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THERMAL RADIATION AND FIRE EFFECTS OF NUCLEAR DETONATIONS

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The material given in Figure 5 and Tables 2 and 3 is derived from laboratory exposure of materials in a plane, normal configuration using a small (maximum diameter, 3/4 in.), apertured spot of uniform irradiation. It therefore ignores any possible influence of sample geometry and area. Some of these data have been confirmed for larger area samples exposed to low yield weapons during weapons tests. However, for the longer pulses of high yield weapons, there is some evidence of increased flaming ignition susceptibility in materials exposed under less ideal conditions - the threshold approaching more closely the threshold for glowing ignition.

The ranges given in Figure 3 are horizontal ranges from ground zero.

ABSTRACT

An unclassified state-of-the-art review of the thermal effects of nuclear weapons, this report summarizes the pertinent information available at the end of 1962. Evidence is presented to show that, in a nuclear weapon attack on targets in urban and rural areas, thermal radiation and fire can be expected to make a major contribution to the destruction of life and property. The characteristics of the emitted thermal radiation, the radiant exposure as a function of distance, and the effects produced by this radiation are summarized. The formation, spread, and control of fires and possibilities for survival in fire zones are discussed. Fire countermeasures which might prove effective in reducing the extent of thermal damage are set forth.

SUMMARY

The Problem:

To assist military and civil defense planners in the assessment of thermal radiation injury and fire potential of large scale nuclear weapons attack.

The Findings:

Lack of information on atmospheric transmittance and the behavior of mass fires prevents precise description of events following a nuclear detonation. It is clear, however, that thermal radiation and fire would make a major contribution to the destruction of life and property caused by the combined effects of the detonation.

The extent of thermal damage can be significantly reduced by (1) the elimination of kindling fuels, (2) the isolation and rapid extinguishment of ignited fuels, (3) the establishment of large fire breaks, (4) the use of properly planned and located underground shelters, and (5) under some circumstances, the pre-attack use of smoke screens and other shielding devices.

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I. INTRODUCTION

Under many circumstances the thermal radiation and fire effects of nuclear detonations may be expected to cause greater numbers of casualties and more destruction over larger distances than nuclear radiation and blast combined. In fact, high yield weapons raise the possibility of high altitude detonations to maximize fire effects. Such detonations present no early fallout hazard nor significant blast effects. Thus, a major concern of any effective civil defense program must be to find means of reducing thermal radiation and fire effects. The growing recognition of this fact has led to some extreme statements concerning the hazard to be expected -- all too frequently with no attempt to indicate the facts behind such statements. This report presents a realistic appraisal of the facts -- indicating what is known to be correct, what is known to be incorrect, and what areas remain quite uncertain. It is hoped that this will provide a realistic picture of what can be expected following a nuclear attack without glossing over the disastrous consequences which may occur and yet without exaggerating a problem which is bad enough even when considered conservatively.

2. CHARACTERISTICS OF THERMAL RADIATION*

All of the energy released by a nuclear detonation, including that of the radioactive debris, ultimately is degraded to thermal energy, i.e., heat. For the purposes of this report, however, we concern ourselves only with the thermal radiation which is intense enough after traversing relatively large distances through the atmosphere, to produce effects on materials. Therefore, we will limit our attention to that fraction of thermal energy, in the visible and near infrared part of the spectrum, which is emitted in seconds or less after the detonation. This report will deal primarily with air bursts (detonations at low altitudes but not so low that the fireball touches the earth's surface). Important deviations for other conditions of detonations will be indicated.

One of the unique characteristics of a nuclear detonation is the release of a large amount of energy in a small mass of material, raising this mass to extremely high temperatures. The result of these high temperatures is the release of large amounts of short wavelength energy (thermal x-rays) which in an air burst are absorbed in a short distance by the surrounding air -- generating a fireball whose color temperature, during the effective part of the thermal radiation pulse,

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* A more detailed discussion of the material in Sections 2 and 3 of this report may be found in Reference 1.

averages some 6,000°C (roughly comparable to the temperature of the sun). As a consequence approximately a third of the energy release of the nuclear reaction appears as thermal radiation distributed over the visible and near infrared regions with roughly equal portions of the energy in each part.

In reality the radiation is emitted in two pulses; but, except for detonations above the atmosphere, the energy contained in the first is an insignificant part of the total. The temporal characteristics of the radiation emitted by the fireball in the second (i.e., effective) thermal pulse are displayed in Fig. 1. The ratio of the total thermal energy, E, to the weapon yield, W, is the thermal efficiency, f, which for air bursts of all yields is approximately constant and equal to 1/3. The time scale in Fig. 1 is normalized to the time of maximum radiant power emission t_{max} to make the figure generally applicable to all yields. Values of t_{max} are scaled as $W^{1/2}$.

If the height of burst is low enough to permit the fireball to contact the surface, interaction between the fireball and surface material lowers the effective temperature of the fireball and reduces the thermal efficiency. The thermal efficiency is reduced from the value 1/3 for an air burst to 1/5 for a contact surface burst, i.e., a burst in which the weapon itself is in contact with the surface at the time of detonation. Of course, for a deep underground burst which

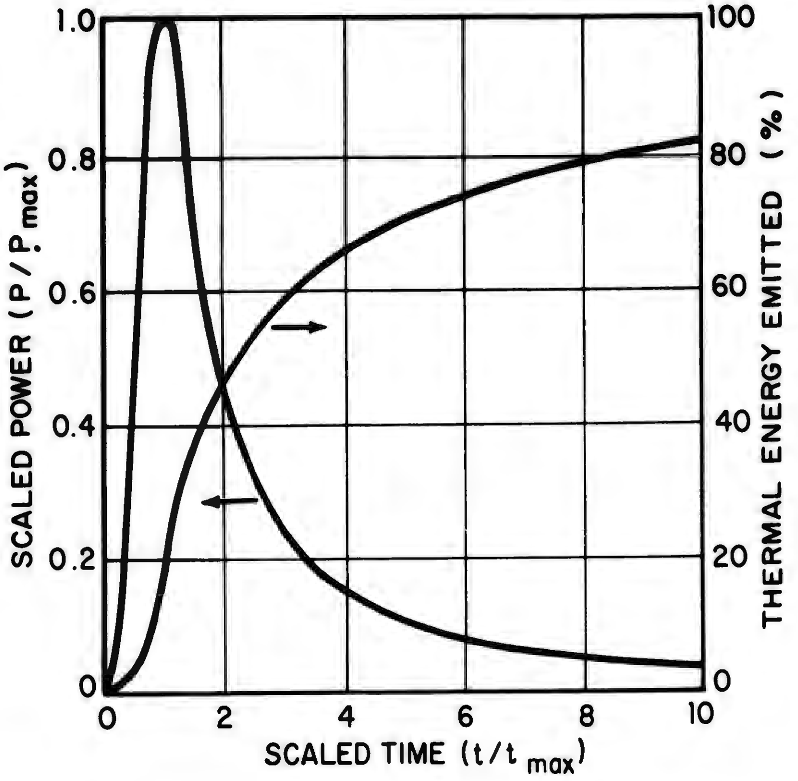

Fig. 1 Effective thermal pulse of an air burst. This plot of scaled power and fraction of thermal energy versus scaled time for the second thermal pulse is generally applicable to all air bursts regardless of yield.

does not break the surface, the thermal efficiency is reduced to zero.

Significant changes also occur in the proportion of energy appearing as blast and thermal radiation for detonations at high altitudes, where the air density is low. Some general statements about high altitude effects can be made based on theoretical considerations and a limited number of tests but the quantitative information is less certain than for low level atmospheric bursts. With increasing altitude above about 100,000 ft, blast energy declines relative to thermal energy and the first short thermal radiation pulse grows until it contains a significant fraction of the total thermal energy. For very high altitude bursts, the thermal radiation arrives at the ground in a single pulse which reaches its peak almost instantaneously and subsides rapidly to a low level which persists for some time. About half of the energy reaching the ground arrives in less than a second for a megaton-range detonation at 250,000 feet. The remaining energy is emitted so slowly that it does not produce any significant effects on exposed materials. Thus, it is expected that the amount of thermal radiation in the effective portion of the pulse from a high altitude burst will be less than from an air burst of the same total yield.

3. RADIANT EXPOSURE OF DISTANT SURFACES

Consider the idealized case of a nuclear weapon detonation in an infinitely extensive non-attenuating atmosphere. The total thermal energy, $E = fW\ (KT) = fW.10^{12}$ (cal) will distribute itself at a distance D (cm) over a sphere of area $4\pi D^2 (cm^2)$. Thus, the energy per square centimeter (called the radiant exposure, Q) falls off as the inverse square of the distance, and at the distance, D will be

$$Q = \frac{fW.10^{12}}{4\pi D^2} \quad (cal/cm^2),$$

or expressing D in miles* (and taking $f = 1/3$)

$$Q \approx \frac{W}{D^2}$$

This is the basis for the popular "rule of thumb" -- for each KT of yield, a radiant exposure of 1 cal/cm^2 will be delivered at 1 mile.

The rate at which the radiant exposure is delivered is called the irradiance H and bears the same relationship to the radiant power P as Q does to E. Therefore, the scaled time relationships of power and energy shown in Fig. 1 apply equally well to the analogous quantities dealing with exposure of a surface at any distance from the point of detonation.

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* The unmodified term "miles" will be used to mean U. S. statute miles.

The radiant exposure of a material will, in general, be less than indicated above. If the exposed surface is not normal to the rays of the radiation, the radiant exposure will be reduced as the cosine of the angle from the normal. Any obscuring material, including microscopic particles, in the air between the fireball and the target will reduce the radiant exposure. Opaque, solid objects completely attenuate direct thermal radiation. Depending upon the wavelength, air both absorbs and scatters it; but, for those wavelengths which are not absorbed relatively close to the fireball, air is primarily a scattering medium. At large distances, the radiation "scattered in" may be as large or larger than the direct radiation. In this case, the shielding afforded by opaque materials in the line of sight may be significantly lessened.

From a practical point of view, it is convenient to express the overall atmospheric transmittance $\bar{T}$ (defined as that fraction of the thermal radiation which arrives at a distant point having traversed an intervening scattering atmosphere) in terms of visibility or visual range. The meteorological term "visibility" is the distance at which it is just possible to distinguish a dark object against the horizon; i.e., it is the distance at which the contrast between an object and its surroundings approaches the visual threshold of discrimination. The optical term "standard visual range" represents an attempt to define the same concept more precisely, namely, as that distance at which the contrast transmission of the atmosphere is 2 percent. For practical purposes the two terms may be used interchangeably. They both embody the concept of exponential reduction in direct (line-of-sight) transmission of light with distance.*

Because the radiant exposure is the sum of both the direct and scattered energy reaching a surface, it is not obvious that the overall transmittance $\bar{T}$ is related in any useful way to the visibility except for the case where scattered radiation is a negligible portion of the total. In fact, in a purely scattering infinitely extensive homogenous atmosphere, $\bar{T}$ is independent of visibility and distance since as much energy is scattered into a given volume as is scattered out. In any real atmosphere, however, a significant fraction of the scattered energy is lost -- as a result of absorption by the ground and upward scatter out the top of the atmosphere. Thus, the clearness of the atmosphere and, hence, the visibility, does appreciably influence the overall transmittance.

An estimate of the variation of transmittance with distance for two different visual ranges is given in Effects of Nuclear Weapons (ENW)[3] and is reproduced here as Fig. 2. Unfortunately, the curves are

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* An excellent discussion of this subject may be found in Reference 2.

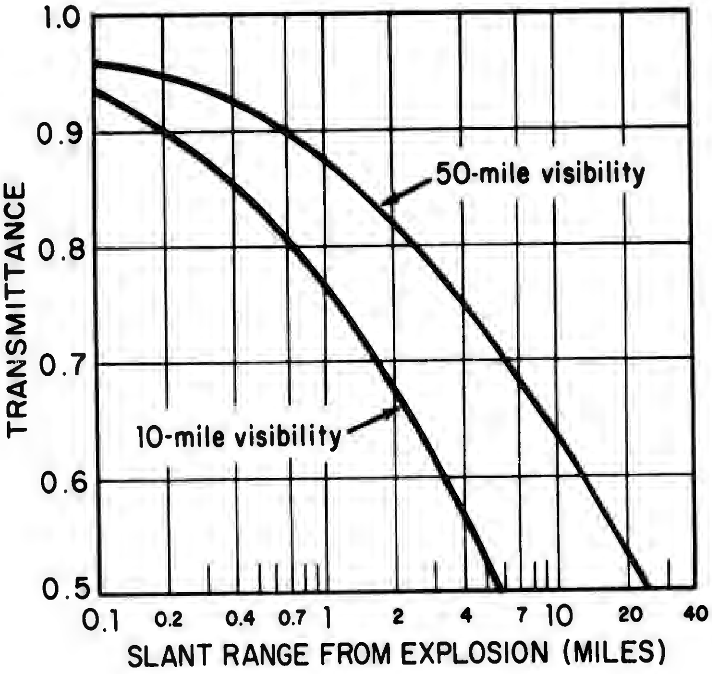

Fig. 2 Atmospheric transmittance as a function of distance for visibilities of 10 and 50 miles.

considered to be reliable only to distances of half the visual range -- although distances of interest for high yield detonations may extend well beyond those given in Fig. 2. Further, recent measurements[4] of transmission from a 4π light source (not a nuclear weapon) out to distances of more than one visual range indicate that the transmittance may fall off faster than indicated in Fig. 2. In Table 1, the transmittance values from the two references are compared with distance expressed in terms of the visual range. There is a large discrepancy even at normalized distances less than 1/2.

TABLE 1 ATMOSPHERIC TRANSMITTANCE AS A FUNCTION OF DISTANCE IN TERMS OF VISUAL RANGE*

Distance in Terms of Visual Range	$\bar{T}$ From Fig. 2[1]	$\bar{T}$ From NRDL-TR-554[4]
0.01	0.92	0.92
0.02	0.89	0.88
0.05	0.82	0.79
0.1	0.75	0.68
0.2	0.67	0.51
0.5	0.52	0.25
1.0	0.4(?)	0.1
2.0	0.2(??)	0.02

*The values in column 2 are averaged for the two curves given in Fig. 2 of this report. The values in column 3 are averaged for visibilities of 6 and 12 miles in Los Angeles and 35 and 65 miles at the Nevada Test Site. Part of the discrepancy may be attributable to the effect of urban air pollutants.

This uncertainty in atmospheric transmittance is an extremely serious one. For large weapon yields it represents an uncertainty in range of thermal effects far and away larger than any others which may be introduced. Further, the discrepancy shown in Table 1 does not represent the extreme, for while the lower set of $\bar{T}$ values probably represent the lowest values proposed, the upper set are by no means the highest.[5]

Currently available weapons test data offer little help in this matter. There is a paucity of pertinent radiant exposure data at distances greater than half the visual range. In a recent Pacific test series a limited number of measurements were made at distances of about 15 to 30 miles from the point of detonation.[6] Visibilities of 10 nautical miles were listed in the weather reports for all events, and preliminary data indicate transmittances in the range of 20 to 25 percent. However, it is quite unlikely that the visibilities were really identical on all events -- particularly since they occurred over a period of a month or more. Probably these estimates are of a gross, subjective nature of the sort made from aircraft or aboard ship when objects of known distance are lacking. For example, "clear" (International visibility code, index 7, ship code 98) and "very clear" (International visibility code, index 8, ship code 99) representing one step in the subjective visibility scale correspond to visual ranges of 10 and 27 nautical miles, respectively. Without better estimates of the visual range, these data do not enable us to choose between the two sets of transmittance values.

In Fig. 3, radiant exposures normalized to 1 KT are displayed as a function of distance for the two sets of transmittance values and for the case of a 15-mile visibility. As may be seen, for distances appreciably greater than 15 miles the curves may differ by almost a factor of 2 in range computed for the same radiant exposure and by factors of 5 or 10 for radiant exposures at a particular distance.

4. EFFECTS PRODUCED

In terms of distance from the point of detonation (but not in terms of numbers of casualties), the production of retinal burns is perhaps the most extensive thermal effect of nuclear detonations. This biological response is expected to occur for radiant exposures as low as 0.1 cal/cm^2 delivered in less than about 0.15 second (the blink reflex time).[7] Such levels are more than an order of magnitude lower than that required for other thermal effects. They occur at distances of the order of 1 - 2 visual ranges for nominal yield weapons at low altitude and at distances of several hundred miles for megaton weapons at high altitude, although for high yield weapons at low altitude, the increased pulse duration greatly reduces the distance at which such levels are found.

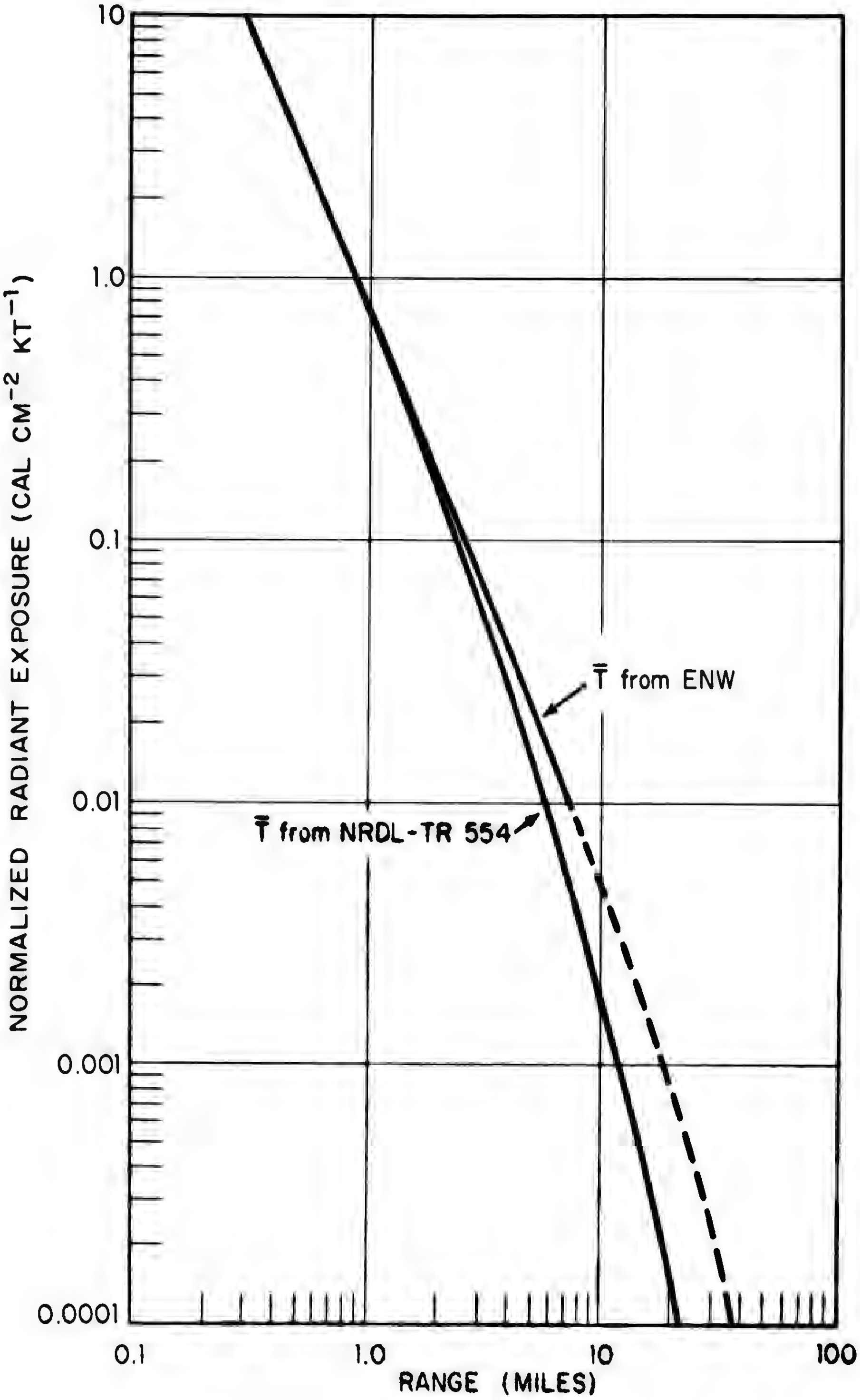

Fig. 3 Radiant exposure per kiloton of yield as a function of slant range.

A cursory glance at the anatomy of the eye and some elementary optics provides an explanation for this extreme sensitivity. The eye consists of a lens system which refocuses any impinging light rays into a retinal image of the emanating source. Assuming a fixed initial condition of the eye and neglecting any effects of atmospheric attenuation, as distance from the detonation increases, the amount of energy per unit area of the retinal image does not change (until chromatic aberration becomes significant). Instead, the size of the image, and therefore the size of the burn lesion, decreases.

Although scattered light can cause temporary flash blindness, it cannot be focused into a small, sufficiently intense image to produce retinal burns. Thus, retinal burns at such extreme distances will occur only in those instances of eyes which happen to be looking in the direction of the detonation at the instant of detonation. Further, since only the more serious burns centrally located in the visual field produce a loss of visual acuity, cases involving a considerable loss of vision will be even more rare.

Coming in closer to the point of detonation, the next effect expected is "flash burns" on bare skin. Thermal radiation "flash burns" are quite similar to burns from other agents and are classified in the same fashion.

First degree: Reddening of the skin. Very painful but not particularly serious. Healing will occur (no scarring) without treatment.

Second degree: Deep with blister formation. Treatment required. Infection likely, combined with loss of body fluid may be fatal (depending on area of burn); at least incapacitating.

Third degree: Full thickness of skin destroyed. Extensive treatment required. Fatal if area is large.

The radiant exposure required to produce a burn is dependent upon the rate at which it is delivered and, therefore, upon the duration of the thermal pulse. Accordingly, for the same radiant exposure, large yield weapons are less effective than small ones, as indicated in Fig. 4 where approximate radiant exposure values for the production of first and second degree burns on bare skin are plotted against weapon yield.[8]

Another important factor influencing the direct thermal radiation effects on exposed personnel is the amount and kind of clothing worn. Clothing in general reduces burn susceptibility. Moderately heavy clothing will provide protection for the covered areas at radiant exposures less than those which will ignite the fabric -- except when the clothing is dark colored and in direct contact with the skin.

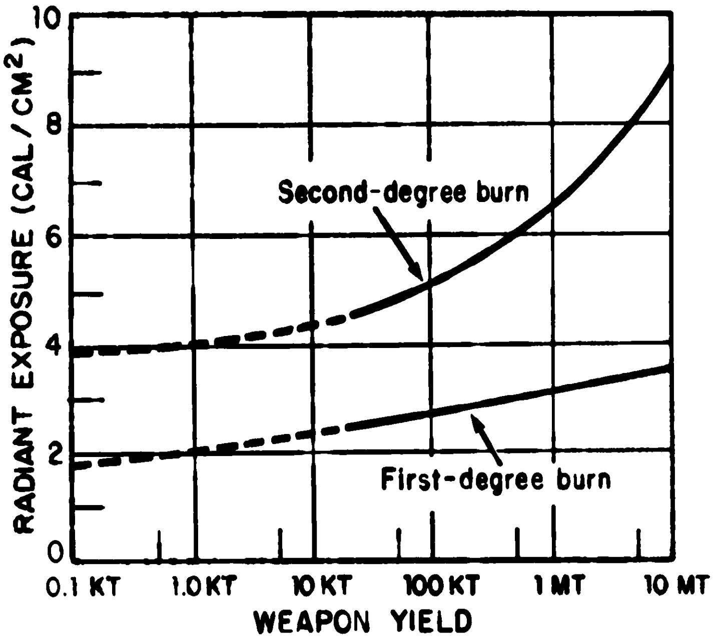

Fig. 4 Radiant exposures to produce burn injuries as a function of weapon yield.

At about the same distance from a detonation at which second degree burns would result from direct exposure of bare skin, some of the more susceptible kindling fuels would ignite. This, then, might be expected to be the extreme range of immediate incendiary effect. Before detailing ranges of incendiary effects and proceeding to the mass fire problem, it is worthwhile to consider the various factors influencing ignition behavior.[9-13]

The radiant exposure required to ignite a material depends primarily on the following factors: the yield of the weapon (or, more rigorously, the time-irradiance characteristics of the thermal pulse); the chemical composition, color, thickness and volumetric heat capacity of the material; and the amounts and kinds of extraneous substances it contains. Secondary factors include: the relative humidity of the environment, and certain ill-defined geometric factors. Some generalizations can be made which simplify the problem of estimating incendiary ranges.

Perhaps the most susceptible kindling fuels to be found are the thin, natural fuels such as dried deciduous leaves, fine grasses, duff and rotted wood (punk). Newspaper is the commonest man-made kindling fuel in this category. A second common, but less susceptible class of kindling fuels is typified by Kraft corrugated board ("cardboard" box material) and includes much industrial trash, heavy paper products, light fabrics, and most of the heavier wildland kindling, such as thick, opaque broadleaf leaves and conifer needles. A third class is typified by drapery-weight fabric and includes awnings, furnishings, and other heavy fabrics. Materials much thicker than those in the third class are not ignited to sustained combustion by the thermal pulse of a weapon detonation. The thicker fuels may char, perhaps quite badly, and flames may often be produced during the application of radiant energy; but the temperature through the fuel will not be raised sufficiently to sustain ignition, and any flames which are started die out immediately after the exposure.

Figure 5 shows the ignition behavior of three commonly occurring materials representing the three classes of susceptibility. In this figure, the radiant exposure for ignition is plotted against weapon yield. Also shown is the extreme limit for glowing ignition, i.e., ignition which produces smoldering combustion rather than flames. This limit is derived from the observation that the peak irradiance of an airburst thermal pulse, up to the maximum yield considered (100 MT), must exceed about 1 cal $cm^{-2}sec^{-1}$ for ignition to occur at all in cellulosic materials (no matter how high the yield, the irradiance at the instant of ignition must exceed 0.5 cal $cm^{-2}sec^{-1}$), and must be considerably higher than that to produce flames. It must be emphasized that this is only a necessary (and not of itself a sufficient) condition

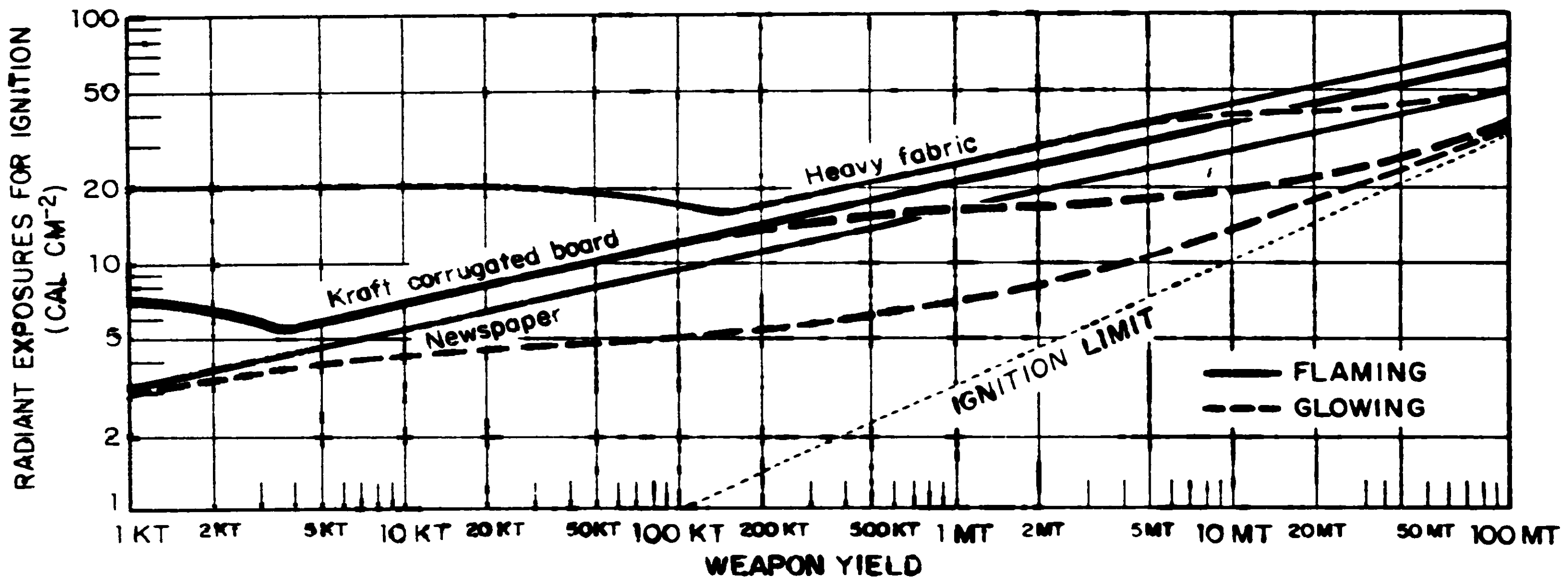

Fig. 5 **Radiant exposures to ignite materials (40 to 50 percent relative humidity) as a function of weapon yield.**

NOTE: **The material given in Figure 5 and Tables 2 and 3 is derived from laboratory exposure of materials in a plane, normal configuration using a small (maximum diameter, 3/4 in.), apertured spot of uniform irradiation. It therefore ignores any possible influence of sample geometry and area. Some of these data have been confirmed for larger area samples exposed to low yield weapons during weapons tests. However, for the longer pulses of high yield weapons, there is some evidence of increased flaming ignition susceptibility in materials exposed under less ideal conditions - the threshold approaching more closely the threshold for glowing ignition.**

for ignition since the radiant exposure values also depend upon the thickness of the material as demonstrated in the three example curves. The limit is included in Fig. 5 only to provide a way for estimating the extreme incendiary range as a function of weapon yield.

The incendiary range of practical importance in any actual situation will depend upon the type and distribution of kindling fuel within that particular target area. Whether or not a major fire develops depends upon how many fine fuels are ignited and how they are distributed with respect to the thicker fuels into which the small fires must merge and spread. Each situation will be different, and in any fire assessment procedure based on radiant exposure levels, it will be necessary to take these factors into account.

Many urban and industrial areas and most rural and wildland areas have high concentrations of thin cellulosic materials distributed in such a way as to constitute a significant fire hazard. For areas like these, radiant exposure values for the ignition of the more common members of the most susceptible class of kindling fuels probably provide a realistic estimate of incendiary range. For example, when exposed to a 1 KT detonation under conditions of 40 to 50 percent relative humidity, class 1 materials ignite at radiant exposures between 2 and 3 cal cm^{-2} (flaming and glowing ignition thresholds are essentially indistinguishable for a 1 KT detonation). Assuming a 15 mile visibility, these materials will, therefore, ignite out to a radius of about a half mile from the point of detonation. The same materials exposed to a 10 MT air burst will exhibit glowing ignition at radiant exposure values of 10 to 15 cal cm^{-2} -- approaching the irradiance-governed ignition limit (Fig. 5). The corresponding radius for the assumed environmental conditions will be roughly 10 to 20 miles depending upon our choice of atmospheric transmittance for 15-mile visibility. Flaming ignitions will require exposures greater than the 1 KT case by nearly an order of magnitude -- extending out some 9 to 13 miles from ground zero.

Earlier in this report it was pointed out that high altitude detonations are thermally less efficient than low altitude air bursts. Detonations at about 1 to 2 fireball radii above the surface clearly maximize the initial fire zone for small and intermediate yield weapons. With increasing yield above about 10 MT, however, it appears likely that the incendiary ranges of high altitude bursts become large compared to those for air bursts. This comes about, despite the inherently larger slant ranges, because of two factors: (1) the brief thermal pulse of a high altitude burst is more efficient at igniting materials, and (2) the reduced path through dense air minimizes atmospheric attenuation.

Because of the short pulse time, the radiant exposure values for ignition by the high altitude detonation of megaton yield weapons are probably not greatly different from the values for a 1 KT airburst. Our limited experiences with high altitude bursts suggests that "effective" pulse durations are measured in hundreds of milliseconds -- increasing with yield but decreasing with height of bursts (HOB). Recent laboratory measurements indicate that, for pulses this short, radiant exposures for ignition are essentially independent of pulse duration.*

The increasing downward curvature that atmospheric attenuation introduces into the radiant exposure versus distance curves, especially the lower curve in Fig. 3, suggests that for low altitude bursts there is a point of diminishing returns in range of effects with increasing yield. For high-altitude detonations it is very difficult to assess the atmospheric transmittance. The radiation passes through air of widely varying density and composition on its way to the earth's surface. The same uncertainties which muddied our picture of the airburst are compounded by additional ignorance of the vertical distribution of scattering and absorbing media. It is clear, however, that in the absence of cloud cover, the attenuation will be less than for an equal distance along the ground.

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*A USNRDL Technical Report is in preparation on the subject of ignition of cellulosic kindling fuels by very brief radiant pulses.

One way of estimating the effect of the atmosphere on radiant levels from high altitude bursts is to use the "reduced height" concept.[14] For radiant transmission purposes, the atmosphere is thought of as being completely contained in a uniform layer at sea level density. The transmittance values for along-the-ground propagation are applied to that portion of the radiation path which passes through this layer. This type of calculation gives a 50 to 60 percent transmittance for angles above the horizon greater than about 40 degrees when the visibility along the ground is 15 miles. These values are independent of the overall distance. Thus, for example, at a horizontal distance of 50 miles from the ground zero of a 50-mile HOB detonation, the radiant exposure would be at least half of the inverse square value for surface visibilities of 15 miles or more.

Table 2 displays the estimated radiant exposures for ignition of kindling fuels for weapon yields ranging from 1 KT to 100 MT. Table 3 summarizes the material presented to this point by listing ranges of effects anticipated for several weapon yields under conditions of moderate relative humidity and average-to-good visibility.

TABLE 2 THRESHOLD RADIANT EXPOSURES FOR VARIOUS EFFECTS

(All values in cal/cm^2)

Weapon Yield	Second Degree Burns	Ignition of Most Susceptible Fuels		Ignition of Kraft Corrugated Board		Ignition of Heavy Fabrics	
		Glow	Flame	Glow	Flame	Glow	Flame
1 KT	4	2-3	2-3	--	7	--	20
10 KT	4.5	3-4	4-5	--	7	--	20
100 KT	5	4-5	6-9	--	12	--	17
1 MT	6	5-7	11-16	16	21	--	25
10 MT	9	10-13	20-30	19	36	38	43
100 MT	?	30	60	35	64	48	75

NOTE: Materials with significant mineral content exhibit increased susceptibility to glowing ignition. Radiant exposure values for glowing ignition may be reduced as much as a factor of 2 from indicated values. High mineral contents enhance glowing to the exclusion of flaming.

TABLE 3 APPROXIMATE HORIZONTAL RANGES OF EFFECTS FOR 15-MILE VISIBILITY

(All values in miles)

		Ignition of Most Susceptible Fuels		Ignition of Kraft Corrugated Board		Ignition of Heavy Fabrics	
Weapon Yield	Second Degree Burns	Glow	Flame	Glow	Flame	Glow	Flame
1 KT	0.5	0.6	0.5	--	0.4	--	0.2
10 KT	1.3	1.5	1.3	--	1	--	0.8
100 KT	3.5	3.5-4	3	--	2.3	--	2
1 MT	7-9*	7-10*	6.5	5-6	4.5-5.5	--	4-5
10 MT (air burst)	12-19*	11-18*	9-13*	10-14*	8-11*	8-11*	7.5-10*
10 MT (20-mile HOB)	--	--	15-25*	--	--	--	--
100 MT (air burst)	--	17-28*	14-22*	16-26*	14-22*	15-24*	13-21*
100 MT (50-mile HOB)	--	--	60-90*	--	--	--	--

* Indicates larger value (based on $\overline{T}$ from ENW) determined by extrapolation beyond half the visual range.

5. FORMATION, SPREAD AND CONTROL OF FIRES*

The ignition of thin kindling fuels by thermal radiation is of concern only because fire has the property of spreading to contiguous thicker fuels. Thus, the growth from a large number of small, isolated ignitions to a fully-developed mass fire depends not only on the presence of kindling fuels, but also on the presence and spacing of all combustible material in the area. Consequently, fuel factors which affect susceptibility in conventional fires are also of concern in assessing vulnerability to thermal radiation.

Open areas -- bodies of water, marshes, roads and airport runways, cemeteries, and golf courses and similar recreation areas -- have few locations in which fire can originate, and any small fires which do start usually cannot spread far. If these areas are large, they constitute a major firebreak between the more susceptible regions. The more sparsely populated and vegetated surburban regions represent areas in which fires may spread beyond their point of origin, but are not expected to merge and form mass fires. In the more densely populated urban areas, and in highly vulnerable brush and forest lands, mass fires -- fire storms or conflagrations -- are to be expected when conditions are right.

Considerable information concerning fire spread has been obtained from the many wildland fires which occur annually in the United States.

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* A more detailed discussion of the material in this section may be found in Reference 15.

A check of such fire records indicates that there are predictable periods of the year which, on the basis of rainfall, temperature, and relative humidity occurrence, may be defined as the fire season. Such normal fire seasons, as determined by local climate and natural fuel conditions, are shown in Fig. 6 for the different parts of the United States.[16]

During the fire season, high humidity in the period preceding an attack would be important only in the beginning stages of a fire. Kindling fuels are thin and respond rapidly to changes in humidity. Thus, a very short period of sunshine, even after a heavy rain, will dry out many of these fuels. In fact, the energy in the thermal pulse itself can dry out and then ignite the kindling fuel, although at a somewhat higher energy level than that required for dry fuel. Both laboratory and field data indicate that a good estimate of the effect of relative humidity in increasing the radiant exposure over that necessary for ignition of the dry fuel may be made by multiplying by the simple factor

$$F = 1 + 0.005\,H$$

where H is the relative humidity in percent.[5]

In urban areas, weather does not influence fire spread as much as has been frequently assumed. For example, if one considers the danger from indoor ignition, one finds that the seasons considered

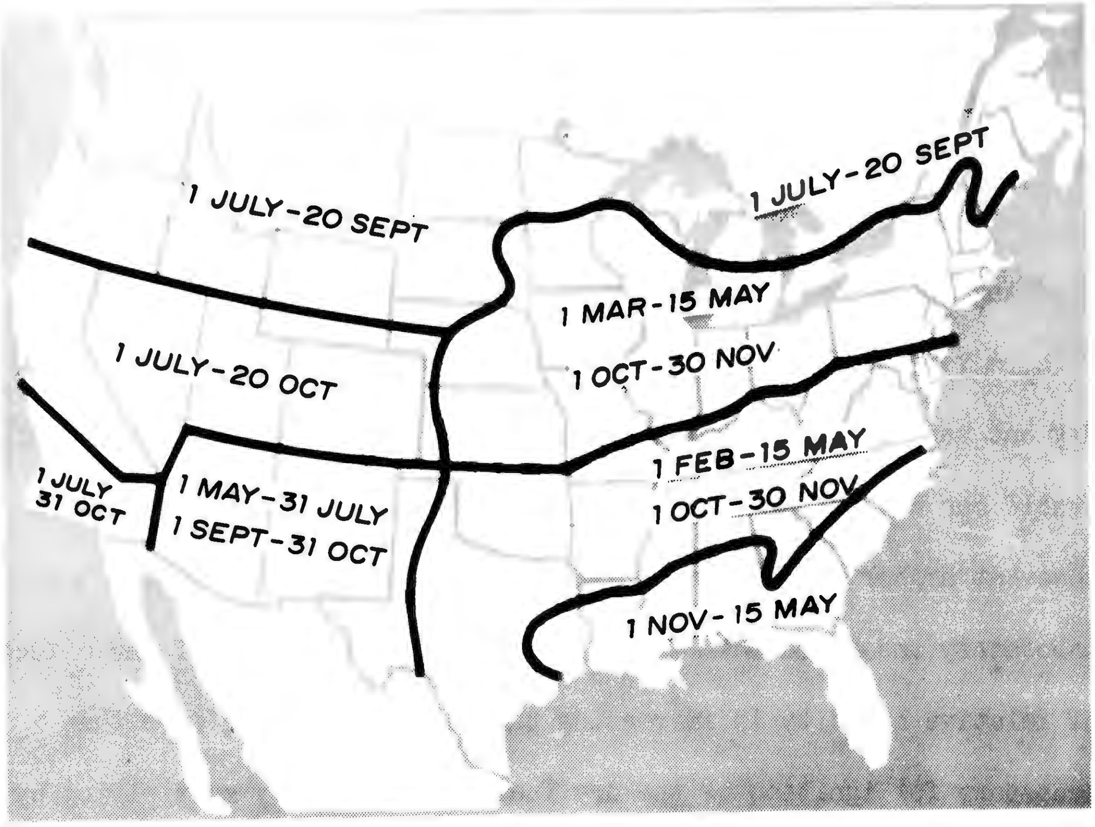

Fig. 6 Fire Seasons Map of the United States (From Reference 16).

safe in the case of forest fires are frequently the most dangerous in the case of nuclear attack. Thus, in the northern part of the United States, the winter months are considered as a period of safety from forest fires. Yet, during these months most buildings are heated. Where humidifiers are not in use, the humidity conditions indoors are dangerously low, perhaps lower than they ever are outdoors; and the hazard from fire starting indoors is extremely high. Once a fire is well established indoors, it can readily overcome the retarding effect of moisture in heavier exterior fuels. Studies conducted during the last war indicate that even when rain was falling during conventional fire bomb attacks, the damage produced averaged only 20 percent less than that produced under favorable weather conditions.

Appropriate fire control action may be directed along three lines, namely, (1) reduction in number of potential ignitions, (2) provision for isolation or rapid extinguishment of ignitions to prevent formation of serious fires, and (3) minimization of fire spread potential should large-scale fires be produced. Effective fire control steps which may be taken range from very simple ones, readily put into effect, to complex and costly ones. For example, reduction in the number of potential ignitions may be accomplished by removal of kindling fuels. The elimination of wood as a construction material and its replacement by concrete, brick, and metal, of course, is one step (a rather expensive one) in this direction. Continuous upkeep of existing wood structures to prevent the exposure of rotting wood is a cheaper step in the same direction.

The effectiveness of eliminating kindling fuels in reducing ignitions was rather strikingly demonstrated in a civil defense experiment during Operation Upshot-Knothole, the atom bomb test series conducted in Nevada in 1953.[17] Three mock-up frame houses were constructed at identical distances from ground zero and exposed to one shot during that operation. One of the houses was well maintained and had a painted wood siding and a clean yard. Another house had a clean yard but had unpainted, weathered, decayed siding. The third house was poorly maintained and was surrounded by adjacent dry weeds and trash. After the detonation, the first house showed only mild scorching and was not significantly damaged. The second house smoldered awhile but finally burst into flames and burned to the ground. The third house was ignited and quickly consumed.

If kindling fuels cannot be eliminated, shielding of such fuels from a heat flash is an effective means of eliminating the danger. Thus, ignitible trash in covered metal containers will not be ignited by a heat flash. Covering windows in existing structures or constructing windowless buildings can minimize ignition of internal kindling fuels. Shielding of large regions by smoke screens may effectively reduce vulnerability to heat, whereever the smoke is dense enough to reduce the energy delivered to levels below critical. The screen must (1) be laid down before the detonation, (2) be large enough to minimize the probability of fire spread to the covered area, and (3) be absorbing or, if scattering, sufficiently low so that it does not scatter or reflect additional radiation downward.

Once the number of potential ignitions has been reduced to a bare minimum, the next major step is to plan and train for the elimination of those ignitions which do occur before they can grow into serious fires. Ignitions remote from any large combustible complex may be allowed to burn out with minimal over-all effect. Since all other ignitions must be extinguished promptly, a first aid type of fire fighting must be adopted. Everyone must be taught to act promptly after the immediate effects of a detonation are over and to try to extinguish all such incipient fires within his immediate reach. In the first few minutes many of these fires can simply be stamped out. Small fire extinguishers, readily available, or even buckets of water or sand are extremely useful in these early times. If each person extinguishes enough of these small fires early enough, perhaps few will grow sufficiently large to require the services of a professional fire department.

Even after everything possible has been done to minimize the probability of formation of large fires, steps must be taken to minimize the effects of these fires should they occur. Fire fighting plans must utilize natural firebreaks to provide the utmost in fire protection (whether or not they ultimately prove to be effective). In planning the location of such potentially useful firebreak areas as new parks and freeways, their fire protection utility must be taken into account. Highly combustible regions must be eliminated as soon as possible. Finally, considerable research and training effort must be expended on techniques for the fighting of such mass fires.

6. SURVIVAL IN FIRE ZONES*

In seeking information about the environment in large scale fires we find, unfortunately, all too much practical experience to draw upon.

London in 1666, Moscow in 1812, Chicago in 1871, and San Francisco in 1906 are perhaps the best known examples. Not so well known are the large forest fires -- single fires that have covered millions of acres. For example, on October 8, 1871, the date of the Chicago fire, fires in Wisconsin and Michigan burned almost four million acres, with a loss of life many times greater than was experienced in Chicago.

The bombing attacks of World War II, however, added a new dimension to the fire problem. Large areas could now be ignited more

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*A more detailed discussion of the material in this section may be found in Reference 18.

or less simultaneously, enveloping whole cities in fire and burning them to the ground in a matter of hours. The old city section of Hamburg took four days to burn in 1842. In contrast, in the fire raid on Hamburg on July 27, 1943, two-thirds of all the buildings in a 5-square-mile area were ablaze within 20 minutes. Within a few hours, the fire had begun to run out of fuel and die down, although hot rubble made large areas unapproachable for several days.

There is a tendency to forget that even before the introduction of atomic weapons at the end of World War II, such total devastation had been inflicted a number of times by conventional fire attacks on cities in Germany and Japan. For example, a fire raid on Tokyo on March 9, 1945, caused a mass fire which destroyed an area of 16-square-miles (compared with less than 5-square-miles in Hiroshima and less than 2 in Nagasaki), and caused more than 80,000 deaths and more than 100,000 injuries, perhaps more casualties than in Hiroshima and Nagasaki combined.

The largest fires already observed have been sufficiently large that no new factors are expected which would significantly influence the environment within the fire zone. For example, the violent indrafts so characteristic of a fire storm can penetrate less than half a mile into a fire area. Inside these limits, air to feed the fire comes as a result of mixing with the atmosphere above, rather than laterally. Thus, to people in the center of a mass fire a mile or so in diameter, the fire is already infinitely large, and their environment would be no different if the fire were ten or a hundred or a thousand times larger.

Once a mass fire has formed, the usual prognosis for people trapped within the fire area is not very favorable. However, a careful look at our fire experiences of the past, together with experimental results obtained on a much smaller scale indicate that, with certain precautions, a survival in simple underground shelters in the middle of a fire zone is highly probable.

It must be conceded that people trapped in the open or in combustible structures in mass fire areas will succumb from a large variety of effects, and in such situations speculations as to the major cause of death is most unprofitable. In the same category may also be included effects on people in make-shift combustible shelters located in the basements of combustible residences. Since rubble in a burned out area may smolder for days -- producing high temperatures and toxic atmospheres -- shelters (and in particular shelter vents) located where they will be covered by deep piles of hot rubble offer little protection, except in the case of heavy reinforced concrete shelters located deep underground and with an independent supply of conditioned air. However, what can happen to persons in a simple backyard shelter located so that neither the shelter nor its vent can be covered by rubble, with 3 feet of earth overhead and a mass fire raging around the shelter?

One claim is that all the air will be sucked out of the shelter, implying the creation of an extreme vacuum overhead. There is no evidence to indicate that anything but a very slight drop in pressure can possibly occur. Another argument, which probably formed the rational basis for the first one, is that the fire will consume all of the oxygen in the vicinity. However, if one computes the amount of oxygen needed to completely burn the typical single family residence, he will find that the necessary oxygen is available in the immediate vicinity of the fuel.

The next argument is that large quantities of carbon monoxide and other toxic gases will be produced and will be drawn into the shelter. Unfortunately, experiments have shown that this is indeed possible. In fact, concentrations of carbon monoxide as high as 7 percent have been measured in large fires burning freely out-of-doors[19] (a concentration above 1 percent can cause death in 1 to 3 minutes). However, the amount of fuel available in any single location is consumed in a relatively short period of time -- an hour or two of active burning at the most. Also, almost any shelter big enough to get into is habitable for an hour or two without any elaborate precautions.

Thus, if the ventilation system can be closed down for an hour or so, shelter occupants should have little difficulty in surviving the flaming portion of the fire burning overhead and, provided the vent is located so that it will not be buried by rubble, any air drawn in subsequently should be relatively free of carbon monoxide and other toxic gases.

The final concern of anyone underground in a fire area would be the heat. Here again it is easy to show that heat transferred into the shelter through 3 feet of earth, or its equivalent, during the period of an hour or two is negligible and, again, the only problem that can conceivably occur would result from smoldering rubble piled high above the shelter.

Thus, all evidence, both from a study of the major fires of the past and from simple small-scale experimentation and theoretical considerations, points to the relative safety of an underground location in a cleared area within a mass fire zone. Simple fallout shelters, built in the backyard rather than in the basement and with intake vents located as far as possible from an combustible material, can be expected to provide good protection against the fire as well as against the fallout effects of a nuclear detonation. Since such fire effects may, under the right circumstances, cover areas far exceeding the areas of severe fallout hazard, this additional feature should be considered carefully by anyone contemplating the construction of a fallout shelter.

7. CONCLUSIONS

The range of significant thermal radiation levels increases rapidly with weapon yield. As larger weapons are built and delivery methods improved, military and civil defense planners must continually reassess the seriousness of thermal effects relative to the effects of blast and ionizing radiation. The response of material and biological systems to short pulses of thermal radiation can be predicted with satisfactory exactness. But even at this late date, only very crude estimates can be made of thermal radiation levels at a distant target because of the large uncertainties in atmospheric transmission. Despite the uncertain nature of prior estimates of area of initial involvement, such estimates are relatively good compared to those for the final burned-over area. It does appear probable, however, that in any large-yield, nuclear weapon attack on urban and rural targets, mass fires would be generated which, in the absence of effective countermeasures, would in many cases burn over areas vastly larger than those initially ignited.

Countermeasures which should prove effective in reducing the amount of thermal radiation and fire damage include: the elimination of kindling fuels wherever possible, the isolation and quick extinguishment of ignition points, the establishment of suitably large fire breaks and, under some circumstances, the pre-attack use of smoke screens and other shielding devices.

A properly planned and located underground shelter of the type designed for fallout protection is expected to provide complete safety for its occupants even in the center of a mass fire zone if the air intakes are closed off during the hour or so of active burning in the immediate vicinity.

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