SECTION III

THERMAL RADIATION PHENOMENA

3.1 General

The extremely high temperatures in the fireball result in a large emission of thermal radiation. The relatively large fraction of the total energy of a nuclear detonation which is emitted as thermal radiation is one of its most striking characteristics. This radiant energy amounts to approximately one-third of the total energy of an air burst weapon; it is sufficient to cause serious burns to exposed personnel and to start fires in some combustible materials out to considerable distances. The duration of the thermal radiation emission depends upon the weapon yield, and is longer for the larger yields.

For a surface burst having the same yield as an air burst, the presence of the earth's surface results in a reduced thermal radiation emission and a cooler fireball when viewed from that surface. This is due primarily to heat transfer to the soil or water, the distortion of the fireball by the reflected shock wave, and the partial obscuration of the fireball by dirt and dust (or water) thrown up by the blast wave.

In underground bursts the fireball is obscured by the earth column, and therefore thermal radiation effects are negligible. Nearly all of the thermal radiation is absorbed in fusing and vaporizing the earth.

Thermal radiation from an underwater detonation is increasingly absorbed in vaporization and dissociation of the surrounding medium as the depth of burst is increased. Its direct effects are insignificant for most practical purposes; e.g., for a 20 KT burst in ninety feet of water, thermal effects are negligible.

3.2 Thermal Scaling

a. General. In paragraph 1.4b(2) the fireball was described as emitting thermal radiation in a pulse characterized by a rapid rise to a first maximum, a decline to a minimum, another rise to a second maximum and a subsequent final decline. The first phase of this pulse occurs so very rapidly that less than 1 percent of the total thermal radiation is emitted. Consequently, it is the second phase of the pulse which is of interest in weapons effects considerations at altitudes in the lower troposphere.

Throughout, the fireball may be considered to radiate essentially, though not ideally, as a black body, for which the radiant power is proportional to the radiating area and the fourth power of the temperature. After the minimum the radiating area and area increase relatively slowly, so that the radiant power is predominately determined by the temperature cycle of the fireball. An illustration of the apparent temperature and fireball radius versus time for a 20 KT air burst is shown in figure 3-1. It should be emphasized, however, that the actual radiating area may vary substantially from that of the luminous fireball. Very little quantitative information is available concerning the rate of growth of the fireball following the time at which "breakaway" occurs (approximately 0.015 second for the 20 KT burst shown in figure 3-1). Up to the time of breakaway, however, the radius increases approximately as the 0.4 power of the time after detonation.

b. Thermal Pulse. The shape of the pulse after the radiant power minimum (t_{min}) is sufficiently similar for nuclear detonations that a single curve may represent the time distribution of radiant power emitted (fig. 3-2). This curve has been developed by using ratios. The ratio p/p_{max} is plotted against the ratio t/t_{max}, where p/p_{max} is the ratio of the radiant power at a given time to the maximum radiant power, and t/t_{max} is the ratio of time after detonation to the time to the second thermal maximum for that detonation.

The percent of the total thermal radiation emitted versus the ratio t/t_{max} is also shown on figure 3-2. From this figure it is seen that approximately twenty percent of the total emission occurs up to the time of the second power maxi-
mum, whereas approximately 82 percent is emitted prior to 10 times the time to the second maximum. By this time the rate of delivery has dropped to such a low value that the remaining energy is no longer of significance in damage production.

c. Time scaling. It has been found that both the time to the minimum and the time to the second maximum are proportional to the square root of the weapon yield. Thus, for airbursts at altitudes of burst below about 50,000 feet, the time to the minimum \( t_{\text{min}} \) is 0.0027 \( W^{1/2} \) second. The time to the second maximum \( t_{\text{max}} \) is 0.032 \( W^{1/2} \) second. (See figures 3–3A and 3–3B. These curves may also be used for surface bursts.) It should be noted that for weapon yields lower than 6 KT the actual values of \( t_{\text{max}} \) may be as much as 30 percent higher than those given by figure 3–3A. This is caused by the higher mass-to-yield ratio characteristic of low yield weapons. These relations indicate that a one megaton weapon delivers its thermal radiation over a period 32 times as great as does a one kiloton weapon. This can be expected to result in variations in total thermal energy required for a given effect. The significance of the dependence of delivery rate on weapon yield is discussed in the sections dealing with thermal injury and damage.

d. Thermal Yield. Measurements of the total thermal energy emitted for air burst weapons of low yield indicate that this energy is proportional to weapon yield and is about one-third of the total yield. From this and figure 3–2 a scaling procedure for maximum radiant power may be derived. Thus \( p_{\text{max}} = 4W^{1/2}\text{KT/sec or } 4 \times 10^9 W^{1/2} \) cal/sec.

Measurements from the ground of the total thermal energy from surface bursts, although not as extensive as those for air bursts, indicate that the thermal yield is a little less than half that from equivalent air bursts. For a surface burst the thermal yield is assumed to be one-seventh of the total yield. For surface bursts, the scaling of the second radiant power maximum \( p_{\text{max}} \) cannot be determined on the basis of available data. Similarly, there are no data which show what the thermal radiation phenomena may be for detonation altitudes in excess of about 50,000 feet. It is expected that the thermal energy may increase with altitude of burst, and figure 3–4 gives a purely theoretical estimate of this increase.

3.3 Radiant Exposure vs. Slant Range

a. Spectral Characteristics. At distances of operational interest, the spectral (wavelength) distribution of the incident thermal radiation, integrated with respect to time, resembles very closely the spectral distribution of sunlight. For each, slightly less than one-half of the radiation occurs in the visible region of the spectrum, approximately one-half occurs in the infrared region and a very small fraction (rarely greater than 10 percent) lies in the ultraviolet region of the spectrum. The color temperature of the sun and an air burst are both about 6,000° K. A surface burst, as viewed by a ground observer, contains a higher proportion of infrared radiation and a smaller proportion of visible radiation than the air burst, with almost no radiation in the ultraviolet region. The color temperature for a surface burst is about 3,000° K. A surface burst viewed from the air may exhibit a spectrum more nearly like an air burst.

b. Atmospheric Transmissivity. The atmospheric transmissivity \( (T) \) is defined as the fraction of the radiant exposure received at a given distance after passage through the atmosphere, relative to that which would have been received at the same distance if no atmosphere were present. Atmospheric transmissivity depends upon several factors; among these are: water vapor and carbon dioxide absorption of infrared radiation, ozone absorption of ultraviolet radiation, and multiple scattering of all radiation. All of these factors vary with distance and with the composition of the atmosphere. Scattering is produced by the reflection and refraction of light rays by certain atmospheric constituents, such as dust, smoke and fog. Interactions such as scattering which divert the rays from their original paths result in a diffuse, rather than direct, transmission of the radiation. As a result, a receiver which has a large field of view (i.e., most military targets) receives radiation which has been scattered toward it from many angles, as well as the directly transmitted radiation. Since the mechanisms of absorption and scattering are wavelength dependent, the atmospheric transmissivity depends not only upon the atmospheric conditions, but also upon
the spectral distribution of the weapon's radiation. In figures 3–5A and 3–5B the atmospheric transmissivity is plotted as a function of the slant range for air and surface bursts. For each type of burst three sets of atmospheric conditions are assumed. It is believed that these conditions represent the average and the extremes normally encountered in natural atmospheres. These conditions correspond to a visibility of 50 miles and a water vapor concentration of 5 grams/cubic meter; 10 miles visibility and 10 grams/cubic meter water vapor concentration; and 2 miles visibility and 25 grams/cubic meter of water vapor concentration. Curves are presented in appendix I to show under what conditions of ambient temperature and relative humidity the above water vapor concentrations are applicable. The curves of figures 3–5A and 3–5B are plotted to slant ranges equal to one-half the visibility for the three visibility conditions. The reason for this is that the empirical relationships used to obtain the transmissivity values have not been verified for ranges beyond one-half the visibility. As a result, the curves cannot be extrapolated to greater distances with any confidence. If the curves are extended beyond one-half the visibility, there is reason to believe that the values of transmissivity would be too high. Where cloud cover is appreciable or the air contains large quantities of fog or industrial haze, knowledge of the interactions with the radiation is too limited to provide estimates of atmospheric transmissivity.

c. Reflection. If a weapon is burst in the air below a large cloud, the thermal radiation is diffusely reflected downward from the cloud, resulting in greater radiant exposures at a given distance than would be received if no cloud were present. Similarly, if the weapon is burst near the earth's surface, the radiant exposure received at some altitude above the burst (as in the case of an aircraft flying above the detonation) will be greater than that which is received at the same distance on the ground. If the receiver is directly over the burst and the terrain has a high albedo, the reflected radiation from the terrain may be as much as twice the direct radiation. If a reflecting or scattering layer such as a cloud is between the detonation and the target, however, the radiant exposure received will be reduced considerably.

d. Calculation of Radiant Exposure. The radiant exposures at various slant ranges from air and surface burst weapons can be calculated from the following expressions:

\[ Q = 3.16 \times 10^6 \frac{W}{D} \, \text{cal/sq cm (air burst)}, \]

\[ Q = 1.35 \times 10^6 \frac{W}{D^2} \, \text{cal/sq cm (surface burst)}, \]

where \( Q \) = radiant exposure (cal/sq cm), \( \frac{W}{D} \) = atmospheric transmissivity, \( W \) = weapon yield (KT), \( D \) = slant range (yds).

The values of \( \frac{W}{D} \) for both air and surface bursts are obtained from the appropriate curves in figures 3–5A and 3–5B. Curves showing the radiant exposure \( Q \) as a function of slant range \( D \) for three atmospheric conditions for both air and surface bursts are shown in figures 3–6A and 3–6B. These curves are plotted for ranges up to one-half the visibility for the reasons explained in b above. The surface burst curves differ from the air burst curves for two reasons—the apparent thermal yield when viewed from the surface for a surface burst is lower than that for an air burst, and the spectral distribution of the surface burst is sufficiently different from that of an air burst to require the use of different atmospheric transmissivity curves. Radiant exposure for a burst in the transition zone may be estimated by interpolation between these curves as explained on the instruction page for figures 3–6A and 3–6B. It should be emphasized that these surface burst curves apply to the radiant exposure of ground targets. When the surface burst is viewed from the air, as from aircraft, the apparent radiating temperature and the thermal yield will be greater than when viewed from the ground. All of the curves plotted in figures 3–5A and 3–5B are for a total weapon yield of 1 KT. For weapon yields greater or less than 1 KT these radiant exposures should be multiplied by the yield of the weapon in question.
3.4 Other Influences on Thermal Radiation Propagation

a. Topography and Clouds. Propagation of thermal radiation from a nuclear detonation, like that from the sun, is affected by topography and the atmosphere. At close ranges, where the fireball subtends a relatively large angle, the shadowing effects of intervening objects such as hills or trees are less than are experienced with the sun. As discussed earlier, clouds in the atmosphere significantly affect the propagation of radiation through the atmosphere.

b. Fog and Smoke. Where the burst is in the air above a fog covering the ground, a significant fraction of the thermal radiation incident on the fog layer is reflected upward. That radiation which penetrates the fog is scattered. These two effects result in substantial reductions in thermal energy incident on ground targets covered by fog. White smoke screens act like fog in the attenuation of thermal radiation. Reductions as large as 90 percent of incident thermal energies are realized by dense fogs or smoke screens.

c. The Wilson Cloud. The Wilson Cloud, which is sometimes formed in a detonation, does not appreciably affect the thermal radiation incident on a target.
FIGURE 3-2

GENERALIZED THERMAL PULSE

Figure 3-2 shows the radiant power relative to the second maximum and the percent of total thermal radiation emitted as functions of time after burst relative to the time of this maximum, for weapons burst at altitudes between 50,000 feet and the surface. Only the second phase of the pulse is shown, since the first phase includes less than one percent of the emitted thermal energy and is usually neglected in effects considerations.

Scaling. The second radiant power maximum and the time to this peak both scale as the square root of the yield. To determine any instantaneous level of radiant power and the corresponding time of this level after detonation for a weapon of yield \( W \) KT, the values obtained from figure 3-2 are multiplied by \( P_{\text{max}} \) and \( t_{\text{max}} \) respectively. The latter are determined by:

\[
P_{\text{max}} = 4 \times 10^{12} \frac{\text{W}}{\text{sec}} = 4 \times 10^{12} \text{cal/sec}.
\]

\[
t_{\text{max}} = 0.032 \frac{\text{W}}{\text{sec}}.
\]

Example.

Given: A 90 KT air burst.

Find: The radiant power at 2 seconds and the percent thermal radiation emitted up to 2 seconds.

Solution: From the scaling above, \( t_{\text{max}} = 0.032 \times (90)^{1/2} = 0.304 \) second. For a 90 KT air burst, when \( t = 2.0 \) seconds,

\[
\frac{t}{t_{\text{max}}} = \frac{2.0}{0.304} = 6.6.
\]

Reading from figure 3-2, for a value of \( \frac{t}{t_{\text{max}}} = 6.6 \), one obtains a value for \( \frac{P}{P_{\text{max}}} = 0.06 \).

From the scaling above, \( P_{\text{max}} = 4 \times (90)^{1/2} \) KT/sec = 38.0 KT/sec.

For a 90 KT air burst, when \( t = 2.0 \) seconds, \( P = P_{\text{max}} \times 0.06 = 38.0 \times 0.06 = 2.28 \) (± 0.68) KT/sec. Answer.

Reading from the percent emitted curve, when \( \frac{t}{t_{\text{max}}} = 6.6 \), one finds the value of 76 percent. Answer.

Reliability. The radiant power values obtained from figure 3-2 are reliable to within ±30 percent for air burst yields between 6 and 100 KT. The reliability decreases for air burst weapon yields lower than or above this range. Times are reliable to ±15 percent for air burst weapons in the range 6 KT to 100 MT. For air burst weapon yields lower than 6 KT the times may be as much as 30 percent higher than those obtained from the above scaling relationship.

For other bursts, the reliability of the scaling of radiant power is expected to be lower than that shown for air bursts; nevertheless, the reliability cannot be estimated on the basis of available data.

Related material.

See paragraph 3.2.
Figures 3-3A and 3-3B give the time to the second radiant power maximum ($t_{\text{max}}$) and the time to the radiant power minimum ($t_{\text{min}}$) as a function of weapon yield for air burst weapons at altitudes below 50,000 feet, and may also be used for surface bursts.

*Example.*

*Given:* The air burst of a 1 MT weapon.

*Find:* The time to the radiant power minimum and the time to the second radiant power maximum.

*Solution:* Find 1 MT on the abscissa of figure 3-3B and read from the two time curves $t_{\text{min}}=0.085 (\pm 0.009)$ second. Answer.

and $t_{\text{max}}=1.1 (\pm 0.2)$ second. Answer.

*Reliability.* The times read from the $t_{\text{min}}$ curve of figures 3-3A and 3-3B are reliable to ±10 percent. The times read from the $t_{\text{max}}$ curves of figures 3-3A and 3-3B, in the range 6 KT to 100 MT are reliable to ±15 percent. For weapon yields lower than 6 KT the values of $t_{\text{max}}$ may be as much as 30 percent higher than those given by figure 3-3A.

*Related material.*

See paragraph 3.2c.

See also figures 3-1 and 3-2.
RADIANT POWER
TIME TO SECOND MAXIMUM ($t_{\text{max}}$)
AND TIME TO MINIMUM ($t_{\text{min}}$)
VS. WEAPON YIELD

$\\ t_{\text{max}} = 0.032 \sqrt{\frac{W}{K}}$

$\\ t_{\text{min}} = 0.0027 \sqrt{\frac{W}{K}}$

Yield (kilotons)

Time (seconds)
RADIANT POWER
TIME TO SECOND MAXIMUM ($t_{\text{max}}$)
AND TIME TO MINIMUM ($t_{\text{min}}$)
VS. WEAPON YIELD.

$t_{\text{max}} = 0.032 W^{1/2}$

$t_{\text{min}} = 0.0027 W^{1/2}$
Figure 3-4 gives an estimate of the relative thermal yield for various burst altitudes. The values of atmospheric transmissivity at very high altitudes are not known with any certainty, but are believed to be only slightly less than unity.

To calculate the radiant exposure, \( Q \), at a given slant range from a high altitude burst, use the following equation:

\[
Q = \frac{3.16 \times 10^6 \ W F}{D^2} \text{ cal/sq. cm.}
\]

where
- \( W = \) weapon yield (in KT)
- \( F = \) relative thermal yield (from figure 3-4)
- \( D = \) slant range from detonation (yards)

**Example.**

**Given:** A 10 KT burst at 50,000 feet.

**Find:** Radiant exposure at 1,000 yards from the detonation.

**Solution:** From figure 3-4 the relative thermal yield, \( F \), at 50,000 feet is 1.02. Therefore,

\[
Q = \frac{3.16 \times 10^6 \times (10) (1.02)}{(1,000)^2} = 32.2 \ (\pm 4.8) \text{ cal/sq cm. Answer.}
\]

**Reliability.** The values given for the relative thermal yield are subject to errors of \( \pm 15 \) percent at 50,000 feet and to increasingly larger errors at greater altitudes.

**Related material.**

See paragraph 3.2d.

See also figures 3-6A and 3-6B.
ATMOSPHERIC TRANSMISSIVITY

Figures 3–5A and 3–5B give the atmospheric transmissivity versus slant range for three sets of atmospheric conditions for both air and surface burst weapons. These curves are presented for illustrative purposes, since these were used to derive the radiant exposure vs. slant range curves of figures 3–6A and 3–6B.

The differences between the air burst and surface burst curves are caused by the difference in apparent radiating temperatures (when viewed from the ground) and the difference in geometrical configuration of the two types of burst. The three sets of atmospheric conditions represented are:

- 50 mile visibility and 5 gm/m² water vapor.
- 10 mile visibility and 10 gm/m² water vapor.
- 2 mile visibility and 25 gm/m² water vapor.

It is believed that these conditions pertain to the extreme and the average atmospheres which occur naturally.

Reference can be made to the atmospheric water vapor concentration curves in appendix I to ascertain under what conditions of relative humidity and ambient temperature a particular water vapor concentration will occur.

Reliability. The curves of figures 3–5A and 3–5B have not been verified at ranges beyond one-half the visibility and, as a result, are subject to considerably reduced reliability beyond these ranges.

Related material.

- See paragraph 3.3b.
- See also figures 3–6A and 3–6B.
FIGURE 3-5A

ATMOSPHERIC TRANSMISSIVITY VS. SLANT RANGE-AIR AND SURFACE BURSTS
FIGURE 3-5B

ATMOSPHERIC TRANSMISSIVITY VS. SLANT RANGE-AIR AND SURFACE BURSTS

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1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1

0.0

1,000 2,000 4,000 7,000 10,000 20,000 40,000 70,000

Slant Range (Yards)

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3-15
RADIANT EXPOSURE FROM AIR AND SURFACE BURSTS

Figures 3-6A and 3-6B present the radiant exposure (i.e., incident radiant energy per unit area) versus slant range curves for 1 KT air and surface bursts. The solid curves are for the air burst, those above 180 $W^{0.4}$ feet. For bursts at heights between 180 $W^{0.4}$ feet and the surface, the radiant exposure will lie between the corresponding solid and dashed curves. Until further data are obtained, a linear interpolation between the two curves should be made for bursts in the transition zone (see example 2). For each type of burst shown, three curves are presented: 50 mile visibility and 5 gm/m³ water vapor; 10 mile visibility and 10 gm/m³ water vapor; and 2 mile visibility and 25 gm/m³ water vapor.

Figures 3-6A and 3-6B are based on the air and surface burst thermal yields (par. 3.2d) and the atmospheric transmissivity curves of figures 3-5A and 3-5B.

Scaling. For a given slant-range the radiant exposure, $Q$, is proportional to the weapon yield, $W$:

$$\frac{Q_1}{Q_2} = \frac{W_1}{W_2}$$

In figures 3-6A and 3-6B, $Q_i$ is given for $W_i=1$ KT.

Example 1.

Given: A 40 KT detonation at 3,000 feet height of burst and a 10 mile visibility.

Find: The slant range at which the radiant exposure is 10 cal/cm².

Solution: The scaled burst height is $\frac{3,000}{(40)^{0.4}} = 685$ feet; therefore, the air burst curve should be used.

Then $Q_1 = 10 \left( \frac{1}{40} \right) = 0.25$ cal/cm². From figure 3-6B, the slant range at which 0.25 cal/cm² would be received from an air burst (visibility = 10 miles) is 3,000 yards. Answer.

Example 2.

Given: A 500 KT detonation at 1,200 feet height of burst and a 50 mile visibility.

Find: The slant range at which the radiant exposure is 25 cal/cm².

Solution: The scaled burst height is $\frac{1,200}{(500)^{0.4}} = 100$ feet; therefore, for this transition burst, the range sought will lie $\frac{100}{180}$ of the distance between the surface and air burst values.

Then $Q_i = 25 \left( \frac{1}{500} \right) = 0.05$ cal/cm².

From figure 3-6B, the ranges at which 0.05 cal/cm² would occur for surface and air bursts (visibility = 50 miles) are 4,100 and 7,000 yards, respectively. The answer is then:

$$4,100 + \frac{100}{180} (7,000 - 4,100) = 5,700$$ yards.

Answer.

Reliability. Factors limiting the applicability of figures 3-6A and 3-6B are discussed in paragraphs 3.36 and 3.3d. In addition, the reliability is expected to decrease as the weapon yield is increased above 100 KT, and as the slant range is increased beyond one-half the visibility, as noted in figures 3-5A and 3-5B.

Related material.

See paragraphs 3.2 and 3.3.

See also figures 3-5A and 3-5B.
RADIANT EXPOSURE VS. SLANT RANGE
AIR AND SURFACE BURSTS
2, 10 AND 50 MILE VISIBILITIES
1 KT BURST

- --- Air Burst
- --- Surface Burst

Slant Range (yards)
Radiant Exposure (cal/sq.cm)