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PROTECTIVE CONSTRUCTION



UNITED STATES OFFICE OF CIVILIAN DEFENSE
Washington, D. C.

BIBLIOGRAPHY

The Office of the Chief of Engineers of the War Department has a very large bibliography of secret, confidential, restricted, and highly technical information gathered through research and reports of observers. For obvious reasons, many of these reports cannot be made generally available; others are highly specialized in their interest. It is believed that the selected list of official publications below will meet general needs for information.

Publications issued by the Air Raid Precautions Department of the Home Office (London: His Majesty's Stationery Office):

- A. R. P. Handbook No. 5, Structural Defense (1st ed., 1939), viii, 58 pp.
- A. R. P. Handbook No. 5A, Bomb Resisting Shelters (1st ed., 1939), 6 pp., plus diagrams.
- A. R. P. Handbook No. 6, Air Raid Precaution in Factories and Business Premises (1st ed., 1938), 69 pp.
- A. R. P. Memorandum No. 10, Provision of Air Raid Shelters in Basements (no date), 38 pp.
- Air Raid Precautions for Government Contractors (1939) 37 pp.

Wartime Building Bulletins of the Department of Scientific and Industrial Research, Building Research Board (London: His Majesty's Stationery Office).

1940:

- No. 1, Economical Type Designs in Structural Steelwork for Single Story Factories, 29 pp.
- No. 2, The Application of Reinforced Concrete to Wartime Buildings, 9 pp.
- No. 3, Type Designs for Small Huts, 22 pp.
- No. 4, Supplementary Type Designs in Structural Steelwork for Single Story Factories, 19 pp.
- No. 5, Economical Type Designs in Reinforced Concrete for Single Story Factories, 15 pp.
- No. 6, Part 1, Arch Construction without Cen-

tering, Part 2, Further Designs for Hut Type Buildings, 9 pp.

No. 7, House Construction, 14 pp.

No. 8, Part IA: Walls for Factory Buildings; IB, Columns for Factory Buildings; II, Tubular Steel Trusses and Purlins for Factory Buildings; III, A System of Heating for Wartime Factories, 16 pp.

No. 9, Conservation of Cement and of Clay Bricks, 22 pp.

No. 10, General Principles of Wartime Buildings, 28 pp.

No. 11, Precautions for Concreting and Bricklaying in Cold Weather, 12 pp.

1941:

No. 12, Emergency Pipe Repairs.

No. 13, The Fire Protection of Structural Steelwork.

No. 14, Centerless Arch Designs.

No. 15, Standard Designs for Single Story Factories for War industries.

No. 15A, Supplement to Bulletin No. 15.

No. 16, Jointing Mortars for Brickwork.

No. 17, Resistance of Reinforced Concrete Structures to Air Attack.

No. 18, Fire Stops for Timber Roof.

Publications issued by the United States Office of Civilian Defense:

Glass and Glass Substitutes.

Report of Bomb Tests on Materials and Structures.

Air Raid Shelters in Buildings (in preparation).
Blackouts.

Protection Against Gas.

Note.—It is understood that the British publications listed above may be purchased through The British Library of Information, 50 Rockefeller Plaza, New York City; Brentano's Book Stores, Inc., 1 West Forty-seventh Street, New York City; or any house dealing in foreign publications.

INTRODUCTION

This bulletin is published to present the general background necessary for intelligent consideration of the subject of protective construction. In no sense should issuance of this bulletin be construed as the signal to start work immediately on any of the protective structures described. Nevertheless, it is deemed essential that responsible civil officials and civilian engineers give thought to methods, plans, and especially procedures that can be followed in their respective localities should such protective structures become necessary in the future.

The material presented here is the result of study of the latest information available from foreign sources, chiefly British, and of the results of research in the United States. It is intended as a general summary of such information. Many subjects are necessarily treated very briefly.

It will be evident that the designs shown in this publication utilize some materials which are of importance to many phases of war production. A construction program of such shelters should not be undertaken under present conditions, due to the military requirements for the same material. It is therefore desirable that less strategic and possibly less promising materials be investigated. Studies of this nature are being pursued under the direction of the Chief of Engineers, and, as they develop material of value, the results will be published.

Prepared under the direction of the Chief of Engineers, U. S. Army, with suggestions of the National Technological Civil Protection Committee and the Committee on Passive Protection Against Bombing, of the National Research Council.

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I. AERIAL ATTACK

Aerial attack insofar as it concerns construction may conveniently be treated under three headings:

- (A) The weapons used.
- (B) Ballistics of bombs.
- (C) Effects of bombs.

A. WEAPONS USED:

Protection must be provided against bombs and gunfire.

1. Bombs—Bombs may be classified according to purpose.

a. *To damage or destroy structures.*—Such bombs are intended to cause principal damage by the detonation of high explosive. The bomb case serves as a carrier for the explosive charge from plane to objective. If the main purpose of the bomb is to cause a maximum blast, the case will be made as light as possible and the maximum percentage of the total weight will be devoted to explosive. Typical of such a bomb is the parachute mine. In contrast, should the purpose of the bomb be to pierce armor or other highly resistant material before detonating, the case must be made heavy, particularly at the nose. This involves sacrificing to the case a substantial amount of the total weight with a corresponding reduction of explosive. The armor-piercing bomb is of this type. For the purpose of damaging or destroying structures it is sufficient to recognize three types:

Armor-piercing or semi-armor-piercing bombs in which the charge/weight ratio is low, seldom exceeding 20 percent, are capable of great penetration, and may attain higher impact velocities than other types, but past experience does not indicate their use except against highly resistant targets.

General purpose or demolition bombs are designed for the primary purpose of demolishing buildings and other structures. They range in weight from 50 to 4,000 pounds, about half the weight being the explosive. Bombs of this class in the smaller and medium sizes are used against

ammunition dumps, light structures such as dwellings, apartments, commercial and manufacturing plants, airdromes, and railroad tracks; the heavier bombs are used against factories, harbor works, bridges, major fortifications, and naval vessels. However, large bombs intended for factories or railroad yards may land in a residential district, even when no civilian bombing is intended. Bombs in the larger sizes may be used against any target, but the extent of damage is greater for an equal weight of smaller bombs. In attacks on European cities the majority of bombs dropped have not exceeded 550 pounds in weight.

Aerial mines are very large bombs, weighing from 2,000 to 8,000 pounds, similar in design to submarine mines. Their terminal velocity is approximately 60 to 90 feet per second since they are equipped with a parachute. Detonation occurs either on contact with, or in the proximity of, the objective, to produce intense blast effect. They may be used against miscellaneous targets, including densely built up residential areas, or on military concentrations.

b. *To set fire to structures.*—Though high-explosive bombs may sometimes start fires the incendiary bomb is the chief weapon in fire attack. It is probably the most destructive weapon for general attack which has yet been devised.

Incendiary bombs, usually weighing from 2 to 100 pounds, are composed principally of magnesium, thermit, oil, or other highly combustible material, and are used chiefly against inflammable targets such as congested dwelling areas in cities, munitions dumps, etc. Some phosphorus bombs have been developed and used in certain instances. Incendiary and high-explosive bombs are often combined in bomb loads.

c. *To kill or injure personnel.*—Incendiary bombs carrying small amounts of explosive may cause casualties; high-explosive bombs are lethal by reason of fragmentation and to a lesser degree by blast. The weapons specifically directed at personnel are of the following types:

Fragmentation bombs, which weigh from 4 to 40 pounds, are effective chiefly against personnel. They can be used against aircraft on the ground, mobile equipment, searchlights, and any other targets which are easily damaged or destroyed by fragments, although demolition bombs are generally used for this purpose.

Gas bombs may be used either alone or in conjunction with other types of bombs. Quick-acting types of gases may be employed to produce immediate casualties, throw the population into a state of panic and disrupt their defensive organization. Slow-acting chemicals, which remain effective in liquid form for several days, may be used to "contaminate" important areas so as to prevent their use or delay the repair of damage to them caused by explosive bombs. It is a reasonable assumption that the better the people are equipped and trained to deal with gas, the less likelihood there is of it being used against them. Gas bombs affect the design of air raid shelters chiefly in that provisions for gastight inclosures, gas lock, and ventilation with gas filter would be required as preventive measures.

2. Gunfire.

Aerial gunfire is of relatively little importance in comparison with the destruction of bombs to ground structures; however, aerial attack may include machine-gun and cannon fire in addition to bombardment.

Present-day military aircraft mount .30 and .50 caliber machine guns, and cannon as large as 37 millimeters. Any structure that is adequately protected against bomb splinters may be considered safe against aerial machine gun fire; however, if the size of cannon mounted in planes continues to increase, provisions must be made for protection against them.

Fragments from anti-aircraft shells and other spent projectiles are very dangerous, thus overhead protection must be furnished all personnel or material that may be easily damaged. Where lateral protection has been provided against splinters and overhead protection is sufficient to resist penetration of incendiary bombs, the structure can be considered as affording satisfactory protection against anti-aircraft shell fragments.

B. BALLISTICS

1. Trajectory, Angle of Impact, and Impact Velocity

The trajectory of a bomb released from an airplane in a vacuum would be parabolic, with a constant horizontal component due to the velocity of the plane at the time of release and an increasing vertical component due to the acceleration of the bomb by gravity. In air, however, the parabolic path is modified in shape and affected by the size and density of the bomb. Moreover, as the bomb velocity increases, the air resistance increases more rapidly until finally the air resistance prevents any additional acceleration. Thus any given bomb has a maximum velocity, which is called its "terminal velocity" and must be sharply distinguished from the striking velocity. From low plane altitudes theoretical velocities in vacuo and actual striking velocities are not significantly different; at higher altitudes there is more discrepancy, and finally, there is a ceiling for any given bomb above which no greater velocity can be expected as the bomb will have reached its terminal velocity. Such ceilings are usually above normal bombing altitude for all but the lightest bombs. Save for these lightest bombs, velocity is relatively independent of size. Like the velocity, the angle of impact will depend upon altitude and speed of the plane. Table 1 gives approximate impact velocities and angles of impact for demolition bombs, weighing from 100 to 2,000 pounds, released at various plane altitudes and speeds. The angles of impact stated therein are for still air, and are accurate to about 1 percent. The velocities given are also for still air and are accurate to about 5 percent. The terminal velocity of very light bombs such as the 1-kilogram incendiary is of the order of 300 feet per second; for medium sized demolition bombs it is approximately 1,000 feet per second; and for very heavy armor piercing bombs, having high sectional pressures, the terminal velocity approaches 1,500 feet per second.

C. EFFECTS OF BOMBS

The forces released by a bomb are the result of impact and detonation. Impact may result in penetration, and detonation may result in blast

Table 1.—Impact velocity and angle of impact (with the horizontal) for general-purpose bombs, altitude and airplane speed being as given

Altitude (feet)	Airplane-speed (miles per hour)							
	150		200		250		300	
	Impact velocity	Angle of impact	Impact velocity	Angle of impact	Impact velocity	Angle of impact	Impact velocity	Angle of impact
	<i>Feet per second</i>	<i>Degrees</i>	<i>Feet per second</i>	<i>Degrees</i>	<i>Feet per second</i>	<i>Degrees</i>	<i>Feet per second</i>	<i>Degrees</i>
5,000-----	560	70	585	65	615	59	640	54
10,000-----	735	76	750	72	765	68	785	65
15,000-----	850	79	860	76	870	72	880	69
20,000-----	920	81	925	78	930	74	935	71
25,000-----	970	82	970	79	980	76	980	73
30,000-----	1,000	83	1,000	80	1,000	78	1,000	74

(known as shock in earth or other solid media, or simply blast in air) and fragmentation of the bomb case.

1. Penetration

The amount of penetration of any bomb depends on its physical characteristics (shape, weight, dimensions, sectional pressure, strength of case, etc.), its striking velocity, the angle of impact, the physical properties of the material struck, and whether the bomb is equipped with an instantaneous or a delayed-action fuse. In general, bombs have considerably less penetration than shells fired from guns. This is because the striking velocity is much less, and with the greater charge/weight ratios usually employed, the deformation of the case is greater, leaving less energy available for penetration. The penetration of bombs with instantaneous fuses is small, and at the usual impact velocities, those with a delay fuse, striking a thick concrete slab, may bounce out of the resulting crater if the slab is not perforated. The bomb will then detonate in air or when at rest on the surface of the ground or structure. The tendency of a delayed-action bomb to deviate from a straight path in penetrating the earth should be particularly noted. This phenomenon makes the detection and removal of unexploded bombs difficult, and affects the design of the foundations of buildings and shelters. Obviously, a bomb that penetrates a

structure or the ground over or under a structure before exploding will do much more damage than one exploding on impact. For this reason, delayed-action fuses are generally used for demolition bombs.

There have been many attempts to develop a theory of bomb penetration; a number of formulae (Pétry, Peres, Poncelet, di Giorgi, Vieser and others) have been written. All of them have proved difficult to use, and indeed impossible to use with confidence at this time; however well the theory underlying them may be in accord with what must be the physical facts, they are not presently useful because the proper constants for various materials are unknown. A similar dilemma has confronted students of armor for many years, therefore they rely on empirical formulae for which there is a great deal of data, at least in the range of immediate interest. There is far less data on the materials attacked by bombs in other than military and naval installations. Experiments have been in progress for some time to determine the proper parameters for sound theoretical formulae and, pending that achievement, to provide a basis for a reasonably accurate prediction of penetrations to be expected. From these, taking into account uncertainties and the effect of scabbing, it is possible to predict proof thicknesses. Typical proof thicknesses for concrete, considering various bombs dropped from 20,000 feet, are shown in table 2.

Table 2.—Predictions of proof thickness for bombs dropped from 20,000 feet

Bomb characteristics			Proof thickness for concrete of strength indicated	
Weight (pounds)	Explosive weight ÷ total weight	Sectional pressure	4,200 pounds per square inch	3,400 pounds per square inch
	<i>Percent</i>	<i>(Pounds per square inch)</i>	<i>Feet</i>	<i>Feet</i>
General purpose (medium case):				
250	33	3.4	3.6	4.0
500	32	4.6	4.8	5.5
1,000	31	5.7	6.2	7.0
2,000	30	7.3	8.3	9.5
Semi-armor piercing:				
500	17	6.9	7.5	8.6
1,000	17	8.6	9.5	10.9

When a projectile perforates a thin material, the diameter of the hole formed may be approximately equal to the diameter of the projectile, as for example when a bullet strikes a sheet of plate glass with high velocity. But if the material is a thick slab of concrete, the minimum diameter of the hole through the slab will be about the caliber of the projectile or bomb, while in addition large portions of concrete will be torn off the surface struck (spall) and the rear (scab).

Scabbing is the flinging off, from the rear of the slab, of a piece of material opposite the point

struck; it may occur whether or not the slab is perforated. The degree of scabbing is evidently related to the intensity of impact or explosion, the tensile and shearing strength of the material and its thickness, but the exact relations are unknown. It may be reduced by continuous support underneath, such as might be provided if the slab were resting on sand. Such a backing is principally of assistance in holding the scab in place; this may have the effect of preventing complete bomb perforation. The shape of a scab is usually similar to that shown in figure 1.

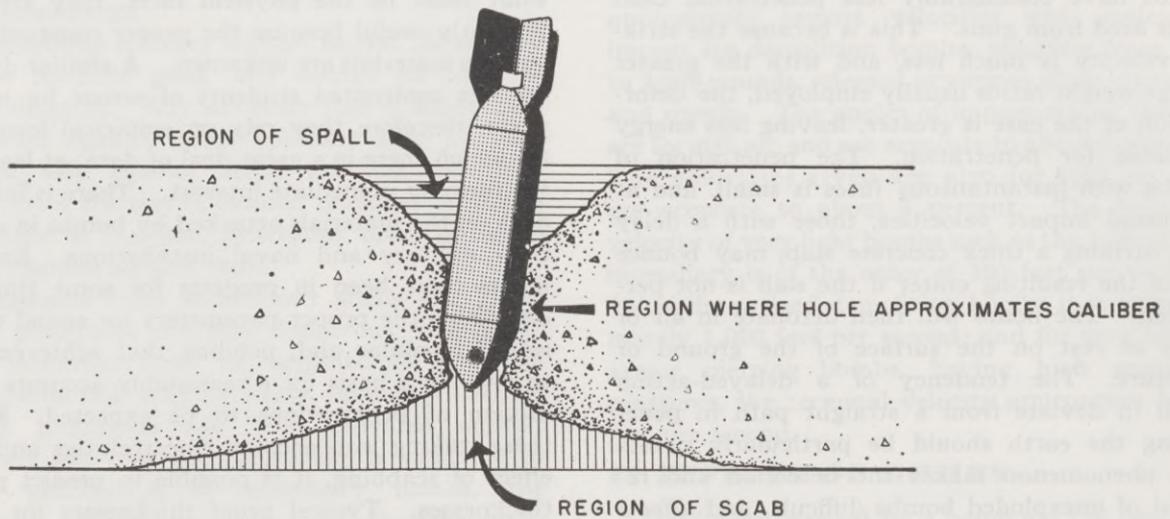


Figure 1.—Regions of spall and scab.

2. Blast.

By blast is meant the compression and suction waves which are set up by the detonation of a high explosive. At every point in the neighborhood of an explosion there occurs first a momentary wave of high positive pressure (for about 0.005 second for a 500-pound demolition bomb), and then a negative "suction" pressure. Like the pressure component, the suction component of the blast wave lasts only for a fraction of a second, but as a rule it lasts for a longer period than the compression wave (up to 0.02 second for a 500-pound demolition bomb).

PRESSURE

POUNDS PER
SQUARE INCH

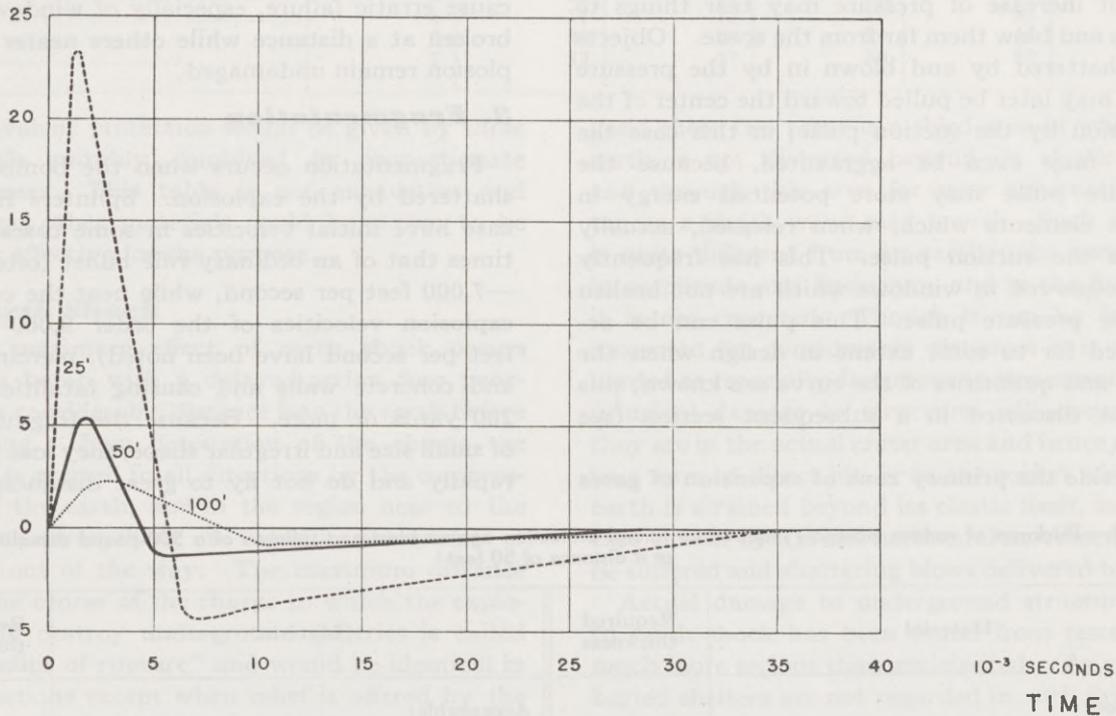


Figure 2.—Pressure-time curves for 500-pound bomb at 25, 50, and 100 feet.

The actual form of a pressure-time curve for the blast of one 500-pound bomb measured at different distances is shown in figure 2. The curves may be looked upon as typical.

The blast wave may be considered as a shell of compressed gas increasing in radius with extreme rapidity. The pressure which the moving gas

exerts on an object is the summation of the static pressure and pressure caused by its velocity. This is comparable to static and velocity heads in hydraulics. Any surface parallel to the direction of motion of the gas will be subjected to static pressure alone. Any surface facing the explosion will be subjected to pressure resulting from the velocity of the gases in addition to the static pressure. Furthermore, the static pressure in this case will be approximately twice that on a surface parallel to the direction of motion of the gas, due to reflection of the pressure wave.

The wave of pressure is highest in the region of

the explosion and falls off rapidly the farther it moves away. Close to the explosion the pressure resulting from the velocity of the gases may be as great as the static pressure. It falls off more rapidly with distance than does the static pressure. Everything in the immediate neighborhood of a big bomb therefore will be exposed suddenly

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to a violent pressure wave of many times atmospheric pressure, whereas, depending on the bomb, everything 50 feet away may be exposed only to two or three times atmospheric pressure. At 100 feet, the excess pressure may be only a fraction of an atmosphere.

The suction component of the blast wave is always much weaker than the pressure component, but is of greater duration.

Both the pressure and suction phases of the explosion (at least in the regions of interest to the structural engineer) then result in impulsive loads measured by the integral of the force-time curve. In the regions of interest, the compression and tension impulses are approximately equal, the lesser magnitude of the tension force being compensated for by its longer duration. This is not to say that their effects will be identical. The violent increase of pressure may tear things to pieces and blow them far from the scene. Objects not shattered by and blown in by the pressure pulse may later be pulled toward the center of the explosion by the suction pulse; in this case the effect may even be aggravated, because the pressure pulse may store potential energy in elastic elements which, when released, actually assists the suction pulse. This has frequently been observed in windows which are not broken by the pressure pulse. This pulse can be accounted for to some extent in design when the shape and quantities of the curve are known; this will be discussed in a subsequent section (see p. 14).

Outside the primary zone of expansion of gases

the disturbance sets up longitudinal waves in the air. These waves have the usual characteristics of wave phenomena in elastic media such as reflection and refraction. Structures affected by blast are seldom isolated but are usually grouped with others which interfere with the passage of the waves, causing reflection and refraction. In streets, where the blast is to some extent confined in a narrow space, the blast wave undergoes successive reflections and a periodic disturbance is set up. The frequencies of the waves thus differ at various distances from the bomb. Thus all things in the immediate area of an explosion would experience a violent pressure pulse and would be blown away from the explosion. Next, all things not destroyed would be pulled toward the explosion by the suction. Finally, the possibility of resonance damage due to the street effect may cause erratic failure, especially of windows being broken at a distance while others nearer the explosion remain undamaged.

3. Fragmentation

Fragmentation occurs when the bomb case is shattered by the explosion. Splinters from the case have initial velocities in some cases several times that of an ordinary rifle bullet (often 5,000—7,000 feet per second, while near the center of explosion velocities of the order 9,000—10,000 feet per second have been noted), piercing brick and concrete walls and causing fatalities up to 200 yards or more. Because the fragments are of small size and irregular shape, they lose velocity rapidly and do not fly to great distances. If a

Table 3.—Thickness of various materials required for lateral protection against blast and splinters of a 500-pound demolition bomb at a distance of 50 feet¹

Material	Required thickness	Material	Required thickness
Preferred:		Acceptable:	
Reinforced concrete—3,000 pounds per square inch or better.....	<i>Inches</i> 12	Brick wall—cement or cement-lime mortar.....	<i>Inches</i> 13
Reinforced brick—cement or cement-lime mortar.....	13	Plain concrete.....	15
		Sand or gravel between wood sheathing or corrugated iron.....	24
		Sandbag wall.....	30

¹ Recent tests indicate that the above thickness will withstand perforation of splinters at 25 feet except in rare cases.

bomb penetrates into the earth or a solid target before exploding, the danger from fragments will be small since the projection of fragments will be decreased by the surrounding material. Table 3 gives the thickness of various materials required to stop fragments of a 500-pound bomb at a distance of 50 feet.

moved with such great velocity and force as to break down its elastic properties, and in this area it will not return to its original position. While everything in the first zone is quite likely to be seriously affected, the momentum of the earth in the second zone is so great as to cause severe though not always unpreventable damage. Be-

Table 4.—Crater dimensions in sandy loam

Bomb characteristics (weight)	Type of fuse					
	Instantaneous			Delayed-action		
	Crater depth	Crater diameter	Earth displaced	Crater depth	Crater diameter	Earth displaced
<i>Pounds</i>	<i>Feet</i>	<i>Feet</i>	<i>Cubic yards</i>	<i>Feet</i>	<i>Feet</i>	<i>Cubic yards</i>
100	2	9	4	6	20	25
300	3	13	10	11	27	75
600	5	17	17	17	37	225
1,100	6	20	28	26	45	500
2,000	7	22	47	39	50	950

Equivalent protection would be given by these materials suitably combined in proportionate thicknesses. This table is not exhaustive and doubtless other materials could be shown to be equally effective for the purpose.

4. Earth Shock

The maximum effect of earth shock occurs when a bomb with a delayed-action fuse penetrates a considerable distance into the earth before exploding. Upon detonation of the charge the energy is exerted in all directions by the compression of the earth, and in the region near to the explosion everything is literally pulverized or moved out of the way. The maximum distance from the center of the charge to which the explosion will destroy underground galleries is called the "radius of rupture" and would be identical in all directions except when relief is offered by the surface. If the depth of the bomb is less than the radius of rupture, the explosion will blow out at the surface, forming a crater. Characteristic crater dimensions are shown in table 4 for various sizes of bombs. In a region outside the ruptured area, but still extending for some distance concentrically with the ruptured area, the earth is

yond these two areas is a third area in which the earth is not distorted beyond its elastic limit, and through this area for very substantial distances a shock wave may travel. Such a wave is quite different from an earthquake wave both in amplitude and frequency, and in the fact that it is not repeated. Though it can be felt and measured for considerable distances it is not regarded as especially dangerous to structures. The principal damage to structures will occur when they are in the actual crater area and hence subject to a form of direct hit, or in the region where the earth is strained beyond its elastic limit, in which case violent uplifts and horizontal movements may be suffered and shattering blows delivered to walls.

Actual damage to underground structures due to earth shock has been found from tests to be much more serious than anticipated. As a result, buried shelters are not regarded in such favorable light as they were before the significance of earth movement was demonstrated. In tests¹ conducted by the Office of the Chief of Engineers, U. S. War Department, at Aberdeen Proving Ground, only one buried or semiburied shelter, of corrugated iron, was able to withstand the earth shock of a 600-pound bomb detonating at

¹ "Report of Bomb Tests on Materials and Structures" published by the Office of Civilian Defense, 1941.

a distance of 10 feet from the shelter. There is no doubt that steel is an excellent material, as it can suffer relatively large deformations without collapse.

Military demolition engineers have developed values which represent safe distances from tamped explosions for underground timbered galleries. This distance, "horizontal radius of rupture," is defined as the distance at which structural damage does not occur to a timbered gallery from the detonation of explosive buried so that it will form a camouflet, i. e., will not produce a surface crater. As most bombs will cause craters and a camouflet is the extreme condition, these distances are therefore conservative. Table 5 gives horizontal radii of rupture for various sizes of bombs and different soil conditions. No conclusive data is available for determining the required thickness of a wall to resist tamped explosion. However, it may be assumed that a reinforced-concrete underground structure, similar to *bomb-resistant* surface structures, will not be damaged by earth shock when detonation occurs at two-thirds of the distances tabulated in table 5.

bombs may be divided into primary and secondary damage. Primary damage is the direct result of the impact and explosion of the bomb; these cause damage to structural elements such as concrete, brick, or stone walls, concrete or steel beams, and to nonstructural elements such as partitions, roofing materials, windows, doors, plaster, etc. Secondary effects are those resulting indirectly from primary effects, and include the collapse of structures where members have been destroyed by explosion or displaced by blast, or when falling debris has overloaded undamaged members.

The effects of blast on nonstructural parts of buildings, such as windows, doors, ceilings, etc., depend upon many factors. The extent of confinement or obstruction of the blast wave plays an important role in the interior damage caused by an exploding bomb. In the immediate vicinity of the bomb the pressure wave tends to destroy walls by pushing them away from the explosion, while at a greater distance either pressure or suction, or both, will cause the partitions, windows, etc., to collapse toward the explosion. Usually plaster is stripped from ceilings and walls, windows

Table 5.—Horizontal radii of rupture for timbered galleries.

Bomb weight	Weight of charge	Hard rock (limestone)	Medium rock (stone masonry)	Soft rock (average brick-work)	Blue clay	Sandy loam, clay or gravel	Hard sand, soil with vegetation	Soft sand, heavy made ground	Soft made ground
<i>Pounds</i>	<i>Pounds</i>	<i>Feet</i>	<i>Feet</i>	<i>Feet</i>	<i>Feet</i>	<i>Feet</i>	<i>Feet</i>	<i>Feet</i>	<i>Feet</i>
110	60.5	13.0	15.2	16.8	24.3	26.5	29.8	30.5	37.9
220	121.0	16.3	19.1	21.4	30.6	33.4	37.5	38.5	47.8
550	302.5	22.2	26.0	29.1	42.2	45.3	51.0	52.2	64.8
1,100	605.0	28.9	32.7	36.6	52.3	57.1	64.2	65.8	81.7
2,200	1,210.0	35.1	41.2	45.7	65.9	71.9	80.8	82.9	102.9

5. General Effects of Bombs on Buildings

The effects of bombing on buildings are dependent on the type and size of bomb, the length of time-delay in the fuse, the height of release, the angle of impact, and the type and construction of the buildings affected. Apart from damage from impact and fire, the effects of high-explosive bombs are due to three factors: blast, fragments, and shock. Which of these three is the most important in a particular instance depends upon the other conditions mentioned above.

For purposes of analysis, the damage caused by

and doors are blown from fastenings, and light partition walls destroyed; these effects occur even when bombs fall outside the building. In the latter case, the blast enters through the windows or other openings and acts on the interior panels. Failure occurs in the weakest portion of windows, doors, and panels. Whole window frames have been removed by blast and blown across a room, landing on beds with the glass panes unbroken.

Vertical glass windows may shatter and fragments fall away from or toward the explosion. Fragments of broken glass constitute a serious danger to personnel. Glazed roofs in factory

buildings are particularly vulnerable and breakage may interrupt production by interfering with blackout measures. Known glass treatments are at best but palliatives. They may reduce the radius of the circle within which a bomb will surely break the glass but will not eliminate danger from glass scattering under nearby explosion.

The shock from the blast wave acts very quickly and has been known to tear swinging doors free from their hinges rather than cause the door to swing. In this connection it should be pointed out that blast vents consisting of light materials which are easily blown off will not in general function to protect the rest of the structure in the immediate vicinity of a bomb explosion. In single-story industrial structures blast waves may be reflected from roof coverings before the inertia of the roof can be overcome, effecting its removal.

Fragments of bombs ordinarily do not affect the structural stability of a building, but if a bomb explodes close to concrete beams or columns, damage from fragments may be quite severe, causing pieces of concrete to be broken away and exposing the reinforcing. Fragments may pierce ordinary partitions and walls (see table 3, p. 6). They will also pierce light roof coverings and windows.

Structural damage from earth shock may be more serious than that resulting from blast alone. Extremely high accelerations have been recorded in the earth near a 550-pound test bomb. Masonry and brick wall-bearing buildings fare very badly as a result of earth shock. Bearing walls are stable under usual loads for which designed, but when subjected to heavy lateral loads (such as may be produced by earth shock), they generally collapse. Uplift may occur before the lateral thrust and this will usually result in still greater damage. Even walls protected by trenches, which will not transmit the earth shock, can be severely damaged by the sheer energy of moving earth masses thrown across the trenches at great speed. Obviously the bomb must penetrate the earth and explode underground before causing damage by earth shock.

Multi-story steel and concrete buildings are inherently resistant to the effects of bombing. Concrete is more fire-resistant than steel but is

more easily damaged by blast and splinters. Steel frame structures, designed in accordance with the principle of continuity, with particular attention to the conditions of fixity at connections between beams and columns, suffer little from the effects of earth shock, unless a footing is destroyed. Even in this case damage is likely to be local. Except by impact or when the explosion is in direct contact, it is difficult to destroy a single important member of a frame. However, even if a member were severed, in a building designed in accordance with the principles of continuity, the damage would be localized, as cantilevering action of the beams and floor slab would resist failure. Damage sustained by concrete columns is usually due to the effects of lateral pressure or to reverse loading resulting in tensile failure. External columns are particularly susceptible to damage from an explosion either within or outside the building. A solution is to inset the columns so that in effect they become internal, isolated columns, thus allowing rapid equalization of lateral pressure. The problem of defeating bombing effects involves consideration of loadings not dealt with in conventional design and by necessity requires the use of additional amounts of strategic materials.

Brick or masonry wall-bearing structures, or any building where the walls support the floors and roof suffer the greatest damage. Such walls are readily destroyed in considerable lengths by direct hits or near misses. As a result, floors or roofs supported by them collapse, and usually the structures must be rebuilt. If brick walls are bonded to light steel columns, the result may be to distort the column as well as to destroy the walls, and the effect is similar to that above noted. If a bomb explodes above ground level, further damage may be caused by the collapse of floors and walls beneath because of the load of debris. In this way areas of damage produced by a single explosion may be multiplied.

The blast of bombs exploding on roofs or inside one-story factories usually destroys large portions of the roof. This is particularly true in the case of large areas of glass or asbestos-cement roofing. The effect of blast on heavier types of roofing, more strongly attached, may be to distort structural members before the roof fails.

Extent of internal damage of factories depends largely on whether factories are of the single-story or multi-story type. In the single-story industrial-type building the bomb may burst either on the roof or on the ground. The chief damage from bombs bursting on the roof is from bomb fragments projected downward and from the dislocation or destruction of roof trusses or girders. Bombs bursting on or in the ground are apt to displace and wreck machinery. Where each machine is individually powered, the damage is usually less extensive than where line shafting is used. In multi-story factories and similar buildings, such as warehouses, department stores, apartments, office buildings, etc., the bomb is apt to explode either in the top story or to penetrate two or three floors, exploding between them. Cases have occurred where six or more floors have been perforated by a bomb with a long-delay fuse. When the bomb explodes between floors, the degree of confinement of the explosion determines in a large measure the structural damage.

The general effects of such explosions seem to be more serious upward than downward. Below the bomb one floor may be breached, several beams sheared, perhaps even a column crushed. The next lower floor may suffer some damage from debris. Above the bomb, however, the entire adjacent parts of the building may be destroyed. Columns may fail in tension and then be badly buckled under the descending impact of the debris. The problem of designing against such effects first resolves itself into deciding what is to be protected. If for example one wishes to save the frame, freely supported floors which would rise from the frame under uplift might well let the undistorted frame withstand the subsequent impact. This will usually, however, result in a maximum destruction of contents. On the other hand, if floors are well anchored to beams and beams to columns the structural damage may be more severe, but the contents of the building may be more fully protected.

At one extreme, in very large structures with uninterrupted floor areas and high clearances, the explosion may occur almost as in free air and may do little or no structural damage. At the other extreme, bombs bursting in small rooms may completely disintegrate walls and ceilings. In a

large floor area unbroken by walls, though the bomb may do little damage to the structure, fragments can travel long distances with great hazard to machinery and personnel. For this reason it is frequently desirable to break up such spaces by baffle walls which will aggravate the damage near the bomb but reduce the total probability of loss in personnel, equipment and production.

Fire may result from attack by incendiary bombs or from dislocation and destruction of gas mains by action of explosive bombs. In non-fire-resistant buildings the hazard of fire and consequent damage is great. In concrete-frame structures this hazard is relatively less. Normal concrete construction is more resistant to fire than the unprotected steelwork which is often found in industrial buildings. Steel-frame buildings, built under modern building codes in which adequate fireproofing is provided, are, of course, less vulnerable to fire damage than un-fireproofed steel buildings. It is said that in England for every ton of structural steel irreparably damaged by high-explosive bombs, 10 tons are destroyed by fire.

6. General Effects of Bombs on Utilities

Underground utilities suffer serious damage from earth shock and movement, which dislocates sections of pipe, caves in large-diameter brick sewers, or breaks individual sections between joints. Underground utilities in the immediate vicinity of a bomb crater are usually completely shattered. Cast-iron and steel water mains are often found with longitudinal splits in the pipe as well as transverse cracks. Gas mains, usually of cast iron, are badly damaged also.

Sewers may continue to function, even after considerable damage, since they are ordinarily laid approximately to a hydraulic grade line and are not usually under pressure.

Underground telephone and telegraph cables suffer probably the least from the effect of bombs since the conductors can stand considerable displacement and bending without destruction. Power and telephone cables carried on towers or poles also suffer little damage unless supporting structures are destroyed. The destruction of insulators by bomb fragments may cause serious

difficulties until the insulators can be replaced. Electrical machinery and generating equipment in power plants are subject to damage by movement of foundations, and particularly by fragments. Oil transformers suffer damage from fragments piercing transformer casings. The result may be fire or destruction of the transformer.

7. General Effects of Bombs on Railroads and Bridges

Direct hits on railroad tracks result in limited damage which may be repaired readily. Terminal stations, switch towers, freight concentration

and make-up yards, tunnels, and bridges are sensitive points. Destruction of or damage to these elements cause longer delays in the movement of traffic than destruction to track or roadbed.

Steel-truss bridges ordinarily suffer only local damage from bombing and may be repaired readily. A few members may be cut and the rail bed displaced. In the case of a plate-girder bridge a direct hit may bend one girder without destroying its serviceability. It is quite possible that a direct hit with a large bomb would destroy a small bridge, particularly if the hit occurred behind the abutments.

II. MEASURES OF DEFENSE AGAINST AERIAL ATTACK

The second part of this bulletin is concerned with measures of defense against aerial attack. Consideration is given to the protection of buildings, to the protection of utilities and industrial plants, and to air raid shelters.

A. PROTECTION OF BUILDINGS

It has been pointed out that framed buildings of steel or reinforced concrete construction are relatively much less affected even by direct hits than are buildings of wall-bearing construction. Modern public, commercial, and industrial buildings are usually of steel or concrete framed construction and should withstand bombing very well.

Bomb fragments may pierce building walls where the thickness is less than that indicated by table 3 (p. 6), and light wall panels and windows can be destroyed easily by blast. Temporary protection can be given by sandbag walls, which are effective if properly laid up to a minimum thickness of 30 inches. The laying of sandbags is an important detail. The bags should be filled not more than one-half to three-fourths full with

sand or earth and the opening sewed or fastened by other means. They should be laid flat with the material evenly distributed and the courses lapped longitudinally and laterally. Each layer should be thoroughly tamped to form a good bond and to compact the material. A batter of approximately 4 on 1 should be maintained on the outside faces for stability. It should be noted, however, that in climates subject to normal rainfall and snow untreated sandbags deteriorate very quickly and usually disintegrate in a few months if exposed to weather. *Therefore, sandbags generally should be considered as a temporary expedient to be replaced by brick or concrete walls when possible.*

There is little that can be done toward making a wall-bearing structure safe from bombing. Sandbag barricades may protect the contents from fragments of bombs detonating outside the structure but they cannot prevent demolition of the entire structure by blast. Buildings of this type often have wood floor systems which add to the fire hazard.

In the design of new buildings specifically to resist bombing effects, the vulnerability of wall-bearing structures practically precludes their use in all but exceptional cases and it narrows the choice of structures to one where the frame is of steel or reinforced concrete. If connection of the beams and columns are rigid and if the principle of continuity is followed, it is possible to design a building in which extensive collapse is very unlikely even under a direct hit of a very heavy bomb.²

The cost need not exceed materially that of a similar structure in the design of which no provision is made for the effects of bombs. Industrial structures with light roof covering should be designed, if possible, so that the destruction of one main member, such as a roof girder or column, will not overload the adjacent members to the extent that progressive collapse results. The dangers of collapse can be reduced considerably if the connections of the roof members to the columns are designed strongly enough to permit considerable distortion of the columns or lateral displacement of their bases without failure of the connections.

Wall panels of one- or two-story industrial-type steel or concrete framed buildings should not be bonded to columns or other structural elements since serious damage to the structure may be caused by blast.

The protection against scattering of glass fragments of window or skylight glazing by adhesive treatment, such as muslin glued over the whole surface of glass and lapped onto the sash frames, has proved reasonably effective. Any adhesive treatment should be extended over the frames surrounding the glass. Factories with glazed roofs present unusually dangerous hazards to workmen because of the possibility of fragments of glass falling within the factory. One-half inch woven or welded wire mesh may be installed overhead in the interior as near as possible to glazing or roof, to catch fragments of glass and other shattered roof coverings falling from the roof.

In the construction of new factories, skylights should be dispensed with, if practicable, and recourse had either to artificial lighting or to lighting from side windows.

² See Prof. J. F. Baker, "The Resistance to Collapse of Structure Under Air Attack," *Journal of the Institution of Civil Engineers (London)*, October 1940.

B. PROTECTION OF UTILITIES AND INDUSTRIAL PLANTS

1. Utilities

The protection of utilities so as to permit continuation of service during and after air attacks is of paramount importance in maintaining industry and production.

Utility organizations in regions where there may be danger of attack should make plans for the following:

- a. Continuation of electrical service and measures to be taken to minimize the effect of bombing.
- b. Measures of defense in the construction of new power installations to minimize the effects of bombing.

a. Continuation of service and protection of existing facilities.—One of the best methods of providing continuation of service is that of having all sources of power interconnected so that even complete destruction of an important plant would result in the minimum interruption to the power supply. All vital control apparatus and conductors should be duplicated in so far as is practical and should be so arranged that in the event of destruction of one unit, its duplicate could be put immediately into service. Another protective measure is to have replacement units and parts of equipment strategically located and designed for rapid transportation to replace a partially destroyed element.

The general statements made previously as to the relative vulnerability of, and means of protection for, various structures may be applied to power-plant structures.

A reinforced concrete roof $3\frac{1}{2}$ inches thick will prevent perforation of the standard 1-kilogram German incendiary, at its apparent terminal velocity of 300 feet per second; a $2\frac{1}{2}$ -inch slab of reinforced concrete supported on conventional wood joist and plank construction, or $\frac{3}{16}$ inch of mild steel similarly supported will also prevent penetration. The walls should be thick enough to give protection against bomb fragments. (See table 3, p. 6.) Where walls are of insufficient thickness, a sandbag, brick, or concrete wall may be

provided, in addition to the existing wall, to increase the protection. Large windows may be made less dangerous by closing part of the opening with sandbags, or preferably, with concrete or brick walls. Individual power units such as generators and turbines may be given protection by protective blast walls; however, plant protection is a specialized study.

Massive concrete dams suffer little or no damage by aerial bombardment. In certain cases, head gates and spillway gates with their operating mechanism, intake screens, or trash racks may be damaged; in these instances, a degree of overhead protection may be provided, although such installations are so varied that definite recommendations cannot be made.

High-tension lines are not easily destroyed or broken down by aerial bombing. Few direct hits can be made by enemy planes unless they have the most favorable conditions for attack and fly very low over and along the transmission right-of-way. Even in such cases, direct hits resulting in the destruction of the steel towers seldom occur. Towers are sometimes damaged by fragments of exploding bombs, but in most cases this damage is not sufficient to interrupt the power supply.

The comparatively few interruptions of power supply on transmission lines, which are usually caused by damage to the conducting cables or insulators, may be repaired quickly and the broken insulators replaced. When towers are destroyed by direct hits, service can be restored in a very short time by providing temporary lines. Multiple transmission lines having different routings or widely separated rights-of-way, and selective relay protection for the different circuits, will reduce the interruption of power service to a minimum.

b. New construction.—New buildings of permanent construction which house important equipment or operations should be designed as framed, fire-resistant structures, with walls of sufficient thickness to resist fragments, and roofs at least heavy enough to stop light incendiary bombs.

Power-plant machinery and other vital equipment should be given protection against fragments. Provision should be made for adequate fire-fighting equipment, and for concrete fire walls or barriers to prevent such spread of fire as might happen

when oil-filled transformers and switches are used.

The construction of outdoor stations should be arranged so that sectionalization or cutting off of damaged sections may be done quickly and service restored over undamaged sections. A wider separation of the more vulnerable units, such as transformers, will serve to decrease the liability and extent of damage. Outdoor substations preferably should be of latticed angle-iron construction and the transformers and oil switches should be protected against splinters and incendiaries.

Those penstocks, gates, etc., which are particularly likely to be damaged should have adequate control equipment and valves to localize the damage to prevent flooding, loss of water, and permit repairs.

Outside flow-line equipment, including penstocks, oil piping, gas pipes, and other vital appurtenances of hydroelectric plants should be placed underground or in strongly constructed concrete ducts or tunnels, wherever this is feasible and financially practical.

Steam plants are probably more liable to injury than hydroelectric plants, because of the vulnerability of boilers and auxiliary equipment, and because of high chimneys which may be destroyed, damaging the part of the plant on which they fall. Protection from bomb fragments for steam plants may be obtained, in general, by protective blast walls about boiler rooms and isolating as much as possible the various elements of the plant.

2. Special Measures for the Protection of Industrial Plants

In general, many of the points covered under the protection of buildings and utilities are applicable to industrial plants. Steam boilers, machinery, essential water and gas mains, switchboards, and electrical cables should receive special attention. Besides causing disruption of operations, the destruction of supply pipes by bombs might involve flooding or explosion.

The storage of highly inflammable material, such as gasoline, oil, or chemicals in tanks, should receive special consideration on account of the serious fire risk. This may involve the construction of dikes around tanks, placement of tanks underground, or removal of tanks to a less dangerous location.

Communications must be maintained for emergency service. Duplication of lines and location of telephones in shelter and first-aid stations are necessary for adequate control.

Sandbags have been used to protect essential machinery against fragments, and wooden boxes filled with sand are an excellent substitute. Both may result in sand being thrown about and, since sand is abrasive, this may not be desirable. Better construction would use baffle walls of brick or concrete.

Since factories cannot ordinarily be made bomb-resistant, the problem is to limit the loss of production, due to hits, by measures which will not unduly limit production under normal conditions. The requirements are evidently contradictory and require careful individual study. Ideally, machines doing the same job would be so separated that no single bomb could damage many; unique machines would be given special protection; and large areas would appropriately be broken up by baffles so arranged that, in failing, they will not increase the damage to the structure as a whole. Where practicable, duplicates of vital machinery, tools, dies, and special fittings should be obtained, if not already available, and stored as additional insurance against interruption. These duplicates should be dispersed, and should be stored away from the main buildings.

As previously mentioned, incendiary bombs may be expected to pierce light roofs and burn on the floor of the top story. Although most modern industrial buildings are of steel or concrete construction and consequently are less vulnerable to fire, the contents of many such buildings are highly inflammable. It is most important, therefore, to take all possible steps to reduce the risk of fire by having adequate portable fire-fighting equipment, to supplement permanent installations of equipment which may possibly be damaged during an attack. Reserve supplies of water in static tanks or other reservoirs should be provided. Stocks of inflammable material should be reduced as far as possible.

Study should be made of the problem of carrying on work if supplies of water, electricity, and gas from public or private sources are interrupted by damage to producing stations or service mains. Auxiliary power plants should be provided and

maintained in working condition. Duplication of power and communication lines, switchboards, and other utilities is desirable.

Protection for personnel by the construction of shelters, internal or external, will be discussed in Section C.

C. AIR RAID SHELTERS

In connection with air raid shelters, consideration must be given to various problems of design, general requirements for shelters, shelters in existing buildings, and external shelters. Each of these subjects is discussed below.

1. Structural Design

a. The Problem of Design.—When a bomb strikes a structure, it possesses a large amount of kinetic energy (9 million foot-pounds for a 1,000-pound bomb dropped from a plane traveling 300 miles per hour at an altitude of 10,000 feet). When it detonates in contact with a structure, a much greater amount of energy is released (of the order of 30 times the impact energy); however, only a fraction of this energy is effective in producing damage to the structure, and it is spread over a larger area than in the case of a direct impact. The problem of designing a roof slab or a side wall to resist such large amounts of energy is obviously a new one for engineers. Simple structural forms can be designed in terms of energy loads and energy capacities. Complex units involving a nonuniform state of stress, such as an ordinary beam, may be designed for energy loads, if the maximum stresses are below the elastic limit. The greatest amount of energy capacity is available for many materials in the plastic range, however, and consequently the problem of design in terms of energy loads may become highly involved. If stress states were uniform, it would perhaps be a simple matter to evaluate design units. Stress states in beams and slabs subject to high impact loads are nonuniform and it is difficult to determine surface energy capacities and the highly localized effects of impact and explosion.

Engineers have long recognized the difficulties inherent in "energy design," and consequently the practice of using "equivalent static loads" has been prevalent. The usual definition of equivalent static load, as the average value of the force

during the time in which it acts, is only applicable in case the fundamental period of the structure on which it acts is small compared with the duration of the force. Thus in the case of the bomb cited above, assuming a penetration of 4.5 feet into reinforced concrete, the average force would be 2 million pounds, with an impact duration of about one-eightieth of a second. If the fundamental period of the member or structure impacted is larger than this time, the deformation will be less than that computed from the "equivalent static load," as computed above. In the very cases in which advantage is to be gained by making use of the fact that the impact and blast durations are exceedingly short, this traditional method of computing the load is invalid.

A more appropriate and more useful definition of "equivalent static load" must therefore take into account not only the magnitude and duration of the actual load, but also the vibration characteristics of the structure upon which this load acts. Such a definition is: *The equivalent static load is that load which, if maintained steadily upon the structure, would produce the maximum stress as that produced, at some time, by the actual load.* Obviously, the precise working out of a theory of design based upon this concept must begin with the theory of vibration of the members or structures involved. This problem is complicated by the probability that the properties of the materials may be different under rapid rates of strain than under the quasi-static conditions under which they are usually tested; thus even though the maximum stress developed may be greater than that usually allowed, it may well be that failure will not ensue because the mechanism of rupture has not time to run its course. Only after adequate investigation of these problems can recourse be taken to the standard static theory of design, with complete assurance that the theoretical results will be in accord with fact. Fortunately, a practical procedure of a semiquantitative nature need not await the complete solution of these problems, and it is to be expected that this may rapidly be improved upon as the result of extensive investigations now under way.

The theory of vibrations of a structure within the elastic limits of the materials of construction,

allows the resolution of the vibration into simple modes of vibration, each of which is excited to a degree determined by the particular circumstances of impact—position, distribution, and duration of the applied force. The solution of this problem, in any practical case, may be involved, and should in any case not be driven beyond the point at which further refinement would lessen materially its general applicability. Fortunately, in many cases one mode of vibration, most often the one of lowest frequency capable of being excited by the impact, will predominate; in such a case semiquantitative results of practical value can be had by thinking of the structure as replaced by a simple elastic system (mass upon a spring) of natural frequency f equal to that of the fundamental. The computation of the equivalent static load from the actual load will then lead to an equivalent static load which depends only upon the frequency f ; the analysis involved is at worst tedious, and can be circumvented by mechanical devices. As an example of the results of such analysis, figure 3 gives the equivalent static pressure and the equivalent static suction computed from the pressure-time curve given in figure 2 for the blast from a 500-pound medium case bomb at a distance of 50 feet. Specifically, the broken curve represents the static pressure which would produce the same stress as the maximum actually achieved by a system of frequency f , when subjected to the blast represented in figure 2; similarly, the full curve gives the suction which, if maintained steadily, would cause the same *negative* stress as the worst actually experienced by the system under the actual blast. It is of interest to note that a system whose period was equal to the duration 0.033 second of the blast, would have a frequency f of 30 cycles per second—which lies about at the point at which the equivalent pressure achieves its first maximum of about 3.3 pounds per square inch. The advantage of limberness in the structure is apparent from the way in which the equivalent pressure decreases on going to smaller frequencies f .

The effects of the modes of higher frequency is disregarded in this treatment; they can be taken into account by a computation based upon the degree of excitation, obtained from theory, and upon the *same* equivalent static load curve at the

higher frequencies involved. The corrections to the approximation here discussed are particularly significant for structures of low fundamental frequency, but would lead too far afield to be included in this general description of the method. The importance of these corrections is presumably diminished because of the relatively greater damping of the higher vibration modes.

Much remains yet to be done before a theory, comparable in completeness with that for static loads, can be developed. Perhaps the most fruit-

expulsion of this material to great distances, and heat. If only a small portion of the energy remains to be absorbed by the structure as a whole, the dynamic structural problem becomes unimportant. At some ratio of energy distribution, it will happen that a slab which will resist penetration and explosion will be adequate automatically to take care of the overall structural effects due to the residual energy.

Similarly, if the supports of the slab are of a nature calculated to resist lateral impacts and

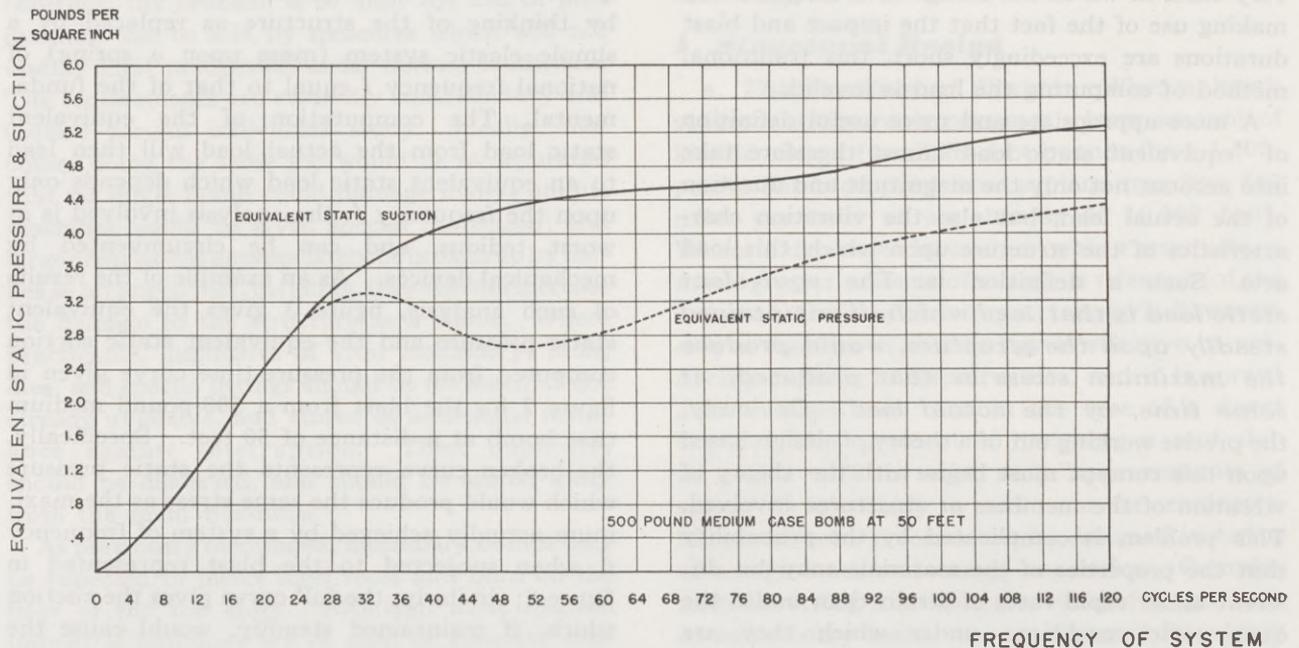


Figure 3.—Equivalent static pressure and suction versus frequency of a structure.

ful application of the partial results so far attained is in enabling a comparison of the relative effectiveness of two alternative designs; e. g., of the effectiveness of blast shields which are simply supported as compared with a cantilever support.

It is the belief of most persons who have been privileged actually to witness and study experimentally impacts and explosions and their results on slabs of concrete or steel, that a very large proportion of the energy released is absorbed immediately by local effects. Such effects include deformation of the projectile case, projection of splinters, pulverizing of structural material immediately adjacent to the impact of explosion,

earth-movement loads, they, too, will take care of the dynamic loads without special analysis. As has been said, most trained observers believe this to be the actual case. Indeed, there is some evidence of the sort of strain produced by projectile impacts throughout the structure of a concrete slab, and these seem to be entirely within the capacity of concrete to absorb, in addition to the permanent strain due to dead load. The evidence on the strains produced by explosion is less clear.

Therefore, where it is immediately necessary to design structures to protect against a direct hit, the best rule of thumb is to design them to resist the local effects of pene-

tration and explosion (see table 2), and then to make certain that they are able to carry with the usual factors of safety, the actual (often very great) dead loads. Slabs for such structures usually will be very thick and pass possibly outside the range of conventional assumptions in the design of slabs; but trained engineers will have no difficulty in dealing with this type of problem.

It is evident that some of the physical properties of concrete may affect the resistance to penetration and explosion; this, too, is under investigation. Various special types of reinforcement may improve the behavior of the slab, but these will be arrived at more safely through a knowledge of strain distribution than through invention.

It does not appear that blast pressures in air will have any important effect on structures of the type under discussion if they are designed for impact and explosion.

Fragments from bombs detonating near concrete structures produce penetrations in slab surfaces which are discussed elsewhere. But when such fragments hit near edges of columns or beams or slabs, they tend to spall off large pieces of material and bare the reinforcing. It is entirely possible that several hits in the vicinity of a concrete structure might cause serious damage by fragment attrition.

There remains the earth wave from a bomb detonating in the ground near a structure. These shocks really cannot be compared with earthquake shock. Although the waves and ground movements are of the same general nature, they are of much less amplitude and much greater frequency and acceleration. (Typical amplitude for earthquake, 2.03 inches; for quarry blast, 0.0113 inch; frequency for earthquake, $\frac{1}{2}$ to 1 cycle per second; for detonation, 15 cycles per second; acceleration for earthquake, 0.4 g.; for 550-pound bomb detonated 22 feet below ground, horizontal acceleration 25 g. and vertical acceleration 75 g. at 30 feet decreasing rapidly with increase in distance.)

The remainder of this section is devoted to some empirical suggestions for specific parts of structures.

b. Roof beams and slabs.—Heavy local shear stresses may result from the impact and explosion of a bomb. Bending stresses are apparently of secondary importance. It appears that any ordinary roof structure designed to carry the dead and live load with the usual design stresses will be perforated before it will fail in bending.

The penetration of bombs of various sizes in concrete and earth has been the subject of considerable investigation abroad. Structures can be built thick enough to resist the most destructive bomb known, but such structures must be very heavy. Concrete designed to resist scabbing and explosion may require special reinforcing. A large number of small reinforcing bars, placed preferably in three dimensions, seems to be more effective than an equivalent weight of large bars in resisting fragmentation, diagonal tension, and shear. A grillage of reinforcing bars running in both directions near the bottom surface of the slab (in fact, near all interior surfaces of such structures) perhaps will help to prevent scabbing and prevent large fragments from falling off. Steel soffit plates of flat, corrugated, or trough section have also been used for this purpose.

c. Burster slabs.—It is a common practice to protect a structure by means of a separate burster course or detonating slab placed over it. The function of such a slab is to prevent penetration and to break the case when the bomb has a delayed-action fuse, or to cause detonation if the bomb has an instantaneous fuse. If the bomb case is broken by the impact with the burster slab, the explosive often functions as a low-order detonation, which reduces its explosive effect.

When a burster slab is used, it must positively stop the bomb, or else it may increase the bomb's effect, since the bomb will explode in the confined space between the slab and shelter with greater force. The thickness of burster slabs varies with the protection to be provided. Tests are now in progress on slabs of various thicknesses, strengths of concrete, and types of reinforcing, which should determine the type and thickness required for protection against the several sizes and types of bombs. There should be only enough earth over the slab to allow for the growth of grass for concealment. More earth would tend to tamp the charge and increase the explosive effect.

The burster slab should extend beyond the structure a sufficient distance to prevent a bomb penetrating the earth and exploding near a wall or underneath the shelter. If the burster slab can be supported independently, the space between it and the shelter should preferably be empty, since it has been shown that air is the best medium for dissipating the gases and shock from an explosion. Generally speaking, it is impractical to provide separate support for the burster slab, particularly if the structure is large. In fortification design it has been the usual practice to place a fill of sand over the structure and pour the concrete burster slab on top of this fill. Adequate drainage should be provided to reduce the transmission of shock.

d. Walls.—When the burster course does not extend far enough beyond the shelter to provide lateral protection, walls below ground must be strong enough to resist the tamped effect of a bomb exploding in the ground adjacent to the wall. No exact design data in convenient form can be furnished at this time for determining the required thickness of a wall to resist tamped explosion.

Walls of buried or semiburied splinterproof structures should be designed to resist the earth shock and debris surcharge resulting from near hits. Preferably, they should be constructed of a material which will permit reasonable distortion without failure. Protection may also be given by use of an open trench or by filling in the space adjacent to the wall with brush or similar material.

Walls above ground may receive an oblique hit from a bomb. The required thickness to resist the reduced impact and untamped explosion is much less than that for the roof or wall below ground. Walls designed to give protection against bomb *blast* and *fragments* only, should have the thickness shown in table 3 (p. 6).

e. Foundations and floor.—Bombs may penetrate underneath foundations or floor slabs. The same considerations apply as in the case of walls subject to tamped explosion, discussed in the preceding paragraph.

2. General Requirements for Shelters

Shelters may range in size and accommodation from hastily excavated trenches offering a mini-

imum of protection to elaborate structures housing thousands. It is not economical to provide complete protection against direct hits of heavy bombs except where large groups are accommodated. Splinterproof shelters which provide reasonable safety at low cost can be designed and built as follows:

- (1) Blast and splinter protection as indicated in table 3 (p. 6).
- (2) Protection against a direct hit of a light incendiary bomb.
- (3) Protection against debris falling from adjacent buildings.
- (4) To resist the effects of earth shock from a 500-pound bomb exploding not nearer than 25 feet.
- (5) Adaptable for protection against gas.

When shelters are built for capacities greater than 50 persons, or are located in particularly dangerous areas, protection should be greater in proportion to the number of persons and relative danger.

There are a few general requirements for shelters, which apply to any type, whether in buildings or outside. Shelters should be situated so that all intended occupants can reach shelter within the least possible time, since the minimum warning period is indefinite. Entrances should be clearly marked and located with respect to population densities. There should be at least two means of egress, since one may be barred by debris. In any structure housing more than a few people, there should be a means of allowing passage into the shelter without permitting gas to enter. This is usually provided in larger shelters by use of a double set of doors in a short passageway. The persons entering close the first door before opening the second one into the shelter. It is preferable to have a right-angle bend or offset in such gas locks so that splinters passing through one door will not pierce the other. In shelters designed expressly for the purpose, the doors may be of steel, heavily constructed, and gas-tight. In improvised shelters in existing buildings, doors should be weatherstripped and all cracks and keyholes plugged. Heavy blankets hung across door openings and held in place by boards may afford some protection in an emergency. These light closures are likely to be blown in by blast, however.

It is desirable to have provision for decontamination at the entrance to the shelter leading off from the gas lock so that persons exposed to persistent gases may wash and change their clothing before entering the shelter room.

The importance of ventilation in shelters depends on the capacity of the shelter, the likelihood of gas attacks, and the probable duration of a raid. Even when gas is not used, some positive means of ventilation is desirable to expel carbon dioxide and moisture. Although natural ventilation is cheaper than artificial, a shelter relying on natural ventilation must be much larger per capita, for the presence of gas requires the sealing up of all places where air may enter, and the air inside the shelter must be sufficient to support respiration during the period of the raid. Authorities generally agree that persons in a hermetically sealed room require a minimum of 50 cubic feet of air per person for 1 hour's occupancy. Continued occupancy for a longer period causes serious physiological disturbances.

Filtration units are required to provide gas-free air. Units should deliver not less than 300 cubic feet of air per person per hour;³ if electrically driven, they should have provision for manual operation. Air is pumped in from the outside and passes through filters which absorb the poisonous gases. The air then passes into the shelter and exhausts through suitable ducts. A slight positive pressure is maintained to prevent the entrance of gas-laden outside air. The life of the filter depends on the concentration of gas and the moisture content of the air passed through it. Gas collects in low places, and the concentration of gas decreases at higher points. Therefore, it is advisable to have the intakes at least 10 feet above ground so that they can draw in clean or less contaminated air. More than one intake should be provided, since one may be damaged or destroyed.

In any but an emergency shelter, lavatories and toilet accommodations should be provided. In shelters above ground the disposal may be to the regular sewers, but in shelters below the ground the sewers will probably be too high, and disposal must

be obtained by chemical closets, septic tanks, or by drainage into special sewers.

Electricity should be provided from the regular mains for lighting and for operation of ventilating-fan motors, but auxiliary power should be provided also. This auxiliary power may be from engine-driven generator sets or, in small shelters, from storage batteries. If a generator is used, it should be separated from the main room of the shelter, and the exhaust from the engine piped outdoors.

Water supply may be from the city mains also, but a second source is desirable. This source may be a storage tank in the shelter. Water should be available in sufficient quantities for drinking and washing and in larger shelters for showers.

Beside the above-mentioned utilities, equipment in a shelter should include food stored in airtight containers, and crowbars, picks, and shovels for digging out should the entrances become blocked. The larger shelters may have a sick bay with beds and trained personnel, if such is recommended by the medical staff of the local civilian defense organizations. Decontamination rooms should have supplies of clean clothing and bins for contaminated clothing. Telephones should be provided in the larger-sized shelters. Radio is likely to be an important means of communication in war, and shelters may be equipped with receiving sets if such are on hand, although more essential items should be provided first.

3. Shelters in Existing Buildings

It has been pointed out that steel or concrete framed buildings are relatively safe from anything but a direct hit from a high-explosive bomb, and the convenience and relative economy of a shelter inside a building may be determining factors in selecting the location of a refuge. Shelters within buildings have the advantage that they are easily accessible to occupants of the building and can be kept warm and livable. With a few exceptions, modern office, factory, and apartment buildings of more than four stories are usually of reinforced concrete or steel frame construction and offer suitable and very accessible locations for shelters within them.

³ See "Protection Against Gas" published by the Office of Civilian Defense, Washington, D. C., 1941.

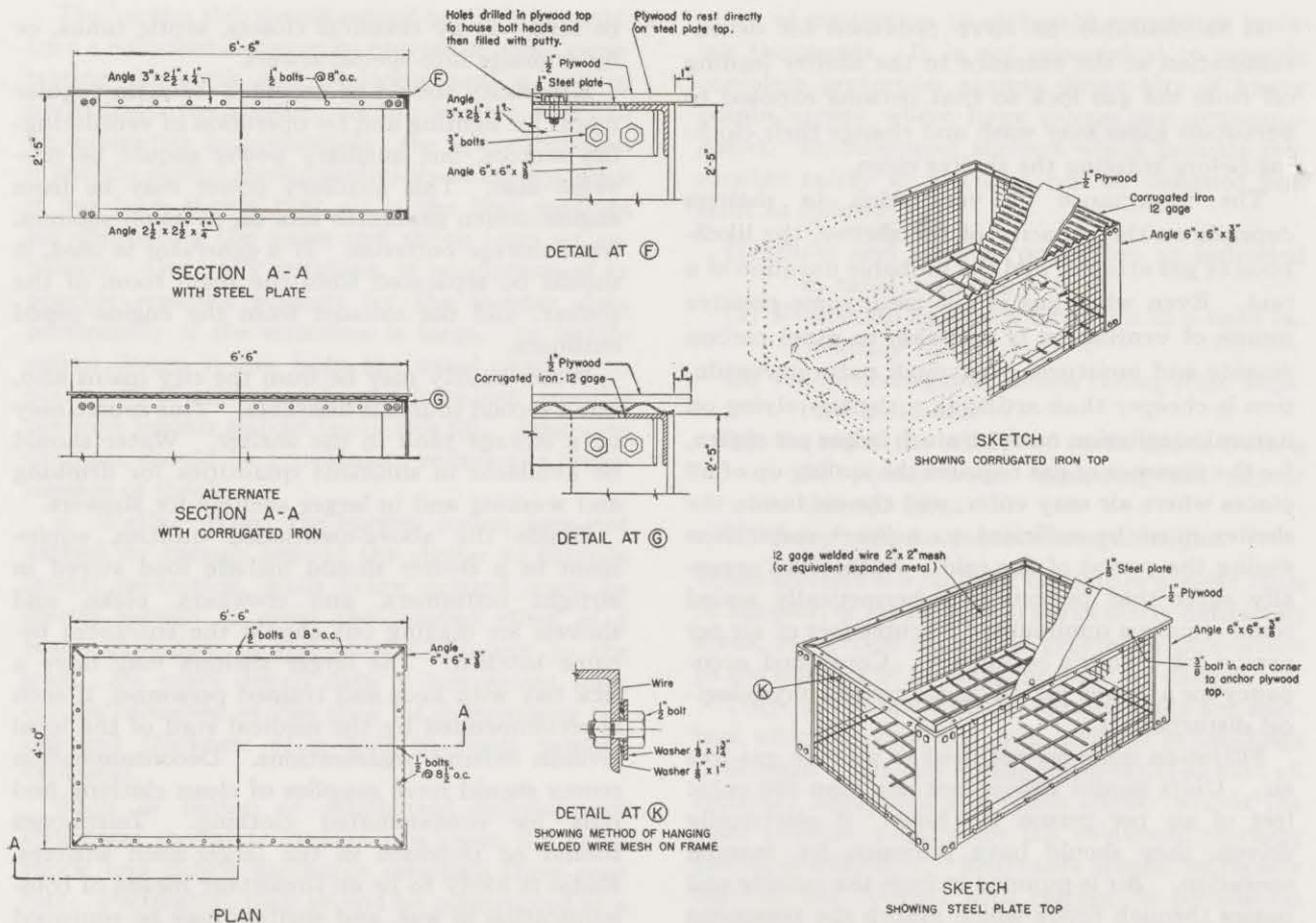


Figure 4.—Steel Table Shelter.

A simple method of providing protection within the home is by means of a table shelter shown in figure 4. This steel shelter will accommodate two persons comfortably and is quite resistant to falling debris. A similar shelter constructed of wood may be preferable from the standpoint of not using strategic material. A mattress may be placed inside the shelter for comfortable occupancy.

The room selected for a refuge should have its ceiling strengthened to support any debris loads which may come upon it; lateral protection should be obtained by closing up window and door openings with concrete or brick or, in an emergency, with sandbags. Preferably, no gas, refrigeration, or steam piping should enter or pass through the room.

The amount of bracing or shoring necessary to

withstand debris loads is quite large. Special methods of strut reinforcing are required for strengthening shelter-room ceilings to prevent collapse by falling debris. The danger of occupants being buried under debris is tremendous, as demonstrated by the considerable number of casualties abroad resulting from building collapse. Improper installation of shelter-room strutting is extremely hazardous when subjected to the effects of bombing. Suitable methods for strutting shelter rooms are described in a pamphlet entitled "Air Raid Shelters in Buildings" soon to be published by the Office of Civilian Defense. English and German specifications require strengthening to carry a load from 200 to 400 pounds per square foot in masonry buildings. In framed buildings this could probably be somewhat less.

In some buildings basements are particularly suited for refuge rooms. Basements offer the greatest lateral protection from blast and splinters, and the floor overhead may afford protection from light bombs. On the other hand, the weight of debris is likely to be greatest on the floor system acting as the basement roof, and there is danger from heavy gas collecting in low regions. Water and sewer mains bursting nearby constitute another danger. The possibility of fire in buildings of nonfireproof construction should be borne in mind. The decision as to whether the basement should be used as a shelter must be made after consideration of the factors present in each specific situation.

In some steel or concrete framed buildings the intermediate floors (for example, the second or third floors in an eight-story building) are well suited for shelters. A special case is that of a very narrow building which may not offer any suitable shelter. Floors at intermediate levels have the important advantage of being generally above the level of gases, and the danger from splinters is decreased. It is probable that in many buildings such locations would be more accessible to all the occupants. Even in the event of a direct hit, the bomb may explode on the roof or pass through to the basement, leaving the shelter little damaged. The danger of being trapped in the shelter would probably be less than in a basement structure. Also, the fact that close watch could be had on the progress of the raid from lookout windows would be important for directing operations and assisting fire and decontamination squads.

It is suggested that in a large building several small shelters be constructed in preference to one large one. This arrangement facilitates entrance and egress and prevents total loss of life if one shelter is hit. Shelters may be located advantageously in corridors; They are usually easily accessible and are given lateral protection by having two or more thicknesses of wall between them and the outside. Some modern office buildings have staircases located centrally with no openings except a door at each floor. These suggest themselves as excellent places of refuge, since they can be reached from each floor, give

good lateral protection, and their general usefulness is not impaired.

Shelters in basements should have at least one emergency exit that does not open into the building. A tunnel leading from the shelter room to a manhole some distance from the building is satisfactory. An area window which has been closed up by sandbags or loose brick also can be a means of escape. In connected buildings an emergency exit may be made by cutting through a party wall. It occasionally happens that separate buildings of a single organization are connected by utility tunnels. These tunnels may afford emergency exits and can be used even as shelters if sufficient cover exists and steam, gas, and other piping can be closed by valves.

A building that is not of fire-resistant construction should not be used for a shelter unless it is impossible to find protection elsewhere. In such a case the attic or space under the roof should be cleared of all inflammable material and equipment should be provided for fighting fire. An incendiary bomb can pierce easily a slate or tile roof but it may lodge on the attic floor. The British Air Raid Precautions Department advises covering the floor with 2 inches of sand if no better covering can be used, but consideration must be given to structural ability of the floor to withstand the added load.

In the selection of a room to be used for a shelter, attention should be paid to the possibility of heavy loads falling onto the shelter as a result of the destruction of supporting members. Figure 5 shows some characteristic features in a typical industrial area which are potential sources of danger, and areas that are well located for shelters. These are discussed below.

Area A is a good location for a splinterproof shelter. The overhead protection is insufficient protection against a direct hit, but there is good lateral protection which can be improved by sandbag or concrete walls. It is centrally located and can be reached conveniently by all the occupants of the building. The floor directly above would be satisfactory but offers less overhead protection.

Area B should be avoided, since injury to columns abnormally exposed would lead to local collapse, resulting in heavy debris loads on the

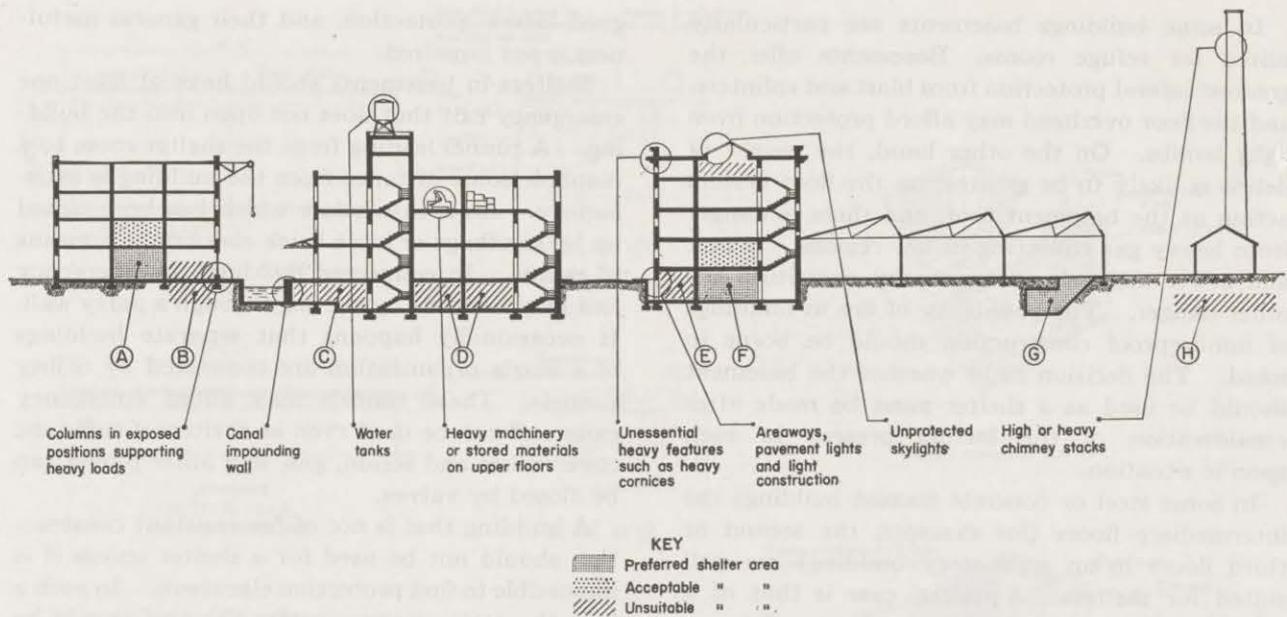


Figure 5.—Hazardous features affecting the location of shelters in buildings of an industrial area.

ground in that area. Hence it would be difficult to provide for emergency exits.

Area C is unsuitable for shelter because it would be flooded rapidly if the canal wall were injured, and because it would be liable to be crushed by the fall of the heavy water tank.

Area D is unsuitable because of its proximity to the base of the water tank and because it will rarely be economical to strengthen the roof of the shelter to withstand the fall of the heavy machinery on the upper floors.

Area E might be a dangerous location owing to the possibility of collapse of the heavy cornice and parapet, and the open areaway would give less than standard lateral protection.

In the case of area F, inflammable construction or the storage of inflammable material immediately under the skylight might present a fire hazard which could endanger the whole building. If proper precautions were taken with respect to fire protection, area F would be a good location for a shelter for the same reason as area A.

In the case of area G, the light construction of this building precludes the use of any section as an air-raid shelter. This situation necessitates the construction of a separate shelter, either under the building, as shown, or elsewhere.

Area H, at the base of a large chimney, is un-

suitable for the location of shelters, due to the possibility of large debris loads.

In general, it may be said that shelters within buildings can be constructed to give approximately the same degree of protection and convenience that can be afforded by external shelters. The choice of the best type of shelter for any given case must be governed by local conditions.

4. External Shelters

There may be many cases where the use of existing buildings for shelter purposes is impractical, inconvenient, or even impossible. Old buildings of poor construction or buildings vulnerable to fire or near important targets are worse than none at all.

External shelters may be designed to give adequate protection against near misses at reasonable cost. Experience indicates a preference for surface shelters. When subjected to earth movement a surface shelter moves with reasonable freedom and if rigidly constructed will withstand such movement without damage or injury to occupants, even when the bomb explodes close to the shelter. These shelters are also easier to keep dry.

Partly buried shelters have shown up well on tests, particularly if constructed of a material which can withstand reasonable movement without failure, such as corrugated metal. A minimum

depth below ground surface (of the bottom of the shelter) is desirable, though it may not be practicable to obtain necessary cover without a reasonable amount of excavation.

Shelters may be buried if space is not available for surface shelters and where soil conditions are favorable. Generally speaking, they should be avoided. Disadvantages to building shelters underground are the difficulties of drainage, the danger of bursting gas and water mains and the dampness which usually exists. Even when the

shelter and entrances are made watertight, a bomb explosion may cause cracks which might result in flooding of the shelter.

Designs of five shelters are shown in figures 6 to 10 inclusive. These designs are based on current practice for *splinterproof* structures. Tests indicate that these shelters will provide protection from the effects of 500-pound demolition bombs exploding not closer than 25 feet, including such effects as blast, splinters, earth shock, and debris from falling buildings.

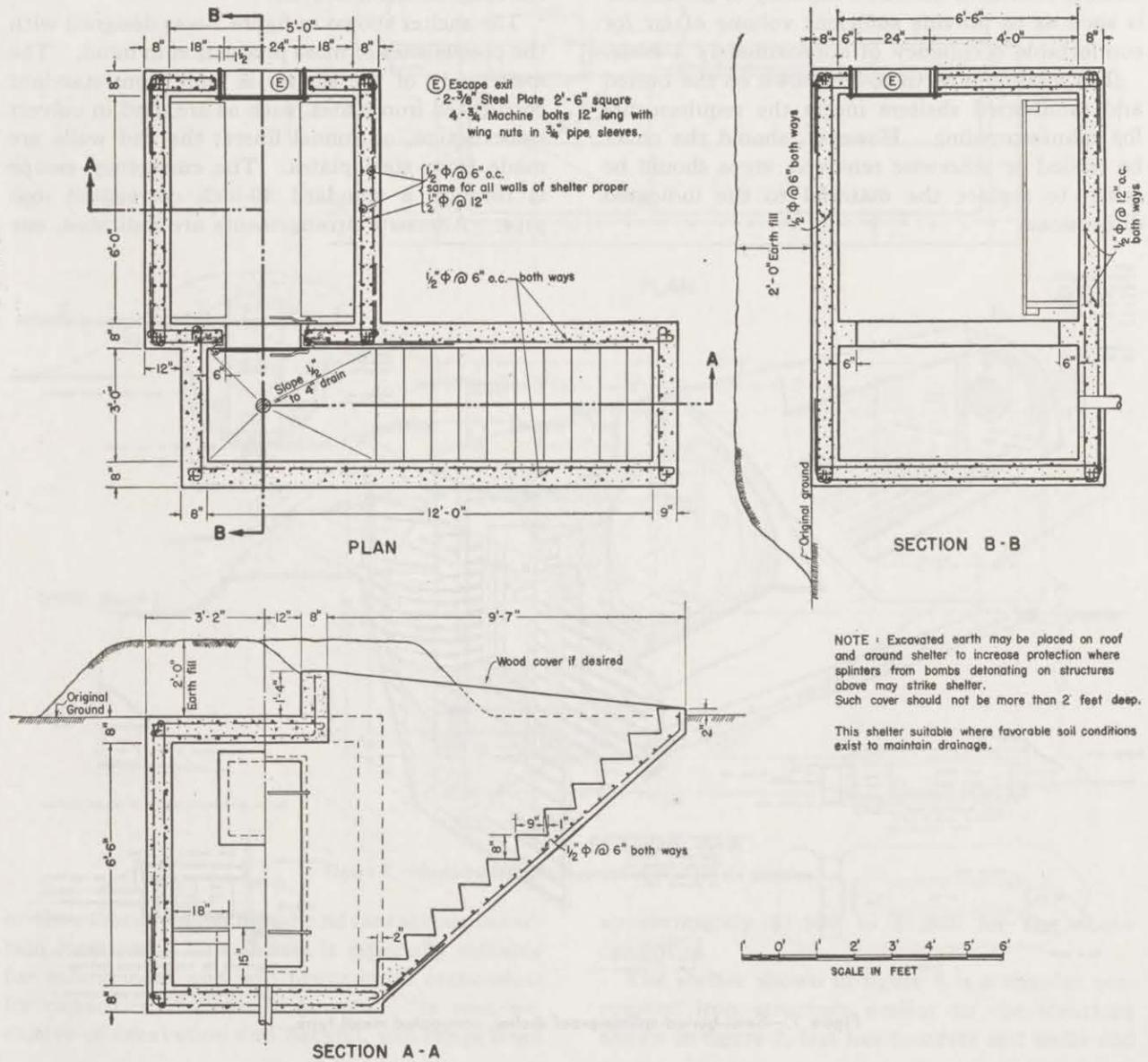


Figure 6.—Buried splinterproof shelter for six persons.

Experience in England suggests that communal shelters are more satisfactory than the family-type shelter because of the feeling of greater security in the presence of others, and because of the better facilities and accommodations that can be provided. However, it is realized that in some cases it may be necessary to construct family-type shelters. For that reason plans of several of this type are included.

All five of the shelters have a door which can be made gas-tight, and although no ventilation equipment is provided, the cubic capacity of the shelter is such as to provide sufficient volume of air for comfortable occupancy of approximately 1 hour.

The minimum earth cover shown on the buried and semiburied shelters meets the requirements for splinterproofing. However, should the cover be eroded or otherwise removed, steps should be taken to replace the material to the indicated dimensions.

All shelters are provided with an emergency exit, in addition to the main door, for egress in event the main entrance is blocked by debris or is otherwise unusable. Shovels, picks, or other excavating tools should be provided to assist in digging out.

The shelter shown in figure 6 is designed for use where it is not desired to interfere with the present use of the area by the construction of a semiburied or surface structure, and where ground water conditions permit such construction. Its cost is in the neighborhood of \$750.

The shelter shown in figure 7 was designed with the possibilities of mass production in mind. The main body of the shelter is built from standard corrugated iron plates, such as are used in culvert construction, or tunnel liners; the end walls are made from steel plates. The emergency escape is through a standard 30-inch corrugated iron pipe. Alternate arrangements are indicated, one

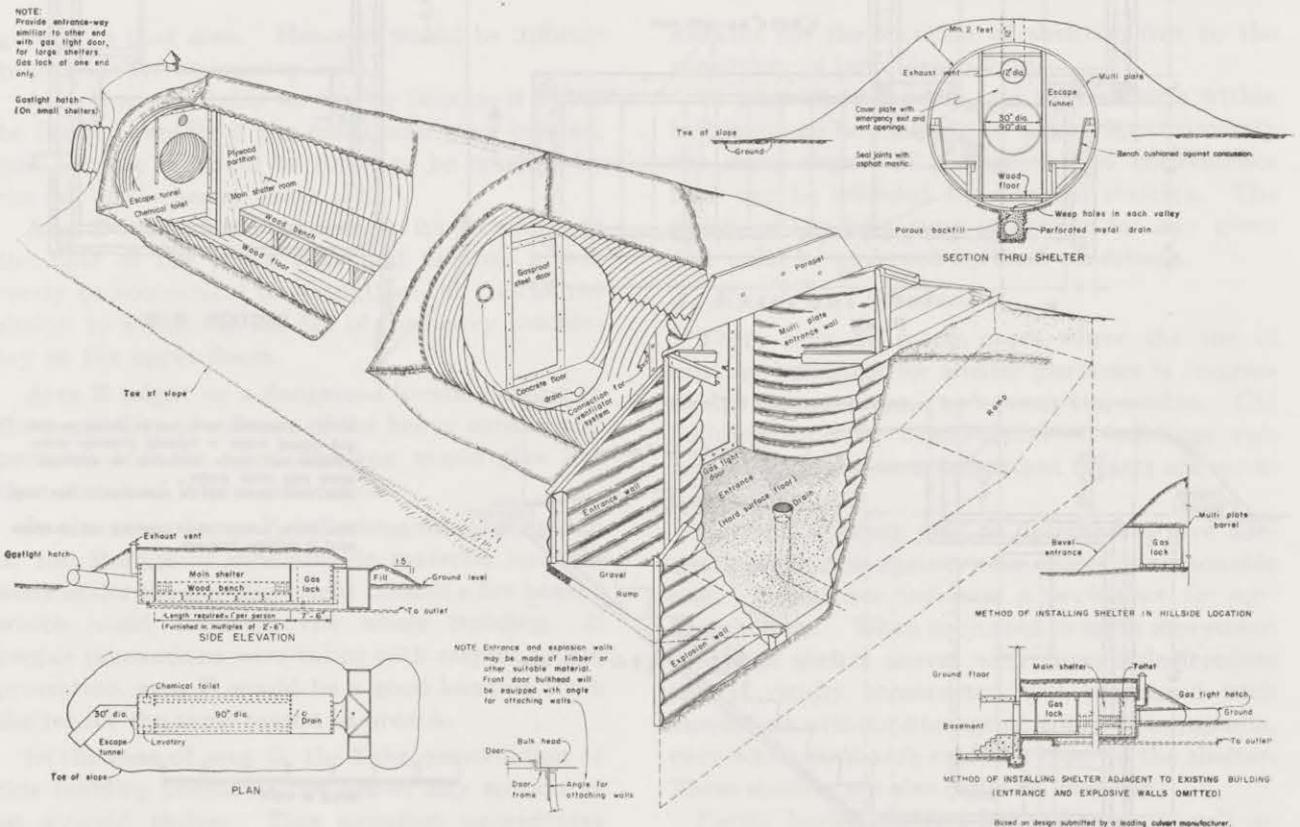


Figure 7.—Semi-buried splinterproof shelter, corrugated metal type.

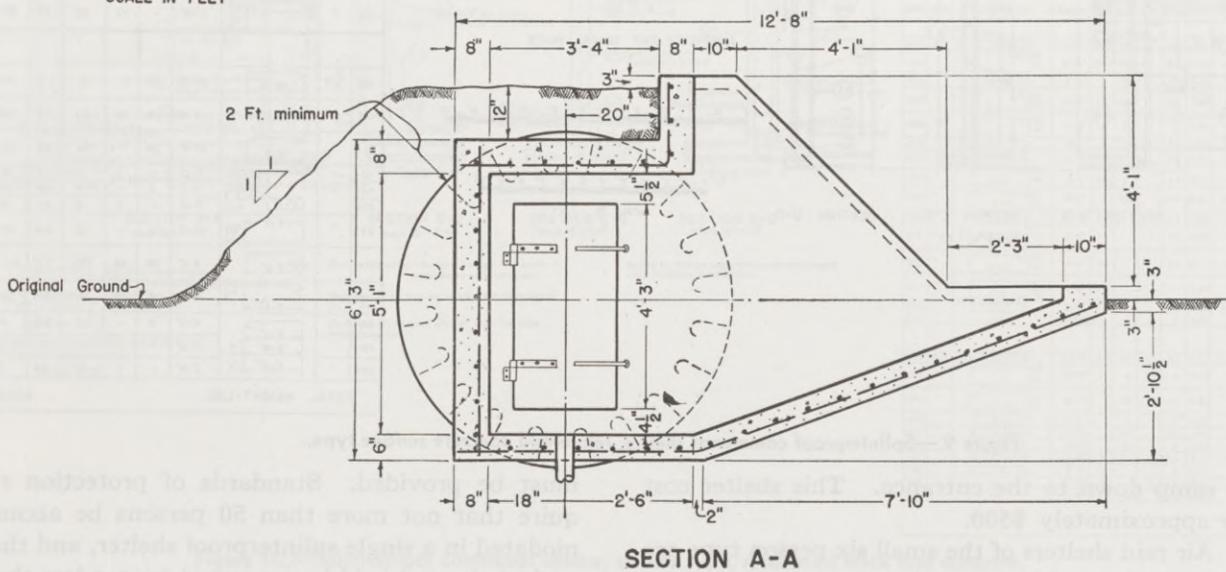
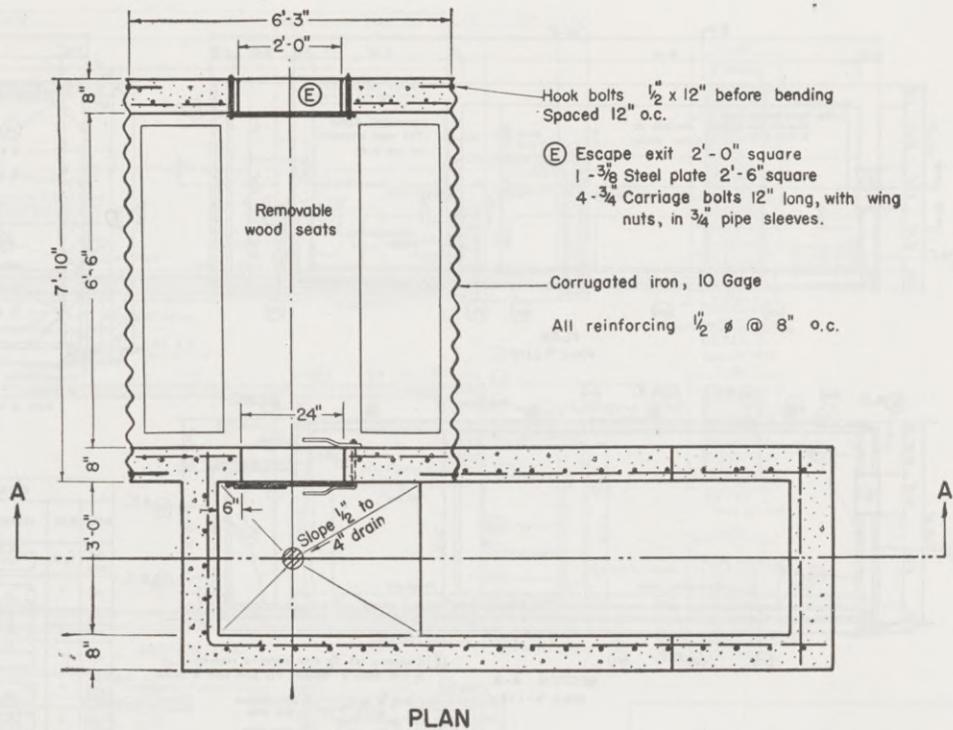


Figure 8.—Semi-buried splinterproof shelter for six persons.

or the other of which may be advantageous in certain locations. This shelter is especially suitable for enlargement and will prove quite economical for capacities of 25 to 50 persons. Its cost, exclusive of excavation and backfill, will range from

approximately \$1,500 to \$1,800 for the above capacities.

The shelter shown in figure 8 is a circular corrugated iron structure similar to the structure shown in figure 7, but has concrete end walls and

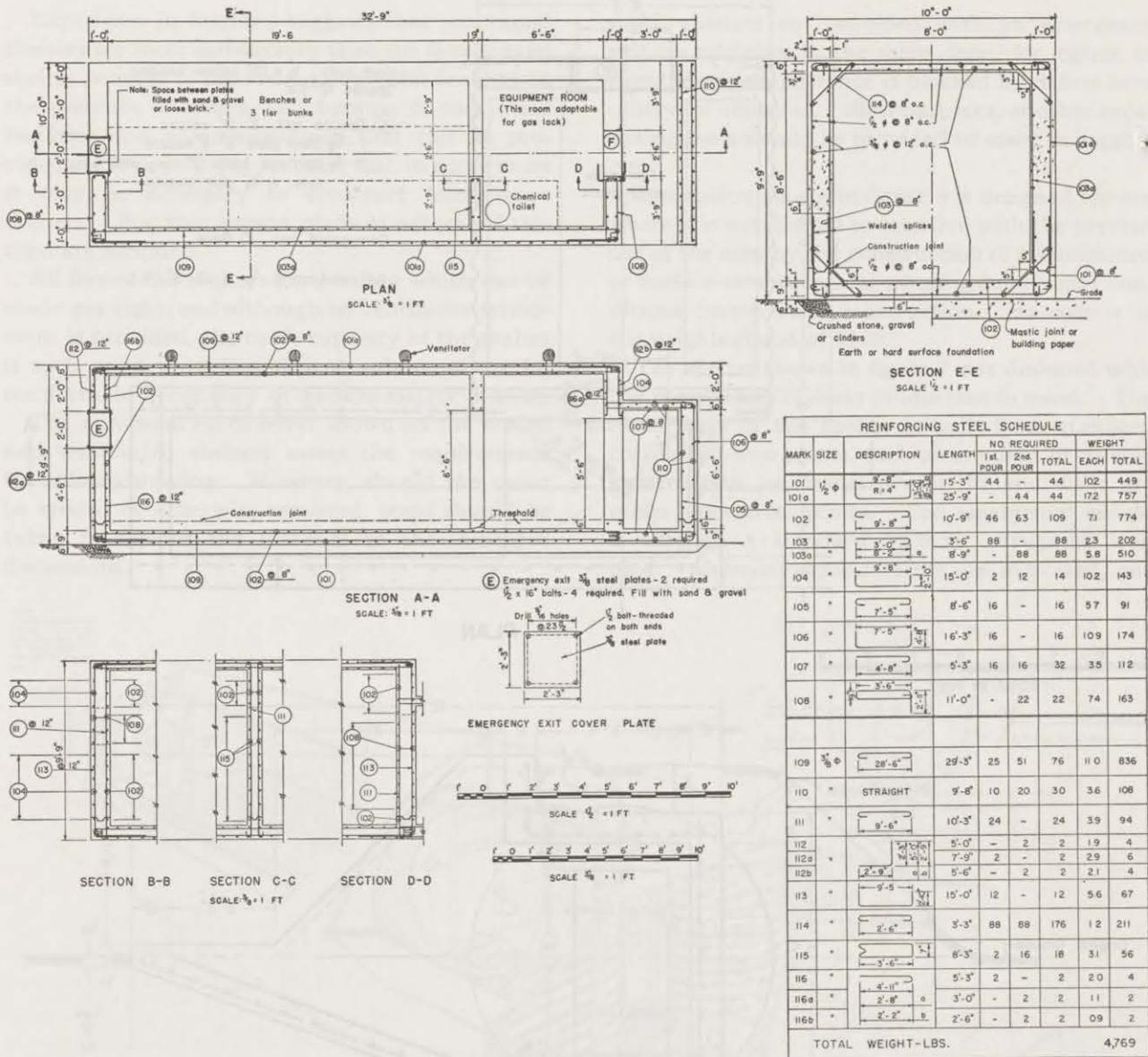


Figure 9.—Splinterproof communal shelter, reinforced concrete surface type.

a ramp down to the entrance. This shelter cost is approximately \$500.

Air raid shelters of the small six-person type are suitable for residences or in areas that are relatively sparsely populated.

These shelters are not practical, however, where large numbers of people congregate, such as in apartment houses, factories, office buildings, etc. In most such cases, shelter can be provided within the buildings, as has been mentioned previously, but in a good many instances external shelters

must be provided. Standards of protection require that not more than 50 persons be accommodated in a single splinterproof shelter, and that such shelters should be separated by not less than 25 feet.

The six-person shelter shown in figure 6 may be extended to accommodate larger numbers, say 10 or 12. Shelters shown in figures 7 and 8 are particularly capable of enlargement. The length of each structure should be increased to allow 6 square feet of floor space for each additional

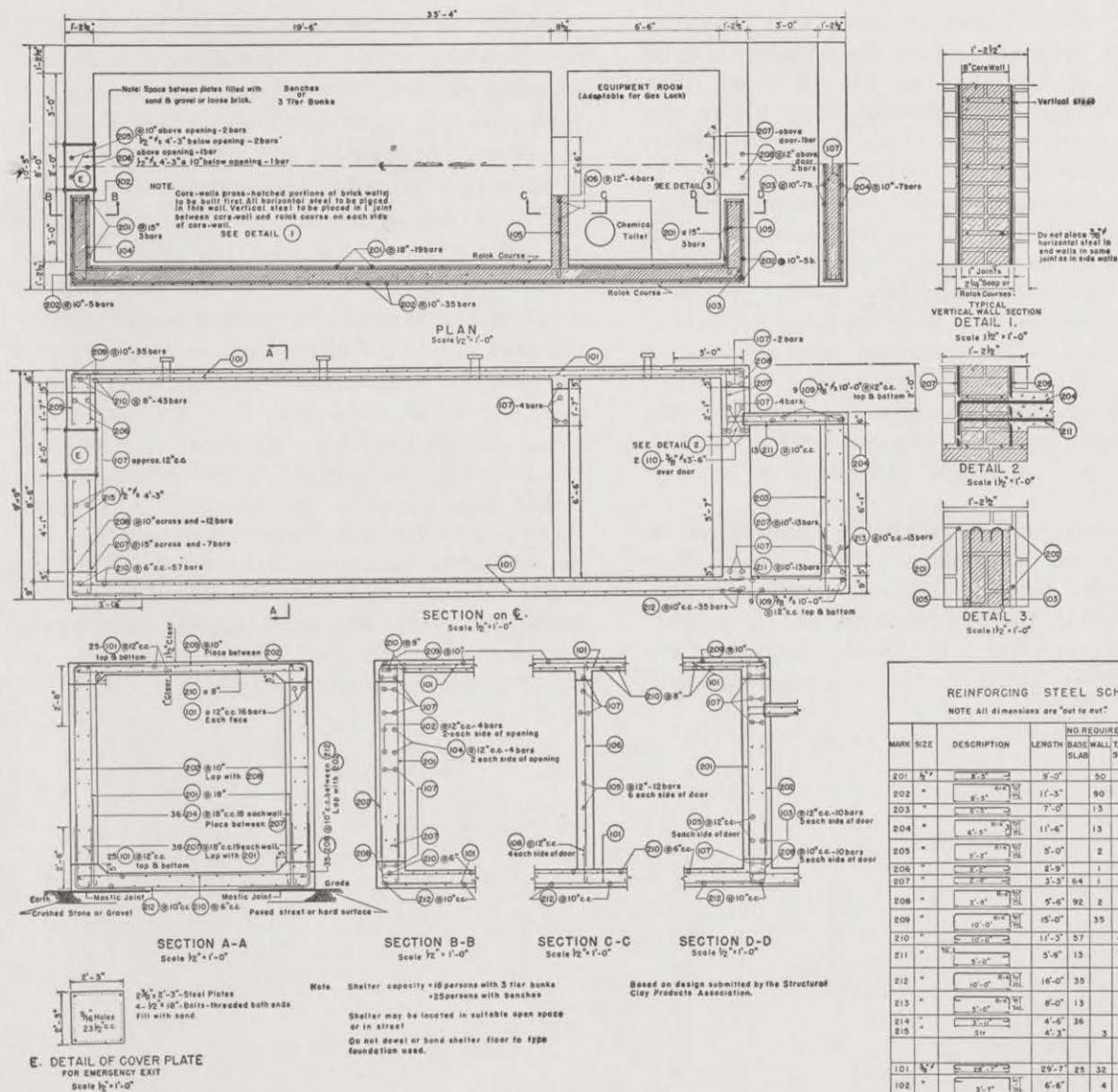


Figure 10.—Splinterproof communal shelter, surface type, reinforced brick and concrete.

person accommodated, and provision should be made for ventilating equipment and chemical toilets.

Figures 9 and 10 indicate a shelter arrangement whereby three-tier bunks may be installed in lieu of benches. The capacity of the shelter will be reduced somewhat if sleeping facilities are pro-

vided. The approximate cost of these shelters is \$1,800 and \$1,600, respectively. Any further accommodations, such as provisions for entertainment and recreation, may be of great value in maintaining morale and spirit, and should be provided when possible.

Tunnels have been constructed to advantage in

certain localities where conditions were especially favorable, but must be quite deep if safety is to be assured. (See table 2, p. 4.) In most cities water will become a problem long before the required depth for safety is reached, and the earth will doubtless require extensive timbering. If tunnels are used, however, frequent independent exits should be provided, and particular protection given against gas. Tunnels running under or parallel to streets should have several entrances located some distance apart to facilitate serving each large area, in case part of the tunnel is blocked. The effect of blast caused by a direct hit in a tunnel may be minimized by making the tunnel zigzag or crenelated in plan or by providing curtain walls, although such a form occupies more space.

In London certain portions of the subway system are being used as shelters. The subways there are tunneled through clay and usually are deep enough, about 150 feet below ground, to provide adequate protection. In general, subways in the United States could not be employed as bomb-

resistant shelters owing to the shallow depth of cover, which would be insufficient protection against a direct hit of a bomb.

Shelters may be designed with a view to use in peacetime. Multi-story garages, the lower floors of which may be used for air raid shelters in time of war, have been suggested. Shelters near factories are expected to have a peacetime use as storage sheds. Refuges near banks and in financial districts may do service as vaults or depositories for precious metals. Shelters may be designed with the idea that buildings will be built later on top of them, the shelter serving as a basement. All these schemes have been advanced so that some benefit might be realized in peacetime for the rather large cost of construction of shelters. However, provision for peacetime use should not be permitted to decrease the efficiency of the shelter as such, and materials stored in shelters should be easily and quickly removable, or to decrease materially the volume of shelter construction because of increased cost.