c.p.s. The tolerance then dropped to one g. in the range of 24 to 27 c.p.s.

A comparison of Curves a, b, and c of Figure A-4 indicates that a higher acceleration at corresponding frequencies can be tolerated for shorter exposure times, although variations in this data are no doubt partially due to differences in the testing procedure, type of body support, posture, subjective responses, definition of tolerances, etc. For even shorter exposure times associated with the ground shock, corresponding tolerances may very well increase beyond Curve b in the same manner as Curve b increased above Curve a, although the extent of this extrapolation is not known (Section B-8).

Observation of the relative tolerances for various frequencies indicates that the body is evidently more sensitive to vibration at particular frequencies, suggesting body-organ and appendage resonance. From evaluation of Figure A-4 and also based on mechanical impedance test measurements (Reference 3.1), it appears that critical frequencies may exist at all frequencies below 10 c.p.s. depending on the direction of the vibration and the body posture. Above 10 c.p.s., tolerance tends to increase although some sensitivity may occur at particular ranges. After 80 c.p.s. there is a sharp increase in tolerance.

Based on the available personnel vibration data as summarised in this section, the following tolerances for restrained personnel (restrained refers to those persons strapped to chairs or cots) were considered for use in this study: 2 g. for less than 10 c.p.s.; 5 g. for 10-20 c.p.s.; 7 g. for 20-40 c.p.s.; and 10 g. above 40 c.p.s. These values are considered to be safe for personnel subjected to the vibrations (of a shock-isolated floor or seat) resulting from ground-shock structure motions (Section B-8). The 2 g. value was adopted for use in this study. The higher g. values were not used because the required restraining devices at these values would generally be too elaborate for civil defense purposes. In addition, it appeared to be advisable not to use the higher g values, considering the type of shelter inhabitants--elderly persons, children, etc.

Reference 3.4 (Section A-4.2n) presents tentative suggestions for vibration tolerances for personnel subjected to ground-shock structure motions. These recommendations were based on vibration tests similar to those described above. Tolerance values are 1.75 g. for seated, well-restrained personnel; and 0.75 g. vertical and 0.50 g. horizontal for standing personnel. The latter values for standing personnel were adopted for use in this study for non-restrained persons (standing, seated, and reclined).

To better understand the application of these tolerances as design criteria for personnel subjected to the vibrations of a shock-isolated floor or support, it would be well to illustrate their use in conjunction with the specific shock environment designated for this study. The design spectra calculated for the design studies (Chapter VII) are plotted in Figures 7-8 and 7-9 of Chapter VII. Referring to Figure 7-8 and considering the vertical acceleration tolerance values of 0.75 g. (non-restrained) and 2 g. (restrained), it is determined that shock isolation to the frequencies listed in Table 3-1 would be required. Displacements of the shock-isolated platforms relative to the structure are also listed. From Figure 7-9, horizontal values for 0.50 g. (non-restrained) and 2 g. (restrained) are as listed in Table 3-2.

The required frequencies listed . Tables 3-1 and 3-2 would generally necessitate the use of a flexible connection for the platform supporting the personnel. Such flexibility can be achieved by the use of springs (see Chapter V). A support system with a frequency greater than the above values would respond at intolerable acceleration levels. Rattle space equal to the above displacements must be provided between the

Table 3-1 Shock Isolation Requirements Vertical Direction

Overpressure (psi)	0.75 g. Frequency (cps)	0.75 g. Displacement (in)	2 g. Frequency (cps)	2 g. Displacement (in)
25	2.3	1.5	6.0	0.6
100	1.0	7.0	2.0	5.0
300	0.7	14.0	1.2	5.0

Table 3-2 Shock Isolation Requirements Horizontal Direction

Overpressure (psi	0.50 g. Frequency (cps)	0.50 g. Displacement (in)	2 g. Frequency (cps)	2 g. Displacement (in)
25	2.2	1.0	8.5	0.3
100	1.5	2.3	3.0	2.0
300	1.0	5.0	2.0	5.0

isolated platform and the concrete shell. Overhead clearance equal to at least the above vertical displacements must be included to prevent impact of personnel with the concrete ceiling.

3-2.3 Impact Tolerance

Impact effects involve a sudden single-pulse type shock or motion, such as caused by explosions and impacts and blows from rapid changes in body velocity or from moving objects. Possible damage (Reference 3.1) includes bone fracture, lung damage, injury to the inner wall of the intestine, brain damage, cardiac damage, ear damage, tearing or crushing of soft tissues, etc. Differences in injury patterns arise from differences in rates of loading, peak force, duration, localization of forces, etc.

It is pointed out in Reference 3.5 (Section A-4.2d) that, should a person be subjected to impact, it is likely that considerable variation in the body area of impact will occur. In addition, there are many circumstances in which impact may involve glancing contact with an object; also, a great variation in the shape, weight and consistency of the decelerating object or surface may be involved. The character of the decelerating surface, the angle and area of the body involved at impact, the impact velocity, and the decelerating time and distance are each critical factors. Any modification of the time of deceleration and the distance over which it occurs will markedly influence the magnitude of the load and the rate at which it develops. Such factors are responsible for human survival after experiencing impact velocities greater than that expected for mortality. Frequently, in these cases the surface struck is soft ground and the impact area of the body is large - the back, side, or ventral surface - thereby indicating that any cushioning of the impact, such as by use of mats on the shelter floor, could considerably reduce the impact effects on personnel.

In References 3.5, 3.6, 3.7 (Sections A-4.2d, e, f), it is concluded that one can tentatively take 10 ft./sec. as "an-on-the-average safe" impact velocity for adult humans and regard the probabilities of serious injury and even fatality for man to increase progressively as the impact velocity is elevated above this figure. This tolerable velocity is based on impact with a flat, hard surface and for various body postures, including impact of the head, impact in the standing position with knees locked, and impact in the seated position. It was indicated that a higher impact velocity could be tolerated for cases where the impact area of the body was larger, such as the back, side, or ventral surface, or if the surface collided with was not hard, such as soft ground. Impact with a 90-degree sharp corner would be much more severe than with a flat surface. Only about one-seventh of the impact energy to cause skull fracture due to impact with a flat surface would be required for skull fracture due to impact with a 90-degree sharp corner. This would correspond to an impact velocity of one-third of the value for a flat surface. According to Reference 3.5, the impact velocity for the threshold of mortality would be about 21 ft./sec.

Reference 3.8 (Section A-4.2g) states that, for a standing person with locked knees, no fractures can be expected at relative (impact) velocities below 11 ft./sec., and serious damage to the brain can be expected if relative velocity at contact is 16 ft./sec. or more.

As reported in Reference 3.9 (Section A-4.2h), men and dummies were exposed to deck motions on a ship when large explosive charges were detonated under water. These motions were characterized by a short-duration upward acceleration which can be equated to a sudden velocity change. The duration of the accelerations was less than 10 msec. This was followed by a deceleration phase lasting about 50 msec. In other words, the rise time to the peak velocity was less than 10 msec. and the decay to zero velocity took an additional 50 msec. The acceleration phase of this velocity pulse would be similar to the acceleration phase of the sharp, downward ground-shock velocity pulse. However, the decay of the ground-shock velocity pulse is considerably longer, in the order of a second or seconds. Since it appears that the body is primarily sensitive to sudden changes in velocity, this data would be pertinent. This type of shock velocity would have an effect on the body similar to that produced by a drop test. In both cases a near instantaneous velocity change is experienced due to the relative velocity between the body and a flat surface. In the tests of Reference 3.9, a stiff-legged subject and a subject seated in a hard wooden chair experienced 15 g. for 8 msec. (peak velocity of 4.0 ft./sec.) after which the tests were discontinued. This discontinuation does not indicate that a tolerable limit was attained since no physiological effects were reported except for some discomfort in the stiff-legged position. A subject with bent knees experienced an acceleration of 30 g. for 8 msec. (peak velocity of 8 ft./sec.) without discomfort. This figure does not necessarily represent a tolerable limit, but it does indicate that, in the bent-knee position, humans are capable of tolerating a higher impact velocity.

Reference 3.10 (Section A-4.2i) reports on studies of personnel injuries resulting from the wartime explosion of a minesweeper. Injuries were correlated with deck motions. It was found that, for personnel without advance warning and in random body positions, injury due to an initial acceleration of 50 g. for 6.5 msec. (peak velocity of 11.5 ft./sec.) can occur. For personnel hurled through the air, deck velocities of about 15 ft./sec. resulted in collision-impact injuries. This latter value is probably higher because of collision with a large impact surface of the body.

References 3.11 (Section A-4.2j) and 3.12 (Section A-4.2k) describe other data relevant to impact on ships, including the use of protective shoes. In a laboratory test of cadavers, a velocity of 12 ft./sec. reached in 1.3 msec. caused some fractures to those without protective shoes and no injury to those with protective shoes. In addition, it was stated that protective shoes and mats will protect standing personnel against direct impact effects for velocities up to 20 ft./sec. It was concluded that forces effective in producing impact injuries are of very short duration (1-2 msec.) producing extremely high accelerations (200-800 g.) and peak velocities of about 12 ft./sec.

From the data pertaining to impact due to falls or by other mechanisms causing sudden velocity changes, it appears that the impact velocity can be taken as the significant injury parameter. Although various combinations of acceleration and duration (or deceleration and duration for collision) have been imposed on personnel, in general, no injuries were reported until an impact velocity greater than about 11 ft./sec. occurred. The time durations (time for peak velocity change) are all extremely short, i.e., generally in the range of 10 msec. or less. For longer time durations, consideration of an impact tolerance in terms of the same peak velocity change may be too conservative. This is apparent by considering the use of a mat or protective shoes which increase the stopping time and thereby permit a higher tolerable impact velocity. Thus, for extremely short time durations a tolerance may be considered in terms of an approximately constant peak velocity change, and for relatively longer time durations the tolerable velocity would increase as the time increases. This phenomenon is due to the fact that, as the stopping time becomes small, the acceleration response of the body reaches a peak (because of the body flexibility) and shorter times and higher accelerations are no more severe than the most critical impact case of the body colliding with a rigid surface. For these short acceleration durations, injury is related to the kinetic energy which must be absorbed by the body.

This characteristic of impact effect on the body is indicated in Reference 3.13 (Section A-4 2m) which states that subjects strapped to a seat experienced a trapezoidal acceleration pulse. For the trapezoidal pulses of extremely short durations (in the range of 10 msec. or less), the areas of the pulses were of the same order of magnitude, indicating that the tolerance could be approximately related to a peak impact velocity. However, for the longer duration pulses, the areas of the pulses increased which corresponds to an increase of the tolerable velocity.

Based on the available data summarized in this section, an impact tolerance velocity of 10 ft./sec. was adopted for use in this study. This applies to impact with a hard, flat surface in various body postures and to impact of the head. If the line of thrust for head impact with a similar surface is directed along the longitudinal axis of the body, the 10 ft./sec. value would not apply since the head would receive the kinetic energy of the entire mass of the body. An impact velocity of 10 ft./sec. is considered to be generally safe for personnel subjected to impact resulting from structure motions (Sections B-4 and B-8). It is important to note that greater impact velocities may be tolerated if the body is in a flexible position or if the area of impact is large.

The effect of horizontal motions on the throwing of personnel off balance or on hurling them laterally would depend on the body stance and position, the acceleration intensity and duration, and the rate of onset of acceleration (jolt). Investigations of data concerning sudden stops in automobiles and in passenger trains indicate that personnel could (depending on stance and jolt) sustain accelerations which are less than 0.4 g. without being thrown off balance. However, these accelerations have durations of several seconds. Hence, the ground shock acceleration required to throw personnel off balance will probably be greater because of the shortened duration and associated jolts of the acceleration. The tolerable horizontal acceleration of 0.50 g. (recommended in Reference 3.4) for ground shock protection of standing personnel was adopted for use in this study for non-restrained persons (standing, seated, and reclined).

Application of the above impact data as design criteria for personnel subjected to the non-shock-isolated structure motions is not as simple as in the case of the vibration tolerances for personnel located on a shock-isolated platform. One cannot evaluate all the effects of the shock environment directly from the design shock spectra. Furthermore, the impact intensity resulting from a shock depends upon several factors, namely, the location of personnel in the shelter, whether or not they are thrown off balance, and the relative motion of personnel (non-restrained) with respect to the shelter floor. It is possible, however, to consider these factors in connection with the shock environment designated for this study.

Table 7-5 lists the peak structure motions for the design studies presented in Chapter VII. These motions describe the movement of the structure as a unit.

It is seen from Table 7-5, that the peak velocity at all the overpressure levels is not greater than 10 ft./sec. Therefore, personnel attached to the structure (restrained in a seat or cot) could tolerate the structure motions.

Velocity of individual exterior walls may be higher than the abovementioned velocities because of the structural deflections resulting from the blast loading on the walls. The blast loading will also cause a transverse compression wave to propagate through the wall. This compression wave could be transmitted to the body if a subject is in contact with the wall during the time of the blast loading. Because of these factors and also because the personnel may have a velocity due to having been thrown off balance, personnel should be prevented from entering into contact with exterior walls. An alternate method would consist of providing protective cushioning material on the walls (see Chapter VI).

The relative motion of the personnel with respect to the structure floor can be estimated by comparing the structure displacement versus time with the personnel free-fall displacement due to gravity. An approximate (synthesized) displacement-versus-time curve was computed in accordance with the procedure given in Reference 3.14 (Section A-7.2j). This procedure is presented in Appendix D. Displacement-versus-time curves were computed from each of the design spectra curves in Figures 7-8 and 7-9. These displacement curves are equivalent to corresponding spectra; i.e., the maximum response, of a simple oscillator (Figure 2-1) subjected to a support motion which is equal to the computed displacement versus time, would be the same as the response spectrum value at the frequency of the oscillator.

Figures 3-1, 3-2, and 3-3 show a plot of computed downward structure displacements and free-fall displacements for the 25-, 100-, and 300-p.s.i. overpressures, respectively. It is seen that the peak relative displacements are equal to 0.3 inches, 2.1 inches, and 8.4 inches for 25, 100, and 300 p.s.i., respectively. Overhead clearances equal to, or greater than, these values should be provided to prevent impact of personnel with the ceiling or with other overhead objects. Such impact could not be tolerated because the head would absorb energy from the entire mass of the body. If sufficient overhead clearance cannot be provided, protective cushioning material should be provided.

The impact velocity at the impact point (Figures 3-1, 3-2, and 3-3) for each pressure level was computed. The impact velocity is equal to the downward velocity of the personnel minus the downward velocity of the structure at the time of impact. These velocities are listed in Table 3-3.

Table 3-3 Downward Impact Velocities

Overpressure	Personnel Free-Fall Velocity at Impact	Structure Vel. at Impact	Impact Velocity
25 p.s.i.	2.5 ft./sec.	1.1 ft./sec.	1.4 ft./sec.
100 p.s.i.	5.[illegible] ft./sec.	1.2 ft./sec.	4.3 ft./sec.
300 p.s.i.	8.6 ft./sec.	0.5 ft./sec.	6.1 ft./sec.

For the cases considered above, the personnel will regain contact with the floor slab before the peak displacement occurs. The associated impact velocities in the vertical direction are all less than 10 ft./sec., and are, therefore, tolerable. As the overpressure level increases, impact occurs at a time closer to the time of the peak downward

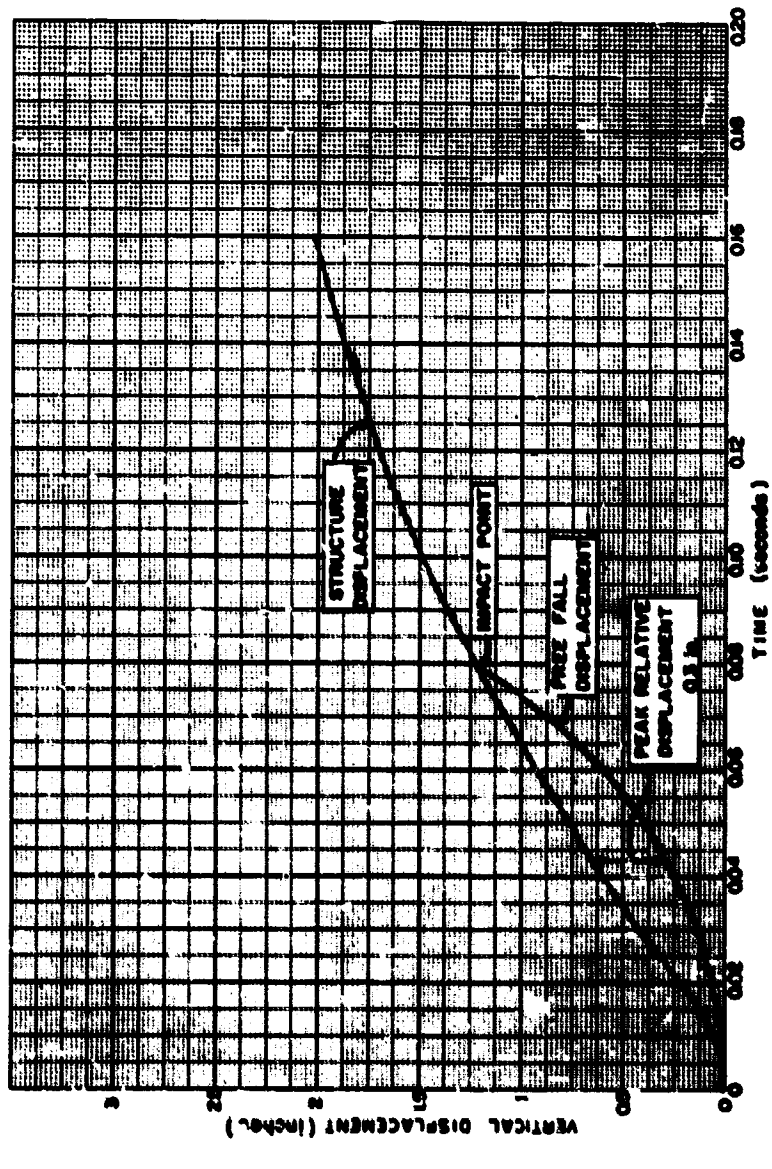


Fig. 3-1 DOWNWARD DISPLACEMENT vs. TIME - 25 psi

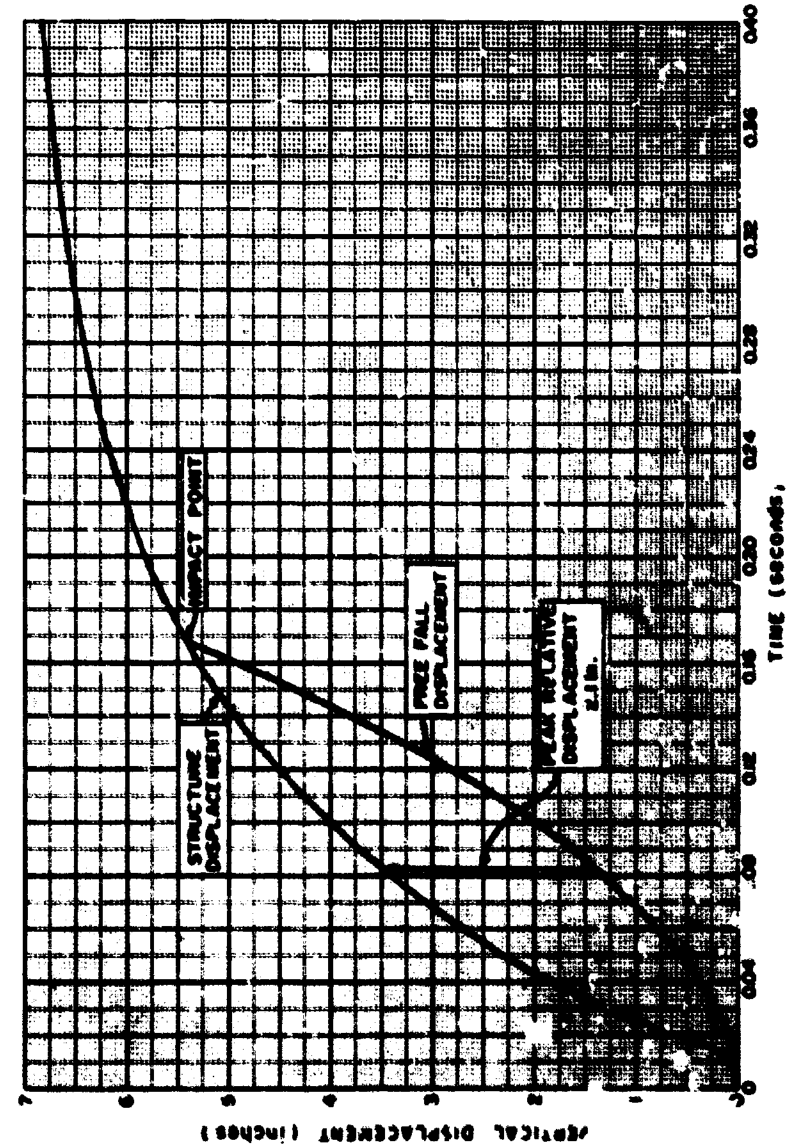


Fig. 3-2 DOWNWARD DISPLACEMENT vs. TIME - 100 psi

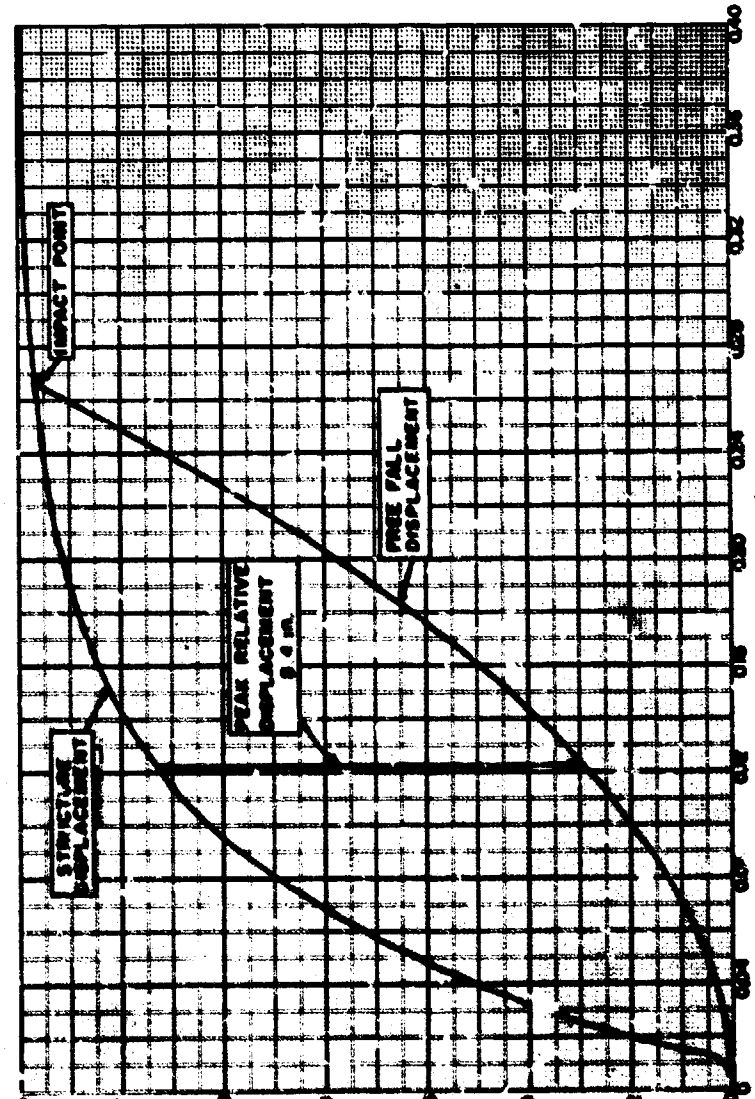


Fig. 3-3 DOWNWARD DISPLACEMENT vs. TIME - 300 psi

displacement of the structure. For overpressures above 300 p.s.i. or for other site conditions, the structure may be rebounding upwards at the time of impact. In such a case, the impact velocity is equal to the free-fall velocity plus the upward velocity of the structure. However, as discussed in Chapter II, rebound velocities are considerably lower than peak downward structure velocities.

Since the structure also accelerates horizontally, the structure floor slab will have moved horizontally at the time of vertical impact. Computed horizontal displacements are plotted in Figure 3-4 for 25, 100 and 300 p.s.i. For the 300- and 100-p.s.i. overpressure levels, the peak structure displacements of 5 inches and 2.3 inches will have virtually occurred at the time of impact. The horizontal structure velocity at the time of impact will be close to zero. For 25 p.s.i., approximately one-half the peak horizontal displacement would have occurred at the time of impact, at which time the horizontal velocity of the structure is about 0.5 ft./sec. These curves depict only an estimate of the time-history motion and it is possible that horizontal velocities may differ at the time of impact. In addition, there may occur the more severe case in which the structure accelerates in the horizontal direction prior to separation of the floor from personnel in the vertical direction.

Based on the magnitude of the peak structure accelerations in the horizontal direction (Table 7-5), non-restrained personnel would be thrown over resulting in an impact with the floor, other people, and other adjacent objects. Such impacts may be at velocities greater than 10 ft./sec. due only to falling to the floor from a standing position. An especially critical case would be falling backwards and striking the back of the head on the floor. It is considered (Section B-8), however, that in most cases such a fall would be cushioned by striking the back or arms. Impact with corners or edges would be extremely critical, even at velocities less than 10 ft./sec.

It is important to note that personnel would not feel the full effect of the peak structure accelerations (Table 7-5) because of their short duration and because a force no greater than the friction force between the floor and the person's

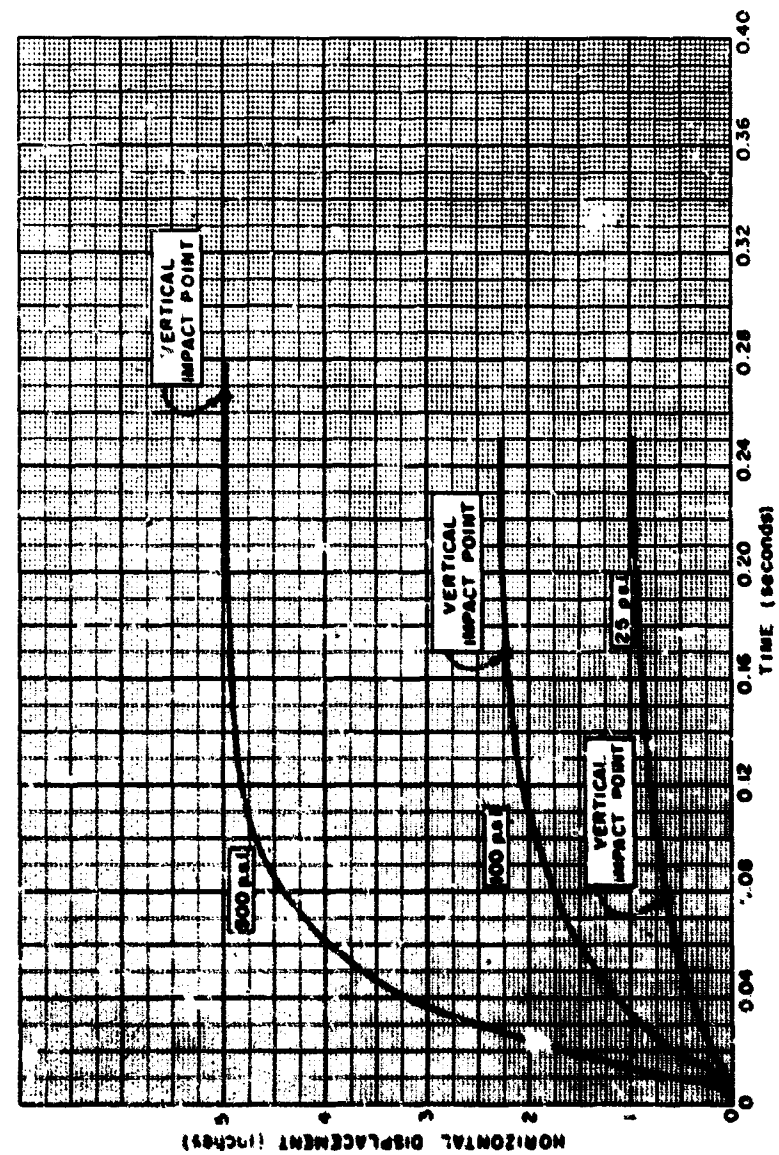


Fig. 3-4 HORIZONTAL STRUCTURE DISPLACEMENT vs. TIME - 25, 100 & 300 psi

shoes (standing personnel) can be transmitted. In addition, as mentioned above, the floor also accelerates in the vertical direction thereby further reducing the horizontal force which can be transmitted. At overpressure levels where the air-blast wave arrives prior to the ground motions (see Section 2-1), structure motions start upon such arrival. For these cases, the effect of the sharp downward slap of the blast loading will begin to be felt before the onset of horizontal motions. At 300 p. s. i., the floor slab may drop from beneath the personnel before a horizontal force, sufficient to throw persons off balance, can be transmitted. At 100 p. s. i., this tendency would be somewhat reduced, and at 25 p. s. i., ground motions would arrive prior to the air-blast wave. These early-arriving ground motions could result in horizontal and upward motions prior to the sharp downward motion. Thus, at the higher overpressures where peak horizontal accelerations are much larger than at lower overpressures, the effect of these accelerations on transmitting a horizontal force, and thereby throwing personnel off balance, may not be any greater than that for the lower overpressures.

In any case, the unrestrained personnel would tend to lose their balance and fall over. It has been calculated that impact velocities due to personnel being thrown over would probably not exceed 17 ft. /sec. This calculation is based on information obtained from studies to provide protection in boxing rings, as presented in Reference 3. 15 (Section A-7. 2n). In most cases, these falls would be cushioned by striking large areas of the body or arms. To protect against injury in those cases where a person falls over and strikes his head at an impact velocity greater than 10 ft. / sec., protective cushioning material should be provided. To protect against injury due to being thrown off balance and striking a sharp corner or edge, protective cushioning should be provided, even for impact velocities less than 10 ft. /sec.

3-3 Recommended Design Criteria

3-3.1 General

Based on the personnel shock tolerance data presented and discussed in the previous sections of this chapter, recommended design criteria for this study are presented below. Criteria are presented for three protection levels. The protection level chosen for a particular design depends upon desired reliability of protection, functional requirements, and cost limitations.

The first protection level affords the most reliable protection of the three levels and requires a shock-isolated interior platform to reduce the high accelerations of the structure to values tolerable for personnel.

The second protection level requires the use of protective cushioning material on the floors, walls, and other surfaces with which personnel may experience impact. At this protection level, the floor is part of the structure shell and will move with the high accelerations of the structure. The cushioning material provides protection from injuries which may be caused by (1) impact at velocities above 10 ft./sec. resulting from falling over; (2) impact with corners, edges, and overhead objects; and (3) compression waves transmitted through exterior walls. In general, the protection reliability of the second protection level would be less than that of the first. However, the additional risk involved depends on the age and the physical condition of the personnel as well as their location and posture within the shelter. Although general protection against impact injury is provided, it is possible that injuries may result for persons of certain age groups if they collide in an awkward position with the structure or against each other. Adults falling on young children could cause injuries to the children. Elderly persons may be injured if they fall over, even though protective cushioning material is provided. It is even possible that one person's head may strike another person's head.

The additional risk for the second protection level is also a function of the design overpressure level. As discussed in Section 3-2, the horizontal forces transmitted to personnel are not necessarily greater for the higher overpressure levels considered in this study. However, the effect of the vertical impact in combination with being thrown over due to horizontal forces would be somewhat greater for the higher overpressures. Thus, since the protection reliability of the first protection level is the same for each overpressure considered, the additional risk for the second protection level increases as the design overpressure increases.

The third protection level requires the use of a limited amount of protective cushioning material. As in the case of the second protection level, the floor is part of the structure shell. Cushioning material is provided to protect from injuries which may be caused by (1) impact with corners, edges, and overhead objects; and (2) compression waves transmitted through exterior walls. For the overpressure levels considered in this study, the only impact velocities exceeding 10 ft./sec. are those due to a subject falling off balance. For the third protection level, it is assumed that a person who is thrown off balance will have his fall cushioned by impact with large areas of the body or the arms. Therefore, protective cushioning material on the floor and interior walls would not be required. The probability of injury to some people is greater than that for the second protection level. However, as in the case of the second protection level, the additional risk involved depends on the category and position of personnel within the shelter and on the design overpressure level.

In selecting a protection level for a particular design, an additional factor is the adaptability of the required shock isolation scheme to the function of the shelter, e.g., emergency operating centers, special-use shelters, and dual-purpose shelters.

3-3.2 Criteria

a. First Protection Level (requires shock-isolated platforms) *

1. Non-Restrained Personnel

The peak acceleration amplitudes of the personnel platforms shall be shock isolated to less than 0.75 g. in the vertical direction and to less than 0.50 g. in the horizontal direction.

* Shock-isolated platforms are discussed in Chapter VI.

2. Personnel Restrained in Anchored Seats or Cots**

The peak acceleration amplitudes of the personnel platform shall be shock isolated to less than 2.0 g. in the vertical and horizontal directions.

b. Second Protection Level (requires protective cushioning materials in lieu of shock-isolated platforms) ***

1. Non-Restrained Personnel

Protective cushioning material shall be provided on such potential impact surfaces as walls, floors, low ceilings, and corners and edges thereof. Edges and corners of interior furnishings shall be provided with protective cushioning. Other surfaces of furnishings require individual evaluation to determine required cushioning material.

2. Personnel Restrained in Anchored Seats or Cots **

Since the peak structure velocities are not greater than 10 ft./sec. (Table 7-5), protective cushioning need not be provided.

c. Third Protection Level (requires limited protection cushioning materials in lieu of shock-isolated platforms) ***

1. Non-Restrained Personnel

Protective cushioning material shall be provided on the following potential impact surfaces: exterior walls and low ceilings, and corners and edges thereof. Edges and corners of interior walls and furnishings shall be provided with protective cushioning material.

2. Personnel Restrained in Anchored Seats or Cots **

Same as the second protection level, item b2, above, i.e., protective cushioning need not be provided.

** Restraining devices are discussed in Chapter VI.
*** Protective cushioning materials are discussed in Chapter VI.

Note: Although the protective cushioning materials designated in b and c above refer to cushioning of various interior surfaces of the shelter, cushioning in the form of protective clothing could be utilized in lieu of the cushioning of surfaces. Bracing mechanisms, which prevent persons from falling over, could also be used instead of protective cushioning materials. Protective clothing and bracing devices are discussed in Chapter VI.

3-4 References

3.1 Goldman, D. E. and von Geirke, H. E., "Effects of Shock and Vibration on Man", Chapter 44, Shock and Vibration Handbook, Volume 3 (ed. Harris, C. M. and Crede, C. E.), 1961, McGraw-Hill Book Company.

3.2 Ziegenruecker, G. H. and Magid, E. B., Short Time Human Tolerance to Sinusoidal Vibrations, WADC Technical Report 59-391, July 1959, Aero Medical Laboratory, Wright-Patterson Air Force Base. Available from the Defense Documentation Center (AD No. 227 341).

3.3 Parks, D. L. and Snyder, F. W., Human Reaction to Low Frequency Vibration, Technical Report D3-3512-1, 24 July 1961. Prepared by The Boeing Company, Wichita Division, for the Office of Naval Research. Available from the Defense Documentation Center (AD No. 261 330).

3.4 A Guide for the Design of Shock Isolation Systems for Underground Protective Structures, Report No. AFSWC-TDR-62-64, December 1962. Prepared by the Ralph M. Parsons Company for the Air Force Special Weapons Center. Available from the Defense Documentation Center.

3.5 Richmond, D. R. et al, Tertiary Blast Effects: The Effects of Impact on Mice, Rats, Guinea Pigs and Rabbits, DASA 1245, 28 February 1961. Prepared by Lovelace Foundation for Medical Education and Research, for the Defense Atomic Support Agency.

3.6 White, C. S., Biological Effects of Blast, DASA, 1271, December 1961. Prepared by Lovelace Foundation for Medical Education and Research, for the Defense Atomic Support Agency.

3.7 White, C. S., Biological Blast Effects, Report No. TID-5564, September 1959. Prepared by Lovelace Foundation for Medical Education and Research, for the United States Atomic Energy Commission. Available from the Office of Technical Services, Department of Commerce.

3.8 Protective Construction Review Guide (Hardening), Volume II, June 1961. Prepared by Newmark, Hansen & Associates for the Office of the Assistant Secretary of Defense (Installations & Logistics) (Secret-Restricted Data).

3.9 Hirsch, A.E. and Thompson, W.M. Jr., Shock Tests on USS Fullam (DD 474) Phase 1B-Personnel Protection Study (Project 8) - "The Response of Men and Dummies to Deck Motions", Report C-1346, April 1962. Department of the Navy, David Taylor Model Basin (Confidential).

3.10 Durkovic, R.G. and Hirsch, A.E., Personnel Injuries and Estimated Shock Motions on YMS 368 During a Mine Attack, Report C-1318, May 1962. Department of the Navy, David Taylor Model Basin (Confidential).

3.11 Draeger, R.H. et al, Personnel Hazards and Protection from Solid Blast, Part B of USNMDL Report No. 73 on BUSHIPS Project GX-13 PROGIGS, March 1956. Medical Research Department, U.S. Navy Mine Defense Laboratory, Panama City, Florida (Confidential).

3.12 A Study of Personnel Injury by "Solid Blast" and the Design and Evaluation of Protective Devices, Research Project X-517, Report No. 1, 30 March 1945, Naval Medical Research Institute and U.S. Naval Hospital, National Naval Medical Center, Bethesda, Maryland.

3.13 Eiband, A.M., Human Tolerance to Rapidly Applied Accelerations: A Summary of the Literature, Memo 5-19-59E, June 1959, National Aeronautics and Space

Administration. Available from the Defense Documentation Center (AD No. 218 269).

3.14 Weissman, S. et al, "Nuclear Weapon Blast and Ground Shock Effects on Dynamic Response of Interior Components and Equipment in Underground Structures", Shock Vibration and Associated Environments, Part III, Bulletin No. 29, July 1961, pp. 324-337. Prepared by Ammann & Whitney, Consulting Engineers for the Office of the Secretary of Defense (Research & Engineering). Available from the Defense Documentation Center (AD No. 260 564).

3.15 Dye, E.R. and Smith, M.D., "Mechanical Properties of Low Density Foams as Energy Absorbers", Mechanical Engineering, Volume 80, No. 12, December 1958. Prepared by Cornell Aeronautical Laboratory, Inc. for presentation at 1958 Semi-Annual Meeting of the American Society of Mechanical Engineers.

CHAPTER IV

SHOCK TOLERANCES FOR EQUIPMENT

4-1 Basic Concepts

In order to provide adequate shock protection of mechanical and electrical equipment and other components housed within hardened civil defense shelters, appropriate shock tolerances for these items must be established. To prevent equipment damage or malfunction, the peak accelerations resulting from the ground shock environment must be attenuated to tolerable values. Knowing the acceleration tolerances, the necessary degree of shock isolation or the necessary additional strength can be determined for a particular ground shock environment. This environment is specified by design shock spectra (Figures 7-8 & 7-9).

The types of equipment items depend to some extent on the requirements for the particular shelter, i.e., the function of the shelter (personnel shelter, control or communications centers, etc.), the required level of protection, the time interval on which occupancy should be based, the population (family or community shelter, etc.), and other factors. The normal peacetime function of dual-purpose structures will also be a factor. The basic types of equipment likely to be housed would include heating, ventilating, air-conditioning, water supply, sanitation, and electric equipment, including emergency power supply equipment and communications equipment. Other interior components include interior furnishings, partitions, ductwork, etc. A breakdown of the various items is presented on page A-60 of Appendix A.

Damage to equipment may result in failures which can be divided into two classes: temporary and permanent failures. Temporary failures, often called "malfunctions", are characterized by temporary disruption of normal operation when a shock or a vibration is applied. In some cases, subsequent adjustments may be required for restoration of service. Permanent failures are characterized by breakage, resulting in damage so severe that the ability of the equipment to perform its intended function is impaired permanently.

The capacity of an equipment item 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 its physical characteristics: the strength of the item (frame, housing, and components), and to some extent the nature of the excitation to which it is subjected. For example, an equipment item may sustain a single peak acceleration due to a transient ground shock disturbance but may fail under a vibration-type input having the same peak acceleration amplitude. This effect arises from the fact that the fragility level for a piece of equipment is actually a tolerable peak acceleration of the equipment frame under a particular shock test (tolerable in the sense that the equipment frame, housing, and components were not damaged or disrupted). However, under a different shock input resulting in the same peak acceleration of the equipment as a whole, components of the equipment may have responded differently. For this reason, fragility data should be considered in conjunction with such factors as the natural frequencies and damping characteristics of the equipment components as well as the characteristics of the test input used to determine the tolerance. The test input must be compared to the probable ground shock input.

Equipment items will generally be bolted or otherwise attached to their supports. Shock protection would be achieved by mounting the equipment on flexible supports (springs). Thus, the equipment will be subjected to a vibratory motion (ground shock input). Provision of shock mounting to reduce the peak acceleration amplitude to a tolerable value may introduce resonance problems because of the vibratory input.

4-2 Summary of Results of Research

Pertinent data concerning shock effects on equipment and other interior components were obtained from a review of literature and at meetings with various organizations. Data compiled from pertinent publications are presented and discussed in detail in Section A-4 of Appendix A. Minutes of the meetings are presented in Appendix B. This section summarizes the significant results of this research.

It is evident that, for the wide range of equipment which may be used in shelters, the maximum shock tolerances will vary considerably more than those for personnel. Although personnel shock tolerances may vary depending on the age and physical condition of individual persons, it was possible to establish one set of values which would have general application (Chapter III). To establish the maximum shock tolerance for a particular item of equipment, it is necessary to perform tests or analyses. The shock tolerances for items of similar function may vary depending on the manufacturer and the exact construction of the equipment.

Only select items of equipment have been tested to determine shock tolerances applicable for protection from the damage which may be caused by ground-shock motions. However, data are available concerning general shock effects, indicating strength and ruggedness or sensitivity of equipment. In many cases, safe acceleration values are known, although it is recognized that maximum tolerances may be considerably higher even though the actual limit has not been verified by testing or analysis. These safe values were established on the basis of the shock environment during shipment of the equipment in railroad cars and trucks and on the loads sustained during normal operation of the equipment.

Based on transportation and conventional operational shock requirements, most commercial mechanical and electrical equipment items are known to be able to sustain at least 3 g. See Sections B-2 and B-7, and References 4.1 (Section A-5.2g) and 4.2 (Section A-5.2i).

Fragile equipment (such as electronic equipment) can generally sustain 1.5 g. See Section B-2 and References 4.3 (Section A-5.2a), 4.4 (Section A-5.2b), and 4.5 (Section A-5.2j).

Shock tolerances for commercial mechanical and electrical equipment are in many cases higher than 3 g. -- probably 5 g. and greater. However, the use of such acceleration values would require verification by shock testing. See Section B-7 and References 4.2, 4.4, and 4.5.

Examples of expected tolerances for equipment are given in Table 4-1. See References 4.1, 4.2, 4.5, and 4.6 (Section A-5.2h).

Table 4-1 Examples of Equipment Shock Tolerances

Item	Peak Acceleration
Fluorescent Lighting Fixtures (with lamps) (References 4.1, 4.2, & 4.6)	20 to 30 g.
Heavy Machinery - Motors, Generators, Transformers, etc. (4000 lb.) (Reference 4.5)	10 to 30 g.
Medium-Weight Machinery - Pumps, Condensers, Air Conditioners, etc. (1000-4000 lb.) (Reference 4.7)	15 to 45 g.
Light Machinery - Small Motors, etc. (1000 lb.) (Reference 4.7)	30 to 70 g.

As previously mentioned, peak tolerable accelerations for a vibratory input depend on the frequency of the input motion. If the input frequency is close to the frequencies of the equipment components, amplifications due to resonance will occur effecting a lower, tolerable input-acceleration amplitude. It is recommended (Reference 4.3) that equipment frequencies between 1/2 and 2 times those of the support for the equipment be avoided, or that provision be made for them by considering a resonance phenomenon with a sustained harmonic input. The effect of resonance can be minimized or eliminated by providing sufficient damping in the shock isolation system. However, when designing shock isolation systems for equipment, low-frequency systems (compared to equipment frequencies) will be achieved in most cases, and resonance should not be a problem (Section B-7). Based on the relatively high frequencies of the components of most equipment items, shock isolation at frequencies below 10 c.p.s. would probably be low enough to prevent amplifications due to resonance with equipment frequencies.

In general, maximum shock tolerances for standard commercial equipment will not be known. Thus, safe tolerable accelerations of 3 g. for mechanical and electrical equipment (most equipment in a civil defense shelter will be in these categories) and 1.5 g. for electronic equipment would have to be used for design values, unless shock testing is to be conducted. A discussion of shock testing facilities and current techniques used for shock testing is presented in Section A-6 of Appendix A.

For the shock environment designated for this study (design spectra plotted in Figures 7-8 and 7-9 of Chapter VII), the shock-isolation frequencies and the relative displacements required to limit the accelerations to 3 g. are listed in Table 4-2.

Table 4-2 Shock Isolation Requirements

	Vertical Direction		Horizontal Direction	
Overpressure (psi)	Frequency (cps)	Displacement (in)	Frequency (cps)	Displacement (in)
25	9.0	0.4	13.0	0.2
100	3.0	3.2	4.4	1.5
300	1.4	14.0	2.4	5.0

Except for the horizontal direction at 25 p.s.i., the isolation frequencies are less than 10 c.p.s. To reduce the 13.0-c.p.s. value, a lower acceleration and a higher relative displacement would have to be used in the design. The frequencies listed in Table 4-2 (particularly for 100 & 300 p.s.i.) necessitate the use of flexible connections for equipment supports. Such flexibility can be achieved by the use of springs (See Chapter V). To isolate fragile electronic equipment to 1.5 g., lower frequency systems than those listed in Table 4-2 would be required.

In the case where maximum shock tolerances are known from tests and particularly when the equipment is rugged, it may not be necessary to provide a flexible (spring) shock mounting. For example, referring to the design spectra (Figures 7-8 and 7-9), if the acceleration tolerance is greater than 18 g., no shock isolation would be required at the 25-p.s.i. overpressure level. In this case, the equipment could be anchored rigidly to the floor slab, providing there is no problem due to resonance with the frequencies of the floor, and also provided that the required strength can be attained in the connection to develop the high acceleration forces.

For other interior components, such as partitions, furniture, cabinets, hardware, ductwork, piping, etc., it is not practical to designate general acceleration tolerances. Each item would require individual analysis to determine the strength of the item compared to the imposed dynamic forces. If the items are rigidly connected to the structure floor, wall, or ceiling, they must have sufficient strength to sustain the high accelerations of the structure. These accelerations would be somewhat reduced if the item itself is flexible. If necessary, shock mounting similar to that provided for equipment can be utilized.

Unattached furniture may be subjected to less severe loadings than those imposed on attached furniture since the high initial accelerations of the structure will not be felt. However, the stability of the furniture would have to be evaluated in addition to the possible hazard to nearby personnel. The curves in Figures 3-1 to 3-4 can be used to estimate the relative motion of the furniture with respect to the structure.

4-3 Recommended Design Criteria

4-3.1 General

Based on the shock tolerance data summarized and discussed in the previous sections of this chapter, recommended design criteria are presented below. Criteria for equipment are presented for two categories: (1) non-shock-tested equipment and (2) shock-tested equipment. Criteria for miscellaneous interior components are also given.

In addition to satisfying the acceleration and frequency limitations for equipment, other design factors must be considered: (1) sufficient rattle space, as determined from the design spectra, must be provided to accommodate relative displacements resulting from the flexibility introduced by the shock mounting; (2) cables and wires connected from the structure to the shock-mounted equipment must be flexible enough to accommodate the relative displacements; (3) the effect of rocking or tilting on the performance of the equipment must be considered; and (4) mounting connections must be provided with sufficient strength to transfer the forces due to the peak accelerations.

4-3.2 Criteria

a. Equipment Category One: Non-Shock Tested Equipment

The peak acceleration amplitudes in the vertical and horizontal directions and the peak frequency of the isolated system shall not be greater than the following:

Mechanical and Electrical Equipment	3 g., 10 c.p.s.
Electronic Equipment	1.5 g., 10 c.p.s.

b. Equipment Category Two: Shock-Tested Equipment

For this case the tolerable accelerations as a function of the frequency of isolation will be used.

c. Miscellaneous Interior Components

For miscellaneous interior components, such as partitions, furniture, hardware, ductwork, piping, etc., each item must be evaluated and sufficient strength, anchorage, and flexibility provided.

4-4 References

4.1 Emergency Operating Centers (Review Draft), Professional Guide PSD-PG-80-7, November 1962. Prepared by Praeger-Kavanagh-Waterbury, Engineers-Architects, for the Office of Civil Defense, Protective Structures Division.

4.2 Mechanical Shock & Electrical Apparatus, Report of tests performed under WS-107-A2 Titan Shock Testing Program, 1960. Westinghouse Electric Corporation.

East Pittsburgh, Pennsylvania.

4.3 Protective Construction Review Guide (Hardening), Volume I, June 1961. Prepared by Newmark, Hansen & Associates for the Office of the Assistant Secretary of Defense (Installations & Logistics).

4.4 Protective Construction Review Guide (Hardening), Volume II, June 1961. Prepared by Newmark, Hansen & Associates for the Office of the Assistant Secretary of Defense (Installations & Logistics) (Secret-Restricted Data).

4.5 Vulnerability Handbook for Hardened Installations - Volume I - Response to Large-Yield Nuclear Weapons, Part A - Procedures, 31 March 1962. Prepared by Newmark, Hansen and Associates for Headquarters USAF. Available from the Defense Documentation Center (AD No. 329 342) (Confidential).

4.6 Shock Test on Fluorescent Luminaires, December 1961. Prepared by Webcor, Inc. and General Electric Company for the Benjamin Division of Thomas Industries, Inc., New York City.

CHAPTER V

SHOCK ISOLATED PLATFORMS

5-1 Introduction

The design of shelters for personnel protection level one (Section 3-3) and/or for equipment (Section 4-3) will require the use of flexible support systems to attenuate to tolerable levels the high accelerations associated with the structure motions. Effective methods of accomplishing this are: (1) a combination platform and spring support system and (2) individual spring mounts. The former is usually employed when a number of pieces of equipment require shock isolation and/or when personnel are to be protected while the latter is used for the shock isolation of individual pieces of equipment. This discussion will deal primarily with the former.

In most cases, shock-isolated platforms will have to be low-frequency systems in the order of 2 or 3 c. p. s. or less for personnel protection (Tables 3-1 and 3-2) and slightly higher (Table 4-2) for protection of equipment. Frequencies of these magnitudes usually require flexible systems for both the horizontal and the vertical motions of the structure. Two methods (Reference 5.1 to 5.8; Sections A-7.2c to A-7.2j) are generally being used at this time to produce the required flexibility; i.e., (1) pendulum arrangements whereby the platforms are suspended from spring supports which in turn are attached to the roof, or near the roof, of the shell of the structure, and (2) base-mounted, shock-isolated platform; platform resting on spring supports which in turn are mounted on the base slab of the shell. The selection of the appropriate system for use in a specific design is dependent upon the design criteria (population, site condition, pressure level, and functional requirement) in addition to being interrelated with the required shape and dimensions of shell (also dependent design criteria), the reliability, and the costs. These factors will be discussed in more detail in subsequent sections.

5-2 Springs and Spring Assembly

5-2.1 General

A spring assembly consists of the spring and its associated equipment. The type of equipment will depend upon the spring type and the method used to support the platform (pendulum or base mounted).

Several different types of springs are available which lend themselves to use in shock-isolated systems. They consist of (1) air springs, (2) liquid springs, (3) conical volute springs, (4) helical coil springs, and (5) beam springs. The use of any of these springs in a particular system will be governed by the magnitude and direction of the accelerations and displacements associated with the motions of the structure, the platform size (total load: dead load plus dynamic load), the method of supporting the platform, and the reliability.

The use of the air or liquid springs is generally associated with relatively large loads and displacements (in the order of two feet or more) (Sections A-7.1 and B.3). For the loads and displacements associated with the shock environment for the pressure levels considered in this report, the use of these springs will probably be uneconomical. The air and liquid springs (except in a closed system) require air or liquid pumps to maintain the pressures necessary to cushion the input loads. The reliability of these springs in shelters is probably somewhat less than that of the other types mentioned above because of the ever present possibility of the occurrence of pressure leakage within the spring system. This possibility of leakage usually will require continuous inspection which would probably be undesirable for civil defense shelters. Beam and volute springs will be useful when small structure motions are encountered. That is, beam springs will usually suffice for displacements of one or two inches while volute springs can be used for displacements in the order of four to six inches. However, in most cases the use of helical springs for structure displacements less than approximately twenty-four inches will produce the most efficient suspension system insofar as strength and economy are concerned. Helical springs, at the present time, are available in wire sizes up to 3-1/2 inches in diameter and free-heights up to five or six feet.

5-2.2 Helical Coil Springs and Assembly

A helical coil spring is available in one of two possible types, i. e., compression and extension (tension) springs. The compression spring consists of a continuous, open-wound helical coil finished at the ends so as to provide resistance to compression forces. The extension spring differs from the compression spring (insofar as general appearance is concerned) only in that it has a close-coiled helical shape with ends so formed as to permit its use in applications requiring resistance to pulling forces.

a. Load Application to Spring

A load can be applied to a compression helical spring in one of two ways, i. e., in the first method, the load is transferred through a series of bearing plates and steel rods with the spring acting as an intermediary (Figure 5-1), while the second method consists of applying the load directly to the top of the spring which in turn will transfer the load to the support below (Figure 5-2. b). The first method is typical of the pendulum-supported, shock-isolated platform while the second method is utilized in a base-mounted isolation system.

b. Pendulum Assembly

In the case of the pendulum, the structure motions are applied first to the steel rod which is connected to the concrete shell (Figure 5-1) and supports the spring by means of a flange plate at the bottom of the rod. As the rod and the plate move down (structure motion), the load within the spring is relieved, thereby relieving the pressure on the top flange plate which supports the spring cage which in turn supports the platform attached below. By relieving the compression in the spring, the platform will fall due to gravity until such time as it will begin to overtake the bottom flange plate. At this instant, the spring will again begin to recompress. The spring then vibrates about its "at rest" position (deflected position of the spring caused by the static load of the platform) until damping brings the system to rest.

In general, this system should be designed for a dynamic load response not to exceed one g. Loads greater than

Note: Universal connections at the top and bottom of the pendulum are not shown.

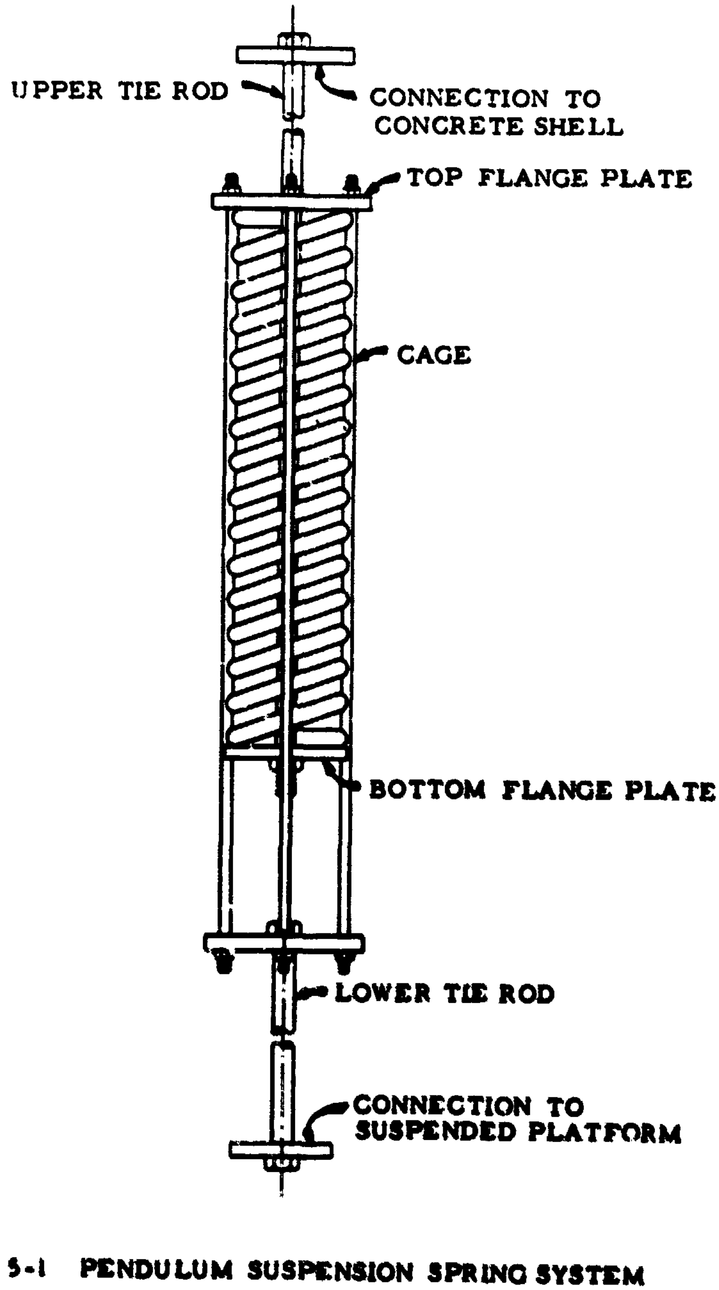


Fig. 5-1 PENDULUM SUSPENSION SPRING SYSTEM

Note: Source Reference 5.

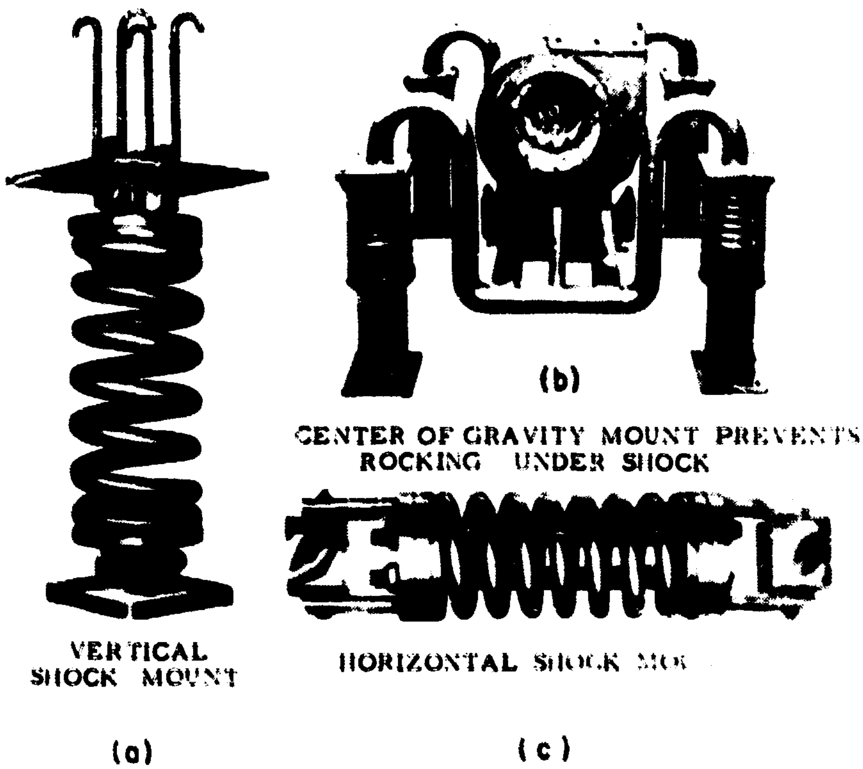


FIG. 5-2 HELICAL COMPRESSION SPRING M[illegible]

one g. will extend the spring beyond its free height which is undesirable and may cause buckling of the tie rod (Figure 5.1). Furthermore, a dynamic load larger than one g. will produce an unstable suspension system due to the existence of the ball-type (universal) connections at the top and bottom of the spring assembly. The physical arrangement of the assembly is adaptable to the pendulum system because of the latitude which exists in the selection of the length of the tie rods; in addition, the pendulum connection to the platform usually can be made near the center of gravity of the platform load.

The pendulum spring assembly is quite adaptable to shock-isolated platforms for personnel. Here, the system can be designed economically for the low dynamic response required for personnel protection (Section 3-4), particularly the dynamic response due to the horizontal motions of the shelter. Pendulum lengths in the order of approximately 10 feet or greater will usually reduce the horizontal accelerations of the structure to as low as 0.2 g. or less which is far below the design criteria of Section 3-4. For the purpose of analysis, the vertical and horizontal motions can generally be uncoupled (Reference 5.1; Section A-7.2c) except for a very short pendulum length in which case a non-linear coupling between the vertical and horizontal motions will occur. This non-linear coupling results in an unstable system when the vertical frequency is twice the horizontal frequency. However, this effect becomes small when the ratio is greater than 2.5 (Reference 5.1 and 5.4; Sections A-7.2c and A-7.2f) for the motions considered. The short pendulum system usually can be made stable with the use of horizontal springs (Figure 5-1c) or dampers.

c. <u>Base-Mounted Assembly</u>

The base-mounted spring assembly is a simple system in comparison to that of the pendulum. Here, flanges are attached rigidly to the top and bottom of the spring. The top flange is connected to the platform while the bottom flange is attached to the foundation slab. These connections must be of a rigid type to produce a stable system; therefore, the springs of the base-mounted system will essentially function as a cantilever under the action of the horizontal motions of the structure.

The base-mounted spring system is similar to a short pendulum system insofar as the occurrence of non-linear coupling of the vertical and horizontal motions will exist. In addition, the base-mounted system will be subjected to rocking motions due to the eccentricity of the platform load in relation to the center of gravity of the springs. The primary effect of this rocking is the increase of the vertical deflection of the springs above that resulting from the pure vertical motion of the system.

Quite often the base-mounted shock isolation platform will require a "soft" system to attenuate the vertical accelerations of the structure to a safe level (as in the case of personnel protection). This flexibility quite often will result in an unstable system under the action of the horizontal motions of the shelter. Stability usually can be obtained with the use of horizontal springs. Beam springs have been found to be useful for this purpose.

5-3 Platforms

The platforms used in protective shelters usually consist of structural steel framing with deck plates, steel gratings, or some other commonly used flooring material. The interior steel structure may consist of one, two, or many stories depending upon the population, the amount of equipment, and the shape of the shell. In most cases, the use of one- or two-story platforms will produce the most economical arrangement.

Generally, the use of pendulum-type supports with suspension systems having two or more stories is more practical than base-mounted systems because the attachments of the pendulums to the platforms can be made near the centroid of the steel structure. If base mounts are used, the large rocking effects resulting from the eccentricity of the platform load will substantially increase the required spring capacity and will probably somewhat increase the overall dimensions of the structure (suspension system and shell). Therefore, if possible, the use of base-mounted shock-isolated platforms should be restricted to single-story levels where large eccentricities will not occur. The use of base-mounted springs and platforms is an effective method of shock isolating the individual pieces of equipment. Here, the equipment can be mounted near the centroid of the spring supports in a manner similar to that shown in Figure 5-2c.

In those structures where both personnel and equipment are shock isolated for protection, the use of a single unit will usually be preferable to utilizing separate platforms. Here, the use of the lower shock tolerances for the personnel will be required, thereby giving the system as a whole a greater reliability.

In most cases when equipment, partitions and other such items are supported on platforms, they should be attached to prevent any relative motion with respect to the platform. Furniture, on the other hand, probably need not be attached directly to the platform but should be arranged such that any movement is minimized by friction.

5-4 Advantages and Disadvantages of Support Methods Used for Shock Isolation Platforms

Each of the support systems (pendulum and base mounted) mentioned previously will present certain advantages and disadvantages which may or may not have a bearing upon the final selection of the type of shock-isolated platform to be utilized in a particular design. The relative importance of these advantages and disadvantages will be dependent upon various parameters (pressure level, site condition, population, structure configurations, etc.) which affect the design as a whole, i.e., in shelters with a large population, the platform span would have a significant bearing upon the selection of the support system while in small shelters other factors would be more important. Therefore, the weighing of the relative importance of each of the advantages and disadvantages in a particular situation must be made by the designer.

The following discussion of the two supports systems is not for the purpose of comparison but only to point out the merits of each system.

5-4.1 Pendulum System

a. Advantages

1. Pendulums having lengths approximately 10 feet or greater will not usually require horizontal stabilizing systems (horizontal springs or dampers).

2. Horizontal accelerations associated with pendulums having lengths approximately 10 feet or greater will usually be less than the horizontal acceleration tolerances specified for personnel protection (Section 3-5).

3. Pendulum systems can be utilized to produce flexible supports required to attenuate the high acceleration associated with the vertical motion of the structure, in order to provide protection for personnel.

4. The use of pendulum systems will facilitate the use of both single and multistory platforms in suspension systems.

5. For short platform spans, no intermediate supports are required with pendulum systems.

6. Pendulum-type supports are readily adaptable in those structures where curved foundation slabs (horizontal cylinders or dome type foundation) are present.

b. Disadvantages

1. For short pendulum lengths, non-linear coupling of the vertical and horizontal motions may produce unstable shock-isolation systems.

2. Short pendulum lengths require the use of horizontal springs or dampers to prevent the occurrence of unstable shock-isolation systems.

3. Vertical accelerations greater than one g. may produce buckling of pendulum struts and/or unstable shock-isolation system.

4. In pendulum systems, the supports will extend above the platforms.

5. Large platform spans will require either intermediate supports, which extend above the platform, or very heavy framing when pendulums are used.

6. Pendulums are required to be suspended from the roof or the walls of the structure shell.

7. Because the roof support for a pendulum-type shock-isolation system must first be in place, the assembling and the mounting of the platform may be required after the completion of the structure shell.

8. The volume of the shell must be increased to provide sufficient rattle space for the movement of the platform.

5-4.2 Base-Mounted System

a. Advantages

1. In most cases, the base-mounted support systems can be used to attenuate the high accelerations associated with the structure motions to a tolerable level for personnel and equipment protection.

2. Base-mounted systems can be used in shock isolation systems with dynamic loads greater than one g. (restrained personnel or equipment protection).

3. The use of base-mounted spring systems will usually facilitate the shock isolation of individual pieces of equipment.

4. The use of the base-mounted system will facilitate the use of single-story platforms.

5. Spring supports for base-mounted shock-isolation systems will not extend above the level of the platform.

6. For short platform spans, no intermediate supports are required.

7. Short continuous platform spans will not require intermediate supports which extend above the surface of the platform.

8. Light framing may be used with continuous-span platforms because intermediate spring supports are readily adaptable to the base-mounted system.

9. Base-mounted support systems are appropriate for use in shelters which have monolithic foundations.

10. Platform supports need not be attached to the roof or walls of the shelter.

11. The shell need not be completed before the assembly and the mounting of the platform is performed.

b. Disadvantages

1. Rocking motions associated with base-mounted support systems will require additional length and strength of the springs.

2. Flexible spring supports for the vertical motion of the structure may result in an unstable system for the horizontal motion of the structure.

3. Horizontal springs or dampers may be required in some cases to prevent the occurrence of an unstable system.

4. Base-mounted support systems are to be avoided when floating floor slabs exist within a shelter.

5. The volume of the shell must be increased to provide sufficient rattle space for movement of the platform. In addition, headroom within the shelter must be made available so as to provide space for the springs below the platform.

5-5 Comparison of Support Methods Used for Shock Isolation of Platform

A direct comparison of the two support systems is only significant when it is related to a specific design condition where the actual weighing of the individual qualities or disadvantages of a system can be expressed quantitatively. For the purpose of this report, a qualitative comparison of the properties of the two systems has been made. This comparison is presented in Table 5-1 in a "check list" type of presentation:

5-6 References

5.1 A Guide for the Design of Shock Isolation Systems for Underground Protective Structures, Report No. AFSWC-TDR-62-64, December 1962. Prepared by The Ralph M. Parsons Company for the Air Force Special Weapons Center. Available from the Defense Documentation Center.

5.2 Ground Shock Problems in Hardened Facilities, Volume I, April 23, 1962. Prepared by American Machine & Foundry Company for the Office of the Chief of Engineers, Protective Construction Branch.

5.3 Barton, M. V., "Ground Shock and Missile Response", Shock and Structural Response, August 1960, The American Society of Mechanical Engineers, New York City, pp. 69-79.

5.4 Sevin, E., "On the Design of Shock Isolated Floor Systems", Shock, Vibration and Associated Environments, Part III, Bulletin No. 28, September 1960, pp. 22-35. Prepared by Armour Research Foundation for the Office of the Secretary of Defense (Research & Engineering). Available from the Defense Documentation Center (AD No. 244 784).

5.5 Harlam, R., "Shock Isolation at Hard Bases", Shock, Vibration and Associated Environments, Part III, Bulletin No. 28, September 1960, pp. 175-181. Prepared by American Machine & Foundry Company for the Office of the Secretary of Defense (Research & Engineering). Available from the Defense Documentation Center (AD No. 244 784).

Table 5-1 Qualitative Comparison of Support System

Comparable Items	Platform Support System: Pendulum	Base Mounted
Attenuation of vert. accelerations	one g. or less	as required
Attenuation of horiz. accelerations	usually 0.2 g. or less	slightly higher
Rocking	usually negligible	more pronounced
Type of platform	single & multistory	single story
Platform supports	extend above platform	below platform
Short single-platform spans	desirable	desirable
Large single-platform spans	less desirable	less desirable
Short continuous-platform spans	less desirable	desirable
Large continuous-platform spans	less desirable	less desirable
Attachment points	roof or walls	base slab
Foundation-slab shape	curved or straight	straight
Foundation-slab type	floating & monolithic	monolithic
Use of horiz. springs or dampers	seldom	more often
Volume of shell	increased	further increased

5.6 Dowdy, R. W., "Nuclear Ground Shocks Environment", Shock, Vibration and Associated Environments, Part III, Bulletin No. 29, July 1961, pp. 305-323. Prepared by Daniel, Mann, Johnson and Mendenhall and Associates for the Office of the Secretary of Defense (Research & Engineering). Available from the Defense Documentation Center (AD No. 260 564).

5.7 Concept Study Report - Barksdale Air Force Base Combat Operations Center, June 1961. Prepared by Ammann & Whitney, Consulting Engineers, for U. S. Army Engineer District, Little Rock, Arkansas.

5.8 Weissman, S. et al, "Nuclear Weapon Blast and Ground Shock Effects on Dynamic Response of Interior Components and Equipment in Underground Structures", Shock, Vibration and Associated Environments, Part III, Bulletin No. 29, July 1961, pp. 324-337. Prepared by Ammann & Whitney, Consulting Engineers for the Office of the Secretary of Defense (Research & Engineering). Available from the Defense Documentation Center (AD No. 260 564).

5.9 Vibration-Shock-Noise Control and Measurement, Bulletin K4K, 1963, Korfund Dynamics Corporation, Westbury, New York, AIA File No. 39D.

CHAPTER VI

PROTECTIVE CUSHIONING MATERIALS, PROTECTIVE CLOTHING, AND RESTRAINING AND BRACING DEVICES

6-1 Introduction

The personnel protective measures discussed in this chapter include the use of (1) protective cushioning materials (energy-absorbing padding placed on interior surfaces of the shelter); (2) protective clothing (helmets, padding, torso girdles, and protective shoes); (3) restraining devices (lap belts, shoulder belts, ankle and wrist restrainers, and secured seats); and (4) bracing devices (handholds and protective railings). These devices can all provide a degree of protection against injuries caused by impact loads. The method chosen would be based on the degree of protection desired, the functional requirements, and the cost. It may be desirable to use several of these methods in a particular shelter.

Protective cushioning materials offer the advantage of providing protection without relying on the personnel in the shelter to perform any precautionary task. Effective use of protective clothing requires an element of control in assuring that the clothing will fit and will be worn during the emergency since protective clothing may be cumbersome and uncomfortable if prolonged use is required. An important advantage in using protective clothing is that the dual-purpose function of the shelter area during non-emergency periods would not be affected. With advanced planning and proper supervision of the personnel, restraining devices can provide protection against injuries resulting from impact. Bracing devices can be used to provide supplementary protection in conjunction with one or more of the other methods.

6-2 Protective Cushioning Materials

6-2.1 General

Protective cushioning materials can be used as energy-absorbing padding to protect personnel from injuries caused by impact. As specified in Section 3-3, cushioning materials are to be provided on such potential impact surfaces as floors, walls, low ceilings, and interior furnishings, including flat surfaces as well as corners and edges.

Cushioning is required on flat impact surfaces where impact may occur at velocities greater than 10 ft./sec. resulting from falling over in which case it has been calculated that impact velocities would probably not exceed 17 ft./sec. (Section 3-2). Protection against injuries to the head are of particular concern. Cushioning is also required to protect against injuries resulting from falling over and striking a corner or edge. On exterior walls, protection must be provided against injuries which may be caused by compression waves transmitted by the blast loading.

Cushioning materials must possess high-energy-absorbing properties. Other desirable properties include:

1. Ease of application to any surface.
2. Ease of cutting and shaping.
3. Low flammability and free from release of toxic gases when burned.
4. Low water absorption.
5. Ease of cleaning.
6. Vermin-proof.
7. Resistance to chemicals and substances found in shelters, including gasoline, oil, soap, etc.
8. Good aging properties.
9. Stable properties over the range of temperature anticipated in the shelter.

For use on floors, the materials must have good wear resistance or should be capable of being coated with a wear-resistant surface that will not impair the energy-absorbing properties. None of the materials available are capable of resisting the damaging effects resulting from the concentrated loads imposed by high-heeled shoes. To minimize damage to the padding, it is important to exercise control over the type of shoes that will be worn in the shelter.

An important property of shock-absorbing materials is low rebound. For materials with high rebound, much of the energy is transmitted back to the body rather than being absorbed.

6-2.2 Design

Although danger exists from impact to other parts of the body, the most severe injuries are produced by blows to the head. These injuries are illustrated by the data on automobile and aircraft accidents presented in Reference 6.1 (Section A-7.2n) in which it was pointed out that 75 percent of fatalities are due to injuries to the head. Based on such observations, it is generally accepted that protection of the head against injuries which may result from impact is critical in the design of protective cushioning. Thus, by providing protection for the head, adequate protection also results for other parts of the body.

The critical factors in designing for impact protection for the head are (Reference 6.1):

1. The maximum g. loading
2. The maximum rate of change of g.
3. The peak intensity of pressure in line with the blow.
4. The initial impulse of the head striking an object. This impulse is determined by:

   Initial Impulse = $M_h (V_2 - V_1)$, where

   M_h = Mass of the head.

   V_2 = Velocity before contact.

   V_1 = Velocity after contact.

To determine the magnitude of these factors, it is necessary to perform tests on each cushioning material to insure its adequacy for the specified environment. A test procedure is recommended in Reference 6.1. In this test, a simulated head form having a weight of 30 lb. and a radius of 3-1/2 inches is recommended. The 30-lb. weight, which is about three times as heavy as a human head, accounts for additional body energy which may be contributed by the torso through the neck. The head form is impacted at various velocities on test specimens of the material and the measurements are made of the above factors. Control values of these factors for developing padding for head impact protection are:

1. Maximum g. loading - 60 g.

2. Maximum rate of change of g. - 20,000 g./sec.

3. Maximum pressure in line with blow - 600 p.s.i.

4. Initial impulse (threshold of fracture) - 5.3 lb./sec.

The maximum acceleration, the maximum rate of change of acceleration, and the initial impulse given above are based on tolerable values for the head whereas the maximum pressure indicates that the cushioning material has become solid.

Because the properties of the materials are quite different when used on a corner than on a flat surface, it is necessary to evaluate corners by separate tests. However, if the backup material has a radius of curvature greater than 2 inches, the impact effect is similar to that of a flat panel.

Using the above control values, safe impact velocities can be determined by recording the impact velocity at which the values are satisfied.

6-2.3 Materials

Several materials are available that possess suitable characteristics for shock absorption. Among the most important are the foam plastics, including the resilient forms of polystyrene foam, polyurethane foam, and foamed polyvinyl chloride. These materials are also available in rigid forms which possess outstanding shock-absorbing characteristics. However, the rigid foams are suitable for protection from one blow only and, in shelter use, would not provide adequate protection.

As mentioned earlier, good shock-absorbing materials must have low rebound. For this reason, elastic materials, such as foam rubber and felt, are not suitable.

Tests were performed (Reference 6.1) in accordance with the procedure and controls described in Section 6-2.2 in order to determine the effectiveness of various energy-absorbing materials in providing protection for the head against impact injuries. These materials are suitable for protection against more than one blow. Based on these tests, safe impact velocities were determined as listed in Table 6-1.

Table 6-1 Safe Impact Velocities of the Head Using Protective Cushioning Materials

Cushioning Material on Hard Flat Surface	Limit of Safe Impact Velocity
1 in.-thick Polystyrene Foam: 1-3/4 lb./cu. ft.	15 ft./sec.
2 in.-thick Polystyrene Foam: 1-3/4 lb./cu. ft.	18 ft./sec.
1 in.-thick *Ensolite (Polyvinyl chloride) 22266: 7 lb./cu. ft.	17 ft./sec.
2 in.-thick Foam Rubber: 6 lb./cu. ft.	11 ft./sec.
2 in.-thick Polyurethane Foam: Formulation "A"	16 ft./sec.

(* Trade name of United States Rubber Company, Mishawaka, Indiana.)

It is seen from the results of the tests that one inch of Ensolite 22266 provides the best protection per inch of thickness. The safe impact velocity of 17 ft./sec. satisfies the maximum impact velocity resulting from a person falling over. Most other materials would require a thickness of 2 inches or greater. This illustrates the outstanding properties of Ensolite 22266. One inch of this material has been used successfully as a floor mat in boxing rings.

Vinyl coatings may be applied to the cushioning material to increase its wear resistance for use on shelter floors.

Because of the extremely low density and the flexibility of the cushioning materials compared to concrete, such materials would be very effective in protecting personnel from injuries caused by the compression wave transmitted through the exterior concrete walls. Only a small fraction of the peak intensity of the compression wave would be transmitted from the concrete to a one-inch thick pad of cushioning material.

Protective cushioning materials have more effective energy-absorbing characteristics when applied to a flexible backing instead of to a rigid backing. Backing construction such as thin-gauge steel, aluminum, or plastic are all effective. However, to evaluate the properties of the combined padding and backing, tests must be made on the combination.

6-3 Protective Clothing

6-3.1 Helmets

Efficient helmet designs incorporate a system that distributes the load over a large area of the skull and also includes energy-absorbing materials. Load distribution is accomplished by using a hard shell suspended by padding or support webbing at a distance of 5/8 to 3/4 in. from the head (Reference 6.2). In a proper design, high local-impact forces are distributed over the entire side of the skull to which the blow is applied.

Tests referred to in Reference 6.2 (Section A-7.2a) indicate that helmets with web suspension distribute the blow more uniformly than those with contact padding. However, helmets with contact padding permit less slippage. A combination of contact padding and web suspension, therefore, is desirable.

The shell of the helmet must be as stiff as is compatible with weight considerations. When the shell is struck by a blow, its deflection must not be large enough to permit it to come in contact with the head. For use in shelters where comfort is an important consideration, the weight should be kept to a minimum. Among the shell materials that can provide the required stiffness along with light weight are steel-wire-reinforced bakelite, laminated bakelite, high-strength aluminum alloy, vulcanised fiber, and various reinforced-plastic laminates.

Padding materials, such as polystyrene and polyvinyl chloride foams, incorporate energy-absorptive features. Many padding materials, e.g., foam rubber and felt, are too elastic to absorb a blow. Therefore, it is important to consider padding materials carefully and to choose those materials that incorporate energy-absorbing properties.

The helmet design should consider the need for protecting the back of the head near the neck and the front of the head. Protection for the front of the head may be cumbersome and uncomfortable and it may be desirable to eliminate this protection for reasons of comfort. An uncomfortable helmet which will not be worn is of no use at all.

In choosing helmets from standard stocks, the above features should be carefully evaluated.

6-3.2 Miscellaneous Padding

In addition to the head, other areas of the body can be padded to protect against injuries which may result from impact. Such items as hip pads and pads to protect the back and spinal column are desirable. However, these items may become uncomfortable if prolonged wear is required.

For maximum protection, items of this type should be designed with a hard outer shell placed over energy-absorbing padding.

6-3.3 Torso Girdles

With impact or with high accelerations, the large gut mass may be displaced, resulting in rupture of the lungs or liver and fracture of the vertebral column. By enclosing the abdomen in a rigid girdle as discussed in Reference 6.3 (Section A-7.2m), this danger can be considerably reduced.

The need for this type of protection in the shelters considered for civil defense use is somewhat questionable. The structure motions that are encountered even at the 300-p.s.i. overpressure level are usually not severe enough to warrant the use of torso girdles. The major source of possible injury is from personnel being thrown about in the shelter, resulting in impact with the structure and items of equipment.

Because of the limited protection that may be obtained from the use of torso girdles, their use in civil defense shelters is not recommended.

6-3.4 Protective Shoes

Protective shoes are generally not required for protection within a shelter. The principal structure motions are downward, resulting in separation of the personnel from the structure floor. The high accelerations that accompany the structure motions, therefore, are never imposed on the body through the feet. However, as a result of the separation which may occur between the structure floor and personnel, the body will be subject to impact through the feet as a person falls and catches up with the decelerating floor. Maximum, computed impact velocities for overpressure levels up to 300 p.s.i. are less than 10 ft./sec. and are, therefore, within the tolerance for human impact (Chapter III).

6-4 Restraining Devices

Restraining of personnel within chairs or cots greatly alleviates the danger of injury due to impact with the shelter structure or items within the structure. Personnel could be restrained so that there is little possibility of impact with surfaces or sharp corners. In a practical design, it is not possible to restrain all the personnel. However, by keeping traffic to a minimum and by making maximum use of restraints, the danger of injury is minimized.

Seats to which personnel are restrained must be rigidly attached to the floor and must be designed to take the full acceleration loading applied by the personnel and the deadweight of the chair.

Restraining devices for fixing a person to a chair or cot may include lap belts, shoulder straps, chest straps, thigh straps, ankle and wrist restrainers, and handholds. In shelter structures where comfort is an important consideration and where it is practical to eliminate any possible impact surfaces forward of the head, only lap belts and handholds may be practical although additional protection is obtainable where the other devices are used.

A person restrained by a lap belt may flail about under the suddenly applied structure motions. His hands, feet, and upper torso may swing forward and, in some cases, his chest may hit his knees. Wrist and ankle restrainers or handholds attached to his chair can be used to reduce these motions. In addition, lap straps should be kept as tight as comfort will permit.

With restrained personnel, there is the danger of injury due to the rapidly applied structure motions being transmitted to the body. The maximum tolerable impact velocity is 10 ft./sec. (Chapter III). However, for the design studies (Chapter VII), the maximum structure velocity will not exceed 10 ft./sec. If the velocity of a structure exceeds 10 ft./sec., the use of energy-absorbing padding must be considered.

As described in Reference 6.4 (Section A-7.21), lap belts recommended for use in automobiles are 3-inch-wide nylon with a loop strength of 3,000 to 4,000 lb. This belt also appears to be adequate for use in shelter structures.

To minimize the loads applied to the seat and to reduce the danger of failure in the restraining device, lap belts should be attached to the floor rather than to the seat.

Impact to the head can be avoided if the backs of the seats do not extend above the shoulders.

6-5 Bracing Devices

As an aid in preventing people from falling over, handholds may be used along the structure walls and corridors. To prevent personnel from impacting with the walls, protective railings may be used.

Handholds should not be rigid hard materials that present a potential hazard to falling personnel unless these materials are padded. More suitable handholds can be fabricated of rope or similar material.

Protective railings also should be of flexible rather than rigid construction except in shelters where the entire structure is suspended on shock-isolating springs, in which case the structure motions are minimized reducing the likelihood of personnel falling. Flexible railings can be fabricated of rope (similar in design to boxing rings), nets, flexible wire mesh, canvas, etc. In some cases, railings of pipe may be desirable; however, if these are used, padding should be provided.

To prevent seated personnel from being thrown laterally, sides should be provided on the seats. In the case of bench-type seats, dividers should be provided for every 3 or 4 persons so as to protect the entire group from impacting against each other.

To prevent personnel from falling out of bunks, a pair of vertical straps extending from the lower bunk to the bunk above should be provided. Netting on the side of the bunk or other devices may also be used.

6.6 References

6.1 Dye, E. R. and Smith, M. D., "Mechanical Properties of Low Density Foams as Energy Absorbers", Mechanical Engineering, Volume 80, No. 12, December 1958. Prepared by Cornell Aeronautical Laboratory, Inc. for presentation at 1958 Semi-Annual Meeting of the American Society of Mechanical Engineers.

6.2 Goldman, D. E. and von Geirke, H. E., "Effects of Shock and Vibration on Man", Chapter 44, Shock and Vibration Handbook, Volume 3 (ed. Harris, C. M. and Crede, C. E.), 1961, McGraw-Hill Book Company.

6.3 Degan, J. W. and Williams, D. W., Human Survivability: Human Tolerance to Ground Shock and Low Frequency Vibrations in Command and Control Facilities (Task 139), Interim Report, Technical Memorandum TM-3057, April 24, 1961. Prepared by The MITRE Corporation under Contract No. AF 33(600)39852.

6.4 Automobile Seat Belts, Report of the Special Subcommittee on Traffic Safety, Committee on Interstate and Foreign Commerce, House of Representatives, 85th Congress, 1st Session, House Report No. 1275, 1957, U.S. Government Printing Office.

CHAPTER VII

DESIGN STUDIES

7-1 Scope

This chapter presents design procedures and a description and discussion of the design studies performed in conjunction with this project. These studies were developed to a point which will establish design layouts, illustrate typical methods used for providing protection from structure motions due to ground shock, and furnish estimates of the cost of those portions of the structures which affect, or are affected by, the method of shock isolation used.

The designs were performed for pressure levels of 25, 100, and 300 p. s. i.; for populations of 10, 100, and 250 persons using various type structures; and for foundations at the various pressure levels. In this study, buildings with one or more stories were considered, and in all cases they were assumed to be shallow buried. All three personnel protection levels (Chapter III) were considered in the designs. For equipment design criteria, both categories one and two (Chapter IV) were used.

7-2 Design Procedure

In order to select the most suitable structural configurations for the shelters and to arrive at a reasonable estimate of their cost, the following procedures have been used in this report.

1. Determine the nuclear environment (blast data, weapon size, etc.), design population, and type of structural configurations to be considered in the study.

2. Establish site conditions and perform site evaluation for ground shock.

3. Determine both free-field and design shock spectra, in addition to evaluating the relative displacements

between the structures and their interior components.

4. The next steps are the determination of the shock tolerances for both the personnel and equipment, and the establishment of the type of shock isolation method to be used.

5. Determine the size, shape, and method of operation of the isolation system for the specified population and shock environment. Also, design the structural system.

6. Determine the specific configuration of the shell of the structure based on the results of step 5 and on the nuclear environment of step 1.

Steps 5 and 6 may require reevaluation to produce a more compatible design of both the isolation system and shell.

7. Determine the cost of those portions of the structure which either affect, or are affected by, the shock isolation method.

7-3 Blast Load Data

The inclusion of nuclear and thermal radiation protection in a design will generally be confined to providing small modifications in the basic shelter designed for air-blast and shock protection. These modifications generally will be limited to those portions of the structure where modifications will not significantly affect the type of the shock isolation or the additional cost for providing it, i. e., entranceways, air intake and exhaust, earth cover, etc. Therefore, in this study radiation has been neglected.

On the other hand, blast overpressures and ground shock will be quite significant in selecting the shelter configuration, especially in the larger pressure levels (50 to 75 p. s. i. and higher) where flat roof construction becomes less economical. The overpressure will usually govern the selection of the type of structure and foundation whereas the ground shock will influence the interior arrangement of the shelter. In most cases, it is necessary to effect a compromise in the selection of the best structural arrangement for overpressure and ground shock so as to produce the most efficient overall system.

The structures studied in this section are designed to resist the effects (exclusive of radiation) of a nuclear weapon, with a yield of 20 MT, detonated near the earth's surface; these structures are assumed to be located at a distance from ground zero that would produce surface overpressures of 25, 100, or 300 p.s.i. and will remain operable after being subjected to such effects. Basic data for the proposed blast wave characteristics for the prescribed weapon yield and pressure levels are summarized in Table 7-1. The idealized pressure-time variations for all three pressure levels are shown in Figure 7-1.

Table 7-1 Blast Characteristics
Surface Burst (20 MT)
(Ref. 7.1)

Peak Overpressure (P_{so}), p.s.i.	25	100	300
Distance from Ground Zero (r), yds.	5,700	3,100	2,060
Arrival Time (t_1), sec.	5.0	1.4	0.5
Duration of Positive Phase (D_p), sec.	3.4	2.3	2.6
Peak Dynamic Pressure (P_{do}), p.s.i.	12	115	470
Positive Impulse (I_p), p.s.i.-sec.	24	48	85
Shock Front Velocity (U), f.p.s.	1,710	2,800	4,800
Fireball Radius (R), ft.	--	4,000	--

7-4 Soil Conditions

For the designs, it was assumed that the soil profile comprised a 10-ft.-thick surface layer, a 90-ft.-thick intermediate layer, and an underlying layer extending to a great depth. The assumed seismic velocity for each layer is as follows:

Table 7-2 Assumed Seismic Profile

Soil Layer	Depth Below Ground Surface (feet)	Seismic Velocity (ft./sec.)
Surface Layer	0-10	1,200
Intermediate Layer	10-100	2,500
Underlying Strata	Below 100	6,000 avg.

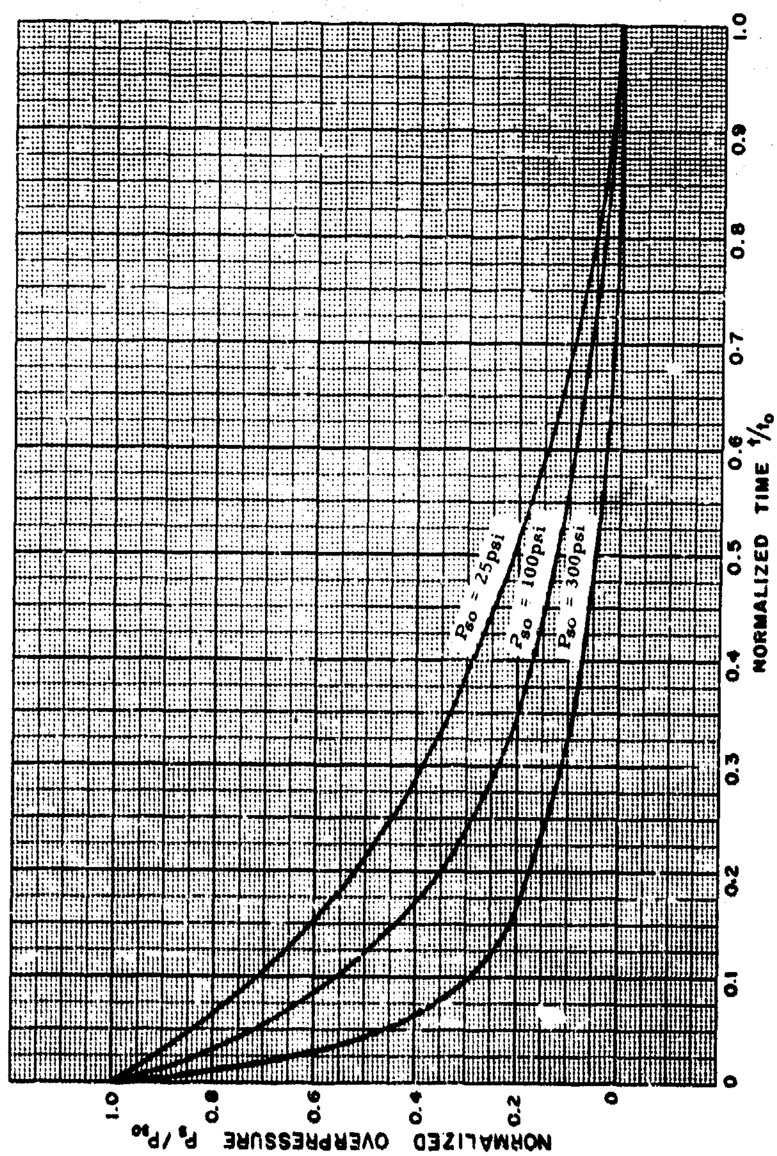


Fig. 7-1 IDEALIZED INCIDENT OVERPRESSURE - TIME CURVES

The seismic velocity for each layer is in the order of magnitude generally encountered at typical soil sites. Although this seismic profile represents a typical soil site, the profile could vary (with respect to both seismic velocity and layer thickness) for other sites. Somewhat lower or higher values of the seismic velocity at each layer as well as an increased or decreased thickness of the surface and/or the intermediate layer and even a site of additional distinct layers could also be considered typical. Thus, the above profile could more appropriately be designated as a sample of a typical site.

7-5 Shock Spectra

7-5.1 Free-Field Ground-Shock Spectra

The free-field ground-shock spectra as computed in accordance with the procedures of Section 2-3, for a 20-MT surface burst for the surface and 10-, 20- and 30-ft. depths below the ground surface are plotted in Figures 7-2 to 7-7 as follows:

Figure 7-2	Vertical Spectra	25 p.s.i.
Figure 7-3	Horizontal Spectra	25 p.s.i.
Figure 7-4	Vertical Spectra	100 p.s.i.
Figure 7-5	Horizontal Spectra	100 p.s.i.
Figure 7-6	Vertical Spectra	300 p.s.i.
Figure 7-7	Horizontal Spectra	300 p.s.i.

The peak ground motions are for the air-induced effect since the direct-transmitted ground-shock effect results in smaller values for the type of site and pressure levels considered. For computing the elastic displacement component, an effective average seismic velocity (5,000 f.p.s.) was used which is assumed to be equivalent to the actual layered site. The peak horizontal displacements, velocities, and accelerations are equal to 1/3, 2/3, 1 times the vertical values, respectively. The peak vertical-displacement spectra values are equal to the peak vertical ground displacements. The peak vertical-velocity spectra values are equal to 1.5 times the peak vertical ground velocities. The peak vertical-acceleration spectra values are equal to the peak vertical ground accelerations. The boundary spectra values for both the vertical

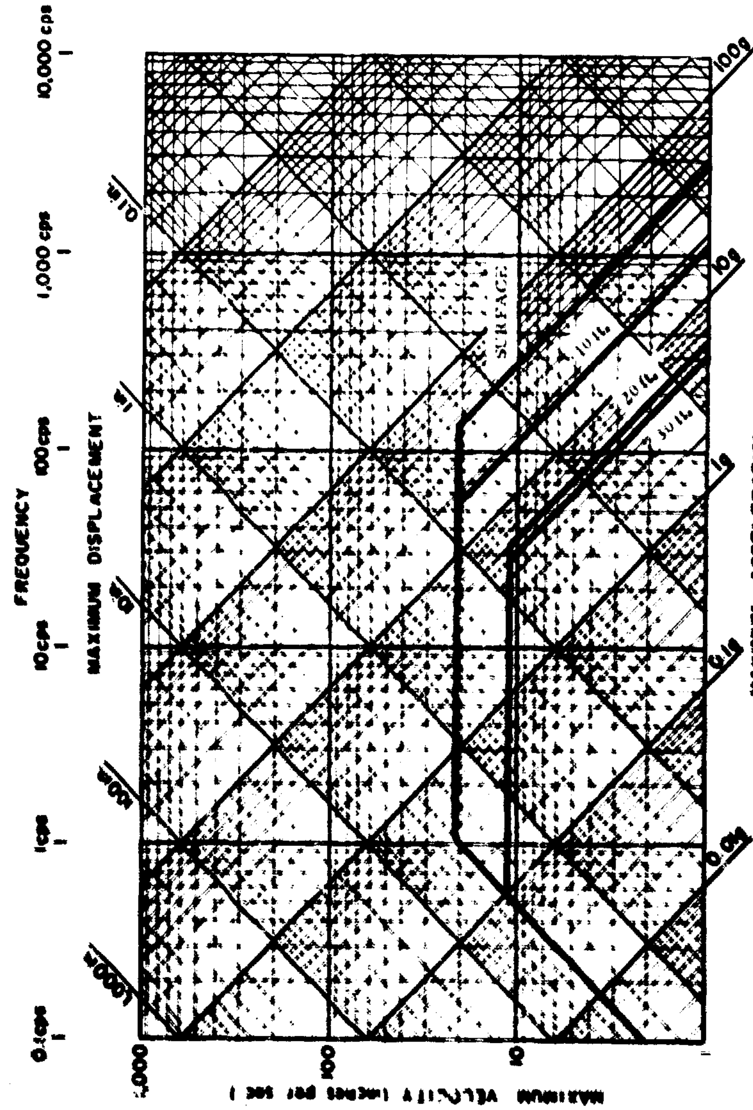


Fig. 7-2 FREE-FIELD VERTICAL GROUND SHOCK SPECTRA
25 psi

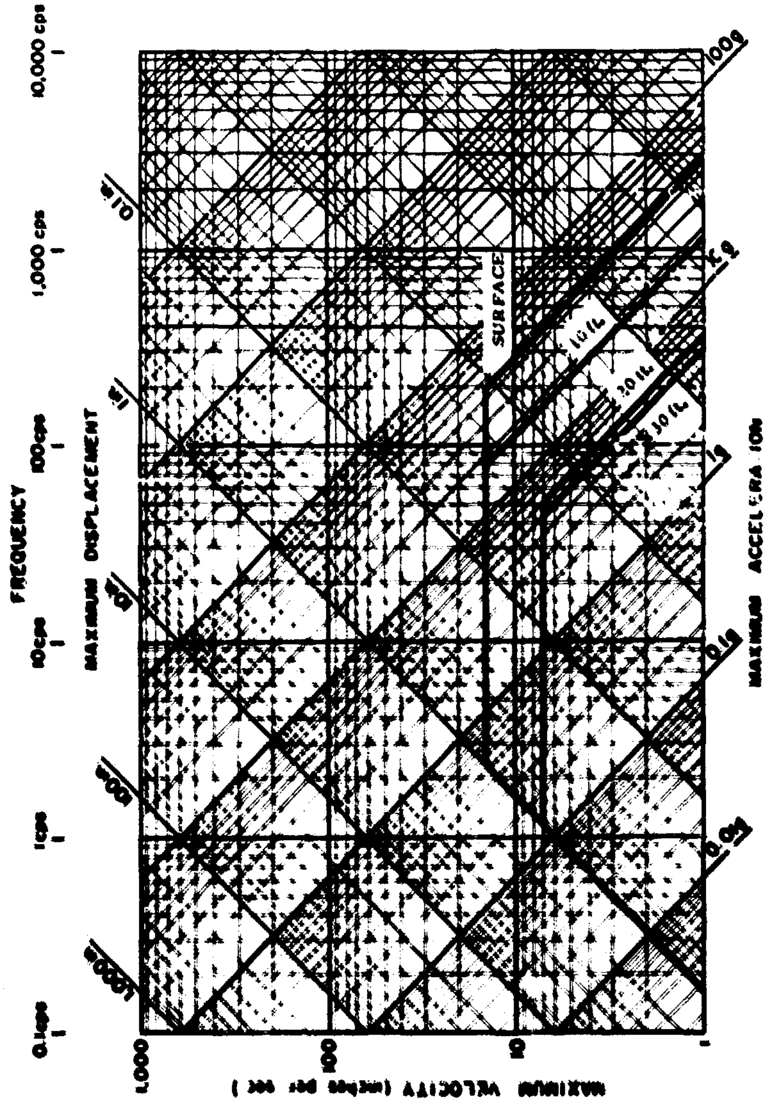


Fig. 7-3 FREE-FIELD HORIZONTAL GROUND SHOCK SPECTRA
25 psi

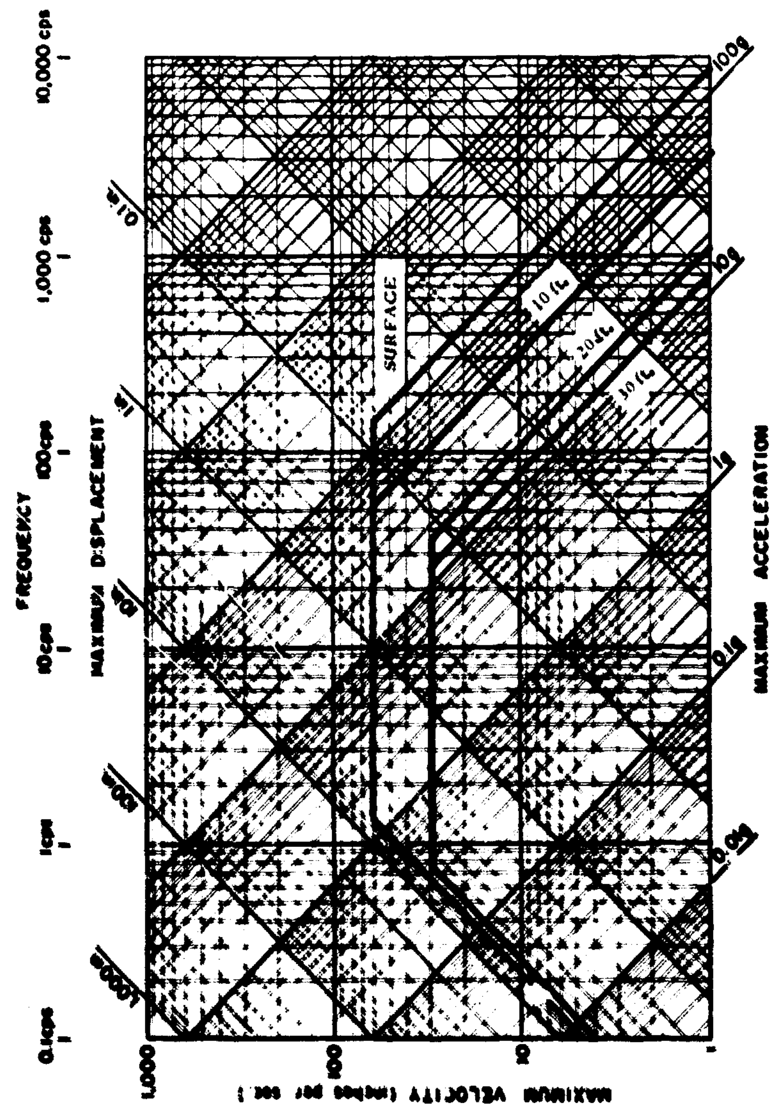


Fig. 7-4 FREE-FIED) VERTICAL GROUND SHOCK SPECTRA
100 psi

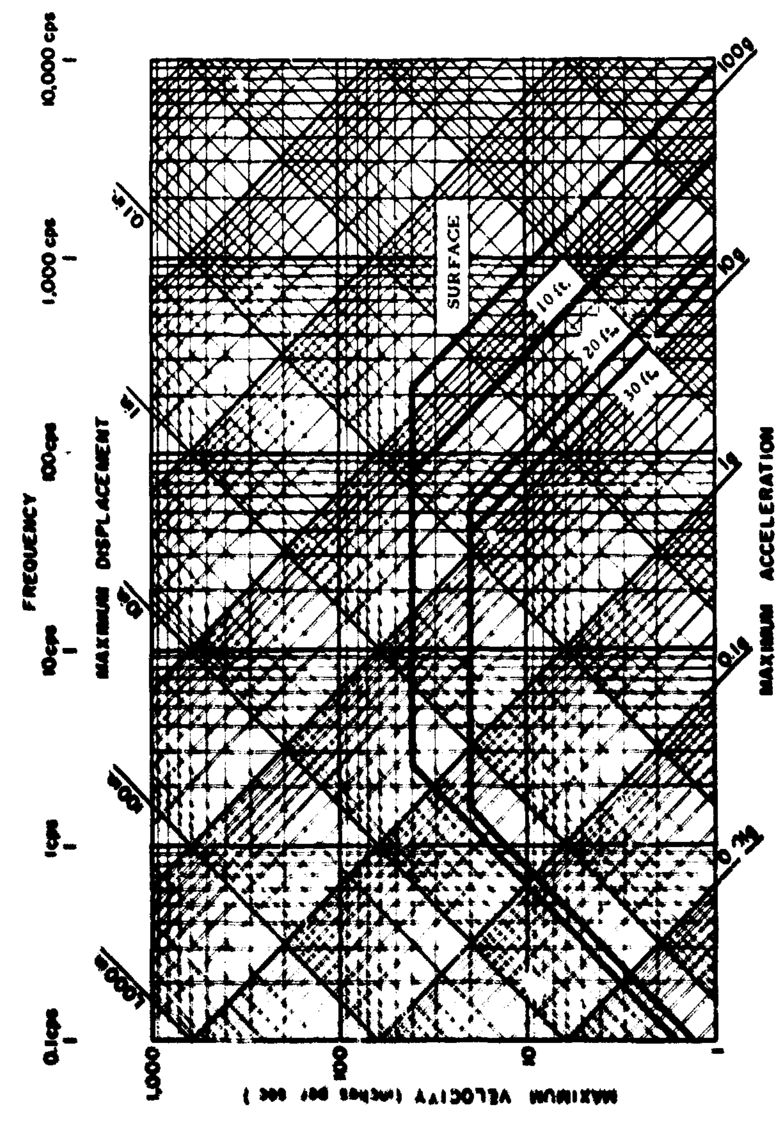


Fig. 7-5 FREE-FIELD HORIZONTAL GROUND SHOCK SPECTRA
100 psi

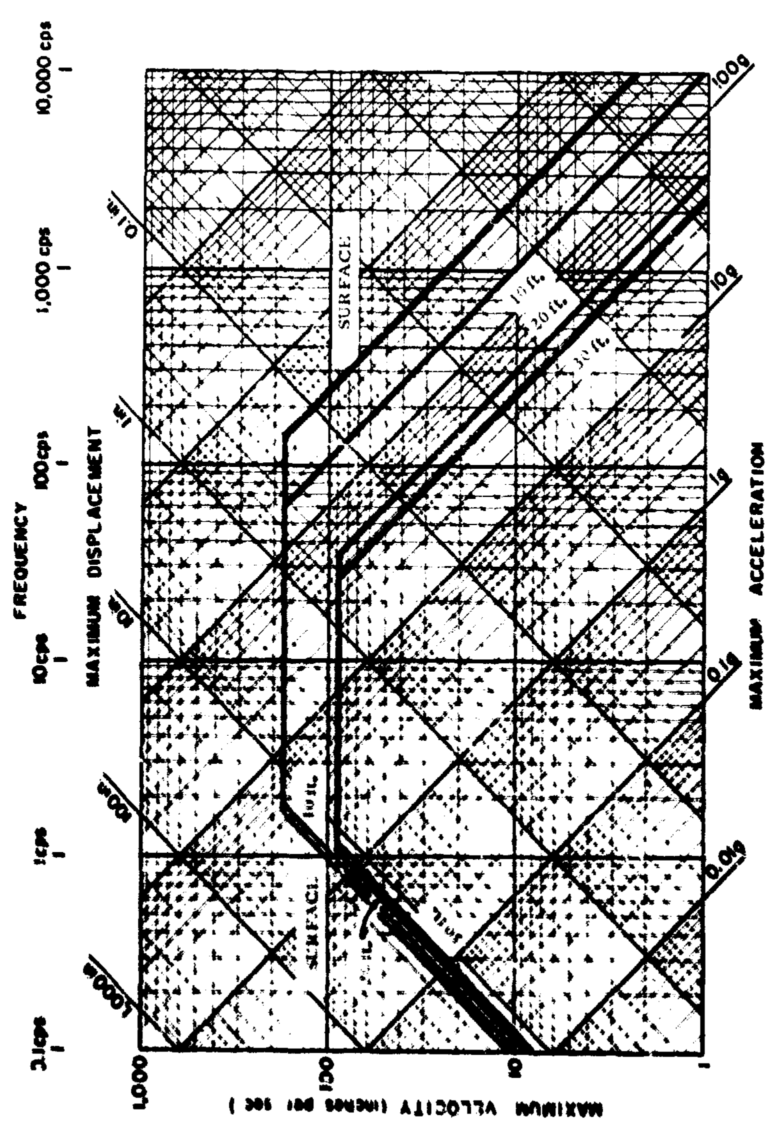


Fig. 7-6 FREE-FIELD VERTICAL GROUND SHOCK SPECTRA
300 psi

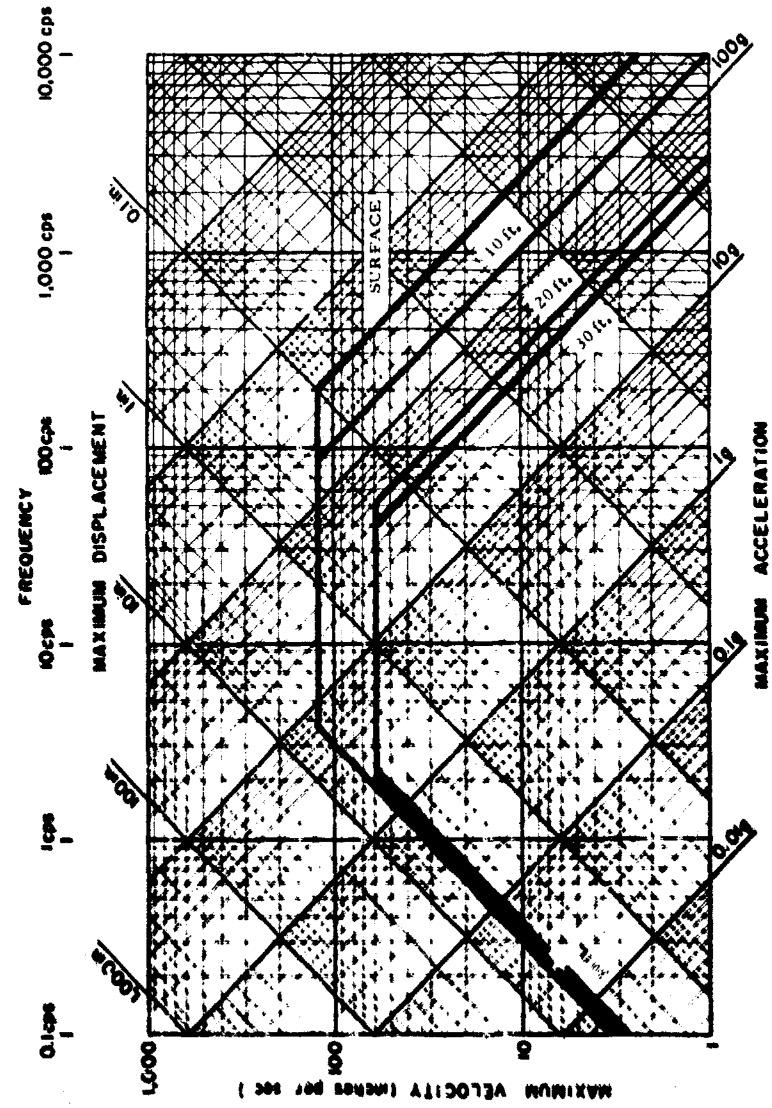


Fig. 7-7 FREE-FIELD HORIZONTAL GROUND SHOCK SPECTRA 300 psi

and horizontal displacements, velocities, and accelerations are listed in Table 7-3 (p. 7-13).

The spectra of Figures 7-2 to 7-7 could be considered to represent a band of spectrum values for the pressure range being considered, e.g., better sites of 300 p.s.i. or poorer sites of 100 p.s.i. would lie somewhere between the 100- and 300-p.s.i. spectra. In fact, these spectra may also represent other pressure levels, e.g., a typical site of somewhat higher seismic velocities at 150 p.s.i. could result in the 100-p.s.i. spectra. To illustrate the above discussion it may be interesting at this point to indicate the variation that may be expected in the soil displacements depending upon the site conditions and pressure levels.

Table 7-4 Site Variations

Type of Soil	Seismic Velocity * (ft./sec.)	Displacement (in.)		
		25 psi	100 psi	300 psi
Poor	2,500	6	12	23
Typical	5,000	3	7	14
Rock	10,000	1.6	2.7	4.2

* Effective Average Seismic Velocity

7-5.2 Design Shock Spectra

To determine the response of intermediate floor slabs and bearing walls, which are integral with the concrete shell, and of internal shock systems attached to the shell, the free-field ground motions at the 10-ft. and 30-ft. depths have been assumed to be equal to the motions of the shallow (one and two stories) and taller buildings respectively. Although Chapter II recommends that approximately the mid-height of the shallow structures be used to determine the motions of structures, it was felt that the 10-ft. depth would be a more realistic estimate of the actual motions because of occurrence of the layer change at the 10-ft. depth in the assumed soil profile of section 7-4. Above the layer change the free-field velocities and accelerations would be somewhat higher than those immediately below and, therefore, the use of the mid-height motions would not properly account for the effects of

Table 7-3 **Boundary Spectra Values for Free-field Ground Motions**

Direction	Depth	25 p.s.i.			100 p.s.i.			300 p.s.i.		
		Displ. (in.)	Vel. (in./sec.)	Accel. (g.)	Displ. (in.)	Vel. (in./sec.)	Accel. (g.)	Displ. (in.)	Vel. (in./sec.)	Accel. (g.)
Vertical	Surface	3	21	44	7	60	125	15	180	375
	10 ft.	3	21	18	7	60	50	14	180	150
	20 ft.	3	11	6	6	29	16	13	87	49
	30 ft.	3	11	5	6	29	12	12	87	37
Horizontal	Surface	1	14	44	2.3	40	125	5	120	375
	10 ft.	1	14	18	2.3	40	50	4.7	120	150
	20 ft.	1	7	6	2	19	16	4.3	58	49
	30 ft.	1	7	5	2	19	12	4	58	37

the surface layer on the structures. The free-field motions at the 30-ft. depth were selected to represent the motions of the taller building based on the recommendation of Chapter II. For shallow-type structures, Figures 7-8 and 7-9 are plots of the vertical and horizontal design spectra, respectively. The design spectra for the taller buildings are not shown because of this secondary importance of the structures in this report, although their values may be obtained from the free-field spectra if desired.

When determining the motions of personnel, equipment and other items attached directly (no shock isolation system) to the structure shell, the free-field ground motions at the forementioned depths are used. A tabulation of the peak values of these motions is given in Table 7-5.

For determining the separation between items (not attached directly or indirectly to the interior of the structure) and the structures, the variation of the downward motions of the structures and the free-fall displacement of the unattached items with time for the 25-, 100-, and 300-p.s.i. overpressure levels are given in Figures 3-1, 3-2, and 3-3, respectively. The variation of the horizontal motions of the structures with time is plotted in Figure 3-4. Both the vertical- and horizontal-motions-versus-time relationships have been computed using the design shock spectra previously mentioned and the procedures outlined in Section 3-2.

7-6 Space Allowance

The size of each structure was based upon a minimum floor area of 10 sq. ft. per person (not including utilities, toilets, storage areas, and partitions) for the total specified population. In the personnel areas, the headroom was maintained at a minimum height of 6'-0" except in those areas immediately adjacent to the sides of cylindrical structures (horizontal cylinders and arches); in such areas the height is equal to 6'-0" plus the vertical displacement of the suspension system or the separation of items not attached to the floor. In general, the limited headroom (below 8 ft.) extends only over approximately 5 percent of the floor area. In some of the design structures, a headroom slightly less than

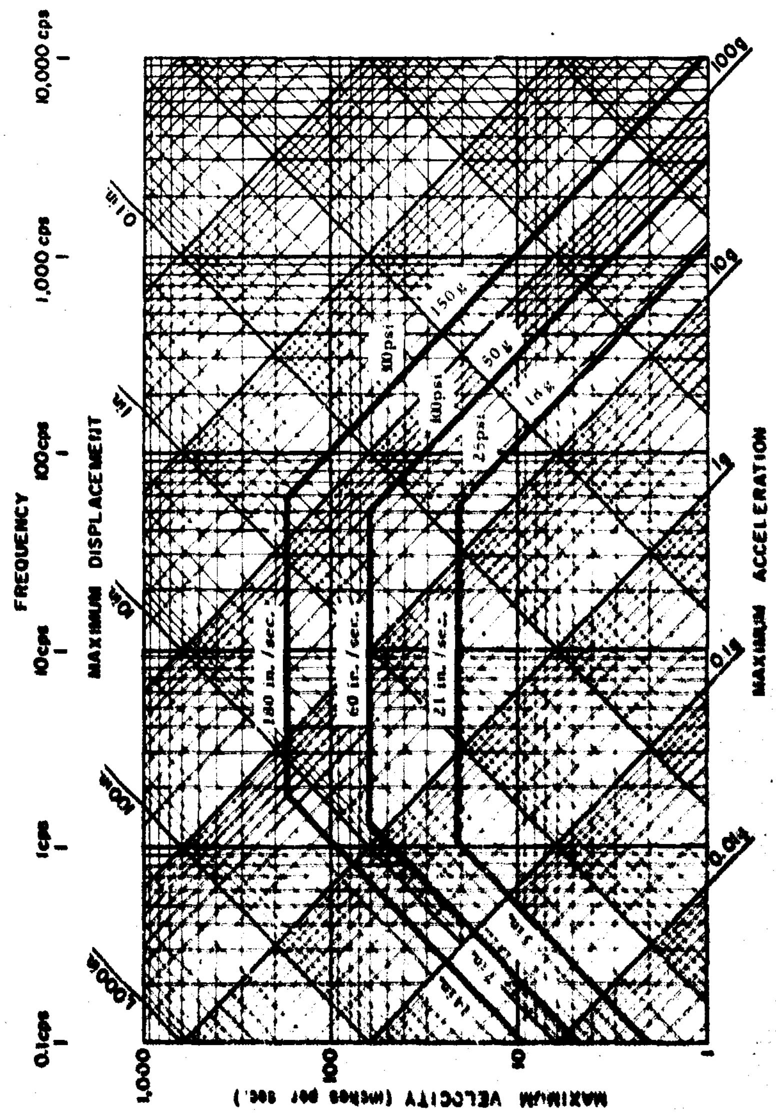


Fig. 7-8 VERTICAL DESIGN SPECTRA - 25, 100 & 300 psi

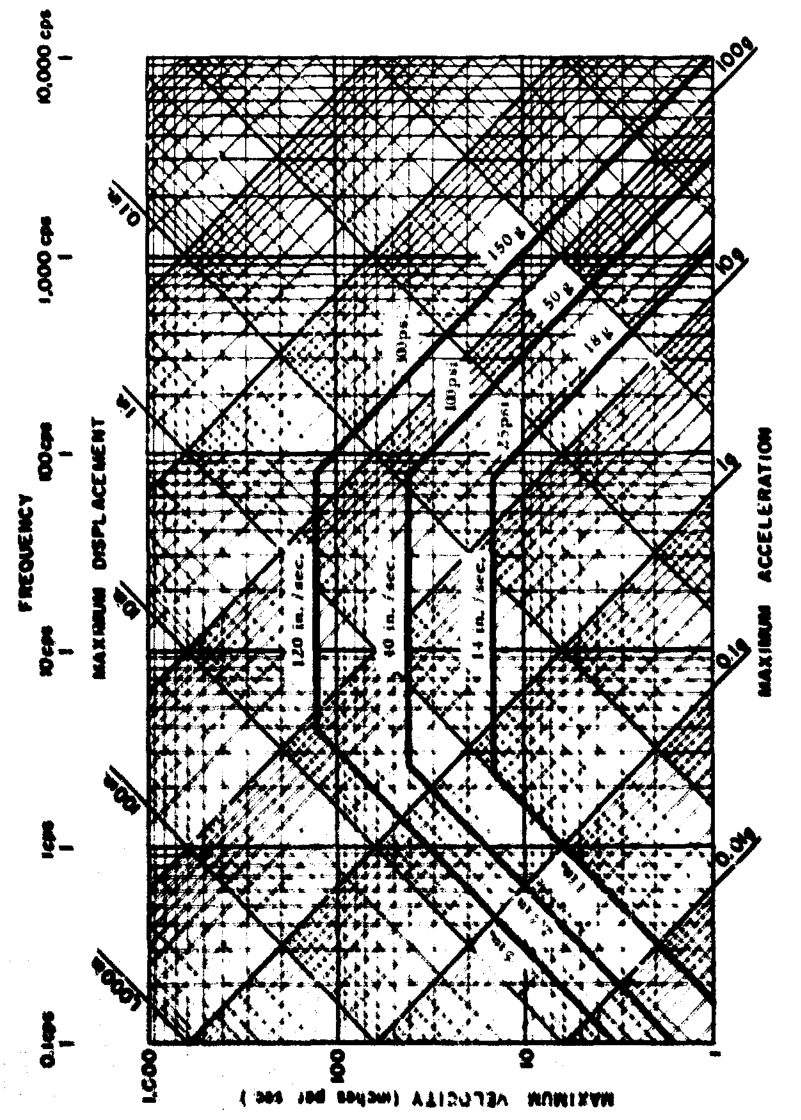


Fig. 7-9 HORIZONTAL DESIGN SPECTRA - 25, 100 & 300 psi

Table 7-5 Peak Motions of the Structures

Structure Type	Overpressure (p. s. i.)	Displacement (in.)		Velocity (in./sec.)		Acceleration (g.)	
		Vert.	Horiz.	Vert.	Horiz.	Vert.	Horiz.
Shallow	25	3	1	14	9.3	18	18
	100	7	2.3	40	27	50	50
	300	14	5	120	80	150	150
Tall	25	3	1	7.3	4.9	5	5
	100	6	2	19	13	12	12
	300	12	4	58	38	37	37

8 ft. was used in the mechanical areas.

A specific space allocation will depend upon the assumed position (sleeping, sitting, or standing) of the occupants within the structure and also upon the anticipated length of stay as well as the amount of movement allowed. The following are some recommended minimum space allowances (Ref. 7.2) which will provide a reasonable degree of comfort.

Sleeping (Tier Bunks)
- Area - 13 sq. ft./bunk
- Vertical Distance between Tiers - 2'-0" plus relative motion *
- Main-Aisle Width - 4 ft.
- Secondary-Aisle Width - 2 ft.

Sitting (Short-Duration Stay)
- Area - 7.0 sq. ft./person
- Vertical Clearance - 4.5 ft. plus relative motion *
- Main-Aisle Width - 4 ft.
- Secondary-Aisle Width - 2 ft.

Sitting (Long-Duration Stay)
- Area - 8 to 11 sq. ft./person
- Vertical Clearance - 4.5 ft. plus relative motion *
- Main-Aisle Width - 6 ft.
- Secondary-Aisle Width - 3 to 4.5 ft.

Standing (No Circulation)
- Area - 2 sq. ft./person
- Vertical Clearance - 8 ft.

Standing (Circulation)
- Area - 10 sq. ft./person
- Vertical Clearance - 8 ft. **

* Relative motion applies to movement of suspension system and/or relative displacement between unattached items and the structure proper.

** 6.0 ft. is acceptable over a limited area.

7-7 Design Loads, Applicable Codes, and Allowable Stresses

7-7.1 Design Loads

This section lists the applicable loads used for the preliminary designs described in this report. Static and dynamic loads are presented for the exterior shell as well as for the interior portions of the structures. Both the method of application and the amplitude of each load are listed.

Exterior Shell
- Amplitude
  - Earth Load (varies with type of structure) - 2 to 7 p.s.i.
  - Dead Load (varies with type of structure) - 1 to 2 p.s.i.
  - Blast Load (dynamic response of one) - 25, 100 & 300 p.s.i.
- Application
  - Circular Structures - Radially
  - Rectangular Structures - Normal

Interior of Structure
- Amplitude
  - Static Loads
    - Dead Load - As given
    - Mechanical Area - 100 p.s.f.
    - Personnel Area & Toilets - 40 p.s.f.
  - Dynamic Loads -
    - Dead Load - As given
    - Mechanical Area - 100 p.s.f.
    - Personnel Area & Toilets - 175 lbs./pers.
- Application
  - Static Loads - 1 g.
  - Dynamic Loads - Dynamic Response

7-7.2 Applicable Code

The structural design of the illustrated structures conforms to the current ACI Building Code, including the appendix on ultimate strength design.

7-7.3 Allowable Stresses

The following is a list of the allowable stresses used in this design study:

Allowable Stresses for Static Loads

- Concrete Compression (f'_c), Axial or Flexural - 3000 p.s.i.
- Pure Shear - 0.15 f'_c
- Bond - 0.15 f'_c
- Diagonal Tension - ACI Code
- Reinforcement (ASTM A432) - 60,000 p.s.i.
- Soil Bearing Stress - 4 t.s.f.

Allowable Stresses for Blast Loads

- Concrete Compression (f'_c), Axial or Flexural - 1.25 f'_c
- Pure Shear - 0.18 f'_c
- Bond - 0.18 f'_c
- Diagonal Tension - ACI Code
- Reinforcement (ASTM A432) - 78,000 p.s.i.
- Soil Bearing Stress (Dynamic Response of 2) - 8 t.s.f.

Allowable Stresses for Ground Shock

- Structural Steel (ASTM A36) - 36,000 p.s.i.
- Spring Steel (Ref. 7.3) - 80,000 p.s.i.

7-8 Description of Design Concepts

Of the thirty-five schemes included in this study, nine structures were designed for the 25-p.s.i. overpressure range while sixteen and ten structures were designed for the 100- and 300-p.s.i. pressure levels, respectively. The schemes for the 25-p.s.i. overpressure range were limited to rectangular-type buildings whereas for the higher pressure levels several different structural arrangements were investigated for feasibility of construction. The latter included horizontal and vertical cylinders as well as arches. Personnel protection levels 1, 2, and 3 (Chapter III) were considered for all three overpressure levels, and for the equipment tolerances categories 1 and 2 (Chapter IV) were used. For personnel protection No. 1, suspension systems, consisting of one, two, or more platforms were studied for the structures at the 100 and 300 p.s.i. pressure levels. In the case of the rectangular structures, only single-story systems were used. All three population sizes (10, 100, 250) were included in the studies of the 25-p.s.i. structures while the buildings for the higher pressure levels were designed for 100 and 250 persons only. These combinations of the pressure levels, population size, protection level, and suspension systems, along with an outline description of the structures, are presented in Table 7-6. The designation of the structures listed in Table 7-6 is described by the following example. The structure designation HC(T) 300-250-1, identifies the horizontal cylinder with a two-story interior suspension system located at the 300-p.s.i. overpressure range, having a capacity of 250 people and a personnel protection level of one. In the following discussion, the number of levels refers to the total number of stories integral with, or suspended within, the shell of the structure.

In the following discussion, those structures which were found to have the most favorable structural and/or economical arrangement are described in more detail. These structures, referred to as basic concepts, are as follows:

Overpressure	Configuration
25 p.s.i.	Rectangular
100 p.s.i.	Horizontal Cylinder
300 p.s.i.	Horizontal Cylinder

7-8.1 Basic Concepts for 25-p.s.i. Pressure Range

a. Structure RE(S) 25-250-1

This scheme, as shown in Figure 7-10, is a single-story reinforced-concrete rectangular structure designed for 250 persons. The overall plan dimensions of the building are 59 ft.-8 in. by 59 ft.-8 in. while its interior clear height is 10 ft.-3 in. The roof slab is a flat plate 1 ft.-9 in. thick, supported along its periphery by a 10-inch-thick exterior wall and at the center by a reinforced concrete column. The walls are supported on a continuous foundation the thickness of which is the same as that of the roof slab.

The interior of the building consists of a single-story shock-isolated steel structure or platform which is supported by twenty helical compression springs mounted on the continuous floor slab. The overall distance between the top of the suspended platform and the floor slab is 1 ft. -3 in. This will allow for a vertical downward motion (from its at-rest position) of the platform of approximately 6 inches. The horizontal clearance between the platform and the shell of the structure is 6 inches. The clear distance between the top of the platform and the ceiling of the building is 9 ft. -0 in. This provides for a headroom of eight feet in addition to a one-foot-high overhead space for conduits and ducts. The platform has a usable area of approximately 3400 sq. ft. and is divided into three main sections: (a) personnel area, (b) mechanical area, and (c) toilets. Both the mechanical and toilet areas, which are located on the same side of the structure, are separated from the personnel area by metal partitions. The personnel area, which comprises the major portion of the platform, is protected along its periphery by a metal railing, 3 ft. -6 in. high. Access between the main structure (entranceway, exhaust and intake shaft) and the platform is by means of removable metal plates. All partitions, railing, etc., are of standard design.

b. <u>Structures RE- -250-2 and RE-25-250-3</u>

These schemes, shown in Figure 7-11, have the same overall roof area and thickness as those of structure RE-25-250-1, and were designed for the same population. The 10-inch-thick exterior walls, which have a clear height of 9 ft. -0 in., support the roof along its periphery while a reinforced concrete column supports its center. The walls are supported on individual footings except in the area of the mechanical equipment where a combined foundation is used. Outside this latter area the floor slab is of the floating type. The column is supported on its own foundation.

From an architectural standpoint, each building is separated into three sections, i.e., the personnel area, the mechanical area, and the toilets. The mechanical area and toilets are located on the same side of the structure adjacent to one another. Their combined floor area is equal to approximately 20 percent of that of the building. These areas are separated from the main shelter area by a reinforced concrete wall.

Both the personnel area and the toilets are located on the concrete floor slab of the structure, while the mechanical equipment is mounted on a shock isolated platform. The platform is supported on ten helical compression springs which in turn are mounted on the monolithic section of the foundation. The top of the platform is located 1 ft. -3 in. above the base slab and 7 ft. -9 in. below the roof. The clearance between the foundation and the base of the platform provides room for a vertical movement (of the platform) of approximately six inches. A six-inch rattle space is provided around the mechanical equipment support system. Movement between the mechanical area and the remainder of the building is across a removable steel plate.

Structures RE-25-250-2 and RE-25-250-3 were designed for personnel levels 2 and 3, respectively. In structure RE-25-250-2, the floors, exterior walls, and corners of interior concrete partitions in the personnel area and the toilets are padded with one-inch-thick energy-absorbing material, while in structure RE-25-250-3 only the exterior walls and the corners of the interior walls are padded. In both structures, the corners are chamfered in order to provide the required two-inch radius of the cushioning so as to produce the required protection (See Chapter VI). No cushioning is provided in the mechanical area because of the presence of the suspension system.

c. Structure RE(S)-25-100-1

This structure, shown in Figure 7-10, is designed for a population of 100 persons and is structurally similar to that described in Section 7-8. la with the exception that its overall plan dimensions are reduced to 41 ft. -8 in. by 41 ft. -8 in. This reduction of the size of the building decreases the usable floor area of the structure and of the steel platform to 1600 and 1520 sq. ft., respectively. Twelve helical compression springs are required to support the suspension system as compared to the twenty springs of structure RE(S)-25-250-1.

d. Structures RE-25-100-2 and RE-25-100-3

These structures, as shown in Figure 7-11, are similar to the structures of Section 7-8. 1b except that the overall plan dimensions are reduced to that of Structure RE-25-100-1. In these structures, six compression springs are used to support the equipment platform in the mechanical area.

e. Structure RE(S)-25-10-1

This scheme is a rectangular reinforced-concrete shelter as shown in Figure 7-10. The structure was designed for a population of 10 persons and, therefore, has overall dimensions of 16 ft. -8 in. by 12 ft. -8 in. As in the case of the other rectangular structures for personnel protection one, an interior shock-isolating steel structure is supported on the four helical springs which in turn are supported on the continuous concrete foundation of the shell. The overall headroom and the rattle spaces around and beneath the platform were maintained identical to those of the other rectangular structures with the larger populations. The architectural arrangement of the platform is similar to that of the larger structures with the exception that the floor areas of the individual rooms are proportionally reduced.

f. Structures RE-25-10-2 and RE-25-10-3

The floor plan of these structures (Figure 7-11) is of the same size as that of structure RE-25-10-1, and the vertical dimensions are the same as those of the structures of Sections 7-8. 1b and 7-8. 1d. Structures RE-25-10-2 and RE-25-10-3 are designed to provide personnel protection level two and three, respectively. The cushioning in these buildings is the same as that described in Section 7-8. 1b.

7-8. 2 Basic Concepts for 100- and 300-p.s.i. Pressure Ranges

a. Structures HC(T)-100-250-1 and HC(T)-300-250-1

These schemes, as shown in Figure 7-12, are single-level, horizontal cylindrical concrete structures with a two-story interior shock-isolation system in each.

The interior diameter of the cylinder is 25 ft. -0 in. and its length is 99 ft. -0 in. The ends of the cylinder are sealed by two hemispherical domes which have an interior radius of 12 ft. -6 in. The thickness of the walls of both the cylinder and the spheres of the 100-p. s. i. shelter is 0 ft. -8 in. while the shell thicknesses of the cylinder and spheres at their springing lines in the 300-p. s. i. building are 1 ft. -0 in. The thickness of the crowns of the latter spheres is 1 ft. -0 in.

The interior shock-isolation system is a steel structure which is attached to the shell of the concrete portion of the building by eight helical compression springs forming a pendulum-like arrangement. The clear distance between the shell and the suspension system is governed by the required minimum headroom near the edge of the upper platform and is 1 ft. -9 in. in both structures. The upper story of the interior structure of each building has a usable floor area (for personnel and/or equipment) of approximately 2,200 sq. ft., while the usable floor area of the lower level is approximately 1,200 sq. ft. The overall distance between the two floor levels is 9 feet. Means of access between the upper and lower stories is by stairs located near the center of the structure. The main shelter area for personnel is situated on the top level while a smaller personnel area is located at the bottom of the stairs on the lower floor. This latter area separates the mechanical area and the toilets located at each end of the lower floor. The periphery of the open area of both levels of the interior structure is provided with a 3 ft. -6 in.-high metal partition for personnel protection. The partition is also used around the stairs at the upper level. The lower portion of the stairs and those areas (mechanical, storage, and toilets) separated from the personnel areas are enclosed with light metal partitions. Access between the main structure and the support is by means of removable metal plates. All partitions, railings, etc., are of standard design but are reinforced to resist impact forces resulting from the movement of objects (personnel, furniture, etc.) within the structure.

b. Structure HC(S)-100-250-1 and HC(S)-300-250-1

These schemes, as shown in Figure 7-13, are reinforced-concrete one-level horizontal cylinders, with interior radii of 9 ft. -0 in. The structures are sealed at their ends by hemispherical domes which have the same interior radius as the cylinders. The length of the cylindrical portion of the 100-p.s.i. structure is 238 ft. -0 in. For the 300-p.s.i. building its length is 256 ft. -0 in. Both the domes and cylinder of the 100-p.s.i. structure have a shell thickness of 0 ft. - 8 in., while those of the 300-p.s.i. building are 1 ft. -0 in. thick.

The interior of both buildings consists of a suspended platform forming the floor slab for the mechanical area, personnel area, and toilets. The platform is 15 ft. -0 in. and 14 ft. -0 in. wide in the 100- and 300-p.s.i. structures, respectively, and is suspended from the upper portion of the exterior shell by a pendulum arrangement consisting of sixteen helical compression springs. The minimum clear distance between the shell and the platform in the 100- and 300-p.s.i. structures are 1 ft. -0 in. and 1 ft. -9 in., respectively. The mechanical area and toilets are located at opposite ends of the platform with the personnel area situated in the middle. The approximate usable floor area of the platform is 3,400 sq. ft. Like the two-story suspension systems, the periphery of the personnel area is bordered by a 3-ft. -6 in. -high metal partition railing while the mechanical area and toilets are enclosed with 8-ft. -high metal partitions and roof panels.

c. <u>Structures HC-100-250-2, HC-100-250-3 and HC-300-250-2, HC-300-250-3</u>

These schemes (Figure 7-14) are single-level reinforced-concrete horizontal cylinders with an interior radius of 9 ft. -0 in. The ends of the cylindrical portions of the shelters are sealed with hemispherical sections, the interior radii of which are the same as that of the cylinder. The shell thickness of both the cylinder and the spheres is 0 ft. -8 in. for the 100-p.s.i. structure and 1 ft. -0 in. for the 300-p.s.i. building, while the length of the cylinders is 205 ft. -0 in. in all the shelters.

From an architectural viewpoint, the buildings are separated into three sections, i.e., the personnel area, the mechanical area, and the toilets. The mechanical area and toilets are located at opposite ends of the shelters and are separated by the area used for the personnel. Reinforced concrete walls are used to separate the personnel area from the other two sections of the structure. Both the personnel area and the toilets are located on the concrete floor slab situated 3 ft. -6 in. below the center of the cylinder. The width of this slab is 16 ft. -0 in. and is formed by filling (monolithically) the lower portion of the cylinder with concrete to the desired elevation. The mechanical equipment is shock isolated on a structural steel platform. The platform is supported by helical compression springs (four and eight springs in the 100- and 300-p.s.i. structures) which, in turn, are supported on the floor of the cylinder. Also provided in the 300-p.s.i. structures are eight beam springs for lateral stability of the platform. The cylinder floor in the mechanical area (all structures) is 3 ft. -3 in. below that of the personnel area. All movement between the platform and the other areas is across removable metal plates.

Structures HC-100-250-2 and HC-300-250-2, which are designed for personnel protection level 1, have all their walls (interior and exterior) and their floor slabs in the personnel area and toilets padded with one-inch-thick energy-absorbing material while only the exterior walls and the corners of the interior walls are padded in those structures designed for personnel protection level 3. In all the structures, the corners are chamfered in order to provide the required two-inch radius of the cushioning to produce the required protection. No cushioning is provided in the mechanical areas of the buildings. An alternate method of providing protection for those persons who are situated next to the interior walls, is the use of cargo nets or some other suitable materials. In this case, the purpose of the netting is primarily to prevent the personnel from making direct contact with the walls in addition to cushioning their falls.

d. <u>Structure HC(T)-100-100-1 and HC(T)-300-100-1</u>

These schemes, as shown in Figure 7-13, are similar to the structures of Section 7-8.2a, except that the length of the cylindrical portion of the shell is 36 ft. -0 in. In addition, a slight rearrangement of the architectural features of the structures has been effected. To utilize more efficiently the available floor area of the interior suspension system, the toilets were relocated to the end section of the upper story adjacent to the air exhaust, and the lower story was used primarily for the mechanical area. A small personnel area is retained near the bottom of the stairs on the lower platform.

e. Structure HC(S)-100-100-1 and HC(S)300-100-1

These buildings, shown in Figure 7-16, are similar to those of Section 7-8.2b except that the lengths of the 100- and 300-p.s.i. structures are reduced to 125 ft.-0 in. and 133 ft.-0 in., respectively, to correspond with the reduced population.

The length of the platform of the suspension system has been reduced to 117 ft.-0 in. (100 p.s.i.) and 125 ft.-0 in. (300 p.s.i.) and has a usable area of approximately 1800 sq. ft. Eight helical compression springs are used to support the platform in the 100-p.s.i. shelter while twelve springs are utilized in the 300-p.s.i. building.

f. Structures HC-100-100-2, HC-100-100-3 and HC-300-100-2, HC-300-100-3

These shelters (Figure 7-17) are similar to those described in Section 7-8.2c except that the lengths of the structures have been shortened to accommodate the reduced population. The cylindrical portions of the structures are 93 ft.-0 in. and the overall interior length of each structure is 111 ft.-0 in. In these buildings the shock isolation platforms for the mechanical equipment are supported by four helical springs in all the shelters. The springs in turn are supported by the concrete floor. The arrangement of the cushioning for personnel is given in Figure 7-17.

7-8.3 Other Concept Studies

a. Arch-Type Structures

Figures 7-18 to 7-20 are illustrations of reinforced concrete arches designed to withstand a blast overpressure of 100 p.s.i. Structures AR-100-250-1 and AR-100-100-1 are designed to provide protection level one for personnel while structures AR-100-250-2, AR-100-250-3, AR-100-100-2 and AR-100-100-3 provide personnel protection levels two and three.

Those structures designed for protection level one consist of a 180-degree arch with an interior radius of 14 ft. - 6 in. The concrete arch is supported on a monolithic foundation slab 6 ft. -0 in. thick. Suspended from the interior surface of the arch is a pendulum-like structural-steel isolation system consisting of a structural-steel platform supported by helical compression springs. The platform houses the three areas which comprise the shelter, namely, the personnel area, the mechanical area, and the toilets. The arch design for protection levels two and three consists of a 180-degree reinforced concrete structure with an interior radius of 12 ft. - 6 in. The personnel area and toilets are located on a concrete foundation slab similar to that described above while the mechanical equipment is shock isolated on a separate structural steel platform. This platform is supported by springs which are suspended from the arch. The personnel area and toilets are shock isolated by means of cushioning.

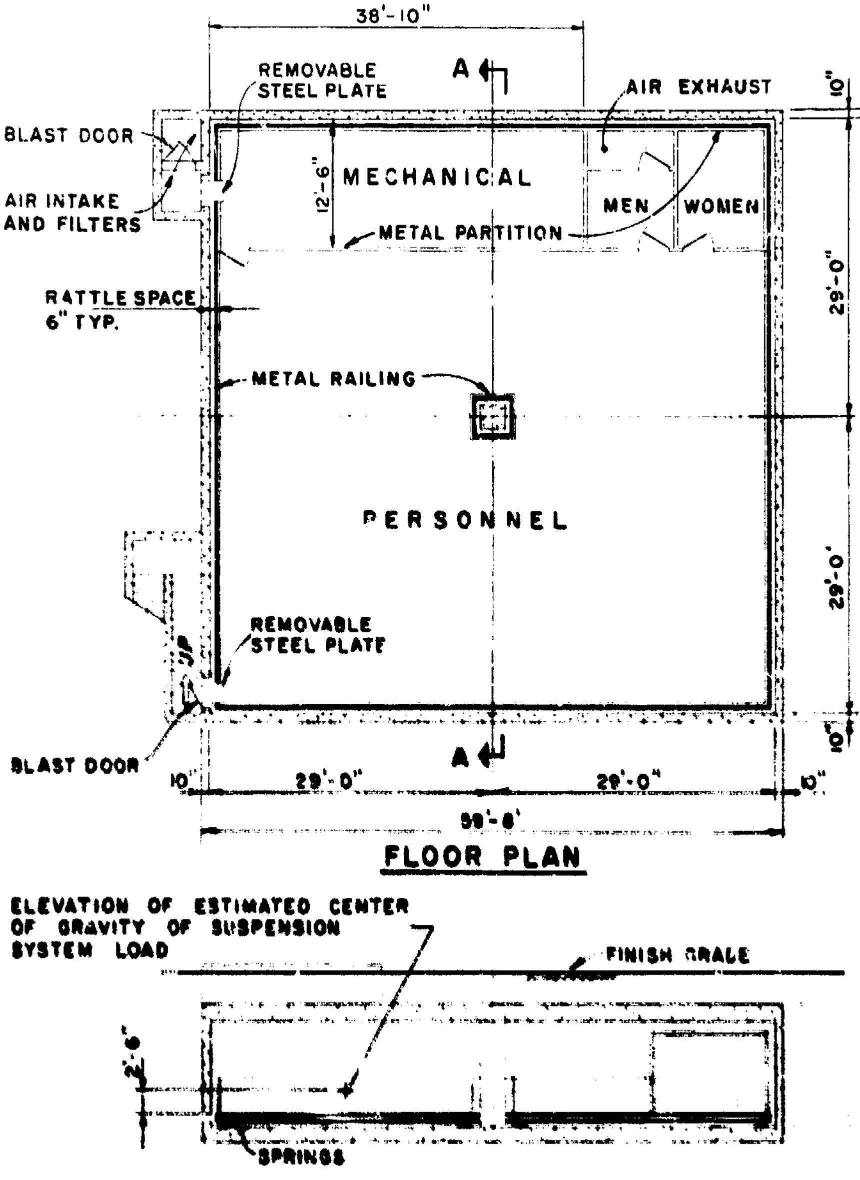
b. Vertical Cylinders

Layouts of the vertical cylinders are shown in Figure 7-21. The structures were designed for the 100- and 300-p. s. i. pressure levels, populations of 100 and 250 persons, and a personnel protection level of one. The 250-person shelters for the 100- and 300-p. s. i. pressure levels are six and ten stories, respectively, while the 100-person structures for the 100- and 300-p. s. i. pressure ranges are three and five stories in height. The distance between floor levels of the vertical cylinders is nine feet. It should be noted that, in the designs of the cylinders at the 300-p. s. i. pressure, hemispherical end sections were used on the upper and lower ends of the cylinders while at the 100-p. s. i. level, circular slabs were used to seal the structure. In the latter case, a reinforced concrete column was used to support the central portion of the slabs.

Table 7-6 Designation and Description of Design Concepts

Structure * Designation	Pressure Level (psi)	Population	Protection Level	Equipment Category	Type of Structure	No. of Levels	Shock Isolation Systems: Personnel	Shock Isolation Systems: Equipment
RE(S)25-250-1	5	250	1	1	Rectangular	1	Base Mounted Plat.	Base Mounted Platform
RE 25-250-2	25	250	2	1&2	Rectangular	1	Cushioning	Base Mounted Platform
RE 25-250-3	25	250	3	1&2	Rectangular	1	Limited Cushioning	Base Mounted Platform
RE(S)25-100-1	25	100	1	1	Rectangular	1	Base Mounted Plat.	Base Mounted Platform
RE 25-100-2	25	100	2	1&2	Rectangular	1	Cushioning	Base Mounted Platform
RE 25-100-3	25	100	3	1&2	Rectangular	1	Limited Cushioning	Base Mounted Platform
RE(S)25-10-1	25	10	1	1	Rectangular	1	Base Mounted Plat.	Base Mounted Platform
RE 25-10-2	25	10	2	1&2	Rectangular	1	Cushioning	Individual Mounted
RE 25-10-3	25	10	3	1&2	Rectangular	1	Limited Cushioning	Individual Mounted
HC(T)100-250-1	100	250	1	1	Horiz. Cylinder	2	Suspended Platform	Suspended Platform
HC(S)100-250-1	100	250	1	1	Horiz. Cylinder	1	Suspended Platform	Suspended Platform
HC 100-250-2	100	250	2	1&2	Horiz. Cylinder	[illegible]	Cushioning	Base Mounted Platform
HC 100-250-3	100	250	3	1&2	Horiz. Cylinder	1	Limited Cushioning	Base Mounted Platform
AR(S)100-250-1	100	250	1	1	Arch	1	Suspended Platform	Suspended Platform
AR 100-250-2	100	250	2	1&2	Arch	1	Cushioning	Suspended Platform
AR 100-250-3	100	250	3	1&2	Arch	1	Limited Cushioning	Suspended Platform
VC(M)100-250-1	100	250	1	1	Vert. Cylinder	5	Suspended Platform	Suspended Platform
HC(T)100-100-1	100	100	1	1	Horiz. Cylinder	2	Suspended Platform	Suspended Platform
HC(S)100-100-1	100	100	1	1	Horiz. Cylinder	1	Suspended Platform	Suspended Platform
HC 100-100-2	100	100	2	1&2	Horiz. Cylinder	1	Cushioning	Base Mounted Platform
HC 100-100-3	100	100	3	1&2	Horiz. Cylinder	1	Limited Cushioning	Base Mounted Platform
AR(S)100-100-1	100	100	1	1	Arch	1	Suspended Platform	Suspended Platform
AR 100-100-2	100	100	2	1&2	Arch	1	Cushioning	Suspended Platform
AR 100-100-3	100	100	3	1&2	Arch	1	Limited Cushioning	Suspended Platform
VC(M)100-100-1	100	100	1	1	Vert. Cylinder	3	Suspended Platform	Suspended Platform
HC(T)300-250-1	300	250	1	1	Horiz. Cylinder	2	Suspended Platform	Suspended Platform
HC(S)300-250-1	300	250	1	1	Horiz. Cylinder	1	Suspended Platform	Suspended Platform
HC 300-250-2	300	250	2	1&2	Horiz. Cylinder	1	Cushioning	Base Mounted Platform
HC 300-250-3	300	250	3	1&2	Horiz. Cylinder	1	Limited Cushioning	Base Mounted Platform
VC(M)300-250-1	300	250	1	1	Vert. Cylinder	3	Suspended Platform	Suspended Platform
HC(T)300-100-1	300	100	1	1	Horiz. Cylinder	2	Suspended Platform	Suspended Platform
HC(S)300-100-1	300	100	1	1	Horiz. Cylinder	1	Suspended Platform	Suspended Platform
HC 300-100-2	300	100	2	1&2	Horiz. Cylinder	1	Cushioning	Base Mounted Platform
HC 300-100-3	300	100	3	1&2	Horiz. Cylinder	1	Limited Cushioning	Base Mounted Platform
VC(M)300-100-1	300	100	1	1	Vert. Cylinder	3	Suspended Platform	Suspended Platform

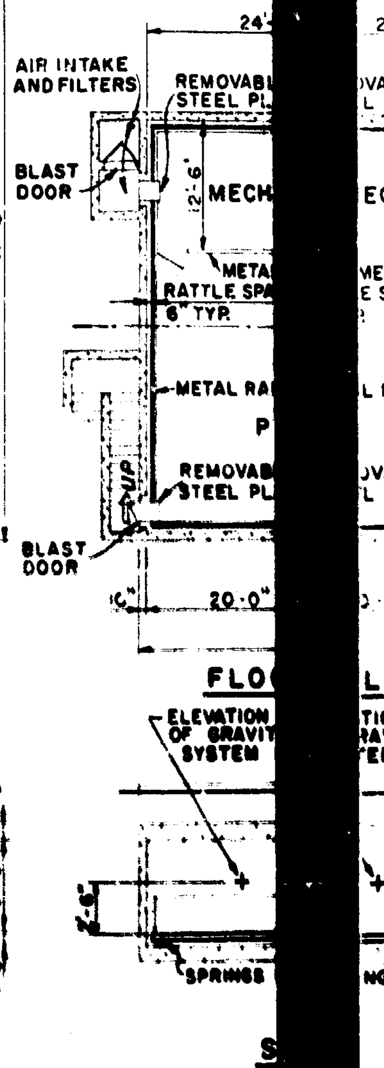
* HC - Horizontal Cylinder
VC - Vertical Cylinder
AR - Arch
RE - Rectangular
(S) - Single-Story Suspension System
(T) - Two-Story Suspension System
(M) - Multi-Story Suspension System

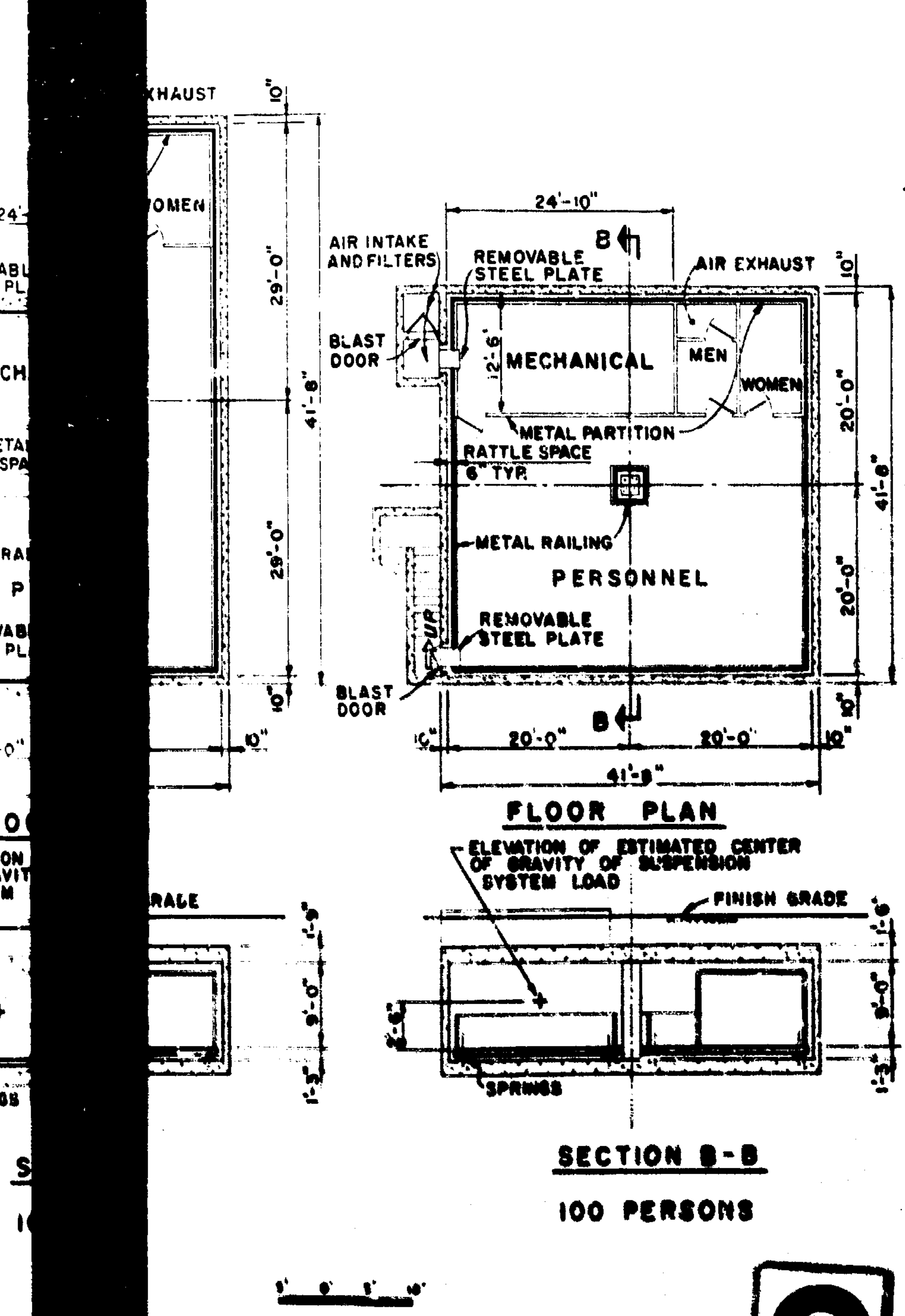


FLOOR PLAN

SECTION A-A

250 PERSONS





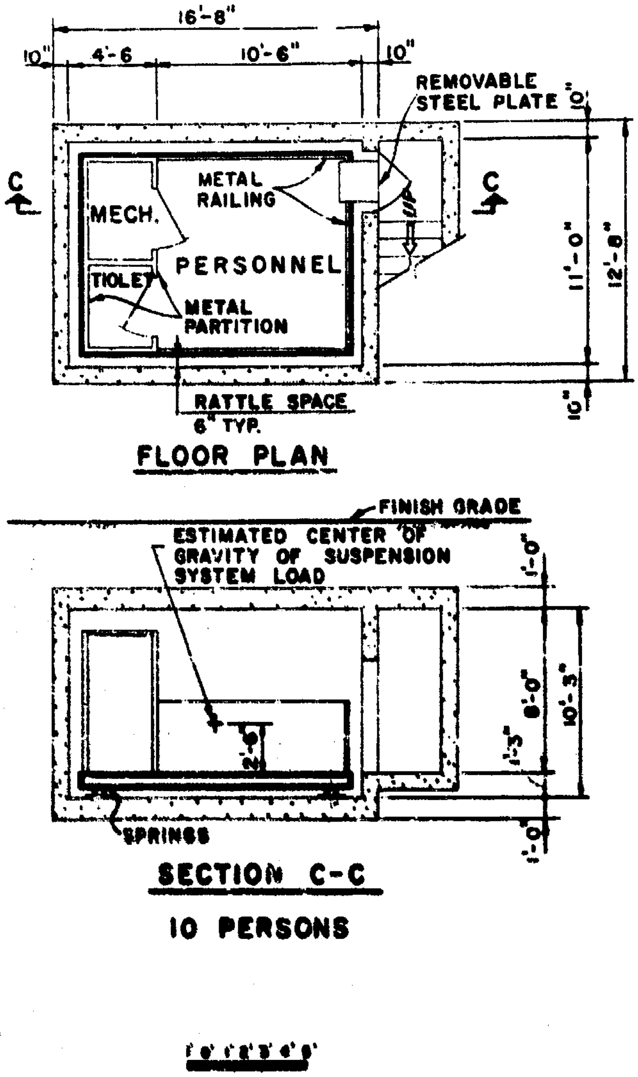
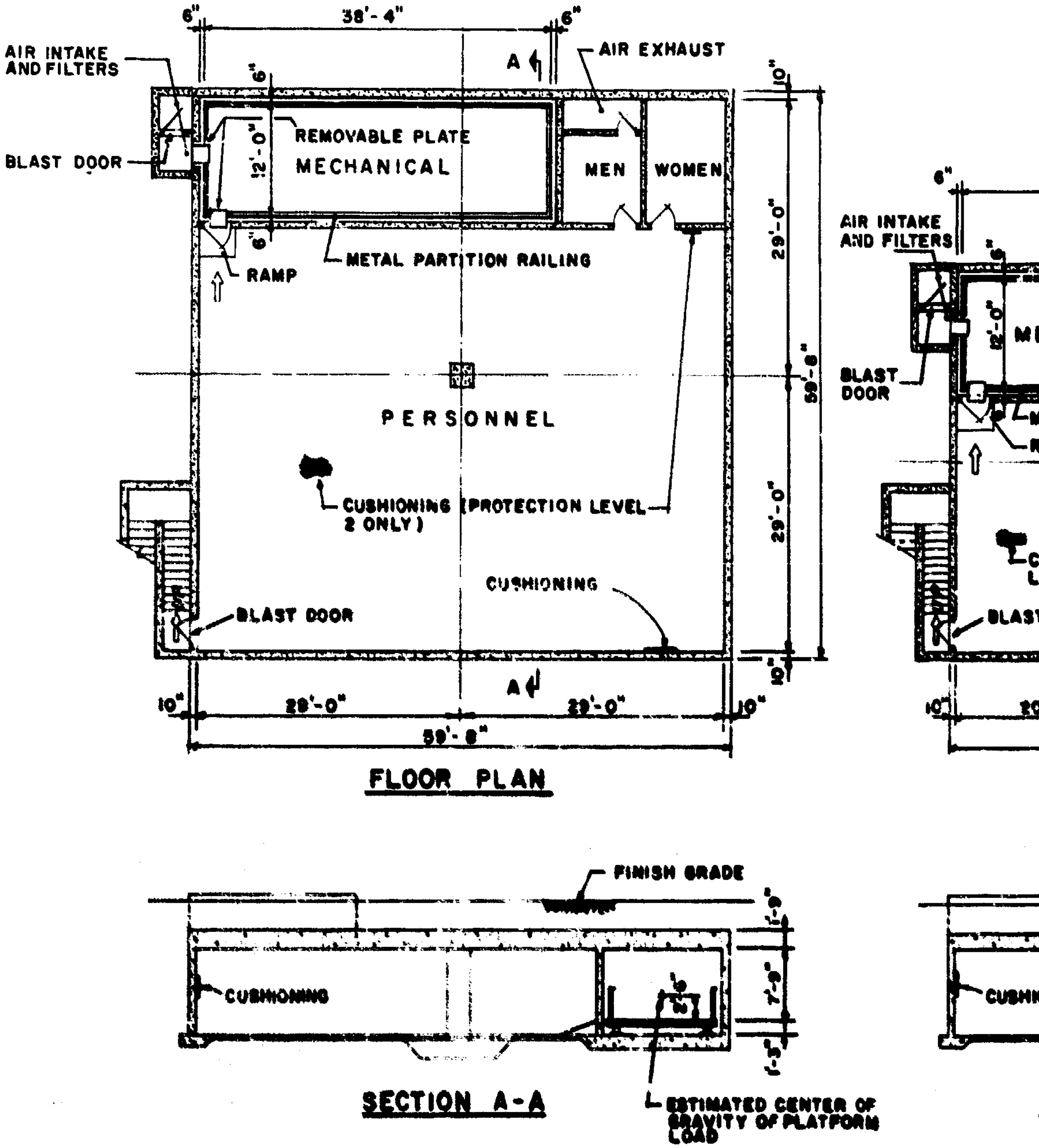


Fig. 7-10

RECTANGULAR SHELTER
(25 psi)
FOR 10, 100 AND 250 PERSONS
PERSONNEL PROTECTION
LEVEL I

2



250 PERSONS

PROTECTION LEVEL 2 & 3

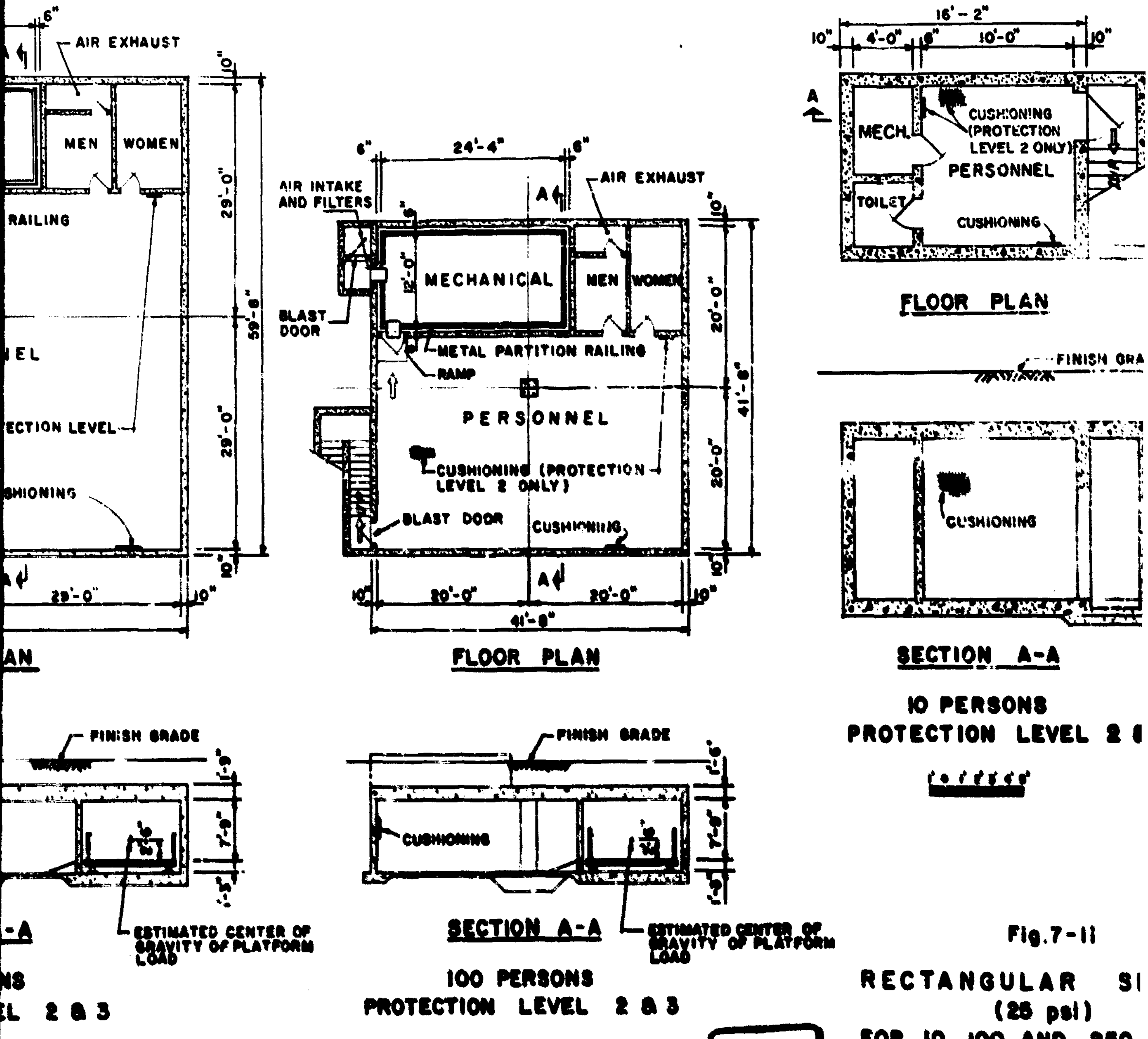


Fig.7-11

RECTANGULAR S

(25 psi)

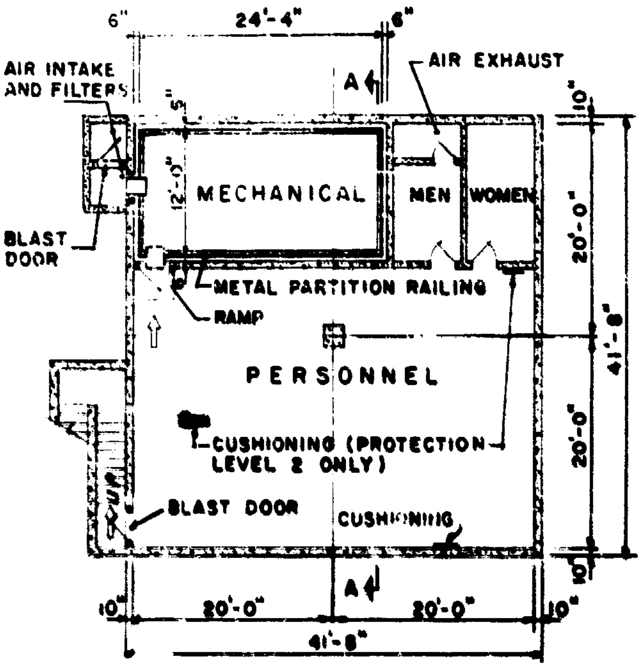
FOR 10, 100 AND 250

PERSONNEL PROT

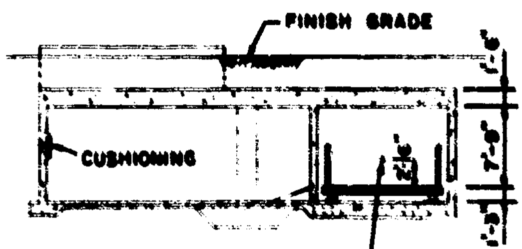
LEVEL 2 & 3

2

7-33 and 7-34



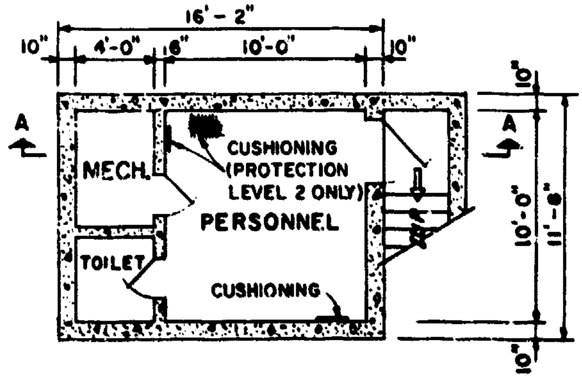
FLOOR PLAN



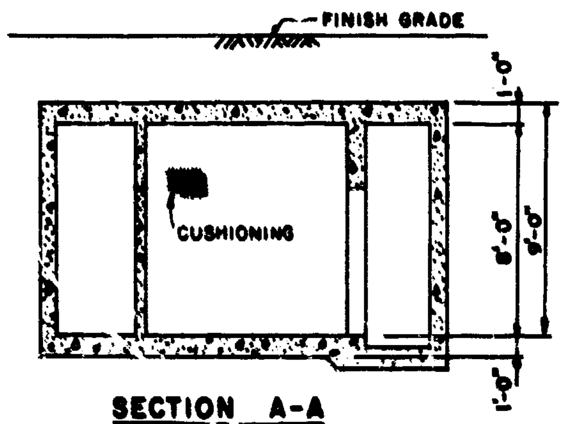
SECTION A-A

ESTIMATED CENTER OF GRAVITY OF PLATFORM LOAD

100 PERSONS
PROTECTION LEVEL 2 & 3



FLOOR PLAN

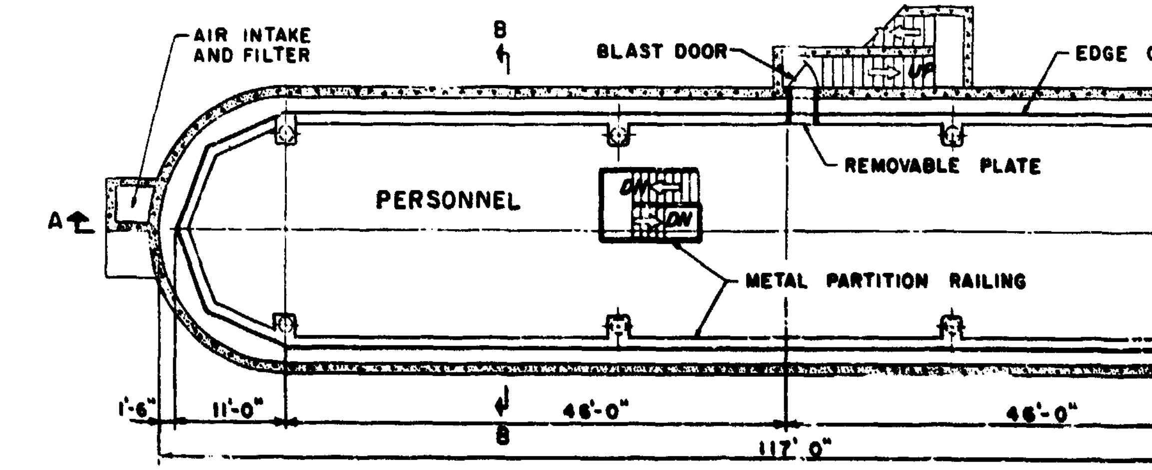


SECTION A-A

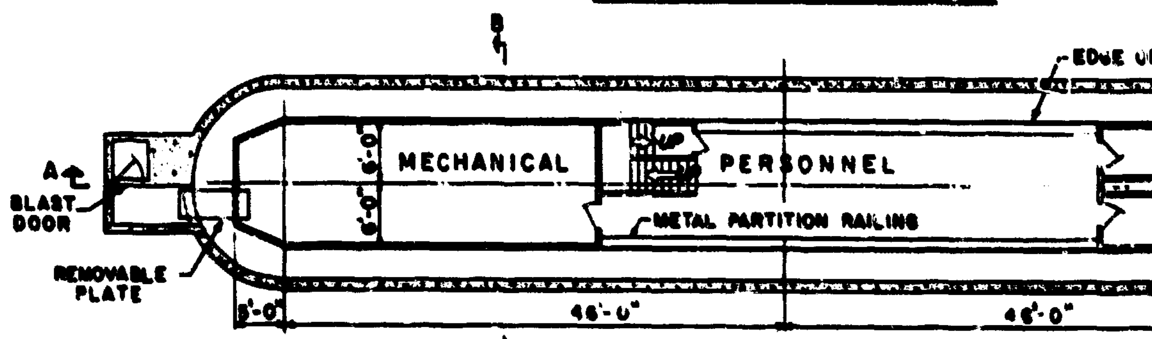
10 PERSONS
PROTECTION LEVEL 2 & 3

Fig. 7-11

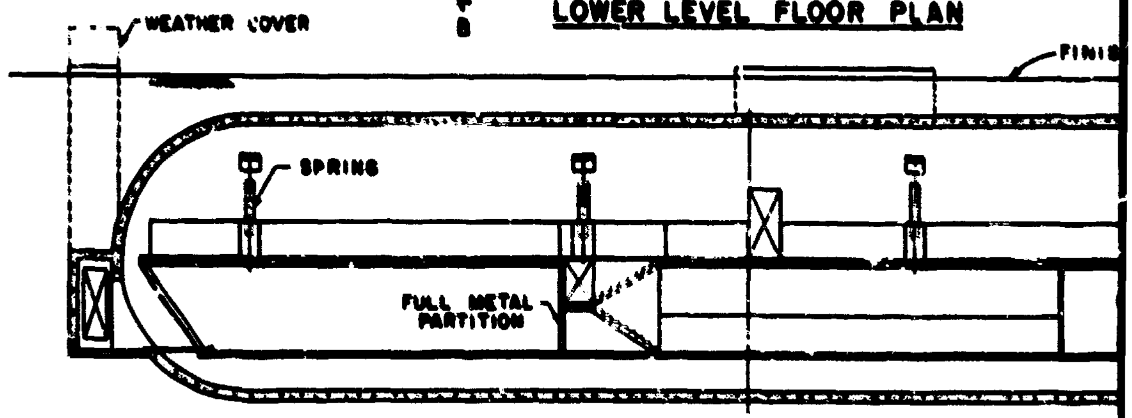
RECTANGULAR SHELTER
(25 psi)
FOR 10, 100 AND 250 PERSONS
PERSONNEL PROTECTION
LEVEL 2 & 3



UPPER LEVEL FLOOR PLAN



LOWER LEVEL FLOOR PLAN



SECTION A-A

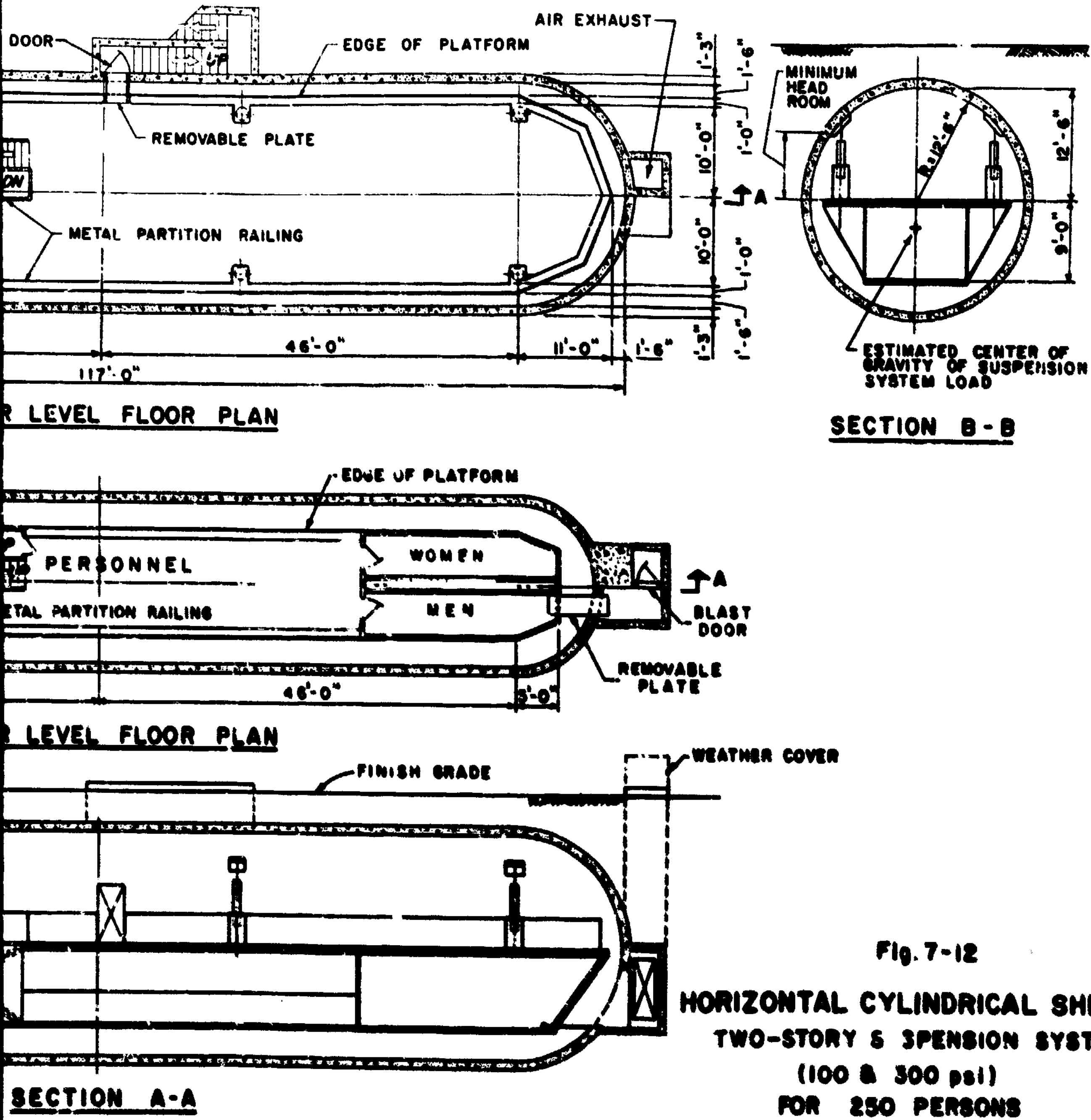
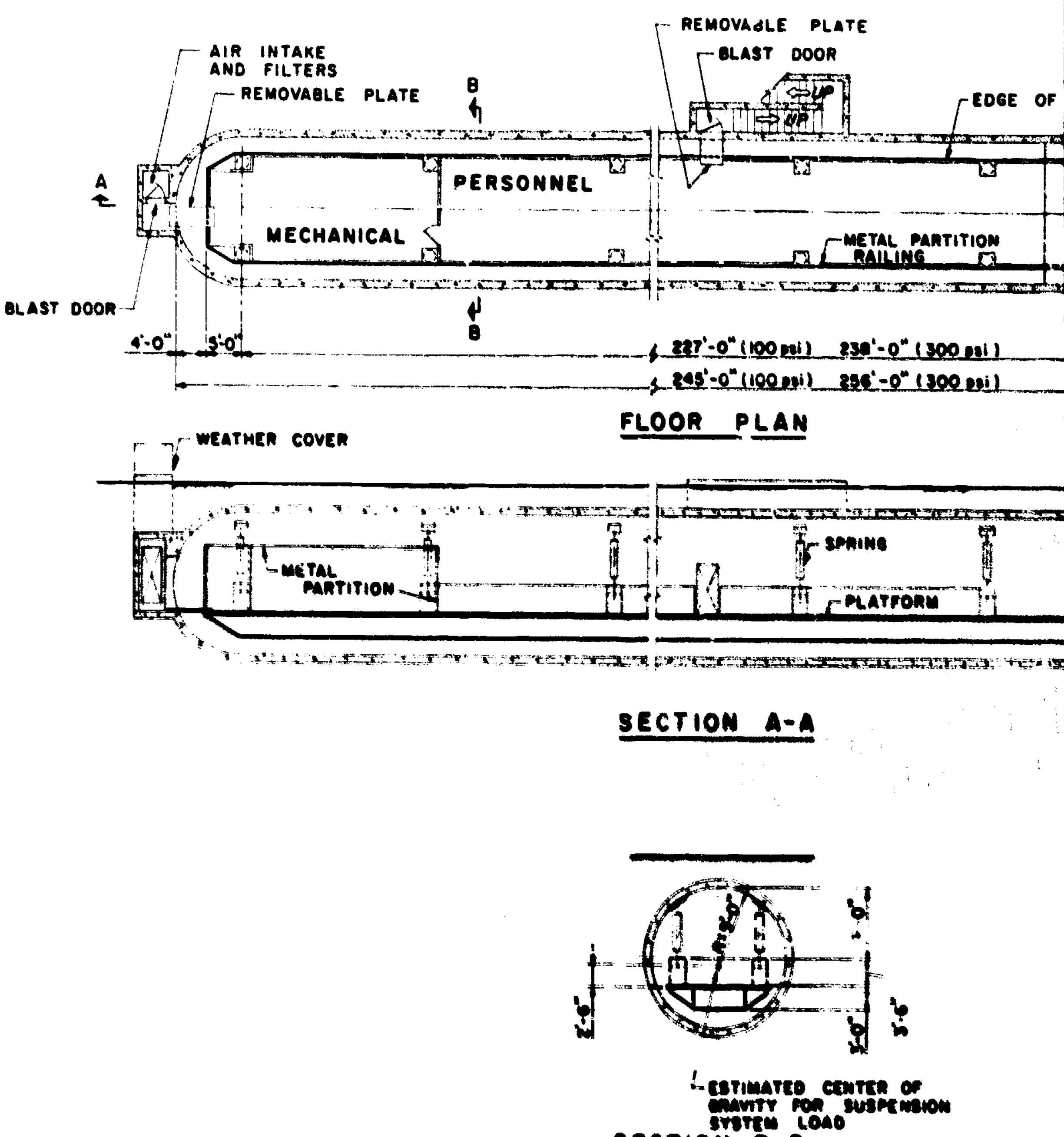


Fig. 7-12

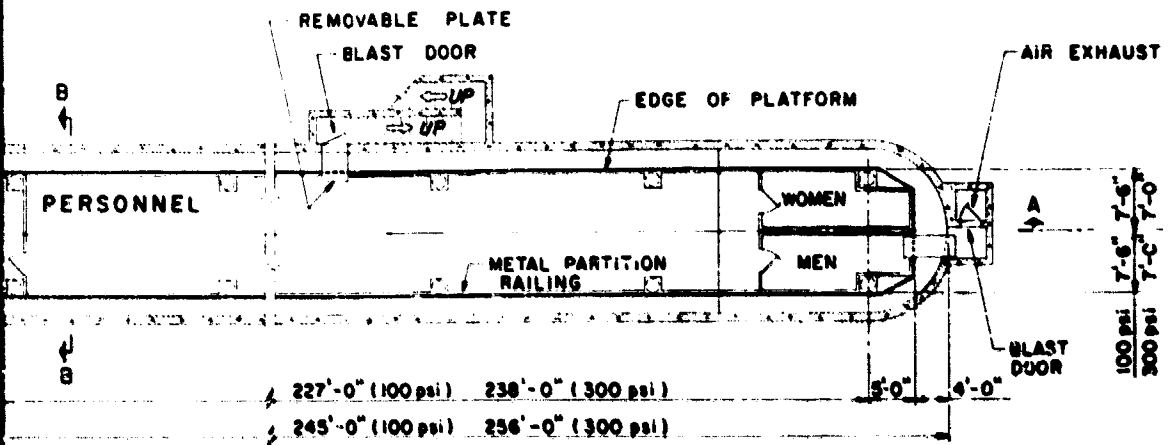
HORIZONTAL CYLINDRICAL SHELTER
TWO-STORY SUSPENSION SYSTEM
(100 & 300 psi)
FOR 250 PERSONS
PERSONNEL PROTECTION
LEVEL I



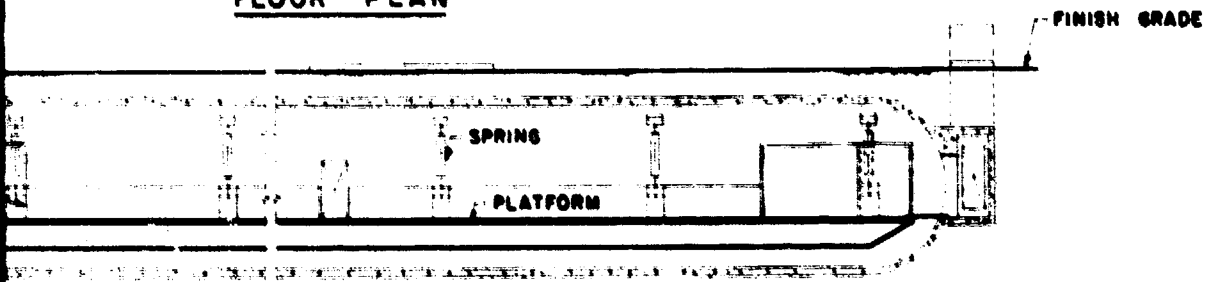
FLOOR PLAN

SECTION A-A

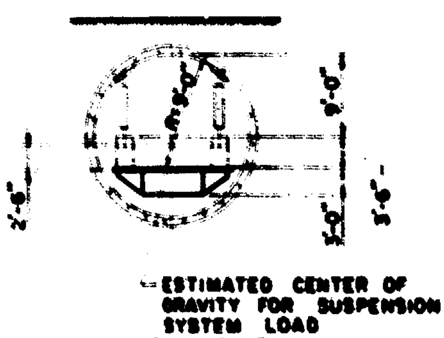
SECTION B-B



FLOOR PLAN



SECTION A-A

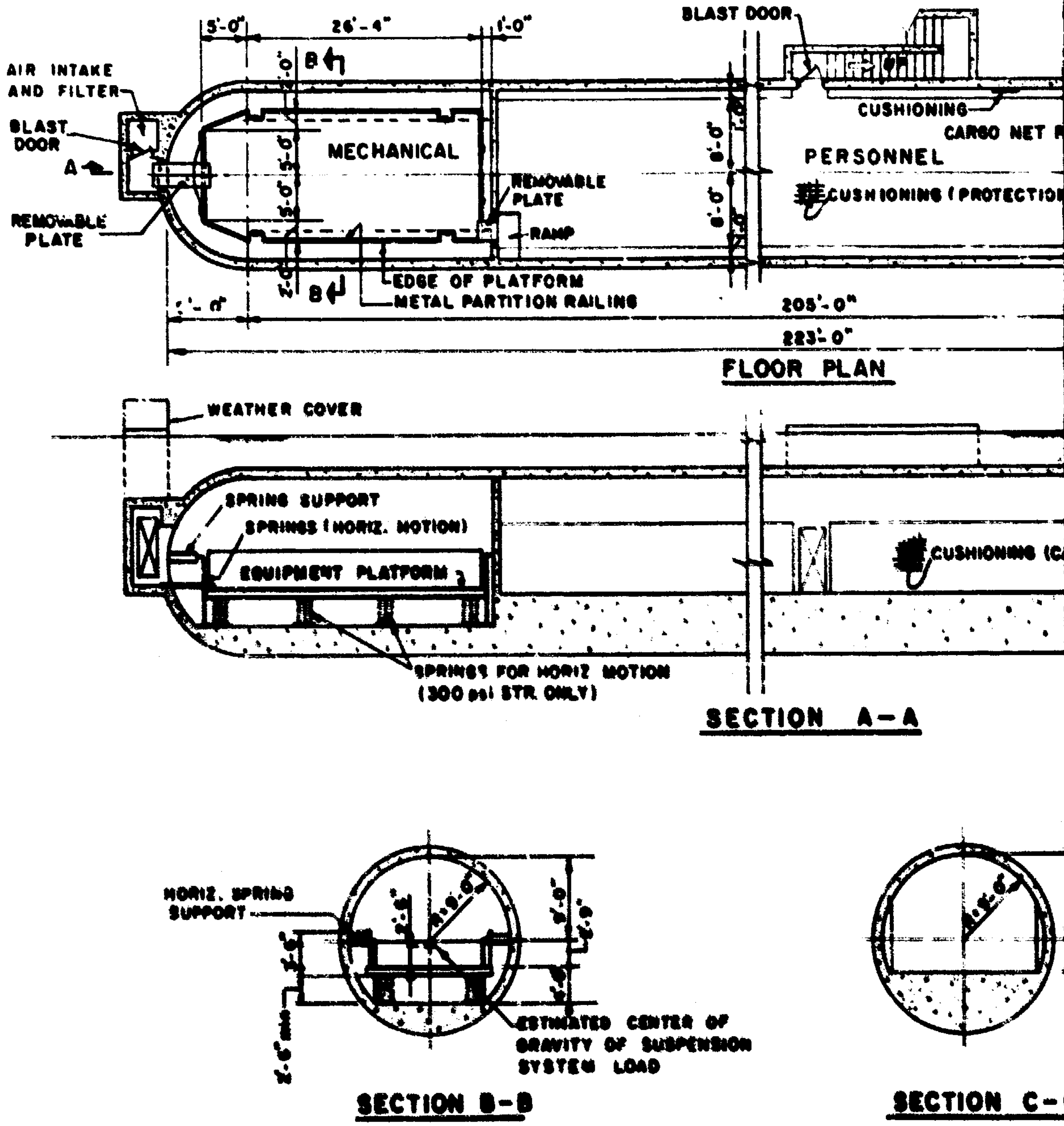


SECTION B-B

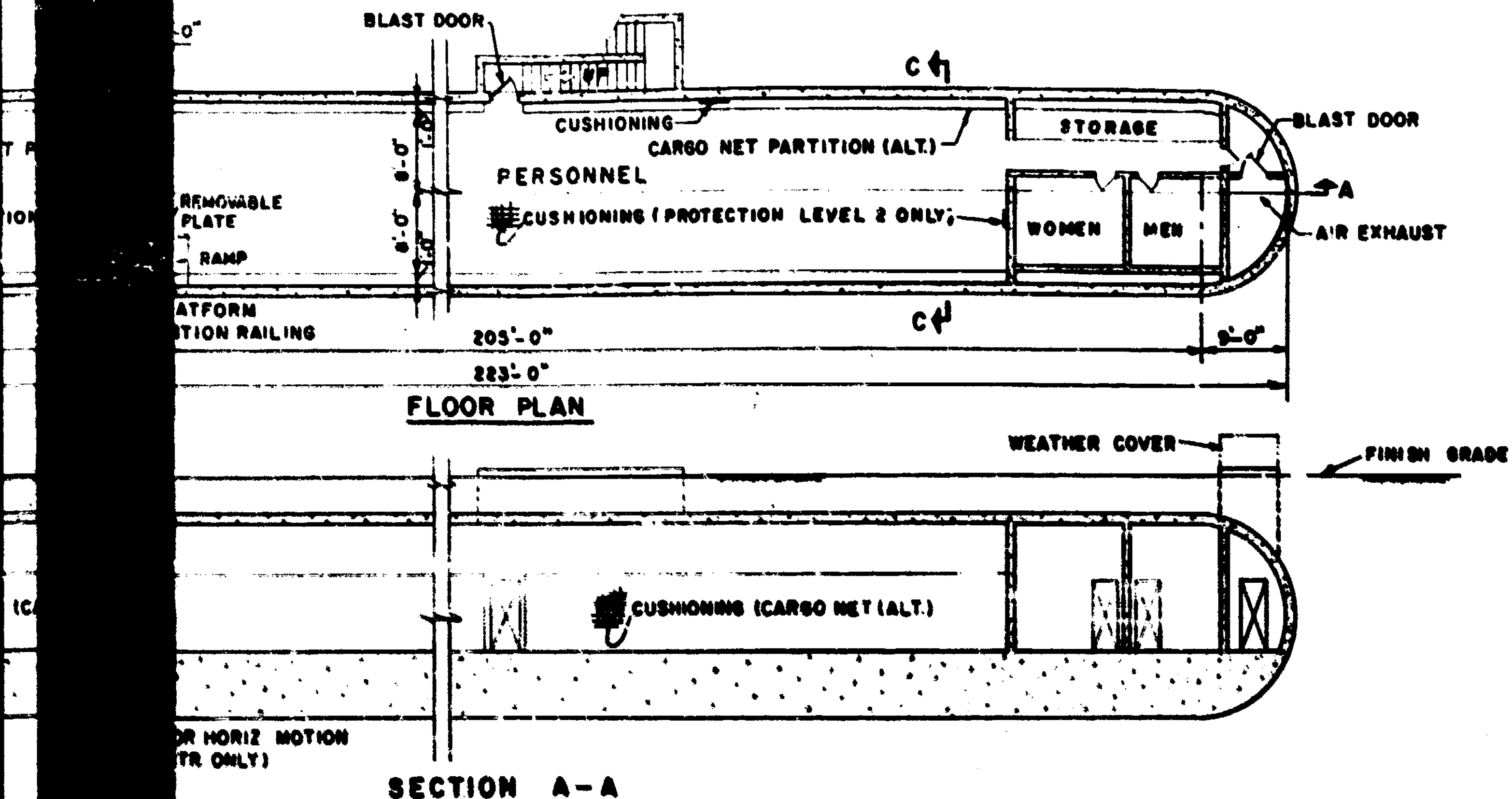
Fig. 7-13

HORIZONTAL CYLINDRICAL SHELTER
(100 & 300 psi)
FOR 250 PERSONS
PERSONNEL PROTECTION
LEVEL I

2



AIR INTAKE AND FILTER
BLAST DOOR
REMOVABLE PLATE
MECHANICAL
REMOVABLE PLATE
RAMP
EDGE OF PLATFORM
METAL PARTITION RAILING
BLAST DOOR
CUSHIONING
CARGO NET
PERSONNEL
CUSHIONING (PROTECTIO
5'-0"
26'-4"
1'-0"
205'-0"
223'-0"
FLOOR PLAN
WEATHER COVER
SPRING SUPPORT
SPRINGS (HORIZ. MOTION)
EQUIPMENT PLATFORM
CUSHIONING (C
SPRINGS FOR HORIZ MOTION (300 psi STR. ONLY)
SECTION A-A
HORIZ. SPRING SUPPORT
ESTIMATED CENTER OF GRAVITY OF SUSPENSION SYSTEM LOAD
SECTION B-B
SECTION C-



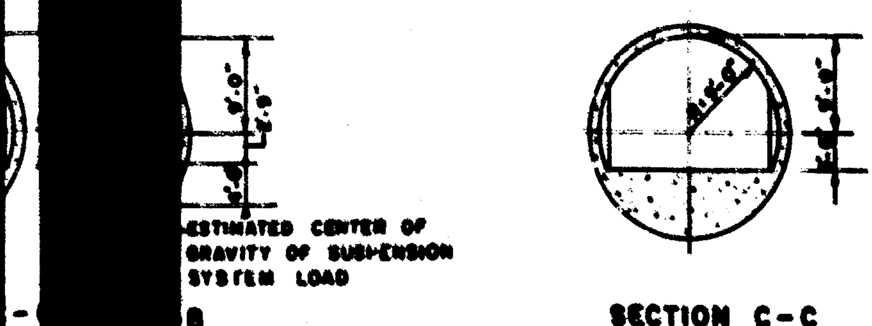
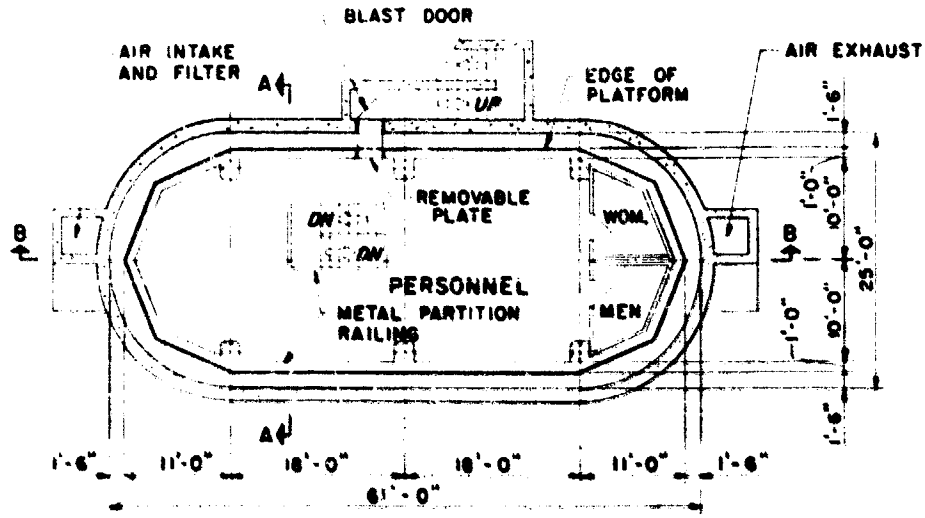


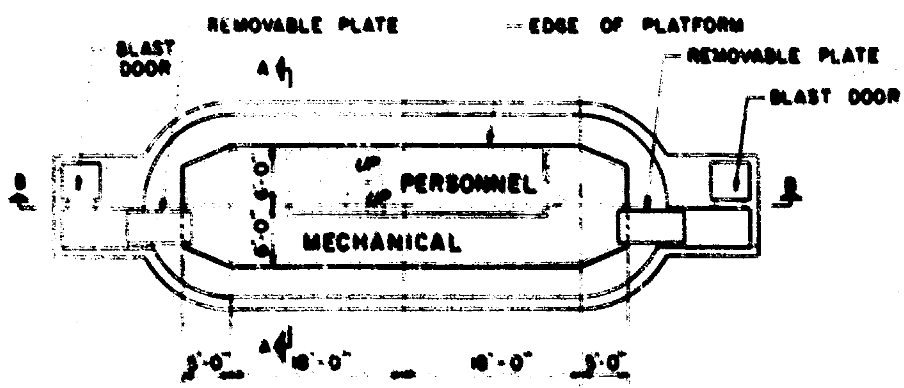
Fig. 7-14

HORIZONTAL CYLINDRICAL SHELTER
(100 & 300 psi)
FOR 60 PERSONS
PERSONNEL PROTECTION
LEVEL 2 & 3

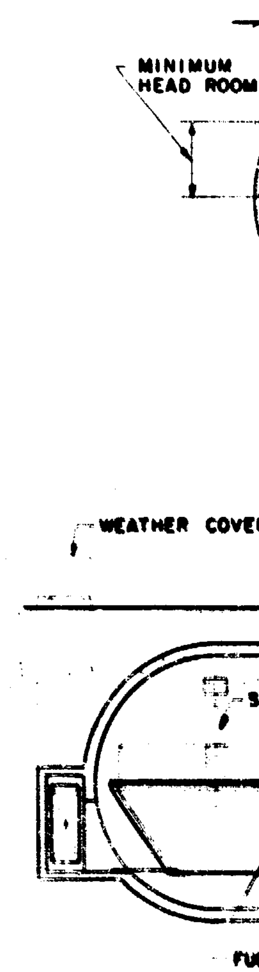
2



UPPER LEVEL FLOOR PLAN



LOWER LEVEL FLOOR PLAN



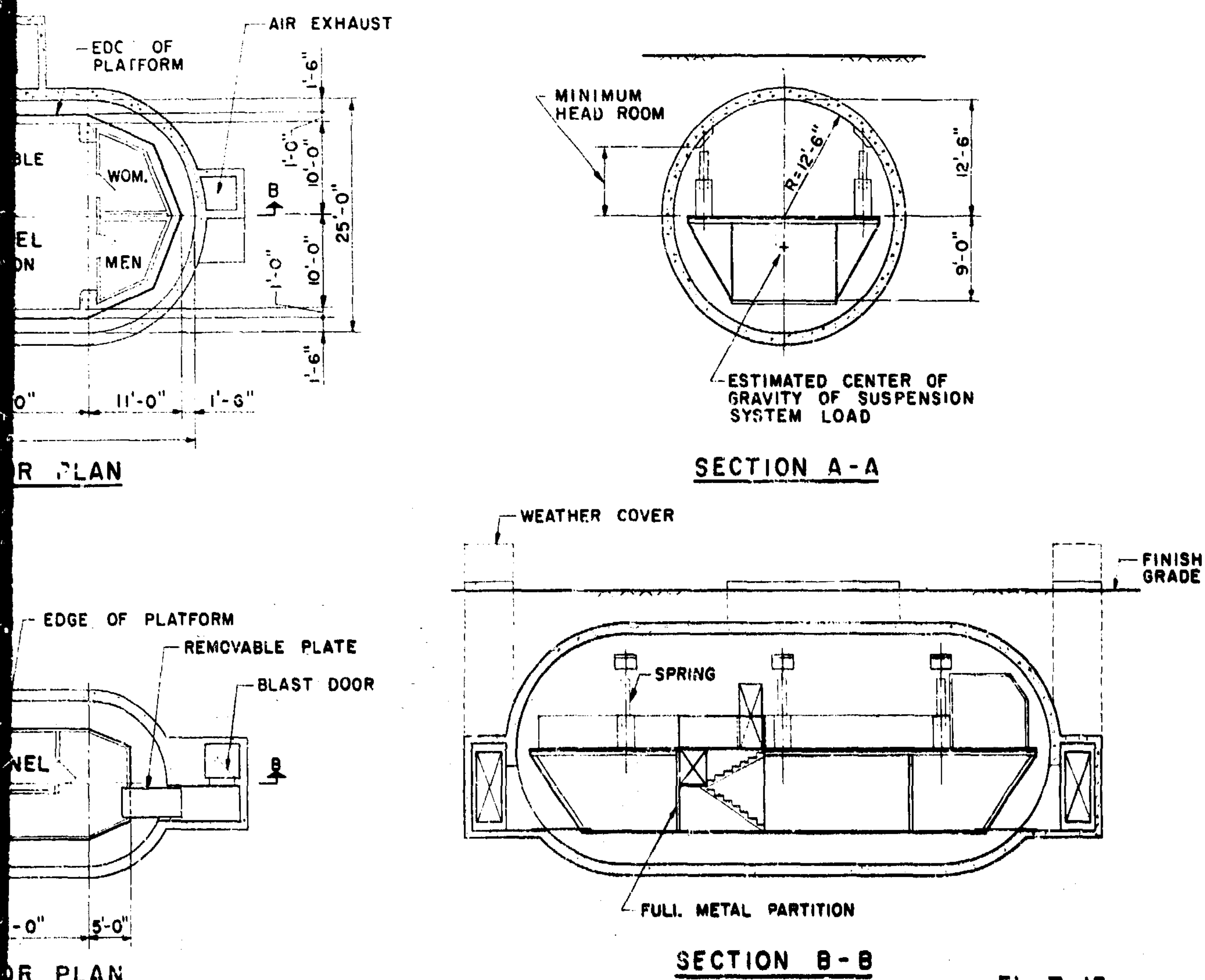
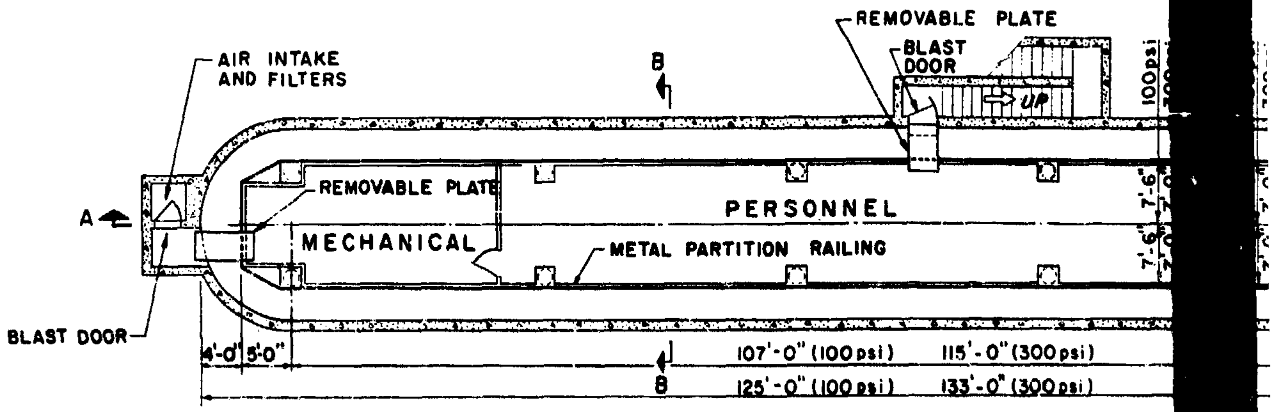


Fig.7-15

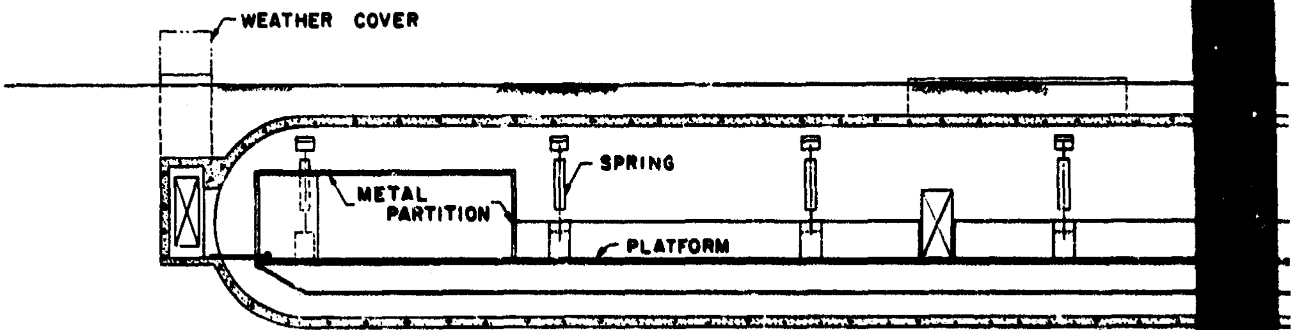
HORIZONTAL CYLINDRICAL SHELTER
TWO-STORY SUSPENSION SYSTEM
(100 & 300 psi)
FOR 100 PERSONS
PERSONNEL PROTECTION
LEVEL I

2

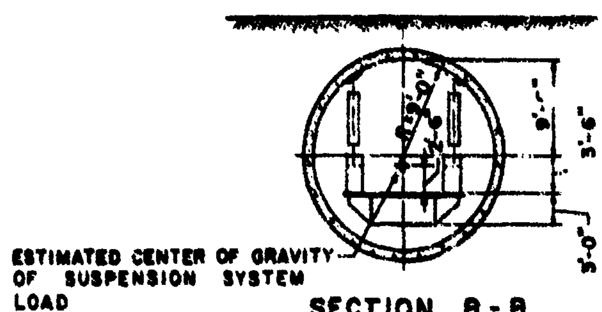
7-41 and 7-42



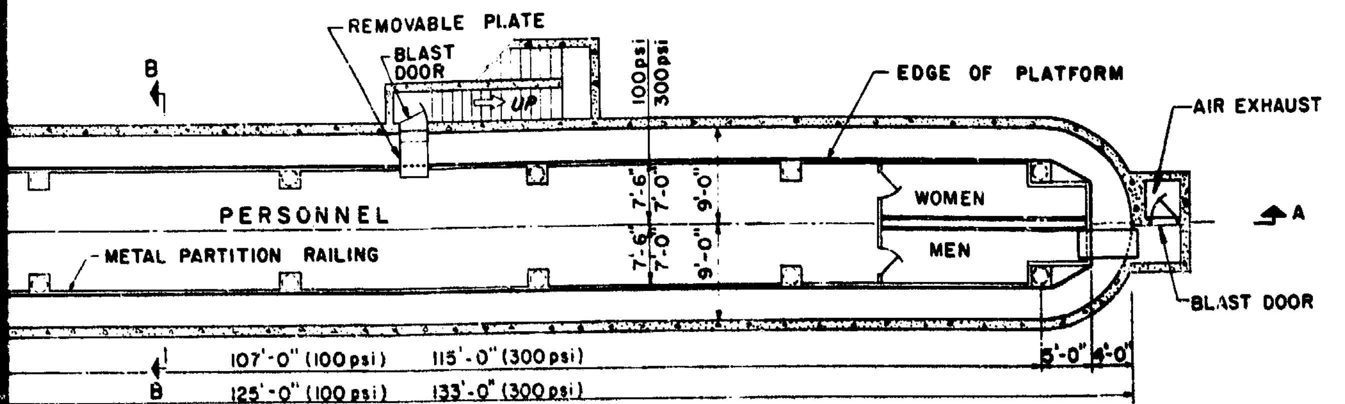
FLOOR PLAN



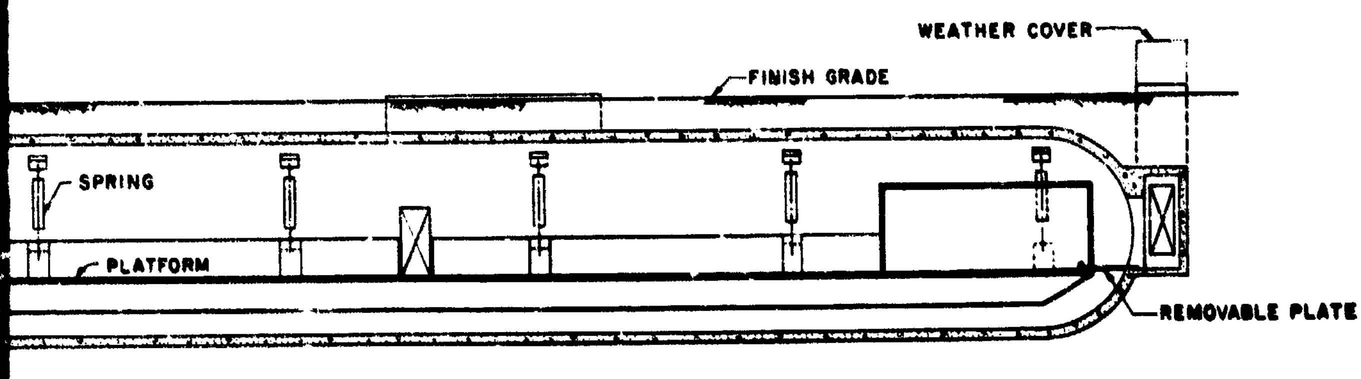
SECTION A - A



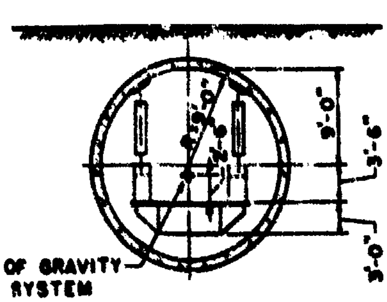
SECTION B - B



FLOOR PLAN



SECTION A - A



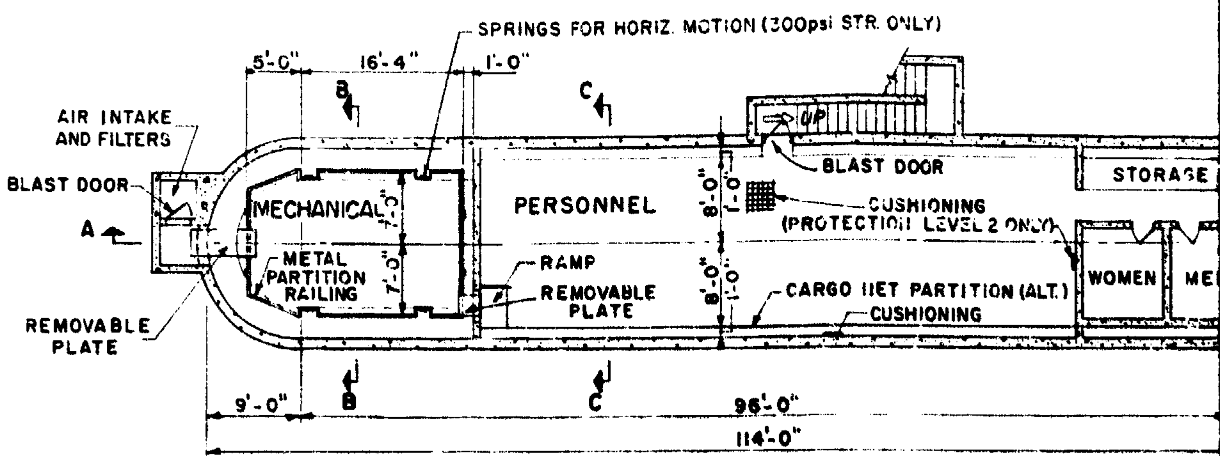
ESTIMATED CENTER OF GRAVITY OF SUSPENSION SYSTEM LOAD

SECTION B - B

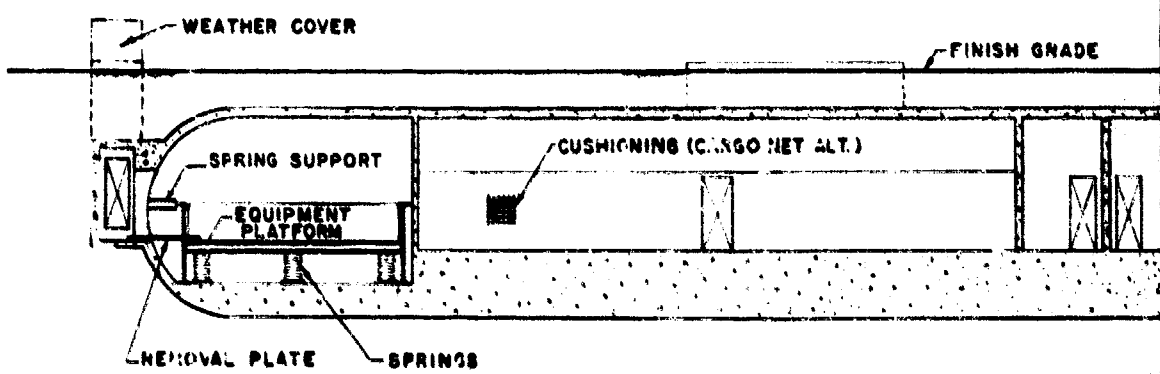
Fig. 7-16

HORIZONTAL CYLINDRICAL SHELTER
SINGLE-STORY SUSPENSION SYSTEM
(100 & 300psi)
FOR 100 PERSONS
PERSONNEL PROTECTION
LEVEL I

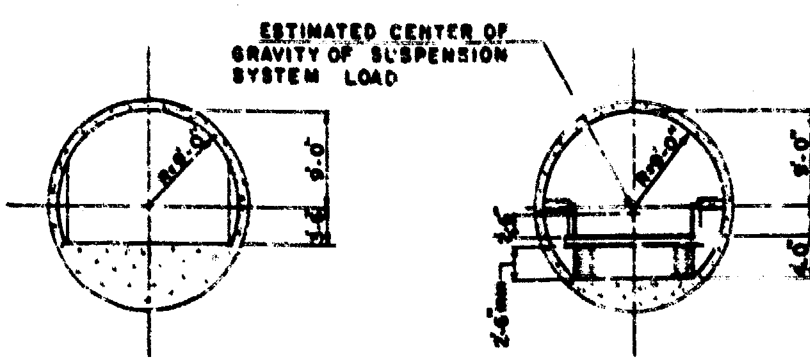
2



FLOOR PLAN



SECTION A-A



SECTION C-C

SECTION B-B

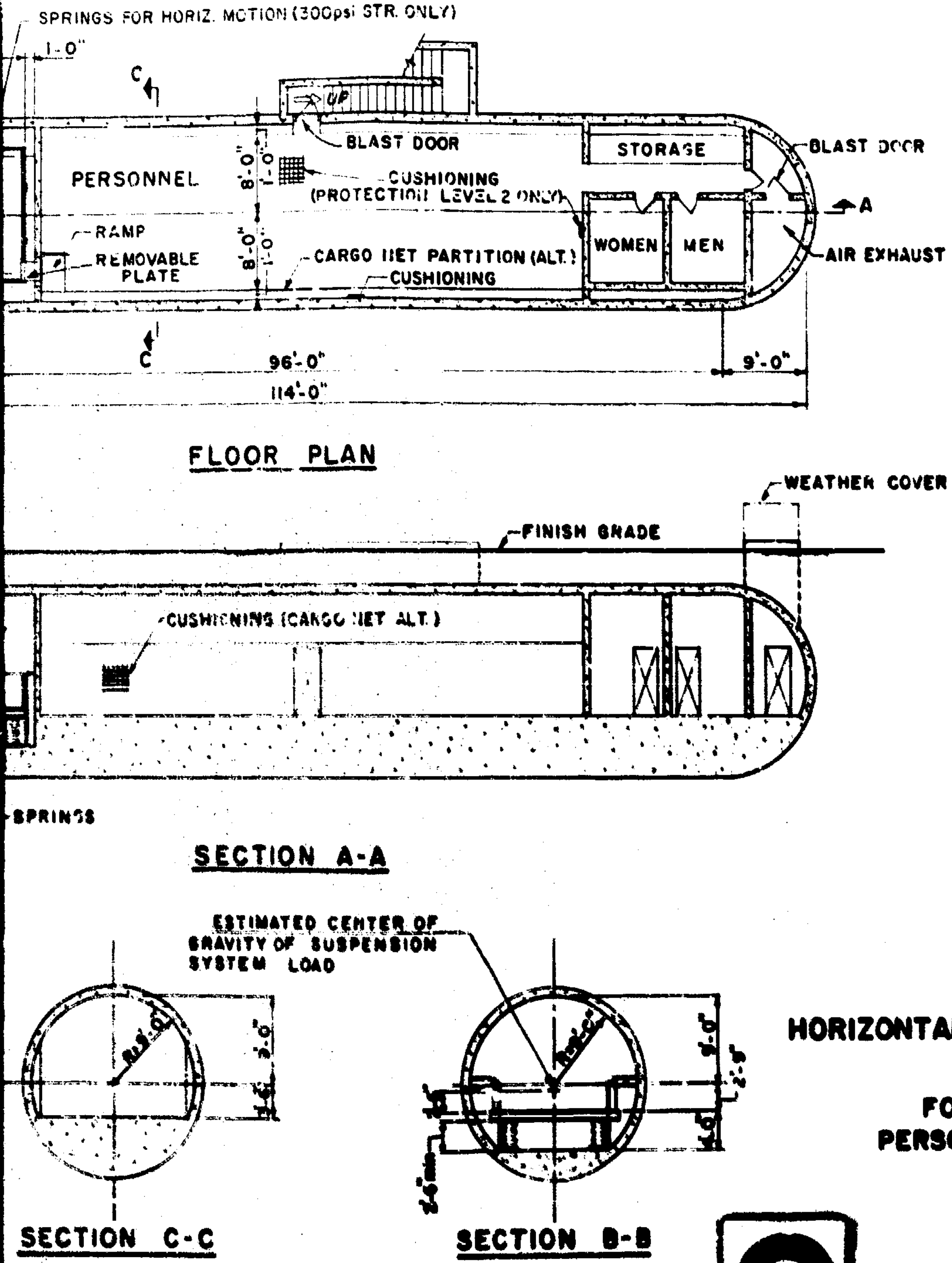


Fig. 7-17

HORIZONTAL CYLINDRICAL SHELTER

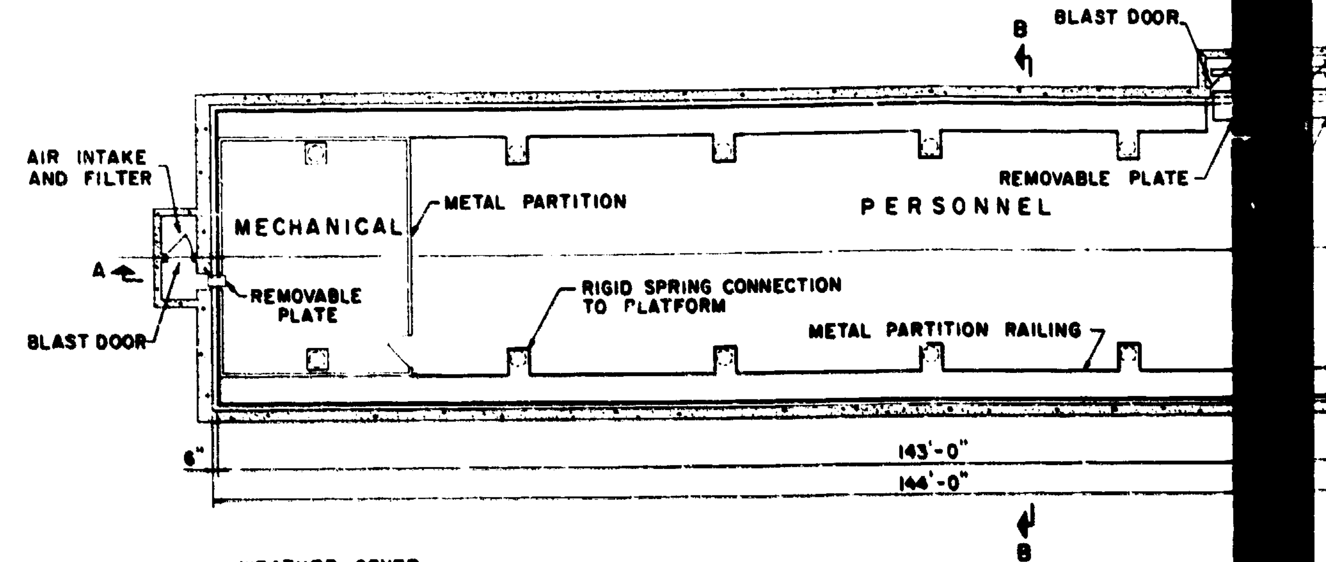
(100 & 300 psi)

FOR 100 PERSONS

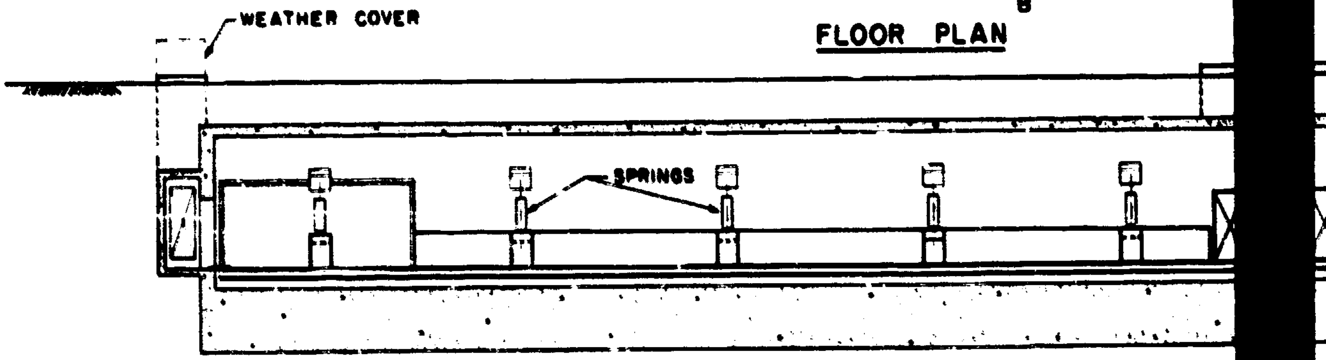
PERSONNEL PROTECTION

LEVEL 2 & 3

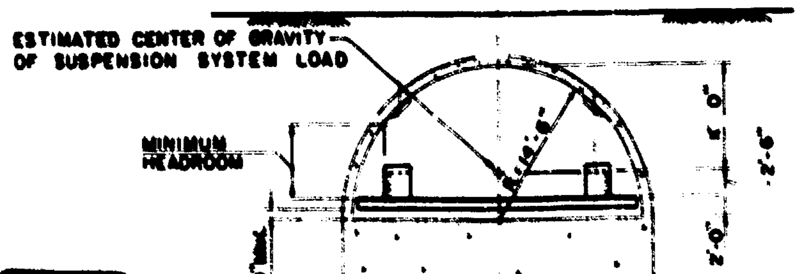
2



FLOOR PLAN



SECTION A-A



SECTION B-B

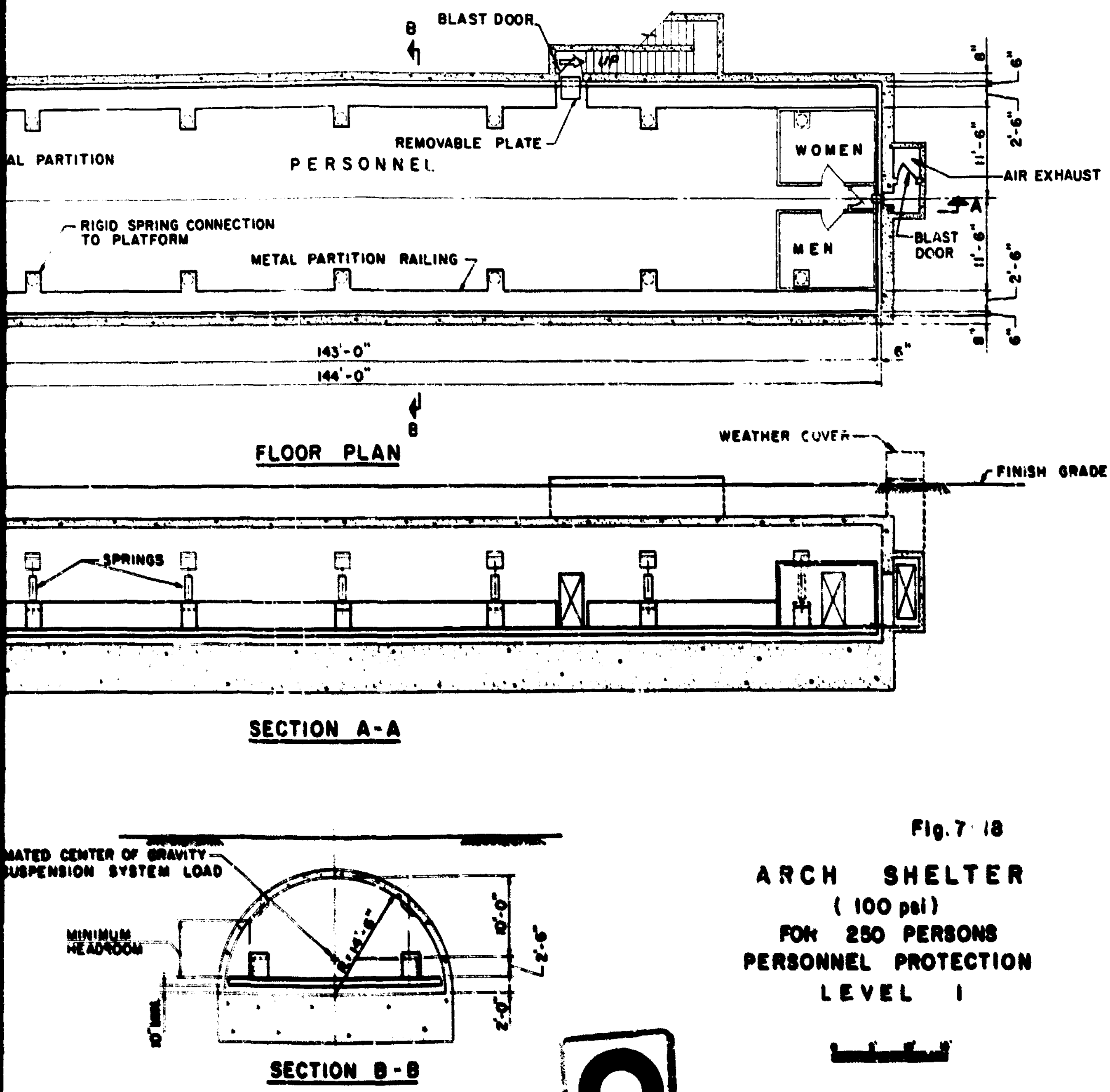
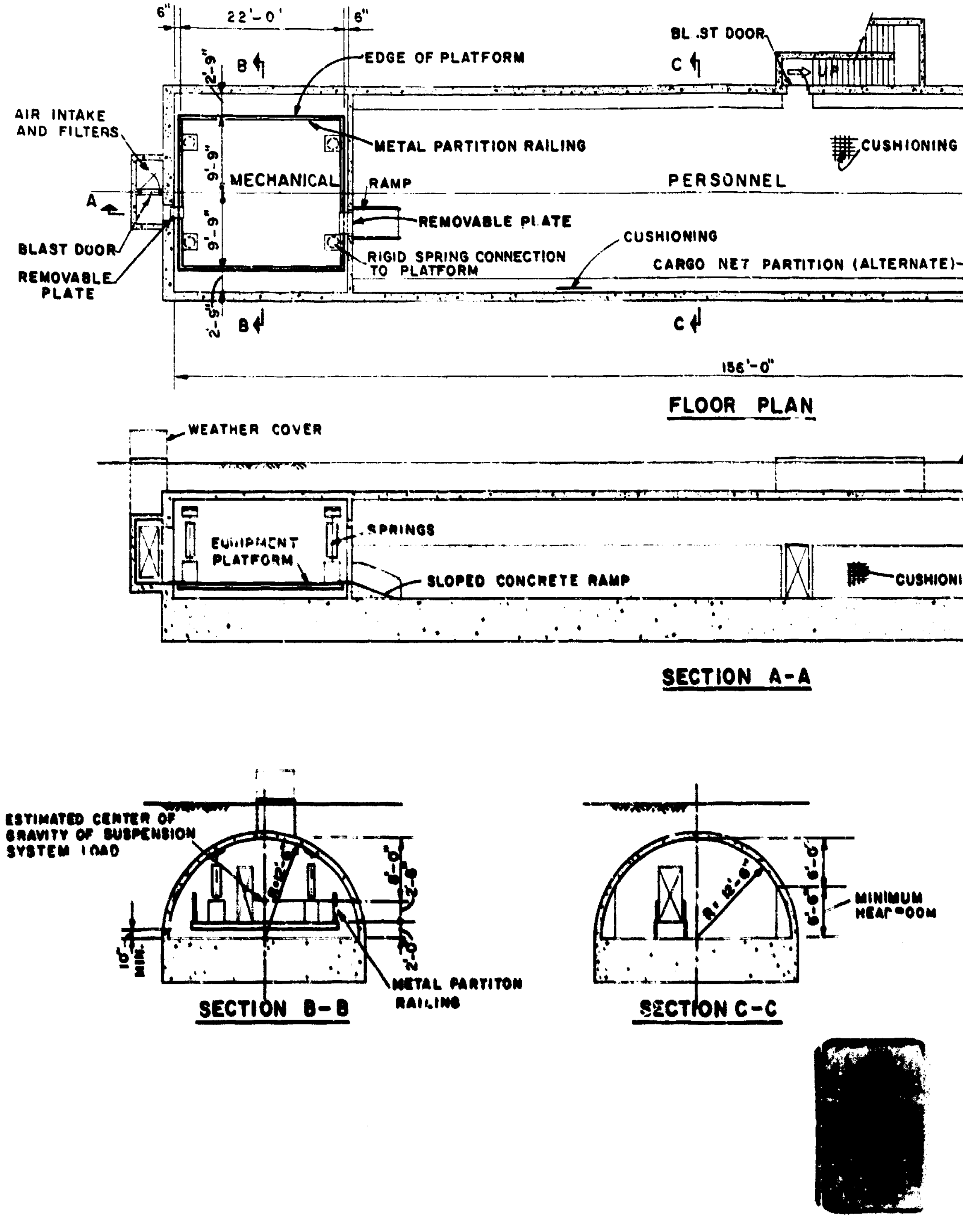


Fig. 7-18

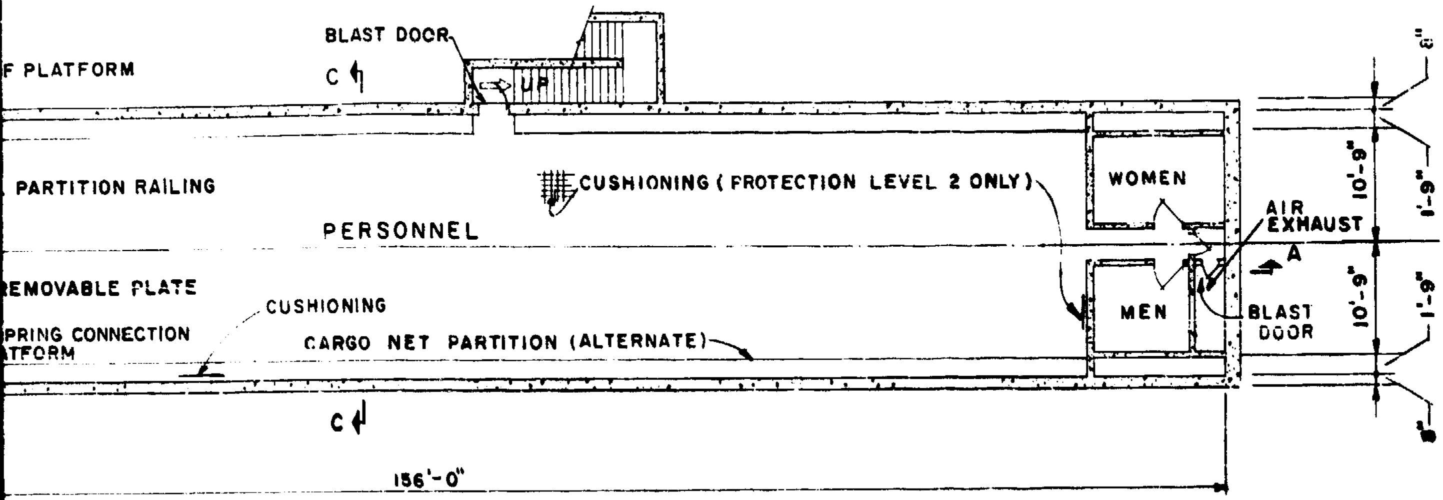
ARCH SHELTER
(100 psi)
FOR 250 PERSONS
PERSONNEL PROTECTION
LEVEL I

2

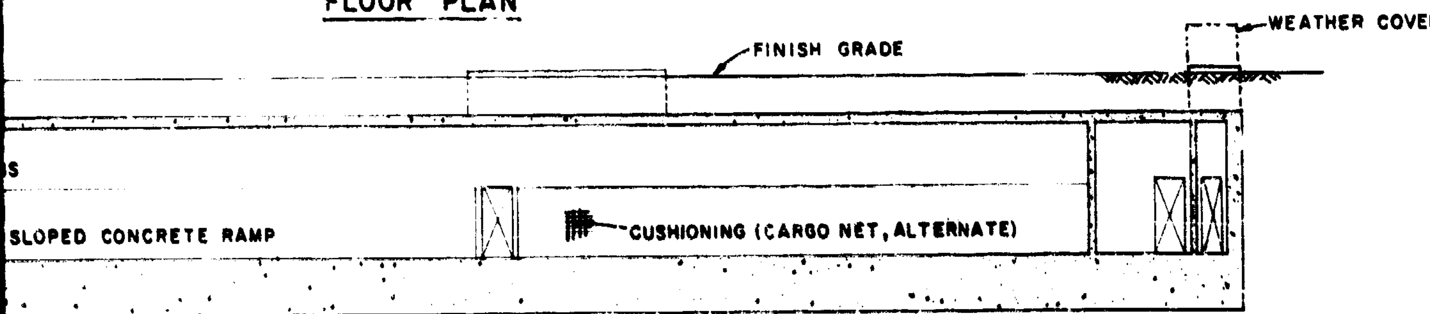
7-47 and 7-48



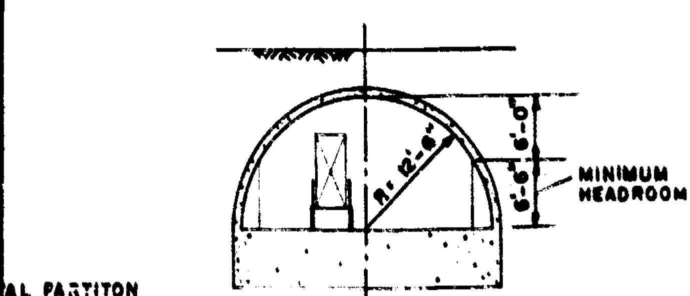
6"
22'-0'
6"
BL ST DOOR
B
C
EDGE OF PLATFORM
AIR INTAKE AND FILTERS
METAL PARTITION RAILING
CUSHIONING
MECHANICAL
RAMP
PERSONNEL
A
REMOVABLE PLATE
BLAST DOOR
CUSHIONING
RIGID SPRING CONNECTION TO PLATFORM
CARGO NET PARTITION (ALTERNATE)
REMOVABLE PLATE
156'-0"
FLOOR PLAN
WEATHER COVER
SPRINGS
EQUIPMENT PLATFORM
SLOPED CONCRETE RAMP
SECTION A-A
ESTIMATED CENTER OF GRAVITY OF SUSPENSION SYSTEM LOAD
MINIMUM HEADROOM
METAL PARTITON RAILING
SECTION B-B
SECTION C-C



FLOOR PLAN



SECTION A-A



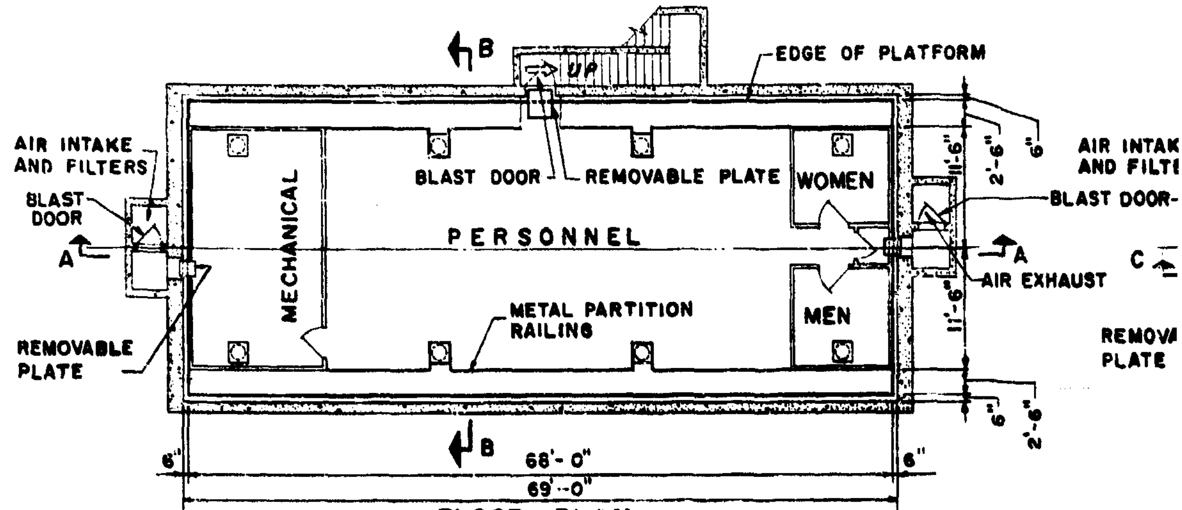
SECTION C-C

Fig. 7-10

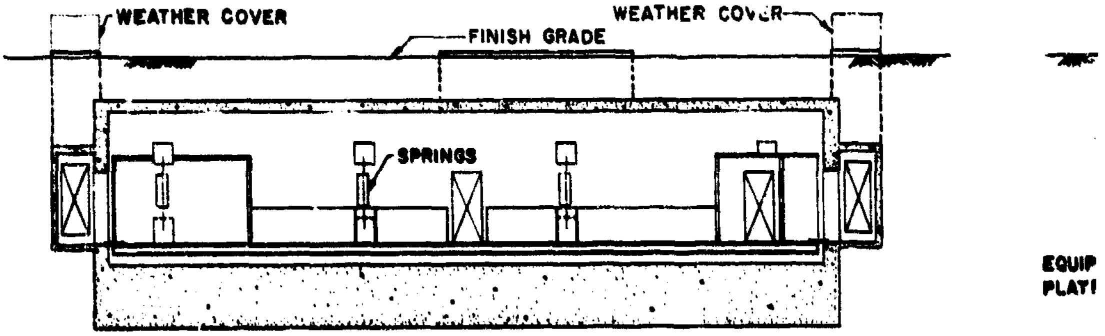
ARCH SHELTER
(100 psi)
FOR 250 PERSONS
PERSONNEL PROTECTION
LEVEL 2 & 3

0 5' 10' 15'

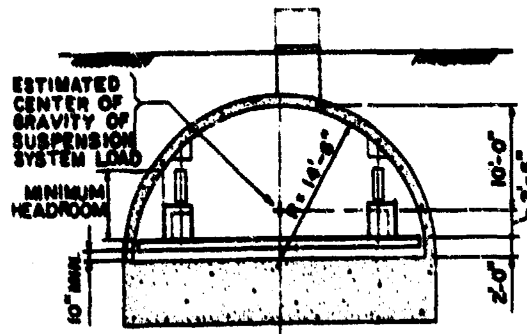
2



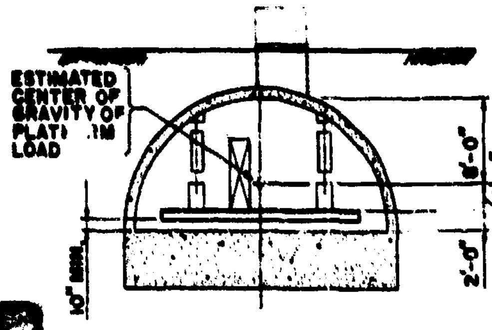
FLOOR PLAN



SECTION A-A



SECTION B-B



SECTION D-D

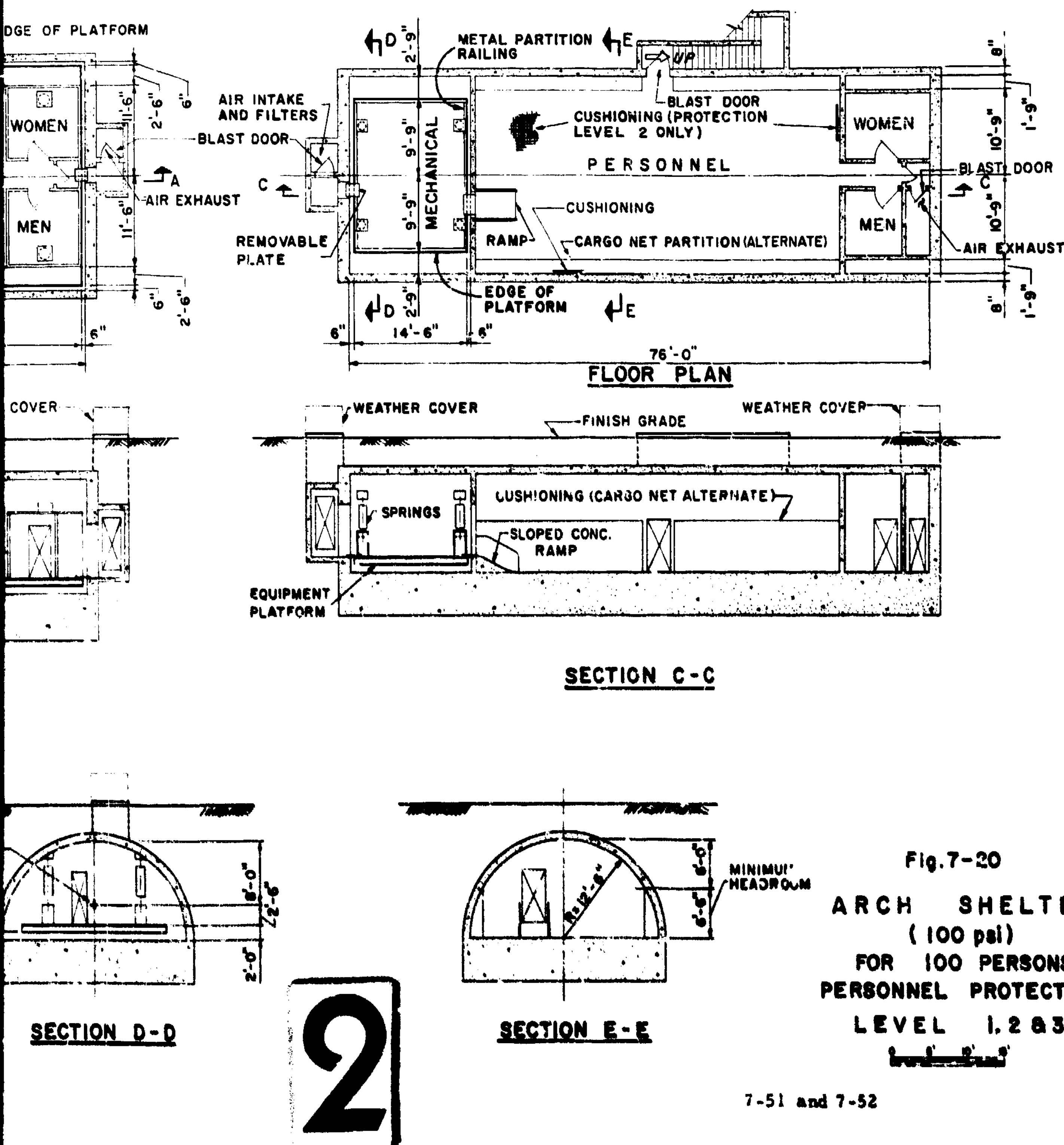


Fig. 7-20

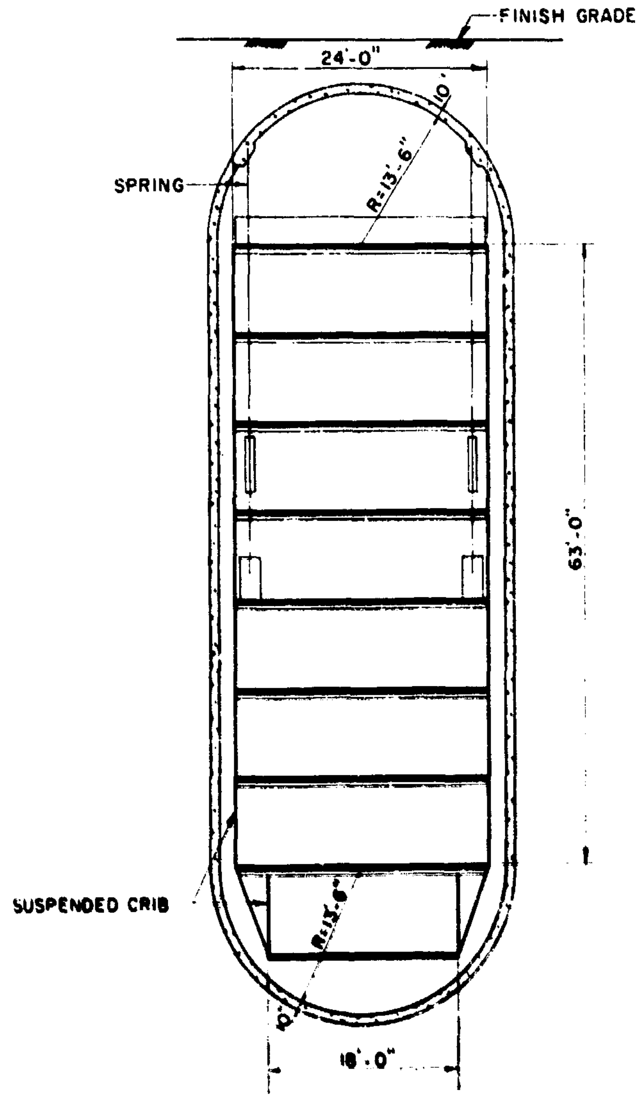
ARCH SHELTER

(100 psi)

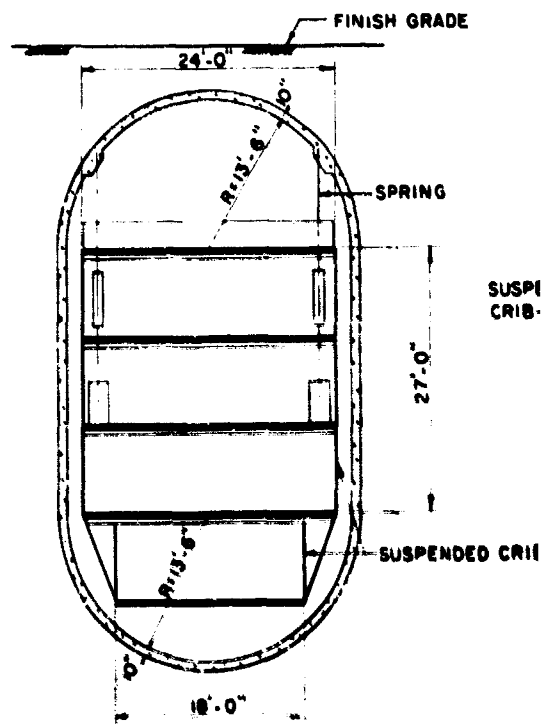
FOR 100 PERSONS

PERSONNEL PROTECTION

LEVEL 1, 2 & 3



250 PERSONS



100 PERSONS

300 psi

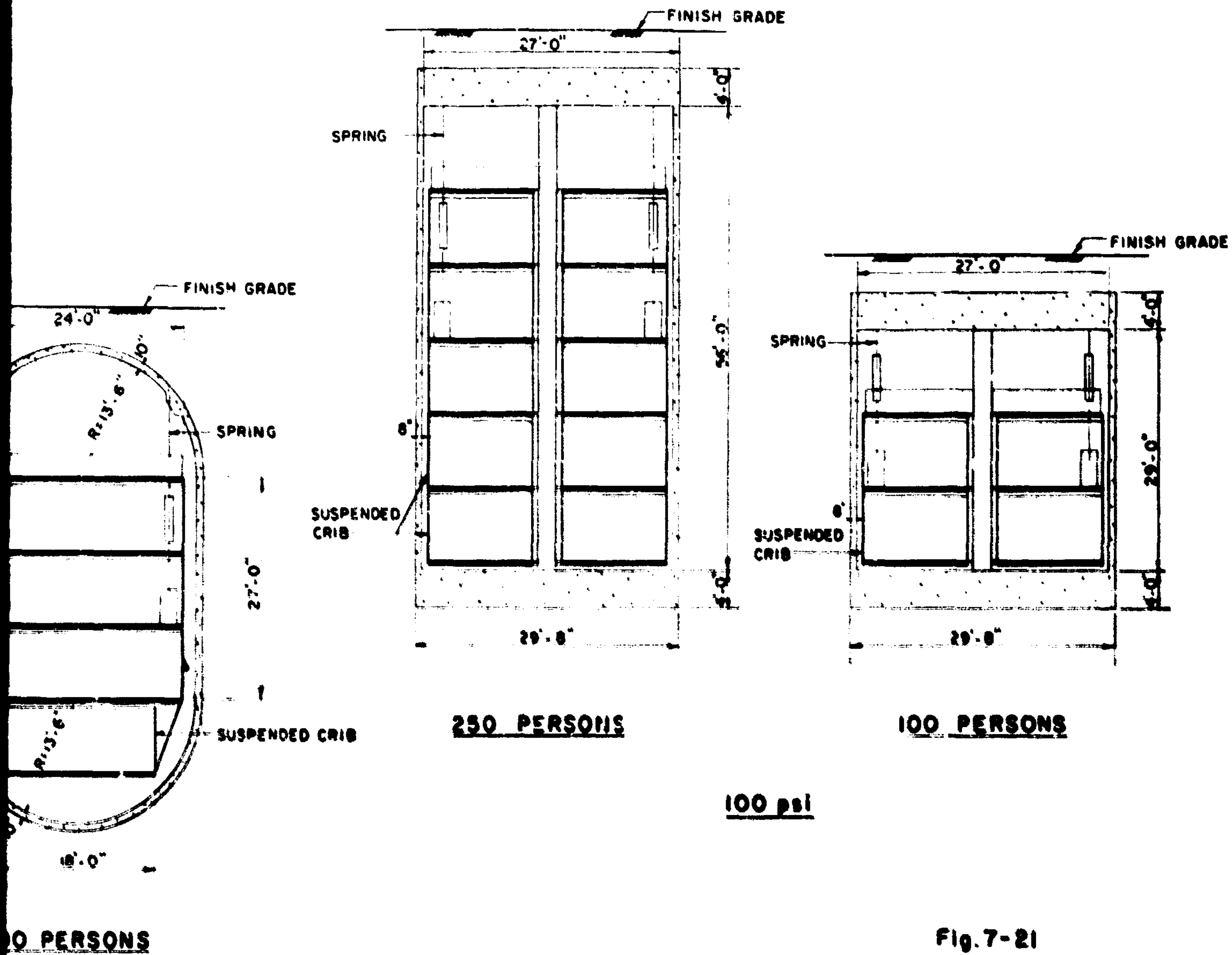


Fig. 7-21

VERTICAL CYLINDRICAL SHELTERS
(100 & 300 psi)
FOR 100 AND 250 PERSONS
PERSONNEL PROTECTION
LEVEL I

7-53 and 7-54

2

7-9 Cost Estimates

The following section summarizes the quantities and cost estimates for each of the shelters illustrated. The unit prices are based upon national average costs (Reference 7.4) and are subject to some local modifications, but the quantities should remain essentially constant.

The estimates were limited to those structural items of the shelters which either affect, or are affected by, the shock isolation system. Cost estimates are given for the earthwork (not including real estate), main structural shell (excluding entrances, exits, air intakes and exhausts), interior structural partitions (concrete and steel), and the isolation system. The structures were assumed to be located in a normal soil environment (not rock) with the water table below the foundation.

Excavation criteria for the various structures varied depending upon the structural configuration. The open-cut excavation for the rectangular shelter and the arches was calculated on the basis of a one-on-one slope extending upward from a perimeter one foot outside the base of the foundation while the open-cut excavation for the horizontal cylinders is based on a one-on-one slope extending upward from a perimeter one foot outside the shell at the mid-height of the cylinder. Below the mid-height, the excavation has the same shape as the structure. For the vertical cylinders, vertical shaft excavation was used throughout with the exception of the 300-p.s.i. shelter where formed excavation was utilized for the lower hemispherical end.

7-9.1 Description of Tables and Charts

The total cost of each of the thirty-seven shelters studied in addition to the total cost for non-shock-isolated structures (structures whose shell is capable of sustaining the blast load and the effects of ground motion) for the various pressure levels and population sizes are given in Table 7-7 (pp. 59-63). This table includes individual costs of the main structures and the shock isolation system as well as the cost per square foot of the shelter and the cost per person. Relative costs for each pressure level and population size are also given for the various personnel protection levels. These costs are relative to the cost of the non-shock-isolated structure (NSI). All of the cost data of the above table includes a 25 percent increase of the material cost to account for the contractor's profit, overhead, and contingencies. No allowance was made for architect-engineer fees.

In Tables 7-8 to 7-18 (pp. 65-75), quantity and cost breakdowns for various structural components are given for the shelters investigated. Also included are the quantity and cost breakdowns for the non-shock-isolated structures previously mentioned.

A plot of the relative costs versus the personnel protection levels is given in Figure 7-22 (p. 7-76), for basic concepts of Section 7-9. The costs are plotted relative to the cost of the 250-person, rectangular (25 p.s.i. overpressure), non-shock-isolated structure. This figure indicates the most economical one-and two-story buildings investigated.

Figure 7-23 (p. 7-77) indicates the variation of cost (per person) of structures versus overpressure. The curves are plotted for all three protection levels in addition to the no-shock-isolation case. Chart "a" gives the cost variation for the 250-person shelters, while chart "b" indicates the cost-versus-protection level relationship for the 100-person structure.

7-9.2 Discussion of Tables and Charts

Except for the two-story structures (protection level one), the relative costs of the shelters investigated will increase with decreasing protection level (Figure 7-22 and Table 7-7). This increase is primarily the result of the additional material required for the lower protection level, i.e., the addition of the cushioning and mechanical equipment suspension systems for protection levels two and three and the addition of the suspension system and the increase of the shell size for protection level one. In all cases, the relative cost for the two-story structure(protection level one) is less than those for protection levels two and three (Figure 7-22). The relative cost increase, above that for the no-shock-isolation system, of the two-story structures is equal to or less than five and twelve percent for the structures at the 100- and 300-p. s. i. pressure levels, respectively.

The relative cost for a particular pressure level, structural configuration, and protection level is greater for the 100-person shelter than that for the 250-person structure; while in the case of the 25-p. s. i. -rectangular structure, the relative cost for the 10-person shelter is less than those for the 100- and 250-person buildings. The increase of the relative cost of the 100-person shelter above that of the 250-person shelter is the result of the more predominant effect that the cost of the shock isolation system has on the total cost in the former shelter in comparison to that of the latter, e.g., the cost of the shock isolation system of structure RE(S)-25-100-1 is 63 percent of the cost of no-shock-isolation structure (25 p. s. i. and 100 person) while in structure RE(S)-25-250-1, the cost of the shock isolation system is only 49 percent of the cost of the no-shock-isolation shelter.

It is interesting to note that the costs of the isolation systems in the structures studied can be as high as 68 percent of the cost of the shell (Table 7-19) (p. 7-78). The cost of the suspension systems for the two-story structures (protection level one) will vary between 53 and 68 percent of the cost of the shell while the variation for the one-story buildings (protection level one) will be between 42 and 53 percent except for the arch structures where the suspension system costs are 24 and 34 percent of that of the shell for the 250-and 100-person shelters, respectively. This reduction in the percent cost of the arch suspension system is a result of the relatively high cost of the structure shell due to the presence of the monolithic foundation slab. In all cases, the percent cost of the support systems for protection levels two and three is less than thirty.

In Figure 7-23, the solid lines indicate the most economical structures for the various protection levels while the dash line indicates the most economical single-story structures. Though not indicated in the tables, the cost per person of a two-story rectangular structure will be approximately the same as that of a one-story shelter at the 25-p. s. i. pressure. Therefore, in the above figure, solid lines were drawn between the point indicating the cost of the single-story rectangular structures at the 25-p. s. i. overpressure range, and the points which indicate the cost of two-story horizontal cylinders at the 100-p. s. i. pressure level.

Table 7-7 Summary of Estimated Costs

Pressure p.s.i.	Type Structure	Population	Item	Personnel Protection Level 1 (Two Story / Single Story)	2	3	No Shock Isolation
25	Rect. Cyl.	250	Main Structure	$ 58370	49460	49480	49480
			Shock Iso. Sys.	24190	11760	7310	--
			Total Cost	82560	61240	56790	49480
			Total Floor Area, SF	3250	3260	3260	3260
			Cost Per SF	25.40	18.79	17.42	15.18
			Cost Per Person	$330.24	244.96	227.16	197.92
			Relative Cost	1.67	1.24	1.15	1.00
25	Rect. Cyl.	100	Main Structure	$ 28100	22630	22630	22630
			Shock Iso. Sys.	14310	7040	4780	--
			Total Cost	42410	29670	27410	22630
			Total Floor Area, SF	1520	1530	1530	1530
			Cost Per SF	28.05	21.63	20.15	17.03
			Cost Per Person	$424.10	296.70	274.10	226.30
			Relative Cost	1.87	1.31	1.21	1.00
25	Rect. Cyl	10	Main Structure	$ 4590	4350	4350	4350
			Shock Iso. Sys.	2080	690	440	--
			Total Cost	6670	5040	4790	4350
			Total Floor Area, SF	140	140	140	140
			Cost Per SF	47.64	36.60	34.21	31.07
			Cost Per Person	$667.00	504.00	479.00	435.00
			Relative Cost	1.53	1.16	1.10	1.00

Table 7-7 continued

Pressure p.s.i.	Type Structure	Population	Item	Personnel Protection Level 1 Two Story	1 Single Story	2	3	No Shock Isolation
100	Horiz. Cyl.	250	Main Structure	$ 55190	$ 80190	91450	91450	89560
			Shock Iso. Sys.	37040	35960	15900	11030	--
			Total Cost	92230	116150	107350	102480	89560
			Total Floor Area, SF	3280	3280	3280	3280	3280
			Cost Per SF	28.12	35.41	32.73	31.24	27.30
			Cost Per Person	$368.92	464.60	429.40	409.92	358.24
			Relative Cost	1.03	1.30	1.20	1.14	1.00
100	Horiz. Cyl.	100	Main Structure	$ 28080	$ 42260	46760	46760	45250
			Shock Iso. Sys.	19000	20710	11800	8940	--
			Total Cost	47080	62970	58560	55700	45250
			Total Floor Area, SF	1560	1560	1560	1560	1560
			Cost Per SF	30.18	40.37	37.54	35.71	29.01
			Cost Per Person	$470.80	$629.70	585.60	557.00	452.50
			Relative Cost	1.04	1.39	1.29	1.23	1.00
100	Arch	250	Main Structure		$135630	118160	118160	115990
			Shock Iso. Sys.		32490	14610	10010	--
			Total Cost		168120	132770	128170	115990
			Total Floor Area, SF		3280	3280	3280	3280
			Cost Per SF		51.26	40.48	39.08	35.36
			Cost Per Person		$672.48	531.08	512.68	463.96
			Relative Cost		1.45	1.14	1.11	1.00

Table 7-7 continued

Pressure p.s.i.	Type Structure	Population	Item	* Two Story	Personnel Protection Level 1 Single Story	2	3	No Shock Isolation
100	Arch	100	Main Structure		$ 69190	62050	62050	59940
			Shock Iso. Sys.		20840	9610	6890	--
			Total Cost		90030	71660	68940	59940
			Total Floor Area, SF		1560	1560	1560	1560
			Cost Per SF		57.71	45.94	44.19	38.42
			Cost Per Person		$900.30	716.60	689.40	599.40
			Relative Cost		1.20	1.15	1.00	1.00
100	Vert. Cyl.	250	Main Structure	$ 80500				
			Shock Iso. Sys.	44500				
			Total Cost	125000				
			Total Floor Area, SF	3100				
			Cost Per SF	40.32				
			Cost Per Person	$500.00				
			Relative Cost	--				
100	Vert. Cyl.	100	Main Structure	$ 54340				
			Shock Iso. Sys.	29100				
			Total Cost	83440				
			Total Floor Area, SF	1550				
			Cost Per SF	53.83				
			Cost Per Person	$834.40				
			Relative Cost	--				

Table 7-7 continued

Pressure p.s.i.	Type Structure	Population	Item	Personnel Protection Level 1: * Two Story	Personnel Protection Level 1: Single Story	Personnel Protection Level 2	Personnel Protection Level 3	No Shock Isolation
300	Horiz. Cyl.	250	Main Structure	$ 72660	95560	104240	104240	101800
			Shock Iso. Sys.	39080	40450	22150	17280	--
			Total Cost	111740	136010	126390	121520	101800
			Total Floor Area, SF	3280	3280	3280	3280	3280
			Cost Per SF	34.07	41.47	38.53	37.05	31.04
			Cost Per Person	$446.96	544.04	505.56	486.08	407.20
			Relative Cost	1.10	1.34	1.24	1.19	1.00
300	Horiz. Cyl.	100	Main Structure	$ 37610	49350	54030	54030	51140
			Shock Iso. Sys.	19740	23200	14180	11310	--
			Total Cost	57350	72550	68210	65340	51140
			Total Floor Area, SF	1560	1560	1560	1560	1560
			Cost Per SF	36.76	46.50	43.72	41.88	32.78
			Cost Per Person	$573.50	725.50	682.10	653.40	511.40
			Relative Cost	1.12	1.42	1.33	1.28	1.00
300	Vert. Cyl.	250	Main Structure	$ 88890				
			Shock Iso. Sys.	53750				
			Total Cost	142640				
			Total Floor Area, SF	3170				
			Cost Per SF	45.00				
			Cost Per Person	$570.56				
			Relative Cost	--				

Table 7-7 continued

Pressure p.s.i.	Type Structure	Population	Item	Personnel Protection Level 1 * Two Story	1 Single Story	2	3	No Shock Isolation
300	Vert. Cyl.	100	Main Structure	$ 48090				
			Shock Iso. Sys.	34560				
			Total Cost	82650				
			Total Floor Area, SF	1580				
			Cost Per SF	52.31				
			Cost Per Person	$826.50				
			Relative Cost	--				

* Vertical Cylinders are Multi-Story Structures.

* * * * * * * * * * * * * *

Table 7-8 **Structural Cost Estimate - Rectangular Structure**
(25 p.s.i. - 250 Persons)

Item	Unit	Unit Price	PL 1 Quantity	PL 1 Cost	PL 2 & 3 Quantity	PL 2 & 3 Cost	N.S.I. Quantity	N.S.I. Cost
Earthwork								
Excav. Open Cut	cy	$ 0.65	3740	$ 3430	3460	$ 2250	3460	$ 2250
Backfill	cy	1.20	1930	2320	1820	2180	1820	2180
Main Structure								
Concrete	cy	35.00	540	18900	423	14810	423	14810
Reinf. Steel	tons	340.00	35.7	12140	28	9520	28	9520
Formwork								
Roof	sf	1.50	3460	5190	3450	5180	3450	5180
Walls & Footings	sf	.65	5640	3670	7120	4630	7120	4630
Dampproofing	sf	0.10	10370	1040	10080	1010	10080	1010
Subtotal				46690		39580		39580
Shock Iso. Sys.								
Struct. Steel	tons	480.00	3	1440	1.2	580	--	--
Steel Deck	sf	2.40	3250	7800	460	1100	--	--
Spring Assem.	ls	--	--	2400	--	920	--	--
Jacking Sys.	ls	--	--	2000	--	750	--	--
Railing	lf	10.00	242	2420	90	900	--	--
Metal Partitions	sf	4.70	700	3290	--	--	--	--
Cushioning, PL2	sf	1.00	--	--	5160	5160	--	--
Cushioning, PL3	sf	1.00	--	--	1600	1600	--	--
Subtotal				19350	PL2	9410		00
					PL3	5850		
Total				$66040	PL2	$48990		$39580
					PL3	$45430		

Table 7-9 Structural Cost Estimate - Rectangular Structure (25 p.s.i. - 100 Persons)

			Personnel Protection Level (PL)					
		Unit	1		2 & 3		N.S.I.	
Item	Unit	Price	Quantity	Cost	Quantity	Cost	Quantity	Cost
Earthwork								
Excav. Open Cut	cy	$ 0.65	2030	$ 1320	1600	$ 1040	1600	$ 1040
Backfill	cy	1.20	1260	1510	710	850	710	850
Main Structure								
Concrete	cy	35.00	247	8650	182	6370	182	6370
Reinf. Steel	tons	340.00	16.3	5540	12	4080	12	4080
Formwork								
Roof	sf	1.50	1590	2390	1570	2360	1570	2360
Walls & Footings	sf	.65	3850	2500	4300	2800	4300	2800
Dampproofing	sf	0.10	5690	570	5480	550	5480	550
Subtotal				22480		18050		18050
Shock Iso. Sys.								
Struct. Steel	tons	480.00	1.5	720	0.5	240	--	--
Steel Deck	sf	2.40	1520	3650	290	700	--	--
Spring Assem.	ls	--	--	1600	--	600	--	--
Jacking Sys.	ls	--	--	1200	--	450	--	--
Railing	lf	10.00	160	1600	70	700	--	--
Metal Partitions	sf	4.70	570	2680	--	--	--	--
Cushioning, PL2	sf	1.00	--	--	2940	2940	--	--
Cushioning, PL3	sf	1.00	--	--	1130	1130	--	--
Subtotal				11450	PL2	5630		00
					PL3	3820		
Total				$ 33930	PL2	$23680		$18050
					PL3	$21870		

Table 7-10 Structural Cost Estimate - Rectangular Structure
(25 p.s.i. - 10 Persons)

Item	Unit	Unit Price	PL 1 Quantity	PL 1 Cost	PL 2 & 3 Quantity	PL 2 & 3 Cost	N.S.I. Quantity	N.S.I. Cost
Earthwork								
Excav. Open Cut	cy	$ 0.65	495	$ 320	425	$ 280	425	$ 280
Backfill	cy	1.20	418	500	355	430	355	430
Main Structure								
Concrete	cy	35.00	32	1120	30	1050	30	1050
Reinf. Steel	tons	340.00	2.0	680	1.9	650	1.9	650
Formwork								
Roof	sf	1.50	165	250	145	220	145	220
Walls & Fo[illegible]	sf	.65	1075	700	1170	760	1170	760
Dampproofing	sf	0.10	1010	100	935	90	935	90
Subtotal				3670		3480		3480
Shock Iso. Sys.								
Struct. Steel	tons	480.00	0.2	100	--	--	--	--
Steel Deck	sf	2.40	140	340	--	--	--	--
Spring Assem.	ls	--	--	200	--	100	--	--
Jacking Sys.	ls	--	--	100	--	--	--	--
Railing	lf	10.00	40	400	-	--	--	--
Metal Partitions	sf	4.70	110	520	--	--	--	--
Cushioning, PL2	sf	1.00	--	--	450	450	--	--
Cushioning, PL3	sf	1.00	--	--	250	250	--	--
Subtotal				1660	PL2	550		00
					PL3	350		
				$5130	PL2	$4030		
Total				$5330	PL3	$3830		$3480

Table 7-11 Structural Cost Estimate - Horizontal Cylinder
(100 p.s.i. - 250 Persons)

Item	Unit	Unit Price	Personnel Protection Level (PL) 1: Two Story Quantity	Two Story Cost	Single Story Quantity	Single Story Cost	2 & 3 Quantity	2 & 3 Cost	N.S.I. Quantity	N.S.I. Cost
Earthwork										
Excav. Open Cut	cy	$ 0.65	3450	$ 2240	4410	$ 2870	3910	$ 2540	3650	$ 2370
Excav. Formed	cy	5.30	1480	7840	1370	7260	1190	6310	1100	5830
Backfill	cy	1.20	1970	2360	3040	3650	2720	3260	2540	3050
Main Structure										
Concrete	cy	35.00	233	8160	370	12950	779	27270	813	28460
Reinf. Steel	tons	340.00	11.5	3910	18.5	6290	17.1	5810	16.2	5510
Formwork										
Shell	sf	1.50	12440	18660	19710	29570	17110	25670	16140	24210
Walls & Footings	sf	.65	--	--	--	--	1440	940	1440	940
Dampproofing	sf	0.10	9780	980	15620	1560	13620	1360	12820	1280
Subtotal				44150		64150		73160		71650
Shock Iso. Sys.										
Struct. Steel	tons	480.00	5	2400	3	1440	1.2	580	--	--
Steel Deck	sf	2.40	3280	7870	3280	7870	480	1150	--	--
Spring Assem.	ls	--	--	8700	--	8000	--	2000	--	--
Jacking Sys.	ls	--	--	2000	--	2800	--	1200	--	--
Railing	lf	10.00	320	3200	320	3200	90	900	--	--
Metal Partitions	sf	4.70	1160	5460	1160	5460	--	--	--	--
Cushioning, PL2	sf	1.00	--	--	--	--	6890	6890	--	--
Cushioning, PL3	sf	1.00	--	--	--	--	2990	2990	--	--
Subtotal				29630		28770	PL2	12720		00
							PL3	8820		
Total				$73780		$92920	PL2	$85880		$71650
							PL3	$81980		

Table 7-12 Structural Cost Estimate - Horizontal Cylinder (100 p.s.i. - 100 Persons)

Item	Unit	Unit Price	PL 1 Two Story Quantity	PL 1 Two Story Cost	PL 1 Single Story Quantity	PL 1 Single Story Cost	PL 2 & 3 Quantity	PL 2 & 3 Cost	N. S. I. Quantity	N. S. I. Cost
Earthwork										
Excav. Open Cut	cy	$ 0.65	1980	$ 1290	2380	$ 1550	2060	$ 1340	1875	$1220
Excav. Formed	cy	5.30	540	2860	695	3680	590	3130	530	2810
Backfill	cy	1.20	1440	1730	1685	2020	1470	1760	1345	1610
Main Structure										
Concrete	cy	35.00	122	4270	194	6790	370	12350	400	14000
Reinf. Steel	tons	340.00	6.0	2040	10.4	3540	9.9	3370	9.0	3060
Formwork										
Shell	sf	1.50	6500	9750	10270	15410	8810	13220	7950	11930
Walls & Footings	sf	.65	--	--	--	--	1440	940	1440	940
Dampproofing	sf	0.10	5150	520	8170	820	6990	700	6320	630
Subtotal				22460		33810		37410		36200
Shock Iso. Sys.										
Struct. Steel	tons	480.00	2.3	1100	1.5	720	0.5	240	--	--
Steel Deck	sf	2.40	1560	3740	1560	3740	290	700	--	--
Spring Assem.	ls	--	--	3000	--	3600	--	2800	--	--
Jacking Sys.	ls	--	--	1200	--	1600	--	1200	--	--
Railing	lf	10.00	75	750	150	1500	80	800	--	--
Metal Partitions	sf	4.70	1150	5410	1150	5410	--	--	--	--
Cushioning, PL2	sf	1.00	--	--	--	--	3700	3700	--	--
Cushioning, PL3	sf	1.00	--	--	--	--	1410	1410	--	--
Subtotal				15200		16570	PL2	9440		00
							PL3	7150		
Total				$37660		$50360	PL2	$46850		$36200
							PL3	$44560		

Table 7-13 Structural Cost Estimate - Arch Structure

(100 p.s.i. - 250 Persons)

Item	Unit	Unit Price	PL 1 Quantity	PL 1 Cost	PL 2 & 3 Quantity	PL 2 & 3 Cost	N.S.I. Quantity	N.S.I. Cost
Earthwork								
Excav. Open Cut	cy	$ 0.65	8100	$ 5270	7800	$ 5070	7700	$ 5010
Backfill	cy	1.20	5150	6180	5360	6430	5310	6370
Main Structure								
Concrete	cy	35.00	1202	42070	1055	36930	1033	36160
Reinf. Steel	tons	340.00	101.6	34540	77.0	26180	75.5	25670
Formwork								
Shell	sf	1.50	11200	16800	10500	15750	10300	15450
Walls & Footings	sf	.65	3510	2280	5010	3260	4965	3230
Dampproofing	sf	0.10	13580	1360	9135	910	8995	900
Subtotal				108500		94530		92790
Shock Iso. Sys.								
Struct. Steel	tons	480.00	4	1920	1.2	580	--	--
Steel Deck	sf	2.40	3280	7870	480	1150	--	--
Spring Assem.	ls	--	--	8000	--	2200	--	--
Jacking Sys.	ls	--	--	2800	--	800	--	--
Railing	lf	10.00	220	2200	80	800	--	--
Metal Partitions	sf	4.70	1680	3200	--	--	--	--
Cushioning, PL 2	sf	1.00	--	--	6160	6160	--	--
Cushioning, PL 3	sf	1.00	--	--	2480	2480	--	--
Subtotal				25990	PL2	11690		00
					PL3	8010		
Total				$134490	PL2	$106220		$92790
					PL3	$102540		

Table 7-14 Structural Cost Estimate - Arch Structure
(100 p.s.i. - 100 Persons)

Item	Unit	Unit Price	PL 1 Quantity	PL 1 Cost	PL 2 & 3 Quantity	PL 2 & 3 Cost	N.S.I. Quantity	N.S.I. Cost
Earthwork								
Excav. Open Cut	cy	$ 0.65	4350	$ 2830	4460	$ 2900	4350	$ 2830
Backfill	cy	1.20	2910	3490	3260	3910	2910	3490
Main Structure								
Concrete	cy	35.00	607	21250	540	18900	524	18340
Reinf. Steel	tons	340.00	50.8	17270	38.6	13120	37.5	12750
Formwork								
Shell	sf	1.50	5420	8130	5100	7650	4930	7400
Walls & Footings	sf	.65	2610	1700	4115	2670	4085	2660
Dampproofing	sf	0.10	6830	680	4915	490	4775	480
Subtotal				55350		49640		47950
Shock Iso. Sys.								
Struct. Steel	tons	480.00	1.8	860	0.4	190	--	--
Steel Deck	sf	2.40	1560	3740	290	700	--	--
Spring Assem.	ls	--	--	3600	--	1700	--	--
Jacking Sys.	ls	--	--	1600	--	800	--	--
Railing	lf	10.00	90	900	80	800	--	--
Metal Partitions	sf	4.70	1270	5970	--	--	--	--
Cushioning, PL2	sf	1.00	--	--	3500	3500	--	--
Cushioning, PL3	sf	1.00	--	--	1320	1320	--	--
Subtotal				16670	PL2	7690		00
					PL3	5510		
Total				$72020	PL2	$57330		$47950
					PL3	$55150		

Table 7-15 Structural Cost Estimate - Vertical Cylinder
(100 p.s.i. - 250 and 100 Persons)

Item	Unit	Unit Price	Personnel Protection Level (PL) 250 Persons Quantity	Cost	100 Persons Quantity	Cost
Earthwork						
Excav. Shaft	cy	$ 5.30	1590	$ 8430	975	$ 5170
Backfill	cy	1.20	103	120	103	120
Shaft Liner	sf	4.30	5800	24940	3560	15310
Main Structure						
Concrete	cy	35.00	323	11310	266.5	9330
Reinf. Steel	tons	340.00	25.8	8770	21.5	7310
Formwork	sf	1.50	6762	10140	3849	5770
Dampproofing	sf	0.10	6790	680	4560	460
Subtotal				64390		43470
Shock Iso. Sys.						
Struct. Steel	tons	480.00	16.0	7880	8.0	3840
Steel Deck	sf	2.40	3100	7440	1550	3720
Spring Assem.	ls	--	--	5500	--	4800
Jacking & Locking	ls	--	--	2000	--	1600
Metal Partitions	sf	4.70	1160	5450	1150	5410
Railing	lf	10.00	733	7330	390	3900
Subtotal				35600		23270
Total				$99990		$66740

Table 7-16 Structural Cost Estimate - Horizontal Cylinder
(300 p.s.i. - 250 Persons)

Item	Unit	Unit Price	PL 1 Two Story Quantity	PL 1 Two Story Cost	PL 1 Single Story Quantity	PL 1 Single Story Cost	PL 2 & 3 Quantity	PL 2 & 3 Cost	N.S.I. Quantity	N.S.I. Cost
Earthwork										
Excav. Open Cut	cy	$ 0.65	3500	$ 2280	4510	$ 2930	3950	$ 2570	3720	$ 2420
Excav. Formed	cy	5.30	1210	6410	1460	7740	1260	6680	1190	6310
Backfill	cy	1.20	2290	2750	3050	3660	2690	3230	2530	3040
Main Structure										
Concrete	cy	35.00	455	15930	577	20200	948	33180	973	34060
Reinf. Steel	tons	340.00	26.0	8840	31.1	10570	28.1	9550	26.5	9010
Formwork										
Shell	sf	1.50	13920	20880	19840	29760	17240	25860	16240	24360
Walls & Footings	sf	.65	--	--	--	--	1440	940	1440	940
Dampproofing	sf	0.10	10360	1040	15920	1590	13820	1380	13040	1300
Subtotal				58130		76450		83190		81440
Shock Iso. Sys.										
Struct. Steel	tons	480.00	5	2400	3	1440	1.2	580	--	--
Steel Deck	sf	2.40	3280	7870	3280	7870	480	1150	--	--
Spring Assem.	ls	--	--	10800	--	11230	--	6200	--	--
Jacking Sys.	ls	--	--	2000	--	3200	--	2000	--	--
Railing	lf	10.00	274	2740	320	3200	90	900	--	--
Metal Partitions	sf	4.70	1160	5450	1160	5450	--	--	--	--
Cushioning, PL2	sf	1.00	--	--	--	--	6890	6890	--	--
Cushioning, PL3	sf	1.00	--	--	--	--	2990	2990	--	--
Subtotal				31260		32360	PL2	17720		00
							PL3	13820		
							PL2	$101110		
Total				$89390		$108810	PL3	$ 97210		$81440

Table 7-17 Structural Cost Estimate - Horizontal Cylinder (300 p.s.i. - 100 Persons)

Item	Unit	Unit Price	PL 1 Two Story Quantity	PL 1 Two Story Cost	PL 1 Single Story Quantity	PL 1 Single Story Cost	PL 2 & 3 Quantity	PL 2 & 3 Cost	N.S.I. Quantity	N.S.I. Cost
Earthwork										
Excav. Open Cut	cy	$ 0.65	2200	$ 1430	2270	$ 1480	2100	$ 1370	1920	$ 1250
Excav. Formed	cy	5.30	600	3180	745	3950	640	3390	570	3020
Backfill	cy	1.20	1620	1940	1525	1830	1460	1750	1350	1620
Main Structure										
Concrete	cy	35.00	239	8370	296	10360	475	16630	479	16770
Reinf. Steel	tons	340.00	13.7	4660	16.3	5540	15.0	5100	13.6	4620
Formwork										
Shell	sf	1.50	6630	9950	10320	15480	8880	13320	3020	12030
Walls & Footings	sf	.65	--	--	--	--	1440	940	1440	940
Dampproofing	sf	0.10	5580	560	8420	840	7160	720	6570	660
Subtotal				30090		39480		43220		40910
Shock Iso. Sys.										
Struct. Steel	tons	480.00	2.3	1100	1.5	720	0.5	240	--	--
Steel Deck	sf	2.40	1560	3740	1560	3740	290	700	--	--
Spring Assem.	ls	--	--	3600	--	5400	--	4400	--	--
Jacking Sys.	ls	--	--	1200	--	2000	--	1500	--	--
Railing	lf	10.00	75	750	130	1300	80	800	--	--
Metal Partitions	sf	4.70	1150	5400	1150	5400	--	--	--	--
Cushioning, PL2	sf	1.00	--	--	--	--	3700	3700	--	--
Cushioning, PL2	sf	1.00	--	--	--	--	1410	1410	--	--
Subtotal				15790		18560	PL2	11340		00
							PL3	9050		
Total				$45880		$58040	PL2	$54560		$40910
							PL3	$52270		

Table 7-18 Structural Cost Estimate - Vertical Cylinder (300 p.s.i. - 250 and 100 Persons)

Item	Unit	Unit Price	Personnel Protection Level (PL) 250 Persons Quantity	250 Persons Cost	100 Persons Quantity	100 Persons Cost
Earthwork						
Excav. Shaft	cy	$ 5.30	1760	$ 9330	985	$ 5220
Excav. Formed	cy	5.30	228	1210	228	1210
Backfill	cy	1.20	188	230	183	220
Shaft Liner	sf	4.30	6600	28380	3700	15910
Main Structure						
Concrete	cy	35.00	234	8190	145	5080
Reinf. Steel	tons	340.00	12.5	4250	7.7	2620
Formwork	sf	1.50	7840	11760	5160	7740
Dampproofing	sf	0.10	7630	760	4740	470
Subtotal				64110		38470
Shock Iso. Sys.						
Struct. Steel	tons	480.00	16.2	7780	8.2	3940
Steel Deck	sf	2.40	3170	7610	1580	3790
Spring Assem.	ls	--	--	11900	--	8600
Jacking & Locking	ls	--	--	2000	--	1600
Metal Partitions	sf	4.70	1160	5450	1150	5400
Railing	lf	10.00	827	8270	431	4310
Subtotal				43010		27640
Total				$107120		$66110

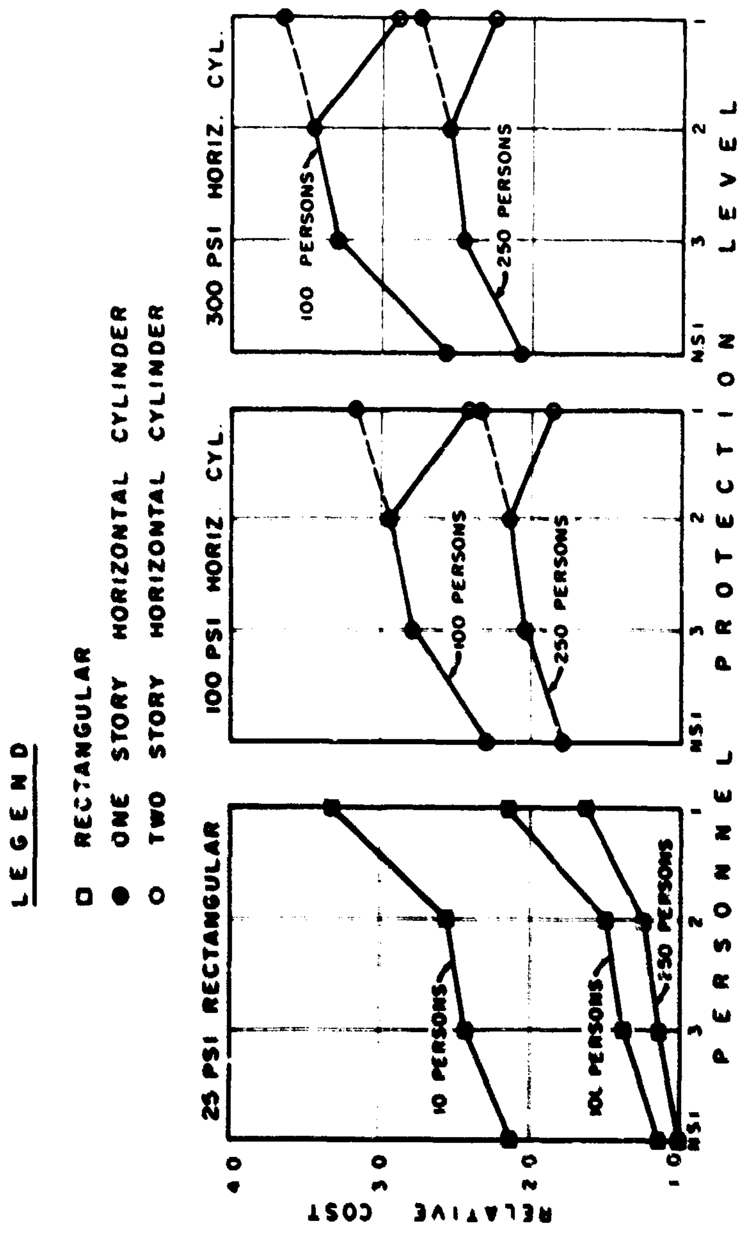


Fig. 7-22 RELATIVE COST vs. PERSONNEL PROTECTION LEVEL

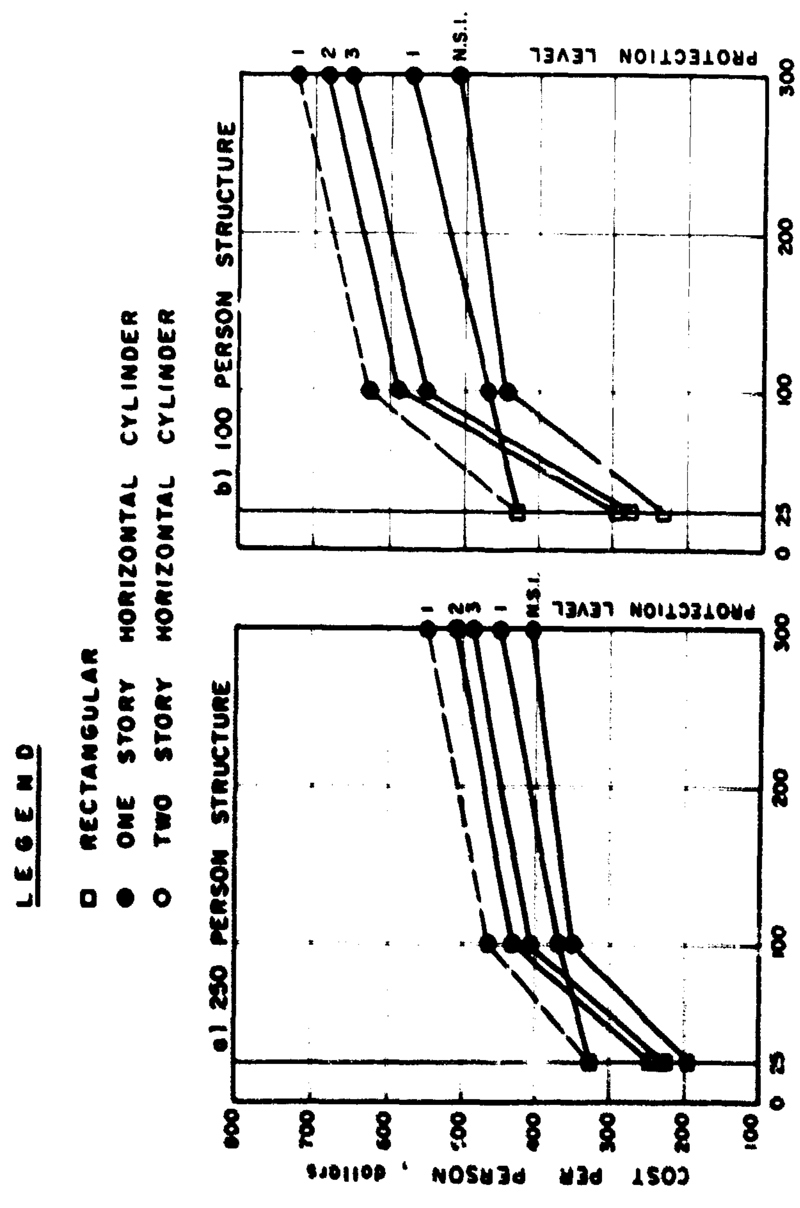


Fig. 7-23 COST PER PERSON vs. OVERPRESSURE

Table 7-19 <u>Cost of Isolation System as a Percentage of the Shell Cost</u>

Population	Pressure Level (psi)	Structure	Personnel Protection Level 1, Two Story	Personnel Protection Level 1, One Story	Personnel Protection Level 2	Personnel Protection Level 3
250	25	Rect.	--	42	24	15
	100	Horiz. Cyl.	67	45	17	12
		Arch	--	24	12	9
	300	Horiz. Cyl	54	42	21	17
100	25	Rect.	--	50	27	19
	100	Horiz. Cyl.	68	49	25	19
		Arch	--	34	16	11
	300	Horiz. Cyl.	53	53	26	21
10	25	Rect.	--	48	21	16

7-10 Discussion of Design Concepts

7-10.1 Structure Shell

The shell of the structures was designed for the blast load applied to the exterior of the shelter whereas partitions, intermediate floor slabs, and other interior items were designed for the structure response to the ground motion.

The selection of the structural configurations for the various pressure levels was based upon the capacity of the structure to resist the blast loads, and the conventionality and economy of construction.

Except for a corrugated arch-type structure, the rectangular shelter was found to be the most economical structural arrangement for use at the 25-p.s.i. overpressure range. Here, individual footings are used for protection levels two and three while the more costly monolithic foundation slab is required for the first protection level. In the design, the individual footings consist of a thickened concrete section under the walls and column which are tied into a thinner slab section spanning between the footings (Figure 7-24a). When movement of the structure occurs due to the ground shock, cracks are formed in that portion of the slab immediately adjacent to the footings, and differential movements are produced between the slab and the footings. For a shelter designed to provide protection levels two and three, this relative motion, when occurring adjacent to the walls (as in the case of small footings), may be tolerable but would be undesirable near the mid-spans of the floor. In the latter case, a footing-slab detail similar to that shown in Figure 7-24b would be more appropriate.

The use of the monolithic foundation for protection level one was predetermined by the use of base-mounted spring supports for the shock isolation system. If a pendulum system were used, the spring supports would have to be attached either to the ceiling near the exterior walls or to points high on the walls themselves. This would result in much longer spans than may be expected in the base-mounted system and, therefore, result in a large increase in cost of the suspension system above that used where the platform spans between the springs

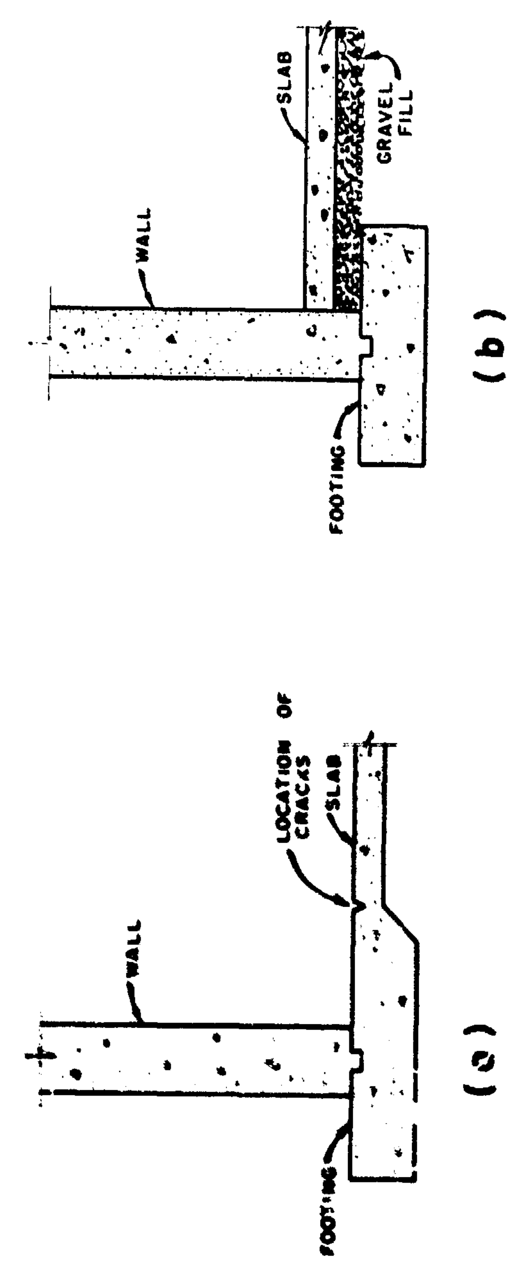


Fig. 7-24 FOOTING DETAILS

are somewhat smaller.

If a corrugated metal-plate arch were used for the shelter configuration at the 25-p. s. i. overpressure range, a one-foot thick monolithic base slab would be required to support the corrugated plate. The reduced cost of the foundation slab of the arch in comparison to that required for the rectangular shelter, in addition to the reduced cost of the superstructure of the former compared to that of the latter, will make the corrugated arch the most economical arrangement even though its use as a permanent-type structure (20 or 30 years) will be limited. This limited life of the corrugated arch and its non-conventionality led to the selection of the rectangular structure for use in this study; nevertheless, it is realized that, in the event of the implementation of a large shelter program, the use of the corrugated arch would merit consideration during planning. The use of the concrete arch at the 25-p. s. i. overpressure range was considered but found to be uneconomical.

At the 100-p. s. i. overpressure level the horizontal and vertical cylinders were studied in addition to the concrete arch. As previously maintained, the horizontal cylinder was found to be the most economical of the three, and because of the equal unconventionality of the three arrangements, the horizontal cylinder was selected as the most practical configuration. In regard to the other two arrangements, the large foundation slab of the arch (monolithic) and the thick roof and foundation slabs of the vertical cylinder rendered these structures uneconomical. In both structures, the use of the monolithic foundation is predetermined by the soil strength utilized (4-ton static). If the structures were designed for another soil condition (say a soil strength of eight tons) individual footings could be used, thereby vastly reducing the structure cost, i.e., for the concrete arch, it is possible to use footings that are eight feet wide and twenty inches thick at each of the springing lines, resulting in a decrease of approximately thirty percent of the cost of the structure (AR(S)-100-250-1); however, this still exceeds the cost of the horizontal cylinder.

Both the horizontal and the vertical cylinders were investigated at the 300-p. s. i. overpressure levels. Each end of both cylinders is sealed with hemispherical domes. The use of the domes serves a twofold purpose; i.e., (1) provide usable volume within the structure thereby reducing the required length of the cylindrical portion of the structure, and (2) eliminate the need for a thick flat plate to sustain the blast load.

Because all of the volume of the horizontal cylinders at the 100-and 300-p.s.i. overpressure range cannot be utilized if the usable floor area is on one level, multi-story inner structures were investigated to determine their efficiency in comparison to the single-story structure. The use of a two-story inner structure was found to provide the most economical arrangement for the populations (100 and 250 persons) considered and a protection level equal to one. When a design was performed for a similar structure for protection levels 2 and 3, it was found, for the spans required, that structural members with frequencies in the order of 10 to 20 c.p.s. would be required and, therefore, their required strength would have to be as much as 20 to 50 g. (Figure 7-8) depending upon the pressure level considered. The members could not be designed for these loads. If an attempt were made to make a more flexible system (say in the order of 2 to 3 c.p.s.), then it can be seen from Figure 7-8 that the displacement of the floor system would be in the order of 3 to 13 inches depending upon the frequency and the pressure range. These displacements would be intolerable for the personnel under repeated vibration (concrete would damp out in approximately 10 cycles while steel members will vibrate many more times than 100 cycles although additional damping will occur in connections of steel structures). From the above discussion it therefore can be seen why single-story buildings were used for protection levels two and three. In the horizontal cylinders designed for protection levels two and three, the lower portion of the structure is filled with concrete to the desired elevation of the floor. The concrete fill is reinforced to sustain the exterior loads; i.e., the thickened concrete section will respond to the blast load in a similar fashion as a foundation slab.

7-10.2 Shock Isolation Systems

a. Shock-Isolated Platform

As previously mentioned, the design of the shock-isolated platforms utilizes both pendulum and base-mounted support systems. The pendulum systems were used in those structures which (1) could not readily support the interior steel structure on their base slabs (cylinders); (2) required an increase of the size of the shell above that required for a pendulum system (arches); and (3) required two-story-interior steel structures while the base-mounted systems are used for those shelters where the pendulum system is not a practical arrangement, e.g., as in the rectangular structure, the large spans would result in a substantial increase in the cost of the platform. F both the pendulum and the base-mounted systems, helical compression springs are used because of their economy and adaptability (Chapter V).

Investigation of the designs of the shock-isolated platform indicated that optimum design value of the dynamic response of one g. will produce the most economical spring system. For dynamic response values less than one g., an increase in the cost of the springs will occur because of the additional length of the springs needed to produce the required larger displacements at the lower response values. For dynamic response values greater than one g., the sise (diameter) of the spring wire must be substantially increased to carry the heavier loads resulting from the higher response, thereby producing a cost increase above that of a one-g. design. On the other hand, the cost of the platform will decrease as the dynamic response decreases, with a minimum value occurring with a static-design load equal to 1.5 g. (design load equal to the weight of the suspension system plus the weight of its content and a safety factor of 1.5). In the case of the large spring-supported platforms (for personnel), the cost of the spring assembly will be in the same order as that of the platform; therefore, an optimum design load for the isolation system as a whole will lie between 1.5 g. (static design) and 2 g. (dynamic response of one g.). In the designs presented herein, the isolated platforms for personnel were designed for a dynamic response of 0.75 g (see design criteria of Section 3-3). For the designs of the equipment-isolated platforms, which are substantially smaller than the personnel isolation systems, the cost of the spring assembly is in the order of 1.5 to 3 times the cost of the platform. Therefore, the most economical design of the spring assembly will predominate in the design of the isolation system as a whole, thereby resulting in a design load of one g. applied dynamically.

Although the designs of the equipment platforms presented herein do not provide protection for personnel (dynamic response equal to or less than 0.75 g.), an economical design which includes personnel protection but which will be slightly more expensive than the one shown, could be provided.

Based on the discussion of the cost of the suspension systems above, it can be seen, in the design concept shown, that the design of shock isolation systems for a dynamic response greater than one g would be uneconomical. Therefore, the utilization of the criteria for restrained personnel (Section 3-3; dynamic response equal to 2 g.) and for the use of the actual equipment shock tolerance which may be considerably higher than one g., (Section 4-3) will be unwarranted.

The clearances required for the design of the shock-isolated platforms were based upon the space allocations of Section 7-6 and upon the vertical and horizontal displacement responses determined from Figures 7-8 and 7-9. The maximum displacements required in the design of the shock isolation system for the structures at the 100-and 300-p.s.i. overpressure levels were equal to the displacement boundary values of the respective spectra curves while for the 25 p.s.i. shelters the displacement values used in the designs were less than the boundary values. In all cases, the rattle space maintained around the shock isolation systems is greater than the resultant of the horizontal and vertical displacement obtained from the spectra. The additional space provides room for rotation of the isolation system due to the dynamic loads in addition to any misalignment of the interior steel structure and/or shell during construction.

Table 7-20 indicates the properties of the springs used in the various designs investigated. It is interesting to note that the maximum uncoupled horizontal frequency for the pendulum-type shock isolation system is 0.26 c.p.s which will conform to a horizontal acceleration of approximately 0.2 g. This is less than one-half the horizontal acceleration tolerance for personnel (Section 3-3). On the other hand, the maximum uncoupled horizontal frequency for the base-mounted shock system of the 25 p.s.i. shelter is 3.1 c.p.s. which conforms to a horizontal acceleration of one g. This latter value exceeds the allowable tolerance for personnel. If so

Table 7-20 S

Type of Shock Iso. System		Structure Designation	Dynamic Response (g.)	Static Load per Spring (kips.)	Mean Diameter (in.)	Wire Diameter (in.)	No. of Active Coils
Pendulum Mounts		HC(T)100-250-1	0.75	36.5	12	2-1/2	14.6
		HC(S)100-250-1	0.75	11.3	12	1-3/4	11.3
		AR(S)100-250-1	0.75	11.1	12	2	11.2
		AR(S)100-250-2&3	1.0	10.1	12	2	10.8
		VC(M)100-250-1	0.75	23.2	12	2	9.4
		HC(T)100-100-1	0.75	19.4	12	2	11.3
		HC(S)100-100-1	0.75	9.75	15	2	6.6
		AR(S)100-100-1	0.75	9.75	15	2	6.6
		AR(S)100-100-2&3	1.0	6.4	12	1-3/4	10.0
		VC(M)100-100-1	0.75	15.3	10	1-3/4	14.4
		HC(T)300-250-1	0.75	20.9	16	2-5/8	15.0
		HC(S)300-250-1	0.75	13.3	12	1-3/4	19.1
		VC(M)300-250-1	0.75	33.75	16	2-1/2	13.3
		HC(T)300-100-1	0.75	19.4	12	2	22.5
		HC(S)300-100-1	0.75	5.6	11	1-1/2	18.1
		VC(M)300-100-1	0.75	15.4	12	2	28.1
Base Mounts	Vertical Coil Springs	RE(S)25-250-1	0.75	13.9	12	1-3/4	2.5
		RE(S)25-250-2&3	1.0	5.2	8-1/8	1-5/8	4.0
		RE(S)25-100-1	0.75	11.5	12	1-3/4	3.0
		RE(S)25-100-2&3	1.0	5.5	7-1/2	1-5/8	5.0
		RE(S)25-10-1	0.75	2.85	6	7/8	6.1
		RE(S)25-10-2&3	1.0	0.2	2-3/4	1/4	5.0
		HC(S)100-250-2&3	1.0	15.6	15	2	6.6
		HC(S)100-100-2&3	1.0	18.0	15	2	6.0
		HC(S)300-250-2&3	1.0	6.8	24-1/2	2-3/8	6.0
		HC(S)300-100-2&3	1.0	6.0	25-1/2	2-3/8	6.0
	Horizontal Springs (Vertical Beams)	HC(S)300-250-2&3	1.0				
		HC(S)300-100-2&3	1.0				

* For pendulum mounts the horizontal frequency is that associated with p
the horizontal frequency is that which would occur if rocking were prev

2

Table 7-20 Spring Properties

Static Load per Spring (kips.)	Mean Diameter (in.)	Wire Diameter (in.)	No. of Active Coils	Total No. of Coils	Solid Height (in.)	Free Height (in.)	No. of Springs	Uncoupled Vertical Frequency (cps.)	Uncoupled Horizontal Frequency (cps.)*	Coupled Frequ (cps.)	
36.5	12	2-1/2	14.6	16.6	41.5	90.5	8	1.00	0.27		
11.3	12	1-3/4	11.3	13.3	23.2	42.5	16	1.00	0.56		
11.1	12	2	11.2	13.2	26.4	45.7	14	1.00	0.35		
10.1	12	2	10.8	12.8	25.6	44.8	4	1.00	0.37		
23.2	12	2	9.4	11.4	22.8	42.1	8	1.00	0.18		
19.4	12	2	11.3	13.3	26.6	72.6	6	1.00	0.27		
9.75	15	2	6.6	8.6	17.2	32.7	8	1.00	0.56		
9.75	15	2	6.6	8.6	17.2	32.7	8	1.00	0.37		
6.4	12	1-3/4	10.0	12.0	21.0	41.5	4	1.00	0.37		
15.3	10	1-3/4	14.4	16.4	28.7	47.9	8	1.00	0.22		
20.9	16	2-5/8	15.0	17.0	39.4	77.8	8	0.72	0.27		
13.3	12	1-3/4	19.1	21.1	37.0	75.4	16	0.72	0.56		
33.75	16	2-1/2	13.3	15.3	38.2	76.5	8	0.72	0.17		
19.4	12	2	22.5	24.5	45.0	83.4	6	0.72	0.27		
5.6	11	1-1/2	18.1	20.1	30.2	68.6	12	0.72	0.56		
15.4	12	2	28.1	30.1	60.2	98.6	8	0.72	0.22		
13.9	12	1-3/4	2.5	4.5	7.9	13.2	20	2.23	2.54	2.18	7.1
5.2	8-1/8	1-5/8	4.0	5.7	8.5	12.0	10	3.00	3.1	2.5	7.1
11.5	12	1-3/4	3.0	5.0	8.8	14.0	12	2.20	2.51	2.02	5.84
5.5	7-1/2	1-5/8	5.0	6.7	10.1	13.3	6	2.80	2.5	2.1	6.2
2.85	6	7/8	6.1	8.1	7.1	12.4	4	2.20	1.77	.98	2.93
0.2	2-3/4	1/4	5.0	6.7	1.6	4.0	4	2.86	3.0	--	--
15.6	15	2	6.6	8.6	17.1	36.0	6	1.18	0.47	.70	2.41
18.0	15	2	6.0	8.0	16.1	34.7	4	1.18	0.79	.66	2.40
6.8	24-1/2	2-3/8	6.0	7.7	17.1	51.0	8	0.83	--	--	--
6.0	25-1/2	2-3/8	6.0	7.7	17.4	51.0	6	0.83	--		
							8		0.96	0.63	2.3
							8		1.03	0.69	2.30

horizontal frequency is that associated with pendulum motion. For base mounts
s that which would occur if rocking were prevented.

ble 7-20 Spring Properties

No. of Active Coils	Total No. of Coils	Solid Height (in.)	Free Height (in.)	No. of Springs	Uncoupled Vertical Frequency (cps.)	Uncoupled Horizontal Frequency (cps.)*	Coupled Frequency (cps.)		Bar Cross Section in x in.	Bar Length (in.)
14.6	16.6	41.5	90.5	8	1.00	0.27				
11.3	13.3	23.2	42.5	16	1.00	0.56				
11.2	13.2	26.4	45.7	14	1.00	0.35				
10.8	12.8	25.6	44.8	4	1.00	0.37				
9.4	11.4	22.8	42.1	8	1.00	0.18				
11.3	13.3	26.6	72.6	6	1.00	0.27				
6.6	8.6	17.2	32.7	8	1.00	0.56				
6.6	8.6	17.2	32.7	8	1.00	0.37				
10.0	12.0	21.0	41.5	4	1.00	0.37				
14.4	16.4	28.7	47.9	8	1.00	0.22				
15.0	17.0	39.4	77.8	8	0.72	0.27				
19.1	21.1	37.0	75.4	16	0.72	0.56				
13.3	15.3	38.2	76.5	8	0.72	0.17				
22.5	24.5	45.0	83.4	6	0.72	0.27				
18.1	20.1	30.2	68.6	12	0.72	0.56				
28.1	30.1	60.2	98.6	8	0.72	0.22				
2.5	4.5	7.9	13.2	20	2.23	2.54	2.18	7.1		
4.0	5.7	8.5	12.0	10	3.00	3.1	2.5	7.1		
3.0	5.0	8.8	14.0	12	2.20	2.51	2.02	5.84		
5.0	6.7	10.1	13.3	6	2.80	2.5	2.1	6.2		
6.1	8.1	7.1	12.4	4	2.20	1.77	.98	2.93		
5.0	6.7	1.6	4.0	4	2.86	3.0	--	--		
6.6	8.6	17.1	36.0	6	1.18	0.47	.70	2.41		
6.0	8.0	16.1	34.7	4	1.18	0.79	.66	2.40		
6.0	7.7	17.1	51.0	8	0.83	--	--	--		
6.0	7.7	17.4	51.0	6	0.83	--				
				8		0.96	0.63	2.[illegible]	6x1	80
				8		1.03	0.69	2.30	5x1	80

ciated with pendulum motion. For base mounts
ng were prevented.

Table 7-20

7-85 and 7-86

3

desired, the latter system could be designed to protect personnel mereiy by the addition of horizontal springs and more flexible vertical spring systems.

b. <u>Cushioning and Other Protective Devices</u>

In the design of the structures for personnel protection levels two and three, protective cushioning material is utilized on the floors, the interior concrete walls and/or exterior walls, the corners of concrete partitions and those portions of the interior furnishings which may form a hazard.

For protection level two, the one-inch thickness of the cushioning on the floor was predetermined by the impact velocity sustained by the head due to people falling over (Chapter VI). The cushioning on both the interior surface of the interior and exterior walls is also provided for people falling over. Furthermore, the cushioning on the exterior wall protects personnel from the effects of the pressure wave, which is transmitted through the walls, in addition to the velocity effects of the walls resulting from the overall and local motions of the structure shell. It was assumed in the designs that falling over against the exterior walls would not occur simultaneously with the other dangers exhibited by these walls and, therefore, cumulative thicknesses of cushioning would not be required. It can be seen from the above discussion that the predominating factor in determining the thickness of the cushioning, in those structures (designed for protection level two) is the falling over effects; therefore the cushioning thickness is independent of the overpressure levels. This led to the use of a uniform thickness of the cushioning for the design of those structures with personnel protection level of two.

Like protection level two, those structures designed for personnel protection level three are provided with cushioning on the interior surfaces of the exterior walls. This cushioning is included for the purpose of protecting the inhabitants close to the walls from the pressure and velocity effects associated with the exterior walls--and not for the purpose of cushioning falls. Therefore, the padding thickness will be a function of magnitudes of the pressure wave passing through the walls and of the wall motions which in turn are a function of the overpressure level. This means that the required thickness of the cushioning will vary with the magnitude of the overpressure level. In this study, this variation of the thickness of cushioning is not considered but would be included in a definitive design. Since the injury potential due to a given impact velocity is considerably greater for corners and edges than for flat surfaces (Chapter III and Chapter VI), cushioning is provided on the former surfaces. The cost of providing cushioning for corners is negligible in comparison to the cost of the remainder of the shelter.

The utilization of protective cushioning in a shelter generally will require the use of a certain number of bracing devices to provide the desired protection. As in the case of bunks, straps (as located in Figure 7-25) should be used above the first tier to prevent falling out. In most cases, falling out of the first tier is probably no worse than falling from a standing or sitting position. In the case of the top tier (Figure 7-25), straps would have to be connected to ceiling or an alternate restraining device (seat belts, etc.) would be required. Besides providing safety straps and/or restraining devices for bunks, the cushioning of metal sections of the bunks with which the occupant's head may come in contact or may be a source of danger to persons standing by, should be provided. Padded steel helmets to protect the occupant's head may be substituted for the cushioning on the bunks proper. Other means by which padding can be reduced or eliminated altogether on bunks or other furniture is by the use of handholes. The handholes can be an integral part or independent of the furniture (see Figure 7-26).

The use of protective cushioning along with the other bracing devices mentioned above may be supplemented and/or substituted by the use of protective clothing (Chapter VI). The cost of the supplementary bracing devices or of the protective clothing has not been included in this report.

Note: Fallout bunks (Reference 7.5) modified for shock protection.

Fig. 7-25 BUNKING SYSTEM for SHELTERS

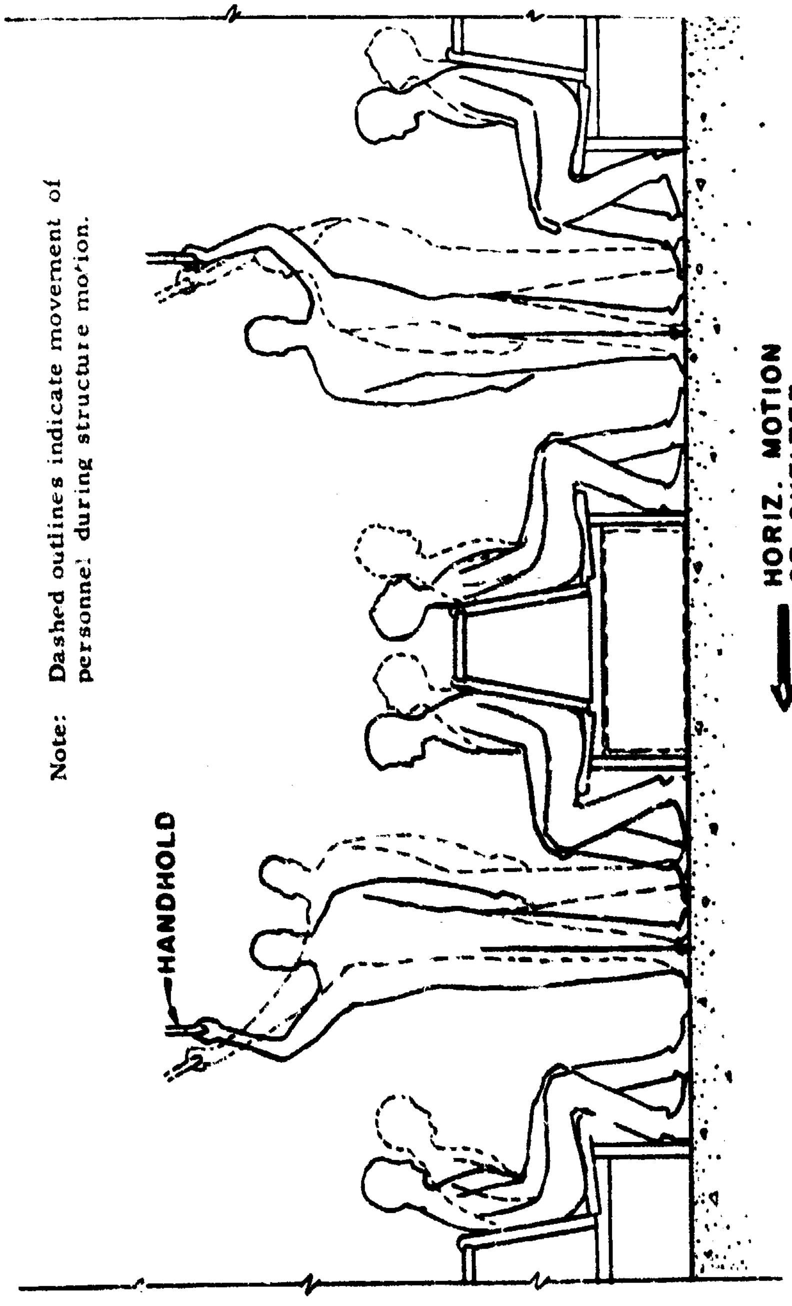


Fig. 7-26 TYPICAL BENCH ARRANGEMENT IN SHELTERS

c. Shock Isolation of Equipment and Miscellaneous Items

The equipment for which shock tolerances are unknown (generators, pumps, electrical equipment) has been assumed to be located on shock-isolated platforms with the shelters. The isolation systems are so designed as to attenuate the shock input environment below that specified in category one of Section 4-3.

On the other hand, the equipment for which tolerances are known (category two, Section 4-3) and are greater than that of the shock environment, has been attached directly to the shell, i.e., in the case of fluorescent light, both the fixtures and lamps can sustain at least a 20 g. -shock load and, therefore, are suspended from the shells of shelters designed for protection levels two and three. Portions of some of the equipment which is not shock isolated must be reinforced to develop its full shock capacity. As in the case of the fluorescent lights, the off-the-shelf connections of the fixtures to the shell would probably have to be strengthened to develop the 20 g. -dynamic load capacity of the lights themselves.

In those structures designed shock tolerance two and three, the furniture will have to be reinforced to sustain the dynamic loads. The bunks (Figure 7-25) and benches (Figure 7-26) will usually require diagonal bracing to resist the horizontal motions of structures in addition to having a relatively wide base to resist overturning. By connecting together several adjacent bunks or benches, the required width usually can be produced. These connections must be capable of transferring applied loads. When two benches or chairs are placed back to back, sufficient space should be allowed to prevent the heads of the people in the adjacent benches from colliding. As mentioned in Section 6-5, arm rests separating every three or four people should be provided on the benches. Seat belts will prevent people from falling off.

Figure 7-26 illustrates a typical seating arrangement in a shelter and the probable movement of the occupants due to the ground shock.

7-11 References

7.1 Brode, H. L., Weapons Effects for Protective Design, Report P-1951, March 31, 1960, The RAND Corporation, Santa Monica, California.

7.2 Architectural and Engineering Planning for Nuclear Protection, OCD Professional Manual PM-100-6 (Interim Edition), June 1, 1963. Prepared by Ammann & Whitney, Consulting Engineers, for the Office of Civil Defense.

7.3 Manual of Spring Engineering, American Steel & Wire Division, United States Steel Corporation, Cleveland, Ohio.

7.4 Godfrey, R. S. et al, Building Construction Cost Data, 21st Edition, 1963, R. S. Means Co., Duxbury, Mass.

7.5 Descriptive Literature of Fallout-Shelter Bunks, United States Steel Products Division, New York, N.Y.

CHAPTER VIII

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

8-1 Summary

8-1.1 Shock Environment

Ground shock caused by the air-blast wave (air-induced shock) is of prime importance for the overpressure levels involved in this study, since the peak intensity of the waves transmitted directly into the ground (direct-transmitted shock) decreases much more rapidly than that resulting from the air-induced effect.

Free-field ground motions are characterized by (1) a low-frequency, downward displacement pulse which reaches a maximum value near the end of the positive phase of the air-blast wave and then rebounds and damps out quickly; and by (2) a high-frequency acceleration which attains a peak value in the extremely early stages of the motion. In some cases (lower overpressure levels), the initial motion may be upward but of less magnitude than the subsequent downward movements. In addition, there is horizontal motion of a similar nature.

The characteristics of the structure motions are similar to those of the free field except that the peak intensity of acceleration is of lower value.

For design purposes, it is convenient to express the ground shock environment in terms of response spectra. Peak, free-field, air-induced ground motions can be calculated as a function of weapon yield, blast overpressure level, and site conditions; and from these peak ground motions, the free-field ground shock spectra are calculated.

Design spectra, for a buried structure, are determined by selecting free-field spectra at such a depth below the roof of the structure as to be equivalent to the design spectra. Design spectra can be obtained in this manner because the rapid attenuation of the free-field acceleration with depth can be utilized to account for the lower structure acceleration compared to that of the free field. The free-field displacements and velocities attenuate gradually with depth and, therefore, proper structure values for these components, which should be in order of magnitude of those of the free field, are obtained.

8-1.2 Shock Tolerances

In a structure subjected to ground shock, vibration produces the predominant effect for persons located on a shock-isolated platform. For persons located on a floor slab which is integral with the structure shell, the predominant effect is due to impact. Shock tests conceived specifically for this ground shock environment have not been performed. However, based on tests and studies of human and animal response to vibration and impact associated with other types of shock environments, it is possible to prepare estimates of tolerances for the ground shock environment although a degree of uncertainty will subsist with such estimates until appropriate tests have been conducted. The basic personnel shock-tolerance values are:

Vibration of Non-Restrained Personnel - Peak Accelerations: 0.75 g. Vertical and 0.50 g. Horizontal.

Vibration of Restrained Personnel - Peak Accelerations: 2.0 g. Vertical and Horizontal.

Impact Against Hard, Flat Surfaces - Peak Impact Velocity: 10 ft./sec.

Based on these tolerance values, personnel design criteria established for this study consists of three personnel-protection levels. The first protection level affords the most reliable protection of the three levels and requires a shock-isolated interior platform to reduce the high accelerations of the structure to tolerable values. The second and third protection levels require the use of protective cushioning materials, in lieu of shock-isolated platforms, to protect against injuries which may be caused by (1) impact at velocities above 10 ft./sec., (2) impact with corners and edges, and (3) compression waves transmitted through exterior walls The second protection level provides for cushioning materials on all impact surfaces within the shelter, and the third protection level is based on the use of a limited amount of cushioning materials. Protective clothing and bracing devices could be used as an alternate or as a supplement to cushioning materials.

Impact may result from the relative motion of the personnel with respect to the structure and from being thrown off balance. Impact velocities due to personnel being thrown off balance would probably not exceed 17 ft./sec.

The relative motion of the personnel with respect to the structure floor can be estimated by comparing the structure displacement versus time with the personnel free-fall displacement due to gravity. An approximate (synthesized) displacement-versus-time curve can be computed from spectra curves.

Mechanical and electrical equipment are generally attached to their support and are, therefore, subjected to a vibratory motion. Shock tolerances for equipment vary considerably for the wide range of available items. Maximum tolerable acceleration values for rugged items are greater than 20 g., whereas tolerances for fragile equipment are as low as 1 to 2 g. Only select items of equipment have been tested. Nevertheless, in many cases, safe tolerances are known based on the shock environment associated with the shipment of equipment on railroad cars and trucks and on loads sustained during normal operation of the equipment. These values are:

Mechanical and Electrical Equipment:	3 g. or less
Electronic Equipment:	1.5 g or less

To avoid amplifications due to resonance with the components of equipment items, the frequency of the isolated system should be less than 10 c.p.s.

Equipment tolerance criteria for this study consists of two categories. Category one considers the use of non-shock-tested equipment and utilizes the above tolerance values. Category two considers the use of shock-tested equipment, in which case actual maximum tolerance values would be utilized in design.

Miscellaneous interior components, such as furniture, partitions, ductwork, etc., require individual evaluation to determine the required strength, anchorage, and flexibility.

8-1.3 Shock Isolation Techniques

In shelters designed for ground shock, protection may be achieved by providing shock isolation systems which separate the occupants and/or equipment from direct contact with the structure shell. These systems consist of (1) shock-isolated platforms and (2) cushioning materials and other protective devices. Their use is dependent upon the desired reliability of protection, the functional requirements, and the cost. For personnel protection level one, both the personnel and the equipment are supported on the same shock-isolated platform; for protection levels two and three, the equipment is usually shock-isolated by platforms and cushioning is used for protecting the personnel.

Shock isolation of platforms can be accomplished in one of two ways, (1) use of pendulum spring supports, or (2) base-mounted spring supports. For relative displacements up to approximately 24 inches, both the pendulum and the base-mounted systems utilize helical compression springs although beam and volute springs can be utilized at smaller displacements.

The pendulum system consists of a series of rods, bearing plates, and springs having its upper end suspended from the upper portion (roof or walls) of the shelter while the lower end of the pendulum is attached to the platform. Usually this type of suspension system is designed for a dynamic response, to the shock input, of one g or less.

The base-mounted support system is supported by the base of the shelter. Here, the platform is mounted on the springs which in turn are supported on the foundation slab. This system can be designed for dynamic response values greater than one g, although the most economical design for the system as a unit is for a dynamic response equal to or less than one g.

Other than shock-isolated platforms, protective measures for personnel consist of the use of (1) protective cushioning materials, (2) protective clothing, (3) restraining devices, and (4) bracing devices. These devices can all provide a degree of protection against injuries caused by impact loads. Moreover, they can be used in combination in a particular shelter.

Protective cushioning materials placed on the interior surfaces of the shelter offer the important advantage of providing protection without relying on personnel to perform any precautionary task. Several types of cushioning materials are available which can provide adequate protection against impact injuries. Of the materials investigated, Ensolite 22266 (trade name of U.S. Rubber Company) provides the best protection per inch of thickness. One inch of Ensolite 22266 will protect the head at impact velocities up to 17 ft./sec.

Effective utilization of protective clothing (helmets, padding, shoes, etc.) requires an element of control in assuring that the clothing will fit and will be worn during the emergency since such clothing may be cumbersome and uncomfortable if prolonged use is required. An advantage in using protective clothing is that the dual-purpose function of the shelter area during non-emergency periods would not be affected. The single most important item of protective clothing is the helmet.

With advanced planning and proper supervision of the personnel, restraining devices (lap belts and shoulder straps, etc.) can provide protection against injuries resulting from impact. Bracing devices (handholds and protective railings) can be used to provide supplementary protection in conjunction with one or more of the other methods.

8-1.4 Design Studies

The design studies included design layouts, illustrations of typical methods used for providing protection from structure motions both for personnel and equipment, and cost estimates of those portions of the structures which affect, or are affected by, the method of shock isolation. The designs were prepared for pressure levels of 25, 100, and

300 p. s. i. (produced by a 20-MT weapon) for populations of 10, 100, and 250 persons; and for various types of structures and foundations. This study included buildings with one or more stories. In all cases, they were assumed to be shallow buried. Three personnel protection levels along with both categories of the equipment design criteria were included in the designs.

The shock environment has been established in accordance with the procedures previously mentioned and has been developed for assumed site conditions. The selection of the site characteristics (layer thicknesses, seismic velocity) was such as to represent a typical site. With the use of assumed site conditions, free-field ground-shock spectra were computed for 10-, 20-, and 30-ft. depths below the ground surface. For determining the response of the interior portions (shock isolation system) of the structures, the free-field ground motions at the 10- ft. and 30-ft. depth have been assumed to be equal to the motions of the low silhouette (one-and two-story shelters) and taller buildings, respectively.

The design concepts included thirty-five schemes, of which nine structures were designed for the 25-p. s. i. overpressure level while sixteen and ten structures were designed for the 100- and 300-p. s. i. pressure levels, respectively. The schemes for the 25-p. s. i. overpressure range were limited to rectangular-type shelters whereas for the higher pressure levels several different structural arrangements, including horizontal and vertical cylinders and arches, were investigated for feasibility of construction. In the latter case. the horizontal cylinder was found to be the most practical configuration both economically and functionally. Personnel protection levels 1, 2, and 3 were considered for all three overpressure levels as were the two design categories for the equipment. All three population capacities (10, 100, 250) were included in the designs of the structures at the 25-p. s. i. overpressure range but only the 100- and 250-person populations were considered for the two higher pressure levels.

In those structures designed for personnel protection level one, both the personnel and the equipment were assumed to be shock isolated on the same platform while in the shelters designed for protection levels two and three, only the equipment was mounted on the isolated platforms. Except for the shelters located at the 25-p.s.i. pressure level, the shock-isolated platforms in the structures designed for personnel protection level one were supported by pendulum-type compression springs while in the former structures and in those shelters where the equipment has been shock isolated by itself, base-mounted support systems were used for the platforms. When protecting personnel, the isolated platforms were designed for a dynamic response to the vertical accelerations of the structure equal to 0.75 g.; and 1.0 g. was used when only the equipment was being protected. The selected response values were equal to or less than the tolerances specified in the design criteria in addition to being the most economical arrangement. The use of a 0.75 g. design value therefore eliminated the need of restraining the personnel.

In the design of those structures for personnel protection levels two and three, protective cushioning material was utilized on the floors, the interior concrete walls and/or exterior walls, the corners of concrete partitions and those portions of the interior furnishings which may form a hazard. Protective cushioning was used on the floors, walls, and corners of those shelters designed for protection level two while for protection level three only the exterior walls and corners are cushioned. Because the impact velocity sustained by the personnel due to the vertical motion of the structure was less than ten ft./sec., the thickness (one inch) of cushioning used in the shelters designed for protection level two was based on the impact velocity sustained by the head due to people falling over. Cushioning with the same thickness was used in shelters designed for protection level three.

In the design of the shell of the structures, the blast load was assumed to be applied to the exterior of the shelter whereas partitions, intermediate floor slabs, and other interior items were designed for the structure response to the ground motions. In the design of the rectangular structures for the 25-p.s.i. overpressure level, both monolithic foundations and individual footings were used depending upon the personnel protection level being considered. For the higher pressure levels where horizontal cylinders were utilized, a thickened (monolithic) section of shell was used for the base slab in the personnel area of the shelters designed for protection levels two and three.

Because all of the volume of the horizontal cylinders at the 100- and 300-p. s. i. overpressure ranges could not be utilized if the usable floor area was on one level, multistory inner structures were investigated to determine their efficiency in comparison to the single-story structure. The use of a two-story isolation system was found to provide the most economical arrangement for the population considered and a protection level equal to one. When a design was performed for a similar structure for protection levels two and three, it was found that for the spans required, the members could not be designed for the high dynamic loads of the ground shock.

Based on the estimate of the costs of the shelters, the relative costs (cost of each structure relative to a non-shock-isolated structure) of the single-story shelters increased with increasing protection. This was found to be primarily the result of the additional material required for the lower protection levels. Unlike the single-story structure, the relative cost of the two-story structure was found to be less than that of the structures for protection levels two or three. It was observed in the cost investigations that the relative cost for a particular pressure level, structural configuration, and protection level was greater for the 100-person shelter than that for the 250-person shelter; while in the case of the 25-p. s. i. rectangular structure, the relative cost for the 10-person shelter was less than those for the 100- and 250-person structures. The increase of the relative cost of the 100-person shelter above that of the 250-person shelter was the result of the more predominant effect than the cost of the shock isolation system has on the total cost in the former shelter in comparison to that of the latter

For the shelter schemes considered in the design studies the increase in cost of the shock-isolated structures varied from 4 to 65 percent of that of the non-shock-isolated structures. The non-shock-isolated structure cost was based on those items which either affect, or are affected by, the shock isolation system, i. e. , shell and earthwork

8-2 Conclusions

8-2.1 General Conclusions

The following conclusions pertain to shallow-buried civil defense shelters at overpressure levels up to 300 p.s.i. and for megaton surface bursts up to 20 MT.

1. Shock-isolation systems can be effectively and economically accomplished for the protection of personnel and equipment against the effects of ground shock.

2. The free-field ground shock environment can be adequately described, for design purposes, in terms of shock spectra.

3. Design shock spectra can be conservatively determined from the free-field spectra. This conservatism, which pertains to the high-frequency range of the spectra, usually will not affect design results.

4. Shock tolerances for personnel, as established in this study, can be designated effectively in terms of either vibration or impact. Equipment shock tolerances are designated effectively in terms of vibration.

5. Shock-isolated platforms are an effective means of providing vibration protection for personnel and equipment.

6. Effective supports for shock-isolated platforms for vertical and horizontal motions can be achieved by utilizing either (1) pendulum spring systems, or (2) base-mounted spring systems.

7. Pendulum systems are usually more effective than base-mounted systems when multistory shock isolation systems are utilized.

8. For structure displacements up to approximately 24 inches, the use of helical springs is generally appropriate in both the pendulum and the base-mounted systems. Volute springs can be used for displacements in the order of 6 inches or less while the upper bound of the displacement for beam

springs is about 3 inches.

9. An optimum dynamic response value between 0.5 and one g. in the vertical direction will generally result in the most economical shock-isolated-platform.

10. Cushioning materials placed on the interior of the shelter are an effective means of providing impact protection for personnel.

11. One inch of cushioning material will usually be sufficient to protect personnel from injuries resulting from impact.

12. Protective clothing and restraining and bracing devices can be used to provide supplementary protection in conjunction with, or as an alternate to, cushioning materials.

8-2.2 Specific Conclusions

In addition to the conclusions in Section 8-2.1, the following conclusions pertain to shallow-buried personnel shelters for the specific shelter populations (10, 100 and 250 persons), overpressure levels (25, 100, and 300 p.s.i. for a 20-MT surface burst), and site conditions (Section 7-4) considered in the design studies.

1. Three personnel protection levels can be utilized which afford varying degrees of protection reliability. On-the-average safety is provided by all three protection levels.

2. For the spans considered, interior structural floor slabs without spring supports cannot be efficiently designed for the dynamic loads associated with the designated shock environment.

3. The optimum value of the dynamic response in the vertical direction for the design of the shock-isolated platforms which support both equipment and personnel, is approximately 0.75 g.

4. The optimum value of the dynamic response in the vertical direction for the design of the shock-isolated platforms which support equipment only, is one g. Therefore, the use of non-shock-tested equipment is practical except when the equipment is attached to the structure shell.

5. The increase in cost of the shock-isolated shelters varies between 4 and 65 percent of the cost of the corresponding non-shock-isolated shelters.

6. The cost per person of the shock-isolated shelters increases with decreasing population sizes.

7. The cost of the two-story horizontal cylinders (personnel protection level one) is less than that of the single-story structures (all protection levels) and the multistory vertical cylinders.

8. In all cases, the increase in cost of the two-story cylinder is equal to or less than 12 percent of the cost of the corresponding non-shock-isolated shelters.

9. The cost of the shock-isolation system varies between 9 and 68 percent of that of the corresponding structure shell.

8-3 Recommendations

Based on the results of this study, the following items are recommended for further study and investigation. These items pertain to tests on personnel subjected to simulated ground shock motions.

1. To substantiate the recommended personnel vibration tolerances, additional vibration testing should be conducted for durations in the order of magnitude of that expected during ground shock up to the durations for which test data is available.

   a. These tests should be conducted for standing, sitting, and reclined personnel and for personnel restrained and non-restrained.

   b. Tests should be performed for combined vertical, horizontal, and rocking vibrations.

2. Testing to obtain additional information concerning the horizontal acceleration required to cause personnel to fall over, considering standing and sitting positions and relative di-

rections of acceleration. The effect of simultaneous vertical accelerations should also be considered. Tests should include estimates of body impact velocities for the various conditions considered.

3. Testing similar to Item 2 for personnel strapped to seats rigidly attached to the floor slab, including study of various types of seats, head supports, and harnesses to provide the most effective protection.

APPENDIX A

REVIEW OF THE STATE OF THE ART

SECTION A-1

INTRODUCTION

Appendix A contains discussions, evaluations, and summaries of publications and data reviewed in order to establish the state of the art in the protective construction field pertinent to this study of shock isolation methods for hardened civil defense shelters. The review was organized in six general categories presented in the following sections:

A-2 Free-Field Ground Motions and Free-Field Ground Shock Spectra.

A-3 Structure Response and Spectra for Structures.

A-4 Shock Tolerances for Personnel.

A-5 Shock Tolerances for Equipment and Other Interior Components.

A-6 Shock Testing Facilities and Current Techniques Used for Shock Testing.

A-7 Current Techniques Used for Shock Isolation Systems.

Available publications obtained through general research, the Defense Documentation Center, and from other agencies in response to our inquiries and requests for information were reviewed. Information was al o obtained at meetings with various organizations.

Under each category a discussion and an evaluation of pertinent information obtained through the review are presented with publications, minutes of meetings, and other sources of information referenced. Following the discussion and evaluation for each category are summaries of pertinent information obtained from the referenced publications. It is emphasized that these summaries contain only those data and that information which are particularly applicable to the present study and should not, therefore, be construed as being representative of integral abstracts of the references involved. A list of these references is presented at the end of this appendix. Minutes of meetings held with other organizations are presented in Appendix B.

SECTION A-2

FREE-FIELD GROUND MOTIONS AND FREE-FIELD GROUND SHOCK SPECTRA

A-2.1 Discussion and Evaluation

For the development of free-field ground shock spectra a review of various publications was unnecessary since Reference A.1 was specified as the reference source for determining free-field spectra. The procedure presented in Reference A.1 is considered the most current available for predicting free-field ground motions and spectra (Sections B-3 and B-6). Free-field ground shock spectra are described in Chapter II.

However, since the computed spectra relates only directly to peak free-field ground motions and peak responses of simple elastic systems to the spectra motions, it is necessary to consider also the nature of the time-history characteristics associated with the ground motion. These characteristics are useful in obtaining a better evaluation and understanding of the effects of ground shock on personnel and equipment not attached to the structure or not completely elastic.

Field measurements of ground shock have been recorded during nuclear weapon tests. However, this data can be used only as a guide when estimating ground motions inasmuch as the scope of the test data was limited to particular weapon sizes and overpressure ranges, and to site conditions which are not necessarily typical. In some cases inconsistencies were apparent, thereby arousing uncertainties concerning the reliability of the data. In addition, proper scaling relationships for sites and blast environments different from the test conditions are also uncertain. Nevertheless, for the purpose of investigating the time-history characteristics associated with ground shock motions, past test data are useful. Figures A-1 to A-3 show typical free-field vertical acceleration, velocity, and displacement versus time records for various depths below the ground surface as recorded at the Nevada Test Site for a 40-KT. weapon yield at 229 p.s.i. peak overpressure (Reference A.2). These data were recorded at a ground range where the air-blast wave arrived

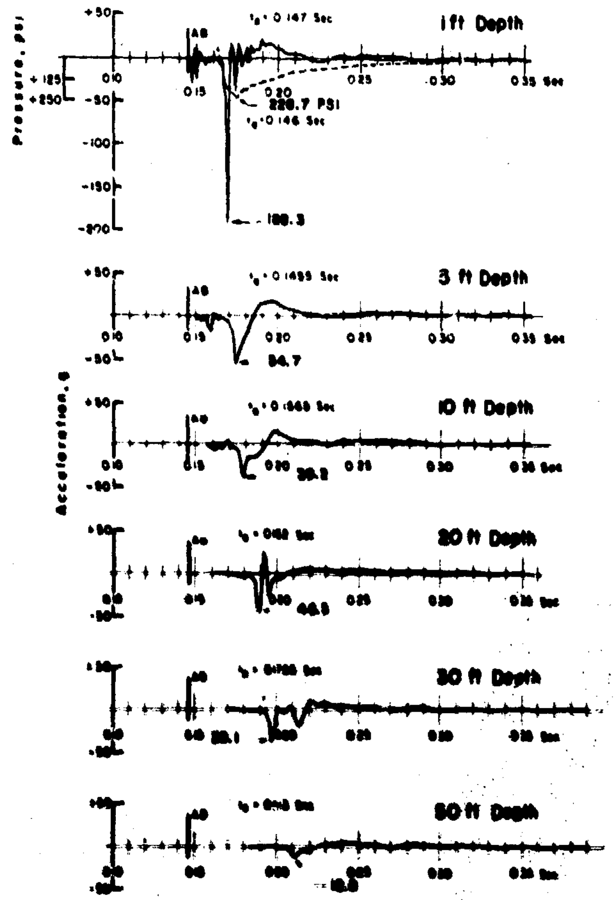


Fig. A-1 VERTICAL GROUND ACCELERATION vs. TIME
W = 40 KT, p = 229 psi

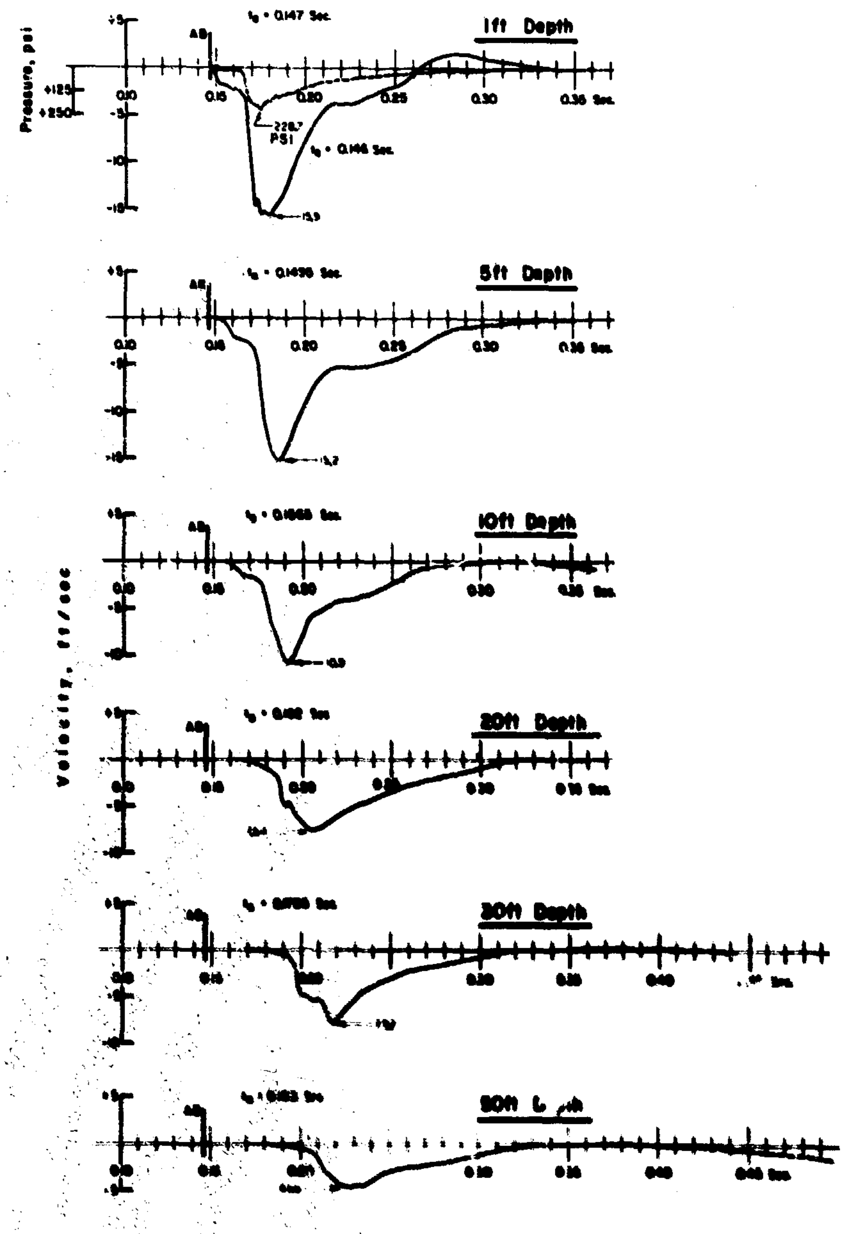


Fig. A-2 VERTICAL GROUND VELOCITY vs. TIME
W = 40 KT, p = 229 psi

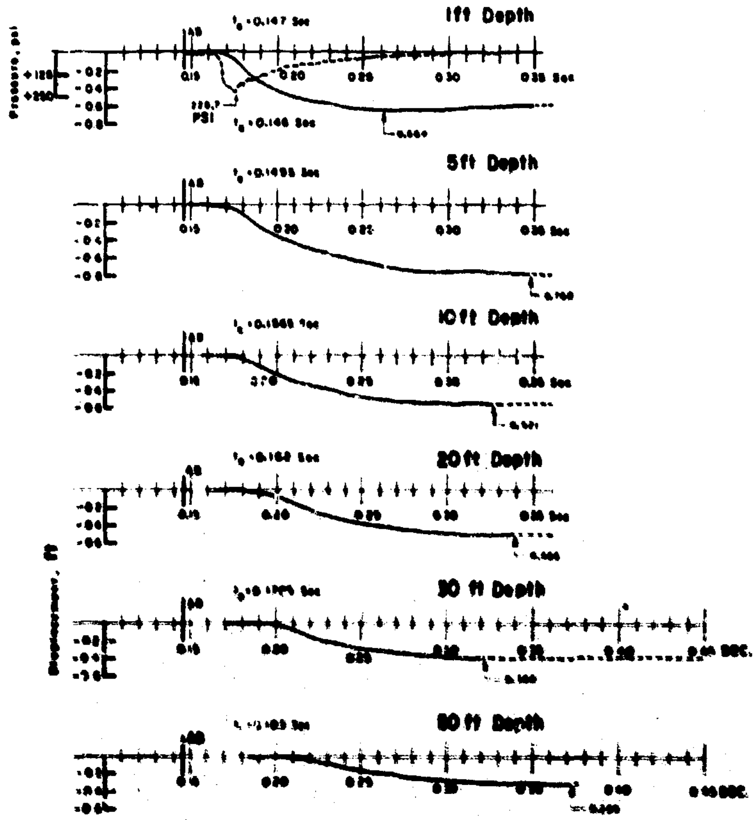


Fig. A-3 VERTICAL GROUND DISPLACEMENT vs. TIME
W = 40 KT, p = 229 psi

prior to the ground wave, at the various depths. The acceleration data were recorded in the field, whereas the velocity and displacement curves were obtained by integration of the acceleration curves.

It is seen in Figure A-1 that the acceleration-time curves are characterized by a single, sharp, downward peak (pulse duration of approximately 10 msec.) preceded and followed by lower amplitude disturbances which become less pronounced with depth because of modification of the wave during its travel through the earth. The surface air-blast arrival time is designated by the vertical line labeled AB, and the arrival time of the motion is indicated. In this case, the early minor disturbances correspond to the precursor, and the peak acceleration is produced by the larger main peak of the air blast. The time of onset of motion at the surface is the same as the blast arrival time, and the delay time with respect to AB at various depths is the time required for the pressure wave to travel from the surface. The accelerations following the peak pulse are associated with the pressure decay, elastic rebound of the soil, and the arrival of ground waves from sources closer to ground zero. As shown in Figure A-1, a rapid attenuation of the peak surface acceleration and decrease of frequency with depth occurred both of which are typical of free-field accelerations in both the vertical and horizontal directions.

For the higher weapon yield (20 MT.) considered in this study, the general characteristics of the acceleration curve would be similar to the records plotted in Figure A-1 except that the sharp peak would be followed by disturbances of longer duration due to the longer positive phase duration of the air blast.

The peak value of the expected ground acceleration corresponds to the peak high frequency acceleration response of the free-field ground shock spectra. The occurrence of early disturbances depends on whether a precursor forms and whether the blast wave velocity is superseismic or subseismic. At the 100-p.s.i. ground range, the blast wave velocity would be superseismic for a typical soil site, and the air-blast wave would arrive prior to any ground waves at the shallow depths being considered. At the 100-p.s.i. ground range, the blast wave velocity would vary from superseismic to transeismic, depending on the particular soil site, with the air-blast wave arriving prior to the ground wave or perhaps at about the same time. At the 25-p.s.i. ground range, the blast wave velocity would be subseismic for a typical soil site, and the ground waves will arrive prior to the air-blast wave. The early-arriving ground wave motions may cause an initial upward acceleration; however, it is expected that these early disturbances will be of minor magnitude compared to the amplitudes associated with the main air-blast shock.

For lower overpressures, the upward peak acceleration following the sharp downward peak tends to increase with respect to the downward peak (Reference A.2) so that at the 100-p.s.i. ground range the ratio of peak downward to upward acceleration would be lower than that at 300 p.s.i. and lower still at 25 p.s.i. In fact, at 25 p.s.i. it may be expected that the upward peak would be equal to the downward peak. The accelerations occurring prior to, and following, the sharp downward peak and first upward peak depend on the ground wave contribution at the particular site and on the precursor effects. These can combine to cause a random-type motion of various frequencies. The wave form preceding and following the pronounced peak is a random motion consisting of many relatively high frequencies tending to decay as the air-blast wave decays. The ground wave contributions from points closer to ground zero tend to extend the duration of the disturbance since they may arrive after the duration of the positive phase duration of the air blast (Reference A.2). A better understanding of this ground motion over its entire duration can be obtained from study of the ground velocity and displacement wave forms.

Velocity-time curves, obtained from a numerical integration of the acceleration-time curves, are plotted in Figure A-2. The shapes of the velocity curves are similar to that of the air pressure. The rebound of the velocity results in a peak upward velocity which is expected to be much smaller than the downward velocity (Reference A.2), although the rebound portion of the plotted curves is not complete or reliable. As may be anticipated, attenuation of the velocity with depth is considerably less than that of acceleration since the duration of the acceleration pulse increases with depth.

Displacement-time curves, obtained from a double integration of the acceleration records, are plotted in Figure A-3. It is seen that the wave forms exhibit a gradual time of rise to the peak value which occurs approximately at the end of the positive phase of the air pressure; however, for other site conditions the peak displacement value may occur at an earlier time. Actually, a near-peak value occurs considerably before the end of the positive phase inasmuch as most of the impulse is expended in the early portion of the air-blast wave because of the rapid decay. These displacement curves obtained by integration of the acceleration records are not reliable beyond the peak displacement value. Other data of direct displacement measurements (References A.3, A.4) indicate that after the peak downward displacement, the displacement rebounds because of elastic action and quickly damps out, resulting in a residual permanent displacement due to plastic action. The peak value of the anticipated ground displacement corresponds to the peak low-frequency displacement response of the free-field ground shock spectra.

It is seen that the displacement and velocity ground motions are characterized by a predominant single downward pulse followed by an upward pulse of lesser amplitude and then by a quick damping out of the motion. In the case of the displacement, the rebound may recover only a portion of the peak downward motion and not result in any net upward value. The duration of the downward velocity pulse is in the order of the positive phase duration, and the duration of the corresponding downward displacement pulse would be in the order of twice the positive phase duration. As previously shown, the acceleration wave form is characterized by a single, sharp downward peak followed by an upward peak and then by a high-frequency random-type acceleration of lower amplitude. The sharp downward acceleration pulse results in the peak ground velocity, and the subsequent accelerations correspond to the decay and rebound of the velocity pulse which, of course, signifies that the net area under the acceleration-time curve, following the downward pulse, is in the upward direction. The acceleration curves indicate that these upward values of acceleration which would be associated with the rebound are very small compared to the downward peak amplitude, although data at the later times may not be as reliable.

Generally, the horizontal free-field ground motions have characteristics similar to those of the vertical motions in which case the initial peak pulse is outward from ground zero and is followed by a rebound in the opposite direction.

A-2.2 Summaries of Information Obtained from References

a. Summary of Reference A. 1

This guide has been used as the approved reference source in the development of free-field ground shock spectra for this study. The guide presents equations for determining peak free-field ground motions. These peak motions are used to develop the corresponding free-field ground shock spectra as described in the guide. In this procedure, only the peak ground motions are evaluated without consideration of the time-history of the motion. Appendix C presents a summary of the equations for calculating free-field ground motions.

b. Summary of Reference A. 2

This report presents results of test measurements of ground accelerations, stress, and strain recorded during Shot Priscilla (approximately 40 KT.) of Operation Plumbbob at the Nevada Test Site. Measurements were recorded at peak overpressures ranging from 59 to 554 p.s.i. Ground acceleration versus time motions were recorded at the surface and at various depths below the surface down to 50 feet. Velocity versus time, and displacement versus time ground motions were determined by integration of the measured acceleration-time curves.

The soil at the test site is alluvial. Stratified and fissured silty-clay and clayey-silt exist at least down to 50 feet, and probably down to 200 feet. Below 200 feet lies the original lake bed and the soil becomes a sand-gravel aggregate. Bedrock exists below the 650-ft. depth. The following seismic velocities were recorded.

Depth (ft)	Velocity (ft/sec)
0 to 10	1,200
10 to 175	2,600
175 to 650	3,600
Below 650	10,000

c. Summary of Reference A.3

This report presents results of test measurements of ground accelerations and displacements recorded during Shot Priscilla (approximately 40 KT.) of Operation Plumbbob at the Nevada Test Site. These measurements were recorded during the same test and at the same site as Project 1.4 (See Reference A.2). Measurements were recorded at peak overpressures ranging from 59 to 270 p.s.i. Ground acceleration versus time, and displacement versus time motions were recorded at the surface and various depths down to 100 feet. Velocity versus time, and displacement versus time were also determined by integration of the measured acceleration-time curves.

Soil conditions are the same as those given in the summary of Reference A.2.

d. Summary of Reference A.4

This report analyses results of test measurements of ground accelerations and displacements recorded during several shots of the Operation Hardtack series at the Eniwetok Proving Ground. These tests were conducted to extend the knowledge of ground motion to different yields, higher overpressure regions, and to different soil types.

SECTION A-3

STRUCTURE RESPONSE AND SPECTRA FOR STRUCTURES

A-3.1 Discussion and Evaluation

a. General

Underground structures experience motions which are a function of the free-field motions of the surrounding soil, the blast pressures applied directly to the structure, and the interaction between the soil and the structure. It is important to note that free-field ground motions and free-field ground shock spectra are computed on the assumption that there is no structure or other large discontinuity of mass and stiffness present within the soil in the area of interest. The motion of a structure placed in the soil, compared to the free-field ground motions, would depend on the dimensions and mass of the structure. Generally, a small light structure would tend to move with the surrounding soil in accordance with free-field motions, whereas the motions of a larger structure would not be the same as the free-field motions.

Theoretically, in order to determine the motions of an underground structure, it is necessary to evaluate the interaction of the structure and surrounding soil during the transient ground shock motions. The phenomena associated with these interaction effects are extremely complex and difficult to analyze, and it is necessary that simplified conditions be assumed to obtain even an approximate solution. In addition, the many problems encountered in the analysis of structures subjected to ground shock are further complicated by the uncertainties associated with the prediction of free-field ground motions and corresponding shock spectra.

In view of the uncertainties involved and by reason of the fact that this study considers typical site conditions and general structure configurations rather than a specific installation, a complicated solution evaluating the structure interaction is not justified. However, appropriate spectra for the structures considered will be established on the basis of current concepts representing the available knowledge in this field. The most convenient criteria would be postulated in terms of a modification of the free-field ground shock spectra in order to establish spectra for the structures placed in the free-field environment.

It is generally felt that spectra measured within a structure would have lower values at certain frequencies than the free-field shock spectra. Reference A.5 mentions that the design (structure) spectra would be less than the input (free-field) due to damping. However, reduction of the free-field spectra to determine the structure spectra does not necessarily mean reduction at all frequencies. Except for an extremely long structure parallel to the direction of the blast wave, the latter will completely engulf the structure and surrounding soil. The loading, lasting several seconds, would cause the structure to experience a peak displacement of the same order of magnitude as the peak free-field displacement. This means that the low-frequency portion of the structure spectra would be similar to that of the free-field spectra. However, it is reasonable to expect that the peak gross acceleration of the structure would be less than the peak ground acceleration because of the longer rise time of the loading on the structure. The reduction in the peak structure acceleration corresponds to lower responses in the higher frequency range of the structure spectra compared to that of the free-field spectra. This pertains to the gross motion of the structure when the structure is considered as a rigid body. Depending on the flexibility of an actual structure, peak accelerations of the roof slab may be higher than the rigid-body acceleration if the roof is near the ground surface. In addition, it may be possible to transmit high-frequency ground accelerations directly through the structure roof or walls although these accelerations would also be reduced because of the structure flexibility and structure damping. This high-frequency motion would only affect systems rigidly attached to the structure and which do not have a large mass compared to the structure shell.

Reference A.1 states that an underground structure may be considered to move with the ground in accordance with the free-field motions at or near its base and that, in general, the structure is rigid enough so that all its parts have the same motions. However, it is also stated that the response of a piece of equipment depends on the part of the structure to which it is attached. This latter statement corresponds to the case where the structure flexibility need be considered. Although the recommendations of Reference A. 1 do not involve a direct attenuation or modification of the free-field motions, use of the free field at the base of the structure corresponds to a reduction in the high-frequency range of the spectra compared to using a more shallow depth, such as the top or mid-height of the structure. The peak ground acceleration which determines the high-frequency range of the spectra attenuates rapidly with depth, whereas the peak ground displacement and velocity would not significantly change for small differences in depth; hence, the low-frequency portion of the spectra would not vary from the top or mid-point to the base of the structure depth. However, the attenuation with depth depends on the soil variation with depth where a sharp change in soil properties could effect a sharper attenuation of the peak motions.

Shock spectra measurements were recorded during nuclear tests in the free field and inside a shallow-buried shelter (Reference A. 6). Pertinent measurements are listed in the Summary of Reference A. 6 (Section A-3. 2c) for the shelter and adjacent free field at 116 p. s. i. for a 40-KT. weapon yield. Although the weapon yield is in the low kiloton range, comparison of free-field and structure shock spectra measurements can serve as a basis for judgment for other protection levels. Horizontal spectra responses in the shelter were approximately of the same order of magnitude as the free-field horizontal values at the corresponding frequencies. The vertical responses in the shelter were considerably less than the free-field values at corresponding frequencies. The free-field vertical values were 1. 6 to 7 times the vertical shelter responses with the higher ratios in the frequency range from 40-180 cps. This indicates greater attenuation in the higher frequencies since, as previously discussed, high accelerations tend to be attenuated by the structure. For frequencies above 200 c. p. s., attenuations were not as great as in the 40-180 c. p. s. range which may be due to special structure characteristics; perhaps the higher frequency motions were transmitted directly through the concrete shell. In any case, there is considerable attenuation in the high-frequency range. The attenuation in the higher frequency range is partially due to the lower depth of the structure gauges. The ratio of vertical to horizontal free-field responses varied from 1.3 to 5 with an average of about 2.9. Thus, since vertical and horizontal peak accelerations are taken as being equal when predicting free-field shock spectra, a reduction of horizontal as well as vertical surface values would be warranted on the basis of the recorded data.

b. Conclusions

Based on review of the data discussed above and summarized in Section A-3.2, the following recommendations are to be used as a basis for establishing design shock spectra for this study: the design spectra for short (less than 30 feet), shallow-buried structures shall be the same as the free-field spectra at depth approximately equal to the mid-height of the structure.

For establishing design spectra for tall, shallow-buried structures, it is advisable that the free-field spectra at a depth above the mid-height of the structure be used to properly account for soil-structure interaction effects associated with a tall structure.

A-3.2 Summaries of Information Obtained from References

a. Summary of Reference A.1

This guide states that in a typical case (P. 5-27) an underground structure may be considered to move with the ground in accordance with the free-field motions at or near the base of the structure and that, in general, the structure is rigid enough so that all parts of the structure have the same motions. However, it is further stated that the response of a piece of equipment depends on the part of the structure to which it is attached. This is probably a more rigorous approach where the structure cannot be assumed rigid.

This guide includes comments on design to resist ground shock motions as summarized below (Page 5C-8):

"Whether the structure be a shallow box, arch, or a deep underground structure, the input motions and the response spectra corresponding thereto, for the free-field motions, are used in the same way, and no distinction is made here between these structures".

"The primary consideration given here is to the type of interior structure which consists of a two-to-four-story building frame supported independently of the roof covering, so that the base motion to which the frame is subjected corresponds in many respects to earthquake base motions. However, many of the comments regarding design of equipment are pertinent to the situation where equipment is mounted directly on a box structure without an independent interior frame."

Additional comments are given regarding equipment mounted in the structure either directly on the bottom floor or on an interior structural element. Where mounted on the floor the input base motion is used. For the second case the input would be modified. Since this modification is rather complicated, tentative recommendations are given for use until further data are available (P. 5C-16). These comments pertain to the response of the interior structure and equipment assuming the base input is known which, in effect, does not consider the structure-soil interaction.

It is further stated in this guide that "the shock motion of the foundation of the building is assumed to be known, corresponding to some relatively simple motion (possibly a single sine curve of displacement) on which is superimposed a random pattern of relatively higher acceleration pulses with only a small amplitude of motion. The net effects of the ground motion are most readily described in terms of a response spectrum".

Based on the recommendations in this guide, the structure motion would correspond to the free-field spectra at the base of the structure and, in general, the structure could be taken as a rigid body. This spectra would be applied directly to systems attached directly to the structure. Where an interior structure is used, the input at the base may be modified for the interior structure to determine the input to the equipment mounted on the interior structural elements.

b. Summary of Reference A. 5

This report, which presents basic equations (similar to Reference A. 1) for determining free-field spectra, contains no directly applicable data pertaining to the modification of the free-field spectra to determine the spectra for the structure except that it is stated that the design spectra would be less than the input spectra due to damping (Page 7-4).

c. Summary of Reference A. 6

Shock spectra measurements were recorded during Shot Smoky of Operation Plumbbob in the free field and inside an adjacent shelter at 116 p. s. i. and approximately 40-KT. weapon size. The peak displacement responses versus frequency are listed below for comparison of the structure and free-field response spectra. The free-field gauges were placed one ft. below the ground, and the structure gauges were placed on the floor slab which was located at the 12-ft. depth.

Vertical Direction

Inside Structure		Free Field			
Gauge 6		Gauge 7		Gauge 8	
f(c. p. s.)	D(in.)	f(c. p. s.)	D(in.)	f(c. p. s.)	D(in.)
2. 54	1. 62	2. 60	5. 45	2. 53	4. 53
8. 72	0. 906	8. 56	1. 52	8. 82	1. 46
21. 9	0. 336	22. 4	0. 845	22. 6	0. 525
37. 0	0. 0744	37. 4	0. 254	37. 1	0. 205
92. 0	0. 0167	91. 0	0. 132	93. 0	0. 103
138	0. 0099	132	0. 0673	137	[illegible]
185	0. 0034	187	0. 0221	180	0. 0199
246	0. 0051	238	0. 0106	236	0. 0122
280	0. 0039	280	0. 0112	294	0. 0055
363	0. 0038	335	0. 0066	[illegible]	0. 0066

Horizontal Direction

Inside Structure Gauge 5 f(c. p. s.)	Inside Structure Gauge 5 D(in.)	Free Field Gauge 9 f(c. p. s.)	Free Field Gauge 9 D(in.)
2.72	2.25	2.55	1.95
9.37	0.453	9.12	0.359
22.3	0.113	22.4	0.189
36.9	0.0451	33.9	0.131
95.0	0.0185	93.0	0.0227
138	0.0101	107	0.0149
184	0.0099	181	0.0107
234	0.0041	203	0.0042
285	0.0022	293	0.0055
296	0.0031	357	0.0027

It is seen by the above values that the horizontal responses in the shelter are approximately of the same order of magnitude as the free-field horizontal values at the corresponding frequencies. This indicates that the structure, or at least the floor slab, tends to move with the soil in the horizontal direction. Since the floor slab is extremely rigid in its plane, there is apparently little isolation of the induced motions through the slab. However, the vertical responses in the shelter were considerably less than the free-field values at corresponding frequencies. The free-field vertical values were 1.6 to 7 times the vertical shelter responses with the higher ratios in the middle frequency range (40 -180 c. p. s.). This indicates greater attenuation in the higher frequencies probably because the structure does not experience the same accelerations due to the structure flexibility in the vertical directions and the effect of the buildup of the blast loading. In addition, there is an attenuation due to the lower depth of the structure gauges. It should be noted that the measurements indicate lower attenuations for frequencies above 200 c. p. s. which may be a result of special structure characteristics; perhaps the structure transmits the high frequency ground motion directly through the concrete shell.

The ratio of vertical to horizontal free-field responses varies from 1.3 to 5 with an average of about 2.9.

The increased attenuation for structure gauges of the vertical responses in the middle frequency range was also observed during Operation Hardtack (Project 1.12). However, attenuations also occured in the horizontal direction with increasing attenuation as the frequency increased.

SECTION A-4

SHOCK TOLERANCES FOR PERSONNEL

A-4.1 Discussion and Evaluation

a. General

Available literature on shock and vibration tolerances for biological systems is reviewed and discussed relevant to the effects of ground shock on personnel in underground structures, and conclusions are drawn which serve as a basis for the design of shock isolation schemes.

For personnel housed in a nuclear protective structure, the principal biological effects of ground shock encompass pain or injuries that might occur as a consequence of the motions of an underground shelter. Proper assessment of this hazard requires knowledge in at least two areas; namely, (a) information concerning the motions of the structure as a function of the site, weapon size, and overpressure level, and (b) man's tolerance to the environment as a function of the motions since these motions determine the nature of the "loading" to which he may be subjected.

The structure motions, which are a function of the "free-field" motions, are transient in nature and are characterized by (1) a low-frequency downward displacement which reaches a maximum value generally near the end of the positive phase of the air-blast wave which then rebounds and damps out quickly, and (2) a high frequency random acceleration which reaches a peak value in the extreme early stages of the motion. In some cases, the initial motion may be upward but of less magnitude than the following downward movements. In addition, there is horizontal motion of the structure of similar character.

Although exact magnitudes of the shock pulses corresponding to the structure motions are not necessary for estimating shock and vibration tolerances for personnel housed within the structure, the nature of the motions and their duration are considered pertinent since tolerance has meaning only in terms of a particular type of environment or exposure.

Because the motions in a ground shock environment are transient in nature and could possibly result in imparting an abrupt velocity change to the body, either in stopping or starting, in addition to a shaking or vibrating of the body, it is necessary that human tolerance to two types of shock exposures be considered; namely, (1) impacts involving velocity shocks causing body acceleration or deceleration and (2) transient body vibrations. Tolerances for these types of exposures and their meaning relevant to the ground shock environment form the basic consideration investigated with regard to personnel.

In a structure subject to ground shock, a person may experience various types of motions depending upon his location and posture within the structure and upon th flexibility of the supporting system. The latter depends on the degree of isolation of the seat and/or floor which supports him, and on whether or not he is attached to his seat by straps or seat belts.

If the floor is not shock isolated, its motions are approximately the same as those of the structure as in the case of a floor slab which is monolithic with the structure shell. Therefore, a subject not attached to the floor is vulnerable to impacts similar to those experienced in free falls (due to the structure dropping from beneath him) and/or similar to those experienced in shipboard explosions (due to the structure rebounding upward beneath him). These impacts result from a collision with the floor. Impacts may also result as a consequence of the subject being thrown off balance due to the initial horizontal acceleration of the structure or to the rebounding or upward motions of the structure resulting in his being thrown bodily against furniture, walls, or other hard surfaces. Impacts in this category also bear a resemblance to those experienced in falls and in shipboard explosions.

If a subject is attached to a structure, he is vulnerable to acceleration forces similar to those experienced in military aircraft and, in addition, he is liable to injury by reason of the shaking or vibrations of the structure.

In any particular case, the seriousness of injury depends upon the frequency, duration, and magnitude of the accelerations directly imposed on the total organism and its several parts and on the impact intensity experienced when collision with hard surfaces is involved. In addition, the extent of possible pain or injury depends upon the posture of the personnel (i.e., whether they are sitting, standing, or reclining) and their position with respect to nearby hard surfaces. In order to reduce or prevent harmful effects, protective measures, such as shock isolation, cushioning or separation of hard surfaces, proper strapping down, etc., can be provided.

The floor system may be shock isolated by either being mounted on springs or being hung from the ceiling. In this case, the motions of the floor differ from the structure motion. Peak structure accelerations will be reduced and the floor response will be a vibration in accordance with the frequency of the system superimposed on the structure displacement. Although the support motion is modified, separation from non-attached personnel may still result depending on the degree of shock isolation. If isolation limits the peak acceleration response to less than one g, separation will be prevented. Personnel attached to a shock-isolated support, such as by seat belts or other strapping, will experience the vibratory response of the support rather than the impact due to collision. A subject may also be isolated by individual isolation of his support, such as a spring-mounted chair or a cot. In this case, he will be subjected to the vibratory response of the individual support. Impact would be minimized by such an individual shock mounting.

The motions of a structure in a ground-shock environment may have several possible effects on personnel housed within such a structure. The motion may interfere directly with physical activity and/or it may result in discomfort, pain, trauma, or mortality. Other effects associated with long-duration vibrations, such as irritation, fatigue, and thermal and chemical effects, are not likely due to the transient nature of the motions.

Generally, there are three simple criteria for subjective responses to shock and vibration: the thresholds of perception, of unpleasantness, and of tolerance. However, only approximate limits to these thresholds under given exposure conditions can be given since the exact physical mode of action of any exposure varies with respect to physical, physiological, and psychological reactions rendering such limits statistical in nature. With this in mind, researchers have established threshold tolerances for man under various shock and vibration exposures at which physical tissue damage or trauma is not likely to occur. Furthermore, some have established thresholds of perception and unpleasantness for various vibration exposures.

Although most of the available data are not directly applicable to the exposures expected in a ground-shock environment, those which are felt pertinent for establishing shock tolerances are summarized and discussed in the following sections covering vibration tolerances, impact tolerances, and conclusions.

b. Vibration Tolerance

As pointed out earlier, personnel housed in a protective underground structure and subjected to ground shock may be isolated on some type of suspension system such that the maximum accelerations of the gross-structure motions are not experienced. For an adequate design, the motions of the system must be within vibration tolerance limits that the personnel can withstand consistent with operational requirements or prevention of injury.

If the system is relatively stiff, resulting in initial downward motions in excess of one g, and the personnel are not attached to the system, then the tolerance to vibrational motion in this "g" range is not important since separation will occur and injury is likely to result from impact. On the other hand, if the personnel are attached, the separation is prevented and tolerance to vibrational motions is of primary concern, particularly for isolated systems.

Although a system may be isolated to within one g., such that no separation ensues for non-attached personnel, vibration tolerance levels to these low-frequency motions may nonetheless be important, especially since it has been reported

(Reference A. 7) that such levels are considerably reduced in the low frequency range due to resonance with the body's natural periods.

Previous studies (Reference A. 7) have been designed to determine whole-body response and tolerance to sinusoidal vibrations in the frequency range from 1 to 70 c.p.s. In these studies, subjects were (non-attached) in a standing, sitting, or lying position on a horizontally or vertically vibrating platform, and at various selected frequencies and amplitudes subjective responses from the threshold of perception to pain were recorded. Exposure times ranged from 5 to 20 minutes. The latter threshold was considered as a tolerance limit and the motions were discontinued beyond this level. Some of the criteria for the subjective responses were: just perceptible, definitely perceptible, noticeable, unpleasant, annoying, painful, and unbearable. It is obvious that these terms are wide open for subjective interpretation and are only used to provide a general classification of the perceived sensations.

In analysing the results of several investigations in terms of willingness of a subject to tolerate various levels of vibration exposure, Reference A.7 shows that the variability among different studies is very great; the results were averaged and simplified as plotted in Curve a of Figure A-4. In this figure subjective reactions indicating tolerance are plotted as a function of frequency and acceleration.

In considering this data relevant to the ground shock problem it should be pointed out that Curve a is a summary of tolerances for relatively long exposure times (on the order of 5-20 minutes) probably rendering the values of tolerance unnecessarily conservative for the transient exposures of a ground shock. According to Curve a, the lower level of tolerance for these relatively long exposures is about 0.25 g. Reference A.7 points out that larger accelerations can be tolerated for transient exposures but does not indicate any precise limit.

From Curve a it is also seen that the average tolerable limit is about 0.3g in the low frequency range, then gradually increases after 30 c.p.s. reaching one g. at about 80 c.p.s. and sharply increasing after 100 c.p.s.

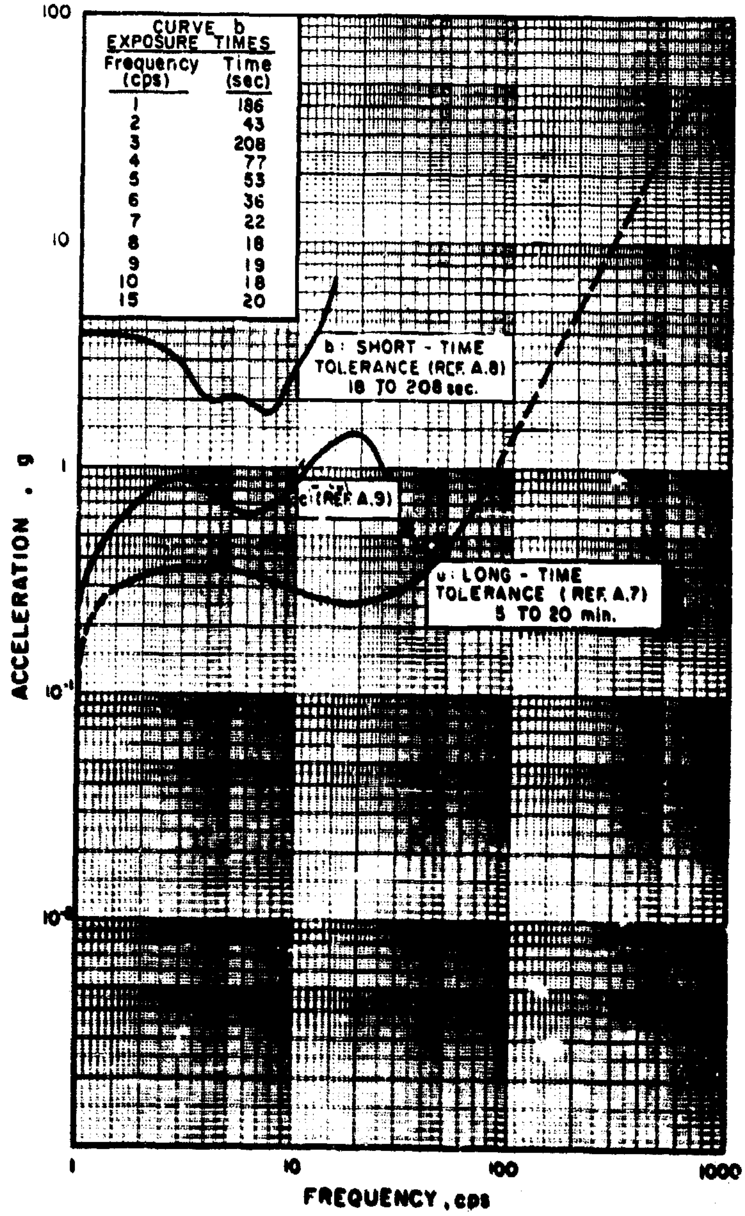


Fig. A-4 VIBRATION TOLERANCE LEVELS

A source of information on shorter time-vibration tolerance for supported (attached) subjects resulted from the experimental work reported in Reference A.8. In these tests each of 10 male subjects was supported in a seat with a standard seat belt and shoulder harness and was exposed to an increasing sinusoidal acceleration at selected frequencies in the range from 1 to 15 c.p.s. At each frequency the amplitude was increased to the point where the subject immediately stopped the run because he thought that further increase might cause bodily harm. This amplitude was considered as a tolerance limit. Exposure times ranged from 18 to 208 seconds.

The average results of these tests are presented in Curve b of Figure A-4 which shows the tolerance for each frequency.

It is to be noted from the curve that the lower level of tolerance is between 1 and 2g. at 3-4 c.p.s. and 7-8 c.p.s., and the higher level is 7-8g. at 15 c.p.s. These levels are considerably higher than the results of other tests (Reference A.9) for similar test support conditions but for somewhat longer exposures. Tolerance levels obtained in the tests of Reference A.9 are shown on Curve c of Figure A-4. In these tests 16 male subjects were supported in a chair and subjected to a vertical sinusoidal vibration at frequencies from 1 to 27 c.p.s. At each frequency the acceleration amplitude was gradually increased and various response levels recorded until a tolerance level (alarming level) was reached. This tolerance level is plotted as Curve c. Relatively high acceleration sensitivity was indicated at 1, 4 to 10, and above 20 c.p.s. The lowest level of 0.25g. occured at one c.p.s. It then increased to 0.8g. at 2-3 c.p.s., decreased to 0.65g. at 4-8 c.p.s., and then gradually increased to the maximum tolerance of 1.4g. at 17-20 c.p.s. The tolerance then dropped abruptly to one g. in the range of 24 to 27 c.p.s.

A comparison of Curves a, b, and c of Figure A-4 indicates that a higher acceleration at corresponding frequencies can be tolerated for shorter exposure times, although variations in this data are no doubt partially due to differences in the testing procedure, type of body support, posture, subjective responses, definition of tolerances, etc. Curve a, which averaged vibration tolerance for various body positions and exposure times from 5 to 20 minutes, resulted in the lowest acceleration tolerance for corresponding frequencies. Curve c, for personnel seated and attached and subjected to gradually increasing accelerations of shorter exposure times, indicates higher tolerances. Curve b, which represents a similar test of exposure times ranging from 18 to 208 seconds with most exposures less than one minute, resulted in higher acceleration than Curve c. For even shorter exposure times in the order of a few seconds or less which would be associated with the ground shock, corresponding tolerances may very well increase beyond Curve b in the same manner as Curve b increased above Curve a. However, this type of extrapolation is not certain. Reference A.18 points out that the acceleration forces experienced by personnel in shelters are of relatively short durations compared with available information on human tolerances and that these tolerances are probably conservative for ground shock effects on personnel.

Although these tolerance values may be conservative for personnel subjected to ground shock, the relative tolerances for various frequencies probably have some general application for shorter exposure times. It is seen that the body is evidently more sensitive to vibration at particular frequencies, suggesting body-organ and appendage resonance. From the low frequency range of Curve a (Reference A.7) sensitivity is indicated below 2 c.p.s. and beyond 8 c.p.s. Above 30 c.p.s , tolerance increases sharply, probably since most of the body does not respond to the high-frequency motion. However, the data of Curve a is not too detailed for small-frequency variations, and the main observation is that tolerance increases sharply in the high-frequency range beyond 80 c.p.s. Reference A.7 also describes results of mechanical impedance test measurements made to determine critical body frequencies. It was found, for vertical vibrations, that below approximately 2 c.p.s. the body acts as a unit mass. Resonance peaks were found between . and 6 c.p.s. for the sitting man and between 5 and 12 c.p.s. for the standing man. Above approximately 10 c.p.s. it was found that vibration amplitudes of the body are smaller than the amplitudes of the exciting table and decrease continually with increasing frequency. Further studies from Reference A.7 on both the sitting and standing subject indicate that, between 20 and 30 c.p.s., the head exhibits a resonance. Eyeball resonance has been observed in the frequency range between 60 and 90 c.p.s. For transverse vibrations it has been indicated that resonant frequencies occurred between 1 and 3 c.p.s. and that the response decreases with increasing frequency (Reference A.7).

It is seen from Curve b (Reference A.8) that acceleration sensitivity occurred between 3 and 8 c.p.s. and that tolerance increased sharply below 3 c.p.s. and above 10 c.p.s. This is generally consistent with the mechanical impedance measurements of Reference A.7, although the data of Curve a (Reference A.7) did not indicate this variation. However, as previously indicated, the low-frequency range of Curve a appears to be somewhat smoothed out. Curve c (Reference A.9) also indicated sensitivity between 4 and 10 c.p.s. followed by an increase in tolerance up to 20 c.p.s. However, a sensitivity was noted beyond 20 c.p.s. This latter sensitivity (beyond the frequency range of Curve b) is somewhat consistent with Curve a and with the impedance measurements. From Curve c it is noted that a sensitivity also occurred at one c.p.s. which is consistent with Curve a but not with Curve b.

It appears that critical frequencies may exist at all frequencies below 10 c.p.s. depending on the direction of the vibration and the body posture. Above 10 c.p.s. tolerance tends to increase and falls off between 20 to 30 c.p.s. beyond which there is a gradual increase although some sensitivity may occur at particular ranges. After 80 c.p.s. there is a sharp increase in tolerance.

Conclusions for vibration tolerances applicable to the ground shock environment are indicated at the end of the discussion under the "Conclusions" (par. e, below).

c. Impact Tolerance

Effects on personnel subjected to a vibratory-or oscillating-type motion were discussed in the last section under Vibration Tolerances. In contrast to vibratory motion, impact effects involve a sudden single-pulse-type shock or motion, such as caused by explosions, explosive compression or decompression, and impacts and blows from rapid changes in body velocity or from moving objects. Possible damage (Reference A.7) includes bone fracture, lung damage, injury to the inner wall of the intestine, brain damage, cardiac damage, ear damage, tearing or crushing of soft tissues, etc. Differences in injury patterns arise from differences in rates of loading, peak force, duration, localization of forces, etc.

In the case of personnel subjected to ground shock motions, impacts would result from structure motions relative to personnel and from personnel colliding with adjacent objects or portions of the structure. For example, the structure motions will be characterized by a sharp downward motion causing the floor slab to drop from under unattached personnel. Personnel will then fall because of gravity and will experience impact with the floor slab. If the structure motion is upward, further impact between the floor slab and personnel will occur, and personnel may be thrown upward and also laterally due to horizontal structure motions, thereby resulting in a subsequent collision with the structure wall or floor or with adjacent objects such as furniture.

It is pointed out in Reference A.10 that, should a human be subjected to impact due to ground shock, etc., it is likely that considerable variation in the body area of impact will occur. In addition, there are many circumstances in which the decelerative experience may involve glancing contact with an object; also, a great variation in the shape, weight, and consistency of the decelerating object or surface may be involved.

It is felt (Reference A.11) that the character of the decelerating surface, the angle and area of the body involved at impact, the impact velocity, and the decelerating time and distance are each critical factors. Most hazardous of all (with certain rare exceptions) is, in all probability, uncoordinated impact against a very hard surface. As noted in Reference A.10, any modification of the time of deceleration and the distance over which it occurs will markedly influence the magnitude of the load and the rate with which it develops. Such factors are responsible for human survival after experiencing impact velocities greater than that expected for mortality. Frequently, in these cases the surface struck is soft ground and the impact area of the body is large - the back, side, or ventral surface - and these factors modify the relationships between impact velocity and biological effects. This indicates that any cushioning of the impact, such as by use of mats on the shelter floor, could considerably reduce the impact effects on personnel.

Personnel attached to the structure, such as by being strapped to a seat which is in turn bolted to the floor slab, will not suffer impact due to separation from the structure and the subsequent collision. However, they will be subjected to the sudden downward motion of the structure (an accelerative impact) which will also affect the human body, although this impact will tend to be cushioned somewhat by the straps and the seat. If the seat is sufficiently shock mounted to reduce the accelerations and thereby the impact, then the vibratory response of the support would be the primary consideration, as discussed in the previous section.

From the studies reported in Reference A.10, it was concluded by the authors that one can tentatively take 10 ft./sec. as "an on-the-average safe" impact velocity for adult humans and regard the probabilities of serious injury and even fatality for man to increase progressively as the impact velocity is elevated above this figure. This tolerable velocity is based on impact with a flat, solid surface and for various body postures, including impact of the head, impact in the standing position with knees locked, and impact in the seated position. It was indicated that a higher impact velocity could be tolerated for cases where the impact area of the body was larger, such as the back, side, or ventral surface, or if the surface collided with was not hard, such as soft ground. It was also pointed out in Reference A.10 that impact with a 90-degree sharp corner would be much more severe than with a flat surface. Only about one-seventh of the impact energy to cause skull fracture due to impact with a flat surface would be required for skull fracture due to impact with a 90-degree sharp corner. This would correspond to an impact velocity of one-third of the value for a flat surface. It would thus be desirable to avoid impacts with sharp corners or to cushion the corners and sharp edges of tables, desks, etc. According to Reference A.10, the impact velocity for the threshold of mortality would be about 21 ft./sec. This indicates a rather narrow range between no injury and serious injury or death.

In References A.11 and A.12, it was also concluded that 10 ft./sec. could be tentatively taken as a safe impact velocity with a hard flat surface.

Reference A.13 states that, for a standing person with locked knees, no fractures can be expected at relative (impact) velocities below 11 ft./sec., and serious damage to the brain can be expected if relative velocity at contact is 16 ft./sec. or more. These values (based on drop experiments) appear to be consistent with data from References A.10, A.11, and A.12.

As reported in Reference A.14, men and dummies were exposed to deck motions on a ship when large explosive charges were detonated under water. These motions where characterized by a short-duration upward acceleration which can be equated to a sudden velocity change. The duration of the accelerations was less than 10 msec. This was followed by a deceleration phase lasting about 50 msec. In other words, the rise time to the peak velocity was less than 10 msec. and the decay to zero velocity took an additional 50 msec. The acceleration phase or rise-time portion of this velocity pulse would be similar to the acceleration phase of the sharp downward, ground-shock velocity pulse. However, the decay of the ground-shock velocity pulse is considerably longer, in the order of a second or seconds. Since, it appears that the body is primarily sensitive to sudden changes in velocity, this data would be pertinent. This type of shock velocity would have an effect on the body similar to that produced by a drop test. In both cases a near instantaneous velocity change is experienced due to the relative velocity between the body and a flat surface. In the tests of Reference A.14, a stiff-legged subject and a subject seated in a hard wooden chair experienced 15 g. for 8 msec. (peak velocity of 4.0 ft./sec.) after which the tests were discontinued. This does not indicate a tolerable limit since no physiological effects were reported except for some discomfort in the stiff-legged position. A subject with bent knees experienced an acceleration of 30 g. for 8 msec. (peak velocity of 8 ft./sec.) without discomfort. This is also not necessarily a tolerable limit, but it does indicate that, in the bent-knee position, humans are capable of tolerating a higher impact velocity. This cushioning of the shock in the bent-knee position is further apparent by the fact that, in the stiff-legged and seated position, the subjects left the deck at the maximum deck velocity, whereas in the bent-knee position the subject left the deck at about 5 to 10 percent of the maximum deck velocity. From other data described in Reference A.14, the authors stated that a stiff-legged or a seated man, for which the maximum velocity is 8 ft./sec., will experience a vertical displacement of about one ft., and in areas in which the deck velocity is greater, some injuries may occur.

Reference A.15 reports on studies of personnel injuries resulting from the wartime explosion of a minesweeper. Injuries were correlated with deck motions. It was found that, for personnel without advance warning and in random body positions, injury due to an initial acceleration of 50 g. for 6.5 msec. (peak velocity of 11.5 ft./sec.) can occur. For personnel hurled through the air, deck velocities of about 15 ft./sec. resulted in collision-impact injuries. This latter value is probably higher because of collision with a large impact surface of the body.

References A.16 and A.17 describe other data relevant to impact on ships, including use of protective shoes. Reference A.16 points out that direct injuries due to movements are associated with a high initial acceleration for a short duration, whereas if the same amplitude is reached under a lower acceleration for a longer time, injury will occur due to the subsequent collision after being hurled into the air. This is consistent with the References discussed above. In a laboratory test of cadavers (Reference A.16), a velocity of 12 ft./sec. reached in 1.3 msec. caused some fractures to those without protective shoes and no injury to those with protective shoes. In addition, it was stated that protective shoes and mats will protect standing persons against direct impact effects for velocities up to 20 ft./sec. However, the danger of indirect injury (subsequent collision) is still present.

Reference A.17 describes similar data and states that forces effective in causing impact injuries are of very short duration (1-2 msec.) producing extremely high accelerations (200-800 g.) and peak velocities of about 12 ft./sec. It was further shown that protection from these forces may be afforded by protective shoes.

From review of the data pertaining to personnel experiencing impact due to falls or by other mechanisms causing sudden velocity changes, it appears that the impact velocity can be taken as the significant injury parameter. Although various combinations of acceleration and duration (or deceleration and duration for collision) have been imposed on personnel, in general no injuries are reported until an impact velocity change greater than about 11 ft./sec. occurred. Of course, the time durations (time for peak velocity change) are all extremely short, i.e., generally in the range of 10 msec. or less. For longer time durations, consideration of an impact tolerance in terms of the same peak velocity change may be conservative. This is apparent by considering the use of a mat or protective shoes which increase the stopping time and thereby permit a higher tolerable velocity change. Thus, for extremely short time durations a tolerance may be considered in terms of an approximately constant peak-velocity change, and for relatively longer time durations the tolerable velocity would increase as the time increases. This phenomenon is due to the fact that, as the stopping time becomes small, the acceleration response of the body reaches a peak (because of the body flexibility) and shorter times and higher accelerations are no more severe than the most critical impact case of the body colliding with a rigid surface. For these short acceleration durations, injury is related to the kinetic energy which must be absorbed by the body.

This characteristic of impact effect on the body is indicated in Reference A.19 which states that subjects strapped to a seat experienced a trapezoidal acceleration pulse. For the trapezoidal pulses of extremely short durations (in the range of 10 msec. or less), the areas of the pulses were of the same order of magnitude, indicating that the tolerance could be approximately related to a peak impact velocity. However, for the longer duration pulses the areas of the pulses increased which corresponds to an increase of the tolerable velocity.

The effect of horizontal motions on the throwing of personnel off balance or hurling them laterally would depend on the body stance and position, the acceleration intensity, duration, and rate of onset (jolt) of acceleration. As described in Section A-2, the ground shock motion would be characterized by a sharp, single, lateral peak acceleration followed by lower amplitude disturbances. The duration of the sharp peak pulse is a small fraction of a second. If the floor slab or supports for the personnel are shock mounted, this peak acceleration will be attenuated, and a lower frequency vibratory acceleration response will result. Reference A.7 presents short-time acceleration loads associated with public transportation and automobiles. Although the effect of these accelerations on throwing personnel off balance is not discussed, it is possible to derive certain conclusions from the values given. For public transit the normal acceleration and deceleration is 0.1 to 0.2 g. for 5 seconds. Since these are considered for normal conditions, it is reasonable to conclude that personnel will not be thrown off balance. For emergency-stop braking from 70 m.p.h., the deceleration is 0.4 g for 2.5 seconds. It is reasonable to assume that this type of sudden stop would throw standing personnel off balance and perhaps throw seated personnel forward off their seats. For automobile stops a deceleration of 0.25 g. for 5 to 8 seconds is considered a comfortable stop, and a deceleration of 0.45 g. for 3 to 5 seconds is considered very undesirable.

From this data on horizontal accelerations it appears that personnel could probably sustain about 0.2 g. without being thrown off balance, and at values of 0.4 g. they would most likely be thrown off balance. For values lying between 0.2 and 0.4 g. the stance of personnel and the jolt associated with the acceleration are probably significant factors. The ground shock acceleration required to throw personnel off balance may be greater because of the shortened duration and associated jolts of the accelerations. Also, the structure may accelerate downward from under personnel before the personnel can respond to the horizontal structure motions. A tolerable horizontal acceleration of 0.50 g. is recommended (Reference A.20) for ground shock protection of standing personnel as described below.

d. Additional Information

The vibration and impact tolerance data presented in the above sections and summarized in Section A-4.2 were discussed with pertinent agencies with regard to establishing criteria for personnel shock tolerances for the ground shock environment. Tentative conclusions and recommendations had been made which served as a basis for discussion at the meetings.

The recommended impact velocity of 10 ft./sec. was discussed at the meeting with the Lovelace Foundation (Section B-4). This velocity is considered an "on-the-average" safe tolerable value for total-body as well as skull impact with a hard flat surface. For impact with sharp corners, the tolerable impact velocity would be considerably less. Since the horizontal motions in combination with the vertical motions would probably throw personnel off balance, it is possible that an uncoordinated type of impact would occur and some injuries may result for persons of certain age groups, for persons colliding in an awkward position, and where a person falls backwards and experiences impact with the back of the head. In the latter case, an impact velocity greater than 10 ft./sec. may be unavoidable. For impact velocities greater than 10 ft./sec. and for added safety at 10 ft./sec., a cushioning material should be provided. Bracing, such as handrails, could be used to prevent personnel from being thrown off balance. It is also pointed out (Section B-4) that strapping a person to a chair could introduce additional hazards due to the vibration loading and the interaction between the body and chair.

As discussed during the meeting at the Air Force Special Weapons Center (Section B-5) and presented in Reference A.20, the tolerances recommended are 1.75 g. for seated personnel and 0.75 g. vertical, and 0.50 g. horizontal for standing personnel. These values are based on the consideration that separation of the floor slab with respect to personnel would result in injury. Therefore, the possibility that impact between personnel and the structure could be tolerable is not considered. As discussed in Section B-5, if separation of personnel with respect to the structure is permitted in civil defense shelters, cushioning material should be provided, and for seated personnel, seat belts should be provided.

As discussed during the meeting at the Defense Atomic Support Agency (Section B-6), personnel protection could best be achieved by providing protective padding or by use of frangible-type material to absorb the impact energy.

It was pointed out during the meeting at the Naval Research Laboratory (Section B-7) that, with regard to personnel ground-shock effects, the high accelerations associated with the high-frequency range of the spectra would not be critical as a direct effect since personnel will not respond to these high-frequency components. Consideration of a sudden velocity change would be more appropriate for evaluating personnel effects. Naval shipboard data have indicated tolerances for impact velocities up to approximately 10 ft./sec. for particular body postures and areas of impact. Personnel are believed to be sufficiently rugged to survive expected motions without appreciable injury. However, personnel should be either strapped into chairs or be provided with hard holds, or else cushioning should be provided on adjacent objects with which personnel could collide. In general, it is advisable to use cushioning material to pad all potential hard impact surfaces so as to provide the most reliable protection. Loose items, such as furniture, etc., should be attached to the structure.

At the meeting at the Naval Medical Research Laboratory (Section B-8), recommended vibration tolerances were discussed with the following values arrived at for suggested criteria: 2 g. for less than 10 c.p.s.; 5 g. for 10-20 c.p.s.; 7 g. for 20 to 40 c.p.s.; and 10 g. above 40 c.p.s. Although these vibration tolerances are based on test data for longer duration exposure than that which would result from structure motion caused by ground shock, it is considered that tolerances for shorter durations may not necessarily be significantly higher. Therefore, the above values shall be adopted for this study. In addition, the available test data for seated personnel are for personnel tested in special protective seats. The impact velocity of 10 ft./sec. with a hard flat surface is considered to be generally safe. If the body were in a flexible position or the area of impact were large, higher impact velocities could be tolerated. Impact with sharp corners should be avoided or the corners should be padded. A possible hazard is falling over backwards and striking the back of the head in which case injury might result even if there were no structure motions, although it is noted that in most cases such a fall would be cushioned by striking the back or arms first. To provide protection against this type of injury, padding is advisable.

As discussed during the meetings (Sections B-4, B-5, B-6, and B-7), no known personnel shock tests have been conducted specifically for the ground shock problem although this type of testing is presently being considered.

e. Conclusions

Based on review of the data discussed in the previous sections and summarized in Section A-4.2, the conclusions presented below constitute recommended basic criteria for establishing personnel shock tolerances. Specific application of this criteria with regard to this study is presented in Chapter III.

For personnel strapped to chairs or cots which are shock isolated, the tolerable peak acceleration amplitudes as a function of the frequency of the vibration are as follows. The values pertain to both the vertical and horizontal directions and are presumed not to result in injury for most people subjected to such vibrations for the expected time durations.

Frequency	Tolerable Acceleration
less than 10 c.p.s.	2 g.
10 to 20 c.p.s.	5 g.
20 to 40 c.p.s.	7 g.
above 40 c.p.s.	10 g.

Note that for the higher frequency ranges given above, the tolerances may be unduly conservative, and consideration of an impact or sudden velocity change may be more applicable since the high frequency vibrations would actually be approximating the gross motions of the structure. This motion is characterized by a velocity pulse which reaches the peak velocity due to a predominant single peak pulse of acceleration, followed by high-frequency lower amplitude disturbances (Section A-2). Consideration of shock tolerance from this standpoint can be related to impact tolerance data which is probably less conservative than the available vibration tolerance data with regard to the ground shock environment. Of course, the high-frequency (high g.) accelerations may still be present, but it has been indicated that humans would not respond to the peak acceleration amplitudes at high frequencies, and physiological effects can be conveniently related to the velocity change regardless of the associated acceleration.

For impact with a hard, flat surface in random body positions with no special protective devices, the tolerable impact velocity (relative velocity between personnel and the surface at impact) which would not result in injury for most people experiencing collisions is to be taken as 10 ft./sec.

For personnel thrown off balance and subjected to an uncoordinated type of impact with a flat, hard surface, it is expected that some persons may experience injury, although, in general, this type of fall will be cushioned by the arms and hands and the large area of impact. Possible injuries can be greatly reduced by providing protective padding.

For impact with a cushioned, flat surface, where mats or protective clothing, etc., are provided, the tolerable values will be considerably higher depending on the cushioning provided. Maximum impact velocities in the range of 15 to 20 ft./sec. could probably be tolerated with proper protection.

For impact with a sharp corner or edge, cushioning must be provided.

For protection of standing personnel, current criteria (Reference A.20) recommends 0.5 g. as a tolerable horizontal acceleration and 0.75 g. as the tolerable vertical acceleration.

A-4.2 Summaries of Information Obtained from References

a. Summary of Reference A.7

This report presents a comprehensive study on the biological effects of shock and vibration and deals with three basic problems: the structure and properties of the human body as a mechanical and biological system, the effects of shock and vibration of this system, and the protection required by the system under various exposure conditions. Numerous data on tolerance criteria for various exposure conditions are presented. Although most of the data is not related directly to the ground shock problem, that which is felt pertinent has been singled out for attention and summarized or indicated below.

Vibration Effects

Biological systems may be influenced by vibration of sufficient amplitudes at all frequencies. This report, however, is concerned primarily with the frequency range from 1 c.p.s. to 100 c.p.s. although studies at higher frequencies are very useful for the analysis of tissue characteristics.

This report explains that structurally, the human body consists of a hard, bony skeleton whose pieces are held together by tough, fibrous ligaments and which is embedded in a highly organized mass of connective tissue and muscle. The soft visceral organs are contained within the rib cage and the abdominal cavity. The combined use of soft tissue and bone in the structure of the body, together with the body's geometric dimensions, results in a system which exhibits roughly three different types of response to vibratory energy depending upon the frequency range. At very low frequencies, below approximately 100 c.p.s., the body can be described for most purposes as a lumped parameter system. Resonances are observed which can be attributed to the interaction of tissue masses with purely elastic structures. For higher frequencies, through the audio range and up to 100 k.c.p.s., the wave propagation of vibratory energy becomes more and more important, but the type of wave propagation (shear waves, surface waves, or compression waves) is strongly influenced by boundaries and geometrical configurations. Above 100 k.c.p.s. and up to m.c.p.s. range, compression waves predominate and are propagated in a beam-like manner. This viewpoint permits not only a phenomenological description of the body's mechanical properties but also forms the basis for attempts to explain the behavior of tissue in terms of microscopic tissue and cell-structure.

The mechanical impedance of a man standing or sitting on a vertical vibrating platform has been investigated. It was found that below approximately 2 c.p.s. the body acts as a unit mass. Resonance peaks were found between 4 and 6 c.p.s. for the sitting man and between 5 and 12 c.p.s. for the standing man. Above approximately 10 c.p.s. it was found that vibration amplitudes of the body are smaller than the amplitudes of the exciting table and decrease continually with increasing frequency. Of course, impedances and transmission factors are changed considerably by individual differences in the body and its posture as well as support by a seat or back rest for a sitting subject or by the state of the knee or angle joints of a standing subject. The resonance frequencies, however, remain relatively constant. Transmission factors as high as 4 have been observed in the frequency range below 10 c.p.s.

Further studies on both the sitting and standing subject indicate that between 20 and 30 c.p.s. the head exhibits a resonance with a transmission factor between head and shoulder of about 3. Eyeball resonance has been observed in the frequency range between 60 and 90 c.p.s.

The impedance of the human body lying on its back on a rigid surface and vibrating in the direction of its longitudinal axis has been determined by ballistocardiograph studies. It was found that the total mass of the body forms a simple, spring-mass system which is in resonance between 3 and 3.5 c.p.s. with a transmission factor between body and slab of about 3.

The physical response to transverse vibration is quite different from that described above for vertical vibration: instead of thrust forces acting primarily along the line of action of the force of gravity on the human body, they act at right angles to this line. The distribution of the body masses along this line is therefore of the utmost importance.

Impedance measurements for transverse vibration are not available. The results of transmission studies indicate that, for both the sitting and standing subject, resonant frequencies are between 1 and 3 c.p.s. and that the response decreases with increasing frequency.

Although impedance measurements tend to indicate critical frequency ranges, this is not true in every case as observed during the vibration tests.

Many methods have been developed to assess man's tolerance to vibration in a quantitative manner, but most of these are based on a limited number, specific types, or a specific interpretation of experiments and contradict each other to a certain degree. These results have been averaged and simplified as given in Curve a of Figure A-4 described in the discussion. The tolerance limit, which represents an average for man in the standing, sitting, and lying positions without any protection and exposure times of 5 to 20 minutes, is plotted as a function of acceleration and frequency.

Data of this type (Reference A.8) for short exposures of less than one minute for the frequency range 1 to 15 c.p.s. are also discussed in this report. Subjects were strapped in a seat and exposed to steadily increasing vertical vibration amplitude until they could no longer tolerate it. They were then asked for their reactions and what their specific reason was for asking to be released. No single criterion for tolerance was found although some reactions were more common than others. The estimated limits of tolerance according to these criteria are shown on Curve b in Figure A-4 and represent the border line beyond which physical tissue damage occurs in a relatively short time.

Although Curve b is for subjects supported in their seats, it does indicate that man's tolerance to vibratory acceleration increases as the exposure time decreases. For exposures on the order of seconds, such as encountered in a ground shock environment, Curve b is probably a lower bound to man's tolerance to the environment, if he is strapped down in a seat attached to the floor slab and isolated so that he does not receive the initial jolt of the impact. In view of the lack of short-duration data, the use of Curve a to assess man's tolerance to transient vibrations when he is not supported or strapped down may be overly conservative. From Curve a it is seen that the tolerable limit is about 0.3g. which gradually increases after about 30 c.p.s. reaching one g. at about 80 c.p.s. and sharply increasing after 100 c.p.s.

Impact Effects

As opposed to vibratory effects the authors consider mechanical shock effects on personnel, such as those caused by explosions, explosive compression or decompression, and impacts and blows from rapid changes in body velocity or from moving objects. Possible damage includes bone fracture, lung damage, injury to the inner wall of the intestine, brain injury, cardiac damage, ear damage, tearing or crushing of soft tissues, etc. Differences in injury patterns arise from differences in rates of loading, peak force, duration, localization of forces, etc. This report refers to impact tolerance data developed by other researchers. Some of these data are presented in the following sections of the appendix.

This report also presents approximate duration and magnitude of short-duration acceleration loads which may give some indication of horizontal acceleration values required to throw personnel off balance. For public transit, normal acceleration and deceleration is 0.1 to 0.2 g. for 5 seconds. For emergency-stop braking from 70 m.p.h., the deceleration is 0.4 g. for 2.5 seconds. For a comfortable stop in an automobile, the deceleration is 0.25 g. for 5 to 8 seconds; for a very undesirable stop, the deceleration is 0.45 g. for 3 to 5 seconds.

b. Summary of Reference A.8

Short time human tolerance criteria for sinusoidal vibration from 1 to 14 c.p.s. were determined using 10 healthy male subjects weighing from 136 to 210 lbs., and ranging from 5 ft. 7 in. to 6 ft. 3 in. in height. Each subject was supported in a seat using a standard seat belt and harness, and at each frequency the amplitude was increased at a constant rate from zero to the point where the subject stopped the run because he thought that further increase might cause bodily harm.

The purpose of the tests was to find the short-time vibration limit of subjective voluntary tolerance and to define this tolerance. Tolerance was defined as the degree of stress human subjects are willing to undergo without noticeable injury.

The lower levels of tolerance were found to lie between 1 and 2 g. at 3-4 c.p.s. and 7-8 c.p.s. The highest tolerance level of 7-8 g. was found at 15 c.p.s. Subjective tolerance limits were caused by one or more of seven specific sensations or sympto ms mainly: abdominal pain, chest pain, testicular pain, head symptoms, dyspnea, anxiety, and general discomfort. Physiological observations during vibration exposure were also made.

Exposure times ranged from 18 to 208 seconds. However, these do not represent exposure at the tolerable value since there was a buildup to the peak acceleration amplitude. It is possible that shorter exposures of the same amplitude may be just as severe. Curve b of Figure A-4 described in the discussion illustrates some of the data recorded in these tests.

c. Summary of Reference A.9

Each of 16 selected male subjects were supported in a chair and subjected to a vertical, sinusoidal vibration at selected frequencies in the range from 1 to 27 c.p.s. The exposure time appears to be in the order of minutes.

Vibration levels were established in terms of four levels defined as definitely perceptible, mildly annoying, extremely annoying, and alarming as acceleration increased slowly for each selected frequency at a constant rate. The alarming level was considered as a tolerance limit and the run was discontinued.

Relatively high acceleration sensitivity was indicated at 1, 4 to 10, and above 20 c.p.s. The lowest level of tolerance (0.25g.) occurred at one c.p.s., then increased to 0.8g. at 2-3 c.p.s. after which it then decreased to 0.65g. at 4-8 c.p.s. and then gradually increased to the maximum tolerance of 1.4g. at 17-20 c.p.s. range. The tolerance then dropped abruptly to one g. in the range of 24 to 27 c.p.s. Some of these data are plotted in Figure A-4 which is described in the discussion. At each frequency the amplitude was increased at a constant rate until the tolerance limit was reached. It was found that the body is evidently more sensitive to vibration at selected frequencies, suggesting body organ and appendage resonance.

d. Summary of Reference A.10

This report describes the results of impact tests on animals and discusses data from literature relevant to humans. Tertiary effects encompass injuries that occur as a consequence of actual displacement of a biological target by winds that accompany the propagation of the pressure pulse. It is also stated that, although damage may ensue during the accelerative phase of movement because of differential velocities imparted to various portions of the body, trauma is likely to be more prevalent and severe during deceleration, particularly if impact with a hard surface occurs. Although the ground shock environment differs in that motions imparted to personnel are not caused by direct wind forces, the latter effect of deceleration impact would be similar to that which could occur during ground shock motions.

It is pointed out that proper assessment of the tertiary blast hazard requires knowledge in at least two areas; namely, (a) information concerning velocities attained by objects having the size and shape of man and (b) man's tolerance to impact as a function of striking velocity. In the case of ground shock, the former could be established on the basis of the structure motions, and the latter would be similar to that investigated in this report.

In the tests described, the various animals were subjected to impact velocities ranging between 25 ft./sec. and 51 ft./sec. in order to establish mortality-impact velocity levels. The desired velocities were generated by allowing the animals to free-fall from various heights to a flat concrete pad. The ventral surface of each animal was the area of impact. Extrapolation of the data to a 70 kg. animal was made to predict lethal velocity levels for an animal of human size. Based on this data, the predicted threshold condition for lethality is 21 ft./sec., and the impact velocity for 50-percent mortality would be 26 ft./sec. This applies to young adult animals subject to impact with a solid flat surface in the prone position.

It is pointed out that, should a human be subjected to impact, such as that due to ground shock, etc., it is likely that considerable variation in the body area of impact will occur. Also, there are many circumstances in which a decelerative experience may involve glancing contact with an object; in addition, a great variation in the shape, weight, and consistency of the decelerating object or surface may be involved. Any modification of the time of deceleration and the distance over which it occurs will markedly influence the magnitude of the g. load and the rate with which it develops. Such factors are responsible for human survival after experiencing impact velocities greater than that expected for mortality. Frequently in these cases, the surface struck is soft ground, and the impact area of the body is large - the back, side, or ventral surface - and these factors modify the relationships between impact velocity and biological effect. However, the authors are concerned with human impact on a flat, solid surface, and the stopping distances are controlled only by the tissues of the body. In this regard the authors reviewed other literature involving humans as summarized below. It is pointed out that one would like to know the relationship between impact velocity and mortality, the threshold of mortality, and the threshold for tolerable trauma, all as functions of the different areas of the body that may come in violent contact with hard surfaces.

1. The minimum impact velocity for skull fracture was near 13.5 ft./sec. which corresponds to an impact energy of 400 in.-lbs. However, for impact with a 90-degree sharp corner, it may require only 60 in.-lbs. of energy to produce skull fracture. These values pertain only to the head striking a surface without the head absorbing any energy due to motion of the remainder of the body and not to the case of an individual travelling horizontally and undergoing a head-on impact. The authors conclude that an impact velocity with a hard, flat surface of 10 ft./sec. should prove to be an acceptable impact velocity for the head of adult man.

2. The "initial velocity" threshold for fracture of the

heel bone of standing subjects (knees locked) was between 11 and 16 ft. /sec. The maximum impact velocity tolerated by human subjects, dropped in a seated position, was reported to be about 10 ft. /sec.

3. Human fatalities in automobile statistics showed 50 percent mortality at vehicular speeds near 33.8 ft. /sec. which is in fair agreement with the 50 percent impact velocity (26 ft. /sec.) obtained in the study as extrapolated from animal tests.

Based on the data discussed in the report, the authors conclude that one can tentatively take 10 ft. /sec. as 'an-on-the-average safe' impact velocity for adult humans and regard the probabilities of serious injury and even fatality for man to increase progressively as the impact velocity is elevated above this figure.

e. Summary of Reference A. 11

This report represents a selective summary of the current status of knowledge regarding biological effects of blast. Primary, secondary, and tertiary effects are defined. For the latter effect, which is of primary concern in a ground-shock environment, the following conclusions were made:

"It is possible to regard the figure of 10 ft. /sec. as 'safe' and to believe tentatively at least, that human injury may occur at velocities much above this; that mortality may, on the average, become significantly frequent for 'uncoordinated' impact at velocities between 15 and 20 ft. /sec., fairly common between 20 and 30 ft. /sec., and near 100 percent fatal between 30 and 40 ft. /sec., providing impact occurs with a hard surface where stopping distance is quite small and the stopping time is almost instantaneous."

These conclusions were based on the data described in the earlier report of Reference A. 10. It was also pointed out in this report that, "though an animal or man bodily hurled through the air may be damaged because of differential displacement of different portions of the body during the general process of acceleration, it is known that the decelerative experience of stopping can be far more dangerous. It is clear that the character of the decelerating surface, the angle and area of the body involved at impact, the impact velocity, and the decelerating time and distance are each critical factors. Most hazardous of all (with certain rare exceptions) is, in all probability, uncoordinated impact against a very hard surface."

f. Summary of Reference A. 12

This report is concerned with primary blast effects caused by variations in environmental pressure, secondary blast injuries which follow the impact of penetrating and unpenetrating missiles energized by blast winds, and tertiary blast effects as a consequence of physical displacement of a biological target. Tertiary effects are of concern in the shock isolation problem. As tentative criteria, displacements involving velocities of 10 ft./sec. due to decelerative impact for a 150-lb. man were considered low enough to avoid significant numbers of serious head and skeletal injuries. It is seen that the tolerance of 10 ft./sec., as recommended in the later reports of References A. 10 and A. 11, was also considered in this earlier report.

g. Summary of Reference A. 13

Human injury induced by motion is a complex phenomenon, depending upon attitude of the person (i.e., sitting, standing, lying down) and the direction and character of motion. For example, in the case of a standing person with a locked knee, if the ground motion is initially upward, the heel bone may be broken if the initial relative velocity of foot and supporting surface is greater than 15 ft./sec. No fractures can be expected at relative velocities below 11 ft./sec. These estimates are based on drop experiments on living persons.

If the ground motions are initially downward at accelerations in excess of one g., separation ensues and the relative motion of the person and the moving support must be studied as a function of time.

Drop experiments on skulls from cadavers indicate that skull fracture can be expected if relative velocity at contact of skull to a hard surface, such as concrete, is 18 ft./sec. or more, and serious damage to the brain can be expected if relative velocity at contact is 15 ft./sec. or more.

The above statements were made regarding shock injury criteria for personnel in hardened protective structures.

h. Summary of Reference A. 14

Men and dummies were exposed to deck motions on the USS Fullam (DD 474) when large explosive charges were detonated under water. The center of gravity displacements were measured when the subjects were seated, standing stiff legged, or standing with knees bent. A comparison of the motions of the men and dummies is made, and the relation of the response to the deck motion is examined. Only motions in the vertical direction are considered. In the report the following general conclusions were made with regard to the relationship between vertical shock and shipboard injury:

1. The stiff-legged subject is most vulnerable to the acceleration and deceleration phases of the ship shock motions. There were indications of some discomfort for this stance at an acceleration as low as 15 g. sustained for 8 msec. (peak velocity of 4.0 ft./sec.) at which time the tests for this position were discontinued. The kickoff velocity was equal to that of the maximum deck velocity.

2. A subject seated in a hard wooden chair might be somewhat less vulnerable to direct shock than the stiff-legged subject. No discomfort was experienced by the seated man exposed to 15 g. for 8 msec. (peak velocity of 4.0 ft./sec.) at which time the tests for this position were discontinued. The kickoff velocity is about equal to that of the maximum deck velocity as for the stiff-legged stance. It is probable that the shock was attenuated by the chair itself.

3. A man standing with bent knees seems capable of tolerating a considerably larger acceleration than do subjects in either of the other two positions; specifically, no discomfort was experienced during an exposure of over 30 g. for 8 msec. (peak velocity of 8 ft./sec.). The man's center of gravity attains a velocity of about 5 to 10 percent of the maximum deck velocity.

4. During an underwater explosion, a stiff-legged man or a seated man at a deck position for which the maximum velocity is about 8 ft./sec. will experience a vertical displacement of about 1 ft. In areas in which the deck velocity is greater, some injuries may occur.

5. The particular type of dummy used in the tests simulated the center of gravity motions of a stiff-legged man and, possibly, of a seated man. In its present form, the dummy does not simulate the motions of a man standing with bent knees.

The duration of the accelerations which corresponds to the rise time to the peak velocity may be of the order of magnitude occurring during ground shock. However, in the case of deck motion, the deceleration phase is in the order of 50 msec. whereas in the case of ground shock these durations are considerably longer, in the order of a second or seconds. The significance of these differences are presented in the discussion section.

Data from other researchers were also included in this report. Men with bent knees on the deck of the YMS 319 were subjected to accelerations as high as 95 g. for 3.8 msec. (peak velocity of 11.5 ft./sec.) without injury. In drop tests, a stiff-legged man experienced as much as 65 g. for 4 msec. (impact velocity of 8.4 ft./sec.) without injury, and a man with bent knees was subjected to 220 g. for 3 msec. (peak velocity of 21 ft./sec.) without injury. A seated man was exposed to as much as 95 g. for 3 msec. (peak velocity of 9.2 ft./sec.) without injury, "although others claim that this is in the injury region".

i. Summary of Reference A.15

Personnel injuries resulting from the wartime explosion of a wooden-hull minesweeper, YMS 368, are correlated with estimated deck motions.

The positions of the personnel at the time of the explosion were summarized from questionnaire forms; the extent of the injuries was taken from medical records. The attack geometry was estimated from documents describing the damage to the hull and equipment of the minesweeper, and the deck motions were deduced from the attack geometry. The following conclusions were made:

1. Direct or primary injury due to the initial acceleration phase of deck motion can occur among unprepared standing personnel when the deck accelerations are about 50 g. for about 6.5 msec. (peak velocity of 11.5 ft./sec.).

2. Secondary or collision impact injuries associated with the deceleration phase of ship motion can occur among unprepared personnel when the deck velocities are about 15 ft./sec.

It is explained that there are two major phases to deck-velocity curves. The first is the initial sharp rise to the peak velocity indicating the acceleration phase. After the peak is reached, the velocity tends to decrease; i.e., there is deceleration. The duration of the deceleration phase varies. During the acceleration phase a man is vulnerable to injuries to internal organs and bones, especially if he is standing stiff-legged or is seated. Previous researchers have accepted as important parameters for this type of injury, the duration and intensity of initial acceleration expressed as a step pulse.

During the deceleration phase men can leave the deck in free flight which may end in collision injury, mostly to the head or upper body region. Such injuries have also been reported by others. At this point it is appropriate to define injury as it pertains to this study. The main concern here is to establish criteria permitting predictions of ship capability impairment due to loss of personnel. From this point of view, an injury can be defined as a mechanically produced trauma which results in the suspension of a man's capability for effective performance of his assigned duties.

It was found that only two subjects were injured by the direct impact acceleration. These men were standing on one leg and suffered broken heel or ankle bones. Indications are, from these data, that a level of 50 g. sustained for 6.5 msec. can cause primary injury.

The remaining injuries were of a secondary nature, probably caused by collision impact. It has been shown that men standing stiff-legged and men in a seated position on an uncushioned chair will leave the deck during the deceleration phase with a velocity which is roughly that of the peak deck velocity.

It should be noted that these injury levels are associated with a ship where there was no advance warning of imminent attack. As a result, men were in random positions, that is, lounging, relaxed, or attending to various duties. In no cases was a man tense, crouching, or holding on to a stable structure for balance as he might have been if advance warning had been received.

j. Summary of Reference A. 16

This report discusses available information regarding solid blast injuries that are typical as a result of deck heave, i.e., shipboard explosions.

It is stated that the movement of ship's structures may be divided into two types as related to personnel injuries:

1. A movement of considerable amplitude having a high initial acceleration for a short distance and capable of causing both direct injuries, such as fractures of the lower extremities, and indirect injuries, such as in 2.

2. A lower acceleration for a greater distance reaching a commensurate amplitude as in 1, and causing only indirect injuries by displacing bodies, thus causing bodily injuries upon impact with other objects.

The phenomenon described in (1) is essentially a severe jolt in relation to the human system whereas that in (2), which involves slower initial body movements, is often referred to as a "whipping action", although any indirect injuries may be the result of severe jolts.

It was concluded that the forces which produce direct solid blast injuries are of very short duration (1 to 2 msec.) producing stresses exceeding the strength of bones and tissues.

In a laboratory test of cadavers, a velocity of 12 ft./sec. was reached in 1.3 msec. without protective shoes causing fractures of some cadavers while those with protective shoes received no injury.

Live personnel were subjected to an impact of 2.6 ft./sec. in normal standing position with regulation shoes and to 5 ft./sec. while standing on their toes. Although these levels were not necessarily the threshold of injury, the tests were not carried beyond these velocities as a safety precaution.

The report presents results of a study of solid blast with regard to protective shoes and mats as summarized below:

1. Protective shoes and mats will protect standing personnel against direct solid blast up to a check velocity of 20 f.p.s. However, the danger of indirect injury is still present.

2. Human volunteers with and without anti-blast shoes and mats, were used in the tests on wooden-hull vessels. Underwater explosions occurred in the vicinity of the vessel.

3. The volunteers were standing on an open deck and therefore not subject to indirect effects), and damage which would have occurred to personnel in other than the standing position cannot be deduced from the results

4. Few quantitative results. The volunteers on the mats felt less shock than did the control volunteers.

k. <u>Summary of Reference A.17</u>

Cadavers were supported in a standing position on a steel platform and exposed to an impact produced by a steel hammer striking the platform from below. The tests were designed to simulate the movement of ship structures when subjected to solid blast effects, to study the mechanism of personnel injury, and to evaluate protective devices.

It is shown that the forces effective in producing solid-blast injuries are of very short duration (1-2 msec.) producing extremely high accelerations (200-800 g.), peak velocities of about 12 ft./sec., and displacements of less than 2 inches. It is further shown that protection against these forces may be afforded by devices which lower to a point within the limits of tissue tolerance, the average and peak accelerations of the part of the body subjected to solid blast.

No conclusions or tentative recommendations are given for man's tolerance to this type of jolt, although the stated impact velocity of 12 ft./sec. necessary to produce injuries is consistent with observations by other authors. With protective shoes, however, a velocity of 12 ft./sec. seems to be tolerable without causing injury.

1. Summary of Reference A. 18

This paper discusses the acceleration forces, produced by both the ground-pressure wave and the air-blast induced earth shock, acting on and within underground shelters and transmitted to the personnel therein and the acceptable limits or tolerances that personnel can withstand with regard to these forces.

It is pointed out that the acceleration forces experienced by personnel in shelters are of an oscillatory nature and of rather short duration (on the order of 10 to 100 msec.), and that information on human tolerances has been obtained only for situations approximating that of personnel in plane catapults and crashes, parachute openings and landings, and pilot ejections where the accelerations are relatively constant (with the exception of relatively slow build-up and decay) and of relatively long durations (on the order of seconds). It is stated, therefore, that it is necessary to correlate the experimental data for relatively constant, prolonged accelerations with the situation as it exists in shelters. It is concluded that prolonged accelerations impose a more severe loading condition on the body and application of the tolerances for these accelerations in connection with the ground-shock environment would probably be conservative.

It is contended that authorities are not in agreement as to the significance of a jolt, that is, the rate of change of acceleration with time. Some references indicate that, as the jolt increases, there is an increase in the level of acceleration that the human body can withstand corresponding to a particular type of injury, although this seems surprising in general. Nevertheless, no conclusions are drawn for the relatively rapidly applied loads of short durations that may be experienced by personnel in shelters. Moreover, the paper does not discuss available literature on drop tests and shipboard explosions where some quantitative information on the effect and significance of sudden jolts is presented.

A general discussion is given on soil-structure and personnel-structure interaction, and recommendations for tests are listed. The tests, it is stated, should be designed to investigate two prime items: that of accelerations experienced and that of the tolerance to such accelerations. No tolerance criteria are presented in this report.

m. Summary of Reference A.19

In this report, literature is surveyed to determine human tolerance to rapidly applied accelerations. Pertinent human and animal experiments applicable to space flight and to crash impact forces are analyzed and discussed. These data are compared and presented on the basis of a trapezoidal pulse. The effects of body restraint and of acceleration direction, onset rate, and plateau duration on the maximum tolerable and survivable rapidly applied accelerations are shown.

It was found that, by use of proper restraints with straps, etc., tolerable values are considerably increased. For the trapezoidal pulse the tolerable magnitude decreases as plateau duration increases, and the tolerable magnitude also decreases as the onset rate increases.

Curves are given indicating injury levels and voluntary human-exposure levels from various test of humans and animals strapped to padded seats and subjected to the trapezoidal acceleration pulse. The points on the curves are plotted for acceleration versus plateau duration and acceleration versus onset rate. The onset rate would correspond to the jolt or derivature of acceleration. For the ground shock environment the intensity of the jolt would not be well known; however, consideration of pulse duration versus acceleration level may have application in regard to a short duration acceleration pulse under ground shock. The data indicate that for extremely short durations (less than 10 msec.) the product of acceleration times time would be of the same order of magnitude; in other words, the tolerance could be related approximately to a peak impact velocity. However, for longer duration pulses the tolerable product increases; in other words, the tolerable peak velocity increases. This indicates that the use of a peak impact velocity as discussed in the summaries for previous references would be conservative for the longer rise times.

n. Summary of Reference A. 20

It is explained that, based on vibration and acceleration pulse tests on humans (not for ground-shock environment), the following criteria have been established for personnel areas of Air Force weapon systems.

Weapon System	Maximum Acceleration in Personnel Areas, g.	
	Vertical	Horizontal
Atlas Silo	1.5	0.125
Atlas Control Center	"...mounted to reduce ground shock without impairing operational ability"	
Titan II (Criteria)	3.0	3.0
(Initial Design)	2.4	0.5
(Revision)	0.5	0.5
Minuteman (Criteria)	1.0 (down) 3.0 (up)	1.0
(Design)	0.5	0.15

In all cases, the natural frequencies associated with the above personnel support systems are less than one cycle per second. The mode of failure in all cases is based on impairment of operational capability of all personnel, some of whom may be standing unsupported and may be unprepared. The downward trend in peak accelerations believed to be necessary to achieve the desired protection is clearly indicated by the differences between those specified by early design criteria and those used in the final design of the Titan II and Minuteman facilities.

It should be noted that all the suspension systems indicated are pendular and that the maximum horizontal acceleration is fixed more by the practical aspects of the pendulum design than by a human shock tolerance.

Human shock tolerance is defined broadly as the level of shock which a person may withstand without impairing his ability to perform essential duties. In some cases, the critical level of shock may be that which produces injury directly, and in others that which causes the man to fall down, indirectly exposing him to injury. Implicit in the shock tolerance, then, is the "mode-of-failure".

The following tolerances are suggested as tentative guidelines for design and it is pointed out that the entire problem of protection for personnel must be considered from the viewpoints of facility mission, shock environment, and modes of failure.

	Maximum Acceleration (g.)	
Direction	Seated and Well-Restrained	Standing Without Support
Vertical	1.75	0.75
Radial	1.75	0.50

SECTION A-5

SHOCK TOLERANCES FOR EQUIPMENT AND OTHER INTERIOR COMPONENTS

A-5.1 Discussion and Evaluation

a. General

Available literature on shock tolerances, fragility levels, and shock vulnerability data for equipment, hardware, and other interior components likely to be housed in hardened civil defense shelters is reviewed and discussed relevant to the effects of ground shock, and conclusions are drawn which serve as a basis for the design of shock isolation schemes.

In order to provide necessary shock protection of mechanical and electrical equipment and other components housed within a protective shelter subjected to a transient ground shock environment, it is necessary that the shock tolerance of these items be known. With this information, the required degree of shock isolation may be established. This requires that the peak acceleration from the ground shock environment to which the various equipment items and other interior components are exposed, be less than or equal to the tolerable accelerations. For linear, single-degree-of-freedom systems, the peak responses may be obtained from the structure shock response spectra. For more complicated systems, such as non-linear, discontinuous, distributed mass and/or two or more degree-of-freedom systems, the peak responses may be obtained by employing a time history of the structure motion by using a synthesized velocity or displacement pulse corresponding to the time history of the structure motions as a forcing function. For linear, but two or more degree-of-freedom systems, an approximate, although conservative estimate of the peak responses may be obtained by the method of "normal modes", which makes use of the shock spectra. In many cases complicated systems may be simplified in order to apply the response spectra.

The types of equipment items and their functional requirements for a hardened civil defense shelter will depend to some extent on the requirements established for the particular shelter, i.e., function of the shelter (personnel shelter, control or communications centers, etc.), the required level of protection, the time interval on which occupancy should be based, the required capacity (family or community shelter, etc.), and other factors. The normal peacetime function for dual-purpose structures will also be a factor. The basic types of equipment likely to be housed would include heating, ventilating, air conditioning, water supply, sanitation, and electric equipment, including emergency power supply equipment as well as electronic communications equipment, such as a radio receiver and possibly a transmitter. Blast valves are also likely to be installed. A breakdown of the various items is tabulated below.

Mechanical

- Fans and Blowers
- Air Conditioning Units
- Dust Collectors
- CBR Filters
- Blast Valves
- Prime Movers
- Silencers
- Heat Exchangers
- Controls
- Storage Tanks (Water, Fuel, or Air)
- Oil Purifiers
- Air Compressors
- Refrigeration Compressors
- Air Preheaters
- Sinks
- Water Closets
- Urinals
- Showers
- Sewage Disposal Systems

Electrical

- Generators
- Battery Charges
- Battery Lanterns
- Transfer Switches

Batteries
Motor Starters and Motors
Panel Boards
Lights and Lighting Fixtures
Clocks
Alarm Systems
Switches and Receptacles
Relays

Communications

Intercom Systems (Telephones)
Radio Receivers
Possibly a Radio Transmitter
Antennas

Miscellaneous and Other Components

Partition Walls
Furniture and Supply Cabinets
Conduits and Wiring
Pipes, Fittings, Valves, Hangers, Anchors
Mounting Brackets and Hold-down Bolts
Ducts
Diffusors
Dishwashers, Washing Machines and Driers
Cooking Equipment
Refrigerators
Water Coolers

As listed above, civil defense shelter equipment items may range from relatively heavy and rugged components such as motors, fans, blowers, pumps and generators to relatively small and fragile items, such as electronic tubes, lights, clocks, alarm systems, relays, fuses, etc. The latter are generally sensitive items, having lower tolerance levels and requiring fine adjustments which must not be excessively disturbed.

Equipment failures may be broadly divided into two classes: temporary and permanent failures. Temporary failures, often called "malfunctions", are characterized by temporary disruption of normal operation when a shock or vibration is applied. For some cases, subsequent adjustments may be required for restoration of service. Permanent failures are characterized by breakage, resulting in damage so severe that the ability of the equipment to perform its intended function is impaired permanently.

The capability of an equipment item to withstand shock and vibration is conventionally stated in terms of its "fragility level". "Fragility level" is defined as the magnitude of shock, generally expressed in g.'s of acceleration, which the equipment can tolerate and remain operational; in other words, a permissible g. level (where one g. is equivalent to an applied force equal to the weight of the equipment) at which the equipment will not malfunction or be damaged. Fragility data for a particular equipment item are dependent upon its physical characteristics, that is, the strength of the item (frame, housing, and components), and to some extent the nature of the excitation to which it is subjected. For example, an equipment item may sustain a single peak acceleration due to a transient ground shock disturbance, but may fail under a vibratory-type input having the same peak acceleration amplitude. This effect arises from the fact that the fragility level for a piece of equipment is actually a tolerable peak acceleration of the equipment frame under a particular shock test (tolerable in the sense that the equipment frame, housing, and components were not damaged or disrupted). However, under a different shock input resulting in the same peak acceleration of the equipment as a whole, components of the equipment may have responded differently. For this reason, fragility data should be considered in conjunction with such factors as the natural frequencies and damping characteristics of the equipment components, compared to the excitation frequency to avoid possible resonance, and the test input used to determine the tolerance as compared to the probable ground shock input.

Reference A.21 points out that equipments that are capable of sustaining a fair amount of shock and vibration generally consist of a housing or chassis to provide structural strength and an array of functional components supported by the chassis. There must also be a proper balance between flexibility and rigidity. For a particular shock motion, the maximum acceleration experienced by an equipment component is dependent primarily upon the natural frequency of the mounted equipment. The acceleration response of the system decreases as its natural frequency decreases. Therefore, components that are susceptible to damage from shock may be given a degree of protection by mounting them on relatively flexible structures, that is, by isolating them. However, this shock isolation may result in a vibratory motion following the shock input as a consequence of the flexibility introduced to attenuate the shock and may lead to stress amplifications of the equipment components as a result of this vibration. Compilations of damage experience (Reference A.21) show that failure of principal structures and mounting brackets is the most common form of damage. During shock, structures may not have sufficient strength to withstand the forces that are applied; during vibration, resonant conditions may develop, and the relatively undamped structures may fail due to stress amplifications.

A discussion of equipment vulnerability is presented in Reference A.22. This report includes a pertinent conclusion obtained by the Navy during shock and vibration testing of shipboard equipment, namely, an item of equipment well designed for vibration was usually very good for shock, whereas an item that passed shock tests satisfactorily may or may not have been capable of passing vibration tests. The reason for these results was that many of the equipment items tested were flexible and in resonance with the testing frequencies. However, the flexibility was usually beneficial for shock if collision (with adjacent objects) did not occur. It is stated in Reference A.22 that, "in general, the vulnerability of equipment to shock and vibration is dependent not only on the components which make up the equipment but also on the mounting of these components in the piece of equipment and also on the mounting of the equipment itself on the structure or element to which it is attached. The sensitivity of each item is dependent upon the overall characteristics of the entire system, and a change in one part of the system may affect the shock sensitivity of all the connected parts. For example, placing a transformer on a flexible plate mounting may change the characteristics of the transformer in resisting shock as well as the characteristics of control equipment mounted on the transformer. Thus, specifying the level of resistance for individual items may not be sufficient. Generally, the item is part of a coordinated system which must remain undamaged to perform its mission satisfactorily." In accordance with these comments, the fragility level or peak tolerable acceleration response for the equipment as a whole would be useful.

With regard to items such as ducts, pipes, and connections, etc., it would appear that distortion rather than acceleration is of most importance, and that the basic problem is to secure them adequately and provide for such distortions. Reference A.22 points out that in long structures or when two elements are connected together and are attached to structures which may move in different manners, relative motion must be considered and may be a definite source of vulnerability. Entrances to tunnels, tunnels connecting structures, piping and shafts, and connections to mechanical and electrical equipment are examples of items which should be examined in this connection, according to this reference.

Reference A.1 presents a discussion on equipment vulnerability relevant to a ground shock environment and points out that it is not sufficient to assess vulnerability in terms of an acceleration only, since the frequency corresponding to this limit is also a factor. It is stated in this reference that in general, a vulnerability spectrum can be drawn as a function of some measure of frequency and that this will have peaks at the natural frequencies of the piece of equipment. If these are close together, possibly a uniform acceleration vulnerability may be postulated, although this probably drops down for low frequency inputs. The implication here is that a piece of equipment will be more vulnerable to shock if it is mounted or isolated at one of its natural frequencies. The fact that equipment vulnerability is generally lower for low frequency inputs is not only because equipment shock isolation at lower frequencies corresponds to lower response accelerations, but it is likely that the natural frequencies of the equipment components would then be higher and out of the range of the input frequency. It is pointed out in Reference A.1 that one need not generally be concerned with inputs having a frequency higher than about 15 to 20 c.p.s. for vertical motion, except near columns, and about 5 c.p.s., even for the highest mode of lateral motion, for horizontal motion. These values are based on natural frequencies of structural members within the shelter. It is apparent that a certain amount of shock isolation would automatically be provided by the supporting structural members. It is recommended in Reference A. 1 that equipment frequencies between 1/2 and 2 times those of the supporting structural members must be avoided, or provision made for them by considering a resonance phenomenon with a sustained harmonic input.

Reference A. 13 mentions that, in general, most items of equipment, including fairly delicate electronic equipment, can sustain shocks which might produce accelerations even on the order of as much as 5 g. provided that the frequency of the element at which this acceleration is experienced is relatively high, on the order of 50 to 100 c.p.s. A five g. acceleration for an element having a low frequency would, however, be much more serious and would produce large relative displacements. Reference A. 22 makes the same statement. Although not specifically stated in References A. 13 and A. 22, the implication appears to be that a peak equipment response of 5 g. due to ground shock would generally require isolation at frequencies below 50 to 100 c.p.s. thereby avoiding possible amplifications due to resonance with the equipment components having frequencies in the range of 50 to 100 c.p.s. However, if the equipment frequencies are lower and in the range of the isolation frequency, amplifications may result and the tolerable peak acceleration of the system would be reduced.

The most delicate types of equipment in terms of shock resistance are reported in Reference A. 22 as follows:

a. Rotary drums, such as magnetic memories
b. Cathode ray display tubes
c. Power supply units
d. Relays in telephone switching circuits
e. Tape units and core storage units

It is stated in this reference that items (a) and (b) may have failures under operating conditions at acceleration levels as low as 2 g. and items such as (c), (d), and (e) at considerably greater accelerations, "for example 5 to 10 g." Reference A. 13 also reports on items (a), (b), and (c) and states that items (a) and (b) may have failures at acceleration levels as low as 1.5 g., and items such as (c) at only slightly greater accelerations if the frequencies correspond to resonance with the natural frequencies of the equipment. Critical accelerations for these fragile items apparently may be less than the 5 g. value.

According to many other sources of information in the field, general tolerable acceleration values applicable for most items of equipment are presented as abstracted below. In order to specify a safe tolerance value which covers a wide range of equipment, these values would appear to be necessarily conservative. In addition, the tolerance values for many of the items are based on experience rather than shock tests. Actual shock tests indicate that considerably higher acceleration values can be tolerated by certain items of equipment.

Reference A.1 states, "It is not clear at this time whether any piece of equipment is in fact sensitive to less than 1.5 g. for the actual type of motion (ground shock motion) to which it may be subjected".

Reference A.23 infers that few, if any, equipment items isolated to within one g. would be vulnerable to damage.

Reference A.24 points out that, during shipment by rail or truck, most equipment sustains a shock of 3 g. or more without any special shock-resistant packaging and, therefore, this value can be considered as a safe fragility value. However, if special precautions are required to cushion sensitive components during shipping, a lower fragility level must be assumed. Fluorescent lighting fixtures (with lamps) have been tested and fragility levels found to be in excess of 20 g.

Reference A.25 describes several shock tests of fluorescent fixtures with lamps where peak tolerable accelerations varying between 29 and 32.5 g. were recorded.

As discussed at a meeting with the Korfund Dynamics Corporation (Section B-2), they consider that 3 g. for general mechanical equipment and 1 to 2 g. for fragile electrical and electronic equipment are safe tolerable shock values. The values are based primarily on transportation requirements

According to Westinghouse Corporation (Reference A.26), most of their commercial (not ruggedized) apparatus (primarily electrical) will withstand up to 5 g. without important structural damage; however, it is pointed out that a malfunction may result at this value or even at a lower value. A list of apparatus certified to withstand a response of 3 g. (not tested) is presented. Ruggedized equipment tested indicated that most such equipment would tolerate a peak acceleration of 20 g. and greater.

Westinghouse Corporation has tested electrical equipment used in the TITAN program (Reference A.26). Tolerable shock levels ranged from 14 to 116 g. with the majority at about 20 g. However, in some cases, particular items were ruggedized to eliminate weak links in the equipment which otherwise may have resulted in damage or malfunction at considerably lower values. This illustrates the large difference between a general safe tolerable value, or say 3 g., for a wide range of equipment and actual values for particular items (although the difference is partially due to modifications).

Reference A.27 presents recommended ground shock vulnerability coordinates (to be used in conjunction with the design shock spectra) for various types of mechanical and electrical equipment. The coordinates are in terms of the frequency and peak acceleration applicable for both horizontal and vertical motion. Values are given for shock mounted and non-shock mounted items and are based on moderate damage. Values for severe damage are also given. These values given in the summary are considerably higher than the general tolerance values based on transportation requirements. In every case, the shock-mounted tolerance is higher than that for the same item not shock mounted. This is probably due to the fact that the non-shock mounted system frequency may be closer to the frequency of the equipment components thereby lowering the tolerance due to amplifications.

As discussed during the meeting with Space Technology Laboratories (Section B-3), it is felt that most standard equipment of the type likely to be housed in civil defense shelters could generally sustain shock responses in the order of 5 to 7 g. without having to be ruggedized.

During the meeting at the Air Force Special Weapons Center (Section B-5) it was pointed out that Reference A.20 presents a summary of test results for equipment. The test environment data for these tests are generally in terms of a hammer drop distance associated with an impact test. This information alone is not sufficient to be directly related to a peak tolerance which can be considered in conjunction with ground shock response spectrum. However, for some of the shock tests, spectra have been recorded which may be comparable to the ground shock spectra. It was pointed out that there is a lack of shock test data on commercial grade equipment.

As discussed during the meeting at the Naval Research Laboratory (Section B-7), most equipment can sustain a peak acceleration greater than 3 g., although a sustained vibration of plus and minus 3 g. could cause damage depending upon the frequency of the motion as compared to the equipment frequencies. However, when isolating equipment to tolerable acceleration response values, low frequency systems (compared to equipment frequencies) are achieved and resonance should not be a problem. In general, the determination of an appropriate shock tolerance for equipment requires individual consideration by analysis or shock tests.

For other interior components, such as partition walls, furniture, cabinets, ductwork, etc., it is probably necessary to evaluate the peak shock tolerance for each individual item based on the strength and flexibility of the item and its supports. However, most of these items are probably considerably rugged, although unreinforced partition walls may be sensitive to horizontal accelerations. If accelerations are greater than one g., the items will separate from the structure slab unless they are attached. This separation could cause secondary damage due to collision with the floor or other nearby objects as well as injury to personnel.

b. Conclusions

Based on review of the data discussed above and summarized in Section A-5.2, the conclusions presented below constitute recommended criteria pertaining to shock tolerances for equipment and other interior components housed in civil defense shelters. Application of these recommendations with regard to this study is presented in Chapter IV.

Based on transportation and normal shock requirements, standard commercial mechanical and electrical equipment items are known to be able to sustain at least 3 g. Electronic equipment items can generally sustain 1.5 g.

Actual shock tolerances for standard commercial mechanical and electrical equipment are, in general, higher than 3 g., and in most cases, 5 to 10 g.

Equipment specifically ruggedized to resist shock effects can in most cases sustain 20 g. or greater.

Isolation frequencies in the range (between 1/2 and 2 times) of the frequencies of the equipment components should be avoided in the case where the equipment is subjected to a vibratory motion. In most cases, shock isolation at frequencies less than 10 or 15 c.p.s. for standard commercial equipment and less than 20 c.p.s. for ruggedized equipment will avoid resonance problems.

Sufficient rattle space must be provided to accommodate relative displacements resulting from the flexibility introduced by the shock mounting.

The effect of rocking or tilting motion on the performance of the equipment must be considered.

Mounting connections must be provided with sufficient strength to carry the forces due to the peak accelerations.

In order to establish the actual shock tolerance for a particular item of equipment, testing or analysis is necessary. Testing is discussed in the following section (A-6).

For miscellaneous interior components, such as partition walls, furniture, cabinets, hardware, ductwork, piping, etc., each item must be evaluated and sufficient strength, anchorage, and flexibility provided.

A-5.2 Summaries of Information Obtained from References

a. Summary of Reference A.1

This guide advances some data on equipment vulnerability relevant to the ground-shock environment and points out that it is not sufficient to assess vulnerability in terms of an acceleration limit only, since the frequency corresponding to this limit is also a factor. It is stated that "in general, a vulnerability spectrum can be drawn as a function of some measure of frequency of the input motion and that this will have peaks at the natural frequencies of the piece of equipment. If these are close together, possibly a uniform acceleration vulnerability may be postulated, although this probably drops down for low frequency inputs."

The vulnerability to be concerned with is that due essentially to a single pulse for low-frequency inputs or to several pulses for high-frequency inputs, but certainly not that due to a steady state oscillatory input, according to this report. It is stated that "In any case it appears that we need not be generally concerned with inputs having a frequency higher than about 15 to 20 c.p.s. for vertical motion, except near columns, and about 5 c.p.s. even for the highest mode of lateral motion, for horizontal motion."

It is further stated "that if the structural design does not achieve the necessary degree of attenuation of acceleration then the equipment may be shock mounted or the design modified. It is usually cheaper and simpler to shock mount the equipment except in very special cases. It appears entirely feasible to limit the shock accelerations experienced by equipment to about 2.5 g. for vertical motion, and possibly about 1.5 g. for horizontal motion, by approximate measures in the structural design. Any further reductions can be achieved only by unusual methods and require more detailed study and analysis. It is recommended that further reductions, if needed, be obtained by individually shock mounting vulnerable pieces of equipment. It is not clear at this time whether any piece of equipment is in fact sensitive to less than 1.5 g. for the actual type of motion to which it may be subjected. It is possible that higher frequency steady sinusoidal motions may cause damage to equipment at lower accelerations, but this is not pertinent to the problem."

"In order to reduce somewhat the accelerations near the columns, relatively thin energy absorbing pads may be used. These will not achieve a major shock isolation effect, but they will be of help in keeping high frequencies from being transmitted through the columns."

It is pointed out that frequencies between 1/2 and 2 times those of the structure must be avoided, or provision made for them by considering a resonance phenomenon with a sustained harmonic input.

b. Summary of Reference A. 13

This guide gives damage criteria for equipment in a ground shock environment and it states that "in general the sensitivity to shock of a piece of equipment is dependent not only upon the components which make up the equipment, but upon the mounting of these components in the piece of equipment and also on the mounting of the equipment itself on the structure or element to which it is attached. The sensitivity of each item is dependent upon the over-all characteristics of the entire system and a change in one part of this system may affect the shock sensitivity of all the parts connected together. In other words, placing a transformer on a flexible-plate mounting may change the characteristics of the transformer in resisting shock as well as the characteristics of control equipment mounted on the transformer".

It is stated that, "in general most items of equipment, including fairly delicate electronic equipment, can sustain shocks which might produce accelerations on the order of as much as 5 g, provided that the frequency of the element at which this acceleration is experienced is relatively high, on the order of 50 to 100 c.p.s. A 5 g. acceleration for an element having a low frequency would, however, be much more serious and would produce large relative displacements."

The most delicate types of equipment in terms of shock resistance are reported as follows:

a. Rotary drums such as magnetic memories;
b. Cathode ray display tubes; and
c. Relays in telephone switching circuits.

Items such as (a) and (b) may have failures under operating conditions at acceleration levels as low as 1.5 g., and items such as (c) at only slightly greater accelerations if the frequencies correspond to resonance with the natural frequencies of the equipment, according to this report. It is stated that "such items require special shock mounting and substitution of equipment of another less vulnerable type is desirable."

c. Summary of Reference A.20

It is described in this report that shock response spectrum can be employed as the primary criterion of damage potential. The selection of equipment or the decision to provide shock isolation can be made on the basis of a comparison of the spectrum of the service shock with that of a test shock which the equipment has survived.

The following problems are pointed out:

"Rarely has the model and make of the equipment been determined at the stage in the design where the decision whether or not to isolate the equipment must be made. In the usual procurement procedure, the entire facility design is completed before the final selection of equipment. In the interest of economy it is desirable to utilise commercial grade equipment wherever possible. To specify arbitrarily that the equipment withstand the service shock without regard for commercial standards may require that a specially designed unit be constructed."

"A further complication arises from the lack of a comprehensive body of shock test data on commercial grade equipment. Ample test data would provide the isolation system designer with a basis for forming a reasonable estimate of the shock tolerance level of equipment in which he is interested. Many important items have never been tested; in those instances where tests have been made, the strength of the test shock is rarely defined by its response spectrum. In any case, the data are widely scattered."

"As an initial step in assembling shock test data on the type of equipment regularly employed in underground protective structures, a large number of shock-test reports have been abstracted and the results tabulated (in the report)."

The test environment data for the tests reported is generally in terms of a hammer drop distance associated with an impact test. For some of these tests, spectrum were recorded which can be compared to the ground shock spectrum. If the equipment withstood the test and the test spectra is more than the ground shock spectra, then the equipment is capable of surviving the ground shock.

d. Summary of Reference A.21

This report does not present any shock tolerances for equipment, but it does examine the design requirements for equipment required to withstand shock and vibration. Also, a discussion of equipment vulnerability, malfunction, and damage sustained during laboratory tests is presented. The following data are abstracted from this report:

Equipment of a type required to withstand shock and vibration generally consists of a housing or chassis to provide structural strength and an array of functional components. A suitable design is characterized by (1) properly selected or designed components, (2) chassis mounting to minimize damage from shock and vibration, and (3) a chassis capable not only of withstanding shock and vibration but also of providing a degree of protection to the components.

One of the more troublesome problems in the design of equipment is attainment of the proper balance between flexibility and rigidity of the chassis. For a particular shock motion, the maximum acceleration experienced by a component is determined primarily by the natural frequency of the chassis supporting the component. The acceleration decreases as the natural frequency decreases. Thus, components that are susceptible to damage from shock may be given a degree of protection by mounting them on a relatively flexible chassis; however, if the equipment is required to withstand shock as well as vibration, it is possible that the flexibility introduced to attenuate the shock may lead to a failure as a result of vibration.

Failure or damage from vibration usually is the result of a resonant condition, i.e., the chassis or component has a natural frequency that coincides with the frequency of the forcing vibration. In some applications, e.g., on naval ships, the maximum frequency of the forcing vibration is relatively low, and it becomes feasible in most instances to design equipment having natural frequencies greater than the highest forcing frequency. On the other hand, vibration in aircraft is characterized by relatively high frequencies; as a consequence, it is not feasible to design equipment having natural frequencies higher than the forcing frequencies. A condition of resonance often must be tolerated. In extreme conditions, the effect of the resonant condition can be alleviated by the provision of damping or energy dissipation.

Failure of equipment as a result of shock and vibration may consist of (1) damage so severe that the ability of the equipment to perform its intended function is impaired permanently or (2) temporary disruption of normal operation in a manner permitting restoration of service by subsequent adjustment of the equipment or termination of the disturbance. For example, a common type of disruption involves excessive vibration of the elements within an electronic tube; damage may not occur, but the electron tube may generate spurious signals and thus be unable to perform its intended function. Another type of temporary disruption may occur in a relay or circuit breaker where shock or vibration causes unintended and improper operation. Normal operation can be restored readily if the equipment is accessible to personnel for adjustment. Meanwhile, serious consequences may have developed from the disruption.

A record of damage sustained by equipment during a shock or vibration test is significant in emphasizing the considerations that are important in attaining resistance to damage from shock and vibration. Compilations of damage experience show that failure of principal chassis and mounting brackets is the most common form of damage. During shock, a chassis may not have sufficient strength to withstand the forces that are applied. During vibration, resonant conditions may develop and the relatively undamped chassis may fail from fatigue. Failure of electrical leads from fatigue is common, often because the leads are used improperly to support resistors and capacitors. Failure of electronic tubes is common, mainly because they are used in large quantities in electronic equipment although failure in terms of percentage of tubes used is not large. On the other hand, a relatively large percentage of incandescent lamps and cathode-ray tubes experience failure. In some instances, failure may be ascribed to the inherent properties of the components that failed; in other instances, failure is the result of improper installation.

e. Summary of Reference A.22

This report consists of Parts A and B. Part B, reported herein, gives the theoretical basis for the procedures given in Part A. Each part contains a chapter on shock effects covering shock vulnerability of equipment.

The following is quoted from this report:

"The problem of estimating shock vulnerability of equipment is complicated because only small segments of information pertaining to this topic are available. Even when pieced together, information in this area is still fragmentary. As a result, the information may have to be revised periodically as additional information becomes available."

"Damage or failure of equipment may result from fracture or breakage of parts, yielding or permanent deformation, misalignment, relative motion between components (for example, electronic components), loosening of fasteners, low cycle high stress fatigue, etc.".

"A comprehensive summary of shock and vibration damage was published by the Department of the Navy in 1953 ('Damages Resulting From Laboratory Vibration and High-Impact Shock Tests,' Bureau of Ships, Department of the Navy, Publication NAVSHIPS 900, 185, 11 September 1953). As used herein the term vibration refers to continuing oscillatory motion which may damp out with time while shock refers to an abrupt transient disturbance which may be followed by vibration in many cases. Two pertinent paragraphs of the conclusions in this report are quoted below."

'An equipment well designed for vibration was usually very good for shock, whereas, an equipment that passed shock tests satisfactorily may or may not have been capable of passing vibration tests. The reason for these results was that many of the equipments tested were too flexible and thus were resonant in the testing frequencies. However, the flexibility was usually beneficial for shock if collision did not occur. Vibration tests were normally performed on the equipments first, followed by shock, one exception being lighting equipments which were shocked before being vibrated because of the fragile nature of the lamps.'

'One very interesting fact observed in examining the breakdown of damages is that the greatest majority of the damages (approximately 90 percent) resulting either from shock or from vibration can be eliminated in future designs using components currently available. For that matter, in a great many of the present designs damages can be sharply reduced without extensive design changes. The exception would be those equipments where it is not possible to raise the resonant frequency above test frequencies by methods which would not unduly increase the severity of the shock test of the unit.'

"The implication of the last paragraph is that often it is possible to fabricate highly shock-resistant equipment with available components if proper design and shock-proof testing are undertaken. The advent of increased awareness of the advantages of shock testing, coupled with the use of solid-state components, has provided a much larger margin of safety against shock damage for certain types of equipment as compared to earlier years."

"In general, the vulnerability of equipment to shock is dependent not only upon the components which make up the equipment but also upon the mounting of these components in the piece of equipment and also on the mounting of the equipment itself on the structure or element to which it is attached. The sensitivity of each item is dependent upon the overall characteristics of the entire system, and a change in one part of the system may affect the shock sensitivity of all the connected parts. In other words, placing a transformer on a flexible plate mounting may change the characteristics of the transformer in resisting shock as well as the characteristics of control equipment mounted on the transformer. Thus, specifying the level of resistance for individual items may not be sufficient. Generally the item is part of a coordinated system which must remain undamaged to perform its mission satisfactorily."

"The type of shock sensitivity depends on the item; one equipment item may be sensitive to several types of excitation. A good example described involved a cabinet mounted amplifier signal system. Not only were some of the electronic components extremely shock sensitive, but in addition the cabinet framework and panels were damaged in shock tests to such an extent that the rest of the equipment was rendered useless. Generally the vulnerability levels for equipment can be expressed in terms of acceleration (force overloading) or occasionally deflection (relative deflection or permanent set). Occasionally reference is made to frequency at which the acceleration, etc., would damage the equipment or render it useless. Another common criterion involves steady state vibration (frequency, acceleration level, and number of cycles)."

"In order to make use of response spectrum concepts in making a vulnerability analysis for shock it is necessary that the vulnerability criteria (acceleration or displacement) be known as well as the frequency (or band of frequency) in which the damage may occur. It was on this base that estimates of frequency and vulnerability of typical equipment items presented in Part A were prepared. Under certain rare conditions combinations of displacement, velocity or acceleration criteria (without a knowledge of frequency range, for example) can provide a sufficient basis for making a vulnerability analysis."

It is stated that, "in general, most items of equipment, including fairly delicate electronic equipment, can sustain shocks which might produce accelerations even on the order of as much as 5 g (5 times the acceleration of gravity) provided that the frequency of the element at which this acceleration is experienced is relatively high, on the order of 50 to 100 c.p.s. A 5 g acceleration for an element having a low frequency would, however, be much more serious, and would produce large relative displacements."

The most delicate types of equipment, in terms of shock resistance, are reported as follows:

a. Rotary drums such as magnetic memories.
b. Cathode Ray display tubes.
c. Power supply units.
d. Relays in telephone switching circuits.
e. Tape units and core storage units.

It is stated that, "items such as (a) and (b) may have failures under operating conditions at acceleration levels as low as 2 g., and items such as (c), (d), and (e) at considerably greater accelerations (for example 5 to 10 g.)."

It is pointed out that recent magazine advertisements for solid state diodes make open claim for meeting the following typical environments for stable operation.

Instantaneous (Input)shock - 1000 g.
Continuous acceleration - 20 g.
Vibration - 15 g. over 10 to 2000 c.p.s. (but no cycle limit given - the leads would obviously be the weak link here).

It is stated that, "the types of vulnerable items in hardened structures are too many and too diverse to summarise but would include such items as utility systems, batteries, refrigerating units, electronic equipment, motors and generators, bearings, shock mounts, fasteners, gears, latches, ducts, and personnel". It is pointed out that, "in long structures, or when two elements are connected together and are attached to structures which may move in different manners, relative motion must be considered and may be a definite source of vulnerability. Entrances to tunnels, tunnels connecting structures, piping, and shafts, and leads connecting mechanical and electrical equipment, are examples of items which should be examined in this connection".

f. Summary of Reference A. 23

With regard to equipment fragility and tolerances, this report presents a general discussion of the basic elementary concepts involved. It is stated that "if the supporting structure is to be shock isolated to a dynamic load of one g. or less for some reason, little, if any, of the equipment would require additional shock protection or special mounting considerations".

g. Summary of Reference A.24

This report does not present any shock tolerances for equipment but it does point out that studies of shock loadings encountered by equipment during shipping have been reported and indicate that equipment shipped by rail or truck may experience shock loadings of 3 g. or more. It is concluded in the report that if equipment is normally shipped by rail or truck without special shock-resistant packaging, and, if equipment is rarely damaged during the normal shipment, the equipment can be assumed to have a fragility level in excess of 3 g. If special precautions are required to cushion sensitive components during shipping, a lower fragility level must be assumed. Fluorescent lighting fixtures (fixture and lamp) may have fragility levels in excess of 20 g. Several manufacturers have tested fixtures and can certify minimum fragility levels of this magnitude. Incandescent lamps and fixtures generally are not as shock resistant, and "rugged duty" lamps are required.

h. Summary of Reference A.25

Several 4-ft. fluorescent fixtures with lamps were shock tested with the peak tolerable acceleration varying between 29 and 52.5 g.

i. Summary of Reference A.26

This report presents shock tolerances for various electrical equipment items manufactured by Westinghouse. The items were tested (using the Navy High Impact Machine and other test equipment) by Westinghouse specifically for the TITAN program and some of the shock levels noted are for special or ruggedized equipment. In all, 66 items were tested, the shock levels varying from 14 to 116 g. The lowest level of 14 g. was recorded for 3-phase transformers. 14.6 g was recorded for a 1000-watt mercury lamp. The highest level of 116 g. was recorded for a 1000-watt lamp ballast and a 2425-watt 2-lamp reactor. A fluorescent lighting fixture with lamps, a high-bay lamp, starters, relays, transformers, voltage regulators, resistors, transducers and fuses had tolerances of about 20 g. Switchgear components presented tolerances of 50 g.

It is stated in the report that "most commercial (not ruggedized) apparatus will withstand up to 5 g. without important structural damage. Functional derangements (malfunctions), however, may be objectionable even at low peak accelerations if the component response motion renders the apparatus incapable of performing its principal military function even though structurally undamaged."

A list of apparatus certified to withstand a response of 3 g. (not tested) for the TITAN program is presented and includes such items as circuit breakers, 1-phase transformers, panelboards with E-frame breakers, multi-motor starters, overload relays, and timing relays.

j. Summary of Reference A. 27

This report consists of Parts A and B. Part A, reported herein, gives procedures and Part B presents the theoretical basis for these procedures. Each part contains a chapter on shock effects covering shock vulnerability of equipment.

This report describes and illustrates a method of shock vulnerability analysis based on the response spectrum which consists of matching the acceleration spectrum with the vulnerability coordinates (in terms of frequency and acceleration) for the particular class of equipment.

With regard to the vulnerability coordinates, estimates of typical ranges are given for tolerable limits without incurring moderate damage. Also given are recommended values corresponding to moderate damage and severe damage. The typical ranges are listed below. Recommended values (presented in the report) for moderate damage lie midway between the typical ranges; and recommended values for severe damage are four times greater than the acceleration values for moderate damage. It is pointed out that, "softer shock mounting may be used in highly protected structures".

Estimates of Frequency and
Vulnerability of Typical Equipment Items

Item	Shock Mounted	Typical Ranges of Fundamental Natural Frequency	Typical Ranges of Estimated Vulnerability Level
		c. p. s.	g.
Heavy Machinery--Motors, Generators, Transformers, etc. (4000 lb.)	No	5-15	10-30
	Yes	1-5	20-60
Medium Wt. Machinery--Pumps, Condensers, Air Conditioning, etc. (1000 to 4000 lb.)	No	10-20	15-45
	Yes	1-7	30-90
Light Machinery--Fans Small Motors, etc. (1000 lb.)	No	15-35	30-70
	Yes	2-10	50-150
Racks of Communication Equipment, Relays, Rotating Magnetic Drum Units, Large Electronic Equipment with Vacuum Tubes	No	10-50	2-8
	Yes	2-10	10-90
Small Electronic Equipment, Radios, Incandescent Lamps	No	20-80	20-80
	Yes	2-25	50-450
Cathode Ray Display Tubes	No	5-25	1.5-4.5
	Yes	1-5	5-25
Transistorized Computers, Fluorescent Lamps and Fixtures, Nuclear Reactors	No	10-50	5-20
	Yes	1-15	20-200
Storage Batteries (All Types), Piping, and Duct Work	No	5-35	20-120
	Yes	1-10	50-250

SECTION A-6

SHOCK TESTING FACILITIES AND CURRENT TECHNIQUES USED FOR SHOCK TESTING

A-6.1 Discussion and Evaluation

This section is devoted to shock testing facilities and current techniques used for vibration and impact testing of personnel and equipment. It is divided into two parts: "Personnel Testing" and "Equipment Testing".

a. Personnel Testing

A number of shock and vibration testing machines have been developed to study the physical, physiological, and psychological responses of man to vibration and abrupt acceleration or deceleration. These devices are in current use, principally in the military departments, and include mechanical and electrodynamical shake tables, vertical accelerators, shock machines, and horizontal and vertical accelerators and decelerators, e.g., rocket sleds on tracks and drop towers. See, for example, References A.7, A.28, and A.32. Requirements for these shock and vibration machines include adequate safety precautions, safe and accurate control of the exposure, and sufficient load capacity for subject, seat, and instrumentation.

Many fundamental studies of effects of mechanical vibration on man are performed with single-degree-of-freedom sinusoidal forces using mechanical and electrodynamical shake tables. In general, these devices provide relatively simple motion patterns not representative of actual environments, and are used principally for systematic investigations of physiological effects of mechanical vibration under somewhat simplified conditions.

In order to study some of the physiological effects of mechanical vibration on man, a direct-drive, mechanical-vibration shake table capable of providing large sinusoidal vertical displacements has been designed and constructed by the Naval Research Laboratory (Reference A.28). It is used for a long-range research program at the Naval Medical Research Institute and is designed for a maximum tableload rating of 200 lbs. at any combination of displacements and frequencies not exceeding a 15 g. peak acceleration. The frequency range is 2.2 to 50 c.p.s. The excursion or total travel is variable from zero to four inches and may be changed continuously while the machine is operating. The essentially harmonic motion of the table occurs only in the vertical direction.

The Wright Air Development Division houses a shake table designed for sinusoidal motions in either a horizontal or vertical plane (Reference A.7). This device is used for studying human tolerance and biodynamic problems at large-amplitude vibrations and also for testing seats, harnesses, and other equipment. It can operate in the frequency range from 2 to 30 c.p.s. and has a maximum acceleration rating of about 20 g. (at the higher frequencies). The double amplitude is adjustable between zero and 9 inches. In actual studies of human tolerance, the machine produced vertical accelerations in the order of 2 to 3 g. in the frequency range between 3 and 10 c.p.s. (Reference A.8).

Other shake tables widely used for human factors research include the U. S. Army Medical Research Vibrator at the Army Medical Research Center, Fort Knox, Kentucky, and the Boeing Human-Vibration Facility at Wichita, Kansas (Reference A.28). The former device can produce either vertical or horizontal motions throughout the frequency range from 5 to 2000 c.p.s. The maximum displacement (double amplitude) obtainable is 0.5 in. which decreases as the frequency is increased. Accelerations up to 10 g. are possible with a 280-lb. load and 20 g. with a 100-lb. load. The Boeing facility is capable of producing sinusoidal motions of either constant amplitude or varying amplitude in the vertical plane. Vibrations between 1 and 30 c.p.s. with amplitudes of 20 in. at the lowest frequency up to 1/64 in. at the highest frequency are produced.

Since the law of linear superposition is valid only in the linear physical domain, sinusoidal forces alone are not adequate for the study of non-linear physical responses or physiological and psychological reactions to complex force-time functions. Therefore, some machines have been designed uniquely to simulate to some extent certain actual environments. These devices are referred to as motion simulators. A vertical accelerator, for example, (References A. 7 and A. 28) employs a friction drive mechanism to permit the simulation of large-amplitude, low-frequency sinusoidal and random vibrations, such as those encountered in buffeting during low altitude, high-speed flight or those anticipated during the launch or reentry phases of spacecraft. This device can be programmed with random or periodic vibrations and transient acceleration patterns obtained from records under actual flight conditions. It is located at the Wright Air Development Division and can produce vertical sinusoidal motions with an amplitude of $\pm$ 10 ft. with an acceleration limitation of $\pm$ 3.5 g. between 0.3 and 10 c.p.s. In addition, an auxiliary vibrator can shake the platform horizontally with sinusoidal vibrations and is adjustable between 10 and 20 c.p.s. up to 0.12 in. amplitude.

A six-degree-of-motion simulator located at the Aerospace Medical Research Laboratories, Wright Patterson Air Force Base, will be operating in the near future. The purpose of this facility will be to explore human tolerance and performance under high-level angular and linear oscillations as anticipated during the reentry phase of space vehicles, low-altitude, high-speed flights of airplanes, and operation of escape systems at high speed. Simultaneous operation of all six degrees of motion with programmed acceleration patterns will be possible with this device which will have the capability of producing vertical linear motions from zero to 30 c.p.s. The maximum vertical displacements will be variable from 0 to about 10 in., and linear transverse and longitudinal motions will also be produced from 0 to 30 c.p.s. with maximum displacements variable from 0 to about 8 in. Motions in roll, pitch, and yaw will be from 0 to 30 c.p.s. with a maximum displacement of plus or minus 15 degrees in roll and pitch, and plus or minus 10 degrees in yaw.

Other machines for the study of human tolerance to ejection from high-speed aircraft (ejection seat) have upward or downward acceleration tracks with sliding seats projected by explosive charges. Horizontal tracks with rocket propelled sleds which can be stopped by special braking mechanisms have been used to study the effects of linear decelerations similar to those occurring in automobile or aircraft crashes. These devices produce force or acceleration-time functions which are approximately trapezoidal in shape. In actual tests with human subjects (Reference A. 7), rates of onset of acceleration up to 1,400 g./sec. with plateau durations of 40 g. have been used, although the capacity of the machines is generally higher. (See, for example, References A. 28 and A. 32).

In the simulation of shipboard shock motions, the U. S. Navy high-impact shock machine has been used for tests on personnel and cadavers (Reference A. 17). (A description of this device is given in the next section entitled "Equipment Testing".) In some studies to investigate shipboard shock effects on personnel, actual underwater explosions have been conducted against a ship. Devices which simply drop subjects from predetermined heights have been employed in other studies to determine impact effects resulting from falls, parachute jumps, automobile and aircraft crashes, and related decelerative phenomena (Reference A. 10). Various impact velocities may be generated depending upon the height of free fall.

To date, there have been no publications of tests or testing devices which were designed specifically to determine human tolerance to shock motions typical of those encountered in underground protective structures. As discussed with representatives of the Lovelace Foundation, DASA, and the Naval Medical Research Institute (Sections B-4, B-6 and B-8, respectively), shock testing to determine human tolerance to shelter motions would involve a somewhat elaborate program, particularly for civil defense shelters, since a wide range of age groups, physical characteristics, and body positions (sitting, standing, reclining) are involved. For obvious reasons, test results obtained on healthy young subjects (who are likely volunteers) would probably not be representative of tolerances nor of physical characteristics for other age groups. Nevertheless, studies using selected volunteers are well worth making providing care is taken in the interpretation of the data. With regard to future studies, the Air Force Special Weapons Center is considering performing tests on personnel in connection with the Minuteman Weapon System using the abovementioned six-degree-of-motion simulator at the Wright Patterson Air Force Base (Section B-5).

b. Equipment Testing

A great number of devices for shock testing of equipment are in use, particularly in the military departments. The individual capabilities of these devices vary widely in accordance with the shock requirements of, and the type of equipment to be tested, by each device.

In principle, shock testing is concerned with laboratory reproduction of equipment damage analogous to that occurring in field service. The effect of a shock motion on equipment depends not only upon the characteristics of the motion but also on the properties of the equipment and its mounting. In general, the shock motion that occurs in any given field condition is affected by many variables, and the characteristics of the motion vary significantly from one occurrence to the other. Thus, shock machines, in general, have not been designed to simulate a given shock condition, but rather to generate shock motions which have a damage potential at least as great as any probable field shock for which protection is required (References A. 29, A. 30).

There are basically three methods of specifying shock tests (References A. 13, A. 20, A. 24, A. 29). First, a shock motion can be specified. A shock test then consists of causing the points of attachment of the item under test to partake of this motion. Since one of the most characteristic features of shock motions is their infinite variety, an "equivalent" motion is usually specified in terms of a sudden velocity change or as an acceleration pulse devoid of dominant frequencies. Second, a shock spectrum can be specified. A shock test then consists of causing the points of attachment of an item under test to partake of a motion that has this spectrum. Third, a shock machine can be specified together with a procedure for its operation. A shock test then consists of mounting the test item to the machine in a prescribed manner and of operating the machine according to the given procedure. This method of specification requires that those responsible for the test provide a machine which generates appropriate shock motions, or spectra, that is, a shock with the damage potential as may be required.

Reference A. 29 mentions that the first and second methods of specifying shock tests are somewhat similar and impractical of achievement unless the items under test are perfectly rigid or relatively light. The cause of the difficulty is the reaction of the load on the test machine, that is, the influence of the shock-machine loading on its shock motions or spectra. This reaction causes the applied shock motions to become dependent upon the nature of the equipment under test, so that, unless large variations are permitted, the test cannot practically be made as prescribed. The only practical solution to this problem, according to Reference A. 29, is to consider specified values of shock motions or spectra as nominal values.

In the specification of a test shock motion, it is considered necessary to specify both maximum acceleration and velocity damage because most equipment items comrpise component structures with a wide range of natural frequencies having responses to a shock motion which may vary widely depending upon the ratios of the duration of the shock loading to the natural periods of the equipment components (Reference A. 30). Similarly, in the specification of a shock spectrum, it is necessary to specify the spectrum throughout its frequency range.

A number of shock testing machines have been developed for general and special purposes, particularly for the qualification of equipment for military service. See, for example, References A. 13, A. 20, A. 23, A. 24, A. 26, A. 29, and A. 30-A. 33 and Section B. 7. Among some of the characteristic types of shocks produced with certain of these devices are (1) velocity shocks or step velocity changes; (2) simple shock pulses, such as a half-sine acceleration pulse, a rectangular force pulse, and a sawtooth acceleration pulse; (3) single complex shocks; and (4) multiple shocks.

Several devices produce shock motions having spectra which are generally equivalent to the spectra that define the shock used as a basis for the design of equipment in hardened construction sites. These devices include the U. S. Navy high-impact shock machines for lightweight and mediumweight equipment, a medium-impact sand drop table, and a varipulse drop table.

The Navy machines (Reference A. 29) were developed primarily to certify naval shipborne equipment for shocks of the nature and intensity that might occur on board a ship that is subjected to severe, but sublethal, noncontact underwater explosions. They are intended to test equipment that will be secured to or mounted on bulkheads or decks.

The machine for lightweight equipment is used for items weighing up to 250 lbs. The machine can apply shocks along three mutually perpendicular axes (one at a time). Vertical shocks are induced by allowing a 400-lb. weight to fall vertically and strike the top edge of the test equipment mounting plate. Horizontal shocks are produced by allowing a 400-lb. hammer pendulum to swing through a controlled arc and strike the back of the equipment mounting plate. The mounting plates can be rotated 90 degrees so that the hammer strikes the edge of the plate, thereby inducing a shock along the third orthogonal direction. Typical acceleration spectra obtainable with this machine for a 57-lb. rigid load and a one-ft. hammer drop are characterized by limiting displacements of about 1.7 in., limiting accelerations of about 2000 g., and limiting velocities of about 90 in./sec. which rise to about 300 in./sec. near an acceleration of about 500 g.

The Navy machine for mediumweight equipment is used for objects weighing up to approximately 4500 lbs. This machine consists principally of a 3000-lb. hammer pendulum and a 4000-lb. anvil. The hammer can be dropped from a controlled maximum height of 5.5 ft. so as to swing around on an axle and strike the anvil on the bottom, giving it an upward velocity. The anvil is permitted to travel a maximum distance of 3 in. before being stopped by a ring of retaining bolts. For a 4423-lb. rigid load attached to this device, and a 5.5-ft. hammer drop, typical shock spectra are characterized by a limiting deceleration bound of about 500 g., a limiting displacement of about 3 in., and a limiting velocity of about 130 in./sec. which increases sharply to about 600 in./sec. near the limiting acceleration of 500 g.

The sand drop machine mentioned above was developed for the U. S. Air Force for investigations of shock effects on airborne equipment. It consists basically of a drop table the fall of which is arrested by a sand box which forms the base of the machine. An adjustable number of blocks, attached to the underside of the table, penetrate the sand and determine the magnitude and duration of the stopping acceleration. The machines are made of different sizes so that loads up to about 1200 lbs. can be accommodated. The height of free fall may be varied at will to a maximum of 5 ft. Therefore, velocity changes up to about 18 ft. /sec. can be produced. For a free fall of 13 in. and with a test load of 150 lbs., this device produces a shock spectrum having a peak velocity of about 90 in. / sec. and a maximum acceleration of about 100 g.

The abovementioned varipulse drop table is a recent modification of the sand drop table. Carefully shaped lead or rubber-like pellets are used in lieu of the sand and wooden blocks to arrest the fall and produce a pulse of desired shape. Maximum equipment weights of about 400 lbs. can be accommodated with this device. Representative shock spectra are similar to that of the sand drop device. Peak velocity changes of 15 to 20 ft. /sec. can be produced.

It is noted that the size and weight of equipment that can be tested on the sand drop or varipulse shock machines are limited. Furthermore, the drop machines induce vertical shocks only, and special equipment mounts must be employed to orient the equipment parallel to the vertical axes of the test structure so that shocks can be delivered along other axes. Several modified drop test machines have been designed to overcome this mounting difficulty. These include ramped slides, trapeze mounts, and horizontal buffers.

It should be recognized that a variety of shock spectra are obtainable from any particular machine depending upon the mode of operation. The spectra are influenced by the weight of the equipment under test, by the method of attaching the equipment to the machine, and by the energy input to the machine, (i.e., by the height of the hammer pendulum fall in the case of the Navy machines or by the height of free fall, including the block arrangement, sand density, or pellet arrangement in the case of the drop testing machines). For the Navy machines, the height of hammer blows should be specified so as to provide a shock test spectrum which equals or exceeds the design (ground shock) spectrum throughout the frequency range. This requires that the height of the hammer drop be selected to induce a load velocity equal to or greater than the specified response-spectrum velocity. When preparing drop test specifications, the height of fall and the block and sand (or pellet) arrangements should be selected on the basis of acceleration requirements; the resulting displacements and velocities will generally exceed specified spectrum values.

Weight limitations of both the Navy high-impact shock facilities and the drop test machines pose the problem of how to test large and heavy units of equipment, such as diesel engines and refrigeration compressors. In some instances, this problem has been resolved by subjecting the equipment to simple drop tests wherein the equipment is allowed to fall freely from a predetermined height onto a rigid or resilient base. The height of the drop is the height which results in an impact velocity equal to the maximum spectrum-velocity bound. The resiliency of the base against which the equipment collides determines the experimental spectrum acceleration bound, which should equal or exceed the specified bound.

Selected equipment items have been tested under various Federal programs for use in hardened construction sites (References A.24 and A.26). Some tests for hardened-site equipment have usually been performed with drop-type test machines (References A.23, A.26). For example, in the certification of certain electrical and electronic equipments for the Titan Weapon System, two drop testers have been employed: a sand drop table and a "trapeze" spring drop table (Reference A.26). The method of certifying the equipment consisted basically of exposing the equipment to a shock which had a shock spectrum that equaled or exceeded a specified Titan ground-shock spectrum throughout its frequency range. The sand drop table employed in the tests is basically the same as that described earlier. The spring drop table consists basically of a platform which is released from a predetermined height and which is arrested by an assembly of spring-loaded snubbing blocks. Its shock motions, or spectra, are controlled by varying the spring tension and the height of fall.

Tests have been conducted on equipment to be mounted upon shock-isolated floors and structures by using spring-mounted test platforms or by using the actual shock-isolated floors or structures (Reference A. 23). With regard to the Minuteman Weapon System Launch Control Center, shock testing of its air-spring suspension equipment platform with the equipment mounted on the platform is contemplated using a shock-testing facility at the Air Force Special Weapons Center (Sections B-3 and B-5). Some experimental studies of responses of missiles and their shock isolation structures have been carried out at actual hardened sites. Basically, these studies consisted of displacing the isolation structures a predetermined amount by some type of jacking mechanism and then releasing them so that the responses could be measured and compared with theoretical predictions.

A-6.2 Summaries of Information Obtained from References

a. Summary of Reference A.7

This reference presents a section devoted to a discussion of methods and instrumentation used for mechanical shock and vibration studies on man and animals. A summary of the characteristics of shock and vibration machines used for human and animal experiments, as well as the ranges of time and acceleration obtainable with certain devices, is presented. References are made to papers describing the use of the machines for biological purposes.

It is stated in the discussion that the desire to study the physical, physiological, and psychological responses of biological specimens in the laboratory under well-controlled conditions has led to the use of standard and specialized shock and vibration testing machines for experiments on man and animals. An accurate simulation of the environmental conditions to which man is exposed frequently is not feasible for technical and economic reasons or may even be undesirable because of a need for more systematic investigation under somewhat simplified conditions. Thus, most investigations are limited to a study of a single degree of freedom at a time in which the human test speciman is vibrated only in one direction. Many fundamental studies are performed with sinusoidal forces. Usually mechanical and electrodynamic shake tables are employed for this purpose. Requirements for all shock and vibration machines include: adequate safety precautions, safe and accurate control of the exposure, and sufficient load capacity for subject, seat, and instrumentation. Since the law of superposition is valid only in a linear physical domain, sinusoidal forces alone are not adequate for the study of non-linear physical responses or physiological and psychological reactions to complex force functions. Therefore, some of the machines listed are designed uniquely for exposure of humans. One vertical accelerator, for example, employs a friction-drive mechanism to permit the simulation of large-amplitude sinusoidal and random vibrations, such as those encountered in buffeting during low-altitude, high-speed flight or anticipated during the launch or reentry phases of spacecraft. This device can be programmed with acceleration recordings obtained under actual flight conditions. Other machines for the study of human tolerance to ejection from high-speed aircraft (ejection seat) have upward or downward acceleration tracks with sliding seats projected by explosive charges. Horizontal tracks with rocket-propelled sleds which can be stopped by special braking mechanisms have been used to study the effects of linear decelerations similar to those occurring in automobile or aircraft crashes.

b. Summary of Reference A. 8

See Section A-4. 2b.

c. Summary of Rererence A. 10

See Section A-4. 2d.

d. Summary of Reference A. 13

This reference contains a section de[illegible]ted to a discussion of shock testing of equipment for hardened construction sites.

It is stated that it is usually possible, in connecting equipment to a structure, to arrange to have the connecting elements provide some flexibility of deformability so as to permit the element to experience a lower acceleration than it would have if it were connected through a rigid connection to a moving base. Because of the wide variety of mounting conditions, it is desirable to investigate the behavior of the equipment system, including its connections, preferably by means of tests of a standardized nature, involving subjecting the equipment and its typical mounting to a shock input similar to that which might be experienced under practical conditions. Such shock testing can be done with equipment in government laboratories or on shock tables or other similar items of shock testing equipment, and the design of equipment and mounting configurations is best carried out with a trial and error procedure which involves retesting of such items until a satisfactory solution is achieved for a standardized type of input. Usually this input is stated in terms of a particular kind of velocity-time relationship for the base plate or part of the structure where the equipment and mounting are to be attached.

It is also stated that shock testing of items, including both the equipment and typical mountings, can be performed on the high-impact shock-testing machines at the Naval Research Laboratory, and the results would be applicable to the situation in a structure subjected to an earth shock provided that the shock input on the shock-testing machine leads to a response spectrum similar to the response spectrum from the ground shock environment.

It is further stated that, in order to use the data on the high-impact shock-testing machines for the purpose of investigating the behavior of equipment subjected to ground shock in a protected structure, one must ascertain that the kind of motion of the shock table corresponds to the motion of the structure subjected to ground shock. It is sufficient, however, that the response spectra for the two kinds of shock input be similar. If they are reasonably similar in shape and magnitude, then the results of the shock test can be used in designing equipment for field conditions. If they are different, then it may be possible still to use the data to investigate the vulnerability to shock of the item of equipment, and of its mounting, by deriving from the available shock-test data the combinations of frequency and either velocity or acceleration which produce damage to the particular item of equipment. Such analyses of available shock data have not yet been made except in isolated cases.

e. Summary of Reference A. 17

See Section A-4. 2k.

f. Summary of Reference A. 20

This reference presents a discussion of shock testing and shock-testing machines with emphasis on those machines which can simulate the effects of the design ground shock environment. Several wave forms (shock pulses) generated by different devices are presented. Each of the wave forms is classified as being one of three general types: velocity shock, simple shock pulse, and single complex pulse. The influence of shock-machine loading on output characteristics is discussed. Several of the standard shock-testing machines used most frequently in validating equipment for underground protective structures are described in some detail. These include the U. S. Navy High-Impact Machines for Lightweight and Mediumweight Equipment; a Medium-Impact, Variable-Duration. Shock-Testing Machine; Plastic-Pellet Drop Tables; an Inclined-Plane Testing Machine; and the Hyge Shock tester. Improvised shock tests are also discussed. It is mentioned that, if a shock test spectrum envelopes the design spectrum at all frequencies, presumably the equipment will withstand the service shock successfully.

g. Summary of Reference A. 23

This reference presents a section devoted to a discussion of shock testing of equipment for hardened facilities.

It is mentioned that the shock capabilities of equipment for hard sites have been determined by two principal methods in the past: (1) dynamic analysis and (2) shock test, usually with a drop-test machine. It is also mentioned that relatively inexpensive tests have been performed on equipment to be mounted upon isolated floors and structures by using spring-mounted test platforms or by using the actual shock isolated structure.

It is stated that, "shock tests using the machines which are presently available are less than satisfactory for a number of reasons. The first is that they do not reproduce the environment. The present-day machines frequently subject the equipment to a step-velocity disturbance."

"Step-velocity pulses penalize both low and high frequency systems. The high-frequency systems are penalized because there is no limit on the acceleration which can be imposed on them."

"More and more, machines are being used which provide an acceleration ramp prior to the constant velocity portion. That is, a short period of acceleration precedes the constant velocity. These types of pulses can penalize low-frequency equipment rather severely, since low-frequency systems see the pulse as a step velocity even though there may be a ramp in the pulse."

"The principal parameters which an acceleration-ramp-velocity pulse of a shock machine should have can be determined from the shock-response spectrum of the environment. The acceleration ramp has the acceleration value of the spectrum constant acceleration line and the maximum shock-pulse velocity should equal the maximum spectrum velocity. In most ground shock situations, there will be vertical and horizontal ground motions occurring simultaneously. Properly speaking, a shock machine should deliver disturbances to equipment along several axes at once. In order to do this, the shock-pulse parameters should be obtained from a vectorial addition of the vertical and horizontal ground shock spectra, and the equipment should be mounted in the machine at an angle so that the shock is applied along several axes simultaneously. Unfortunately, this appears not to have been done in the past, which seems to be unconservative. Instead, the equipment has been subjected to the shock along each principal axis separately which may not be equivalent to a simultaneous application along several axes."

h. <u>Summary of Reference A. 24</u>

This reference contains a section describing several shock-testing facilities which produce shock motions having spectra generally equivalent to typical ground-shock design spectra. These facilities include the U. S. Navy high-impact shock stands for lightweight and mediumweight equipment, a sand-drop shock machine and a varipulse shock machine. Representative shock spectra for these devices are presented, and methods of specifying shock tests are discussed. These methods include the specification of shock motion, spectra, and shock machines. Improvised shock tests are also discussed.

i. Summary of Reference A. 26

This reference describes shock-testing procedures and testing facilities used by Westinghouse to certify equipment for the Titan Weapon System. The method of performing the tests consisted of exposing the equipment to a shock which had a spectrum that equaled or exceeded a specified Titan ground-shock spectrum throughout its frequency range. To produce the necessary shock spectrum, two drop testers were employed: a sand-drop table and a "trapese" spring-drop table. The sand drop table consists basically of an equipment mounting platform which is allowed to free fall onto a bed of sand. An adjustable number of blocks attached to the underside of the platform penetrate the sand to arrest the fall. The shock spectrum can thus be controlled by varying the number of blocks, the density of the sand, and the height of the fall. The spring-drop table consists basically of a platform which is released from a predetermined height and which is arrested by an assembly of spring-loaded snubbing blocks. The shock spectrum can be controlled by varying the spring tension and the height of fall.

j. Summary of Reference A. 28

This report briefly describes the purposes, design principles, motion capabilities, and control and safety features of some forty facilities designed to study the effects of linear and angular oscillations and of abrupt acceleration on human safety and performance. Some facilities presently (1961) under study but not yet built are also included. Photographs or schematic drawings of the design are presented for those devices for which they are available. The report includes the geographical locations of the facilities and the contact point for obtaining further information on each.

In general, only devices built specifically for human factors research and which have been used for this purpose are listed. Only a few devices are listed which have been used for animal, dummy, or equipment tests rather than for tests on humans. These are listed because of their potential interest for experiments using human subjects.

A brief survey of the characteristics of most of the devices described is presented in a summary chart on oscillation and impact devices. In this chart the devices are grouped according to their motion capabilities. The described motion capabilities include: (1) vibration in a vertical line; (2) vibration in a longitudinal line; (3) vibration in both a longitudinal and vertical line; (4) vibration in a vertical, lateral, and longitudinal line; (5) rotation in a horizontal plane and in one vertical plane; (6) rotation in three planes; (7) linear vibration and rotation combined; (8) sustained acceleration and linear vibration; (9) sustained acceleration, linear vibration, and rotation; (10) rotation in a horizontal plane and in one vertical plane; (11) rotation in three planes; (12) linear vibration and rotation combined; (13) sustained acceleration and linear vibration; (14) sustained acceleration, linear vibration, and rotation; (15) impact or abrupt acceleration in the vertical direction; (16) impact or abrupt acceleration in the horizontal direction.

According to the data in this reference, the maximum acceleration obtainable with a certain oscillatory device is about 20 g. in the high-frequency range up to 2000 c. p. s. The maximum acceleration obtainable with the oscillatory devices generally decreases as the frequency decreases. In the frequency range from about 8 to 50 c. p. s., a certain device can deliver up to 15 g. In the low-frequency range between about one and 8 c. p. s., certain large amplitude devices can deliver accelerations in the order of 3 to 5 g., and even higher above 5 c. p. s. Certain devices for simulating angular motions in roll, pitch, and yaw can produce angular accelerations on the order of about 18 to 20 rad./sec.^{2}. Certain impact or abrupt acceleration devices, mainly drop towers, can deliver about 40 to 50 g. for durations from about 5 to 10 msec. Other devices, mainly rocket sleds on tracks, can deliver about 80 to 100 g. for durations in the order of 10 to 1000 msec. In general, the acceleration obtainable with certain impact and abrupt linear accelerators (as well as decelerators) decreases as the duration increases.

k. Summary of Reference A. 29

In this reference, descriptions are given of the Navy High Impact Shock Machines for lightweight and mediumweight equipment. Shock motions are given for standard loading conditions in terms of acceleration, velocity, and displacement-time relations. Maximum values of velocities and displacements, and of accelerations passed by various low-pass filters, are presented. Shock spectra are presented for selected conditions. Concepts relative to the specification of shock tests are considered. These include brief considerations of analyses of shock motions, methods of specifying a shock test, and what is meant by simulation of field conditions. It is indicated that shock tests should not be specified in terms of shock motions, or spectra, unless the values specified be considered only as nominal values.

l. Summary of Reference A. 30

This reference provides descriptions of existing types of shock testing machines and comments on their use. Also presented are a discussion of the damage process in equipment subjected to shock, an analysis of various shock motions and the resulting responses of equipment to indicate requirements of a shock testing machine for simulating various types of shock occurring in actual service, and the possibilities for improvising shock tests as a substitute for tests on standard testing machines.

m. Summary of Reference A. 31

This reference presents a summary of shock-machine characteristics and describes some 25 existing machines. The machines are grouped and described according to the types of shocks they produce, e.g., velocity shocks; simple shock pulses, such as a half-sine or rectangular force pulse; single complex shocks; multiple shocks; etc. A summary tabulation of the devices is presented, including several output characteristics. Methods of specifying a shock test are discussed, namely, (1) a specification of the shock motions or spectra to which the item under test is subjected, and (2) a specification of the shock machine, the method of mounting the test item, and the procedure for operating the machine.

n. Summary of Reference A. 32

This two-part report includes a listing of shock-testing equipment in government establishments. In Part I are listed Army, Navy, Air Force, and non-military establishments, the items of test equipment which each possesses, and some information on the performance capabilities. Part II lists the performance capabilities of certain arbitrarily chosen, commercial ranges of equipment.

o. Summary of Reference A. 33

This report describes some 25 shock testing facilities available at the Naval Ordnance Laboratory for simulating the shocks experienced by various types of ordnance items (mines, torpedoes, and guided missiles, for example) under actual service conditions as well as under handling and shipping. The capabilities and limitations of the equipment are presented. The types of equipment include air guns, drop testers, rotary testers, and rough-handling machines.

SECTION A-7

CURRENT TECHNIQUES USED FOR SHOCK ISOLATION

A-7.1 Discussion and Evaluation

a. General

Current techniques used for shock isolation have been investigated as summarized in this section. Two basic isolation methods are considered to be applicable in providing shock protection for the contents of hardened structures: (1) Shock Isolation Systems and (2) Protective Cushioning Materials.

Shock-isolation systems consist of such arrangements as interior platforms and interior structures either mounted on springs connected to the base of the structure or suspended from the roof of the structure by means of pendulum springs. Individual shock mounting or suspension of individual items of equipment is also used. Shock-mounted and suspended platforms and structures serve to support both equipment and personnel.

Protective cushioning materials are considered as an alternate method of providing shock protection for personnel. This consists of energy-absorbing materials used as a floor or wall covering, etc., to protect personnel subjected to impact with the structure during the transient ground-shock motions.

Depending on the pressure level and personnel and equipment tolerance criteria, a combination of the two isolation methods may be utilized. For example, equipment could be mounted on a separate isolated platform and protective cushioning material provided in the personnel areas. For small structures, separate shock mounting of individual items of equipment may be appropriate.

Pertinent data concerning the two protection methods were reviewed as summarized in Section A-7.2. A brief discussion of this information is presented below. The applicability of these shock isolation methods to civil defense shelters is presented in Chapters V and VI.

b. Shock Isolation Systems

Several types of hardened military structures have been provided with interior shock-isolation support systems, e.g., missile silos, launch control centers, combat operation centers, etc. Examples of such systems are reported in References A.20, A.23, and A.34-A.39.

For shock protection of missile systems (Atlas, Titan, Minuteman, etc.), the shock-isolation support system commonly utilized consists of a pendulum suspension arrangement. The struts of the pendulum contain a vertical spring to attenuate vertical accelerations, and the pendulum motion provides sufficient flexibility to attenuate horizontal accelerations. In some cases, horizontal damping devices are used to damp out the pendulum oscillations and to provide stability where necessary. The vertical springs generally consist of helical compression springs mounted within the vertical struts. Other types of vertical springs used or considered are air springs and liquid springs which are also mounted within the pendulum struts.

The pendulum suspension systems are generally of low frequency in the vertical as well as the horizontal directions resulting in large displacements (equal to peak shock spectrum displacement). Rattle space equal to this peak displacement is provided around the interior suspended structure between the interior structure and the concrete shell.

Pendulum suspension systems have also been used to isolate other hardened structures, such as missile launch control centers and combat operation centers. For these structures, equipment to be protected is mounted on the suspended platforms. These platforms also support personnel. Other types of isolation systems used in hardened facilities consist of spring beams and helical compression springs used as a base mounting for platforms and individual equipment items. Horizontal helical compression springs are used to provide stability for tall equipment items. Overhead items, such as fluorescent lights, are suspended by helical tension springs attached to the ceiling.

For the ground shock motions considered in this study, coil springs would be practical for satisfying required spring rates and displacements (Section B-3). Non-linear springs would not be advantageous for the displacements being considered (Sections B-3 and B-5).

Air springs are advantageous for very large displacements (above 2 ft.). For displacements in the order of 1 to 1-1/2 ft., helical compression springs provide an effective design. The disadvantages of air springs are (1) reduced reliability due to leakage problems and (2) difficulty in testing (Section B-3).

Methods of analysis for the various types of shock-isolation systems are presented in References A.20, A.35 and A.39.

c. Protective Cushioning Materials

The principal uses of cushioning materials for the protection of personnel against impact injury have been in automobiles and airplanes. Some use has been made of these materials in athletic equipment in various forms. Ensolite (a flexible polyvinyl chloride foam) has been used extensively as a cushioning material for boxing and wrestling rings and gym mats. Protective clothing, such as helmets, padding, and shoes, has been used by athletes as well as military personnel. The value of restraining devices, such as lap and shoulder belts, etc., has been well demonstrated in automobile crashes and in aircraft accidents. Cushioning materials have also been used to some extent for the padding of dashboards and other hard surfaces in automobiles and in aircraft to protect against human impact injury.

Few test data are available regarding the effectiveness of cushioning materials in preventing injury to human beings. Some general qualitative information is available from experience in automobile and airplane crashes, but specific quantitative data are lacking. It has been found that restraining devices (seat belts, shoulder straps, etc.), protective clothing (helmets, torso girdles, etc.) and padding of corners and hard surfaces, are all effective means of reducing injury from impact of the human body in crashes (References A. 7, A. 41 and A. 42) and are recommended for use in nuclear blast shelters (Sections B-4, B-5, B-6, B-7, and B-8).

Most of the work performed on padding and energy-absorbing materials has been in the field of package cushioning. The need for protecting sensitive items during shipment (in particular, expensive guided missile components and electronic instruments) has spurred considerable research in the field of package cushioning materials and methods of design (Reference A. 40). At the present time, data on cushioning materials and design procedures for equipment are relatively well established as shown in Reference A. 40.

Similar procedures may be used in the design of padding for personnel. The major difficulty in designing for personnel protection is the lack of impact tolerance data in terms of allowable stress or "g" loading. Information that is available on personnel tolerances has been reported either as an impact velocity or as an impact energy on a hard flat surface (see Section A-4 and Reference A. 10) primarily because of the difficulties involved in obtaining actual stress data. These data are not directly applicable to the design of padding.

However, somewhat arbitrary but safe estimates of impact shock values for the human skull have been used for evaluating padding (Reference A. 43). The values are given in terms of acceleration, rate of acceleration, pressure, and impulse.

A wide variety of energy-absorbing materials are available for use as protective padding (Reference A. 40). The general classifications are flexible (flexible or resilient) and rigid (crushable). For padding in shelters, the elastic materials are the only suitable type since the non-elastic materials are appropriate for a single impact only. Among the most suitable materials are the plastic foams, including polyvinyl chloride foams (Ensolite), flexible polystyrene foams, polyurethane foams, and polyethylene foams, latex hair, and foam and sponge rubber. The more elastic materials, such as the latex foams and sponge rubber, are less desirable because of their poorer energy-absorbing properties. Nets or inflatable materials may also be used (Section B-6).

The requirements for protective cushioning materials in blast shelters are based principally on the possibility of personnel being thrown about in the structure and being subject to injury when striking hard surfaces and sharp objects. Procedures for establishing the need for cushioning are presented in Reference A. 39.

A-7.2 Summaries of Information Obtained from References

a. Summary of Reference A.7

In addition to the information presented on shock tolerances as discussed in Section A-4, some data are also presented on protection methods and procedures. Most of these data are not related directly to the ground-shock problem. The pertinent information is summarized below.

Protection of man against mechanical forces is accomplished in two ways: (1) isolation to reduce the transmission of the forces to the man and (2) increase of man's resistance to the forces. Isolation systems involve the use of springs or similar isolation devices, such as elastic cushions. Human resistance to mechanical forces is strongly influenced by selecting the proper body position with regard to the anticipated direction of forces. Man's resistance to mechanical forces can be increased by proper distribution of the forces on the body. This is best accomplished by supporting the body over as wide an area as possible. Whenever possible, the bony regions should be loaded to make use of the rigidity available in the human skeleton.

Restraining a subject in a seat reduces the chance of injury by preventing impact with other objects. The loads imposed must be distributed over as wide a body area as possible to avoid concentrations of force. The loads should be transmitted as directly as possible to the skeleton, preferably to the pelvic structure--and not through the vertebral column.

A rigid envelope around the body produces the maximum possible protection by preventing deformation.

A major danger is the possible impact with the interior of the structure. Protruding and easily loosened objects should be avoided.

Proper head support is desirable to prevent neck injury from abrupt accelerations.

Lap belts are desirable to fix occupants to a seat to prevent their being hurled about. From auto and airplane crash studies, it was found that the belt load on the lower abdomen causes no severe intra-abdominal injury or injury to the lower spinal region. Increased safety is obtainable by distributing the impact load over larger areas of the body and fixing the body more rigidly in a seat. Preventing the body from flailing about is also important. For these purposes, additional supports, such as shoulder straps, thigh straps, chest straps, and hand holds are effective. Flexible restraints should be avoided if impact with the structure interior is possible.

With regard to seat cushions for upward-ejection seats, a slow-responding foam plastic with a thickness of 2 to 2.5 inches is satisfactory. This arrangement distributes the load uniformly and comfortably over a wide area of the body.

Protection of the head against impact injury is effectively provided by protective helmets. The impact-reducing properties of protective helmets are based on two principles: the distribution of the load over a large area of the skull and the interposition of energy-absorbing systems. This is accomplished by using a hard shell which is suspended by padding or support webbing at some distance from the head. High local forces are distributed over the entire side of the head to which the blow is applied. However, it has been shown that the web suspension usually provides a better pressure distribution than the contact padding. A combination of web or strap suspension and contact padding is desirable to obtain optimum protection with less slippage of the helmet.

Foam plastics, such as polystyrene and Ensolite are effective energy-absorbing materials whereas foam rubber and felt are too elastic to absorb a blow.

Impact energies of from 400 to 900 in.-lbs. are required to produce skull fractures on a hard flat surface. (Assumed average energy is 600 in.-lbs.) Impact with a 90° corner requires only one-tenth of the energy (60 in.-lbs.) for skull fracture. The form, elasticity, and plasticity of the object injuring the head is of extreme importance. Dry skull preparations require only 25 in.-lbs. to produce a fracture, indicating the protection afforded by the attenuating properties of a small amount of scalp tissue.

b. Summary of Reference A.10

This report contains data on the energies required to cause fracture of the human skull or concussions. Fractures on a hard surface are produced by 400 to 900 in. lbs. energy. As long as the impact energy is kept below 400 in.-lbs., concussion will not occur. With 90° sharp corners, only 60 in.-lbs. of energy would be required to produce a fracture.

c. Summary of Reference A.20

This report presents procedures for the analysis of shock isolation systems. Linear and non-linear systems for single-degree and multi-degree-of-freedom systems are considered. Effects of variations in isolation system design parameters are discussed. The influence of practical operational considerations on the design of shock isolation systems and on the selection of their components is reviewed. Factors modifying coupling and resonance characteristics, the significance of damping and sufficient rattle space, and means for reducing the possible effects of uncertain features of the shock are pointed out and discussed.

d. Summary of Reference A.23

This report discusses methods of obtaining shock isolation within a hardened facility from the effects of transient ground shock. Discussed in particular are: isolated structures, such as isolated areas and floors; isolated equipment, including several items rigidly mounted to a common shock-isolated floor as well as items isolated individually; and resilient free-standing structures supported at their lower ends and more or less similar in construction to ordinary frame structures. It is reported that these methods of isolation are by no means equally appropriate for a given set of circumstances and that the methods can be matched to the shock environment in the following appropriate manner:

Shock Environment	Method of Protection
Mild	Resilient Free-Standing Structures Isolated Equipment
Low Medium	Isolated Equipment Shock-Mounted Floors
High Medium	Shock-Mounted Floors Shock-Mounted Cribs
Severe	Shock-Mounted Cribs

It is reported that this table should be used as a guide only and that there is no information which would allow the assignment of quantitative data to the table.

The advantages and disadvantages of the above noted methods of achieving shock isolation are discussed in the report.

It is reported that shock-mounted floors have been spring mounted in a variety of ways in the past, some of which are:

a. Helical spring, gravity pendulum struts (Titan I, Atlas).
b. Pneumatic spring, gravity pendulum struts (Minuteman).
c. Floor suspended by gravity pendulum rods attached to overhead spring beams (Titan I).
d. Floor supported from below by spring beams and gravity pendulum rods.
e. Floor supported from below: vertically by spring beams and horizontally by columns between the

spring beams and the floor (Titan I).

f. Helical springs distributed beneath the floor (Titan I).

Crib structures have been spring mounted using pendulum struts containing helical and pneumatic springs. Pendulum lengths up to 60 feet have been used to minimize the induced dynamic bending moments in a delicate, vertically stored missile. If the height of the crib is greater than several stories, some additional shock isolation possibilities exist. For instance, the structure might be suspended by long rods of alloy steel if the shock environment is mild. Just the stretch of the rods may provide sufficient resilience. If the rods prove to be too stiff, additional resilience might be obtained by attaching the rods to a flexible beam on the crib structure. Horizontal isolation is obtained from the pendulum action of the rods.

e. Summary of Reference A.34

Some of the problems associated with the protection of missiles, launch control equipment, and miscellaneous hardware in hardened underground structures are discussed.

It is stated that the missile may be suspended on pendulums, soft springs, or other devices which, in effect, allow the silo to move around the missile. If the suspension system is made very soft so as to reduce the loads, the relative displacements between the missile and the silo may become excessive. Load and displacement are, therefore, two criteria that must be satisfied for a suitable design.

It is pointed out that the launch control center presents problems similar to those encountered in the design of the silo. Equipment and personnel quarters must be protected from shock. Rather than attempt to isolate each piece of equipment individually, it may be desirable to mount entire floor slabs on springs or flexible columns. The proper design of such a system is complicated and requires an analysis in which the dynamic characteristics of floor slabs, springs, and equipment must be taken into account simultaneously. Each part must have suitable strength and stiffness so as to limit the shock transmitted to the equipment but not permit structure failure or excessive relative displacements.

It is stated that piping within the silo may be subjected to sufficiently high loads or displacements to cause leaks or breaks. Connections of pipes and conduits to equipment as well as the protection or ruggedizing of equipment for shock are also areas of concern.

f. Summary of Reference A.35

This paper deals with the free vibrations of a vertical and horizontal suspension scheme, applicable in principle to the shock isolation of entire floor systems. The purpose of the investigation was to study the significance of flexibility of floors relative to that of their isolation supports. The suspension scheme analyzed for vertical vibrations consists of a beam simply supported on linear springs. The scheme analyzed for horizontal vibrations is a gravity-type pendulum consisting of a beam simply supported at both ends by means of hangers.

General approaches of obtaining shock isolation within a hardened, buried structure are discussed. It is stated that, "on the one hand, there is the conventional approach of shock mounting individual equipments relative to the primary structure (this reference does not mention personnel protection). On the other is the fairly novel approach of effectively isolating the primary structure relative to the surrounding medium. Somewhere in between these extremes is the possibility of shock isolating entire floor systems within the primary structure, thus permitting equipments to be hand-mounted to the floor."

The following conclusions are drawn in this reference. "We have considered the motions of two general types of suspension schemes applicable in principle to the shock isolation of entire floor systems as might be employed in a hardened military facility. The purpose of the investigation was to study the significance of flexibility of the floors relative to that of their isolation supports. A representative scheme for isolation in the vertical direction was analysed as the basis of a beam simply supported on linear spring mounts. It was found that the motion becomes predominantly that of a flexible beam on rigid supports as the stiffness of the beam approaches that of the supports. For a predominantly rigid displacement motion of the beam it is necessary that the beam stiffness be at least 2.5 times as great as the support stiffness."

"A representative isolation scheme was analyzed on the basis of a beam suspended at either end from a gravity pendulum. The approximate theory developed leads to a system of two non-linear equations whose free vibrations, in certain sense, are found to be either stable or unstable depending on the magnitude of the initial conditions and the ratio of the simple pendulum frequency to the frequency of the beam. Stable vibration is one in which the motion in the beam and pendulum modes is periodic in the usual sense. An unstable vibration is one in which complete energy transfer takes place between the two modes. This phenomenon has been observed in other non-linear systems and has been termed autoparametric excitation. One critical case of instability occurs when the beam (floor) frequency is twice that of the pendulum. A numerical solution of the non-linear equations shows that about 150 cycles of the beam oscillations and 75 cycles of the pendulum oscillations takes place during one complete cycle of energy transfer between the modes."

"Admittedly, the quantitative results obtained may be of little direct importance to the designer of isolation schemes because of the idealizations involved in the analysis. Thus, the mechanical details of actual floor suspension systems were grossly idealized, only free vibrations were considered, and no account was taken of coupling between horizontal and vertical motions. Nonetheless, it is believed that the following important points have been demonstrated, if only in a qualitative fashion."

1. "Unless the various natural frequencies of a floor system exceed those of the isolated supports by at least a factor of three or more, the actual motions of the floor will be of an extremely complicated nature. Experience indicates that floors designed solely on the basis of strength may not satisfy this requirement. In such instances it is naive indeed for the designer to believe that the motion (i.e., displacement, velocity, acceleration) of particular points of the

of the floor is characterized by linear-single-degree-of-freedom equations, such as would be the case if the floor were ideally rigid."

2. "As a corollary of the above, it is evident that the more accurate a prediction of floor motion desired, the more detailed must be the specification of shock input to the system. The usual shock spectra, for example, generally would be inadequate for such purposes."

3. "The pendulum-type suspension system possesses certain peculiar types of motion which heretofore probably were unknown to designers. These motions (e.g., complete energy transfer between modes) may be found to be deleterious to the intended function of the isolation design."

4. "Where motions of the floor are considered critical, it would appear that a detailed study of the modes and natural frequencies of the floor system is a required design task. The techniques for frequency analysis of composite structures as would likely occur in actual floor designs are known, but they involve rather laborious detail even in the relatively simple designs."

g. Summary of Reference A. 36

This paper reports on some hardware (isolators) and missile and antenna isolation systems, including protective mounting of miscellaneous items of equipment, by reference to developments for the Titan weapon system.

It is reported that, based on specifications in terms of a ground-shock response spectrum for both vertical and horizontal motions, very soft isolation systems, both vertically and horizontally, had to be selected in order to protect the missile. The required spring rate for vertical motions was 30,000 lb./in. to support a mass of one million pounds with a dynamic deflection of one foot. The spring rate required for horizontal motions was about 3400 lb./in. with a dynamic deflection of one foot. To achieve the low vertical spring rate, an air spring system was selected after consideration of chemical elastomers, air springs, hydra springs, and mechanical springs. A single air cylinder did not give a linear spring rate (required to utilize the shock spectrum), and a double-chambered air cylinder was designed to meet the linearity requirements.

To take advantage of the depth attenuation of the shock, it was considered desirable to pick the lowest point possible for the attachments of the isolating elements, but this resulted in the missile being unstable in pitching since the C. G. of the entire system fell appreciably above the attachment points of the isolating elements on the crib. To obtain pitch control, a method was devised to cross-couple the vertical cylinders. It is pointed out that pitch restraint, in addition to insuring stability, also limits rattle space, which in turn controls the missile size.

As this design proceeded toward a completion, new shock data became available as a result of further nuclear tests. These data reduced the shock spectra in the pertinent frequency range by factors of 2 to 4. "Agreement was also reached among knowledgeable people that the silo moves essentially as a rigid body restrained at the bottom. Therefore, while depth attenuation is still a factor, it was considered not to have as great an influence as was thought in the beginning. In order to take advantage of the new shock data, some changes were undertaken in the missile isolation system. Specifically, the air springs were replaced with stiffer helical compression springs, permitting deletion of the pitch control."

It is pointed out that, "at this time, mechanical springs (for vertical and pitch isolation), housed in appropriately spaced pendulum arms (for lateral oscillation) attached near the C. G. (for maximum use of the stabilizing force of gravity), offer the least expensive, most reliable isolation for a system requiring a high degree of shock attenuation. This particular scheme was incorporated in the isolation system for the antenna system."

In regard to the Titan launcher and antenna systems, it is reported that service equipment, such as utilities locks, and electrical and electronic equipment, the counterweight and drive systems for the launcher platform, etc., is mounted on underground structures.

A special problem was encountered in the mounting of the launcher drive and counterweight. Both items are geometrically large and very heavy, the drive weighing about 100 kips and the counterweight 250 kips. Their mountings were designed to resist the normal operating loads, both in regard to magnitude and direction. According to the shock spectra, the relative motion associated with a load corresponding to the operating loads was so large that available rattle space was insufficient. A special isolation system (pendulum struts incorporating mechanical springs) was designed. A mechanism was then required to lock out this isolation system during normal functional operation.

The hardware that can match spring constants from the softest to the stiffest are reported as follows: air springs, hydro-pneumatic springs, mechanical springs of all types (such as helical springs, Belleville washers, and torsion bars) hydra springs, and finally, solid bars. It is stated that, "of course, in a design it is not only a question of spring rate but also of required displacement, and both factors determine what specific hardware should be selected."

This reference states, in summary, that "shock isolation at hard bases is a function of shock level, manner of specification, and equipment capability. Selection of shock isolation hardware must include considerations of the effect of failure, reliability, and cost. Different hardware results for any particular group of the above factors."

h. Summary of Reference A.37

This reference presents a resume of some methods of isolating an interior structure from ground shock, including photographs of some typical installations. Illustrated are the use of rubber shock mounts for the shock isolation of pipes and cable trays and the use of coil springs for mounting a cluster of pipes and lighting fixtures.

Also illustrated is a type of shock isolation which is useful when equipment on a lower level is sufficiently rugged to withstand the ground shock and only an upper level needs to be protected. The upper floor is isolated by means of spring beams, located below the lower floor, which take the

the vertical motion while the columns (connected to the spring beams and supporting the upper level) have sufficient flexibility to take the lateral motion. It is mentioned that where only one or two pieces of equipment on the lower floor require isolation, they may be shock mounted separately on the floor.

An individual mounting of a water chiller is illustrated; the mounting employs rubber pads between steel plates.

A system for shock mounting a complete two-story structure by the use of a spring beam unit under the lower floor is illustrated. Horizontal flexibility is accomplished by short 18" pendulums.

An example of a two-level control center with the major part of its delicate equipment located on the second level, requiring only that level to be isolated, is illustrated. The upper floor is supported by columns connected to spring beams below the lower floor.

Several illustrations are presented showing the use of vertical and horizontal coil springs to isolate a complete structure. The vertical springs are placed below the floor, and the horizontal springs are connected to the tops and bottoms of steel columns. It is mentioned that this method of shock isolation is justified only where the shock mounted structure is extremely heavy with a high center of gravity and the space is limited.

i. Summary of Reference A. 38

This report presents the results of a feasibility and cost study of several types of underground structures at high pressure levels. The structures considered were spheres, vertical cylinders, and horizontal cylinders.

For each of these structures, the most effective shock-isolation system consisted of a suspended interior structure using hot-formed, helical compression springs mounted on parallel pendulum shafts.

j. Summary of Reference A. 39

This reference presents the procedures and significant results of studies of the dynamic responses of hardened underground rectangular and silo-type structures subjected to megaton nuclear weapons blast and ground shock effects with particular attention to the transmission of shock and vibration to the interior structural components and contents of the structure. A method of predicting responses of multi-degree-of-freedom, elastoplastic, nonlinear, and discontinuous systems is advanced. It employs a synthesized ground motion (time history) curve derived from design shock spectra. The procedure for calculating the synthesized curve is summarized in Appendix D. Such curves are employed to analyze a multi-degree-of-freedom, shock-isolation system for the Atlas missile crib. The crib is suspended from a silo with coil-compression springs.

k. Summary of Reference A.40

This report is a summary of the state of the art in the design of package cushioning materials. The general design theory of package cushioning is given, and the testing under static and dynamic loading is discussed. Design concepts are evaluated. Design equations and sample problems are included.

Stress properties are given for some of the principal plastic package-cushioning materials as well as data on the effect of temperature and humidity. Specific uses of rigid and semi-rigid plastic foams in cushioning applications are indicated.

The report also presents a summary of test programs for plastic cushioning materials.

The information that is pertinent to our study is summarized below.

As in the case with package cushioning, resilient materials are the only types suitable for cushioning in shelters. In the report, emphasis was placed on the resilient plastic package-cushioning materials. The particular materials covered were: polyurethane, polystyrene, polyethylene, and polyvinyl foams.

In the design of the cushioning material, the following information is required:

a. The fragility of the items to be protected.
b. The severity of the shock to which the item will be subjected.
c. The energy-absorption characteristics of the protective cushioning material.

Knowing these and the weight and size of the item to be protected, the thickness of the cushioning material can be computed.

The use of dynamic-stress data in the design of the protective cushioning is more reliable than the use of static-stress data.

In the report, the cushion factor concept for design is presented. The cushion factor relates the maximum stress on the cushion to the energy absorbed by the cushion at this applied load.

The properties of the four plastic cushioning materials mentioned above are presented. These included the static stress-strain curve and the dynamic properties.

Specific uses for plastic-foam cushioning materials were discussed. These included: (1) high-speed energy dissipators for aerial delivery of military material; (2) military packaging, particularly for guided-missile components; and (3) cushioning for human skulls.

It has been found in the work performedby Cornell Aeronautical Laboratory, Inc., on cushioning for human skulls, that with cushioned corners, if the backup panels have a radius of curvature greater than 2 inches, they will exhibit characteristics similar to those of a flat panel.

l. Summary of Reference A. 41

This report presents data on the effectiveness of seat belts in reducing injury from impact. The report is based on studies of automobile accidents. However, it serves to point out the possible use of seat belts in protecting personnel from the danger of impact within a shelter structure.

m. Summary of Reference A. 42

The pertinent information in this report is summarized below:

Personnel should be protected from flailing, whiplash, dislodgement, crushing, falling, and impact against sharp objects during a period of ground shock. Restraint devices, such as lap and shoulder harnesses, crash helmets, ankle and wrist restrainers, torso girdles, and secured seats, are helpful. Inertia reels are useful in permitting slow deliberate motion, preventing abrupt movements.

Personnel who are walking or unsecured are particularly vulnerable. All unnecessary personnel traffic would have to be restricted, at least during an alert.

Any unsecured objects are potential projectiles which could crash into personnel or equipment. Therefore, all objects should be secured.

n. Summary of Reference A. 43

This article summarizes the results of the work performed at the Cornell Aeronautical Laboratory to evaluate the impact-absorbing properties of plastic foams. The important points in this report are indicated below.

Data collected on automobile and airplane crashes indicate that about 75% of fatalities result from head injuries. Low-density foam energy absorbers can play a very important part in head impact protection.

In a study conducted for the Navy, the injury potential to the head in aircraft cockpits was evaluated, and methods of reducing the injury potential were studied. It was found that the average human skull would fracture on impact against a hard flat surface at an energy level of 600 in. -lbs. A blow of 400 in. -lbs. on a hard flat surface is commonly used as the critical blow for brain damage.

It was found from the study that there were four controls on the injury potential of a flat surface:

(1) The maximum g. level that would be experienced by the head on striking the surface.

(2) Rate of change of g. or the rate of onset of the g. forces.

(3) Peak intensity of pressure on the head in line with the blow.

(4) Initial impulse of head striking an object.

Initial Impulse $= M_h (V_2 - V_1)$

M_h = Mass of head
V_2 = Velocity before contact
V_1 = Velocity after contact

Initial impulse of 5.3 lb.-sec. has been determined as the threshold of fracture.

A desirable property of the padding is that of low rebound. With low rebound, less energy is transmitted back to the head.

In the Navy program, a rigid polystyrene foam with a density of 1-3/4 lb./cu. ft. provided the best head protection per inch of thickness. Using this material, the peak pressure was limited to 50 p.s.i. This material provides only single-blow protection.

On a project sponsored by the New York State Athletic Commission, work was performed to develop a resilient cellular plastic material with the same impact characteristics as the above polystyrene foam. The resulting material, Ensolite 22266, has characteristics close to those of the polystyrene foam; in addition, the material recovers slowly, ready for another blow. The material was developed primarily for use in boxing rings.

In a boxing contest, an impact energy imparted to the head from striking an unpadded mat can be in the order of 1100 in.-lb. (compared to 600 in.-lb. to cause a fracture). With mats padded with Ensolite 22266, no serious head injury by impact with the platform occurred. This indicates that the criteria for which the material was developed were on the safe side.

Tests were also made to determine the effect of body attitude on the percent of the total body energy that would be absorbed by the head. In the tests, the weight of headform used was taken as 30 lbs. to account for the mass contributed by the torso through the neck.

In the work to determine the effectiveness of various energy absorbing materials, the following controls were used for head impact protection:

Maximum g.	= 60 g.
Maximum rate of change of g.	= 20,000 g./sec.
Maximum intensity of pressure in line with blow	= 600 p.s.i.

The maximum acceleration and rate of change of acceleration given above are considered as safe values for the head. The maximum pressure indicates that the cushioning material has become solid.

Curves are presented that illustrate the protection available with different padding materials on hard flat surfaces for various impact velocities. Some of the values taken from these curves are summarized below:

Cushioning Material on Hard Flat Surface	Limit of Safe Impact Velocity
1" thick 1-3/4 lb./cu.ft. Polystyrene Foam	15 ft./sec.
2" thick " " " "	18 "
1" thick Ensolite 22266 - 7 lb./cu.ft.	17 "
2" thick Erethane Foam - Formulation "A"	16 "
2" thick Foam Rubber - 6 lb./cu.ft.	11 "

In tests made with padding on yielding foundations, in contrast to the rigid foundations, it was found that the padding materials became more effective and the yielding panels absorbed a large part of the impact energy. Some of the foundation materials found effective were: light-gage steel, aluminum, and plastic. No correlation was found between the test data for padding on a rigid backing and that on a yielding backing. The materials must be tested in combination to determine the combined properties.

The following general conclusions can be made from the programs of evaluation of low-density energy absorbers:

(1) Most of the energy-absorbing plastic foams do not have linear spring-rate characteristics under impact blows. Therefore, they do not lend themselves to a simple mathematical analysis.

(2) The better energy-absorbing foams resist impact with nearly constant pressure for approximately three-quarters of their thickness.

(3) Dynamic pressure characteristics cannot be determined by static compression tests.

(4) Different formulations of plastic foams that have the same density and rigidity do not necessarily have the same energy-absorbing characteristics.

(5) When used as energy absorbers, most low-density foams exhibit mechanical characteristics that change greatly with temperature, i.e., they tend to get stiffer as the temperature drops.

(6) In cases where the impact energy exceeds the energy-absorbing capacity of the foam and an auxiliary absorbing structure is used (such as a sheet metal panel to back up the padding), a covering of plastic foam produces a large reduction in the peak pressure experienced by the striking object and also distributes the force over a larger surface area by "dishpanning" the panel. It will be noted that back-up panels having a

radius of curvature greater than 2 inches exhibit characteristics similar to those of a flat panel. If the radius drops below 2 inches, the effectiveness of the padding and panel combination is greatly reduced.

SECTION A-8

REFERENCES

A. 1 Protective Construction Review Guide (Hardening), Volume I, June 1961. Prepared by Newmark, Hansen & Associates for the Office of the Assistant Secretary of Defense (Installations & Logistics).

A. 2 Swift, L.M. et al, Ground Acceleration, Stress, and Strain at High Incident Overpressures, Operation Plumbbob, Project 1.4, WT-1404, May 1960. Prepared by Stanford Research Institute for the Defense Atomic Support Agency (Secret-Formerly Restricted Data).

A. 3 Perret, W.R., Ground Motion Studies at High Incident Overpressures, Operation Plumbbob, Project 1.5, WT-1405, June 1960. Prepared by Sandia Corporation for the Defense Atomic Support Agency.

A. 4 Cohen, E. and Weissman, S., "Underground Shock Environment Data and Application to the Design of Underground Structures", Shock, Vibration and Associated Environments, Part III, Bulletin No. 28, September 1960, pp. 269-322. Prepared by Ammann & Whitney, Consulting Engineers, for the Office of the Secretary of Defense (Research & Engineering). Available from the Defense Documentation Center (AD No. 244 784).

A. 5 Newmark, N.M. and Hall, W.J., Preliminary Design Methods for Underground Protective Structures, Report No. AFSWC-TR-60-5, December 1959. Prepared by the firm of Nathan M. Newmark for the Air Force Special Weapons Center. Available from the Defense Documentation Center (AD No. 318 630) (Secret).

A. 6 Cohen, E. and Bottenhofer, A., Test of German Underground Personnel Shelters, Operation Plumbbob, Project 30.7, WT-1454, July 1960. Prepared by Ammann & Whitney, Consulting Engineers, for the

West German Federal Republic under the sponsorship of the Federal Civil Defense Administration. Available from the Office of Technical Services, Department of Commerce.

A.7 Goldman, D.E. and von Geirke, H.E., "Effects of Shock and Vibration on Man", Chapter 44, Shock and Vibration Handbook, Volume 3 (ed. Harris, C.M. and Crede, C.E.), 1961, McGraw-Hill Book Company.

A.8 Ziegenruecker, G.H. and Magid, E.B., Short Time Human Tolerance to Sinusoidal Vibrations, WADC Technical Report 59-391, July 1959, Aero Medical Laboratory, Wright-Patterson Air Force Base. Available from the Defense Documentation Center (AD No. 227 341).

A.9 Parks, D.L. and Snyder, F.W., Human Reaction to Low Frequency Vibration, Technical Report D3-3512-1, 24 July 1961. Prepared by The Boeing Company, Wichita Division, for the Office of Naval Research. Available from the Defense Documentation Center (AD No. 261 330).

A.10 Richmond, D.R. et al, Tertiary Blast Effects: The Effects of Impact on Mice, Rats, Guinea Pigs and Rabbits, DASA 1245, February 28, 1961. Prepared by Lovelace Foundation for Medical Education and Research, for the Defense Atomic Support Agency.

A.11 White, C.S., Biological Effects of Blast, DASA 1271, December 1961. Prepared by Lovelace Foundation for Medical Education and Research, for the Defense Atomic Support Agency.

A.12 White, C.S., Biological Blast Effects, Report No. TID-5564, September 1959. Prepared by Lovelace Foundation for Medical Education and Research, for the United States Atomic Energy Commission. Available from the Office of Technical Services, Department of Commerce.

A.13 Protective Construction Review Guide (Hardening), Volume II, June 1961. Prepared by Newmark, Hansen & Associates for the Office of the Assistant Secretary of Defense (Installations & Logistics) (Secret-Restricted Data).

A. 14 Hirsch, A. E. and Thompson, W. M. Jr., Shock Tests on USS Fullam (DD 474) Phase 1B - Personnel Protection Study (Project 8) - "The Response of Men and Dummies to Deck Motions", Report C-1346, April 1962. Department of the Navy, David Taylor Model Basin (Confidential).

A. 15 Durkovic, R. G. and Hirsch, A. E., Personnel Injuries and Estimated Shock Motions on YMS 368 During a Mine Attack, Report C-1318, May 1962. Department of the Navy, David Taylor Model Basin (Confidential).

A. 16 Draeger, R. H. et al, Personnel Hasards and Protection from Solid Blast, Part B of USNMDL Report No. 73 on BUSHIPS Project GX-13 PROGIGS, March 1956, Medical Research Department, U. S. Navy Mine Defense Laboratory, Panama City, Florida (Confidential).

A. 17 A Study of Personnel Injury by "Solid Blast" and the Design and Evaluation of Protective Devices, Research Project X-517, Report No. 1, 30 March 1945, Naval Medical Research Institute and U. S. Naval Hospital, National Naval Medical Center, Bethesda, Maryland.

A. 18 Albright, G. H. and Dill, A. F., "Effect of Blast Acceleration Forces on Personnel Within Shelters", Chapter 46, Studies in Atomic Defense Engineering, NAVDOCKS P-290. 2, November 196 . Department of the Navy, Bureau of Yards and Docks. Available from the Defense Documentation Center (AD No. 269 133).

A. 19 Eiband, A. M., Human Tolerance to Rapidly Applied Accelerations: A Summary of the Literature, Memo 5-19-59E, June 1959, National Aeronautics and Space

Administration. Available from the Defense Documentation Center (AD No. 218 269).

A. 20 A Guide for the Design of Shock Isolation Systems for Underground Protective Structures, Report No. AFSWC-TDR-62-64, December 1962. Prepared by The Ralph M. Farsons Company for the Air Force Special Weapons Center. Available from the Defense Documentation Center.

A. 21 Fischer, E. G. and Forkois, H. M., "Practice of Equipment Design", Chapter 43, Shock and Vibration Handbook. Volume 3, (ed. Harris, C. M. and Crede, C. E.), 1961, McGraw-Hill Book Company.

A. 22 Vulnerability Handbook for Hardened Installations - Volume I - Response to Large-Yield Nuclear Weapons, Part B - Theory, 31 March 1962. Prepared by Newmark, Hansen and Associates for Headquarters USAF. Available from the Defense Documentation Center (AD No. 329 454) (Confidential).

A. 23 Ground Shock Problems in Hardened Facilities, Volume I, April 23, 1962. Prepared by American Machine & Foundry Company for the Office of the Chief of Engineers, Protective Construction Branch.

A. 24 Emergency Operating Centers (Review Draft), Professional Guide PSD-PG-80-7, November 1962. Prepared by Praeger-Kavanagh-Waterbury, Engineers-Architects, for the Office of Civil Defense, Protective Structures Division.

A. 25 Shock Test on Fluorescent Luminaires, December 1961. Prepared by Webcor, Inc. and General Electric Company for the Benjamin Division of Thomas Industries, Inc., New York City.

A. 26 Mechanical Shock & Electrical Apparatus, Report of tests performed under WS-107-A2 Titan Shock Testing Program, 1960, Westinghouse Electric Corporation, East Pittsburgh, Pennsylvania.

A. 27 Vulnerability Handbook for Hardened Installations - Volume I - Response to Large-Yield Nuclear Weapons, Part A - Procedures, 31 March 1962. Prepared by Newmark, Hansen and Associates for Headquarters USAF. Available from the Defense Documentation Center (AD No. 329 342) (Confidential).

A. 28 von Gierke, H. E. and Steinmetz, E., Motion Devices for Linear and Angular Oscillation and for Abrupt Acceleration Studies on Human Subjects (Impact), Publication 903, 1961, National Academy of Sciences - National Research Council, Washington, D. C. Available from the Defense Documentation Center (AD No. 266 078).

A. 29 Vigness, I., Navy High-Impact Shock Machines for Lightweight and Mediumweight Equipment, NRL Report 5618, 1 June 1961, U. S. Naval Research Laboratory. Available from the Defense Documentation Center (AD No. 260 008).

A. 30 Crede, C. E., "Concepts in Shock Testing Equipment", Shock and Structural Response, August 1960, The American Society of Mechanical Engineers, New York City, pp. 35-51.

A. 31 Vigness, I., "Shock Testing Machines", Chapter 26, Shock and Vibration Handbook, Volume 2 (ed. Harris, C. M. and Crede, C. E.), 1961, McGraw-Hill Book Company.

A. 32 Hollings, A. J., Index of Environmental Test Equipment in Government Establishments, 1961-1962, Prepared by the Centralising Activity for Shock, Vibration, and Associated Environments, Code 4021, U. S. Naval Research Laboratory, Washington 25, D. C.

A. 33 Shock Testing Facilities, NOLR 1056 (Second Revision), 1 March 1956, U. S. Naval Ordnance Laboratory. Available from the Defense Documentation Center (AD No. 98 282).

A. 34 Barton, M. V., "Ground Shock and Missile Response", Shock and Structural Response, August 1960, The American Society of Mechanical Engineers, New York City, pp. 69-79.

A. 35 Sevin, E., "On the Design of Shock Isolated Floor Systems", Shock, Vibration and Associated Environments, Part III, Bulletin No. 28, September 1960, pp. 22-35. Prepared by Armour Research Foundation for the Office of the Secretary of Defense (Research & Engineering). Available from the Defense Documentation Center (AD No. 244 784).

A. 36 Harlam, R., "Shock Isolation at Hard Bases", Shock, Vibration and Associated Environments, Part III, Bulletin No. 28, September 1960, pp. 175-181. Prepared by American Machine & Foundry Company for the Office of the Secretary of Defense (Research & Engineering). Available from the Defense Documentation Center (AD No. 244 784).

A. 37 Dowdy, R. W., "Nuclear Ground Shocks Environment", Shock, Vibration and Associated Environments, Part III, Bulletin No. 29, July 1961, pp. 305-323. Prepared by Daniel, Mann, Johnson and Mendenhall and Associates for the Office of the Secretary of Defense (Research & Engineering). Available from the Defense Documentation Center (AD No. 260 564).

A. 38 Concept Study Report - Barksdale Air Force Base Combat Operations Center, June 1961. Prepared by Ammann & Whitney, Consulting Engineers, for U. S Army Engineer District, Little Rock, Arkansas.

A. 39 Weissman, S. et al, "Nuclear Weapon Blast and Ground Shock Effects on Dynamic Response of Interior Components and Equipment in Underground Structures", Shock, Vibration and Associated Environments, Part III, Bulletin No. 29, July 1961, pp. 324-337. Prepared by Ammann & Whitney, Consulting Engineers, for the Office of the Secretary of Defense (Research & Engineering). Available from the Defense Documentation Center (AD No. 260 564).

A. 40 Gigliotti, M. E., Design Criteria for Plastic Package - Cushioning Materials, PLASTEC Report 4, December 1961, Plastics Technical Evaluation Center, Picatinny Arsenal. Available from the Defense Documentation Center.

A. 41 Automobile Seat Belts, Report of the Special Subcommittee on Traffic Safety, Committee on Interstate and Foreign Commerce, House of Representatives, 85th Congress, 1st Session, House Report No. 1275, 1957, U. S. Government Printing Office.

A. 42 Degan, J. W. and Williams, D. W., Human Survivability: Human Tolerance to Ground Shock and Low Frequency Vibrations in Command and Control Facilities (Task 139), Interim Report, Technical Memorandum TM-3057, April 24, 1961. Prepared by The MITRE Corporation under Contract No. AF 33(600) 39852.

A. 43 Dye, E. R. and Smith, M. D., "Mechanical Properties of Low Density Foams as Energy Absorbers", Mechanical Engineering, Volume 80, No. 12, December 1958. Prepared by Cornell Aeronautical Laboratory, Inc. for presentation at 1958 Semi-Annual Meeting of the American Society of Mechanical Engineers.

APPENDIX B

MINUTES OF MEETINGS

SECTION B-1

INTRODUCTION

Appendix B contains minutes of meetings held with various governmental and private organizations to obtain information pertinent to shock and vibration and to discuss such data with experts in this field.

SECTION B-2

MINUTES OF MEETING BETWEEN KORFUND DYNAMICS CORPORATION AND AMMANN & WHITNEY

Presented below are the minutes of a meeting held at the office of Ammann & Whitney, New York, on December 10, 1962, to discuss shock isolation data in connection with this study.

Attendees at Meeting

Mr. Paul Baratoff, Korfund Dynamics Corporation
Mr. Joseph L. Hammond, Korfund Dynamics Corporation
Mr. Samuel Weissman, Ammann & Whitney
Dr. Joseph Vellozzi, Ammann & Whitney

The meeting was opened with a general discussion of the requirements for shock tolerances in hardened structures. Mr. Hammond reviewed Korfund's activities in the field of equipment and missile shock isolation for hardened installations. Korfund designs and manufactures hardware for shock and vibration control and has been active in the shock isolation of the TITAN, MINUTEMAN, and ATLAS missile hard sites as well as the isolation of equipment for civil defense shelters, including the Denton, Texas, and Albany, New York, shelters. In these shelters, most equipment was shock isolated to 3 g. and sensitive electronic equipment to one g. Standard mounts and springs were used where possible. The shock levels for which Korfund designed were specified in the form of ground-shock response spectra with maximum velocities in the order of 10 to 40 in./sec. and overpressures up to 50 p.s.i. In general, the equipment required isolation at 3 to 10 c.p.s. in order to limit the transmitted accelerations to within 3 g. The systems were expected to damp out in about 30 seconds because of internal damping inherent in the systems.

Korfund indicated that manufacturers usually do not know the fragility level of their equipment, although they feel that mechanical and heavy electrical equipment items can tolerate transmitted shocks of 3 g. and fragile electric and electronic equipment between 1 and 2 g. These values are based primarily on shock requirements during transportation. Although it is possible to test the simpler types of equipment to determine the fragility level, the testing can become extremely complicated and costly in the case of heavy complex equipment. Therefore, in lieu of subjecting every piece of equipment to a shock test, it is more practical to provide shock protection which will transmit no more shock than most equipment can reasonably be expected to withstand. This is the basis for shock mounting to an acceleration of a 3 g. shock or less.

Korfund furnished a listing of the equipment that they isolated at 3 g. even though they felt that the fragility levels were in excess of this value. The equipment included diesel generator sets, air conditioning chillers, water tanks, exhaust fans, heating and cooling coils, pumps, air compressors, panelboards, and most electrical equipment. Lighting fixtures were isolated to 1 g. This is based on tests resulting in failure of the stems supporting the fixtures rather than failure of the lamps. The lamps and fixtures have much higher tolerances, in the order of 20 g.

With regard to shock isolation of equipment, Korfund pointed out that when equipment is mounted on top of a shock-isolated floor care must be exercised so that no disturbing frequency (transmitted by the operation of such equipment as fans, air handling units, compressors, and pumps, etc.) exists which may be in resonance with the natural frequency of the floor. Otherwise, the shock-isolated floor may begin to vibrate in resonance with the equipment. They also stated that, following the ground shock disturbance, the shock-isolated floor will oscillate at its natural frequence (predominately its fundamental if the stiffness of the floor slab is relatively high compared to the stiffness of the isolation supports) and that this becomes the disturbing frequency to which the isolation mountings of the equipment are subjected. Unless the equipment isolator is properly designed and appropriate relationship is maintained between floor and isolation frequencies, it is possible for equipment isolators to amplify by 200 percent or more the shock transmitted by the shock-isolated floor.

In reference to relative motions of equipment, Korfund indicated that the main concern is to enable the equipment to travel freely without striking other equipment and to provide flexible connections for all piping, ductwork, etc. In order to minimize movement of equipment so that the amplitudes do not exceed those calculated from the ground shock spectra, it is often required that the mounting suspension points be in a horizontal plane through the center of gravity of the equipment and that the mounting support be located symmetrically about the center of gravity. Otherwise, the equipment will rock when subjected to shock and the motion may be amplified somewhat because of coupling between the inertia and resisting forces.

Korfund stated that they usually design and provide springs such that the natural vertical and horizontal frequencies on an isolated piece of equipment are identical. These springs are welded to end plates. It is important, when the end plates are fastened to the foundation, that minimum clearance be maintained between bolt holes and foundation bolts. This prevents motion of the base plate under shock.

In the testing of equipment, Korfund has used a drop-test machine which is usually sufficient to determine the fragility level of equipment since all possible equipment modes are excited under the deceleration impact. Reference was also made to Navy impact machines, Bellock College Point, Long Island, New York.

Korfund is considering the development of a series of standard springs and specifications for shock isolation requirements for hardened shelters. They also mentioned that the cost of the engineering analyses required for a particular shock isolation design could be quite high and sometimes greater than the isolation of equipment itself.

Korfund furnished Ammann & Whitney with examples of their work on equipment shock isolation for hardened installations. Also furnished were a bulletin indicating their manufactured products and a copy of the paper, "Shock and Vibration Isolation for Missile Sites", by Donald Vance of Korfund, reprinted from April/May, 1961, Ground Equipment Magazine.

SECTION B-3

MINUTES OF MEETING BETWEEN SPACE TECHNOLOGY LABORATORIES, INC. AND AMMANN & WHITNEY

A meeting was held at the Space Technology Laboratories, Inc., Redondo Beach, California, on January 7, 1963, to discuss shock isolation data in connection with this study.

<u>Attendees at the Meeting</u>

Dr. Millard V. Barton	Space Technology Lab.
Dr. Herbert Suer	Space Technology Lab.
Dr. J. Christensen	Space Technology Lab.
Mr. John Karagozian	Space Technology Lab.
Mr. Edward Laing	Ammann & Whitney
Mr. Samuel Weissman	Ammann & Whitney
Dr. Joseph Vellozzi	Ammann & Whitney

The minutes of this meeting are of a classified nature and cannot be included in this report. However, reference is made in Appendix A to some of the unclassified items discussed at this meeting.

SECTION B-4

MINUTES OF MEETING BETWEEN THE LOVELACE FOUNDATION FOR MEDICAL RESEARCH AND AMMANN & WHITNEY

Presented below are the minutes of a meeting held at the Lovelace Foundation for Medical Education and Research, Albuquerque, New Mexico, on January 8, 1963, to discuss personnel shock effects in connection with this study.

<u>Attendees at the Meeting</u>

Dr. Clayton S. White, M.D.	Lovelace
Mr. I. Gerald Bowen	Lovelace
Mr. Edward Laing	Ammann & Whitney
Mr. Samuel Weissman	Ammann & Whitney
Dr. Joseph Vellozzi	Ammann & Whitney

The meeting was opened with an explanation of the Office of the Chief of Engineers project and of the related work being performed by Ammann & Whitney in the investigation of literature and data pertaining to shock effects on personnel for the purpose of establishing requisite shock tolerances and appropriate protection for personnel housed in a hardened, shallow-buried, civil defense shelter subjected to a ground shock environment associated with a 20-MT nuclear weapon burst for overpressures ranging up to 300 p.s.i. The intensity and nature of the expected structure motions were described and it was pointed out that, in most cases, the personnel in the shelters would be in random positions - standing, sitting, reclined - and in fewer cases personnel may be strapped down in chairs, beds, etc., or be provided with other means of bracing themselves.

It was explained by Ammann & Whitney that, based on their review of available literature, it appeared that many unknown factors exist with regard to ground shock effects on personnel, although data are available pertaining to personnel shock effects for other types of shock environments. Ammann & Whitney studied the blast biology reports received from Lovelace, and three reports in particular were found to contain biological and personnel shock effect data which could be related to the personnel ground shock problem. It was agreed that no known personnel shock tests have been conducted specifically for the ground shock problem although this type of testing is presently being considered by other agencies. These three reports, prepared for the Defense Atomic Support Agency, are:

1. "Tertiary Blast Effects, Effects of Impact on Mice, Rats, Guinea Pigs and Rabbits"
2. "Biological Effects of Blast"
3. "Biological Blast Effects"

It was further explained that Ammann & Whitney have established preliminary shock tolerances for personnel in hardened civil defense shelters on the basis of the data in these reports and other publications investigated, and that considerable judgment was used in the application of this data to the ground shock environment. These tolerances are considered in two categories: (1) impact and (2) vibration. The data in the Lovelace reports were an important source of information for establishing the impact tolerances.

The following is a summary of comments and discussion pertaining to the problems posed by Ammann & Whitney:

1. The three reports listed above, and particularly the first report, are still generally representative of the current knowledge on impact effects. This work was based on drop tests on animals and on a general review of other related literature in the field. Based on this data the "on-the-safe" average tolerable impact velocity of 10 ft./sec. as qualified in the report is recommended. This pertains to the total body as well as to skull impact with a hard flat surface providing the line of thrust for skull impact is not directed along the longitudinal axis of the body in which case the head would be damaged in absorbing the kinetic energy of the remainder of the body mass. For impact with sharp corners, the tolerable impact velocity would be considerably reduced, and this should be avoided or the corners should be padded.

2. Since horizontal motions in combination with the vertical motions would probably throw personnel off balance, an uncoordinated type of impact may result, and although it

is felt that impact velocities less than 10 ft./sec. would generally not be serious, some injuries may result for persons of certain age groups, for persons colliding in an awkward position, or where a person falls backward and experiences impact with the back of the head. In the latter case, an impact velocity greater than 10 ft./sec. may be unavoidable. The ability of the body to prepare itself for a fall due to a sudden motion would depend upon the physical condition, age, and athletic training of the person. However, a person standing stiff-legged would probably have time to assume a bent-knee position if the floor suddenly dropped from beneath him.

3. For impact velocities greater than 10 ft./sec. and for added safety at 10 ft./sec., a cushioning material should be provided. This can be achieved by the use of padded helmets, padded walls, and padded floors. The use of Ensolite (manufactured by U. S. Rubber), for example type AH, as a surface material would be effective. Under normal loadings Ensolite feels rigid but will deform sufficiently under impact loads to afford a considerable reduction in deceleration intensity. In this regard, it was emphasized that only a very small stopping distance (fraction of an inch) will considerably reduce the possibility of body damage due to impact for impact velocities above 10 ft./sec., even as high as 20 ft./sec.

4. It is considered that the use of bracing, such as handrails, would be effective in preventing personnel from being thrown over if it is practical for personnel to assume such a position of preparation.

5. It is felt that imposing a sudden upward velocity to a body may be physiologically different (with regard to tolerance) from dropping a body with the same striking velocity, although as a mechanical system both cases appear to be similar.

6. Strapping a person to a chair which is shock mounted could result in a more critical environment than permitting the person to be displaced relative to the structure even though the shock intensity is reduced. This is partially due to a repeated (vibration) loading and also because injury could result from relative body displacements, depending on the manner in which the body is strapped to the chair. In

addition, impact of the body against the chair may be a potential hazard. Pulling a person down with a sudden velocity may also be different (with regard to tolerance) from dropping a body with the same striking velocity.

7. With regard to future shock tests for civil defense shelters, it is felt that such a program is warranted in view of the present uncertainties. However, tests on healthy young adults would probably not be representative of tolerances for other age groups, and in general it is difficult to obtain volunteers. Testing is potentially dangerous especially since certain internal injuries could occur without the subject feeling pain at the time of the test. Furthermore, the tolerance established varies, depending upon the subjective feelings of the person being tested.

8. Based on the available information, it is felt that the preliminary tolerance values established by Ammann & Whitney are reasonable.

9. Although the Lovelace reports include a review of other literature in the field, for more detailed reading the following publications may be of particular interest; however, such further study would probably not afford any additional information leading to recommendation of more reliable shock tolerance criteria.

Roth, H., Impact and Dynamic Response of the Body, Symposium: Frontiers of Man Controlled Flight, Los Angeles, April 3, 1943.

Coermann, R. R., The Mechanical Impedance of the Human Body in Sitting and Standing Position at Low Frequencies, ASD Tech Report 61-492, Wright Patterson Air Force Base, Ohio, September 1961.

German Aviation Medicine World War II, Vol. 2, by the Department of the Air Force (Edited by Glasser).

Swearington, et al, "Human Tolerances to Vertical Impact", Aerospace Medicine, December 1960, Vol. 31, No. 12.

Draeger, et al, A Study of Personnel Injury by Solid Blast, Naval Medical Research Laboratory, 1945.

SECTION B-5

MINUTES OF MEETING BETWEEN
THE AIR FORCE SPECIAL WEAPONS CENTER
AND AMMANN & WHITNEY

Presented below are the minutes of a meeting held at the Air Force Special Weapons Center, Kirtland Air Force Base, New Mexico, on January 9, 1963, to discuss shock isolation data in connection with this study.

Attendees at the Meeting

Lt. Douglas H. Merkle	AFSWC
Mr. H.R.J. Walsh	AFSWC
Mr. Edward Laing	Ammann & Whitney
Mr. Samuel Weissman	Ammann & Whitney
Dr. Joseph Vellozzi	Ammann & Whitney

The meeting was opened with a short summary of the work being performed by Ammann & Whitney on a study of shock isolation methods for hardened civil defense shelters for the Office of the Chief of Engineers. The shelters being considered are shallow-buried structures designed for a 20-MT weapon burst and for overpressures up to 300 p.s.i. As part of the study, Ammann & Whitney is compiling and investigating sources of current data in the field pertaining to shock tolerances for personnel and equipment and other items, structure (shelter) response to the free-field ground shock, and current methods and techniques used for shock isolation as well as shock-isolation systems previously developed for hardened structures. AFSWC will soon publish a comprehensive guide for the design of shock isolation systems in underground protective structures which represents AFSWC latest information on the subject. Lt. Merkle mentioned that Ammann & Whitney should receive a copy of this report by the end of the month unless there are delays in printing. Shortly after this report is forwarded, Lt. Merkle expects to be in New York and will visit Ammann & Whitney for further discussion of its contents.

With regard to shock tolerances for personnel, Lt. Merkle pointed out that in their report they are recommending that seated and well-restrained personnel be isolated to 1.75 g. for vertical and radial motion and that personnel standing without support be isolated to 0.75 g. for vertical motion and 0.50 g. for radial motion. AFSWC performed a literature search to establish these values, and the conclusions are based mainly on the works of Eiband and Zeigenruecker which Ammann & Whitney also reviewed. The results of this search are presented in the abovementioned AFSWC report. F. L. Murfin of Space Technology Laboratories and J. W. Degan and D. W. Williams of MITRE have also performed a literature search on the subject of personnel shock tolerances relevant to the ground shock environments, and have presented some conclusions and/or recommendations. AFSWC furnished Ammann & Whitney with a copy of some of this data. (Human Survivability: Human Tolerance to Ground Shock and Low Frequency Vibrations in Command and Control Facilities (Task 139), Technical Memorandum TM-3057, The Mitre Corporation, 24 April 1961.)

The AFSWC personnel shock tolerances for standing personnel are less than one g. and, therefore, impact which would result from the separation of personnel with respect to the structure floor is not being considered. However, Lt. Merkle suggested that if separation is to be permitted in the civil defense shelters, cushioning material on the structure floor and walls and/or protective clothing, helmets, and shoes should be provided. For seated personnel, seat belts should be considered to protect personnel by restraining them in their seats. In this regard a copy of a congressional Committee Report on Automobile Seat Belts was given to Ammann & Whitney (House Report No. 1275, 85th Congress, August 1957). Cornell Aero Laboratory in Buffalo, New York, (Mr. John O. Moore and Mr. Edward R. Dye) is also performing studies on seat belts.

AFSWC is considering shock testing of personnel in connection with the Minuteman Weapon System using a six-degree-of-motion simulator available at Wright Patterson Air Force Base. The feasibility of such tests will be discussed with Capt. N. P. Clark of Wright Patterson Air Force Base. Ammann & Whitney was furnished a description of the motion capabilities of the simulator. Col. J. P. Strapp of Holloman Air Force Base may also be consulted by AFSWC to discuss personnel shock testing. Seat-belt tests have been conducted at Holloman Air Force Base, Aero Medical Field Laboratory.

Bell Telephone Laboratories, Whippany, New Jersey, (Mr. Clinton Schaeffer) are doing work on shock isolation for the Army and have performed personnel shock tolerance tests for their own use (information not published). These tests were designed to simulate the motions of an isolation platform in an underground protective structure and consisted basically of applying a motion to a cantilever beam upon which subjects were seated.

With regard to equipment tolerances, the AFSWC report contains a summary of test results. The AFSWC report also presents various velocity pulse shapes for different sites. Also, two basic-type velocity pulse curves are presented: one for the high frequency and one for the low frequency portion of the spectra, respectively.

A plot of the computed vertical response of the Minuteman equipment platform air-spring suspension system was shown. It appeared that the response motions quickly damp out; the amplitude during the second cycle is small compared to the peak response. In this regard AFSWC was presently setting up a shock-testing device which will be capable of testing the entire suspended platform. Lt. Merkle felt that, for the motions being considered in the OCE study, it would be best not to use non-linear springs.

SECTION B-6

MINUTES OF MEETING BETWEEN THE DEFENSE ATOMIC SUPPORT AGENCY AND AMMANN & WHITNEY

Presented below are the minutes of a meeting held at the Defense Atomic Support Agency, Washington, D.C., on January 21, 1963, to discuss personnel shock effects and shock isolation data in connection with this study.

<u>Attendees at the Meeting</u>

Colonel Robert H. Holmes, Surgeon	DASA, Medical Div.
Mr. John Lewis	DASA, Blast & Shock Div.
Major Merrill E. Barnes	DASA, Blast & Shock Div.
Mr. Samuel Weissman	Ammann & Whitney
Dr. Joseph Vellozzi	Ammann & Whitney

The meeting consisted of two parts: (1) a meeting with Colonel Holmes to discuss personnel shock effects and (2) a meeting with Mr. Lewis and Major Barnes to discuss general shock isolation data.

<u>Meeting with Colonel Holmes</u>

The meeting was opened with an explanation of the Office of the Chief of Engineers project and of the related work being performed by Ammann & Whitney in the investigation of literature and data pertaining to shock effects on personnel for the purpose of establishing requisite shock tolerances and appropriate protection for personnel housed in a hardened, shallow-buried, civil defense shelter subjected to a ground shock environment associated with a 20-MT nuclear weapon burst for overpressures ranging up to 300 p.s.i. The intensity and nature of the expected structure motions were described. It was explained by Ammann & Whitney that, based on their review of available literature, including DASA reports prepared by the Lovelace Foundation, preliminary shock tolerances for personnel subjected to the ground shock environment have been established. The available information pertains to personnel shock effects for other types of shock environment and considerable judgment was used in the application of the data for the ground shock environment.

It was explained that Ammann & Whitney had a very informative meeting with Dr. C. S. White and Mr. I. G. Bowen at the Lovelace Foundation at which time the DASA reports as well as other data in field were discussed. The recommended personnel tolerances for ground shock as based on this available information were also discussed with Dr. White who offered very pertinent comments regarding the anticipated nature of possible injuries resulting from the ground shock environment. Dr. White had suggested that Ammann & Whitney discuss personnel effects with Colonel Holmes.

Colonel Holmes agreed that there are many unknown factors relative to ground shock effects on personnel and that no adequate tests have been performed in the past specifically for the ground shock environment. Protection of personnel for the ground shock environment could best be provided with protective padding either by padding the surfaces of impact within the structure or by providing personnel with protective clothing - helmets, shoes, etc. In addition, sharp corners which may be struck should be rounded. Ensolite (manufactured by U. S. Rubber) has been found to be an effective impact-absorbing material when used as floor covering, such as in boxing rings. In some cases it is necessary to bond a low-density Ensolite layer to a higher density sub-layer. The U. S. Army Quartermaster Corps at Natick, Massachusetts, (Attn: Mr. Eddie Baron) is doing research on plastic protective devices. Where practical, personnel should be strapped down to minimize secondary impact effects. However, consideration must be given to the fact that seated personnel are susceptible to vertabrae fracture.

With regard to personnel shock tests, Mr. Hirsch of the David Taylor Model Basin has conducted shipboard tests with personnel.

DASA and the Lovelace Foundation will be conducting a symposium on biological blast and shock effects following the 32nd Shock Symposium scheduled for this coming April.

Meeting with Mr. Lewis and Major Barnes

The meeting was opened with a summary of the scope of work being performed by Ammann & Whitney on a study of shock isolation methods for hardened civil defense shelters for OCE. The shelters being considered are shallow-buried structures designed for a 20-MT weapon size and for overpressures up to 300 p. s. i. As part of the study Ammann & Whitney is investigating and compiling sources of current data in the field pertaining to shock tolerances for personnel and equipment, structure (shelter) response to the free-field ground shock, and current methods and techniques used for shock isolation and shock isolation systems previously developed for hardened structures. Preliminary recommendations for basic criteria for the shock isolation study have been established on the basis of the data investigated.

The following is a summary of comments and discussion pertaining to problems posed by Ammann & Whitney.

1. Prediction of free-field ground shock spectra using Dr. Newmark's procedure is considered to be the most current available for predicting free-field ground motions and spectra. This procedure is presented in, Protective Construction Review Guide, Volume I, Office of the Assistant Secretary of Defense (Installations & Logistics), June 1961.

2. Shock isolation for personnel would probably be best achieved by the use of a cushioning or frangible-type material. For example, a frangible shock isolating concrete has been developed at Waterways Experiment Station, Vicksburg, Mississippi. This concrete is composed of a polyurethane foam aggregate which is inexpensive and can be handled during construction as conventional concrete. Various stress-strain properties can be achieved by varying the foam aggregate-to-cement ratio. This concrete could be used as a footing material, for example, which would support the normal dead plus live load but would yield plastically under the higher ground shock dynamic load. The material could also be placed under the base slab to absorb energy transmitted between the ground and the slab. Spun metals also have been experimented with and show promise as an energy-absorbing material. A report will be available in

August 1963 (CRDL Technical Memorandum 21-10, Edgewood Arsenal, Maryland). Padding could be used within the structure to further protect personnel from possible injuries due to impact with the structure floor, walls, or adjacent objects. An arrangement such as a net or inflated material could be placed along the wall.

3. The literature presently being investigated by Ammann & Whitney generally represents the current knowledge in the field. For a further source of data concerning an actual design the following should be consulted:

> Design for a Cast-in-Place Concrete Shelter, 13 December 1962, U. S. Naval Civil Engineering Laboratory.

SECTION B-7

MINUTES OF MEETING BETWEEN THE NAVAL RESEARCH LABORATORY AND AMMANN & WHITNEY

Presented below are the minutes of a meeting held at the Naval Research Laboratory, Washington, D. C., on January 29, 1963, to discuss shock isolation data.

Attendees at the Meeting

Dr. Irwin Vigness	Naval Research Laboratory
Mr. Samuel Weissman	Ammann & Whitney
Dr. Joseph Vellozzi	Ammann & Whitney

The meeting was opened with a short summary of the work being performed by Ammann & Whitney on a study of shock isolation methods for hardened civil defense shelters for the Office of Chief of Engineers. The shelters being considered are shallow-buried structures designed for a 20-MT weapon burst and for overpressures up to 300 p.s.i. As part of the study, Ammann & Whitney is investigating and compiling sources of current data in the field pertaining to shock tolerances for personnel and equipment and other items, structure (shelter) response to the free field ground shock, and current methods and techniques used for shock isolation and shock isolation systems previously developed for hardened structures. Based on this data preliminary recommendations for basic criteria for the shock isolation study have been established.

During the meeting Dr. Vigness took the Ammann & Whitney representatives on an interesting tour of the NRL shock testing equipment. The mediumweight high-impact machine was demonstrated.

The following is a summary of comments and discussions pertaining to the items posed by Ammann & Whitney.

1. With regard to personnel ground shock effects, the high accelerations associated with the high-frequency range of the spectra would not be critical as a direct effect since personnel will not respond to these high-frequency com-

ponents. Consideration of a sudden velocity change would be more appropriate for evaluating the effects on personnel. Naval shipboard data have indicated tolerances for impact velocities up to approximately 10 ft./sec. for particular body postures and areas of impact. If a person is standing with his legs straight and heels against the floor, the person's feet may be injured.

Personnel are believed to be sufficiently rugged to survive anticipated motions without appreciable injury. However, personnel should be either strapped into chairs, provided with hand holds, or adjacent objects with which personnel could collide should be cushioned. In general, it is advisable to provide cushioning material to pad all hard potential impact surfaces to provide the most reliable protection. Loose items, such as furniture, etc., should be attached to the structure.

Ammann & Whitney's future meeting with Dr. Goldman (Naval Medical Research Institute) should be of particular value with regard to personnel data since Dr. Goldman is an outstanding authority on biological shock and vibration effects.

2. With regard to equipment shock tolerances, most equipment can sustain a peak acceleration greater than 3 g., although a sustained vibration of plus and minus 3 g. could cause damage depending upon the frequency of the motion as compared to the equipment frequencies. However, in isolating equipment down to tolerable acceleration response values, low-frequency systems (in the order of 5 c.p.s. which is generally lower than equipment frequencies) are achieved and resonance should not be a problem. In general, the determination of an appropriate shock tolerance for equipment requires individual consideration by analysis or shock tests.

3. In reference to shock testing of equipment for naval ships, a test specification for impact or vibration tests on particular shock testing machines has been established. Although these tests do not necessarily duplicate actual shipboard motions, they have an equivalent damage potential for the intensity of shipboard shock motion that the equipment must sustain. In some cases, the equipment must be rugged-

ized or shock mounted to withstand the test without damage. For effective tests, it is advisable that the test procedure be established on the basis of the particular test machine. For certain cases, it may be necessary to design special test equipment to achieve the desired input. It may be possible to utilize the Navy high-impact machines to attain the same peak response that the equipment would experience according to the shock spectra. No two shock motions expected for the actual ground shock environment are alike. It is desirable to have a shock test possess the damage potential of any probable shock. This can best be accomplished by smoothing the shock spectra curves so as to obtain maximum responses that are expected from field excitations. The smoothed spectra can usually be obtained from a single acceleration pulse of sawtooth or half-sine shape. These pulses can be easily generated and their magnitudes and durations adjusted to provide a suitable shock spectrum.

4. The residual effect is the sustained vibration at times greater than the duration of the input motion. Dr. Vigness illustrates this effect in terms of a residual spectra which is a plot of the peak response versus frequency for times greater than the input duration. It is recommended that the residual spectra as well as the conventional (primary) spectra be specified. The residual spectra would be helpful for evaluating appropriate requirements for damping out the sustained vibrations. Dr. Vigness is presently developing residual spectra data (not published at present). This data indicates that the residual spectra responses are close to the primary spectra responses in the low-frequency range and tend to be less than the primary spectra in the high-frequency range.

5. With regard to shock isolation systems, the Air Force is currently considering the use of air springs. For civil defense shelters a fiberglass type mater ! used as a subfloor may be effective in absorbing input energy. It is advantageous to isolate equipment on a separate shock-mounted platform. Other springs which can be used are cantilever, torsion, and coil springs.

6. The following sources of information were pointed out to supplement the reports already reviewed by Ammann &

Whitney:

Navy High-Impact Machines for Lightweight and Mediumweight Equipment, I. Vigness, U.S. Naval Research Laboratory, Washington, D.C., June 1, 1961.

Handbook of Environmental Engineering, E.C. Theiss et al, Technical Report TR 61 363, AFS Command, USAF, Wright Patterson Air Force Base, Ohio, Contract No. AF 33(616) 6252,1961.

Contact C. J. Wesson, Director of National Academy of Sciences, Environmental Research Council

SECTION B-8

MINUTES OF MEETING BETWEEN THE NAVAL MEDICAL RESEARCH INSTITUTE AND AMMANN & WHITNEY

Presented below are the minutes of a meeting held at the Naval Medical Research Institute, National Naval Medical Center, Bethesda, Maryland, on February 5, 1963, to discuss personnel shock effects in connection with this study.

<u>Attendees at the Meeting</u>

Cdr. David E. Goldman	Naval Medical Research Institute
Mr. Samuel Weissman	Ammann & Whitney
Dr. Joseph Vellozzi	Ammann & Whitney

The meeting was opened with an explanation of the Office of the Chief of Engineers project and of the related work being performed by Ammann & Whitney in the investigation of literature and data pertaining to shock effects on personnel for the purpose of establishing requisite shock tolerances and appropriate protection for personnel housed in a hardened, shallow-buried, civil defense shelter subjected to a ground shock environment associated with a 20-MT nuclear weapon burst for overpressures ranging up to 300 p. s. i. The intensity and nature of the expected structure motions were described and it was pointed out that, in most cases, the personnel in the shelters would be in random positions - standing, sitting, reclined - and in fewer cases personnel may be strapped down in chairs, beds, etc., or be provided with other means of bracing themselves.

It was explained by Ammann & Whitney that, based on their review of available literature, it appears that many unknown factors exist with regard to ground shock effects on personnel, although data are available pertaining to personnel shock effects for other types of shock environments. The recommended paper by Drs. Goldman and von Geirke, "Effects of Shock and Vibration on Man", was studied and based on this paper and other publications reviewed, Ammann

& Whitney established preliminary shock tolerances for personnel. Considerable judgment was used in the application of the data for the ground shock environment. It was agreed that no known personnel shock data tests have been conducted specifically for the ground shock problem although this type of testing is presently being considered by other agencies.

The following is a summary of comments and discussion pertaining to the problems posed by Ammann & Whitney:

1. The range of magnitude of the preliminary tolerances established by Ammann & Whitney are reasonable for the ground shock environment as based on available information. It was recommended that some of the values for vibration tolerances be modified as follows: For 10 to 15 c.p.s. use 5 g. instead of 3-7 g; for 15 to 20 c.p.s. use 5 g. instead of 7 g; for 20 to 30 c.p.s. use 7 g. instead of 5 g.

Although the vibration tolerances are based on test data for longer duration exposures than ground shock durations, tolerances for shorter durations may not necessarily be significantly higher, and there is no justification for increasing the recommended values unless appropriate test data indicates otherwise. In addition, the available vibration test data for seated personnel are for personnel tested in special protective seats.

The recommended impact tolerance values of 8 to 10 ft./sec. impact velocity with a hard flat surface should generally be safe. If the body is in a flexible position or if the area of impact is large, higher impact velocities could be tolerated. Impact with sharp corners should be avoided. A possible danger is falling over backwards and striking the back of the head in which case injury may result even if there were no structure motions, although it is to be noted that in most cases the fall may be cushioned by striking with the back or arms first. To provide protection against this type of head injury, padding is advisable. Padding is also required on sharp corners.

2. With regard to personnel shock tests for the ground shock environment, such tests would be necessary to establish more accurate tolerances. However, it should be

noted that the reliability of personnel test data may be limited to the particular age range and physical condition of the persons tested. In addition, personnel may be sensitive to the actual motions which may be difficult to simulate for the complex ground shock environment. Moreover, since it is extremely undesirable that volunteers be injured, the tolerance values will tend to be conservative and will also vary depending upon subjective responses. Further information concerning naval shipboard shock tests can be obtained from Mr. Hirsch, David Taylor Model Basin.

3. With regard to additional reference material, the reports reviewed by Ammann & Whitney represent, in general, the current knowledge in the field in that further investigation of more detailed reports would probably not afford additional information leading to recommendation of more reliable shock tolerance criteria for the ground shock environment. However, for further discussion of personnel effects, consultation with Dr. von Geirke at the Wright Patterson Aero-Space Medical Laboratory would be of particular interest. Other suggested sources of information are:

Federal Aviation Agency, Norman, Oklahoma

Wayne University, Attn: Mr. Lissner

APPENDIX C

EQUATIONS FOR CALCULATING FREE-FIELD AIR-INDUCED GROUND MOTIONS

The following are the equations for calculating free-field air-induced ground motions as presented in Reference 2.6.

C-1 Notation

a = maximum vertical transient acceleration, in gravities.

c = seismic velocity of soil in vertical direction, in ft. per sec.

d_e = maximum elastic component of vertical transient displacement, in in.; for a triangular pressure-time pulse $d_e = hp_{so}/2E$.

d_p = permanent vertical displacement after blast, in in.

E = Young's modulus of elasticity, in p.s.i. For plane waves E is given by

$$E = \frac{(1+\bar{\mu})(1-2\bar{\mu})}{(1-\bar{\mu})}\rho c^2$$

where ρ is the mass density of the soil, $\bar{\mu}$ is Poisson's ratio, and c is the seismic velocity as defined above. For values of μ of 0.25 or less, the relationship is approximately $E = \rho c^2$, and for soil with a density of about 115 lb. per cu. ft. an approximate value of E is

$$E \approx 25{,}000 \text{ psi} \left[\frac{c}{1000 \text{ fps}}\right]^2$$

h = depth to which shock extends in time t_i, in ft.;

$$h = ct_i = 400 \text{ ft.} \left[\frac{c}{1000 \text{ fps}}\right]\left[\frac{100 \text{ psi}}{p_{so}}\right]^{0.6}\left[\frac{W}{1MT}\right]^{1/3}$$

L = quantity in units of ft., a function of overpressure and duration, used in pressure and velocity attenuation relationship.

p_{so} = peak overpressure in shock wave, in p.s.i.

t_i = effective duration of shock, corresponding to a triangular pressure pulse having the same impulse as the actual shock, in sec.

$$t_i = 0.40 \text{ sec.} \left[\frac{100 \text{ psi}}{p_{so}}\right]^{0.06} \left[\frac{W}{1MT}\right]^{1/3}$$

t_r = effective velocity pulse rise time, in sec.; field observations indicate that

$$t_r \simeq \frac{1}{2} \frac{y}{c}$$

for a homogeneous medium.

v = maximum vertical transient velocity, in ft. per sec.

W = yield of weapon, in Megatons.

y = depth below surface to point considered, in ft.

α = attenuation factor for velocity or stress.

Subscripts: "s" denotes the surface and "y" denotes a distance y below the surface.

C-2 Free-Field Air-Induced Earth Motions at Surface

C-2.1 Maximum Transient Vertical Displacement at Surface

The elastic component of the maximum transient vertical displacement of a homogeneous material may be taken as follows:

$$d_{se} = 10 \text{ in.} \left[\frac{p_{so}}{100 \text{ psi}}\right]^{0.4} \left[\frac{1000 \text{ fps}}{c}\right] \left[\frac{W}{1MT}\right]^{1/3} \qquad \text{(C-1)}$$

The permanent vertical displacement depends on the overpressure and on the plastic properties of the soil in the upper 50 to 100 ft. It is often of negligible magnitude for overpressures less than 100 p.s.i., but for soft and weak soils it can be as much as 5 or 6 in. at the surface, even at an overpressure as low as 100 p.s.i. If static stress-strain curves for the soil are not available from which to estimate the permanent displacement, it is suggested that it be taken as follows:

$$d_{sp} = \frac{p_{so} - 40}{30} \text{ in.} \left[\frac{1000 \text{ fps}}{c}\right]^{2} \qquad \text{(C-2)}$$

In this equation, c is the seismic velocity near the surface. When the equation is used, a cut-off in permanent displacement occurs at 40 p.s.i. Available evidence indicates that permanent displacements generally are of a negligible magnitude at pressures below 40 p.s.i.; accordingly it is recommended generally that d_{sp} be taken as zero for pressures less than 40 p.s.i. In exceptional cases there may be reason to estimate the permanent displacement for lower pressures from known stress-strain properties when the soil properties are available.

The maximum transient elastic vertical displacement in a layered or in a non-homogeneous system can be different from Eq. (C-1). For a rigid layer near the surface, but at a depth greater than h, there can be a complete reflection which at most could double the value of d_{se} arising from the near surface strains. For a system with variable properties, or layers, the value should be computed for several positions of the shock, taking account of the values of c for each layer, and adding up the instantaneous values of strain so determined.

C-2.2 Maximum Transient Vertical Velocity at Surface

The maximum transient vertical velocity can be taken as:

$$v_s = cp_{so}/E$$

whence

$$v_s = 4.0 \text{ fps} \left[\frac{p_{so}}{100 \text{ psi}}\right]\left[\frac{1000 \text{ fps}}{c}\right] \quad \text{(C-3)}$$

C-2.3 Maximum Transient Vertical Acceleration

This is computed by assuming a rise time for the maximum velocity (or maximum pressure) of about 0.001 sec., from which it follows that

$$a_s = 150 \text{ g} \left[\frac{p_{so}}{100 \text{ psi}}\right]\left[\frac{1000 \text{ fps}}{c}\right] \quad \text{(C-4)}$$

In the last two equations, one must use the surface seismic velocity. However, the maximum acceleration is not necessarily related to the maximum velocity, but may be larger than the value computed from Eq. (C-4). Therefore, it is recommended that even for high seismic velocities, a value of c no greater than 2000 ft. per sec. be used.

C-2.4 Free-Field Horizontal Effects at Surface

For horizontal surface effects, take the maximum displacement as 1/3 the vertical, the maximum velocity as 2/3 the vertical, and the maximum acceleration equal to the vertical.

C-3 Free-Field Effects at Depth

The displacement, velocity, and acceleration are attenuated with depth. Although experimental data are scarce, the following basis seems reasonable for computing the effects at a depth y.

C-3.1 Vertical Displacement at Depth y

The difference in displacement between the surface and the depth y cannot exceed the sum of the maximum strains between these points, and can be considerably less than this. Between the surface and a depth of 100 ft., the maximum possible elastic strain, assuming no attenuation of pressure, gives an upper limit to the elastic component of the differential displacement, of magnitude

$$4.8 \text{ in.} \left[\frac{p_{so}}{100 \text{ psi}}\right] \left[\frac{1000 \text{ fps}}{c}\right]^2 \qquad \text{(C-5)}$$

The actual difference in deflection may be taken as one-half this value, which is considered to be a more reasonable value and considered to vary linearly with depth down to 100 ft. The permanent vertical displacement attenuates rapidly, and can be assumed to vary linearly from the surface value, given by Eq. (C-2), to zero at a depth of 100 ft.

C-3.2 Vertical Velocity at Depth y

The vertical velocity at depth y is attenuated roughly in the same way as the maximum stress, or

$$v_y = \alpha v_s \qquad \text{(C-6)}$$

where

$$\alpha = \frac{1}{1 + y/L}$$

and

$$L = 300 \text{ ft.} \left[\frac{100 \text{ psi}}{p_{so}}\right]^{0.6} \left[\frac{W}{1MT}\right]^{1/3} \quad \text{for } p_{so} \leq 500 \text{ psi}$$

$$L = 138 \text{ ft.} \left[\frac{100 \text{ psi}}{p_{so}}\right]^{0.1} \left[\frac{W}{1MT}\right]^{1/3} \quad \text{for } p_{so} \geq 500 \text{ psi}$$

C-3.3 Vertical Acceleration at Depth y

The time of rise of the maximum velocity from an initial zero value of velocity can be taken as one-half the transit time of the shock wave from the surface to the depth considered. However, the maximum acceleration can be considered to be twice the value obtained from the assumption that the maximum velocity is obtained linearly. This leads to the relation:

$$a_y = 2g \frac{v_y}{t_r} \frac{1}{32 \text{ ft/sec}^2} \quad \text{(C-7)}$$

The rise time of the peak velocity should not be taken as less than 0.001 sec. This procedure gives less attenuation of acceleration in rock than in soft soil, which is reasonable. If no attenuation of velocity or pressure with depth is assumed, the use of Eq. (C-3) and (C-7) gives the following result:

$$a_y = 5g \left[\frac{p_{so}}{100 \text{ psi}}\right] \left[\frac{100 \text{ ft.}}{y}\right] \quad \text{(C-8)}$$

C-3.4 Horizontal Motions at Depth y

The ratios of peak horizontal to peak vertical displacements, velocities, and accelerations at depth y are to be taken as 1/3, 2/3, and 1, respectively.

APPENDIX D

PROCEDURE FOR CALCULATING SYNTHESIZED GROUND MOTION VERSUS TIME

The following is the procedure for calculating a synthesized ground motion versus time as presented in Reference 3.14.

In many cases free-field ground shock spectra cannot be used directly for the analysis of a structure and its contents. However, a synthesized ground motion curve consistent with the spectra is useful. Such ground motions have been synthesized by approximating the ground motion as a single velocity or displacement pulse. Figure D-1 shows a typical velocity and displacement pulse. This pulse was derived from a particular shock spectra curve, and when applied to a series of single-degree-of-freedom oscillators would approximately result in the peak response of the spectra. The velocity pulse is derived from a given response spectra curve by the following relationships and the displacement pulse is determined by integrating the velocity pulse.

A velocity pulse of the following form has been found to agree with spectra within reasonable limits:

$$v = v_o[e]^{-t/\tau} - v_o[e]^{-\alpha t/\tau} \qquad \text{(D-1)}$$

where

v = the velocity of the support as a function of time (inches per second)

v_o = peak velocity input (constant for a particular spectra curve) (inches per second)

t = time (seconds)

τ = parameter in units of time (seconds) (constant for a particular spectra curve)

α = dimensionless parameter (constant for a particular spectra curve)

e = base of natural logarithms

The parameters v_o, τ and α are a function of the shape of the spectra curve (for example, dashed line of Figure 2-2). v_o and τ are essentially dependent upon the low frequency range of the spectra and primarily describe the peak velocity and decay of the velocity pulse. α is dependent upon the high frequency range of the spectra and primarily affects the rise time to the peak velocity of the velocity pulse. First trial values for v_o and τ are obtained by neglecting the second term of Equation D-1 and substituting the displacement response values for two points from the given spectra in the following equations:

$$\tau^2 = \frac{u_2^2 - u_1^2}{u_1^2\omega_1^2 - u_2^2\omega_2^2} \qquad \text{(D-2)}$$

$$v_o = \frac{u_1\sqrt{1 + \omega_1^2\tau^2}}{\tau} = \frac{u_2\sqrt{1 + \omega_2^2\tau^2}}{\tau} \qquad \text{(D-3)}$$

where

u_1 = displacement response (inches) for frequency ω_1

u_2 = displacement response (inches) for frequency ω_2

ω = undamped natural circular frequency (radians per second)

Since Equations D-2 and D-3 are based on the low frequency range of the spectra, it is necessary to select the two points at frequencies below the frequency at which the peak acceleration response of the spectra occurs, a point in the very low frequency range of the spectra curve and another at a higher frequency depending on the particular spectra shape.

Once τ and v_o have been estimated, α is then computed. α is a function of the rise time as follows:

$$t_r = \frac{\tau}{\alpha - 1} \ln \alpha \qquad \text{(D-4)}$$

Where t_r is the rise time. In most cases the rise time will not be accurately known and the following expression can be used:

$$\alpha = \frac{A_m \tau}{v_o} + 1 \qquad \text{(D-5)}$$

Where A_m is the peak acceleration for a particular spectra curve.

It is necessary to check several points on the spectra since the shape of particular spectra may not exactly correspond to the velocity pulse at every frequency. This may be done by substituting values of the natural circular frequency in Equation D-6 below at various points throughout the spectra with the previously determined values of v_o, τ, and α, and comparing the displacement u so determined with the given spectra. In general, the two spectra will not exactly coincide at every frequency and it may be necessary to adjust v_o and/or τ, taking into account the corresponding change in α, in order to obtain a velocity pulse resulting in responses approximately consistent with the entire spectrum curve. In some cases it may be necessary to use a velocity pulse which results in conservative responses at certain frequencies in order that other frequency responses are not too low compared to the given spectra curve.

$$u_\omega = \frac{v_o \ \tau \ (\alpha - 1)}{\sqrt{(1 + \tau^2 \omega^2)(\alpha^2 + \tau^2 \omega^2)}} \qquad \text{(D-6)}$$

where u_ω is the displacement response for a particular frequency ω from the response spectra.

When deriving a velocity pulse from design spectra of the envelope type shown in the solid line of Figure 2-2, the general velocity pulse principles are still valid, although it is not necessary that the velocity pulse correspond to the response at all frequencies. In fact, for this type of spectra the velocity pulse cannot conform at all frequencies since the spectrum does not conform to the response variation consistent with vibration theory in that responses are constant over a range of frequencies. However, this spectra represents conservative values in certain frequency ranges and correct values at the end points and the intermediate point on the spectrum. With the spectra properties in mind, a rational velocity pulse can be derived by matching points which are known to be the controlling response of the design spectra and permitting particular frequency responses resulting from the velocity pulse to be lower than the envelope in accordance with the actual variation for a true spectra curve.

When calculating the first trial values of v_o and τ it is best to choose the following two points on the spectra. (1) The peak displacement response at the left side (very low frequency range) of the spectra, and (2) the lowest frequency at which the peak acceleration occurs. After v_o and τ are estimated, a is computed and it is again necessary to check various points on the spectra and adjust the parameters, if necessary, in accordance with the above discussion.

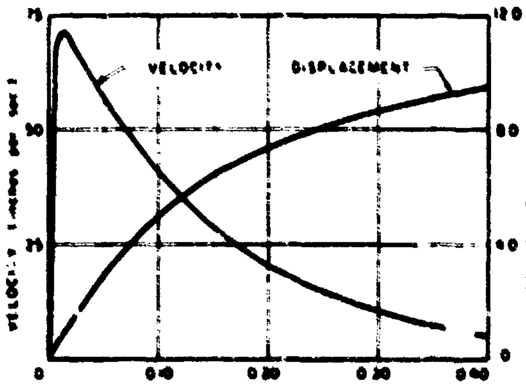


Fig. D-1 TYPICAL VELOCITY AND DISPLACEMENT PULSE

DISTRIBUTION LIST

Addressee	No. of Copies
Office of Civil Defense, DOD, Pentagon, Washington, D.C. 20301, Attention: Director for Research	130
Army Library, Civil Defense Unit, Pentagon, Washington, D.C. 20310	3
Defense Documentation Center, Cameron Station, Alexandria, Virginia 22314	20
Chief of Naval Research (Code 104), Department of the Navy, Washington, D.C. 20350	1
U.S. Naval Civil Engineering Laboratory, Port Hueneme, California	2
Col. Perry L. Huie, Air Force Weapons Laboratory, Kirtland Air Force Base, Albuquerque, New Mexico	2
Chief, Bureau of Yards and Docks, Office of Research (Code 74), Department of the Navy, Washington, D.C. 20360	1
Coordinator, Marine Corps Landing Force Development Activities, Quantico, Virginia	1
Chief, Bureau of Supplies and Accounts (Code 1.12), Department of the Navy, Washington, D.C. 20360	1
Chief, Bureau of Medicine and Surgery, Department of the Navy, Washington, D.C. 20360	1
Chief of Naval Personnel (Code Pers M12), Department of the Navy, Washington, D.C. 20360	1
Chief of Naval Operations (Op-07T10), Department of the Navy, Washington, D.C. 20360	1

Addressee	No. of Copies
Chief, Bureau of Naval Weapons (Code RRRE-5), Department of the Navy, Washington, D. C. 20360	1
Assistant Secretary of the Army (R&D), Washington, D. C. 20310, Attention: Assistant for Research	1
Advisory Committee on Civil Defense, National Academy of Sciences, Attention: Mr Richard Parks, 2101 Constitution Ave., N. W., Washington, D. C. 20418	1
Mr. Lyndon Welch, Eberle M. Smith Associates, Inc., 153 East Elizabeth St., Detroit 1, Michigan	1
Mr. Luke J. Vortman, Underground Physics Division, Sandia Corporation, Albuquerque, New Mexico	1
Dr. Merit P. White, Chairman, Civil Engineering Department, School of Engineering, University of Massachusetts, Amherst, Massachusetts	1
Dr. Robert J. Hansen, Department of Civil & Sanitary Engineering, Massachusetts Institute of Technology, Cambridge 30, Massachusetts	1
Col. A. D. Chaffin, Jr., Chief, Joint Civil Defense Support Group, Room G312, Gravelly Point, Washington, D. C.	1
Atomic Energy Commission, Division of Biology & Medicine, Attention: W. T. Armstrong, Washington, D. C. 20545	1
Lt. Col. James R. Bohannon, Standards & Criteria Branch, Engineering Division, AFOCE-ES, Room 5C-365, Pentagon, Washington, D. C. 20330	1
Mr. Edward R. Saunders, Office of Emergency Planning, Executive Office of the President, Washington, D. C., (Stop #16) 20504	1

Addressee	No. of Copies
Mr. Strode L. Ely, OSD, I&L, Room 3C-771, Pentagon, Washington, D. C. 20301	1
Mr. Joseph C. Walker, Action Office, Public Works Planning Branch, DCS/LOG, Room 2E-573A, Pentagon, Washington, D. C. 20301	1
Maj. Maurice K. Kurtz, AMC, Nuclear Branch, R&D, (AMCRD-DE-N), Room 2721, Building T-7, Washington, D. C.	1
Hayes, Seay, Mattern & Mattern, 1615 Franklin Road, S. W., Roanoke, Virginia	1
Chief of Engineers, Attention: ENGTE-E, Department of the Army, Washington, D. C. 20310	1
Chief of Engineers, Attention: ENGMC-DO, Department of the Army, Washington, D. C. 20310	1
Chief of Engineers, Attention: ENGMC-EM, Department of the Army, Washington, D. C. 20310	11
University of Arizona, College of Engineering, Tucson, Arizona	1
IIT Research Institute, 10 West 35th Street, Chicago 16, Illinois	1
Army Chemical Corps, Department of the Army, Chemical Center, Edgewood, Maryland 20315	1
Atomic Energy Commission, Oak Ridge, Tennessee	1
Atomic Energy Commission, Division of Biology & Medicine, Attention: Dr. Dunham, Washington, D. C. 20545	1
Battelle Memorial Institute, 505 King Avenue, Columbus, Ohio	1

Addressee	No. of Copies
Cornell Aeronautical Laboratory, 4455 Genesee St., Buffalo 21, New York	1
Chief, Defense Atomic Support Agency, Attention: Mr. John G. Lewis, Washington, D.C. 20301	2
Commander, Field Command, Defense Atomic Support Agency, Sandia Base, Albuquerque, New Mexico	1
Dikewood Corporation, 4805 Menaul Boulevard, N.E., Albuquerque, New Mexico	1
DeLeuw, Cather & Company, Chicago, Illinois	1
Department of Engineering Science, Florida State University, Attention: Dr. G.L. Rogers, Tallahassee, Florida	1
General American Transportation Co., 7501 N. Natchez Ave., Niles 48, Illinois	1
Hudson Institute, Quaker Ridge Rd., Harmon-on-Hudson, New York	1
Naval Radiological Defense Laboratory, San Francisco, California	1
Pennsylvania State University, 133 Hammond Building, University Park, Pennsylvania	[illegible]
Guy L. Panero, 630 Third Ave., New York 17, New York	1
Mr. Marc Peter, Jr., E.H. Plesset Associates, Inc., 2444 Wilshire Boulevard, Santa Monica, California	1
Stanford Research Institute, Menlo Park, California	1
Technical Operations, Inc., Burlington, Massachusetts	1

Addressee	No. of Copies
The Rand Corporation, 1700 Main St., Attention: Mr. Harold Brode, Santa Monica, California	1
Mr. Charles F. Coffin, Planning Officer, Technical Analysis Division, Office of Emergency Planning, Executive Office of the President, Washington 25, D. C.	1
Director, U. S. Army Engineer Waterways Experiment Station, P. O. Box 631, Vicksburg, Mississippi	
Attention: Nuclear Weapons Effects Branch	1
Attention: Library	1
Dr. N. M. Newmark, 111 Talbot Laboratory, University of Illinois, Urbana, Illinois	2
Protective Structures Development Center, Attention: Technical Library, Fort Belvoir, Virginia	1
Director, Air Force Nuclear Engineering Facility, Air Force Institute of Technology, Wright-Patterson Air Force Base, Dayton, Ohio	1
United Research Services, 1811 Trousdale Drive, Burlingame, California, Attention: Mr. Carl K. Wiehle	1
Headquarters, U. S. Air Force, Office of Operations Analysis (AFOOA), Attention: B. Kornhauser, Pentagon, Washington, D. C.	1
DIAAP-1K2A, Building B, Arlington Hall, Washington, D. C., Attention: Mr. Charles Walker	1
Praeger-Kavanagh-Waterbury, 126 East 38th St., New York 16, New York, Attention: Mr. Noonan	1