CIVIL ENGINEERING IN A NUCLEAR ENVIRONMENT

Office of Civil Defense
Washington, D.C.

June 1964

T- 2006 (C)

TR-26

Civil Engineering in a Nuclear Environment

A compilation of papers presented at the Environmental Engineering Conference, Atlanta, Georgia, on February 26, 1963, sponsored by ASCE in cooperation with the Office of Civil Defense.

DEPARTMENT OF DEFENSE OFFICE OF CIVIL DEFENSE

JUNE 1964

70

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CONTENTS

CIVIL ENGINEERING IN A NUCLEAR ENVIRONMENT

I. INTRODUCTION:

Because the most powerful weapon produced by man is the thermonuclear bomb, there prevails the widespread opinion among a substantial portion of our population that its destructive power is virtually infinite and, consequently, there can be no protection against it. Although this is contrary to the informed opinions of experts, nevertheless, most people continue to believe that survival would be virtuallv impossible. Of those who believe in the probability of survival, many are dubious of the value of life afterwards. These beliefs stem mainly from ignorance. The prevalence of such beliefs--hence a national attitude--constitutes a very significant weakness in our continuing effort to insure freedom and democracy through strength.

Military preparedness in the nuclear and space age must include the defensive protection of our people and cities. The feasibility of such protection must be thoroughly studied and understood by those elements of community whose profession best qualifies them to make such determinations. High in this category are the architects and engineers whose primary pursuit is to provide for the life environment of man. They must assume the burden of leadership in convincing clients, indeed the entire community, that reasonable provisions for a nuclear war environment are probably no more expensive than air conditioning, art, life insurance, modern schools, and all the sophisticated consumer goods which today constitute the so-called necessities of life. This can be done if, the architects and engineers first master the present state of the art and then dedicate themselves to its improvement by application in their daily practice.

The Environmental Engineering Conference sponsored by the American Society of Civil Engineers in cooperation with the American Public Works Association and the American Water Works Association, held in Atlanta, Georgia, in February 1963, acknowledged once again that the containment or mitigation of a nuclear war environment is one of the responsibilities assigned by society to the architects and engineers.

Reproduced in their entirety in this pamphlet are the papers presented at the Environmental Engineering Conference by leading engineers and scientists. These papers discuss principal aspects of nuclear weapon phenomenology and protection technology. When informed and dedicated engineers, in the short space of a few papers, can demonstrate the feasibility of protection, then the practicing architects and engineers throughout the country can and should undertake the task of providing for the nuclear warfare environment, much as they do for all other natural and man-made environments. This, no doubt, they will do if given the analytical tools. How fast and to what extent these developments take place depends largely on the emphasis and support they receive from the American people. But the people cannot support that which they do not understand--this understanding is a logical task for architects and engineers.

II. HIGHLIGHTS OF THE KEYNOTE ADDRESS by Steuart L. Pittman, Assistant Secretary of Defense (Civil Defense)

One of the most promising and least understood elements of the current federal civil defense program is the mobilization of the skills and ingenuity of the professional community of architects and engineers.

It is now a firmly established requirement of our national security and overall defense planning that there be a steady build-up of civilian protective measures which will maximize survival under nuclear attack.

A great deal can be done, within the limits of a moderate, inexpensive civil defense program, which would significantly reduce our national vulnerability to nuclear attack.

It takes some orientation of technical background of architects and engineers to make the most effective contribution — it takes development and updating of technical competence in a new specialty, namely, nuclear protection.

My office in the Defense Department places a high priority on continuous improvement of the technical base for civil defense pro-ided by the architectural and engineering professions.

I believe that the development of architectural and engineering know-how to its full potential to meet the problems of civil defense can produce more unsubsidized shelter space, both in existing buildings and new construction, than the injection of large sums of federal money is likely to produce.

The Office of Civil Defense is conducting an expanding research and development program on the design and use of protective structures. Of particular significance is the recent opening of the Protective Structures Development Center at Fort Belvoir, Virginia. It will be a place where engineers of government, the military and industry can try out ideas under development. It will be a clearing house of information in this country and abroad on recent developments in the structure and equipment needed for nuclear protection.

We have been working with schools of architecture and engineering to develop the curriculum and course material for long-term development of the professions.

Summer institutes are being conducted each summer for the faculty members of the professional schools.

Several thousand practicing professionals have completed the two-week shelter analysis courses.

We are developing a nationwide service to apply computer techniques to lower the costs of analyzing building designs from the standpoint of protective features.

There will be increasing opportunities for civil engineers to use their knowledge of nuclear protection in the programs for federal buildings, for federal financing of new shelter development, for emergency broadcasting stations, for emergency operating centers, and in work with industrial enterprises.

Although we are concentrating on the fallout problem for cost reasons, we know that a substantial amount of fringe blast protection can be picked up at no great increase over the cost of fallout protection. We also know that improved fire protection can be associated with fallout shelters at little or no extra cost.

Whether or not it is practical, and what it would cost, to provide this minimal protection for the entire population cannot be intelligently debated without first taking inventory of the structural protection which already exists. This job has been completed. I am sure most of you are familiar with the shelter survey which we have conducted.

I see no reason why the average American citizen should spend his nights worrying about the possibility of our military force failing in its deterrent mission to prevent nuclear attack on his home. The initiative and the planning and the farsightedness must come from a broad base of leadership and professional competence. Given this, the great majority of Americans will respond, without tortured soul-searching, to a clear obligation to do what is necessary for the protection of their family and neighborhood. More important, they will do what is necessary to contribute to the defensive strength of their country.

III. ENGINEERING IN A BLAST ENVIRONMENT

DESIGN OF SIMPLE STRUCTURES FOR MODERATE LEVELS OF BLAST RESISTANCE

PART A

by Merit P. White
University of Massachusetts

INTRODUCTION

This paper treats the analysis and the design of simple types of structures--boxes, arches, etc.--subjected to dynamic loadings due to blast pressures up to eight or ten atmospheres (100-150 psi) produced by nuclear weapons of megaton size or larger. The same methods can be used for structures of more complex form, for larger pressures, and for smaller weapons than mentioned above. However, the difficulty of achieving a solution is then greater and the reliability of the analysis is less.

The accomplishment of a program of blast protection consists of the following steps:

1. Determination of appropriate hardnesses or levels of resistance
2. Choice of shelter locations, configurations and materials
3. Determination of dynamic loading patterns on shelters
4. Structural design of shelters to resist these loadings
5. Design of appurtenances, such as doors, blast closures for air vents, antennas, etc.
6. Consideration of hazards other than blast.

Particular reference should be made to the following publications:

1. "Effects of Nuclear Weapons" 1962 Edition (U. S. Government Printing Office, Washington 25, D. C., $3.00)

2. "Design of Structures To Resist Nuclear Weapons Effects" ASCE Manual of Engineering Practice No. 42, 1961 (American Society of Civil Engineers, Engineering Center, New York City, $4.00)

HARDNESS OR LEVELS OF RESISTANCE

The determination of the level or levels of resistance appropriate to a given situation should be the result of an analysis comparing the investment in a hardening program expressed in terms of money, materials, labor and the effect on the local or national economy (depending on the scope of the program) with the return from the program in terms of survival of persons, institutions and the nation. This analysis must take account of a spectrum of probabilities: of conflict, of possible and probable enemy strategies, of the enemy's arsenal of weapons and of his delivery capabilities not only in the present but over a reasonable future period. In view of the numerous uncertainties entering such a study, precise answers cannot be expected and complicated analytical techniques are not needed.

However, some attempt at reading the future is justified, in preference to making arbitrary decisions based on intuition or "judgment."

It can be expected that for normal civilian protection--except for particularly important individuals or services--the optimum hardness of protective structures will lie in the range of 15 to 150 psi.

CONFIGURATION, LOCATION AND MATERIAL

The choice of shape, size, and material of a protective structure, and whether buried or above ground will depend on cost, reflecting design requirements and local conditions. Boxes, arches and domes are possible shapes, with or without inner supporting walls or columns. Unless required on account of dual use of a shelter area, long unsupported spans will be uneconomical, especially at the higher levels of hardness. Except for relatively low hardness levels, below-ground construction will be more economical than above-ground if permitted by local conditions. Structures partly below ground and overmounded with earth are more resistant than when exposed.

Considerable choice of materials exists. Reinforced concrete and structural steel--or combinations of these--can be used either above or below ground. Even systems that are intrinsically very weak, such as corrugated steel arches or domes, are known to have considerable strength when buried. It can be expected that various other materials--wood, plastic sandwich panels (especially in arch form), etc.--will be satisfactory in buried construction.

DYNAMIC LOADING PATTERNS

The loading imposed on a structure by blast is dynamic, that is, a function of time. The intensity and the time variation of the loading depend on the shape and location of the structure as well as on the blast overpressure and the duration of the blast pulse. In general, the more the structure interferes with the motion of the shock front and with the high velocity wind behind the front, the larger are the loads imposed on the structure.

Before discussing the loading cycle to which any particular structure may be subjected, it is convenient to consider the state of affairs that exists a few hundred milliseconds after a nuclear explosion on or near the surface of the earth. Since we are concerned with hardnesses up to only eight or ten atmospheres, we have to deal with blast phenomena that occur more than one half mile from a 1-MT weapon and at times more than 0.5 seconds after its detonation. (For 1-KT divide distances and times by 10; for 1000-MT multiply by 10.)

At this time, then, an approximate hemisphere of atmosphere having its center of curvature at ground zero (GZ) has been affected mechanically by the explosion. At the curved boundary of the hemisphere there is either a shock front (a sharp discontinuity of pressure, density and air velocity) or at least very large gradients of these quantities. Within the disturbed hemisphere these quantities diminish toward the center. The shock front itself travels outward at a speed dependent on the peak pressure immediately behind it. As the hemisphere grows the peak pressure decreases and the shock speed drops, approaching the speed of sound at great distances. The velocity of the air at any point behind the shock front is a function of its pressure history. At a point on the ground with no nearby obstruction to the shock front and to the afterwind a flush pressure gauge will ideally show a rapid or instantaneous rise to the peak pressure, followed by a steady fall to and below atmospheric (zero overpressure) and then a gradual return to atmospheric. An air velocity gauge recording the flow component in the direction from ground zero will ideally show a very similar record, the chief difference being that the time to reversal of air velocity is longer than the time to zero overpressure. Frequently, this difference is ignored and the overpressure positive phase duration is used for the air velocity--or for the dynamic pressure, which depends on it-- as well. Records of overpressure (p), air velocity (v) and of the dynamic pressure ($q = p\ v^2/2$, where p is air density) from nuclear explosions are almost always more complicated than this with a number of superimposed wiggles. For design the ideal form is generally used.

There is a theoretical relationship between overpressure and dynamic pressure. However, for the overpressure levels considered here, the observed dynamic pressures are larger than the theoretical and should be basis for design. Table I gives for a 20-MT weapon burst on or near the ground, values of peak overpressure (p), overpressure positive phase duration (T), dynamic pressure (q), and shock-front velocity (U), at various distances from ground zero.

TABLE I

Certain Blast Parameters for 20-MT Ground Burst

D (ft)	p (psi)	q (psi)	T (sec)	U (ft/sec)
22,000	15	6	4.2	1600
17,000	25	25	3.5	1800
12,000	50	130	2.4	2200
9,000	100	220	2.2	2900
7,500	150	300	2.3	3600

BURIED STRUCTURES

As stated above, the load experienced by a structure exposed to blast depends on the extent to which it interferes with the movement of the shock front and of the afterwind. The least interference is produced by a buried structure with its roof flush with the ground or covered by earth unmounded. In this case, the pattern of vertical loads on the surface is, of course, exactly that of the variation of the overpressure at that point. The fraction of this load that reaches the roof of the buried structure depends in an undetermined manner on the ratio of depth of burial to span and on the flexibility of the structure (decreasing with an increase in either quantity). The nature and the degree of compaction of the covering medium are also significant. A depth of burial equal to the minimum span of the roof is believed to reduce the roof loading by a factor of at least 2 when deflections of a few percent of the span take place. It must be emphasized, however, that the evidence on this point is scanty.

The unsymmetrical loading of short duration that exists while the shock front itself is moving across the earth cover of a buried structure is generally unimportant. The most likely exception is the case of an arch roof with very little earth cover and with the shock moving at right angles to the arch axis.

The vertical stresses in the earth that are directly induced by surface pressure are associated with stresses in all other directions as well. Thus, the side walls of a buried structure are subjected to pressures that are related to the roof and floor pressures but are normally much smaller. In design, it is usually assumed that the ratio between the two is dependent only on the nature of the surrounding medium. Some typical design values of the ratio are given in Table II.

TABLE II

RATIO OF WALL TO ROOF PRESSURES ON BURIED STRUCTURES UNDER BLAST LOADS

Soil	P_h/P_v
Dry sand or gravel	1/4
Dry clay or silt	1/2
Soft clay	3/4
Saturated soil	1.0

ABOVEGROUND STRUCTURES

Aboveground structures interfere in two ways with the shock and afterwind associated with an explosion:

1. A shock front impinging against an obstruction is reflected. This exerts on the obstruction a pressure that may be several times that of the incident wave.

2. The wind along the surface away from ground zero within the region enclosed by the shock front exerts pressures on an obstruction. These are proportional to q, the dynamic pressure associated with the air speed.

It is partly in consequence of these effects that aboveground protective structures become relatively less and less economical with increasing overpressure.

In the analysis of a box-like aboveground structure one side is assumed to face ground zero and to be loaded face-on by the shock. The dynamic pattern of loads acting on that side is determined and is used as basis for calculating the response or for finding the resistance needed by that side. Of course, each side in turn must be assumed to face ground zero.

The loading on the rear wall is also found and the difference between the front and rear loadings, as function of time, is the basis for predicting the response of the whole structure or for finding the resistance that it needs.

The roof and the foundation are subjected to vertical dynamic loadings that are very nearly equal to the overpressure of the blast wave multiplied by the plan area of the structure.

Figure 1 shows the average front and rear wall pressures acting on a box-like structure. The total loads are found by multiplying the ordinates shown here by the projected frontal area. On the front face the pressure is initially equal to the reflected pressure p_r due to reflection of the shock overpressure p. In units of atmospheres,

$$p_r = 2p\left(\frac{7 + 4p}{7 + p}\right) \tag{1}$$

It can be seen that p_r ranges from 2p to 8p depending on the magnitude of p.

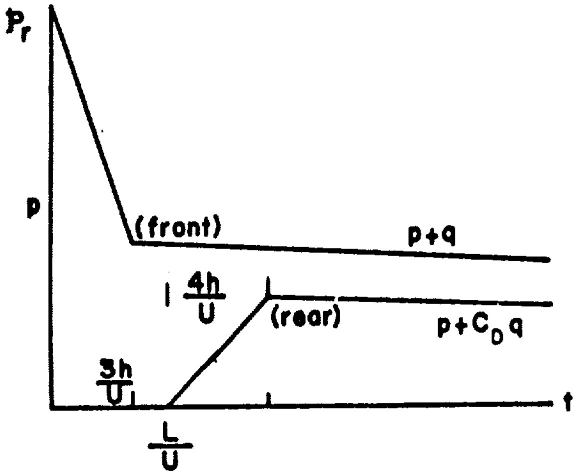

Figure 1 Blast Loading of Box

The large reflected pressure on the front face leaks off rapidly and very quickly reaches a pseudo-steady value p + q (overpressure plus dynamic pressure) which decays with time throughout the rest of the positive phase. The time required to reach this pseudo-steady state, the "clearing time", is usually assumed to equal 3h/U where h is either the height or the half-width of the front face--whichever is smaller--and U is the shock front velocity that is given in Table I. Some designers prefer to use the velocity of sound associated with the pressure p_r instead of U. This is perhaps more logical but the numerical difference is small compared to the other uncertainties in the whole analysis. As will be discussed later, for shelters it is not usually necessary to consider the decrease in the pseudo-steady pressure p + q during the interval following the clearing phase and this quantity can be taken as constant.

On the rear face, loading does not begin until the shock has moved the length of the structure--the distance L--so that rear face loading starts at time L/U (Fig. 1). The rate of load buildup is somewhat slower than the rate of front face leakage so that a time usually taken as 4h/U elapses between the start and the completion of rear wall pressure buildup. The final pseudo-steady pressure on the rear wall is $p + C_D q$, where the drag coefficient C_D is negative and depends on the dynamic pressure level as indicated in Table III.

TABLE III

DRAG COEFFICIENT ON REAR FACE OF BOX

q(psi)	C_D
15	-0.4
20 - 50	-0.3
60 - 300	-0.2

The loadings on other shapes such as cylinders, arches and domes can be determined in somewhat similar fashion described in the references cited above (see page A1). In general, the loads on such shapes are smaller than on boxes on account of a) gradual shock front reflection, since the shock does not strike a plane face face-on, and b) front face drag coefficients that are smaller than unity due to streamlining.

MOUNDED STRUCTURES

Aboveground structures can be strengthened by mounding earth on sides and roof. The reflected and dynamic pressures are smaller for sloping than for vertical sides and, furthermore, only a fraction of the side-slope loadings ever reach the structure within, the rest being transmitted directly to the earth beneath the mound. Another effect of mounding is to smooth off the spike of the diffraction (reflected pressure) loading before it can affect the inner structure. Finally the earth that surrounds the structure furnishes considerable inertial and structural resistance against lateral displacement.

For design purposes the loads that are applied to a mound of trapezoidal cross-section are about as given in Table IV. As discussed below, these are recommended for use only for small thickness of cover.

TABLE IV

BLAST LOADING ON TRAPEZOIDAL MOUNDS

Surface	Slope 1:2	1:3	1:4
Front	p + 0.6 q	p + 0.5 q	p + 0.3 q
Rear	p - 0.4 q	p - 0.4 q	p - 0.4 q
Flat top or side	p	p	p

A conservative analysis would be based on the assumption that the externally applied load is transmitted unchanged to any enclosed structure. However, if the roof and sides of the inner structure are able to deflect, a significant part of the outer load may be resisted by the earthen arch that surrounds it. Very little information exists as to the amount of this participation and the analyst or designer simply has to use his best judgment. When the cover depth equals the width of the inner structure a reduction factor of 2 does not seem unreasonable. In this case, since the average of the pressures on all sides and on the top of the mound is approximately equal to the overpressure p, it is suggested that the reduction factor be applied to the overpressure p and the resulting loading be applied to the inner structure as a uniform hydrostatic pressure on all sides. Only if the cover is small, say less than half the structural span is it necessary to consider the contribution of the dynamic pressure on the sloping sides, and then only if the side slopes extend above the edges of the structure.

The writer wishes to emphasize the fact that the remarks contained in the preceding paragraphs represent his best guesses at the time of writing but that there is no experimental or theoretical evidence supporting them.

STRUCTURAL DESIGN

Structural design means selecting a structural system (geometry and materials) and proportioning its components to resist adequately the loadings expected to be applied to it. "Adequate" in conventional design for static forces involves introducing a load factor or a safety factor between the expected loading and the loading corresponding to initiation of damage (elastic design) or to collapse (limit design). In either case, the structure normally remains elastic and undamaged under working loads, except possibly at unimportant local points such as rivets, etc.

In designing for blast loads the attitude of the designer is somewhat different in that he normally designs with a certain permissible level of damage in mind. There are two reasons for this:

1. Blast loading is conceived to be a one-time loading and

2. Frequently, energy absorption rather than simply furnishing a given level of resistance is the essential function of the structure.

For most structures the energy that can be absorbed elastically (without permanent deformation or damage) is a very small proportion say one per cent - of the energy that can be absorbed plastically before collapse.

Some explanation of the first reason given above should be made. It has been found for most blast resistant structures designed for a given level of damage under a given overpressure, that a small decrease in overpressure - say 5 per cent - causes a very much greater decrease in damage expressed as residual deflection. Consequently, a large number of repetitions - say 5 or 10 - at the small loading is required to duplicate the damage due to single application of full load. Thus, failure might typically require one application at full load, two at 98 per cent or 10 at 95 per cent, etc. Even under an attack or attacks with many weapons the probability that the two worst loadings will lie, say, between 98 per cent and 100 per cent of the design load is remote, except for exceedingly resistant construction.

The designer of blast resistant structures uses the methods of limit design, i.e., plastic analysis, but with consideration of time effects and the inertia of the structure, and allows deflections beyond the elastic limit.

When a structure is caused to deform slowly there is always equilibrium between the applied loading and the internal forces within the structure. For a loading larger than this the excess load causes acceleration, that is, it is in equilibrium with the inertia or d'Alembert forces. In other words, the difference between the actual dynamic loading at any instant and the static loading that corresponds to the state of deformation at that instant is in equilibrium with the inertial resistance of the system. This statement must be modified to some extent since (a) the internal resistance of a structure to deformation increases somewhat if the deformation is rapid instead of slow and (b) the deformed shapes may be somewhat different dynamically and statically. No allowance is normally made for the second effect; sometimes the first effect is allowed for by assuming the dynamic resistance to be equal to the static resistance increased by 10 - 20 per cent. For a system with one degree of freedom - the normal situation - one can write the following equation of motion:

$$M\, d^2x/dt^2 = A\left[p\,(t) - r\,(x)\right] \qquad (2)$$

where x = deflection (of a characteristic point of the structure or element).

M = apparent mass of the structure or element.

A = effective area on which the blast loading acts.

p (t) = average pressure loading, a function of time; it may be due to a combination of overpressure, reflected pressure and dynamic pressure, according to the situation, as was discussed under Dynamic Loading Patterns.

r (x) = the internal resistance to deformation, a function of the deflection x, expressed as a pressure having the same distribution as p.

The resistance r (x) is determined analytically or experimentally as the distributed pressure required to produce a deflection x, possibly increased by 10 - 20 per cent to allow for the effect of rapid deformation.

Normally, r (x) contains an elastic and a plastic phase with some kind of transition state between. The result is a more or less smooth function of x, as shown in Fig. 2. It is convenient and usually accurate enough to replace this function by two straight lines, one of them horizontal, as shown in Fig. 2.

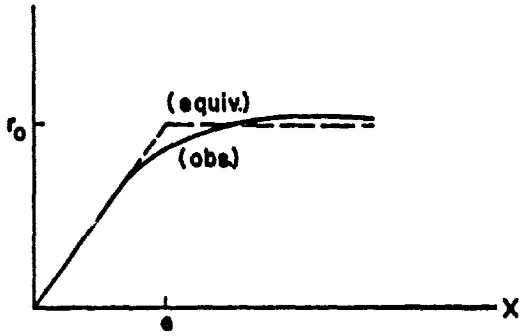

Figure 2 Resistance Deflection Relationship

The elastic line may be found by a normal elastic analysis of the structure loaded by pressure r having the same distribution as the blast load. The horizontal, plastic phase, line is located by means of a normal plastic analysis that determines the collapse load.

The meaning of "apparent mass" M and "effective areas" A must be considered. Ordinarily, a structure or element does not distort as a rigid, non-rotating body and different parts of it have different accelerations, velocities and displacements. The "effective mass" M is most easily defined in terms of the kinetic energy of the system. If the point where the deflection x is measured is assumed to move with a velocity V the velocities of all other points of the system can be found in terms of V, that is, as known multiples of V, according to the geometry of the structure. The total kinetic energy of the system is then calculated, from knowledge of its geometry and the distribution of mass, and equals a constant multiplied by V^2. This kinetic energy is equated to the kinetic energy of the equivalent system, i.e., $MV^2/2$, thus defining M, the apparent mass. For example, consider a simply supported uniform beam of length L and mass/length m. For deformations beyond the elastic limit the beam will deform in a pattern consisting of two straight lines each of length L/2 and with a hinge at the center, as shown in Fig. 3. Assuming the midpoint to have a velocity V, the kinetic energy can be calculated to be

$$KE = 2\ (I\omega^2/2) = 2\left[(1/2)\ (1/3)\ m\ (L/2)^3\ (2V/L)^2\right] = (1/2)\ (mL/3)V^2$$

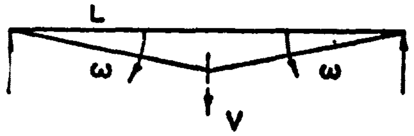

Figure 3 Deflection of Beam with Plastic Hinge

Therefore, in this case the apparent mass of the beam is mL/3, or one-third its actual mass.

By a somewhat similar approach the effective area can be found. In this case the work done by the pressure p (or by the static resistance r) while the system deflects by a small amount x is equated to the work done by the same p (or r) acting on a rigid nonrotating area A also moving through the distance x. Taking the beam of Fig. 3 as an example and assuming it to be loaded by a pressure p acting over the length L and on a constant width b, the work done by p is

$$\text{Work} = p\ b\ L\ x/2$$

Therefore, the effective area A equals bL/2 in this case.

The solution of Eq. 2 is somewhat awkward on account of the discontinuities in both the functions p(t) and r(x). Stepwise integration is quite possible and has been often used, but is time consuming. Moreover, such a solution can be used only for analysis, that is for finding the response of a known structure or element to a given loading. The inverse operation is the one normally required - determining the resistance that a given structure must have to withstand a given loading with a specified degree of damage. Utilization of Eq. 2 for this purpose requires repeated calculations with assumed values of resistance until the correct one is found.

For these reasons and because the level of accuracy that can be maintained in the whole operation is not high, various approximations may be introduced to permit direct design. One of these has been referred to above, the assumption that after the diffraction loading phase (if any) is completed the succeeding load - depending on overpressure or on a combination of overpressure and dynamic pressure - can be considered constant. For this assumption to be valid it is necessary that the reaction time of the structure, the time required for it to respond to the applied loads and to reach equilibrium, be short compared to the positive phase duration of the overpressure, so that the change in the loading is small during the reaction time. This is the case for most shelter structures exposed to megaton size weapons.

Another useful simplifying assumption is that if there is a diffraction loading (due to reflected pressure on an exposed element) its duration is short compared with the reaction time of the structure and it may be replaced by an equal impulse. This assumption is less justified than the first. However, it is a conservative assumption and if not satisfied, the resulting design is somewhat stronger than necessary.

Consequently, for design, the loading p(t) and the resistance r(x) can usually be represented as in Fig. 4. In this figure, p_o is the constant value of the pressure loading and I is the impulse per unit area exerted on the structure during the diffraction phase if there is one. (In Fig. 4 it is the area of the diffraction triangle above p_o.) The constant plastic resistance per unit area is r_o, and e is a kind of elastic limit, actually the deflection defined by extensions of the elastic resistance line and the constant plastic resistance. The units of p and of r are the same and must be consistent with the units of the remaining terms of Eq. 2, i.e., pA/M must have the units of acceleration.

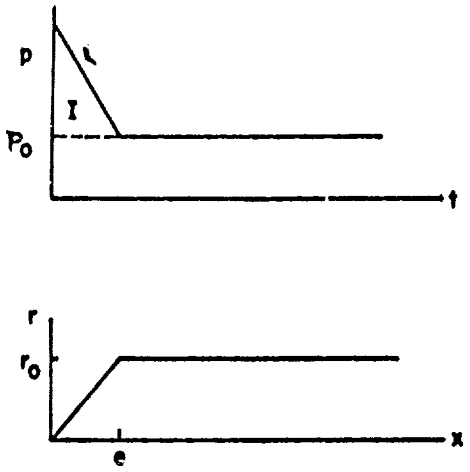

Figure 4 Idealized Loading and Resistance Functions

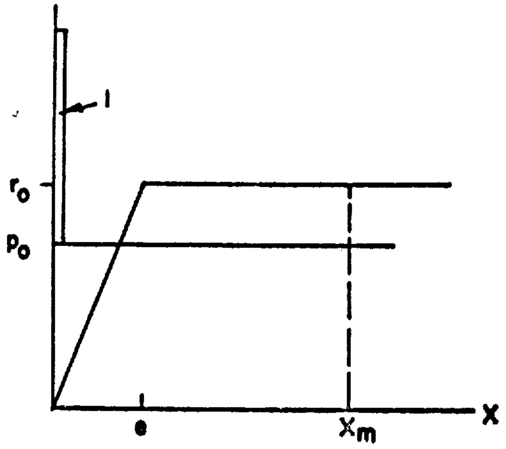

Figure 5 Combined Loading Resistance Diagram

The response corresponding to Fig. 4 can be found easily. After the initial impulse I the load does not vary with time and therefore also is constant with x, as shown in Fig. 5. The maximum deflection of the structure x_m can be determined from consideration of the energy given to the system by the impulse I, the work done by the constant load and the energy absorbed in deforming the structure, the sum of the first two being equal to the third. The initial impulse gives to the system an initial velocity $v = IA/M$. The corresponding kinetic energy is $I^2 A^2/2M$. The work done by the constant pressure p_o while the structure deflects an amount x_m is $p_o A x_m$. Then the energy given to the system is

$$E_i = I^2 A^2/ 2M + p_o A x_m$$

The energy absorbed in deforming the system is proportional to the area beneath the resistance relation,

$$E_a = A \left[r_o x_m - r_o e/2 \right]$$

The two expressions are equated and the resulting equation can be solved for x_m (predicting the maximum deflection of a given structure due to a given loading) or for r_o (determining the resistance needed to produce a specified maximum deflection of a given structure under a known loading):

$$x_m = \frac{I^2 A/M + r_o e}{2(r_o - p_o)} \qquad \text{(for analysis)} \qquad (3)$$

$$r_o = \frac{I^2 A/M + 2 p_o x_m}{2 x_m - e} \qquad \text{(for design)} \qquad (4)$$

If x_m is thought of as a function of r_o and vice versa, it can be shown that for deformations well beyond the elastic limit a small change in r_o corresponds to a large change in x_m. In other words, x_m is sensitive to changes in r_o and r_o is insensitive to changes in x_m. This is convenient for the designer who is finding what resistance is needed in a given situation, and is awkward for the analyst who is attempting to predict the deflection of a structure exposed in a nuclear test.

SHEAR WALLS

Shear walls, whether used as exterior or interior walls, furnish large resistance to horizontal loads parallel to their plane. They can be used in conjunction with either flat or arched roofs.

For maximum usefulness, a shear wall must be continuous with or at least adequately tied to floor or foundation and to roof. If it is contained, so to speak, by a frame of continuous strong horizontal and vertical members of steel or reinforced concrete, its strength is not only increased but is maintained for fairly large deflections, even after the wall itself is badly cracked. See Reference 2 for the prediction of strength and stiffness.

FOUNDATIONS

The foundation of a structure must be able to support for a limited time a vertical load equal to the weight of the structure and its roof cover plus the dynamic roof pressure. Experience indicates that for a loading of short duration the resistance of a foundation may be very much greater than for permanent loads - by a factor of two to five. This is probably due to several contributing factors, among them: (1) inertia of the footing and of the material that would be displaced by its movement, and (2) the overpressure acting on the ground outside the structure furnishing a surcharge tending to stabilize the earth against outward displacement. For example consider a structure resting on a stiff pad of area equal to the roof area. A shock passing over the structure applies a pressure to the roof which is transmitted unchanged to the foundation while the earth on all sides of the structure is subjected to the same pressure. Since this results in a uniform load over the entire area - as though the structure were not present - there is no tendency for differential movement of the foundation.

In fact, however, this type of foundation is not recommended on account of the possibility of producing large vertical accelerations in the floor due to shock on the roof. Footings separate from the floor system are better in this respect.

ALLOWABLE DEFLECTIONS

The allowable deflection x_m is selected by the designer with consideration of such things as the deflection capacity of the structure or element (at which it becomes unstable or begins to lose strength) and the effect of large deflections on the use or function of the structure (interference with operation of doors, or leakage through cracks, for example). Fortunately, as was pointed out above, the amount of the required resistance is relatively insensitive to the choice of x_m.

DESIGN OF APPURTENANCES

Doors, ventilator pipes, antennas and any other exposed elements that must survive the blast must be designed to the same level of hardness as the structure. A door lying in a vertical plane would ordinarily be designed to withstand the full reflected pressure corresponding to the design overpressure assumed suddenly applied. If the door is to suffer no plastic deformation at all, its maximum deflection must not exceed the elastic limit deflection. Eqn. (4) can be applied with the assumptions that $I = 0$, $p_o = p_r$ and $x_m = e$, giving $r_o = 2\ p_r$. (This simply restates the well known fact that a suddenly applied load on an elastic system is equivalent to twice that load applied slowly.)

A vertical baffle immediately in front of such a door would break up the approaching shock front, thus preventing full reflection of the overpressure. The load on the door would then be something between the overpressure p and the corresponding reflected pressure p_r, depending on the dimensions of the wall containing the door and those of the baffle. The baffle must be designed for survival, of course.

On the other hand, a door lying in a horizontal plane has to resist only the overpressure p unless it is immediately in front of a vertical or inclined surface that could cause a reflection of the shock and pressure enhancement in its neighborhood.

Slender, exposed members such as pipes or antennas are not affected by diffraction on account of their extremely short clearing time but are sensitive to dynamic pressure. The loading per unit of projected area (as seen from the direction of blast movement) equals C_D q, where C_D is the drag coefficient for the particular shape.

OTHER HAZARDS

It goes without saying that a shelter must be designed consistently, that is, with consideration of all the hazards that might reasonably be encountered. In the case of nuclear weapons, these are prompt radiation, fallout, heat, smoke and CO from structures burning nearby, oxygen depletion and CO_2 buildup inside, and ground shock.

REFERENCES

1. "Effects of Nuclear Weapons" 1962 edition (U. S. Govt. Printing Office, Washington 25, D. C., $3.00)

2. "Design of Structures To Resist Nuclear Weapons Effects", ASCE Manual of Engineering Practice No. 42, 1961 (American Society of Civil Engineers, Engineering Center, New York City, $4.00)

DESIGN OF SIMPLE STRUCTURES FOR MODERATE LEVELS OF BLAST RESISTANCE

PART B

by Robert J. Hansen
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INTRODUCTION

It is of interest to apply the principles and procedures outlined in Part A of this paper to the partial design of some simple structures above and below ground in a range of pressure regions resulting from a large yield weapon (in the 10-100 MT range). For this comparative study two structural forms are chosen--the box and the arch--both of reinforced concrete. The typical structures and their dimensions are shown in Figure 1. Pressure levels chosen are 25, 50, 100, 200, and 1000 psi.

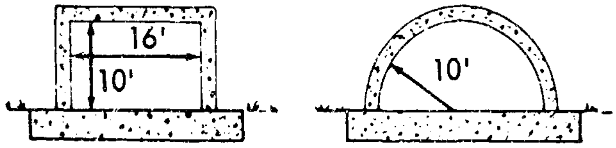
The designs presented relate only to the thickness of the roof and walls of the box and to the thickness of the arch segment. Obviously such a design is incomplete but it does serve to illustrate the effect of pressure level, to compare two structural types, and to indicate the great effect of burial on the required thicknesses or strengths of elements.

A complete design would involve such additional structural elements as end walls, interior framing, if any, foundations, and such structural appurtenances as entrances and ventilation ducts. Further, consideration would have to be given to systems for lighting, ventilation, heating or cooling, communications, etc; and to ground shock effects which could affect equipment and personnel housed in the shelter. These several considerations are excluded from this paper.

LOADING CONSIDERATIONS

To simplify comparison as well as calculations only two conditions for each structural type are considered, i.e., above-ground and below-ground as shown in Figure 2. The major differences in loading for the four conditions of structure (box, arch, above-ground, below-ground) occur between the above and below ground case. In addition, a difference also is present between the box and the arch in the above ground configuration, the box suffering the more severe load.

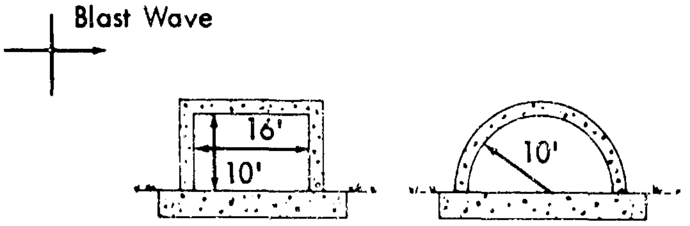
The major difference, that of above vs. below ground loading is illustrated by the following comparison of peak pressures that the box type "sees" on its front wall and roof for the various incident pressure levels.



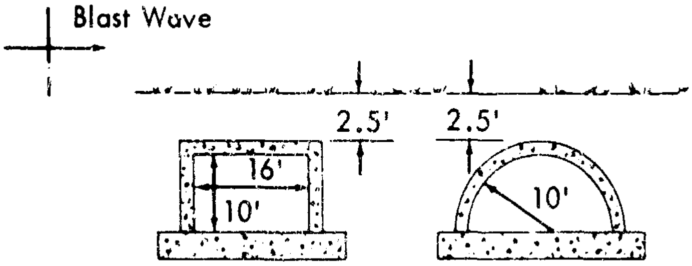
Box Type Arch Type

End walls, entrances, foundations not designed in this study

FIGURE 1. TYPICAL STRUCTURES UNDER STUDY



Above Ground



Below Ground

FIGURE 2. ATTITUDE OF STRUCTURES

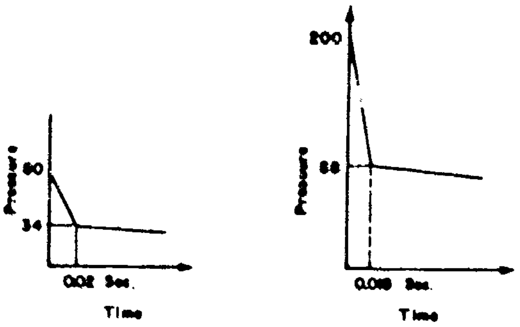
TABLE I

COMPARISON - PEAK PRESSURES

Structure	Position	Incident Pressure (psi)	Peak Pressure Front Wall (psi)	Peak Pressure Roof (psi)
Box	Above-ground	25	80	25
		50	200	50
		100	480	100
		200	1160	200
		1000	8000	1000
Box	Below-ground	25	2.5 to 25*	25
		50	5 to 50	50
		100	10 to 100	100
		200	20 to 200	200
		1000	100 to 1000	1000

*Pressure level dependent on type of soil and position of water table. See Part A.

The very high peak pressures that the front wall sees constitutes the major disadvantages of above-ground construction. True, this reflected pressure does not last long. For example, the initial parts of the front face pressure time curves for the 25 and 50 psi cases are shown in Figure 3.



Incident Pressure = 25 psi

Incident Pressure = 50 psi

FIGURE 3 FRONT FACE PRESSURE TIME CURVES FOR ABOVE GROUND BOX STRUCTURE.

For the below-ground case the pressures that the side wall "see" are a function of soil type and location of water table. However, no reflection effects exist and this constitutes a major advantage.

The loading imposed on below-ground structures located near the ground surface such as those designed in this study as shown in Figure 2 is approximately that of the incident overpressure. Deeper buried structures would "see" lower pressures due to attenuation of pressure with depth. They would, however, be subjected to higher dead load stresses due to the soil overburden.

STRUCTURAL THICKNESSES

Computations have been made for the required thicknesses of the wall and roof elements of the box and the thickness of the arch for the following design criteria.

Strength of concrete	f'_c - 4000 psi
Yield stress of steel	40,000 psi
Percent of steel	1% at ends and center of slabs 1% in arch segments
Allowable deflections	1.3 times deflection at which yielding occurs

Obviously other strengths of concrete and steel, other percentages of steel, and another level of deflection can be permitted with somewhat different results.

The required thicknesses of the various structural elements are given in Tables II and III. A depth of cover over the steel of 1½ inch is used in all cases.

TABLE II

THICKNESSES OF BOX STRUCTURE

Position	Pressure Level (psi)	Thickness	
		Wall (inches)	Roof (inches)
Above-ground	25	18	16
	50	29	23
Below-ground	25	5	16
	50	7½	23
	100	10	30

TABLE III

THICKNESSES OF ARCH SEGMENT

Position	Pressure Level (psi)	Arch Thicknesses (inches)
Above-ground	25	11
	50	18
Below-ground	25	3
	50	4
	100	6
	200	10
	1000	40

These thicknesses are illustrated in Figure 4.

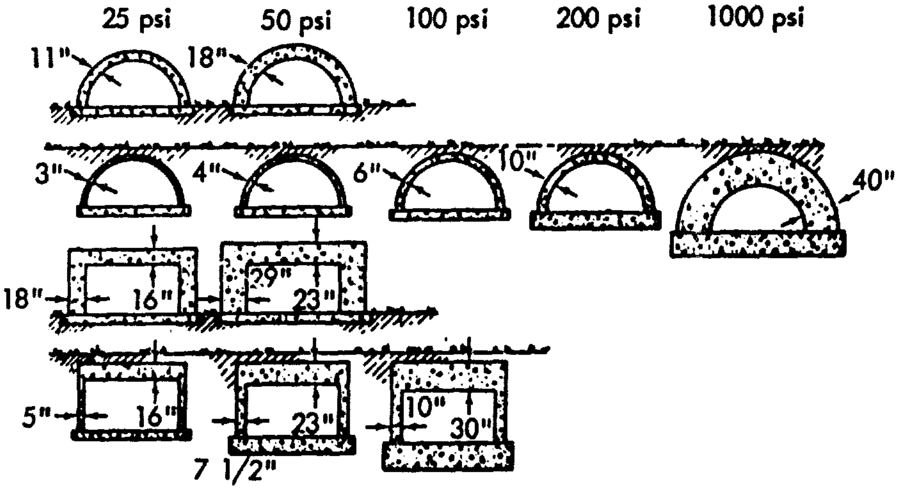


FIGURE 4. COMPARATIVE STRUCTURES

CONCLUSIONS

From the above, admittedly sketchy design, it appears obvious that it is perfectly feasible to build blast resistant structures at small to very intense pressure levels. For example, in the design of a below ground arch structure for the 25 psi region the thickness of the arch will probably be controlled by construction considerations, or whether or not a truck might run over the structure rather than the fact that it might be subjected to a blast wave overpressure of 25 psi, and the arch in the 1000 psi region is only 40 inches thick for the 20 foot span - a not unwieldy thickness at all.[1]

The further obvious conlusion is that if the structure is buried, great advantages accrue since the earth serves to shield the structure from reflected pressures, to attenuate blast induced pressure with depth[2], and serve to arch pressures over the structure.[3] Thus, for the 50 psi region the required arch thickness is reduced from 18" to 4" by the simple expedient of burying the structure. It may or may not be more economical to bury the structure in this region, but the answer is clear cut as the pressure level is increased.

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[1] The problem of providing entrances in this pressure region is, however, not so simple.

[2] Not illustrated in these examples.

[3] Not illustrated here for the box structure.

IV. ENGINEERING IN A THERMAL ENVIRONMENT

PART A

WARFIRE RESISTANCE AND REUSABILITY OF BUILDINGS

by

Edward K. Rice[1], M. ASCE and Kalman L. Benuska[2]

SYNOPSIS

The possibility of a great deal of fire damage occurring in urban areas after a nuclear attack is extremely important to civil defense. Buildings which are not damaged or are readily repairable become a national resource. A procedure for evaluating the fire resistance of buildings, called the Building Reuseability Index, is discussed. This index would combine present-day fire protection criteria with those developed for the warfire environment. Study and research which is needed to define variables not considered in conventional fire protection methods is indicated.

INTRODUCTION

In the event of a nuclear attack there could be great loss of life due to fire in addition to that due to blast and radiation. Experiences of World War II point this way. With multimegaton weapons the range of possible ignition of kindling fuels extends beyond the range of significant blast damage.

Within areas of blast damage, many buildings and their contents will literally be torn apart. Debris will be piled up around the more sturdy structures and will inhibit free movement of fire fighting equipment in the streets. A major portion of the surviving population will be in prepared shelter space within the more sturdy buildings. The debris may sustain fires set by the thermal pulse of the weapon, and by secondary sources such as electrical short circuits, ignited heating fuels and pilot lights.

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[1] President, T. Y. Lin and Associates, Van Nuys, Calif.

[2] Associate, T. Y. Lin and Associates, Van Nuys, Calif.

Primary ignitions in the area beyond the range of significant blast damage may spread to adjoining combustibles and develop into fires of significant proportions.

Mass fires can develop if smaller fires grow out of control and atmospheric conditions are favorable. Initially, these fires are the same as conventional fires in their damage and spread characteristics. However, because of the great number of fires started at the same time, possible loss of water distribution systems and inability of professional fire fighters to respond after the blast, first aid fire fighting and careful preplanning of fire prevention measures are important. One of these measures is the encouragement of construction of fire resistive buildings. Structures must have sufficient protection against fire to prevent collapse and be capable of prompt rehabilitation in the post-attack period.

A building fire resistance evaluation must consider these questions:

1. Are shelter areas adequate for life safety, considering such effects as structural failure, oxygen deficiency, heat build up and toxic gases?

2. What is the probability of rehabilitating a building after severe fire exposure?

The following discussion will cover the second question, namely, how to evaluate potential building reuseability.

PEACETIME FIRE RESISTANCE OBJECTIVES

Present day requirements for fire resistive building elements assume that:

1. The fire usually is within the building.
2. Fire resistive envelopes and coatings remain in place during much of the fire period.
3. Sprinkler and fire alarm systems are in operating condition.
4. Professional firemen and fire fighting equipment will be available and on the scene in a few minutes.

Methods of protecting a building and its contents from ignition by an external exposure include:

1. Open space between buildings.
2. Parapeted fire walls without openings.
3. Fire resistive construction with protected openings.

4. Sprinkler and alarm systems
5. Fire Department hose streams.

The objective of present fire protection criteria is to provide sufficient fire resistance to allow persons inside the building to escape, and to prevent the spread of fire both inside the building and to adjacent buildings.

In the case of a warfire, some of the peace-time methods of fire protection will not be effective. Personnel may have to remain in shelters within the building during the fire. It is highly probably that sprinkler systems connected to a public water supply will not be in operation. Also, the more frangible of the fire resistive coatings may be blown off or seriously damaged. Protection devices for exterior openings may not be in operation due to blast damage. Professional fire fighters will probably not be available to stop the spread of the fire.

PROPOSED EVALUATION

A rating which reflects the probable reuseability of buildings after a fire is useful for civil defense purposes. The purpose of this paper is to present a frame-work into which the details of this rating can be organized.

Estimates are first made of the probable severity of interior fire and the effect of external exposures on exterior walls. These estimates are combined with the fire resistance and economic value building reuseability. This is accomplished by reducing the economic value of the structure according to the expected severity of the fire. It is assumed that the shell of a burned out building is useful in a post attack period, its usefulness being in an inverse ratio to the damage sustained.

If the building is divided into compartments by continuous fire resistive separations, the effectiveness of these separations is rated by determining which separations will prevent the spread of fire from one compartment to the contents in an adjacent compartment. If some separation walls permit the communications of fire to adjacent compartment, a chain reaction fire spread is possible. The critical compartment is the one which initiates a chain reaction involving the largest amount of building area. Compartmentation effectiveness is evaluated by comparing this area to the total building area.

Interior Exposure

The following definitions apply to interior fire exposure:

Compartment: Each portion of the building separated by continuous vertical and horizontal fire resistive construction is considered a compartment.

Interior Combustible Load, L_i: The total weight of combustibles in contents, interior finish, floors and trim.

Potential Interior Exposure, E_i: The potential severity of fire (in equivalent hours) which can occur with total burning of interior combustibles.

Probable Interior Exposure, E_{ip}: The probable severity of fire (in equivalent hours) which will occur, based upon the probable effect of various fire protection measures.

Fire Communication Index, S: A comparison of the probable exposure of a fire separation to its fire resistance time period.

For a given compartment, the potential interior exposure may be expressed as[3],

$$E_i = L_i C/10 \text{ (hours)}. \qquad (1)$$

where,

L_i = Total weight of combustibles in psf.
C = Heat of combustion index.

The heat of combustion index C is taken as 1 for ordinary combustible materials, such as wood, paper and similar organic material. Fats, waxes, petroleum products, etc. are assigned an index of 2.

The effect of interior finish, sprinkler systems, fire extinguisher equipment, occupancy, housekeeping and other factors which influence the probable severity of

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[3] "Building Materials and Structures," Report BMS92, National Bureau of Standards, 1942.

fire are considered by the use of multiplier or modification factors. The modified exposure, called a probable interior exposure, is

$$E_{ip} = (m_1 \quad . \; m_2 \; \ldots)E_i \qquad (2)$$

where m_1, m_2, etc., are modification factors. The factors which tend to increase exposure are assigned ratings greater than one, those which decrease exposure are assigned ratings less than one.

Spread of Fire to Adjacent Compartment

The effectiveness of a compartment division wall is rated by applying reduction factors for potential weak links in the fire separation. The protection of openings is the most important one. A modified probable wall resistance R_{wp} is calculated as

$$R_{wp} = (r_1 \; . \; r_2 \; \ldots)R_w \qquad (3)$$

where,

R_w = Fire resistance rating of separation, without openings, in hours.

r_1, r_2, etc. = Reduction factors.

The modified probable wall resistance R_{wp} is compared to E_{ip} giving the fire communication index

$$S = E_{ip}/R_{wp} \qquad (4)$$

A value of S greater than one is interpreted as a spread of fire to the adjacent compartment.

External Exposure

Exposure to exterior fires may damage an exterior wall. However, for non-combustible material the primary risk is ignition of interior contents, finish, drapes, wood window frames, combustible exterior finishes and combustible roofs. Principle exposure sources can be divided into three groups.

1. Combustibles in the surrounding yard area.
2. Roofs of neighboring buildings.
3. Walls of neighboring buildings.

The potential danger of ignition of the building by external fires depends upon such factors as the temperature of the exposure fire, total heat produced, wind direction and velocity, atmospheric temperature and humidity, geometrical relationship between the external fire and the exposed building, and protection of openings.

It may be possible to express the exterior exposure E_e in hours equivalent to a standard fire test. Comparing the magnitude of the exposure to the fire resistance of the exterior wall construction indicates the adequacy of the wall.

The probability of an interior fire being started is estimated by considering the exposure characteristics, surrounding district characteristics, area of wall openings and protection of openings.

Roof coverings protect combustible roof systems against external fire exposure. Because of the uncertainties in determining the actual exposure, the various classes of roof coverings are given relative ratings reflecting the probability of loss in usefulness of the roof system.

Structural Fire Resistance

The probability of reuse for a structural element is a function of its standard fire resistance and of the maximum standard fire severity to which it has been exposed. Possible values for probability of reuse, or reuse index (R.I.), are given in Tables I A - I E, inclusive.[4] They are expressed as values less than 1.0. Ordinary constructions exposed to their rated fire severity are given a low reuse index whereas protected steel and reinforced concrete structural frames are given high reuse indices.

TABLE I A

REUSE INDICES FOR

STEEL STRUCTURAL FRAME OR CONCRETE STRUCTURAL FRAME;

MASONRY BEARING WALL CONSTRUCTION

Probable Exposure (hours)	Standard Fire Rating (hours)			
	1	2	3	4
1	0.80	0.90	0.95	0.96
2	0.40	0.80	0.90	0.91
3	0.	0.50	0.80	0.86
4	0.	0.	0.60	0.80

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[4] Adapted from unpublished recommendations of G. E. Troxell, Berkeley, Calif.

TABLE I B

REUSE INDICES FOR CONCRETE FLOORS AND ROOFS

Probable Exposure (hours)	Standard Fire Rating (hours)			
	1	2	3	4
1	0.70	0.85	0.90	0.95
2	0.30	0.70	0.85	0.90
3	0.	0.30	0.70	0.85
4	0.	0.	0.40	0.70

TABLE I C

REUSE INDICES FOR HEAVY TIMBER FRAME

Probable Exposure (hours)	Standard Fire Rating (hours)			
	1	2	3	4
1	0.60	0.80	0.90	0.95
2	0.	0.60	0.75	0.85
3	0.	0.30	0.50	0.75
4	0.	0.	0.25	0.50

TABLE I D

REUSE INDICES FOR PARTITIONS:

WOOD OR BAR JOIST FLOORS AND ROOFS

WITH GYPSUM CEILINGS: ORDINARY CONSTRUCTION

Probable Exposure (hours)	Standard Fire Rating (hours)		
	0.5	1.0	2.0
0.25	0.70	0.90	0.95
0.50	0.10	0.70	0.90
1.0	0.	0.10	0.80
1.5	0.	0.	0.70
2.0	0.	0.	0.

TABLE I E

ROOF COVERINGS

ASTM Classification	Reuse Index for Roof System
Combustible Roof Systems*	
A	.9
B	.7
C	.5
Non-Combustible Roof Systems	
A, B, C	1.0

*Multiply factors by 0.5 if a continuous 3' high parapet is not provided.

Building Reuseability

Building Reuseability Index (BRI) is calculated by multiplying the probability of reuse for a given exposure of structural element (walls, frame, etc.) by its percentage of the total cost and adding all values. For example, assuming a probable interior exposure of 1 hour has been determined using methods as previously outlined, a one room building as described in Table II would be evaluated as shown in Table III.

TABLE II

ONE ROOM BUILDING

Element	Description	Fire Rating	% of Cost
Floor	Concrete Slab	--	.15
Exterior Walls	Concrete Block	2	.50
Ceiling-Roof	Wood Joist	2	.30
Roofing	ASTM B	--	.05

A 3' high parapet protects the roof from exposure.

TABLE III

BUILDING REUSEABILITY INDEX

OF ONE ROOM BUILDING IN TABLE II

Element	%Cost	R.I. (Tables IA, D)	R.I. Table IE		
Floor	.15 x	1.00*	-	=	0.150
Exterior Walls	.50 x	.90	-	=	.450
Ceiling Roof	.30 x	.80	.70**	=	.210
Roofing	.05 x	-	.70	=	.035
			BRI	=	0.845

*It is assumed that the floor slab is not damaged.
**This value is used since it is the most severe case.

This example does not consider the effect of external exposure, compartmentation and how the probable interior exposure was calculated. It is important to note the simple method of evaluation. Compartmentation and external exposure influence the magnitude of the fire. For this reason various portions of a compartmented building will have different exposures and the portion of each element exposed to a different fire severity will be considered. However, the basic idea of a building reuseability index does not change.

Damage From Air Blast

A general description of damage to buildings is contained in the following three categories:

1. Severe Damage
   Damage which prevents further use of the building. Collapse is generally implied.

2. Moderate Damage
   Damage to principle members which require major repair.

3. Slight Damage
   Damage resulting in broken windows, slight damage to roofing, blowing down of light interior partitions and slight cracking of curtain walls.

Severely damaged buildings are not reuseable. A moderately damaged building will lose most interior partitions, doors, windows, and gravity water tanks on the roof. This could be included in the building reuseability evaluation by assigning zero reuseability factors for highly damaged elements such as interior partitions; no credit would be given for compartmentation or opening protection. Also, interior sprinkler systems and hoses would not be effective if supplied by a gravity tank on the roof.

The damage to protective coatings may seriously impair the fire resistance of various structural elements. For example columns, which are the key to the integrity of most framed structures, are often steel shapes protected against fire by lath and plaster or other covering which may be severely damaged. Also, lighweight materials are often used which have little resistance to impact resulting from flying debris. The failure of columns may result in superstructure collapse upon basement shelters.

Slightly damaged buildings will be subjected primarily to reduction in protection against external exposure. Damage to roofing will increase the vulnerability of combustible roof systems. Fixed wire glass will be broken, eliminating it as an exterior opening protection. Also, water supply tanks on the roof may be damaged beyond use.

In order to rate the fire resistance of buildings by the reuseability index approach including the effect of blast damage, fire severity modification factors, tables of reuseability, and separation wall reduction factors would be prepared for various levels of blast damage.

Study and Research

More research into the origin, spread and effect of fire is needed before many of the modification factors outlined previously can be evaluated. However, estimates by experienced persons may serve the immediate need. Proper relation of the factors will result in a relative rating of types of buildings incorporating various protection measures which will represent the relative probability of a particular building surviving a wartime fire in a useful condition.

Much of the criteria for fire protection under normal conditions can be modified for the effect of air blast and loss of public water supply. Study of the effect of blast on fire resistive coatings and envelopes is very necessary.

Digital Computer Application

Even though the basic procedure of evaluating building reuseability and the effect of compartmentation is simple, performing the calculations for a large and highly compartmented building will be very tedious. A program could be prepared for use on a digital computer which would remove any computational burden. Also, any attempt to evaluate the fire resistance of a large number of buildings, must use rapid data processing techniques. The use of a computer to evaluate the protection factor for fallout shelters in the recent national survey was a good example.

CONCLUSION

For civil defense planning, the fire resistance rating of buildings should reflect their potential reuseability after a wartime fire. This is accomplished by reducing the economic value of the building elements after consideration of their standard fire resistance rating, the effect of wartime conditions of these ratings, and the probable fire severity.

It is important to systematically increase the fire resistance of our buildings to a warfire as a part of our nations total defense effort. An important by-product of a systematic up-grading would be substantial reductions in the annual multi-million dollar loss from fires.

IV. ENGINEERING IN A THERMAL ENVIRONMENT

PART B

THERMAL RADIATION FROM NUCLEAR EXPLOSIONS

by

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SYNOPSIS

A description of the explosion phenomena which determines the amount and charcter of the thermal radiation is presented together with the effects of atmospheric transmission and altitude of burst. The factors of influence in the response of materials to thermal radiation are outlined, and the nature and extent of large scale fires from nuclear explosions are discussed.

INTRODUCTION

The extent of fires caused by the thermal radiation from nuclear explosions is determined by (1) the explosion characteristics, (2) the modifying influences of transmission through the atmosphere, and (3) the nature of the target materials.

THE EXPLOSION SOURCE

A megaton explosion creates some 10^{15} calories of heat in a few tons of bomb matter in a fraction of a microsecond. Such a high energy density leads to temperatures in the tens of millions of degrees and to a high rate of diffusion of the energy out of the bomb and through the surrounding air. The energy or radiation diffusion is initially faster than any hydrodynamic or shock motions, and within a microsecond most of the bomb's yield has flooded out of the still unexpanded but very hot bomb into a volume of air immediately around the burst point.

The air is fairly opaque to the bomb's initial radiation until the air itself absorbs sufficient energy to rise to temperatures of nearly a million degrees. Air at such high temperatures is completely ionized, with all electrons stripped from its various atomic nuclei, and such a plasma becomes relatively transparent to subsequent radiation - being incapable of much further radiation absorptions. The following flux of x-rays from the bomb experiences only Compton scattering in the hot air and is absorbed only when it reaches the exterior cold air.

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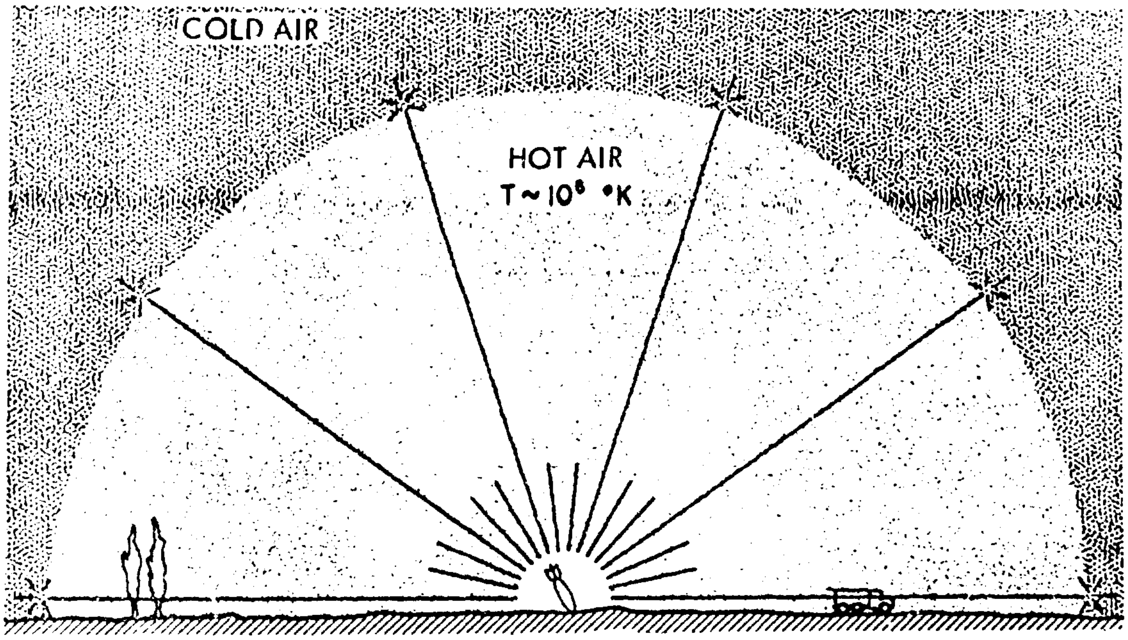

FIGURE 1.

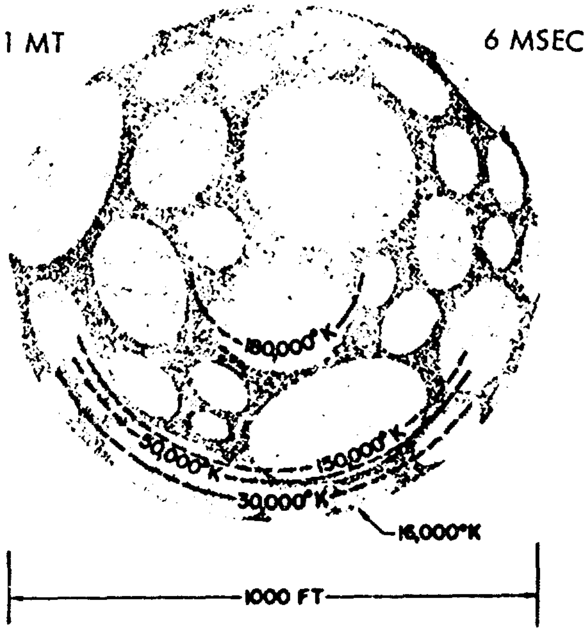

FIGURE 2.

After a few microseconds, the radiation has diffused out into a hot, high-pressure sphere of air of several hundred feet in diameter. (Figure 1.) When the temperature drops much below a million degrees (Kelvin), the rate of diffusion becomes slowed by the increasing opacity of the air as air ions recombine with their electrons. Eventually (in ~100 u secs), shock waves can form and expand the fireball further.

When the shock wave forms it engulfs and heats more air. The shock heated air is incandescent and radiates strongly, but at the same time it is quite opaque, thereby shields or entraps the much higher temperatures in the interior radiation-heated regions. (Figure 2.) What one measures and what one sees in high-speed pictures of these early phases is characteristic of a sphere of radius equal to that of the shock radiating as a black body at the shock temperature, which is in fact the lowest temperature in the fireball at that early time. (The fireball of Figure 2 is typical of this glowing sphere character - showing both the sharp shock appearance of a glassy ball and the blistered appearance caused by blobs of debris splashing against the back of the shock front.)

As this strong shock expands and weakens, it heats the engulfed air less and less. At a stage when the shock heating is no more than a few thousand degrees, the shock front begins to be transparent and we see through it to hotter air behind it. The shock, when it was stronger, raised this air to higher temperatures, and it is still at higher temperatures even though it has expanded some (Figure 3). Since the radiation rate is about proportional to the temperature to the fourth power, a sharp increase in the rate of emission occurs as the hot interior of the fireball shines through the no longer opaque shock front.

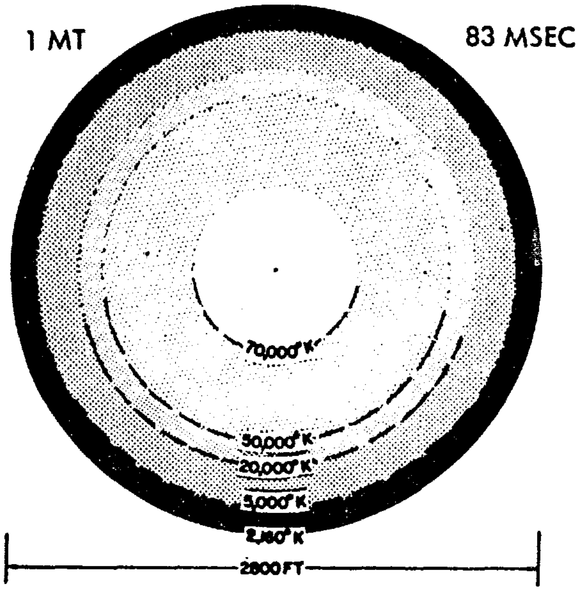

FIGURE 3.

Finally, the vast energies of the hot fireball begin to dissipate, and we see completely through it to the expanding bomb vapors. Only then does the rate of radiation decrease gradually to nothing as the remains of the fireball boil and rise through the atmosphere.

This sequence of optical and hydrodynamic events provides a thermal radiation pulse with two maxima and an intervening minimum (as in Figure 4). The first pulse follows the growth of the shock decreasing in intensity as the shock front cools. The fact that the rate of radiation is proportional to the area of the radiating fireball surface (which is growing with the speed of the shock) is less important than the fact that the shock front is radiating as a black body, and so its radiant flux is decreasing proportional to the fourth power of its temperature (which is in turn decreasing rapidly with increasing shock radius).

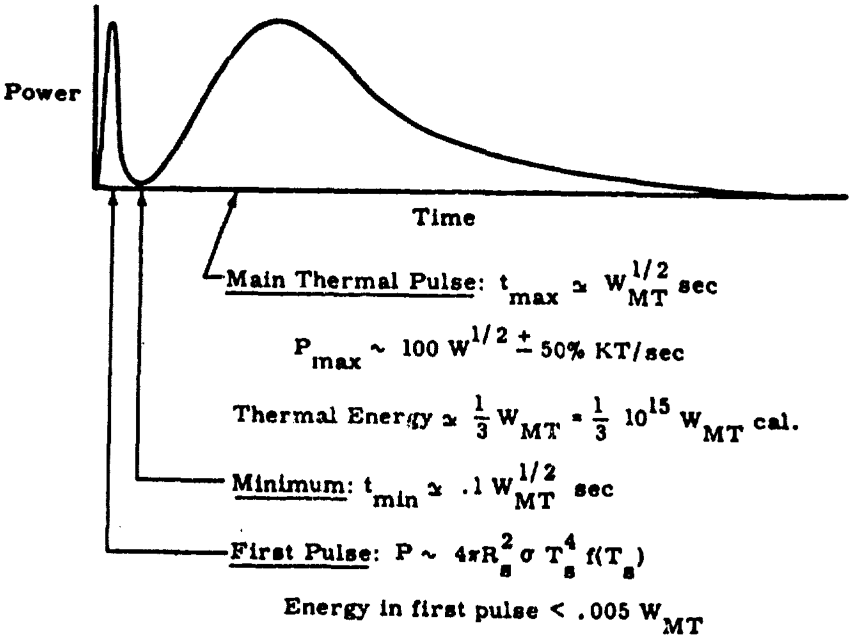

Fig. 4

As the shocked air becomes so cold as to be transparent, the intensity rises again. The first pulse is so fast and comes from so small a radiant sphere that less than half a percent of the total energy of the explosion is radiated away before the time of minimum, but the second pulse lasts for much longer and comes from a much larger effective radiating surface, and so accounts for the radiation of one third to one half of the total yield. Thus a large fraction of the explosion energy escapes as radiant heat shining away to large distances. (It does not necessarily follow that the blast wave is proportionately less effective, since much of this thermal energy is lost too late and from too far behind the shock front to immediately reduce the shock effects.)

The surface of the earth interferes considerably with low bursts or surface bursts so that less than half as much effective radiation as is expected from an air burst can be counted on for a contact or ground burst. As shown in Figure 5, the fireball is no longer a sphere, it is partially obscured by the development of a precursor shock skirt of generally lower luminosity. Perhaps most significantly, its hot interior is thoroughly quenched by the sudden ingestion of vast amounts of cratered material. These megatons of dirt are injected at high velocity and have higher opacities and lower temperatures than the fireball air. This debris does much to suppress the radiant efficiency of the fireball.

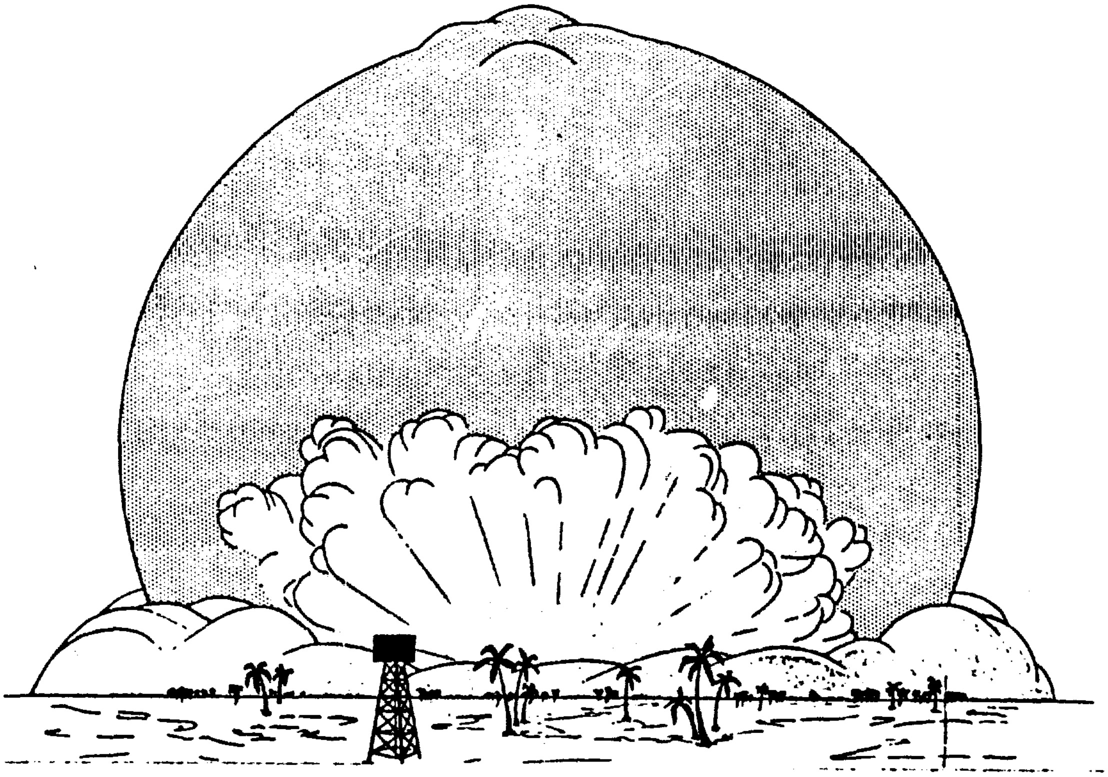

FIGURE 5.

At late times, the turbulent mixing due to the instability of the hot fireball rising against gravity can play an important role in determining the rate at which the relatively opaque mixture of hot air and hot dirt is brought out to a radiating surface.

The spectral character as well as the timing and intensity of the thermal pulse changes with increasing height of burst in the atmosphere. Where the sea level burst is generally typified by the double pulse peeling at about one second and being over in about ten (for one megaton), at high altitudes the duration is more appropriately measured in milliseconds, and the minimum may begin to disappear altogether. Out at the edges of space where there is insufficient air to trap the radiation at all, the burst is more like a great flashbulb with microsecond timing. Figure 6, illustrates this trend. The radiation is encouraged to escape more rapidly as the surrounding air is made less dense (and so less capable of energy absorption or of high opacity behavior).

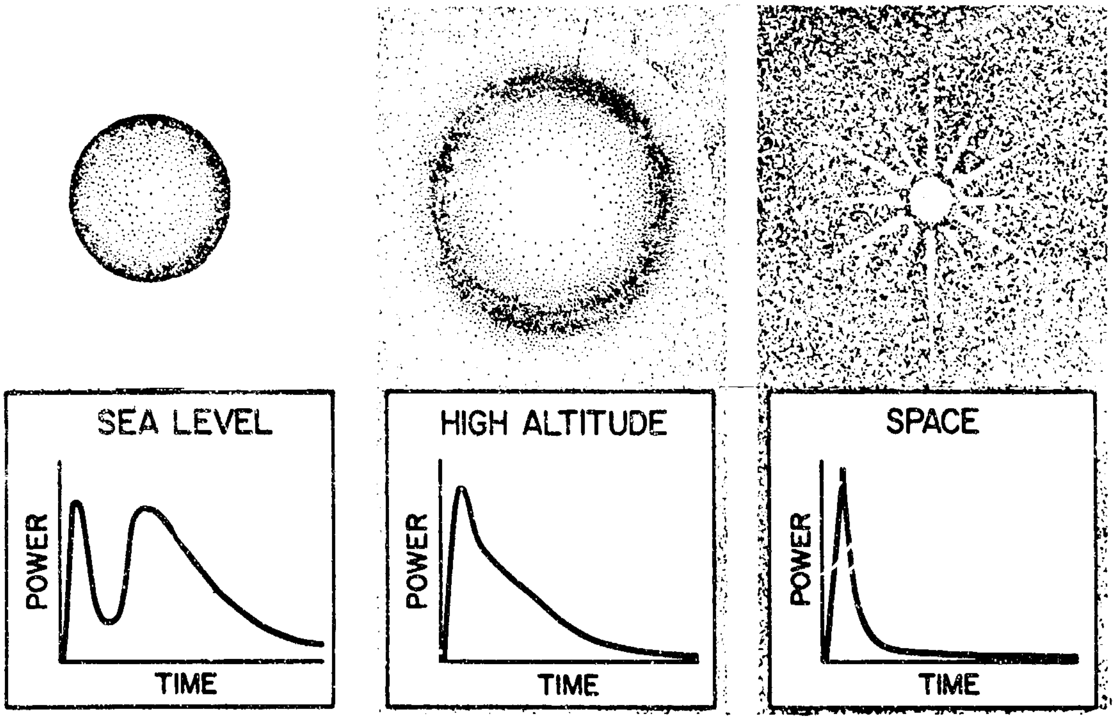

Fig. 6 ALTITUDE EFFECT ON THERMAL PULSE

ATMOSPHERIC EFFECTS

How the fireball develops and also what one observes at some distance away are both influenced by the optical properties of the air. To the distant observer, the ultraviolet and soft x-rays of the early intense fireball are well screened by the intervening air. The usual Plank radiant energy distribution with frequency (for black body radiation) is shown in Figure 7 to emphasize the obscuring effect of the normal atmosphere for the light from a very hot source. Since the air will pass freely only that fraction of the spectrum lying in the visible or infra-red, (and so only that portion of the curves of Figure 7 that lie to the right of the ultraviolet region) the bulk of the radiant energy is not visible until a source has cooled to around 5000°K. That is, incidentally, about the effective surface temperature of the sun, and it is clear that if the sun's radiation spectrum were shifted to a slightly higher (or lower) effective temperature, our atmosphere, indeed our earth, would be much different. It is largely this atmospheric cut-off of the high frequency part of a radiant source spectrum that postpones the final power maximum until the nuclear explosion shock has well expanded.

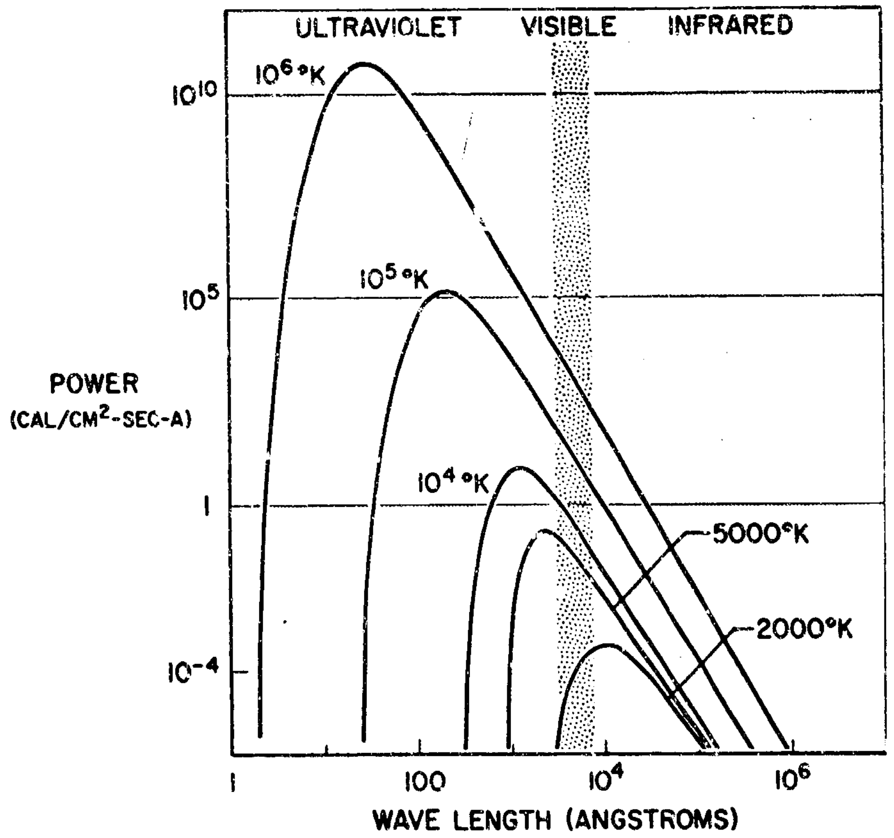

Fig. 7

Even in the visible light part of the radiation spectrum there is some scatter and absorption, and the radiation is reduced in a way expressible in terms of the visibility. Coupling the approximate transmittance factors given in Figure 8 with the geometric decrease of total radiant intensity (incident energy per unit area) can lead to a very approximate recipe

$$Q \simeq WT/D^2 \qquad \text{cal/cm}^2$$

where W is the bomb yield in kilotons, T is the transmittance as suggested in Figure 8 and D is the distance from the burst point in miles. This expression indicates generally appropriate thermal loads from air bursts. The total amount from ground bursts is likely to be less than half of that from an air burst at the same yield and distance.

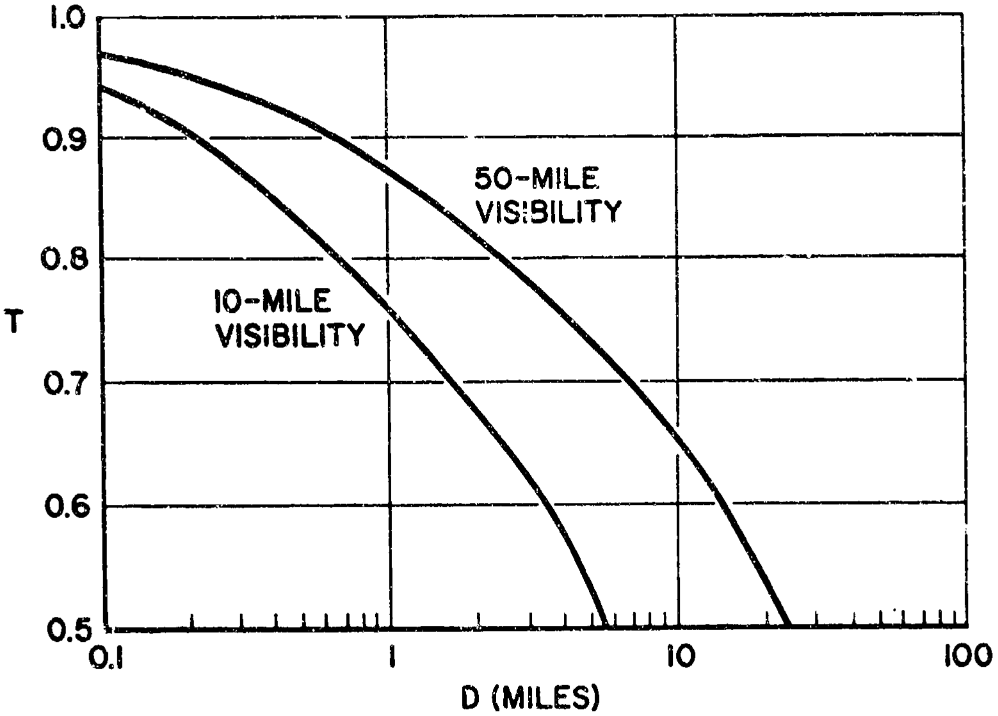

Fig. 8

Thus, at about one mile from one kiloton one expects less than one calorie per square centimeter (a not very serious heat load). At ten miles from one megaton, however, the load could be as much as six calories/cm^2. The atmospheric attenuation becomes more important for the large distances (more of interest for large yields), and there the attenuating and scattering effects are harder to estimate with useful accuracy.

EFFECTS ON MATERIALS

A few calories per square centimeter is sufficient heat load to set afire some materials or to cause serious burn to exposed skin, but many factors influence the damaging effect of thermal radiation and most of these factors tend to limit or minimize the effectiveness. The character of the source has been discussed and it was noted that the total energy, the time, the spectral history, and even the height of burst were significant features. If the radiation is delivered too slowly it is not effective; the desert sun puts out some two calories per square centimeter per minute, and although it is hot, it is not necessarily damaging. If the spectrum is too far in the infrared, then, no matter how long the radiation pours in, it may not be able to raise an exposed surface to a reacting temperature. These source characteristics - the explosion yield, the time and spectral histories of the radiant flux, the fireball geometry and height-of-burst effects clearly can have important practical influence on the response of exposed materials, but equally influencial may be meteorological factors, and perhaps more obviously controlling are some properties of the materials themselves.

The absorption and diffusion through cloud layers or fog can be just as effective with the light from nuclear explosion as it is with sun light. Just as it is ridiculous to attempt to get a sun tan on a cloudy day, the thermal energy getting through from a nuclear explosion above a cloud layer would be reduced by the clouds by something like an order of magnitude. If a burst is beneath a cloud layer, then the scattered radiation will be enhanced, but the direct beam (i.e., the unscattered radiation) is still likely to be the most damaging, and that is not much altered by the contribution of difuse reflection from clouds. Smoke screens, fog, even modern day industrial haze and smog will be at least as effective as they are in filtering sunlight - and perhaps more effective, since for low air burst or surface bursts most of the more distant exposures will be through long paths of the most polluted and opaque air near the earth's surface. Further, since much of the early energy comes in the ultraviolet to which the air is relatively opaque, and since much of the high yield, late time radiation comes out in the infrared to which the water bearing lower atmosphere is fairly opaque, the effective transmittance will be lower than that for sunlight.

The properties of the exposed materials themselves may determine the response more than any other factors. In natural fuels, i.e., outside of urban areas, the single most influential factor is likely to be the same factor that determines the extent of fire hazard from more common sources. Everyone is aware of the sharp increase in fire danger when the countryside has had a dry spell, and the forest conservationists measure the fire danger level by the average moisture content in the forest fuel. When the moisture content falls below twenty percent, the hazard becomes worrisome, but as long as it stays appreciably above that, the danger of spreading of fires is much reduced.

We have all had the frustrating experience of trying to light a fire with green moist, or wet wood. It won't burn. Just as wet wood can't be easily induced to burn, so thick combustibles can't lend themselves to easy ignition. Even a dry two-by-four burns reluctantly and stops burning when it is taken out of the fire. It is a different matter with a shingle or a bunch of kindling! Density also plays some role; a heavier combustible being harder to ignite than lighter weight materials. Of course, the chemistry of the material as it influences kindling temperatures and flammability is an important parameter. Modern plastics tend to smoke and boil - to ablate but not to ignite in sustained burning, while paper trash burns most readily. One feature which is more important under the thermal load than under most other fire sources is the color or reflectivity factor. Most people are aware of such effects; a dark shirt is so much hotter under the sun than a light one. The burns corresponding to the dark patterns of the kimono of the Hiroshima woman dramatically illustrate the effect, as do the movies showing dark feathered gulls going down in flames before a Pacific test fireball while the lighter gulls flew on away.

Just as most materials exposed to the sun are not particularly sensitive to the sun's thermal radiation, and are not highly inflammable nor even ignitible, the surfaces exposed to the thermal intensity of a nuclear explosion are generally not able to respond by sustained burning. Very intense heat loads may mar or melt surfaces, may char and burn surfaces while the heat is on, but may snuff out immediately afterward. Where the exposed materials meet all the favorable requirements, i.e., is thin low density, dry, dark, and easily ignited (low kindling temperature), fires from the thermal radiation will be most likely.

PRIMARY AND SECONDARY FIRES FROM NUCLEAR EXPLOSIONS

Although there would be many fire sources started by the thermal radiation in any urban and in most suburban complexes, such fires should seldom constitute a source of major destruction by themselves. Outside a region of extensive blast damage fires in trash piles, in dry palm trunks, in roof shingles, in auto and household upholstery, drapes, or flammable stores are for the most part readily controllable and accessible. By the very requirement that they start from material exposed to the incident light, the fires thus started can be easily spotted and in the absence of other distractions could be quickly extinguished. Where the blast effects are severe, and damage extensive, little effective fire fighting is likely. Growth and spreading of fires would be encouraged by the exposure of more flammable interiors of homes and by the rubble and kindling-making consequences of the blast.

Where there is blast damage, there is also the likelihood of secondary fires, i.e., fires caused by the disruption of electrical circuits, heaters and stoves, spilling of highly combustible gases or fluids on hot engines or pipes, scattering of embers from open fires.

Both the extensive chemical explosive plus fire bombing of World War II, and the Hiroshima and Nagasaki experience bear out the notion that the serious fires can generally start only in (and may in fact be restricted to) the region of blast damage. In Hiroshima estimates of fire sources suggest that more than half the fires were from secondary or blast generated sources, while in Nagasaki, a greater fraction were traceable to the direct thermal.

LARGE SCALE FIRES - CONFLAGRATIONS AND FIRESTORMS

Most large fires are conflagrations; a burning wind-driven front encroaching on unburned fuels and leaving behind burned out char and ash. The thickness of the burning front depends on both the wind speed and the density and nature of the fuel. A grass fire has a front only a few feet thick, and burns out so quickly that running directly through it may sometimes be safer than running away from it. Although larger amounts of wood are used in house construction in this country than in most other lands, the burning time of a single family residence is usually less than two hours. Such great conflagrations as the Chicago or San Francisco fires burned on such a front for days - shifting with the wind and available fuel - causing vast destruction but relatively little loss of life.

The fire bombing of World War II reached its peak in the great raids on Japanese cities. The huge Tokyo raid started extensive fires in about one third of the city, and the resulting conflagration burned over another third. In that instance, the casualties are quoted as being in excess of 200,000.

The firestorms of Hamburg and Dresden have a different nature. A firestorm is more akin to a bonfire, and the conditions for a firestorm are those required for a bonfire. In a bonfire the rising column of hot air sets up a draft which fans the fire, but at the same time contains the fire. If there is appreciable surface wind, then the rising column of hot air is swept off and the brisk up-draft is destroyed. A firestorm, like the bonfire must have reasonably still air, must have ample fuel, and must have a good start, i.e., the fuel must be burning all over at about the same time.

Hamburg and Dresden and other cities attacked with fire raids in the late stages of World War II were bombed with high explosives to break up buildings, and then seeded with vast numbers of small fire bombs which acted as many simultaneous sources of fire, setting ablaze whole areas all within a short time. A nuclear explosion can provide such fire sources far more effectively. Hiroshima suffered a firestorm from its nuclear attack.

But this nuclear super-match to light the fires cannot cause a firestorm where there is insufficient fuel or where the topography or weather interfere with the other bonfire requirements. Nagasaki did not develop a firestorm as a consequence of an attack similar to the Hiroshima attack. The probable reason lies in the lower density of combustible materials in the extensive blast damage region at Nagasaki together with the partial obstruction provided by the surrounding hills there. Further, the prevailing wind circulation in the valleys discouraged the hot rising column development necessary to the firestorm type of fire.

Thus the primary factors influencing large scale fires can be identified as dealing with (1) the availability of fuel, (2) the density of the fuel, i.e., the extent of wood construction and the degree of builtupness, (3) the combustibility of the fuel, (4) the existence of firebreaks (rivers, parks, lakes, broad avenues, freeways), (5) and target size, i.e., if nothing else can stop a spreading fire, then the limits of the urban area itself determine the coverage. Many other factors contribute to the nature and intensity of large scale fires, of course, but of these one may note as significant such matters as topography (as in San Francisco, Nagasaki, the Santa Monica Mountains - Bel Air fires), building size (as in market, warehouse, or industrial area fires), contents combustibility, and construction continuity.

Still one of the most important factors in any fire situation, after recognizing the existence of ample combustibles and the potentialities of nuclear explosives as fire igniters, is the meteorological influence - the weather. Recall again the consequent rise in fire hazard and the increased potential danger following a few days or weeks of dry weather. The humidity need only drop for a day or two to make the Southern California hills potential tinderboxes. Elsewhere with higher levels of precipitation, the hazard is almost nonexistent, and during much of the time the possibility of fire spreading is negligible. At least during and shortly after rain or snowfall individual fires may burn, but may not spread to adjacent structures.

Although the thermal and blast effects from thermonuclear explosions are indeed capable of starting many fires in typical urban areas, the subsequent spread and amalgamation of these fires and the possibilities for conflagrations or firestorms are matters not peculiar to nuclear war, but are governed by the same factors which are of importance in more conventional conflagrations. Much of the long experience and effort to prevent and to be ready to put out fires is valuable and applicable to the thermonuclear fire problem. However, to the extent that this background does not countenance the wide involvement and the truly simultaneous damaging and igniting of structures possible in nuclear warfare, we may fail to anticipate the extensive consequences and the requisite preparations and fire fighting efforts.

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V. ENGINEERING IN A FALLOUT ENVIRONMENT

PART A

FUNDAMENTAL CONCEPTS IN FALLOUT SHELTER ANALYSIS

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INTRODUCTION

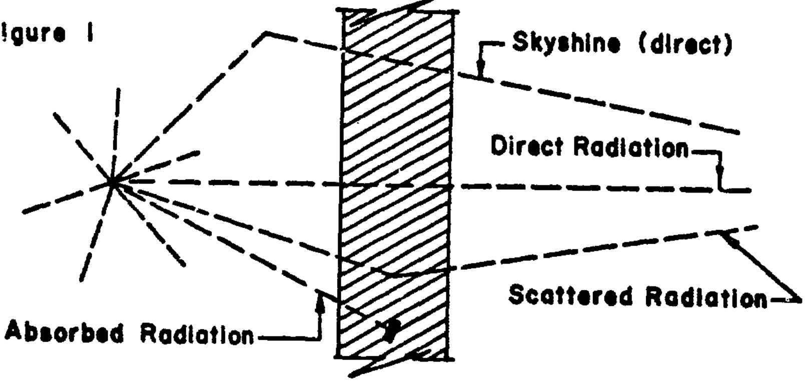
This paper presents basic concepts fundamental to the understanding of a comprehensive method of analysis applicable to the determination of the relative protection afforded by any structure against the penetration of biologically harmful gamma radiation associated with the fallout from surface burst nuclear detonations. The comprehensive method of analysis is presented in detail in References 1 and 2 cited in the appendix to this paper and is based upon fundamental studies reported in Reference 3. Reference 4 presents a general background treatment of all aspects of nuclear explosions including material on the nature, deposition, and biological effects of fallout radiation. All references are essential to a study leading to a complete understanding and mastery of the science and art of fallout shelter analysis and design.

RADIATION EMERGENT FROM A BARRIER

Fission products included in the early fallout from a surface burst nuclear weapon emit radiation in the form of alpha and beta particles and gamma rays. Alpha and beta particles, although biologically harmful if they are ingested or impinge upon exposed living tissue, are attenuated by relatively light shielding and are insignificant in consideration of structure shielding problems. Gamma rays, however, are extremely penetrating and biologically destructuve. They constitute the sole consideration in fallout shelter analysis.

Consider, in Figure 1, a radioactive particle emitting gamma rays in all directions. Gamma radiation consists of continuous

Figure 1



streams of photons which travel in a straight line from their source, the nucleus of a radioactive isotope, until they interact with the electrons of obstructing atoms. Each photon incident upon a barrier may (1) pass through without interaction in which case it is termed direct radiation, (2) lose all of its energy in an interaction with an orbital electron of an atom in the barrier (photoelectric effect) in which case it is termed absorbed radiation; or (3) lose only a portion of its energy to the orbital electron and continue in a different direction with lower energy (Compton effect) in which case the departing photon is termed scattered radiation.

The probability of occurrence of an interaction depends on the atomic number and the number of protons associated with the barrier material, the energy of the photon, and the thickness of the barrier.

The chemical composition of barrier material of the type contemplated in ordinary structures (earth, concrete, wood, clay products, stone, etc.) is such that the atomic number and number of protons are relatively insignificant and the only property of the shielding material that is important is its weight in pounds per square foot of barrier surface termed mass thickness.

Photon energy is a time dependent quantity. At a particular time, something over two hundred different radioactive isotopes may exist in the fission product from a nuclear explosion. These have half-lives ranging from a fraction of a second to milleniums and varying portions emit gamma radiation having energies ranging from about 0.2 Mev to about 3.0 Mev. Both properties are time dependent. This constantly changing gamma radiation spectrum presents the obvious conclusion that the relative protection afforded by a shelter will vary with time. To avoid this complication, it is necessary to make some decision as to a single spectrum to serve as a basis for all data used in analysis that are spectrum dependent. Such data have been derived from consideration of the spectrum that exists about one hour after the explosion. This spectrum is fairly representative of other early times in penetrating power and it turns out that this is a somewhat conservative but realistic choice since the greatest part of exposure is apt to occur during the first few hours.

THE STANDARD DETECTOR

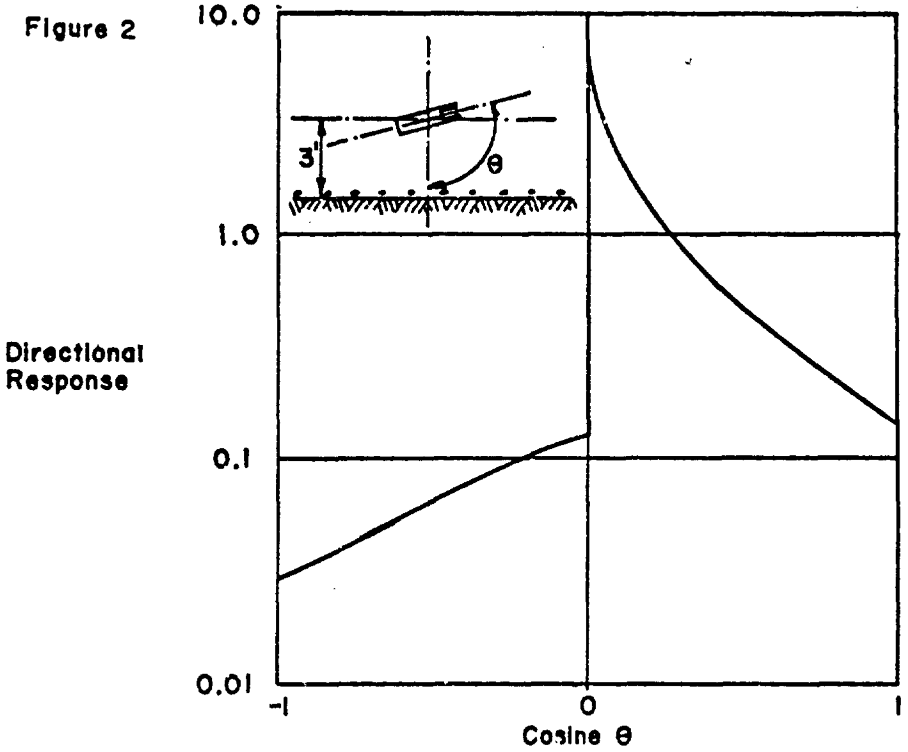
The protection afforded by a structure to some discrete location within is evaluated by comparing the amount of radiation received at a fictitious detector at that location to that which would have been received at an unprotected location. To give universal meaning to such comparisons, it is necessary to assume some reference standard location of a detector against which protection afforded at other locations can be compared. This is analagous to the use of mean sea level as a universal reference for all elevations. The reference standard used in shielding analysis is an unprotected detector which measures the amount of radiation received by it from all directions (a four pi detector) and which is located three feet above a smooth horizontal plane, infinite in extent, and uniformly contaminated with particles having the average energy of the fission product about one hour after detonation. The amount of radiation received at the reference standard is a calculable quantity which can be normalized to unity. Lesser fractions of radiation received at protected locations may then be related to the standard and expressed as a decimal fraction called a reduction factor.

THE STANDARD EVALUATED

Consider, in Figure 2, a collimated detector located in the standard position and pivoted so that it may be revolved in a vertical plane about its horizontal axis. As the detector is rotated through successive increments of the angle θ (theta), measured from the vertical down position, it responds to the radiation "seen" at successively further and further distances along the contaminated plane. At angles approaching ninety degrees, because of the secant effect of the collimated area on the contaminated plane, the detector would respond to radiation "seen" over an infinite extent and one would expect the response curve to rise to infinity as the detector is rotated to the horizon. This would be so were it not for the blunting effect resulting from the attenuation of the radiation by the intervening air. As the detector is rotated above the horizon, the response to <u>direct radiation from ground sources</u> is no longer apparent and it responds only to <u>skyshine radiation</u> which is considered a form of direct radiation manifested by the Compton effect in the air (air scatter). In the figure, the response of the detector to radiation received at various angles of rotation (<u>directional response</u>) is plotted for a half revolution only. The response scale is logarithmic and, although the values shown are realistic, interest exists, for the immediate purpose, more in the relative values than in the actual values. The exact shape of the curve is also, for the immediate purpose [illegible] significant although it is fairly representative. The significance of this plot, if it were made linearly, is that the area under the curve is representative of the response of the standard detector to radiation received from all directions. It is obvious that a polar integration would be required to account for response through all azimuthal sectors but such integration would change only the total magnitude and would have no effect on the relative scale. This is the basic approach used in evaluation of the standard location. As previously stated, such evaluation has been normalized to unity allowing the response at protected locations to be expressed as a decimal fraction called the reduction factor. Particularly significant in a linear plot would be the relative magnitude of total response from above and below the plane of the detector. It is observed that the response from above (skyshine radiation only) accounts for only about ten percent of the total.

The response from below (about ninety percent of the total) is largely the result of direct radiation from the ground sources.

Figure 2

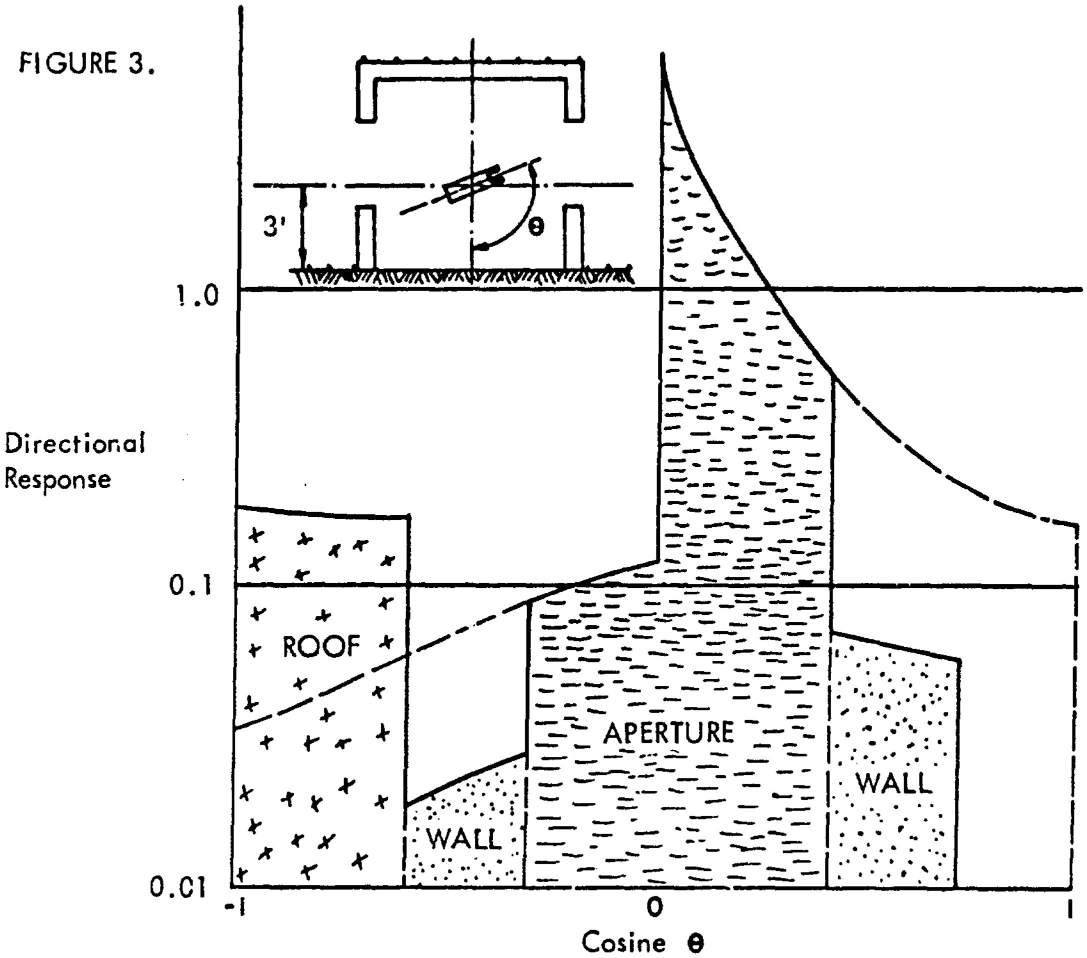


CONCEPT OF RELATIVE PROTECTION

Consider now, in Figure 3, a collimated detector mounted three feet above an infinite smooth plane uniformly contaminated except for a cleared area defined by the wall boundaries of the surrounding cylindrical structure. The roof plane of the structure is also contaminated. A cylindrical structure is assumed in order to eliminate azimuthal orientation from consideration and the detector is again rotated in a vertical plane through successive increments of the angle, theta. Directional response is plotted as a function of the cosine of theta for 180 degrees of rotation. The dashed curve is a replot of the response curve associated with the standard and the solid lines represent the response of the protected detector.

In the first segment of rotation, neglecting an insignificant amount of scatter taking place within the structure, there would be no response since the detector observes only a cleared area. As the detector is rotated to a position where it begins to "look at" the field through the wall barrier, it will respond to radiation emerging from the inside face. In the absence of a barrier the detector would respond to radiation equal to that for the same position of rotation of the standard detector. The effect of the barrier is to reduce the response through all angles of rotation associated with the vertical wall segment. When rotation progresses to the position where the field of view intercepts the contaminated plane through the aperture, the response curve will become coincident with the standard curve and remain so until the field of view intercepts the upper portion of the wall barrier which is, again, effective in reducing the response. As the angle of rotation becomes such as to intercept the contaminated roof plane, the detector will respond to these direct sources (as opposed to only skyshine for the standard detector); and, depending on the mass thickness of the roof barrier, the response may fall above or below corresponding responses for the standard detector. Were this plot made on a set of linear scales, the area under the solid curve would be indicative of the total response of

FIGURE 3.



the protected detector. The relative area (compared to that of the standard curve) expressed as a decimal fraction is the reduction factor for the protected location. It indicates the reduction in radiation reaching the detector and resulting from factors of geometry and mass thickness associated with the structure. The reciprocal of the reduction factor is termed the protection factor. The protection factor expresses the relative degree of protection afforded by the structure. A protection factor of 100, for example, would indicate a shelter position 100 times better from a biological standpoint as the standard position. It would indicate that the protected location receives only one percent of the radiation received at the standard location.

The discussion above illustrates the basic concept of protection and how it is evaluated. A summary view of the response curve of Figure 3 for the protected location leads to considerations that are basic to the comprehensive method of analysis of fallout shelter.

The total area under the response curve can be broken down into several sub-areas as indicated in the figure. These sub-areas represent the response of the detector to radiation emerging through the walls, through the apertures, and through the roof. In application of the method, one makes separate calculations for contributions (sub reduction factors) from walls, apertures and the roof. The sum of these contributions yields the total reduction factor the reciprocal of which is the protection factor.

If attention is directed to any one of the sub-areas as, for instance, the area indicating roof contribution, it is immediately evident that the area is determined essentially as the product of a barrier factor (the height of the curve is a function of the effectiveness of the barrier in attenuating the radiation) and a geometry factor (the intercept on the abscissa is purely a function of the angle through which the roof surface is intercepted. Considering azimuthal rotations the geometry factor can be considered with relation to a solid angle (at the apex of a cone in the case at hand) determined by the physical dimensions of the structure. In this light, a contribution may be considered as the product of a barrier factor and a geometry factor.

DESCRIPTION OF METHOD OF ANALYSIS

In application of the comprehensive method of analysis explained in detail in Reference 1 and 2, one is required to calculate various solid angles (solid angle fractions) from very simple relations determined by the physical dimensions of the structure and to determine the mass thicknesses of the barriers involved. From curves and charts given in Reference 1 and 2 and derived from basic considerations in Reference 3, values of B, barrier factor, and G, geometry factor are determined. These are collected together in the form of functional equations which, when solved, completely define the total contribution to the detector from that segment of structure under consideration. The method is so designed as to allow calculations to be made for contributions from any part of the structure regardless of its orientation in azimuthal direction or vertical or horizontal position. The method is entirely general and is applicable to the determination of the relative protection factor in any location within a structure of any size or shape. Techniques are available for evaluating the effects of such complicating factors as for example, limited fields (shielding from adjacent buildings), ground roughness, and sloping topography.

SUMMARY

Engineers and architects are generally cognizant of the fact that fallout shelter is in increasing demand among their clients. It is rapidly becoming still another functional design requirement for many types of construction. It can and is being economically and realistically achieved. It is important that engineers and architects engaged in structural design should be well versed in concepts, principles, and methods of analysis pertaining to ionizing radiation shielding and in the habitability requirements of a fallout shelter environment. This paper has considered only basic concepts, perhaps over simplified, involved in a comprehensive method of analysis available to all who are interested in furthering their capabilities in this all important aspect of national defense. It is encouraged that as many professionals as can should undertake the responsibility of advancing their knowledge in this relatively new field either by self study or by attendance at one of the many Office of Civil Defense sponsored Fallout Shelter Analysis courses being presented regularly in most major metropolitan areas. Successful completion of such a formal course would lead to certification by OCD of the individual as a qualified fallout shelter analyst.

APPENDIX

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V. ENGINEERING IN A FALLOUT ENVIRONMENT

PART B

FALLOUT PROBLEMS IN CIVIL DEFENSE

by

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In a nuclear attack on this country vast physical damage would be inflicted by the blast and heat effects of the explosions, but in addition it is likely that great areas extending beyond the targets would be subjected to high levels of radioactive fallout. Gamma radiation from this fallout could be lethal to man and animals unless protected and to many plant species both wild and domestic. Beta radiation from fallout is hazardous to man primarily if the fallout material gains entry into his body. Although external exposure to beta can be damaging, especially to small plant and animal life, man can protect against it quite easily--normal clothing, for example provides good protection.

Heavy fallout results from nuclear explosions when these two conditions exist: (1) the debris resulting from the explosion is highly radioactive, and (2) this debris is deposited on the ground in significant concentrations. Heavy fallout is not produced when clean nuclear weapons are detonated or if the weapons, either clean or normal, are detonated so that the fireballs do not come in contact with the ground.

At least now and for some time in the future it would be unwise to assume use of relatively clean weapons if an enemy should attack this country. The technology for clean weapon design is more complicated than is the technology for normal weapons, which get an appreciable portion of their yield from uranium which produces highly radioactive debris. Also it would be dangerous to assume that an attacker would be highly motivated to deliberately make his weapons "humane" especially if such weapons are more costly either to produce or to deliver.

The second condition for heavy fallout production, whether or not the detonation is ground or air burst, is influenced largely by the type of target being considered. If, for example, the objective is to cover the largest area possible with an amount of blast pressure that would assure destruction of such targets as parked bombers or fighter planes, a weapon burst at optimum altitude could provide coverage about twice as large as a ground burst weapon of the same size.

Fallaciously, it has been argued that the kill area for a ground burst for the multi-megaton weapon sizes commonly assumed for Russian missiles, is enough to assure overkill of almost any kind of target. But this does not consider inaccuracies in aiming or uncertainties in target location. When considering these uncertainties the attacker can improve his chances of knocking out any soft target by air bursting his weapons. (A target is considered soft if it is vulnerable to less than about 25 psi.)

For hard targets such as the Titan, Minuteman, and Atlas silos this advantage does not apply. The preferred method of destruction for them is through ground bursts, i.e., to knock out a hard missile silo it in effect must be dug out. To assure an acceptable probability of knocking out certain hard targets the attacker may have to employ more than one weapon. In this case, the fallout pattern produced by a single weapon is, in effect, multiplied by whatever number of weapons is used.

Figure 1 from page 462 of the 1962 edition of the DOD-AEC handbook "The Effects of Nuclear Weapons" shows the best estimate of the fallout pattern of a 15 megaton weapon (BRAVO) detonated at Bikini Atoll, March 1, 1954. If three 15 MT weapons had been ground burst near the same place and at the same time the fallout levels shown would be higher by about a factor of three.

To recapitulate, if the United States is subjected to a nuclear attack, fallout likely will be a serious component of the total hazard. Many of the weapons probably would be ground burst and they would not be clean. Multiple weapons might be used to assure the attacker sufficiently high probability of getting particular targets.

Figure 2 represents a nationwide fallout plot. This is the fallout pattern used during a congressional hearing.* Later it was reprinted in the Bulletin of Atomic Scientists. It did not then, nor does not now, purport to be representative of the type of attack likely to occur. For example, it does not reflect the presence of hard missile launching sites being created by the deployment of Atlas, Titan and Minuteman weapons systems. It does, however, illustrate the extent of areas of the country that could be affected by fallout patterns and the influence of the prevailing high altitude winds.

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*Hearings before the Special Subcommittee on Radiation of the Joint Committee on Atomic Energy, Congress of the United States. May 27, 28, 29 and June 3, 1957.

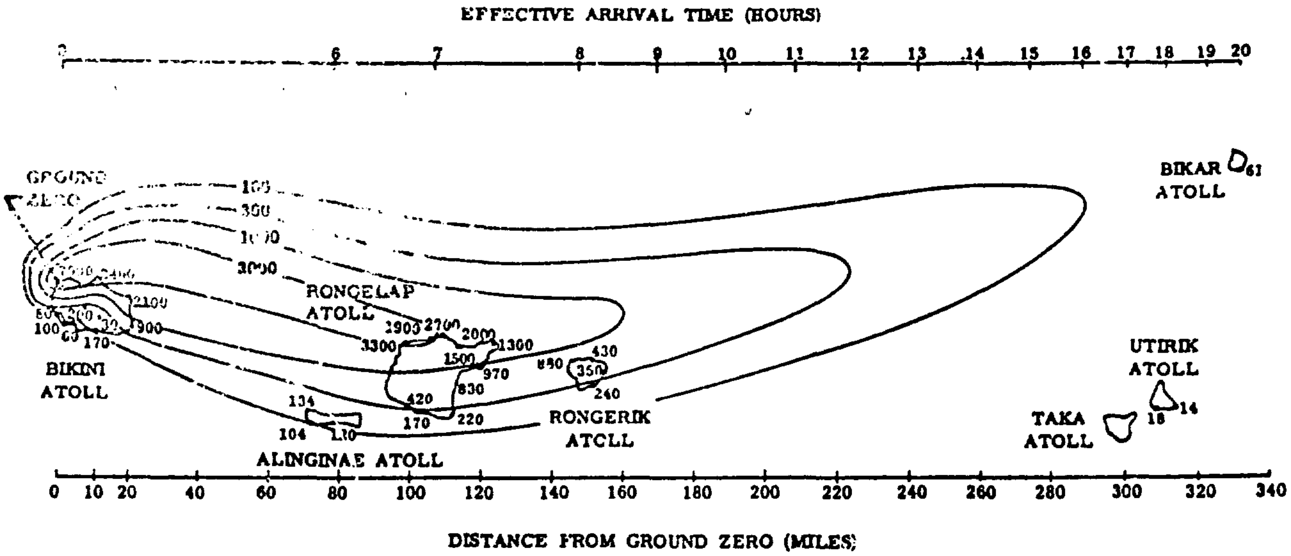

Figure 1. Estimated total-dose contours in roentgens per hours at 96 hours after the BRAVO test explosion.

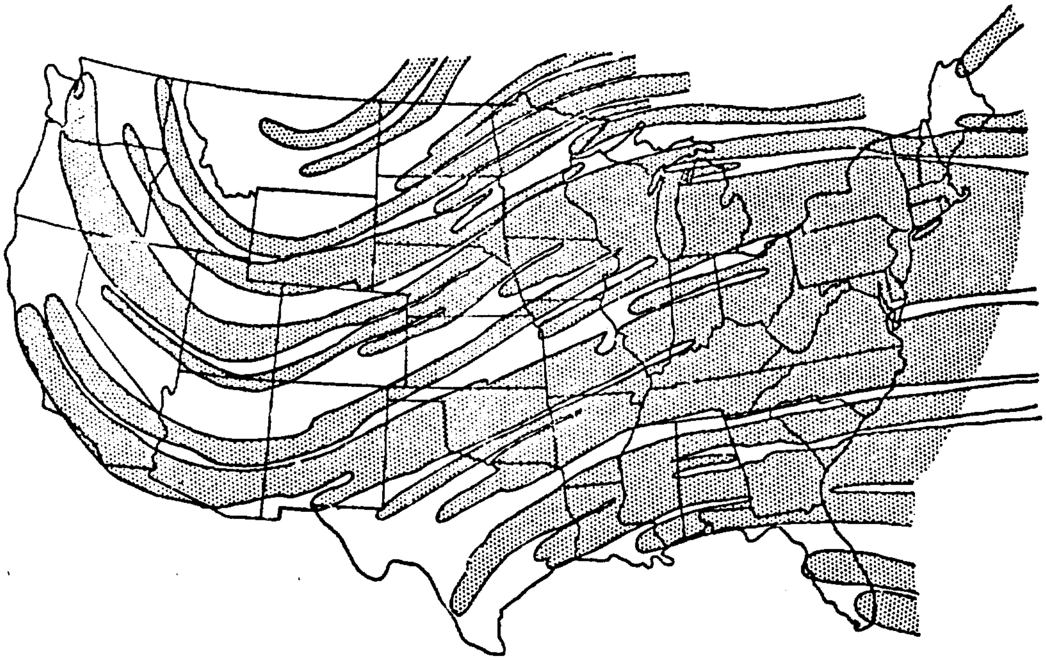

Figure 2.—Fallout areas at 24 hours after detonation

Many uncertainties must be resolved before there is a good understanding of the complete process of fallout formulation and distribution. But a number of fallout models have been postulated that can be used to provide useful descriptions of the fallout phenomena and to show influences of some of the variables. Some models predict only the likely areas to be affected by fallout and others predict dose rate and total dose contours. A model developed by Dr. Carl Miller now at the Stanford Research Institute, predicts the dose rate and total dose contours and also estimates the mass of the fallout material associated with the contours as well as the quantities and biological availability of the individual radionuclides.

From consideration of the time-temperature history of the fireball in relation to the partial vapor pressures of the individual radioactive elements resulting from the explosion and of the constituent elements of the surface material swept up into the fireball, the location of the radioactivity in, on, or external to the fallout particles can be estimated.

Particles with high internal concentration of activity tend to be relatively large and to be deposited fairly close to the burst point, and the radioactive ingredients are not soluble and so are not available for biological assimilation. The surface-contaminated particles are more soluble and would present a greater internal hazard if the particles were ingested. At the time the radioactive elements are being incorporated into or on the particulate material some, principally in the form of inert gases, escape this condensation process and are not generally found in the local fallout area.

Regardless of the physical and chemical characteristics of a particular fallout particle its radiological characteristics are determined only by the particular radioactive element, or elements, incorporated into it. Some 200 individual radioisotopes are formed in a nuclear explosion. Each emits radiation of a particular type, either beta or gamma or both. This radiation has a particular energy spectrum, and is delivered at a particular rate. Strontium 90, for example, is a beta emitter and has a half-life of about 25 years. Cesium 137 produces gamma radiation and gives off half of its radiation in about 30 years. Iodine 131 which emits beta and gamma radiation has a half life of about 8 days.

If these some 200 radioelements, formed by the explosion of a nuclear weapon, are incorporated in fallout material in the approximate ratio they are created, the composite rate of decay of the gamma radioactivity varies as a function of the time after detonation raised to the minus 1.2 power. This leads to the familiar rule that for each seven-fold increase in time after detonation the radiation levels will decrease by a factor of ten ($7^{1.2}$ is approximately 10).

This has led, however, to the faulty statement that the radiation level at a particular location would be 10 fold less at 7 hours than at one hour past detonation and another 10 fold reduction would occur by 7 x 7 or 49 hours. This fails to take into account the location of the fallout material. Much of it would still be in the air at one hour. Even after deposition starts the amount of fallout material and consequent radiation levels build up over a period of time.

A more proper way of estimating the decay of fallout radiation levels is to say that after complete deposition has occurred, i.e., the fallout material is all down, each 7 fold increase in time will reduce the levels by a factor of 10. For example, if fallout deposition is completed 8 hours after detonation and at this time a meter reads 100 r/hr, at 7 x 8 or 56 hours the level will be reduced to 10 r/hr.

The unit of measure for beta radiation dose is the rad. It relates to the amount of beta energy, 100 ergs per gram, absorbed by the exposed specimen - plant or animal. In a particular fallout field the beta dose, or number of rads, would differ depending on the size of the specimen and other physical characteristics.

The unit of measurement for gamma radiation is the roentgen. It is related to the loss of energy in air, 83 ergs per gram at standard temperature and pressure, but is useful over a fairly broad energy range as a basis for estimating biological effects on man, animals, and plants. In a particular fallout field all specimens would receive about the same number of roentgens. If delivered in a short period of time, a few days, or even a week or two, very few people would become sick at exposures less than 200 roentgens; about one-half would die at exposures of around 450 roentgens; and essentially complete lethality would occur at about 800 roentgens.

Long-term biological effects of radiation exposure include the production of cataracts, increased probability of leukemia, the development of bone or thyroid neoplasms, life-shortening, and general debilitation. It is not true that all survivors who had received exposure during a nuclear attack would be subject to all or even any of the above. Most such later effects of radiation exposure are manifested through small increases of already existing small probabilities that such effects would occur anyway.

In controlling radiation exposure in a nuclear attack obviously the first consideration should be to keep people from dying, next to keep them from becoming sick, and finally, particularly because of the long range effects, to keep the general exposure as low as practicable. People never should be subjected to radiation exposure of any kind unless some beneficial purpose would be served, nor should they be subjected to severe stress such as high overcrowding or extreme thirst if such stress could be alleviated at the expense of some radiation exposure.

Most domestic animals have radiation sensitivities comparable to man. If a high probability of survival of farm animals is desired the same degree of shielding is necessary for the cows and horses as for the farmer himself. The inherent protection afforded by a barn should be used. It would improve the chances of survival of cattle especially in light fallout areas, but in no.sense would a barn be a substitute for a high quality shelter.

Protection against gamma radiation may be achieved by interposing either a mass of material, or distance, or various combinations of mass and distance, between those to be protected and the source of radiation - the fallout. The techniques for providing such protection comprises a comprehensive technology in itself.*

Turning to the problem of internal emitters: Certain of the radionuclides produced by nuclear explosion are particularly significant because of their potential of damaging particular organs of the body.

The radionuclides of greatest concern are iodine, strontium, and cesium. Radioiodine is hazardous in the early period after the attack. Although it is unlikely that massive wide scale biological damage would occur, in some situations it would be better for children not to drink milk from cows that had grazed on contaminated pasture. This would apply for a period of a few weeks after the attack. Radioiodine may concentrate in the thyroid gland and since a child's thyroid is small, significant damage could accrue. Because of the size the damage to the adult thyroid would be only a fraction of the damage to the child and the milk radioiodine problem would be much less serious.

Strontium is in the same chemical family as calcium; and strontium isotopes, like calcium, may be deposited in the bones. Ingestion of excessive quantities of radioactive strontium would produce damage similar in nature but not in degree to the damage

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*See Professor Carl Koontz' paper in this series (V - Part A) suffered by the radium watch dial painters of the 1920's. Many of these women, who were using radium bearing paints and who licked their brushes in order to point them, experienced serious bone damage some 15 to 20 years later. Radium also is in the same chemical family as calcium. However, the deposits of radium in the bones were high; probably much greater than could result from the use of strontium contaminated food, milk or water, even for considerable periods after an attack.

Radiocesium chemically behaves similarly to sodium and could be incorporated into the muscle tissue of the body. It has been postulated that ingestion of radiocesium could result in genetic and other long term damage, but again the quantities ingested as a result of a nuclear attack do not appear to present problems nearly as severe as many other attack consequences.

Many persons, including scientists, have made estimates of the effects of these and other radioisotopes. It is possible by making extremely pessimistic assumptions to calculate that disastrous consequences will result. However, the experimental evidence, beginning to accumulate, shows considerably lower values for assumptions, such as the radioisotope availability, solubility, and uptake than originally used. Also, the amount of radioactive material transmitted through animal milk and meat to humans has been found to be less than earlier estimates. The internal emitter problem should not be discounted but if proper precautions are used most scientists familiar with the problem agree that inhalation and ingestion of fallout material is strictly a second order problem compared with exposure to external gamma radiation.

Offsetting the findings of reduced hazards due to internal emitters is the effect of radiation on plant life, which heretofore has been thought to be more resistant than animal life by a factor of at least ten. Experience at the Brookhaven National Laboratory and the Lockheed unshielded reactor at Marietta, Ga., indicates that many plants have radiation sensitivities comparable to many animals, including man. Therefore, it is possible that wide scale fallout could have a significant effect on domestic and wild vegetation resulting in crop damage or even more importantly in ecological upsets. Fortunately research in this field is receiving greater emphasis and this problem should be better understood in a few years.

Finally, for the postattack era when people will emerge from shelter and set about reestablishing the society, decontamination and reclamation procedures have been developed. But, it has been clearly established that decontamination has no practical value unless shelterees and decontamination crews have had substantial fallout protection during the early period after an attack when most of the radiation dose would be accumulated. These decontamination procedures, of course, need improvement, but as of now it is possible to estimate with some confidence the amount of material that would have to be removed in decontaminating, for example, a street or a parking lot. Also known are the types of equipment best adapted to the job, as well as the time it would take, and the radiation dosage the crews would receive during decontamination.

In summary, in a nuclear war we most likely would have to contend with a serious fallout threat. External exposure to the gamma radiation from fission products and induced radionuclides is the most serious part of the problem. The internal emitter problem is of second order importance albeit no doubt worse than "just a bad cold."