THE DESIGN OF BOMB SHELTERS

By

PAUL NEWMAN GILLETT

A THESIS

Submitted to the Graduate School of Michigan
State College of Agriculture and Applied
Science in partial fulfillment of the
requirements for the degree of

CIVIL ENGINEER

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CHAPTER I

INTRODUCTION

The problem of designing structures to withstand the attack of artillery projectiles and aerial bombardment has been the subject of much study since even before the first world war. Research has been carried out by the governments of all the leading nations and countless tests and experiments have been conducted to substantiate or refute theoretical analyses. The nature of the problem, however, is such that there still remains much to be learned before bomb-resisting structures can be designed with the same exactitude and certainty of results as can be anticipated in the design of a bridge or building frame. Since bomb- or shell-resisting structures have in the past been exclusively military installations (gun emplacements, fortifications, etc.,) the matter of expense has been secondary and uncertainties of design could be accounted for by building extremely heavy, thick structures. With the advent of large scale aerial bombardment of cities, however, with the attendant problem of providing protection for countless thousands, such haphazard design procedures could not be applied to air raid shelters because of economic restrictions, and more accurate methods of analysis became necessary.

Although there are as yet many unanswered problems in this field, a great amount of information has been accumulated, both on the structural effects of bombardment and on the general problem of providing satisfactory protection for the populations of cities.

While the probability of aerial attack on the United States is small and appears to be diminishing, such an occurance is by no means impossible. For this reason the problem of air raid shelters should be of interest to engineers and architects and it is hoped that this paper may contribute a small amount of information on this new and little-understood subject.

CHAPTER II

TYPES OF SHELTERS

A. Domestic One-Family Shelters. At the beginning of the present war, the one-family shelter was the basic unit of air raid protection in England. This size of shelter was adopted after a great deal of study and was based on these considerations:

1. In England, most families live in single houses; therefore a shelter designed for a single family is reasonable, from a standpoint of convenience and accessibility.
2. Since absolute protection from a direct hit is economically impossible, the separation of shelters in small units prevents mass casualties should one shelter suffer a direct hit.
3. A single family shelter is small enough to be transported readily (if of a portable type) and is simple enough in construction to be erected by the householder.
4. Functional requirements which complicate the large shelter are absent in the one-family type. A simple door and benches to sit on constitute the essential requirements.

Two of the main premises out of which the British A. R. P. scheme was evolved have been proven by experience to be wholly erroneous. They are, first, that air raids would be of relatively short duration, say a few hours at the most; and second, that the destructive efficiency of aerial bombardment would not be so great but that the protection afforded by the relatively frail family-size shelters would be ample.

These conclusions were doubtless arrived at by observing the effects of bombing in the Spanish Civil War, which we now know was on a very different scale from the present conflict. During that war, excellent air raid protection facilities were worked out, especially in the large cities such as Barcelona and Madrid, and it was quite definitely shown that under the conditions then obtaining, more persons were killed or injured from falling debris, fire, panic and splinters than from the direct explosion of bombs. Thus, shelters giving protection from these secondary effects were used and found satisfactory, and these facts were noted in establishing British A. R. P. measures.

After the heavy attacks on England began, the raids were so intense and of such long durations that many were killed in the small shelters and the people were forced to spend many hours in the shelters (all night in frequent instances) so that greater protection and better accomodations became imperative. For these reasons, the small shelters gradually were abandoned in favor of larger, safer and more comfortable structures which were built as a result of these experiences.

The family-type shelter deserves discussion, however, because of its probable application in the United States. The same factors which led to its use in England exist here, and the factors which led to its abandonment there, namely continuous and intense bombardment, are scarcely likely here.

The family-type shelter in England was designed to meet the following requirements:

1. Protection from the blast and fragments of a 500 lb. high explosive bomb detonated at a distance of 50 feet.
2. Protection from a direct hit of a light incendiary bomb.
3. Sitting accomodations for 6 persons with cubic capacity of 35 cubic feet per person.

All of the so-called "standard" shelters in this class were supposed to fulfill these design requirements. It is believed that most of them did, and in some designs protection and accomodation well above the minimum were provided.

The most widely used shelter of this class was the Anderson shelter, made of corrugated iron and distributed to the public by the British government. Figure 1 is a sketch of this shelter. In most installations of the Anderson shelter it was partly buried in the ground and part of the excavated earth was placed over the top of the structure for additional protection. Entry was by means of a hole in the front plate. There were two wooden benches providing sitting space for six persons. Some additional protection could be obtained by building up earth or sandbag revetments around the sides and entrance to the shelter. The shelter had no floor and there was no means of keeping the interior dry.

When local conditions such as high ground water or paved surfaces prevented setting the shelter in the ground, shelters of concrete or brick were quite common. These were rectangular structures with walls 12 to 18 inches thick and a flat roof of precast concrete about 4 inches thick. A shelter of this type is shown in Figure 2. The accomodations were about the same as in the Anderson shelter.

In some cases where shelter materials were difficult to obtain, family-size shelters were constructed by digging a trench in the ground about 3 feet wide and 6 feet deep with a roof of boards or corrugated iron which was covered with a foot or more of earth. These shelters were so unsatisfactory from a standpoint of safety and comfort that they were rarely used except in emergencies.

Mention should be made of the family shelters which are built within dwellings, as these occasionally have been suggested for use in this country. These shelters are really only refuge rooms, which are generally equipped with articles needed by the family during an air raid, blackout curtains, etc. Care should be taken in selecting the location of a refuge room, as there is a possibility of being crushed or trapped by debris if the building should fall, if ready egress is not provided. In wooden frame houses, it is likely that any room in the house which is readily accessible and with quick means of reaching outdoors, is suitable. The value of the stud walls in providing protection against splinters is not great, but may be increased by sandbag revetments if the householder wants to go to this expense and inconvenience. In a brick house, the 12" exterior walls give a measure of protection but here there is danger of wall collapse that is not present in frame buildings. Basements have been suggested for shelters and are excellent from the standpoint of lateral protection from fragments and blast, but are open to several objections, the most serious of which is the danger of being trapped by fire or crushed by debris. Another is the possibility of flooding from bursting water mains (numerous instances of this have been reported from London), and the danger from war gases, which are always heavier than air and tend to seek lower levels. A sketch of a refuge room is shown in Figure 3.

B. Communal Shelters. There are many instances where one-family type shelters are not suitable. In places where the population density per unit area is high, as in districts of crowded apartment houses in cities, downtown office buildings, and factories, the most efficient type maybe one which houses a large number of persons, from 25 or 50 to several hundred. The larger the shelter, the less is the per capita cost of protection, and such shelters can be equipped with facilities for preparing meals, sleeping and even working. It has generally been the policy of governments to require that the degree of protection be increased in proportion to the number sheltered in a given shelter unit. Thus, a shelter for 25 or 50 persons may give protection from all the effects, including a direct hit, of a one-hundred lb. bomb, while a shelter for 500 may withstand a direct hit of a 500 or 1000 lb. bomb. Communal shelters may be constructed within existing buildings, or may be separate external structures.

1. Communal Shelters Within Existing Buildings.- It is often most convenient to have the occupants of a building sheltered within that building. This is especially true in buildings where people are working, as the shelter within the building makes possible closer supervision and control and means less working time lost in going to and from the shelter. In the case of apartment buildings and institutions such as hospitals, the advantages of a shelter within the building when raids occur at night are obvious.

If the building in which the shelter is located is sound structurally and fairly resistant to bombardment, the shelter can be made relatively secure and will offer a high degree of protection. If the building is old, or of wall bearing masonry construction, it may be very unsafe and non-fireproof buildings should never be used for shelters.

A building of the skeleton frame type, of steel or reinforced concrete is generally very resistant to bombing and ordinarily suffers only local damage even from a direct hit.

The action of a bomb upon hitting a building is either to detonate on impact, causing extreme local damage to the roof and top story, or to penetrate several floors or to the basement before exploding, depending on the fuse setting. Weighing the probabilities of fuse timing and damage from penetration and/or explosion, it seems that the third or fourth floor down from the roof in a five to ten story building is the safest place for a shelter. Floors at these levels have the important advantage of being above the level of gases, and the effects of explosions on the ground (blast and fragments) are lessened. It is probable that such locations would be more accessible to all the occupants.

Shelters in buildings higher than ten stories might well be placed at a relatively lower level, say about halfway down from the top. Since bombs do not drop vertically but in a modified parabolic path, there is a possibility of bombs striking the sides as well as the roof of a building; the probability of this occurance is greater for tall, narrow buildings.

A building of the wall-bearing type is extremely vulnerable to damage from explosion and should not, therefore, be used for shelter purposes. Moreover, such structures often have interior framing of wood which increases the fire hazard. The fact that some wall-bearing buildings, especially old warehouses, have thick walls and small windows, has given rise to the mistaken idea that such structures would make good shelters. Some apartment houses of from 4 to 6 stories are built of wall-bearing exterior walls with wood floor systems and interior columns of structural steel or iron pipe. These structural systems are stable only under vertical loads and should not be used as places of refuge.

2. Communal Shelters Outside Buildings.- It has been found desirable in many cases in Europe to provide shelters for large groups in separate structures outside existing buildings. The occupants of apartment buildings, factories and institutions are often protected in this way. Shelters outside buildings may be classed as underground and surface shelters.

Underground shelters were first used on a large scale in Spain during the Spanish civil war. These were long, deep tunnels lined with concrete or brick; they ran under the streets at a depth of about 45 feet and were generally laid out in the form of a square. Cross galleries connected and intersected the square, and there were several widely separated entrances. Soil conditions in several Spanish cities were particularly suited to extensive and economical tunneling, since ground water was not encountered at ordinary depths, and the nature of the earth was such as to require very little timbering. These shelters were considered to be sufficient to take care of all the inhabitants and passers-by in the vicinity. The protection afforded appeared to be almost 100% for the types of bombs then in use.

Underground shelters have a number of advantages. First, there is no problem of splinter protection since the shelter has a protection of earth cover. Second, the protection afforded is practically a function of the depth; thus the shelter can be rendered proof against even a very heavy bomb by being deep enough in the ground. If the shelter is 30 or more feet underground, the earth surrounding it becomes the protecting material, and the problem of construction becomes merely the driving of a tunnel shaft of suitable dimensions and lining it with concrete or metal tunnel liners. Under certain circumstances, such construction may be much more economical than building a heavy structure of steel or concrete on the surface. Sometimes underground shelters are large, rectangular rooms, built of reinforced concrete and connected to the surface by long ramps, stairs or elevators. Underground shelters may vary greatly in size and accomodation, the smallest giving shelter to a dozen or less, while the largest built in Europe house several hundred, and are equipped with all necessary utilities.

There are a number of disadvantages to underground shelters. Difficulty of access is one of the main objections, and the cost of this type of construction is likely to be excessive in some localities. The net-work of underground utilities in most of our large cities would make it difficult to locate an underground structure without extensive relocations of gas, electricity, water, and sewer conduits. Occasionally the fear of being trapped underground causes the public to avoid such shelters, and makes handling of crowds in the shelter difficult. The necessity of providing gas-tight seals and adequate ventilation is apparent, and some utilities, particularly sewage disposal, are complicated by the depth of the shelter. Preventing the seepage of ground water is another problem.

In discussions of civilian defence in the United States, it has been suggested on numerous occasions that existing subway tubes could be utilized as air raid shelters for large groups. Proponents of this suggestion point out that subway entrances are designed to facilitate the rapid movements of large groups, that subway tubes are extensively used in England for shelters, and that since the tunnels are already in existance, little or no cost would be involved. The official attitude of the government has been to frown upon this suggestion, however, on the grounds that since the subway tunnels in most American cities are relatively near the surface, there would be little or no protection from a direct hit. This is true; there are numerous instances where the roof of the tunnel is within a few feet of the street surface, and a bomb hitting here would doubtless go through and cause tremendous destruction in the confined space below. Protection would be afforded, however, from the splinters and blast of near misses, and from debris and machine gun fire.

Some American cities are located in hilly or mountainous terrain. Here there is a possibility of providing underground communal shelters at relatively small cost by driving tunnels laterally into the hills from the ground surface. Rock Creek Park, in Washington, D. C., is in a narrow valley in the middle of the city, and good shelter for the apartment house dwellers surrounding the park could be had by driving horizontal tunnels into the soft sandstone from the valley floor.

In spite of the numerous problems and disadvantages of deep shelters, they are in wide use today in England. New structures of a design and location such that they will eventually form part of an underground transportation system have recently been built. These shelters have excellent accomodations and facilities for rapid entrance and egress and satisfactorily meet the problem of continued air raids of high intensity. They are deep enough so that occupants are almost undisturbed by even the heaviest raids and it is possible for essential workers to get enough rest to maintain efficient war production.

Surface shelters for large groups are not as numerous as the underground type, but they possess certain advantages and large shelters of this type are known to exist in Germany and some other European countries. Some have been built in Switzerland, and a number were built in Spain during the war there.

As has been noted, surface shelters have a number of advantages over underground shelters. On the whole, it is probable that construction is simpler and more easily accomplished by general contractors with ordinary construction equipment. Surface shelters tend to be massive affairs, with walls and roofs of concrete sometimes several feet thick, but roof spans are short, and procedure is similar to the construction of buildings. Since there is no protecting layer of earth between a bomb explosion and the shelter, the roof must be capable of resisting a direct hit of at least a medium-size bomb and the walls must withstand the effects of blast and splinters. Such construction requires extremely large quantities of material and is very expensive. Cost estimates usually show a decidedly greater cost per capita for surface shelters than those built underground.

The problems of structural design in surface shelters are quite difficult, as the roof structure must be designed to withstand the extreme local stresses resulting from impact and explosion. Experimental data and theoretical analyses are so inconclusive or fragmentary that they are of little help. European practice has been to make the roof several feet thick and reinforce it heavily. Naturally, some of these shelters have withstood bombings and some have not.

The lack of clear space on the ground in the vicinity of most places where communal shelters are required makes the use of surface shelters rather limited. In most installations abroad, it has been found that shelters within existing buildings or separate external shelters underground are more feasible.

CHAPTER III

FUNCTIONAL REQUIREMENTS FOR SHELTERS

A. Location. Shelters should be so located that there will be sufficient time for the whole capacity of the shelter to enter in the time allowed between the warning signal and the beginning of the raid. The amount of time available will depend on the type of bombing technique employed and the efficiency of the air raid warning system. Most civil defence plans assume a warning time of from 5 to 10 minutes, which appears to be logical in comparison to European experience. This indicates that a shelter should be not more than about two city blocks from the most remote person sheltered by it.

Some time ago a firm of British architects made an extensive study on locations for shelters in the metropolitan Borough of Finsbury, London, England[1]. In this study it was first determined where shelters should not be located by reason of proximity to dangerous areas (oil storage tanks, gas holders, etc.), or near obvious targets (railroad yards and docks), or in places which would be endangered by the effects of bombing (near reservoirs which might be damaged and flood surrounding areas). Then, numerous maps of the community were made, with population densities for each block, for various times of the day, plotted on the maps. From these it was possible to determine where shelters had to be located and what their capacity must be to accomodate all the persons in the community, at any time in the day or night.

In most American cities it has been planned that occupants of houses or apartments will be sheltered within their residences, and

[1]This report is contained in the book "Planned A. R. P." by Tecton, Architects. The British Architectural Association, London.

workers in commercial or industrial districts will be sheltered within their places of employment. In Detroit, persons on the street when an air raid alarm is sounded are instructed to go into the lobby or street floor of a building if in a downtown district, or up on the porch of a house if in a residential district. It is unlikely that protection would be much improved by following these instructions, but the effect is to get people off the streets during the raid, which is important.

B. Entrances. Entrances to a shelter should be of such a capacity to allow the total number of occupants to enter in the time available. A single 4 foot wide opening without turns, steps or other restrictions to flow will pass about 60 persons per minute. It is advisable to have several entrances rather than one large one, to allow for better control of crowds and to provide for escape if one or more entrances should become blocked by debris. For this reason, the smallest shelter should have at least two means of egress.

Since entrances usually constitute the weakest part of the shelter structure, it is frequently desirable in the larger shelters to have the entrances protected by a wall and roof or by turning past a baffle wall, even though these devices impede the flow of traffic.

Doors are usually provided for shelters, to control the flow of traffic and to decrease the effect of blast and to provide an air tight seal in the event of a gas attack. It has been found that doors made of steel plate $\frac{1}{4}$" thick, well braced and fitted with heavy hardware are satisfactory.

C. Decontamination. Early in the war there was considerable apprehension in regard to the use of gas in aerial bombardment. All A. R. P. plans, therefore, included gas defence and air raid shelters were designed to give protection from war gas as well as from other phases of aerial attack. Up to the present, however, there have been no reports of gas being used and the likelihood of its employment is diminishing. The technical difficulties attendent to the efficient distribution of war gases, combined with the fact that means of gas warfare are available to all combatants, seem to make this kind of attack unlikely, especially in the United States. Gas attacks by air have been feared, however, in certain tropical regions occupied by our forces, since the extremely humid climates would favor effective employment of mustard gas, Lewisite and other gases which are highly soluble in water.

In view of the unlikelihood of gas attacks in this country it does not seem advisable to provide for gas defence in the construction of shelters or in the formulating of civil defence plans, except when such provision would add little or nothing to the cost or difficulty of the shelter design.

There are two characteristics of war gases which should be borne in mind in providing decontamination and anti-gas protection: the fact that all such gases are heavier than air and therefore collect in low places (such as shelters in basements, or trenches), and the fact that many gases combine with water and form an extremely corrosive liquid.

Shelters designed for protection against large scale gas attack are provided with a double set of doors at each entrance, to form an air lock, so that persons entering from contaminated outside air must close the outer of the two doors before entering the inner one. Fans or blowers provide pure air in the gaslock. The shelter itself has gas tight doors and the ventilation system either has filters to cleanse gas laden air coming in from outdoors or is of the regenerative type, in which the shelter is hermetically sealed and oxygen is supplied to the atmosphere in the shelter from pressure cylinders.

Since persons entering a shelter from gas laden air may bring in considerable gas on their clothing, some of the more elaborate shelters have separate decontamination facilities for men and women, with showers and changes of clothing. A plan of a shelter with gaslock and decontamination facilities is shown in figure 4.

D. Space Requirements. Various air raid protection codes have set up standards of cubic space per person for various size shelters. The minimum for a family-type shelter is 35 cubic feet per person. It has been found that the space ordinarily required for seating arrangements, aisles, equipment, etc. will be such that the cubic capacity per person is sufficient. It is essential, however, to prevent overcrowding by rigidly policing the entrance to a shelter, and shelters in Europe usually have the allowed maximum capacity posted, and the shelter is closed after that capacity is reached. Aside from the obvious reasons of comfort and accomodation, there is danger of suffocation if only natural flow of air is relied on for ventilation. Standards of seating capacity as worked out by architects for theaters and restaurant booths, and in the design of buses and railroad coaches, have been found valuable in establishing seating arrangements and capacities in shelters.

E. Ventilation. The importance of ventilation in shelters depends on the capacity of the shelter, the probability of gas attack, and the probable duration of a raid. Small shelters accomodating up to 25 persons probably need no positive ventilation system, and shelters for larger numbers may be ventilated by a simple fan or blower arrangement. Shelters formed by tunnels underground may be ventilated by shafts or stacks relying on convection currents to provide changes of air. If air in a shelter becomes too damp, trays of calcium chloride or other deliquescent crystals help in lowering the humidity. It seems unlikely that the duration of air raids in this country would be long enough to justify elaborate ventilation facilities in any but the largest shelters.

F. Utilities. In the design of shelters accomodating more than about 25 persons, some sort of provision should be made for water supply, toilet facilities and electricity, particularly if the shelter is planned to be in use for relatively long periods.

Water supply presents no problem. A large shelter can be piped from regular water services, with perhaps a small storage tank within the shelter for use should water mains be destroyed.

Toilet facilities are essential and should be increased with the capacity of the shelter, in the ratio of about 1 toilet for each sex for every 60 persons. Shelters at or slightly below ground level may have sewage disposal to regular sanitary sewers, but shelters underground will probably require pumps to lift sewage to sewer levels. Small shelters may be provided with chemical or bucket-type toilets.

Electrical service is necessary for lighting, for operation of ventilating equipment, pumps, radio, and occasionally for heating. Regular commercial or domestic electric service is generally available and satisfactory. Electric lines will withstand a great amount of bombing but for installations where continuance of power is absolutely imperative, engine-driven generator sets may be used. In this event, air for engine operation should be supplied separately from air for the shelter and exhaust gases piped outdoors.

CHAPTER IV

STRUCTURAL REQUIREMENTS FOR SHELTERS

A. The Effects of Bombs.

1. Types of Bombs.- Aircraft bombs may be classified according to function as high explosive, armor piercing, incendiary, fragmentation and gas bombs. There are some other types and some combinations of function but the above are the most important.

High explosive bombs are by far the most important as regards shelter design. They vary in weight from 100 lbs. to the large 4 ton "block busters" and about half the weight is the explosive. While public attention has been focused on the use of extremely heavy bombs, it should be remembered that there are many targets which can be more effectively bombed with say a thousand 100 lb. bombs than with an equal weight of two or four ton bombs. High explosive bombs characteristically have thin cases which are sufficiently strong to resist the shock of impact with ordinary targets (buildings and civilian structures) but will break up when striking a resistant structure (armored vessel or fortification). Their chief effects are extreme structural damage to buildings and death or serious injury to humans within the range of the bombs' effectiveness. Both of these effects are caused chiefly by the blast of the explosion. [1, 2, 3]

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[1]Autopsy examinations of many blast victims indicate that death is ordinarily caused by collapse of the lung structure, which results in internal bleeding, producing suffocation. Many bombing victims have been found with no external indications of injury whatever. See "Research into the Effects of Air Concussion on Animals, with Special Reference to the Observed Effects of Air Concussion on Soldiers".

Armor piercing bombs have been used chiefly against protected targets, such as armored naval vessels, fortification structures and the like. To make the bomb strong enough to penetrate a resistant material, the case must be very thick and consequently little space is left for the explosive charge. In some bombs in this class, the explosive may constitute only 10% of the total weight. Armor piercing bombs have been little used in the present war and they are seldom considered in the design of bomb shelters.

Incendiary bombs range in size from the one-kilogram bomb used by the Germans to larger bombs weighing 100 lbs. or more. They generally contain a charge of thermite, magnesium, or other highly combustible substance which is designed to ignite on impact. They affect the design of shelters only in the precautions required for fire hazards.

Fragmentation bombs are small, usually weighing about 20 lbs. and are designed to inflict injury to humans by the fragments which fly out from the specially-designed case when the charge detonates. These bombs have not been used extensively in this war; the fragments from the case of an ordinary high explosive bomb seem to have satisfactorily lethal qualities.

There have been no authenticated reports of the use of gas bombs as yet in the present war, although designs for such bombs are known

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G. W. Crile, Col., M. R. C., U. S. A. See also "Experimental Study of Blast Injuries to the Lungs". S. Zuckerman, Ministry of Home Security, London.

[2]See "Blast - E. P. A. R. Memorandum #1". Institute of Civil Engineers, London.

[3]See "Blast - Bulletin B-1". Ministry of Home Security, Research and Experiment Department, London.

to exist and there is reason to believe they may be employed under certain tactical conditions. Gas bombs are merely vessels containing a poisonous gas under pressure or a liquid saturated with a poisonous gas which releases the latter when the case breaks open. Sometimes a small explosive charge may be contained in the bomb, for the purpose of better distributing the gas or liquid. The structural effects of these bombs are slight, and they affect shelter design chiefly in the provisions for ventilation, decontamination, gas tight closures and the like.

2. Penetration of Bombs.- There has been a great deal of research and study on this subject, but very little concrete information which would be useful in designing shelters has been developed. It appears that penetration depends on the physical characteristics of the bomb (weight, shape, cross sectional dimensions), its velocity on impact and the angle of impact, and the density, hardness, and elastic properties of the material struck.

Of the numerous formulae[1] expressing the penetration of aircraft bombs in solid materials, the formula which seems most satisfactory from a theoretical standpoint and from ease of application is the Petry formula, usually expressed in the form:

$$X = KP \log_{10}\left(1 + \frac{V^2}{215,000}\right)$$

where X = penetration in feet

P = sectional pressure of bomb in lbs. per square foot (sectional pressure = weight of bomb in lbs. divided by maximum cross sectional area in square feet)

V = impact velocity of bomb in feet per second

K = a constant depending on the material

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[1]See Samuely and Hamann, "Civil Protection", The Architectural Press, London.

Values of K for various material, based on numerous tests, are of the following order:

limestone		5.4×10^{-3}
reinforced concrete	(3000#)	4.8 "
plain concrete	(2000#)	8.0 "
stone masonry		11.7 "
sandy soil		36.7 "
soft soil		73.2 "

The penetration of a bomb in a slab of limited thickness is increased by the phenomenon of scabbing, which is the breaking off of a cone-shaped piece on the opposite side and directly beneath the point of impact. This is important in the design of shelters, as the scabbing may produce serious injury, and it frequently aids in the complete perforation of the slab.

Penetration also depends on the fuse setting of the bomb. If the fuse detonates on impact, or before maximum penetration is reached, the penetration will obviously be less than if the bomb had continued as a projectile. Thus, bombs aimed primarily at surface destruction (dwellings, factories and surface utilities), will generally be fused to detonate on impact, while bombs designed to produce large craters, disrupt underground utilities, undermine bridge abutments, etc. will be fused to detonate after maximum penetration is reached.

3. The Effect of Explosion on Structures.- The immediate effect of detonation of a high explosive in air is the production of a translatory pressure wave of very high velocity and pressure. This wave is followed by a wave of negative pressure of lesser magnitude but greater duration. Following this, there may be a succession of back-and-forth disturbances until equilibrium is attained. The wave of

pressure[1] is highest in the region of the explosion and diminishes rapidly the further it moves away. Everything in the immediate neighborhood of a big bomb therefore will be exposed to a violent pressure wave of many times atmospheric pressure, whereas, depending on the bomb, everything 50 feet away may be exposed only to 2 or 3 times atmospheric pressure.

A structural element (wall panel or floor slab) when subjected to an explosive blast may (a) be blown away from the explosion by the primary pressure wave, (b) be blown toward the explosion by the secondary suction wave, or (c) be destroyed or damaged by vibration caused by vibrations in the air which approximate in frequency the natural frequency of the structure.

An explosion occurring underground (resulting from considerable penetration by a delayed action bomb) has an effect very similar to an earthquake, in that a shock is transmitted laterally in the earth by a slight movement of the ground.

The resulting destruction to a wall-bearing masonry building from blast may be caused by (a) lateral movement or flexural failure of walls resulting from blast pressure in air, or (b) lateral movement of foundations, resulting from earth shock. Any relative movement in the walls of a wall-bearing structure is very likely to cause complete collapse of the building. Many hundreds of such structures in England have been completely destroyed.

When a framed building, of steel or concrete, is subjected to the effects of blast, wall panels and partitions may be demolished but since they are not load carrying members, the stability of the struc-

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[1]From "Protective Construction" Civilian Defence pamphlet issued by the Division of State and Local Cooperation, Office for Emergency Management.

ture is seldom affected. Even a near underground explosion may not necessarily damage the building unless the foundations are subject to severe movement.

While in the employ of the War Department, the writer participated in the conduct of some experimental bombings of reinforced concrete buildings[1]. These buildings, which were completely demolished by numerous direct hits, neverless demonstrated considerable resistance to bombing and usually were damaged only locally by a single bomb. The most probable type of failure in reinforced concrete buildings was found to be caused by reversal of bending moments in girders and beams, cracking the concrete in places where main steel is absent, as in the tops of beams in mid-span. Another type of failure in reinforced concrete structures is the apparent destruction of bond between reinforcing and concrete, caused either by impact of a bomb or extreme stresses set up by blast of an explosion. Examinations of buildings in the aforementioned tests showed numerous examples of apparent separation of steel from concrete. One explanation offered for this phenomenon points out that since the velocities of propagation of shock waves are different in steel and concrete, there may be differential movement between the two materials, resulting in this separation.

B. Structural Design.

1. Roofs and Burster Slabs.- The design of a roof system to resist a direct hit of a bomb presents many new problems not encountered in ordinary structural engineering.

Frequently the roof is protected by what is known as a burster slab or detonation slab, which is a thick slab of concrete above the shelter and overhanging it on all sides, usually separated from the

[1]These buildings are illustrated in Figures 5 and 6.

shelter by several feet of earth. The function of the burster slab is to stop the bomb and cause it to either break up or detonate, so that the only load to the roof of the shelter is the force of impact distributed over a fairly large area. The procedure of design in such a structural system would be as follows:

1. Assume size of bomb to be protected against and its impact velocity.
2. Calculate penetration X from Petry formula (page 20), using the K value for reinforced concrete.
3. Make the thickness of the burster slab double the calculated penetration(1).
4. Calculate the kinetic energy of the bomb on impact and determine force of impact from the following:

$$\text{force of impact} = \frac{\text{K.E. of bomb}}{\text{depth of penetration}}$$

5. Assume the force of impact to be spread out through the earth between the burster slab and roof in a "cone of pressure". The unit live load on the roof is then equal to the force of impact divided by the area of the base of the cone.

This analysis gives a reasonable treatment for impact stress alone but dynamic loads occasioned by explosion occur almost at the same time.

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(1)There seems to be no exact knowledge of how reinforcing in the burster slab helps to prevent penetration, and designs for reinforcing vary. An arrangement frequently used consists of mats of $\frac{1}{2}$" round bars at 12" on center each way, the mats to be spaced vertically about 2 feet apart. The burster slab must definitely resist perforation of the bomb, or else it will be worse than useless, as the bomb exploding between the burster slab and roof would be able to exert a much greater force.

Explosion forces are known to be large but as yet no quantitative evaluations have been developed. Structures resisting impact loads have in a good many cases also withstood the force of explosion. It may be that the character of the explosion force is such that stresses set up as a result are not as serious as has been supposed.

If the roof of a shelter is not protected by a burster slab, the problem of structural design is much more difficult. It is next to impossible to prevent extreme local destruction at the point of impact and the magnitude of the loads involved is such that ordinary design methods within the elastic limit do not give reasonable results. Flexural resistance appears to be of secondary importance, as the slab will either fail or resist the bomb by local shear resistance before the structure begins to bend. Current practice in the design of such structures seems to be to make the slab very thick, use a large amount of shear reinforcing and provide a steel plate on the soffit of the slab, well anchored in with welded anchors, to prevent the under surface of the slab from scabbing away under impact.

2. Walls and Base Slabs.- If a structure is built above ground, the walls should be designed to resist penetration of fragments and the large explosion pressures of a nearby bomb. Usually walls thick enough to support a heavy bomb-resisting roof will be ample. If the walls are below ground but not so deep as to be below the probable penetration of a bomb, they must be thicker, of the order of several feet, to resist the tamped explosion of a delayed action bomb. Walls in a deep shelter need be designed only for lateral earth pressure plus a moderate shock wave from a distant explosion. Base slabs or footings can be designed by ordinary structural practice, and the live load of the impact of the bomb may be largely neglected in proportioning footing sizes. If the shelter is not protected by a burster slab, the

base slab should be designed for the possibility of a bomb penetrating the earth near the shelter and turning in its path and exploding under the shelter. This phenomenon has been reported on numerous occasions in England.

CHAPTER V

EXAMPLES OF SHELTER DESIGN

A. Family Type Shelters. Before the outbreak of the present war, the Office of the Chief of Engineers, U. S. Army, was directed to prepare designs for family-type air raid shelters for civilian use. These structures were to utilize various materials and were to have the same amount of protection as their British prototypes, namely, protection against all the effects of a 500 lb. bomb exploding at a distance of 50 feet, debris from falling buildings, and a direct hit of a light incendiary bomb. A number of shelters were designed and built and tested with bombs. The two which most successfully resisted bombing are shown in Figures 7 and 8. The shelter in Figure 7 is made of Armco #10 gage sheets and in a commercial size, 6'3" diameter. By caulking the joints it can be made watertight, and a removable plate in one end provides a second means of egress. The shelter may be partly or completely buried, and the entrance or exit may be extended by adding lengths of pipe to the openings. The shelter in Figure 8 is of reinforced concrete, is designed to be buried and access is through a gas tight door at the bottom of a concrete stair. An escape exit is provided at the opposite end. Both of these shelters were subjected to severe bombings and the resulting damage indicated the shelters were much safer than required in the design criteria.

B. Communal Shelters for Large Groups. The Office of the Chief of Engineers also prepared designs for large shelters and two are shown in Figures 9 and 10. The underground shelter shown in Figure 9 has a capacity of 100 persons and access is down a long ramp and through a gas lock. The burster slab just below the surface is intended to stop bombs and overhangs the shelter on all sides by a sufficient amount to obviate the danger of an underground explosion near the shelter.

The shelter shown in Figure 10 is a two story structure, based on British designs, and has a capacity of 200 persons. The roof slab is 5 feet thick and the walls and base slab are proportionately massive. The per capita cost of this shelter was about 15% greater than the structure in Figure 9. Note the baffle walls in front of each entrance to protect the steel doors from fragments and blast.

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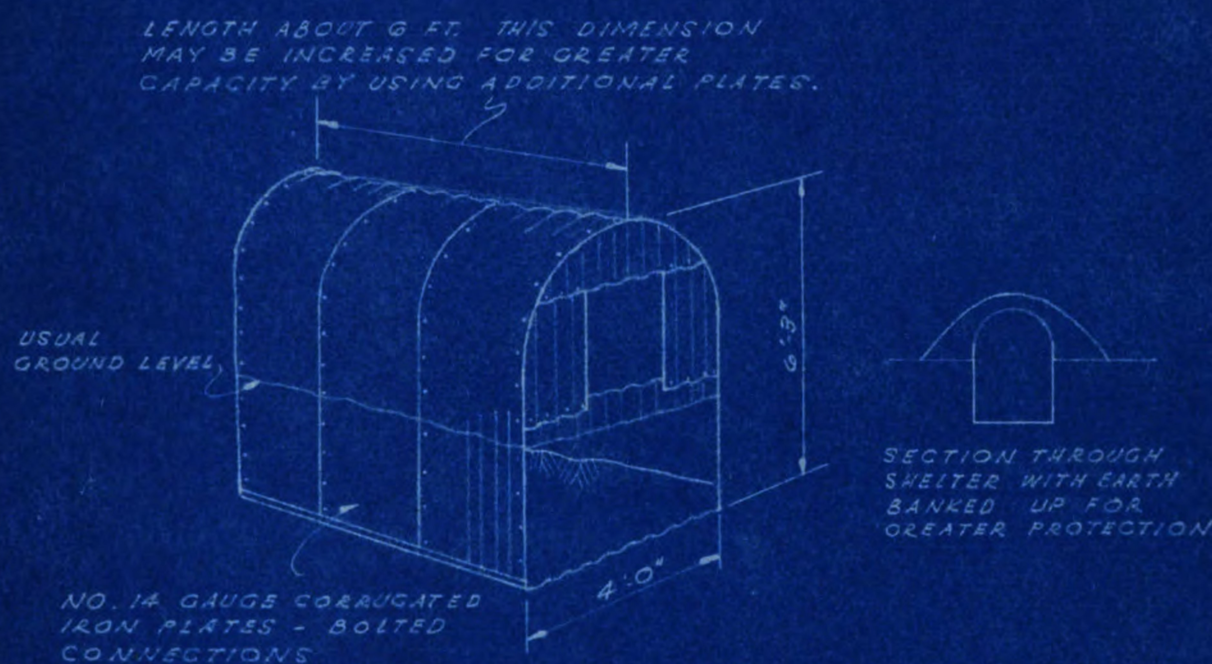


FIG. 1
ANDERSON TYPE AIR RAID SHELTER

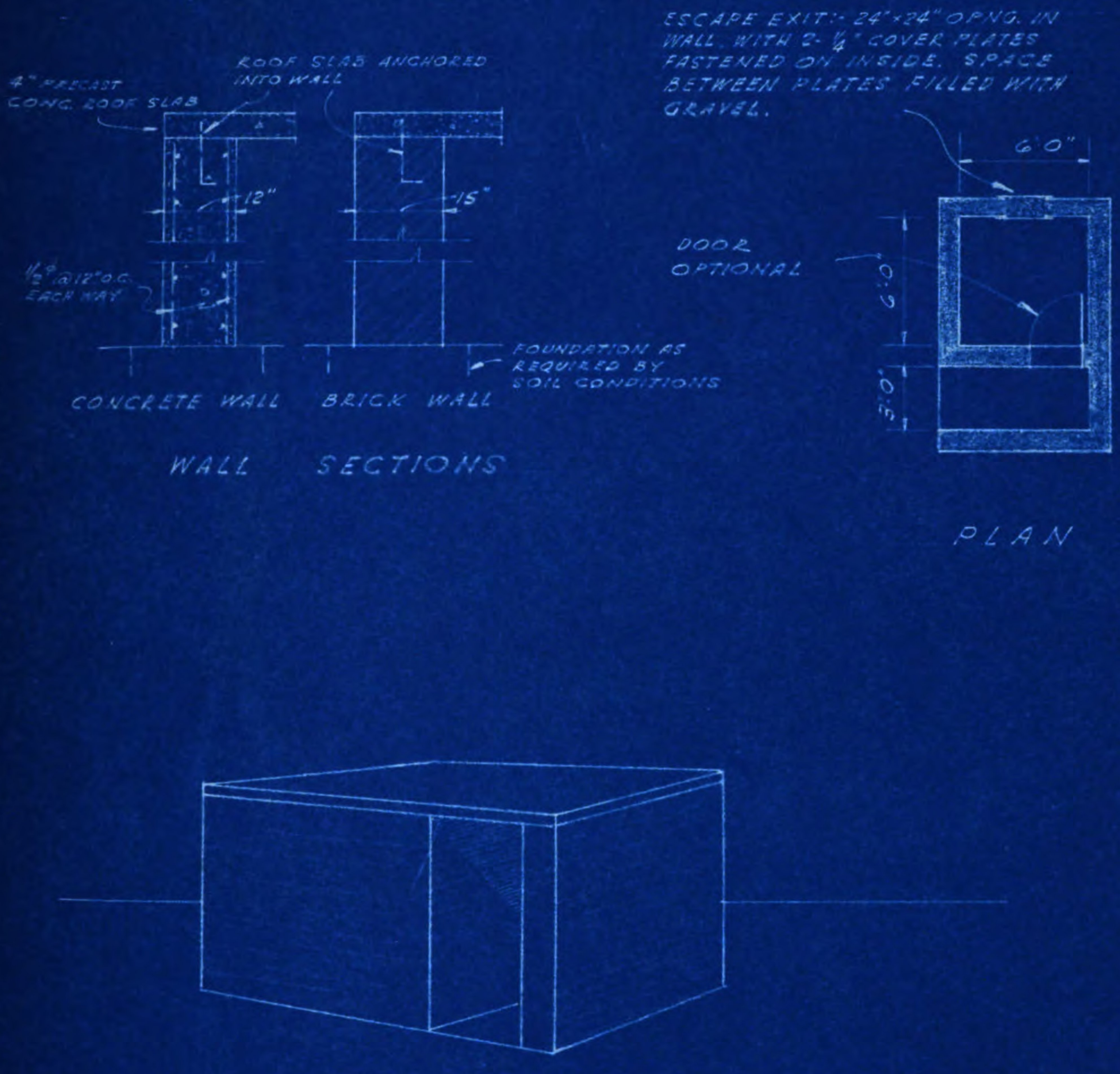


FIG 2

SURFACE SHELTER FOR SIX PERSONS

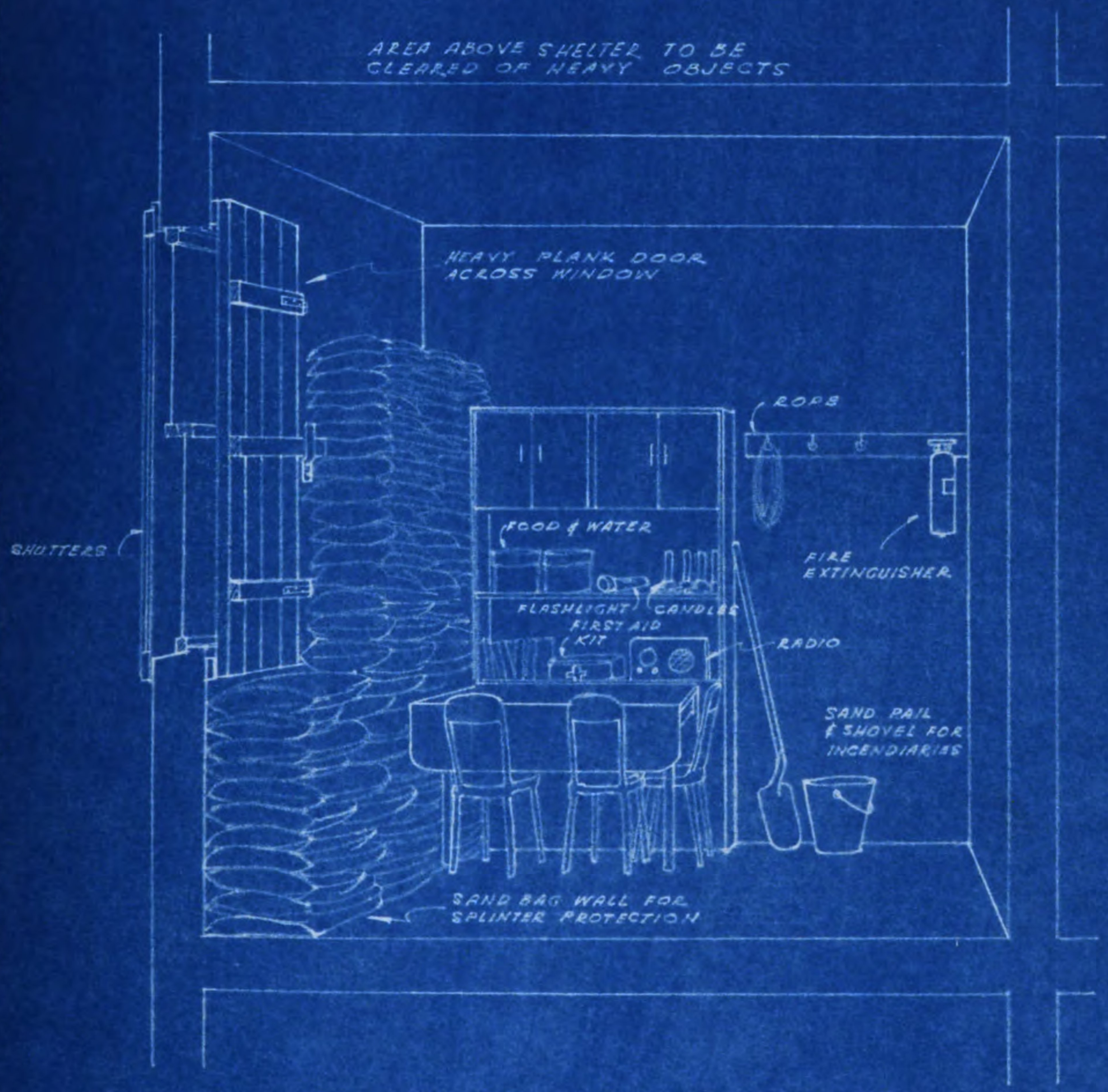


FIG. 3
REFUGE ROOM IN A DWELLING

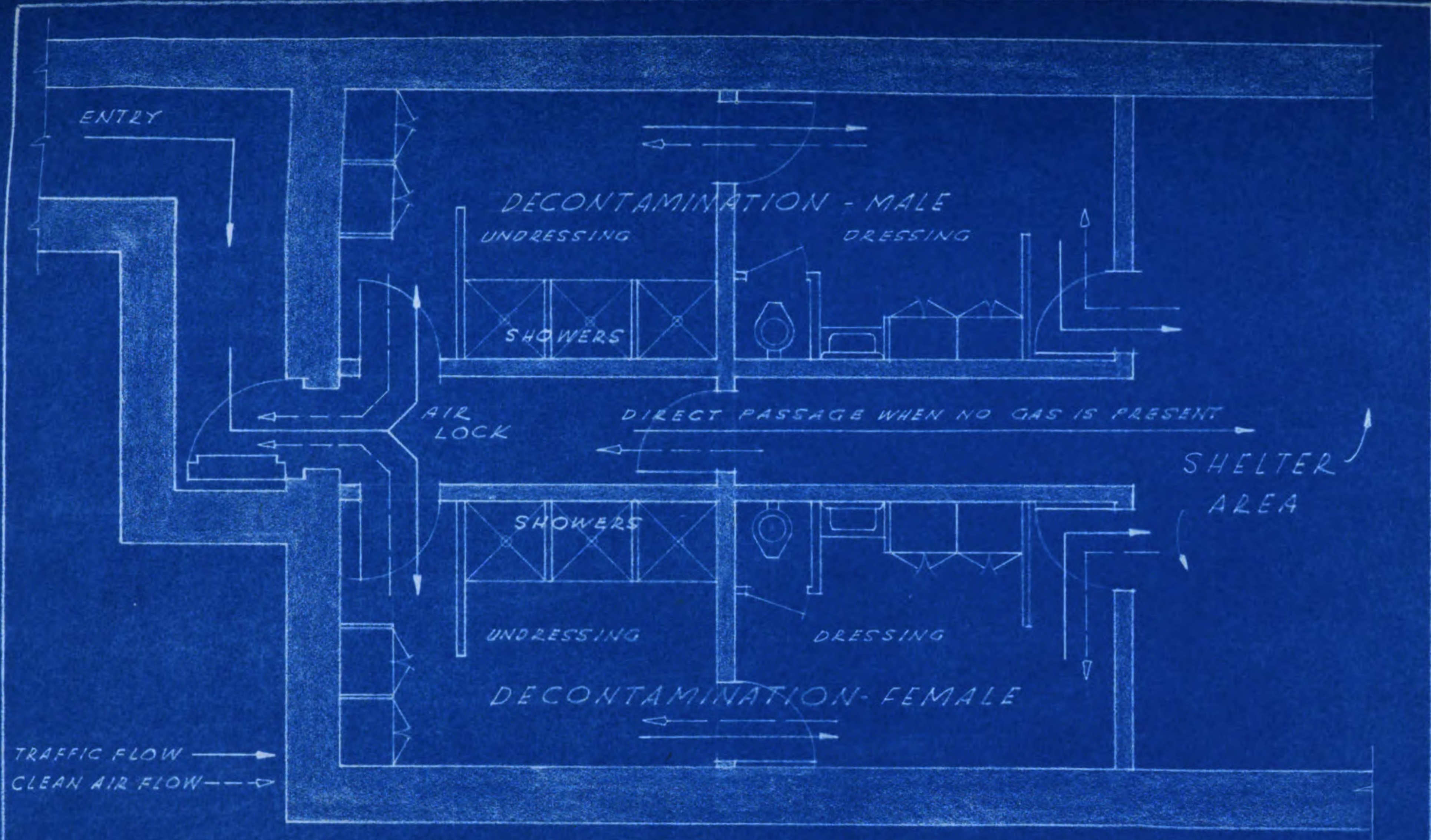


FIG. 4

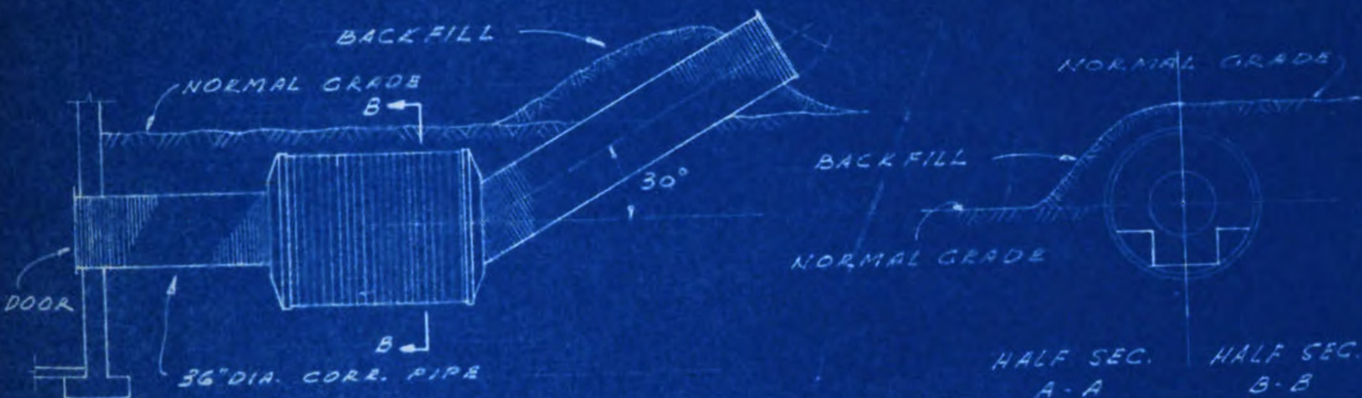
PLAN OF SHELTER ENTRANCE WITH DECONTAMINATION FACILITIES

FIG. 5

FIG. 6

Figures 5 and 6: These are one-story beam-and-girder buildings with a designed live load on a 6" slab of 185 lbs. per square foot. Note diagonal tension failure in beam "A" in Fig. 5 and girder "B" in Fig. 6, also breaking away of concrete in plane of slab reinforcing at "C" in Fig. 5. The column footing under "D" in Fig. 5 was subjected to a buried explosion from a delayed-action bomb. The column at "E", Fig. 6, was undermined by the same explosion.

The damage shown here is the result of numerous low-level attacks for test purposes and is much more severe than what might be expected from an actual air raid.



BURIED SHELTER WITH
ENTRANCE FROM BASEMENT

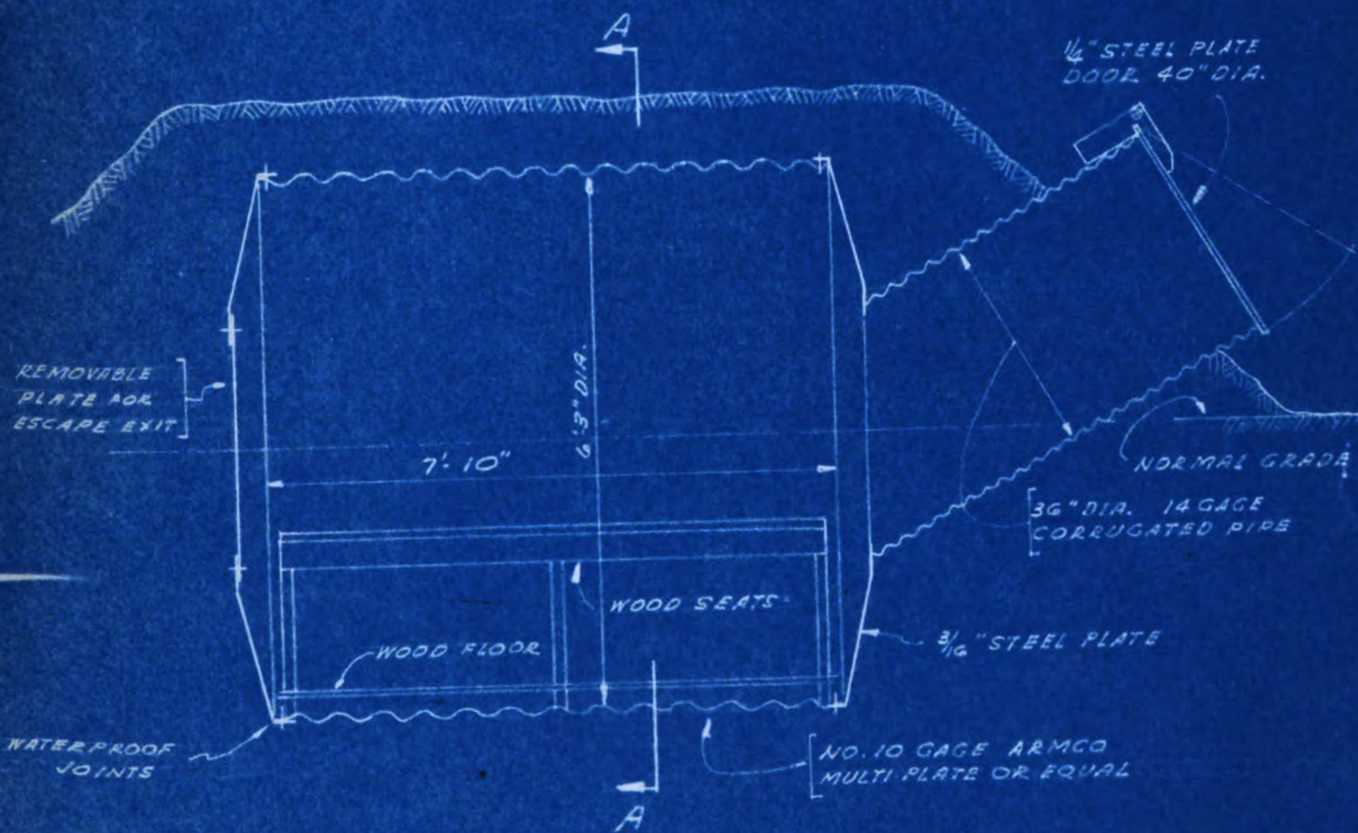
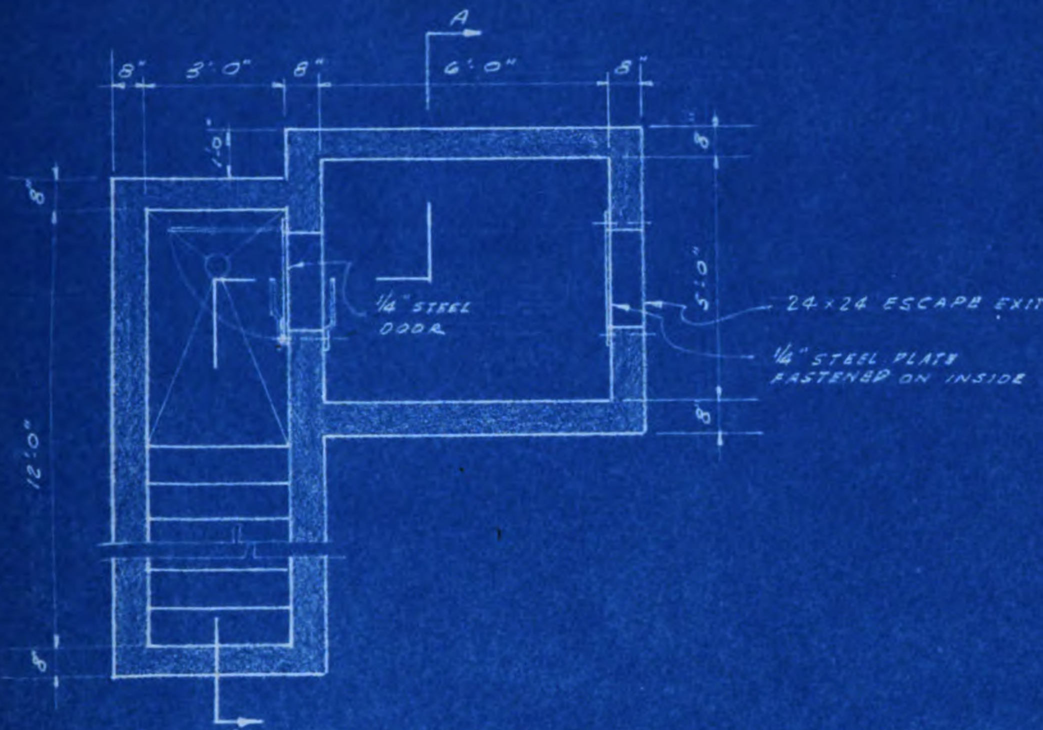
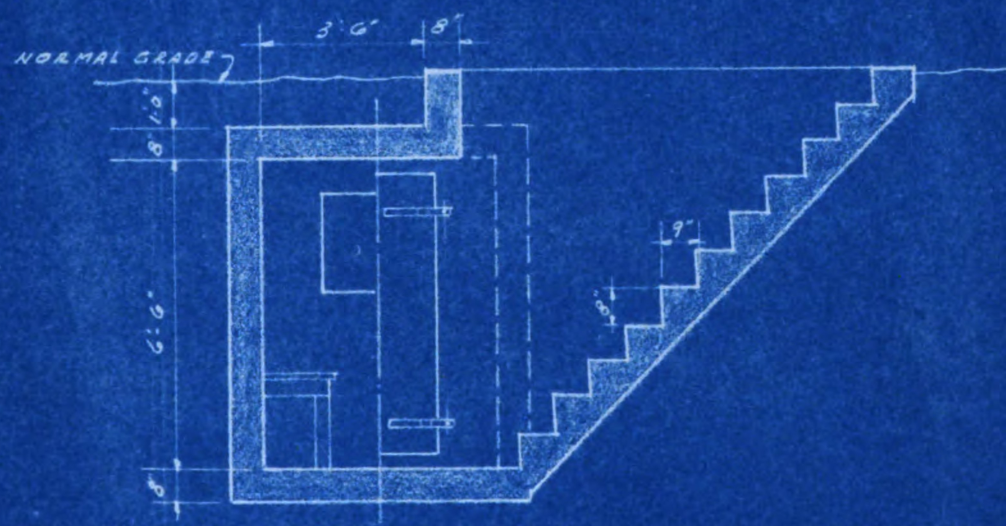


FIG. 7
FAMILY TYPE CORRUGATED IRON SHELTER
DESIGNED BY U.S. ARMY ENGINEERS



PLAN



SECTION A-A

FIG. 8
FAMILY TYPE CONCRETE SHELTER

DESIGNED BY U.S. ARMY ENGINEERS

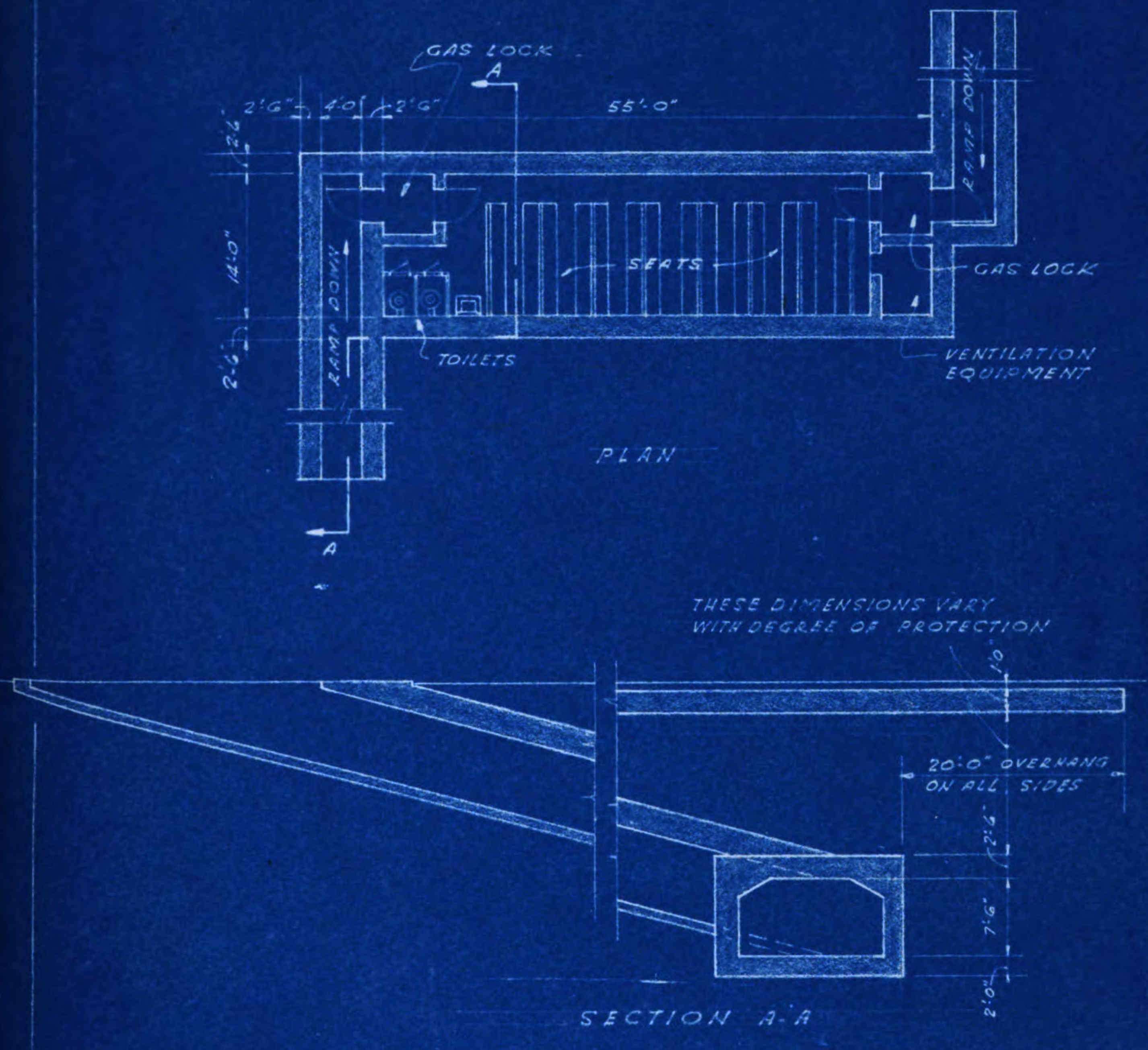


FIG. 9

UNDERGROUND SHELTER - 100 PERSON CAPACITY

DESIGNED BY U.S. ARMY ENGINEERS

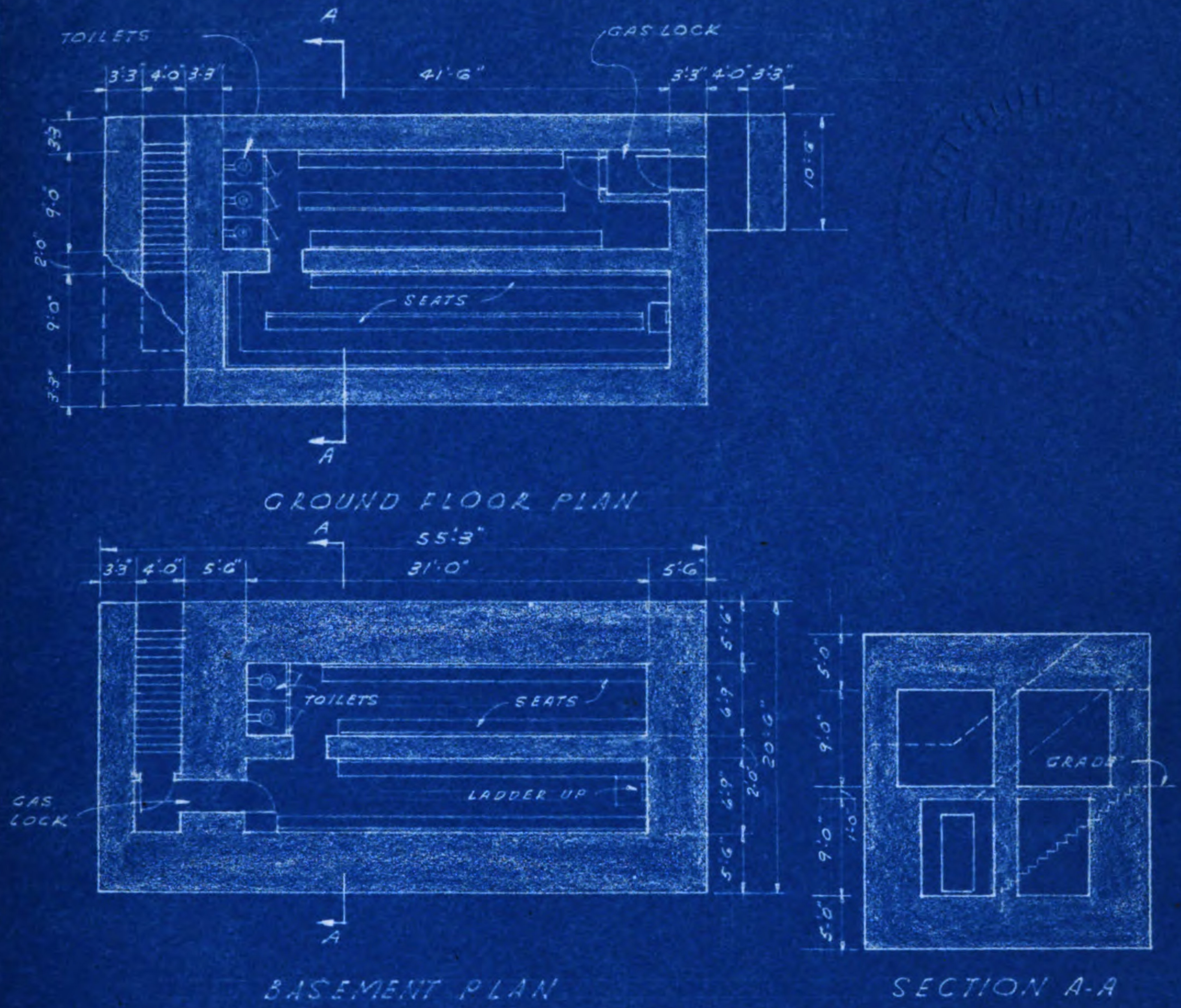


FIG. 10

SURFACE SHELTER - 200 PERSON CAPACITY

DESIGNED BY U.S. ARMY ENGINEERS

THESIS BINDING SPECIFICATIONS

Weight of paper: 20 lb. for original and 16 lb. for carbon copies.

Binding: The thesis should be bound in half black leather and black canvas. The page, after binding, shall measure $8\frac{1}{4}$ x 11 inches. The bound volume shall measure $8\frac{1}{2}$ x 11 inches.

The thesis title should be stamped in gold on the outside of the front cover. The proper arrangement of its imprint is below:

THE DESIGN OF BOMB SHELTERS

Thesis for degree of C. E.

Michigan State College

PAUL NEWMAN GILLETT

1943