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MASTER

UNDERGROUND PROTECTIVE BUILDINGS

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A Term Paper For

C. E. 471 Building Construction

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LIST OF ILLUSTRATIONS

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CHAPTER I

INTRODUCTION

In the last few (5-10) years, the civil engineering profession has seen an increasing amount of interest in the placing of buildings--indeed, in some instances, complete community units--underground. This interest has been predicated upon the development of extremely powerful weapons having a very large radius of destruction for conventional buildings located above ground. Most of the existing instances of the construction of underground buildings have been for the protection of military personnel and material. However, some underground buildings have been built for the protection of the civilian population. It is conceivable that this civilian-use trend will increase in this country as it already has in certain foreign countries.

Considering the situation described above, today's young civil engineer should take it upon himself to become aware of the many problems--construction as well as design--that are associated with the location of buildings below the surface of the ground. During his ensuing career, it may well be, if the present world situation continues, that he may become involved in such a project. Fortunately, there is now available information--not as plentiful nor as accurate as might be desired--on this subject that he may obtain to educate himself.

Purpose of this Paper

It is the purpose of this paper to provide a brief survey of the general subject of underground protective buildings. It is not intended to be a handy-dandy design manual on the subject. But, by serious study of the references listed in the bibliography--all of which may be easily obtained--a competently trained civil engineer can become proficient to some degree in this subject. If this paper serves to stimulate an interest and provide some help in continuing study of the subject at hand, it will have satisfied the author's intent.

Subject Coverage

The general subject of underground protective buildings is very broad. The coverage of it in this paper is not complete but must be limited in order to keep the paper manageable. For the most part, this paper will be limited to

--weapon yields in the megaton and larger range

--blast overpressures (on the surface) of 200 psi or less

--surface burst (contact) cases

In general the discussions will be limited to shallow buried bi buildings--within one hundred feet of the surface of the ground--but some information will be included on examples of deep underground buildings.

Types of Underground Buildings

Four general types of underground buildings will be described in this paper.

Personnel shelters. Underground buildings designed primarily for the protection of groups of people will be considered as personnel shelters. These buildings range from simple, shallow, home-built, fall-out shelters through a community of underground homes to large buildings located deep enough to provide a large amount of blast protection to the occupants. An entire school building has been located underground in New Mexico. Although this paper will not deal with simple, shallow fall-out shelters, some of the material in Chapter II is useful for this sort of structure.

Launch structures (silos). The launch structures of hardened missile sites are probably the most common (in numbers) of underground buildings built to date. Several hundred such structures have been completed. Construction and design procedures have been rather well worked out ~~for these~~ based on the experience to date. Although launch structures are a very specialized type of underground building, there are many interesting aspects to their design and construction.

Launch control buildings. Closely associated with launch structures are the underground buildings that serve as control centers for the hardened missile sites. Designed to protect the operating personnel and delicate control equipment necessary for launching and controlling modern missiles, these buildings contain many sophisticated design and construction details.

Deep underground buildings. There are a few instances where the construction of extensive building complexes have been made deep underground. These installations are usually built in hard rock areas and are designed to permit the survival of personnel and equipment of major command centers from any type of attack. The problems in construction and design of these buildings present real challenges to the engineers involved.

CHAPTER II

SURFACE ENVIRONMENT NECESSITATING UNDERGROUND BUILDINGS

A brief survey of the environment resulting from a surface burst of a megaton or larger nuclear weapon is contained in this chapter. An understanding of the surface environment is very important in the design and construction of underground buildings. It is the source of the special loadings that must be considered if such buildings are to survive and perform their intended functions.

A great amount of work and study on defining this environment and its effects has been performed during the last decade and a half. Two excellent references are available that describe this environment in considerable detail (both have been used extensively in preparing this chapter). They are The Effects of Nuclear Weapons[1] and A Review of Nuclear Explosion Phenomena Pertinent to Protective Construction.[2] An engineer interested in further study of the subject of underground buildings should obtain copies of each.

Air Blast

The severe air blast overpressures resulting from a nuclear explosion are the primary reasons dictating the underground location

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[1] The Effects of Nuclear Weapons, U. S. Department of Defense and Atomic Energy Comm., U. S. Government Printing Office, Washington, D. C., April 1962, ($3).

[2] H. L. Brode, A Review of Nuclear Explosion Phenomena Pertinent to Protective Construction; A Report Prepared for U. S. Air Force Project Rand, R-425-PR, (Santa Monica, California: The Rand Corporation, May 1964).

of buildings intended to survive such an attack. Although the interaction of these overpressures with the ground result in sizable induced ground shocks, the soil structure attenuates this effect to a very great degree. Utilization of this attenuation permits the construction of underground buildings with far greater economy than if blast-resistant above-ground construction were used.

The magnitude of the peak overpressure as it varies with distance from ground zero (point of burst on the surface) for a 20 megaton surface burst is shown in Figure 1. A normal, i.e. non-blast resistant, designed building will be severely damaged at overpressure levels around 5 psi. Referring to Figure 1 shows that this type of building would not survive inside a radius from ground zero of 40,000 feet. It is generally regarded as uneconomical to construct an aboveground rectangular building to resist pressures greater than 30 psi peak overpressure, hence such a building would not survive inside the two mile radius. (Note-distance scales as the cube root of yield for these kinds of explosions.)

Of interest, Figure 2 shows the duration of the positive phase of the air blast as it varies with distance from ground zero for the same size (20 MT), surface burst. As can be seen, the duration of this positive phase is quite sizable.

Ground Shock

An underground building may be made quite safe from the direct effects of air blast, as well as from nuclear and thermal radiations as shown later, so that the primary remaining problem is associated with the violent movements of the surrounding earth--the ground shock ~~shock~~.

Ground shock

PEAK OVERPRESSURE versus DISTANCE

20 MT SURFACE BURST

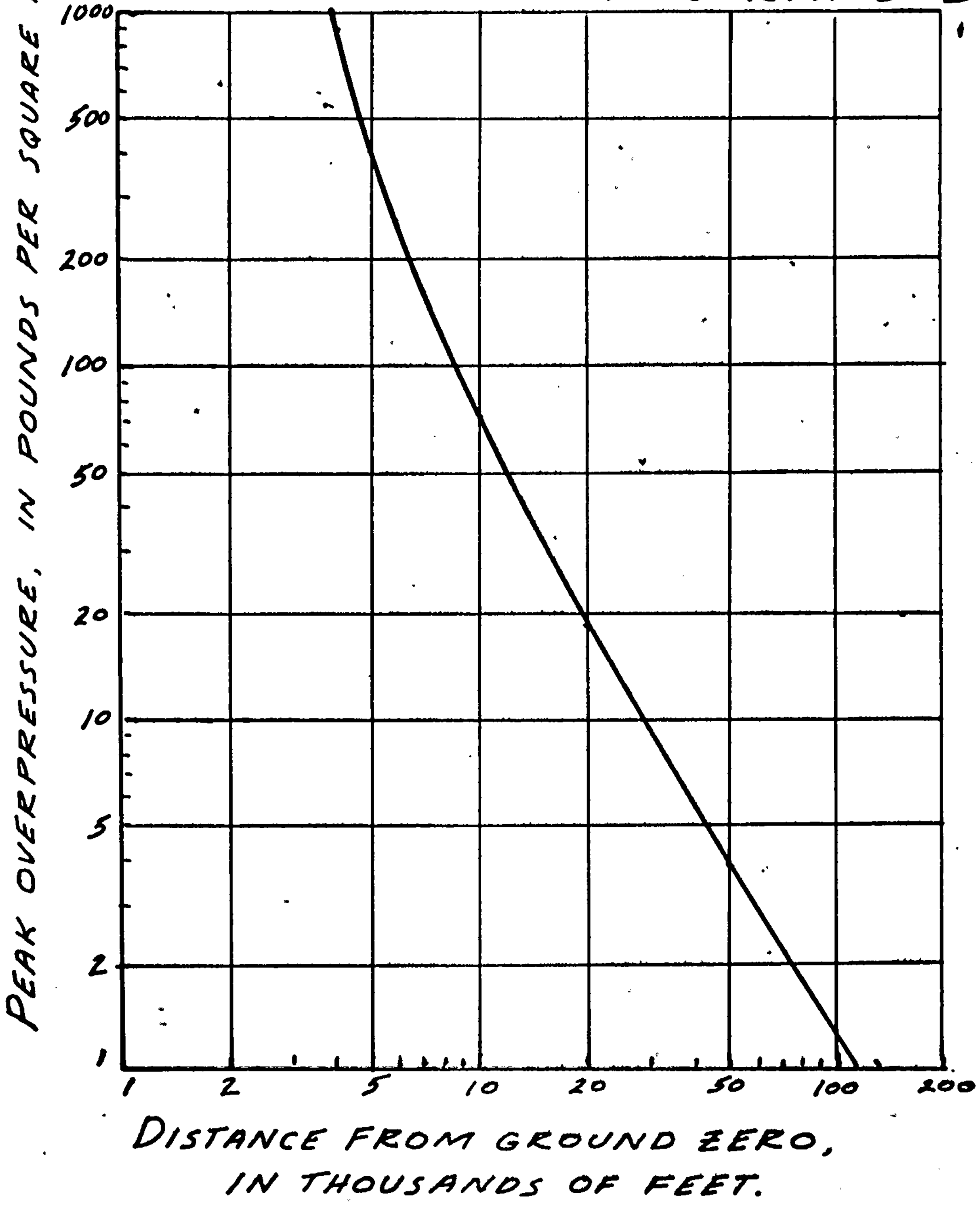
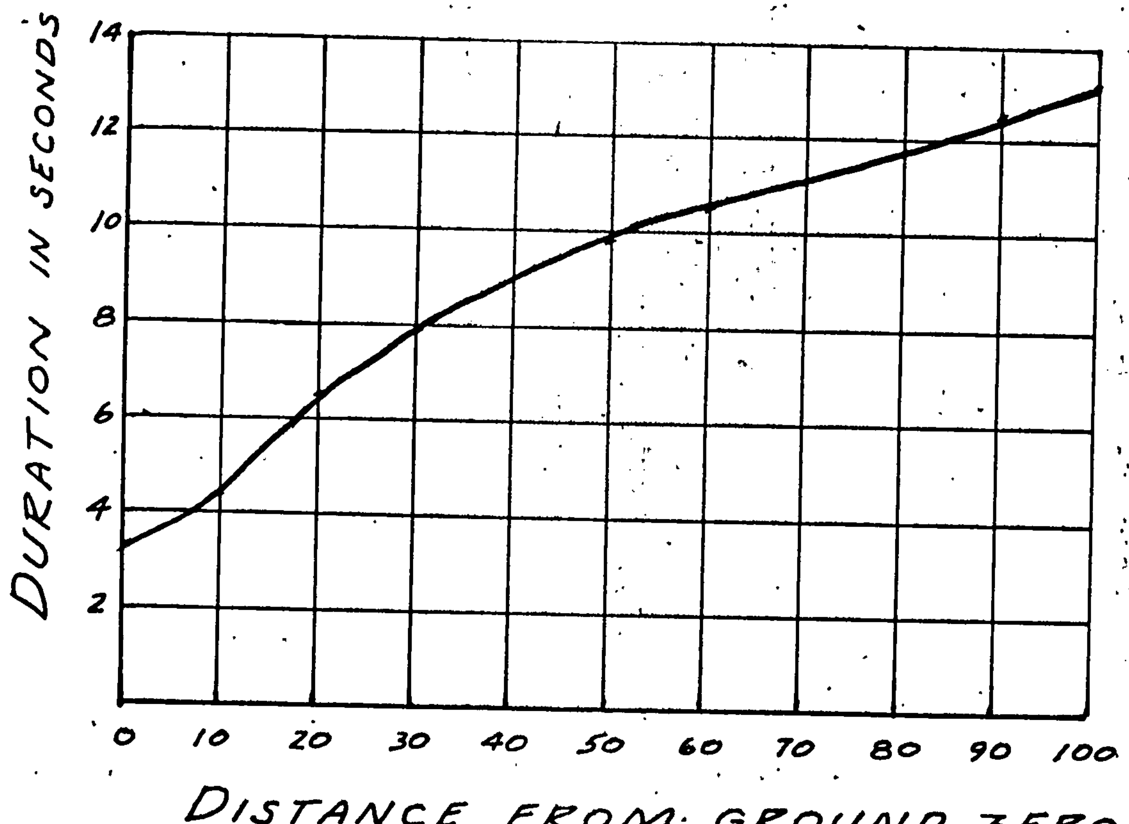


FIGURE 1

POSITIVE PHASE DURATION

20 MT SURFACE BURST



DISTANCE FROM GROUND ZERO
IN THOUSANDS OF FEET

FIGURE 2

Ground shock transmitted to an underground building comes from two causes, direct shock and air-induced ground shock. In most underground buildings (less than one hundred feet burial), the air-induced ground shock is of greater significance since it is extended to large radial distances from ground zero by the air blast (Figure 1), while direct ground shock is rapidly attenuated by passing through the intervening ground mass.

The geometric stress attenuation in soils with depth has been approximated from the formula proposed by Newmark[3];

$$\sigma_{vm} = \alpha_z \Delta P_s$$

$$z = \frac{1}{(1 + Z)/L_W}$$

$$L_W = \frac{2300\ W^{1/3}}{(\Delta P_s)^{1/2}}\ \text{ft.}$$

where ΔP_s is the peak overpressure at the surface (psi), σ_{vm} is the maximum stress (psi) at depth Z (ft.), α_z is the geometric attenuation factor, and W is the yield (megatons). This expression applies only for the lower surface overpressures ($<$1000 psi). This relationship is plotted in Figure 3 for typical overpressures and yields.

Thermal Radiation

Approximately one-third of the energy of a nuclear detonation is released in the form of thermal radiation. Since this radiation has properties damaging to materials and humans it must be considered in the planning of the details (entrance ways, closures, blast doors, etc.) of an underground building. Generally, the thermal effects are of secondary importance since in protecting against nuclear radiation

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[3] N. M. Newmark and J. D. Haltinwanger, Principles and Practices for Design of Hardened Structure, AFSWC-TDR-62-138, (Albuquerque: Air Force Speical Weapons Center, December 1962).

ATTENUATION IN VERTICAL STRESS WITH DEPTH

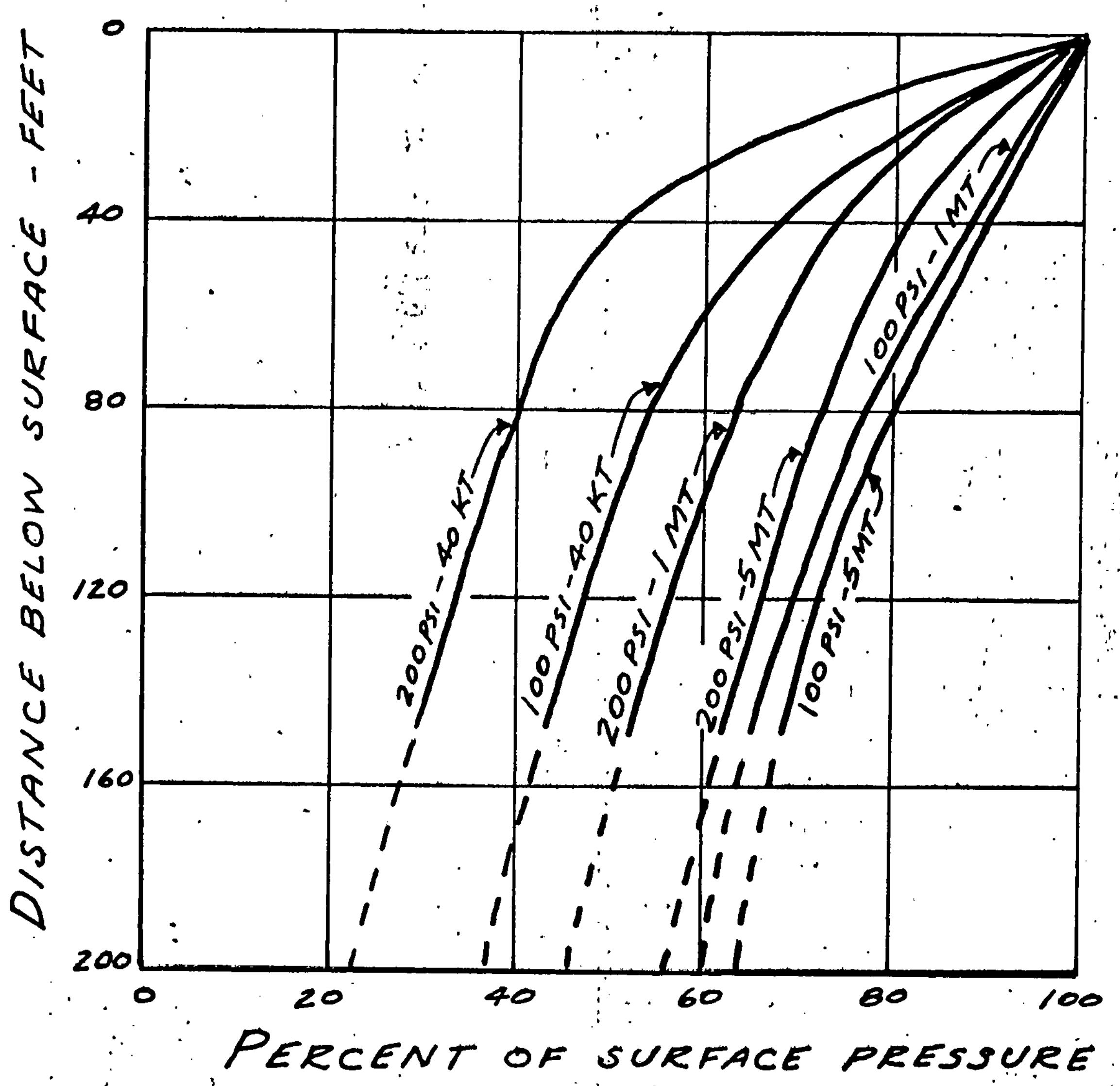

FIGURE 3

and blast pressures, the thermal radiation problem is automatically eliminated.

The thermal radiation environment is quite excessive and is shown here for general appreciation. Figure 4 indicates the thermal energy received at various distances for a 20 megaton surface burst.

Nuclear Radiation (Initial)

The initial radiation from a nuclear explosion is defined as that released within the first one minute. The gamma rays and neutrons emitted can travel considerable distances through the air and cause harmful effects in humans and equipment. A graphical display of radiation dose versus distance is shown in Figure 5. As a point of interest, doses of about 450 R may be expected to kill 50 percent of the humans exposed, while doses of over 700 R will cause 100 percent falalities.

Nuclear Radiation (Residual-Fallout)

The residual radiation--defined as that emitted after one minute from the time of the burst--is commonly termed "local" or "early" fallout. This hazard is the result of fission products from the explosion attaching to earth debris thrown out of the crater to altitudes of several tens of thousands of feet. This debris then drifts back to earth in a matter of hours.

There are many factors that enter into the calculation of residual radiation including terrain, yield, wind conditions, humidity, etc. For further information, a study of The Effects of Nuclear Weapons[4] is suggested.

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[4] The Effects of Nuclear Weapons, op cit, Ch. IX.

THERMAL ENERGY RECEIVED AT VARIOUS DISTANCES

20 MT SURFACE BURST VISIBILITY 2 TO 50 MILES

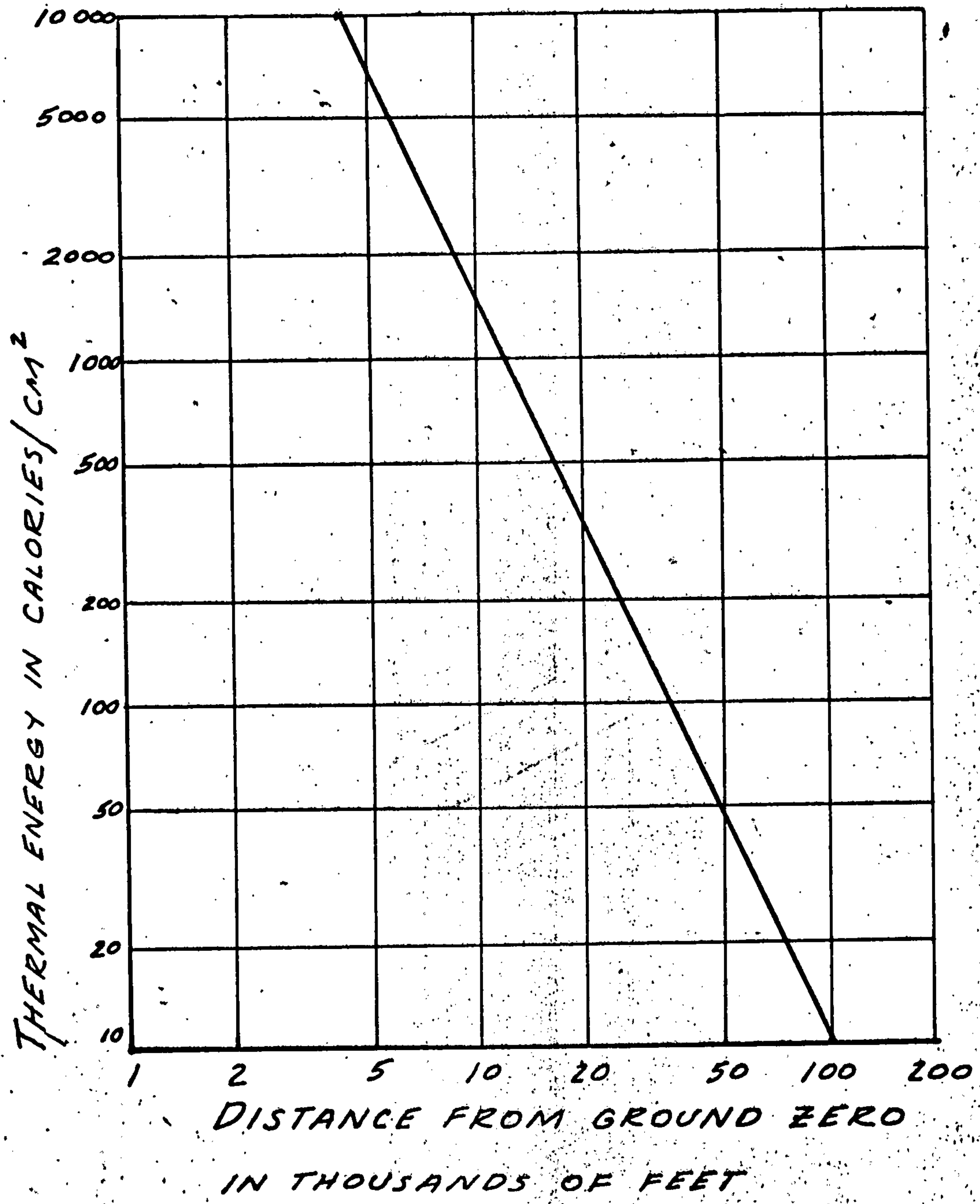

FIGURE 4

RADIATION DOSE vs. DISTANCE

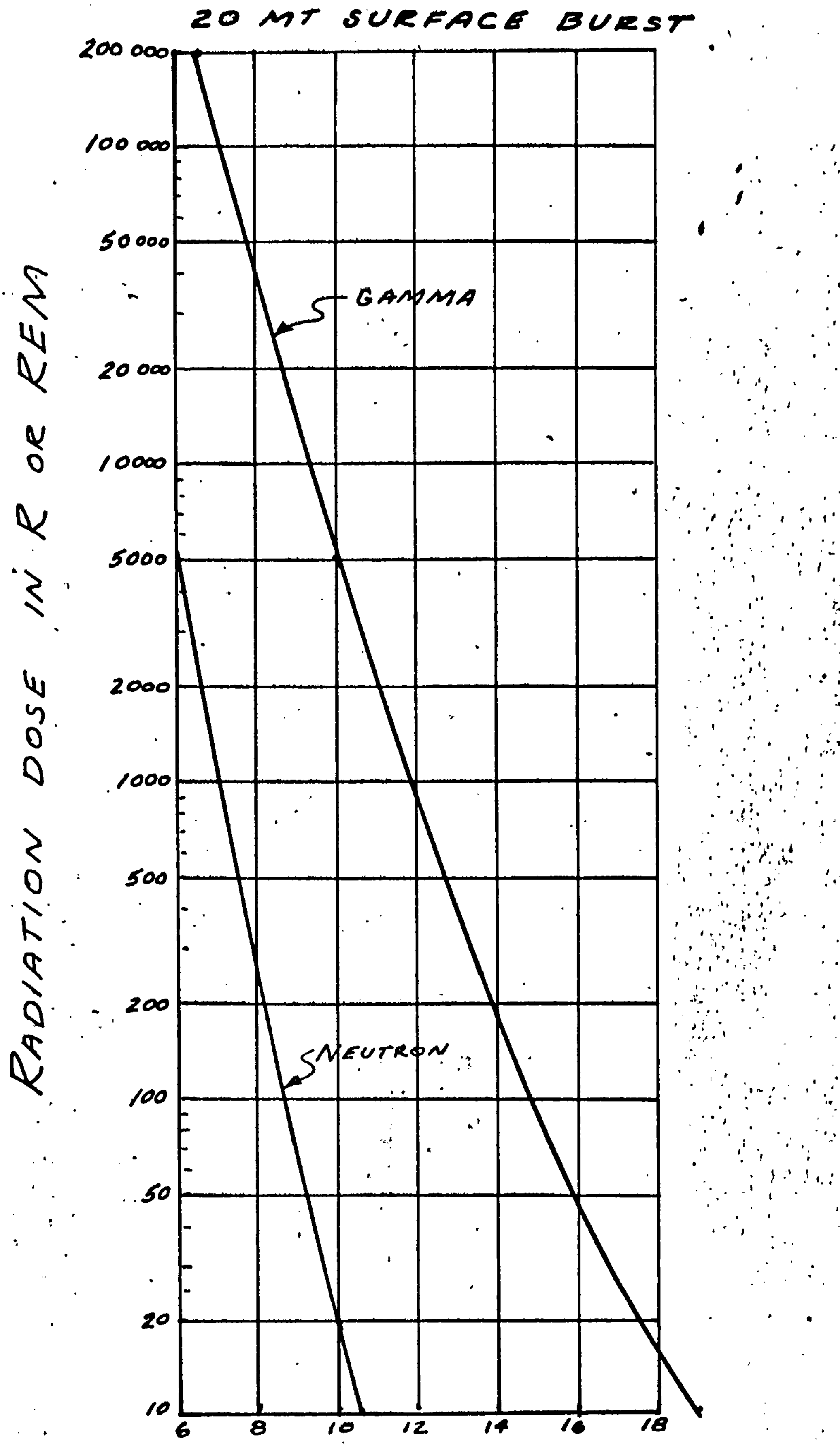

FIGURE 5

Fire Storms

The effects of thermal radiation and the results of structural damage by the air blast cause wide-spread fires over an area subjected to a nuclear explosion. Under certain conditions of weather and density of combustible materials, a raging, all-consuming "fire storm" can develop. In such a case, the heat is so intense and the oxygen of the local atmosphere is so depleted that any underground building in the area must be completely closed off. A method to provide sufficient air (oxygen) must be available within the building to enable the occupants to survive. The duration of a fire storm has been observed to be several (6-8) hours, after which only separate fires continue.

CHAPTER III

STRUCTURAL SYSTEMS FOR UNDERGROUND BUILDINGS

It has been stated earlier that aboveground blast-resistant buildings are uneconomical to construct in regions of overpressures greater than 30 psi. For overpressures of 100 psi or greater, underground buildings must be constructed. Semi-underground buildings may survive in regions of 30-100 psi overpressures, but this cannot be regarded as a blanket statement. Foundation conditions, size of building, shielding requirements, entrance conditions, and local geology all affect the relative economy of fully underground versus semi-underground construction.

Basic Consideration

The principal structural materials used in underground protective buildings are soil, reinforced concrete, and steel. Soil is an important material for this usage since it is a good shield against nuclear and thermal radiation and it may be used to reduce the magnitude of blast loading on the building.

Reinforced concrete is the predominant material used in this type of construction. If properly designed and placed, it can offer good strength and ductility while having the mass to serve as a radiation shield.

Structural steel, used alone or in reinforced concrete, has the desirable strength and ductility characteristics for this application.

In the form of archplate, it is particularly economical for underground buildings.

Several types of structural systems for underground buildings using the desirable materials noted above have been considered and used. The most commonly used ones are: rectangular structures, arches, domes, and vertical cylinders, Several combinations and variations of these common structural systems have been used.

As with any building, the structural system used depends upon the influence of several factors. Some of these considerations are economy of construction, availability of materials, site conditions, contractor experience, time schedules, etc. The most important consideration, however, for the structural system selection in the highly specialized field of underground protective buildings, is the ability of the structure to withstand the loads to which it is subjected.

Design of Structural System

Rectangular structures. The depth of burial of a rectangular structure is of great importance in determining the type of loading it will receive and thus its structural strength. Figure 6 shows the two conditions of primary interest for rectangular structures. In both cases, the structure can be considered underground from the standpoint of blast loading.

When located as shown in Figure 6 (a) the slope of the surface of the earth should not be greater than 1 on 4 for a distance of twice the height of the building on all sides. However, if located as shown with the building roof flush with the surface, the roof elements must survive the loading resulting from the air blast directly.

UNDERGROUND RECTANGULAR STRUCTURES

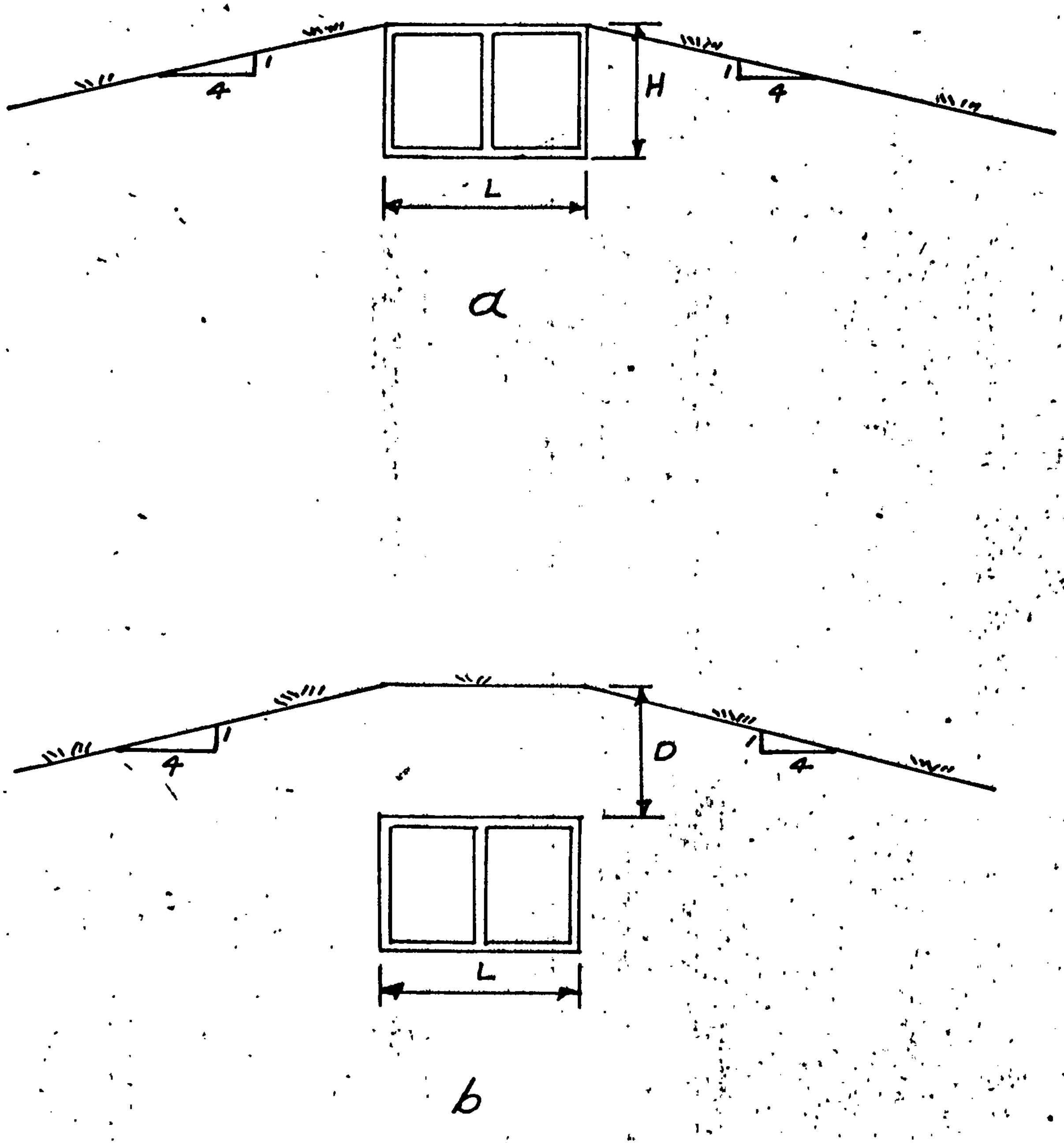

FIGURE 6

If the building is located completely below the surface as shown in Figure 6 (b),the loading from the air blast can be modified to account for the attenuation of peak pressure using the Newmark formula given earlier. In addition, if the burial depth D is considerably greater than the building length L divided by 2, the loadings on the structure may be reduced because of arching in the soil,if backfilling during construction has been well accomplished.

The vertical walls should be designed to have a strength sufficient to resist a uniformly distributed load from the surface pressure pulse that has been attenuated (using the Newmark formula) to the depth of the mid-height of the well. This attenuated vertical pressure must be related to the uniformly distributed horizontal pressure by using a factor depending upon the soil type and condition. Estimated values of this factor may be found in the ASCE Manual No. 42.[1]

Arches. An underground building in an arch shape possesses very high structural strength. This is due primarily to the manner in which it is loaded when buried. Initially, the underground arch is subjected to non-uniform intensities of load at any depth to which it is buried. However, as the shock progresses across the arch, one side is loaded prior to the opposite side and tends to deflect inward which in turn forces the opposite side outward into the soil. This outward deflection is resisted by the passive pressure developed in the soil which is ~~a~~ very sizeable ~~amount~~. Therefore, below some critical depth at which the passive resistance of the soil becomes adequate to prevent significant flexural deflections, the pressures on the arch

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[1] Design of Structures to Resist Nuclear Weapons Effects", Manual of Engineering Practice No. 42, (New York: American Society of Civil Engineers, 1961), P. 54.

from the loading tend to be equalized. Below this critical depth, the arch must resist a uniform radial pressure, an ideal situation for such a structural system. It is believed that this critical depth at which the arch is subjected to uniform radial pressure is L/8 where L is the length of the arch from hinge point to hinge point.

If close control is exercised over the construction procedures, especially backfilling, the pressure pulse already attenuated by the depth factor, can be further reduced BECAUSE OF THE ~~to consider~~ arching.

Domes. The previous discussion on arches applies directly to underground buildings built as domes.

Vertical Cylinders. The design loadings to be used in determining the structural strength of vertical cylindrical buildings (silos) is based on judgment and limited theoretical studies. Terzaghi[2] has studied the state of stress around vertical shafts in granular materials. In the CASE ~~use~~ of vertical cylinders (silos), the static loads due to the dead weight of the soil may be a very important contribution to the loading.

In regard to the transient loading of a vertical cylinder, the situation is the same as discussed for arches. However, the horizontal component of the vertical load must be used as discussed for sidewall loading of rectangular buildings. The critical depth at which uniform radial loading occurs for vertical cylinders is considered to be equal to the diameter of the cylinder.

General criteria. The design of underground protective buildings is essentially an ultimate strength design aimed at the standards of performance required by the function of the building. Thus, the

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[2] K. Terzaghi; Theoretical Soil Mechanics, (New York: John Wiley and Sons, Inc., 1943) pp. 206-215.

resulting "factor of safety" can be considered as being unity, considering one predetermined set of loading conditions.

An underground protective building should be designed to have as large a "ductility ratio" as performance requirements will permit. Ductility ratio is defined as the ratio of the maximum response to that response at which elastic behavior stops. It is important that this ratio be large because, (1) greater ductility permits greater energy absorption capability, i.e. greater efficiency in resisting time dependent loads, (2) ductility is essential to permit structural deformations required to mobilize the inherent strength (passive) of the soil that surrounds the underground building. The choice of the ductility ratio depends upon several considerations: (1) the functional requirements of the building, (2) repetitions of design loads, (3) allowable damage to equipment and personnel from concrete spalling, (4) ductility of the construction material~~s~~, and (5) the failure mode of the structural system.

Since design of buildings of this type is based on ultimate strength, the dynamic strengths of the materials of construction must be used to account for the rapid rates of straining that occur in a building loaded by blast forces. Under these conditions, materials develop higher strengths than they do in the case of statically loaded members. Not a great deal is known yet about dynamic strengths of materials, but some information can be obtained from ASCE Manual No. 42.[3]

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[3] "Design of Structures to Resist Nuclear Weapons Effects", op. cit., pp. 63-64.

CHAPTER IV

FUNCTIONAL REQUIREMENTS OF UNDERGROUND BUILDINGS

The functional requirements of underground protective buildings vary greatly according to their intended usage. Personnel shelters are intended to insure the survival of the occupants and their safe exit. A launch structure should protect its missile and associated equipment in an undamaged condition so that it can perform its mission when required. A launch center building must protect personnel and delicate guidance equipment so that its operation can proceed smoothly. The command center (deep underground building) must protect its occupants and communication systems to insure maintenance of intelligence and continuity of operations.

Provisions must be made in the buildings as constructed to permit the realization of these requirements.

Environmental Equipment

The environmental equipment must be designed to eliminate the possibility of nuclear radiation entering via surface connected ducts into the building areas where it cannot be tolerated. The geometry of the ducting system may be the critical factor and, in some cases, occupants and equipment may need be isolated from radioactive areas.

The provision of a highly reliable environment may be a critical problem, Commercial air-conditioning equipment may require upgrading to meet the reliability requirements. The system must be adequate to handle all of the normal loads, plus providing capacity to maintain the desired environment for extended periods during which the building must be "buttoned up."

Power Supply

An underground protective building must be independent of a commercial power supply system which may be destroyed. To provide this independence, stand-by generat~~ions~~ors must be inside the protective building. ~~It~~ They will then survive and be available to provide power during the button up period. The power demand should be minimized during the period of operation on stand-by power. Provisions for adequate fuel and water supplies must be made as well as accomodations for removing exhaust fumes.

Blast Closures

Blast closures are of two types--blast valves for smaller diameter ducts, and blast doors for entrance and exit ways. Blast valves should be designed to stay open during normal operations to permit the normal flow through the ducts to the surface to continue. They must be closed immediately upon the occurrance of a blast hazard. They usually have a moving component that causes the valve to close tightly either on a signal or by the momentum caused by the blast forces. A blast valve must survive the ground shock and blast and be able to open following the passage of the overpressure.

Blast doors are usually built to remain closed during normal operation. They require no quick-closing components. However, they too must survive the ground shock and blast so that they can be operated afterwards.

Shock Isolation Systems

Under the ground shock environment discussed in Chapter II, the entire soil mass containing ~~continuing~~ an underground building is given a sizeable displacement, velocity and acceleration. Human and equipment shock tolerances are must lower than the expected shock environment from the nuclear explosion. For that reason, a shock isolation system must be built within the building to protect its occupants.

Several systems for providing isolation from ground shock have been used. In some instances, what amounts to a building within a building is constructed. The inner structure being isolated from the outer protective structure by a series of springs and dampers. This permits the reduction of the ground motion forces to acceptable shock levels for people (about 1 g. is the design goal).

CHAPTER V

CONSTRUCTION OF EXISTING UNDERGROUND BUILDINGS

Underground construction is not a new field of endeavour for the civil engineer. Indeed, construction projects of sizeable nature in underground locations have been built for thousands of years. Construction of underground aqueducts is known to have occurred long before the birth of Christ. Extensive underground mines are known from biblical times.

These ancient projects and indeed most of the underground construction until the past few decades was of a nature that did not provide for human living accomodations for extnesive periods. Neither were the past underground projects designed to survive the environments described in Chapter II.

The accelerated program of the U. S. Department of Defense for building extensive complexes of underground buildings for launch structures and control centers has resulted in a vast increase in the experience of underground building.

Missile Base Projects

Warren Air Force Base construction was begun in late 1962. Underground building construction consisted of 200 launch structures for Minuteman missiles and 20 launch control buildings.[1] It is located

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[1] "ICBM Silos Excavating Like Postholes," Engineering News-Record, (November 14, 1963) p. 99.

in on 8,000 square mile area where Wyoming, Nebraska and Colorado meet.

Many geological formations were encountered in constructing such a number of underground buildings spread out over so large an area. Clay, stable sand, sandstone, gravel, siltstone, shale and limestone have been encountered. The construction problems that have resulted from working under such a variety of conditions have required many unusual solutions.[2] When saturated, some of these materials have resulted in "quick" conditions that have greatly hampered construction.

Construction of missile bases to date has been done under short time schedules. The contractors have operated under extreme pressure to complete their construction in the shortest possible time. As a result, many novel methods to expedite construction have been evolved. Minuteman silos--vertical launch structures--require a 14 foot 8 inch diameter hole about 94 feet deep. One method of digging this hole that has been used extensively is to bore it as one ~~should~~ would do for a giant post-hole. A large auger has been developed and several of them have been built for these jobs.

In starting the construction of a silo, a 30 foot deep excavation about 40 feet in diameter is scraped out using conventional earth-moving equipment. At the bottom of this hole, a drill rig is set up and a 3 foot diameter pilot hole is bored for an depth of 64 feet. Soil samples are taken as this boring is done. If soil conditions permit, one of the giant augers is moved in and the final 14'8" hole is bored. This auger rotates very slowly (3 rpm) while cutting. After it has cut about 3 cubic yards of spoil, it is raised above the lip of the

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[2] V. E. Zadnik, "Engineering Geology Problems at Missile Sites," The Military Engineer, November-December, 1963.

hole and accelerated to about 20 rpm. This causes the spoil material to be thrown off the auger beyond the lip of the hole where it is removed by conventional loaders.

In cases where the soil is too hard to bore the big hole in one pass, the pilot hole is first enlarged with a 6 foot diameter auger, further enlargement is made with a 10 foot auger and finally finished with the full-sized one.

The occurrance of large boulders or strong rock formations require conventional blasting operations before boring can continue. To maintain the sides of the hole under unstable soil conditions, steel liner plate is installed as the drilling progresses. In some cases, the sides of the holes ~~were~~ are sprayed with Gunite to prevent sloughing.

After drilling is completed, the base of the hole is belled out by hand labor. A concrete base is poured in the bottom of the hole. A 12 foot diameter steel liner is then lowered into the shaft and the space between the liner and the sides of the hole is ~~are~~ filled with concrete. It is very important that great care ~~is~~ be observed in placing this concrete so that it is in intimate contact with the ground surface around the hole with no voids present. This is necessary so that full advantage can be taken from the soil arching effect when the structure is loaded by the shock wave.

The upper portion of the silo ~~side~~ that houses the operating equipment, doors, etc., is completed after the liner has been placed. The horizontal sliding doors are built of concrete and operate on a set of rails.[3]

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[3] "Wyoming Missile Base Project," Western Construction, July, 1963, pp. 41-44.

The launch control structures, housing the operating personnel and delicate contol and launch equipment for ten missiles, are built by more conventional methods. These buildings are of a horizontal cylindrical shape with ~~doneed~~ domed-ends. They are built of heavily reinforced concrete in open excavations. Inside the protective structure, a two ~~storied~~ story steel framed building mounted on a large spring suspension system for shock isolation is built. Located on this structure are the personnel and equipment.

Associated with the launch control building are several satellite structures including water tanks, fuel supply tanks, etc. Automatic, pressure-actuated blast valves are built into all vents leading to the surface. These buildings are equipped with environmental equipment and supplies to maintain normal operation for extended periods of time with no outside contact.

Deep Underground Buildings

A most interesting example of current underground building construction is that of command centers that are built very deep underground, These buildings are generally located in mountain sides or other locations where they can be built under many feet of hard rock. Utilizing the blast resistance of hard, strong rock, these buildings can provide a very high degree of protection from nuclear explosions.[4]

Space for the construction of these buildings is obtained by blasting and excavating huge caverns out of the solid rock. Conventional hard-rock mining techniques utilizing the latest methods and equipment are used in opening these caverns. The inside surfaces

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[4] J. M. Norvell, "The Rock-NORAD COC", The Military Engineer, September-October, 1963, pp. 309-311.

of the tunnels and chambers thus excavated are covered with wire mesh fabric held in place with rock bolts up to 20 feet long. This covering is necessary to protect the future buildings from rock fragments that may be spalled off from the ground shock of the explosion. Some of the caverns that have been thus constructed are as large as 45 feet wide, 60 feet high, and 300 feet long.

Within the caverns, three story buildings are constructed. Steel rigid-frame, ship-type construction with metal outer walls are used. Working quarters, sleeping quarters, kitchen and dining facilities and a medical dispensary are provided for full-time operation. Cellular steel deck floors to provide for ducts and conduits to the operating equipment are used.

Several such buildings are built and are separated by narrow air spaces. They are joined by flexible walkways at each level. Each building is mounted on springs made of 3 inch diameter steel wire. The springs are about 48 inches in height and up to 20 inches in diameter. They provide shock isolation for the entire building and its contents.

Fuel and water supplies are stored in huge open vats carved from the rock at a level lower than the buildings. Water is piped in from outside to maintain the supply. Small tunnels to the outside are used for exhaust air.

Massive blast doors are provided to seal off entranceways to the outside. Exhaust tunnels have blast valves in them. In the event of a nuclear attack, such a facility can be tightly sealed off from the outside. Normal operations can continue and such a vital nerve center can function for very long periods.

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