CHAPTER 3

EFFECTS OF NUCLEAR EXPLOSIONS

SECTION I - GENERAL

301. Introduction.

The basic differences in the mechanisms of energy production and related characteristics of conventional as compared with nuclear detonations were discussed in Chapter 2. In this chapter that discussion will be extended to consider the forms in which the energy produced in such detonations affects the surrounding environment. The location of the point of detonation in the environment is as important as the yield in determining the way the energy is distributed, and this factor will be discussed in some detail.

302. General Effects of Nuclear Explosions.

a. While the destructive action of conventional explosions is due almost entirely to the transmission of energy in the form of a blast wave with resultant mechanical damage, the energy of a nuclear explosion is transferred to the surrounding medium in three distinct forms: blast; thermal radiation; and nuclear radiation. The distribution of energy among these three forms will depend on the yield of the weapon, the location of the burst, and the characteristics of the environment. For a low altitude atmospheric detonation of a moderate sized weapon in the kiloton range, the energy is distributed roughly as follows:
   (1) 50% as blast;
   (2) 35% as thermal radiation; made up of a wide range of the electromagnetic spectrum, including infrared, visible, and ultraviolet light and some soft x-ray emitted at the time of the explosion; and
   (3) 15% as nuclear radiation; including 570 as initial ionizing radiation consisting chiefly of neutrons and gamma rays emitted within the first minute after detonation, and 10% as residual nuclear radiation. Residual nuclear radiation is the hazard in fallout.

b. Considerable variation from this distribution will occur with changes in yield or location of the detonation. This is best shown by comparing the ranges of damage due to these effects of weapons of different size yields (Table 3-I).

c. The distribution of weapon energy yield is altered significantly by the enhanced radiation nuclear warhead. In simplest terms an enhanced radiation warhead is designed specifically to reduce the percentage of energy that is dissipated as blast and heat with a consequent increase in the percentage yield of initial radiation. Approximate percentage energies are 30% blast; 20% thermal; 45% initial radiation; and 570 residual radiation.

*Table 3-I. Radii of Effects of Nuclear Weapons**

Effect	1 Kt	10 Kt	100 Kt	1000 Kt
Ionizing radiation (50% immediate transient ineffectivenss)	600m	950m	1400m	2900m
Ionizing radiation (50% latent lethality)	800m	110m	1600m	3200m
Blast (50% casualties)	140m	360m	860m	3100m
Thermal radiation (50% casualties, second degree burns under fatigue uniform)	369m	110m	3190m	8020m

* HOB 60W $^{1/3}$

303. Initial Energy Transfer and Formation of Fireball.

a. Because of the tremendous amounts of energy liberated per unit mass in a nuclear detonation, temperatures of several tens of million degrees centigrade develop in the immediate area of the detonation. This is in marked contrast to the few thousand degrees of a conventional explosion. At these very high temperatures the nonfissioned parts of the nuclear weapon are vaporized. The atoms do not release the energy as kinetic energy but release it in the form of large amounts of electromagnetic radiation. In an atmospheric detonation, this electromagnetic radiation, consisting chiefly of soft x-ray, is absorbed within a few meters of the point of detonation by the surrounding atmosphere, heating it to extremely high temperatures and forming a brilliantly hot sphere of air and gaseous weapon residues, the so-called fireball. Immediately upon formation, the fireball begins to grow rapidly and rise like a hot air balloon. Within a millisecond after detonation, the diameter of the fireball from a 1 megaton (Mt) air burst is 150 m. This increases to a maximum of 2200 m within 10 seconds, at which time the fireball is also rising at the rate of 100 m / sec. The initial rapid expansion of the fireball severely compresses the surrounding atmosphere, producing a powerful blast wave, discussed below.

b. The fireball itself emits enormous amounts of electromagnetic radiation, similar in its spectrum to sunlight. This is usually termed thermal radiation. The visible light component accounts for the blinding flash seen upon detonation as well as the subsequent brightness of the fireball, while the infrared component results in widespread burns and incendiary effects.

c. As it expands toward its maximum diameter, the fireball cools, and after about a minute its temperature has decreased to such an extent that it no longer emits significant amounts of thermal radiation. The combination of the upward movement and the cooling of the fireball gives rise to the formation of the characteristic mushroom-shaped cloud. As the fireball cools, the vaporized materials in it condense to form a cloud of solid particles. Following an air burst, condensed droplets of water give it a typical white cloudlike appearance. In the case of a surface burst, this cloud will also contain large quantities of dirt and other debris which are vaporized when the fireball touches the earth's surface or are sucked up by the strong updrafts afterwards, giving the cloud a dirty brown appearance. The dirt and debris become contaminated with the radioisotopes generated by the explosion or activated by neutron radiation and fall to earth as fallout.

d. The cloud rises for a period of approximately 10 minutes to a stabilized height which depends on the thermal output of the weapon and atmospheric conditions. It will continue to grow laterally assuming the familiar mushroom shape and may remain visible for an hour or more under favorable conditions. For example, the nuclear cloud from a 1 Mt surface burst will stabilize at an altitude of over 20 kilometers (km) and will have a mean lateral diameter of 35 km.

304. Types of Bursts.

The relative effects of blast, heat, and nuclear radiation will largely be determined by the altitude at which the weapon is detonated. Nuclear explosions are generally classified as air bursts, surface bursts, subsurface bursts, or high altitude bursts.

a. *Air-Bursts.* An air burst is an explosion in which a weapon is detonated in air at an altitude below 30 km but at sufficient height that the fireball does not contact the surface of the earth. After such a burst, blast may cause considerable damage and injury. The altitude of an air burst can be varied to obtain maximum blast effects, maximum thermal effects, desired radiation effects, or a balanced combination of these effects. Burns to exposed skin may be produced over many square kilometers and eye injuries over a still larger area. Initial nuclear radiation will be a significant hazard with smaller weapons, but the fallout hazard can be ignored as there is essentially no local fallout from an air burst. The fission products are generally dispersed over a large area of the globe unless there is local rainfall resulting in localized fallout. In the vicinity of ground zero, there may be a small area of neutron-induced activity which could be hazardous to troops required to pass through the area. Tactically, air bursts are the most likely to be used against ground forces.

b. *Surface Burst.* A surface burst is an explosion in which a weapon is detonated on or slightly above the surface of the earth so that the fireball actually touches the land or water surface. Under these conditions, the area affected by blast, thermal radiation, and initial nuclear radiation will be less extensive than for an air burst of similar yield, except in the region of ground zero where destruction is concentrated.

In contrast with air bursts, local fallout can be a hazard over a much larger downwind area than that which is affected by blast and thermal radiation.

c. *Subsurface Burst.* A subsurface burst is an explosion in which the point of the detonation is beneath the surface of land or water. Cratering will generally result from an underground burst, just as for a surface burst. If the burst does not penetrate the surface, the only other hazard will be from ground or water shock. If the burst is shallow enough to penetrate the surface, blast, thermal, and initial nuclear radiation effects will be present, but will be less than for a surface burst of comparable yield. Local fallout will be very heavy if penetration occurs.

d. *High Altitude Burst.* A high altitude burst is one in which the weapon is exploded at such an altitude (above 30 km) that initial soft x-rays generated by the detonation dissipate energy as heat in a much larger volume of air molecules. There the fireball is much larger and expands much more rapidly. The ionizing radiation from the high altitude burst can travel for hundreds of miles before being absorbed. Significant ionization of the upper atmosphere (ionosphere) can occur. Severe disruption in communications can occur following high altitude bursts. They also lead to generation of an intense electromagnetic pulse (EMP) which can significantly degrade performance of or destroy sophisticated electronic equipment. There are no known biological effects of EMP; however, indirect effects may result from failure of critical medical equipment.

SECTION II - BLAST

305. Formation of Blast Wave.

a. As a result of the very high temperatures and pressures at the point of detonation, the hot gaseous residues move outward radially from the center of the explosion with very high velocities. Most of this material is contained within a relatively thin, dense shell known as the hydrodynamic front. Acting much like a piston that pushes against and compresses the surrounding medium, the front transfers energy to the atmosphere by impulse and generates a steep-fronted, spherically expanding blast or shock wave. At first, this shock wave lags behind the surface of the developing fireball. However, within a fraction of a second after detonation, the rate of expansion of the fireball decreases to such an extent that the shock catches up with and then begins to move ahead of the fireball. For a fraction of a second, the dense shock front will obscure the fireball, accounting for the characteristic double peak of light seen with a nuclear detonation.

b. As it expands, the peak pressures of the blast wave diminish and the speed of propagation decreases from the initial supersonic velocity to that of sound in the transmitting medium. However, upon reflection from the earth’s surface, the pressure in the wave will be reinforced by the fusion of the incident and the reflected wave (the Mach effect) described below.

c. A large part of the destruction caused by a nuclear explosion is due to blast effects. Objects within the path of the blast wave are subjected to severe, sharp increases in atmospheric pressure and to extraordinarily severe transient winds. Most buildings, with the exception of reinforced or blast-resistant structures, will suffer moderate to severe damage when subjected to overpressures of only 35.5 kiloPascals (kPa) (0.35 Atm). The velocity of the accompanying blast wind may exceed several hundred km/hr. Most materiel targets are drag- or wind-sensitive.

d. The range for blast effects increases significantly with the explosive yield of the weapon. In a typical air burst, these values of overpressure and wind velocity noted above will prevail at a range of 0.7 km for 1 kiloton (Kt) yield; 3.2 km for 100Kt; and 15.0 km for 10 Mt.

306. Propagation of Blast Wave in Air.

During the time the blast wave is passing through the superheated atmosphere in the fireball, it travels at supersonic velocities. After it leaves the vicinity of the fireball, it slows down to the normal speed of sound in the atmosphere. As long as the blast wave is expanding radially, its intensity decreases approximately as the square of the distance. When the expanding blast wave from a nuclear air burst strikes the surface of the earth, however, it is reflected (Figure 3-I), and the reflected wave reinforces and intensifies the primary wave.

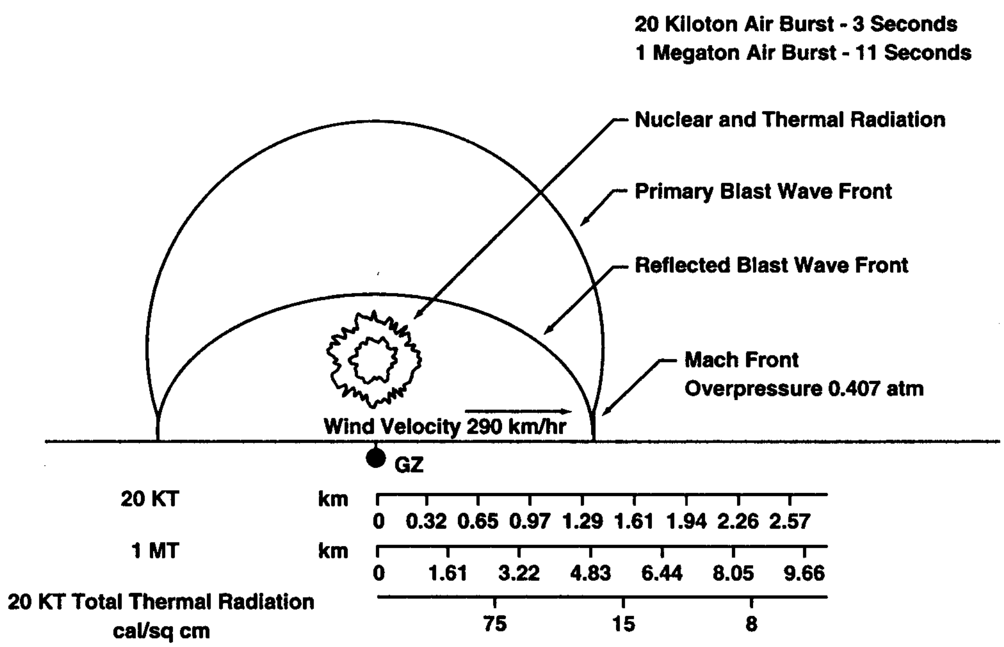

Figure 3-I. Chronological Development of an Air Burst

a. Targets in the vicinity of ground zero may actually be subjected to two blast waves: the initial or incident wave, followed slightly later by a secondary reflected wave. This limited region close to ground zero in which the incident and reflected waves are separate is known as the region of regular reflection.

b. Beyond the area of regular reflection as it travels through air which is already heated and compressed by the incident blast wave, the reflected wave will move much more rapidly and will very quickly catch up with the incident wave. The two then fuse to form a combined wave front known as the Mach stem. The height of the Mach stem increases as the blast wave moves outward and becomes a nearly vertical blast front. As a result, blast pressures on the surface will not decrease as the square of the distance, and most direct blast damage will be horizontally directed, e.g., on the walls of a building rather than on the roof.

c. As the height of burst for an explosion of given yield is decreased, or as the yield of the explosion for a given height of burst is increased, Mach reflection commences nearer to ground zero and the overpressure near ground zero becomes larger. However, as the height of burst is decreased, the total area of coverage for blast effects is also markedly reduced. The choice of height of burst is largely dependent on the nature of the target. Relatively resistant targets require the concentrated blast of a low altitude or surface burst, while sensitive targets may be damaged by the less severe blast wave from an explosion at a higher altitude. In the latter case a larger area and, therefore, a larger number of targets can be damaged.

d. A surface burst results in the highest possible overpressures near ground zero. In such a burst, the shock front is hemispherical in form, and essentially all objects are subjected to a blast front similar to that in the Mach region described above. A subsurface burst produces the least air blast, since most of the energy is dissipated in the formation of a crater and the production of a ground shock wave.

307. Static Overpressure and Dynamic Pressure.

a. Two distinct though simultaneous phenomena are associated with the blast wave in air:

(1) Static overpressure, i.e., the sharp increases in pressure due to compression of the atmosphere. These pressures are those which are exerted by the dense wall of air that comprises the wave front. The magnitude of the overpressure at any given point is directly proportional to the density of the air in the wave.

(2) Dynamic pressures, i.e., drag forces exerted by the strong transient blast winds associated with the movement of air required to form the blast wave. These forces are termed dynamic because they tend to push, tumble, and tear apart objects and cause their violent displacement.

b. In general, the static overpressure rises very abruptly from normal atmospheric in the unaffected air in front of the blast wave to a sharp peak (Figure 3-II). It then decreases behind the front. As the blast wave moves out from ground zero, the peak overpressure of the front diminishes while the decay of overpressure behind the front becomes more gradual. After traveling a sufficient distance from the fireball, the pressure behind the front actually drops below normal atmospheric pressure, the so-called negative phase of the blast wave.

c. In passing through the atmosphere, the blast wave imparts its energy to the molecules of the surrounding air, setting them into motion in the direction of the advancing shock front. The motion of these air molecules is manifested as severe transient winds, known as “blast winds,” which accompany the blast wave. The destructive force associated with these winds is proportional to the square of their velocity and is measured in terms of dynamic pressure. These winds constitute decay forces which produce a large number of missiles and tumbling of objects. These dynamic forces are highly destructive.

d. Most of the material damage caused by a nuclear air burst is caused by a combination of the high static overpressures and the dynamic or blast wind pressures. The relatively long duration of the compression phase of the blast wave (Figure 3-II) is also significant in that structures weakened by the initial impact of the wave front are literally torn apart by the forces and pressures which follow. The compression and drag force phases together may last several seconds or longer, during which forces many times greater than those in the strongest hurricane are present. These persist even through the negative phase of a blast wave when a partial vacuum is present because of the violent displacement of air.

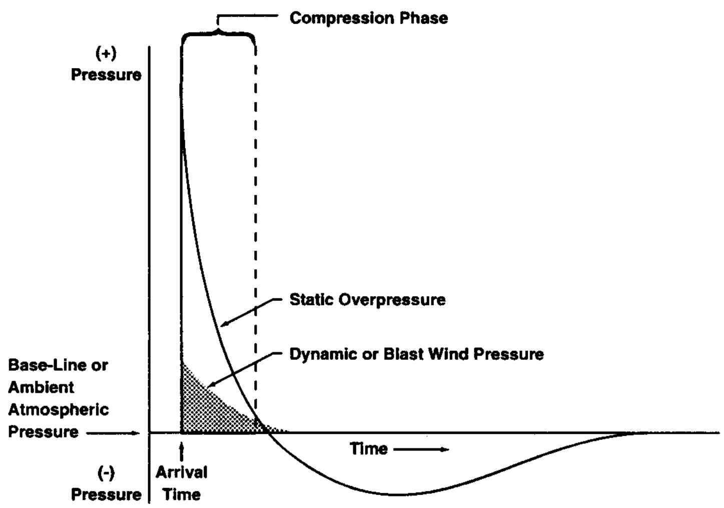

Figure 3-II. Variations of Overpressure and Dynamic Pressure with Time

e. It is of practical value to examine the variation in pressure at a fixed location as a function of time. For a short period of time after a nuclear air burst, there will be no increase in pressure since it takes a finite time for the shock front to reach a given point. This arrival time, which may range from a few seconds to minutes, will depend primarily on the distance of the location from the center of burst and to a lesser extent on the yield of the explosion. Initially, the speed of the shock front is many times the speed of sound because it is traveling through superheated air, but as it travels away from the fireball it slows down to the speed of sound, 330 m / sec, in normal atmospheres. With high yield detonations, the early velocity of the shock front and the distance traveled through superheated air is greater. Therefore, time is somewhat less. Upon arrival of the shock front, both the static overpressure and the dynamic pressure increase almost immediately from zero to their maximum values.

The peak values of pressure will, of course, depend on the distance from ground zero, the height of burst, and the yield and will be further modified by differences in terrain and meteorological conditions. With passage of the blast front, both the static and dynamic pressures decay, though at slightly different rates. Most blast damage will be experienced during the positive or compression phase of the wave. The duration of this positive phase increases with yield and distance from ground zero and ranges from 0.2 to 0.5 sec for a 1 KT nuclear air burst to 4 to 10 sec for a 10 Mt explosion. This compares with only a few hundredths of a second for the duration of a blast wave from a conventional high-explosive detonation.

f. Because of the much longer duration of the blast wave from a nuclear explosion, structures are subjected to maximum loading for correspondingly longer periods of time, and damage will be much more extensive for a given peak overpressure than might otherwise be expected. During the negative phase, which is generally of even longer duration, the static pressure will drop below normal atmospheric pressure and the blast winds will actually reverse direction and blow back towards ground zero. Damage sustained during the negative phase is generally minor, however, because the peak values of underpressure and wind velocity are relatively low. Blast effects associated with positive and negative phase pressures are shown in Figure 3-III.

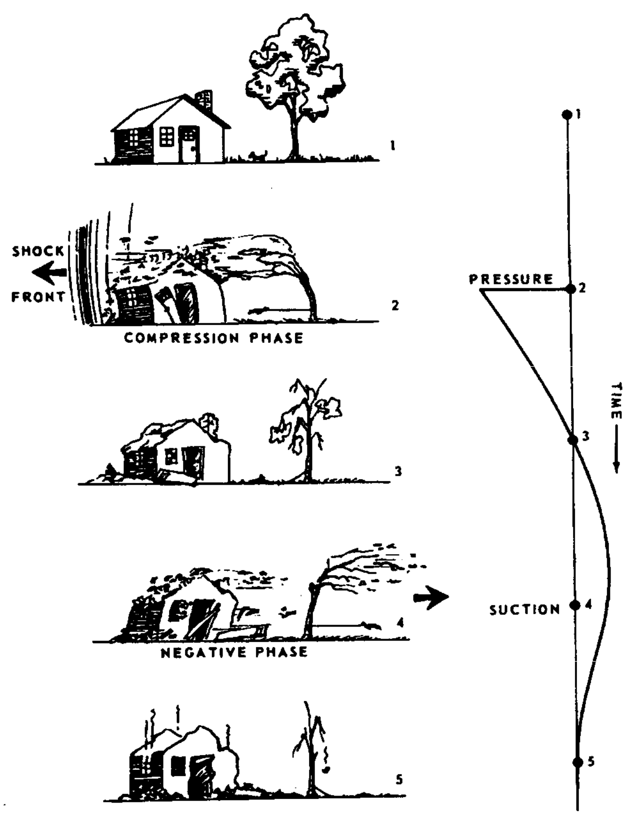

Figure 3-III. Variations of Blast Effects Associated with Positive and Negative Phase Pressures with Time

308. Blast Loading.

When a blast wave strikes the surface of a hard target, such as a building, the reflected wave will reinforce the incident wave, and the face of the building will be subjected to overpressures 2 to 8 times that of the incident wave alone. The severity of this additional stress depends on many factors, including the peak overpressure of the incident blast wave, as well as the angle at which the wave strikes the building. As the shock front advances, it bends or diffracts around the building, and the pressure on the front wall decreases rapidly. However, during the brief interval in which the blast wave has not yet engulfed the entire structure, a considerable pressure gradient exists from front to rear that places a severe stress on the building. For small objects, this period of so-called diffraction loading is so small that no significant stress is encountered. For large buildings, however, the stress of diffraction loading will be considerable. Even after the shock front has passed across the building, the structure will still be subjected to a severe compression force and to severe drag forces from the transient winds. The actual overpressures required to produce severe damage to diffraction sensitive targets are actually quite low. Table 3-II depicts failure of sensitive structural elements when exposed to overpressure blast loading.

Table 3-II. Failure of Overpressure Sensitive Structural Elements

Structural element	Failure	Approximate side-on peak overpressure (kPa)	Approximate slant range (km)	
			20 Kt	1 Kt
Glass windows, large and small	Shattering usually, occasional frame failure	3.45 - 6.9	6-10	20-30
Corrugated asbestos siding	Shattering	6.9 - 13.8	3-6	12-22
Corrugated steel or aluminum paneling	Connection failure followed by buckling	6.9 - 13.8	3-6	12-22
Brick wall panel, 20 cm or cm thick (not reinforced)	Shearing and flexture failures	20.7 - 69.0	1-3	4-10
Wood siding panels standard house construction	Usually failure occurs at the main connections, allowing a whole panel to be blown in	6.9 - 13.8	3-6	12-22
Concrete or cinder-block wall panels, 28 cm or 30 cm thick (not reinforced)	Shattering of the wall	10.35 - 38.0	1.5-4	6.5-15

309. Drag Loading.

All objects in the path of the blast wave, regardless of size or structure, will be subject to the dynamic pressure loading or drag forces of the blast winds. Drag loading is influenced to a moderate degree by the shape of the target. Round objects are relatively unaffected by the winds, while flat or recessed surfaces offer great resistance and hence are subjected to increased impact pressure and probability of damage. The effect of dynamic pressure is generally dependent on the peak value of dynamic pressure and its duration. While the dynamic pressure at the face of a building is generally less than the peak overpressure due to the blast wave and its reflection, the period of dynamic loading is much longer than that of diffraction loading, and hence the damage to frame-type buildings, bridges, and other structures will be considerable. Equipment and personnel are relatively resistant to static overpressures but highly vulnerable to dynamic pressure. For example, military vehicles, from jeeps to tanks, are most likely to suffer damage when pushed, overturned, and thrown about by the blast winds. Likewise, blast winds are the cause of most blast injuries. Because of the violence of the winds associated with even low values of overpressure, mechanical injuries due to missiles sent into motion by the winds or to violent bodily translation will far outnumber direct blast injuries due to actual compression of the organism.

310. Shock Waves in Other Media.

a. In surface and subsurface bursts, a sizable portion of the yield is transmitted in the form of ground or water shock waves. In the case of a surface burst on land, a crater is formed at ground zero, the size of which depends primarily upon yield. Relatively little damage beyond a distance of approximately three crater radii will occur due to ground shock. Most damage will be due to the accompanying air blast wave. In subsurface bursts the crater will be formed either by ejection of material as in a shallow explosion or by the collapse of ground into the cavity formed by a deeper explosion. Since the overpressure in a ground shock wave decreases very rapidly with distance, shock damage will again be confined to a region close to the point of detonation.

b. Ground shock waves will also be induced as a result of an air burst. If the overpressure in the blast wave is very large, the ground shock will penetrate some distance into the ground and may damage underground structures and buried utilities, etc.

c. Because of the density and relative incompressibility of water, shock waves in that medium have very high peak overpressures and velocities of propagation. The peak overpressure at a distance of 1 km from a 10 Kt underwater burst is approximately 6080 kPa (60 atm (atmospheres of pressure)), while the peak overpressure in air at the same distance from an air burst is only 111.4 kPa (1.1 atm). The resulting surface waves at this distance will be approximately 10 m in height. The shock front will also travel at approximately five times the speed of the blast wave in air. Severe damage to naval vessels may result from the shock wave produced by an underwater or water surface burst. Although the major portion of the shock energy is propagated in the water, a significant amount is also transferred through the surface as a typical air blast. This blast wave could probably be the principal source of damage to land targets if the explosion occurred in a coastal area.

SECTION III - THERMAL RADIATION

311. Formation of Thermal Radiation.

Large amounts of electromagnetic radiation in the visible, infrared, and ultraviolet regions of the electromagnetic spectrum are emitted from the surface of the fireball within the first minute or less after detonation. This thermal radiation travels outward from the fireball at the speed of light, 300,000 km/sec. The chief hazard of thermal radiation is the production of burns and eye injuries in exposed personnel. Such thermal injuries may occur even at distances where blast and initial nuclear radiation effects are minimal. Absorption of thermal radiation will also cause the ignition of combustible materials and may lead to fires which then spread rapidly among the debris left by the blast. The range of thermal effects increases markedly with weapon yield.

312. Propagation of Thermal Energy.

a. Most of the energy released in the fission or fusion processes is initially in the form of the kinetic energy of the products of the reactions (e.g., fission fragments, etc.). Within millionths of a second after detonation, numerous inelastic collisions of these vaporized atoms give rise to a plasma of intensely hot weapon residues. Since the temperature of this system is of several tens of million degrees centigrade, it emits enormous quantities of energy in the form of electromagnetic radiation. This radiation is subsequently absorbed by the surrounding atmosphere, which is heated to extremely high temperatures, causing it to emit additional radiation of slightly lower energy. This complex process of radiative transfer of energy is the basic mechanism by which the fireball is formed and expands.

b. Because this thermal radiation travels at the speed of light, and its mean free path (distance between point of emission and point of absorption) is relatively long, the initial expansion of the fireball is extremely rapid, much more so than the outward motion of gaseous material from the center of the burst responsible for production of the blast wave. Consequently, the blast wave front at first lags behind the radiative front (surface of the fireball).

c. However, as the fireball expands and its energy is deposited in an ever-increasing volume its temperature decreases and the transfer of energy by thermal radiation becomes less rapid. At this point, the blast wave front begins to catch up with the surface of the fireball and then moves ahead of it, a process called hydrodynamic separation. Due to the tremendous compression of the atmosphere by the blast wave, the air in front of the fireball is heated to incandescence. Thus, after hydrodynamic separation, the fireball actually consists of two concentric regions: the hot inner core known as the isothermal sphere; and an outer layer of luminous shock-heated air.

d. The outer layer initially absorbs much of the radiation from theisothermal sphere and hence the apparent surface temperature of the fireball and the amount of radiation emitted from it decreases after separation. But, as the shock front advances still farther, the temperature of the shocked air diminishes and it becomes increasingly transparent. This results in an unmasking of the still incandescent isothermal region and an increase in the apparent surface temperature of the fireball. This phenomena is referred to as breakaway.

313. Rate of Thermal Emission.

a. The rate of thermal emission from the fireball is governed by its apparent surface temperature. From the foregoing discussion, it should be apparent that the thermal output of a nuclear air burst will then occur in two pulses (Figure 3-IV), an initial pulse, consisting primarily of ultraviolet radiation, which contains only about 1% of the total radiant energy of the explosion and is terminated as the shock front moves ahead of the fireball, and a second pulse which occurs after breakaway.

b. The thermal radiation emitted from the fireball surface during the second thermal pulse is responsible for most of the thermal effects. It consists chiefly of radiation in the infrared, visible, and ultraviolet regions of the electromagnetic spectrum. Thermal exposure (measured in joules per unit area of exposed surface) will be less farther from the center of the explosion because the radiation is spread over a greater area and is attenuated in passing through the intervening air. Since the fireball is very close to a point source of thermal radiation, the quantity of thermal radiation at any given point varies approximately with the square of the distance from the explosion. The inverse square law does not apply exactly because thermal radiation, particularly ultraviolet, will also be absorbed and scattered by the atmosphere. The degree of atmospheric visibility affects the attenuation of thermal energy with distance to a limited degree, but less than would be expected from the purely absorptive properties of the atmosphere, because the decrease in transmission is largely compensated by an increase in scattered radiation.

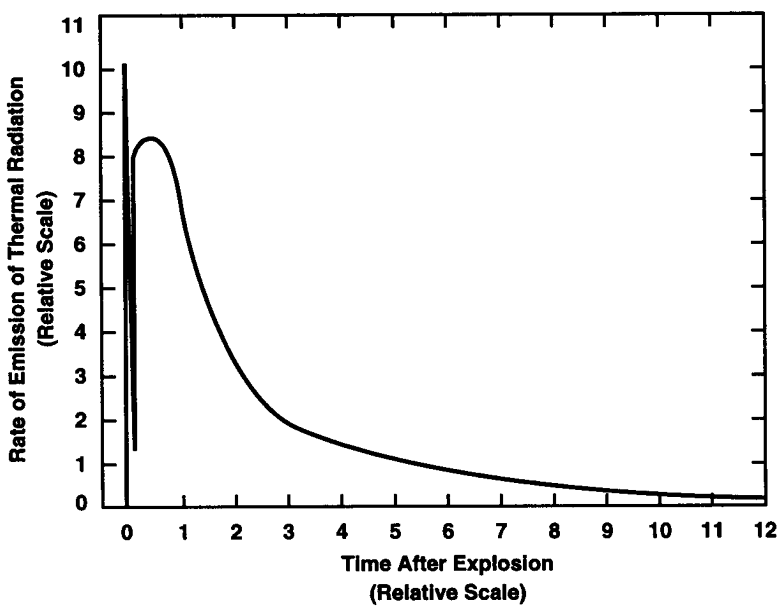

Figure 3-IV. Emission of Thermal Radiation in Two Pulses in an Air Blast

314. Shielding.

Since thermal radiation travels in straight lines from the fireball (unless scattered) any opaque object interposed between the fireball and the target will act as a shield and provide significant protection from thermal radiation. If a significant amount of scattering is present, as is the case when visibility is poor, thermal radiation will be received from all directions and shielding will be less effective.

315. Yield and Altitude.

a. *Yield.* The total amount of thermal radiation, the period of time during which it is emitted, and the range for thermal effects increase with the yield of the nuclear explosion (Figure 3-V).

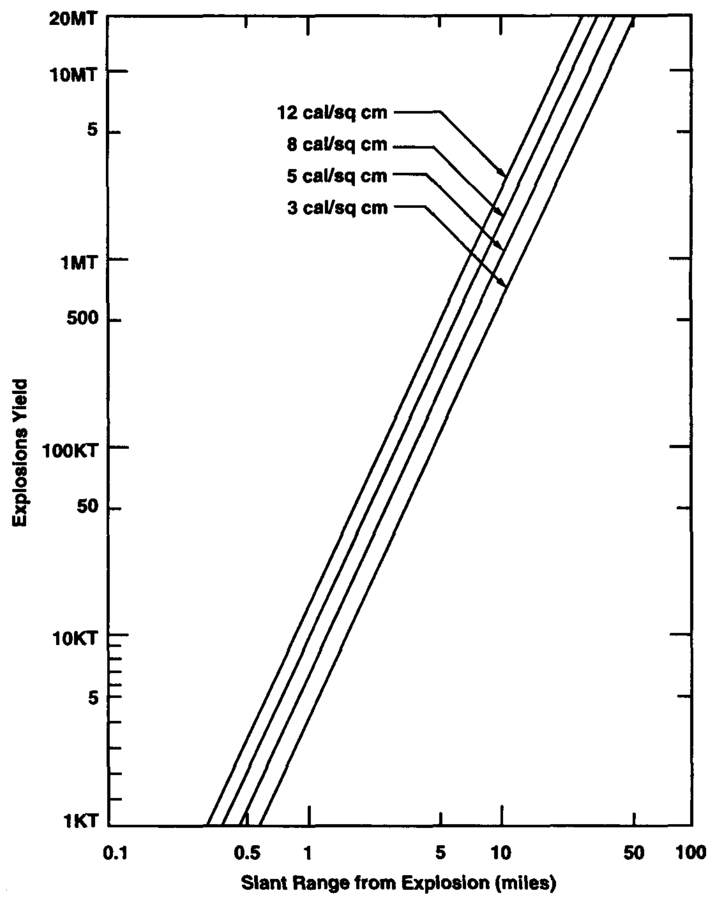

Figure 3-V. Slant Ranges for Specified Radient Exposures as Functions of Energy Yield of the Explosion

b. *Altitude Effects.* The thermal radiation intensity at a given point will depend on the altitude and the type of burst. In general, the thermal hazard is greatest in the case of a low altitude air burst. General thermal effects will be less for surface bursts and frequently nonexistent for subsurface bursts. In surface bursts a large part of the thermal energy is absorbed by the ground or water around ground zero. In addition, shielding due to terrain irregularities of dust, moisture, and various gases in the air near the surface of the earth will tend to reduce the amount of thermal energy reaching a target. In subsurface bursts without appreciable penetration, most of the thermal energy is absorbed and dissipated in heating and vaporizing soil and water below the surface.

c. *High Altitude Effects.* In high altitude air bursts (above 30 km), the low density of the atmosphere alters the nature of the thermal radiation process because the primary thermal radiation is absorbed in a much larger volume of air, and the temperature of the system is correspondingly less. While a greater percentage of the yield of the explosion appears in the form of thermal radiation, much of the radiation is emitted so slowly that it is ineffective. About 25-35% of the total yield is emitted in a single pulse of very short duration. Moreover, because of the relatively great distance between the center of the burst and the earth's surface, the intensity of thermal radiation at ground level is generally low.

316. Thermal Effects.

a. When thermal radiation strikes an object, part will be reflected, part will be transmitted, and the rest will be absorbed. The fraction of the incident radiation that is absorbed depends on the nature and color of the material. A thin material may transmit a large part of the radiant energy striking it. A light colored object may reflect much of the incident radiation and thus escape damage. Thermal damage and injury is due to the absorption of large amounts of thermal energy within relatively short periods of time. The absorbed thermal radiation raises the temperature of the absorbing surface and results in scorching, charring, and possible ignition of combustible organic materials, such as wood, paper, fabrics, etc. If the target material is a poor thermal conductor, the absorbed energy is largely confined to a superficial layer of the material.

b. The radiation exposure (# Joules / sq / cm) required for the ignition of materials and other thermal effects increases with the yield of the weapon (Table 3-III). This is so because increased thermal energy is required to compensate for energy lost via conduction and convection during the longer thermal pulse of higher yield weapons. For lower yield weapons, the thermal pulse is so short that there is not much time for these processes to cool the exposed surface. Hence, a much higher percentage of the deposited thermal energy is effective in producing thermal damage. This increased thermal requirement does not mean that the thermal hazard is less significant for higher yields. On the contrary, the total thermal energy released during a nuclear explosion increases markedly with yield, and the effects extend over much greater distances. Therefore, although more thermal energy is required to produce a given thermal response for a large yield explosion, the effective range to which this level extends is very much greater.

c. Actual ignition of materials exposed to thermal radiation is highly dependent on the width of the thermal pulse (which is dependent on weapon yield) and the nature of the material, particularly its thickness and moisture content. At locations close to ground zero where the radiant thermal exposure exceeds 125 Joules/sq cm, almost all ignitable materials will flame, although burning may not be sustained (Table 3-III). On the other hand, at greater distances only the most easily ignited materials will flame, although charring of exposed surfaces may occur. The probability of significant fires following a nuclear explosion depends on the density of ignition points, the availability and condition of combustible material (whether hot, dry, wet), wind, humidity, and the character of the surrounding area. Incendiary effects are compounded by secondary fires started by the blast wave effects such as from upset stoves and furnaces, broken gas lines, etc. In Hiroshima, a tremendous fire storm developed within 20 minutes after detonation. A fire storm burns in upon itself with great ferocity and is characterized by gale force winds blowing in towards the center of the fire from all points of the compass. It is not, however, a phenomenon peculiar to nuclear explosions, having been observed frequently in large forest fires and following incendiary raids during World War II.

SECTION IV - NUCLEAR RADIATION

317. Sources of Nuclear Radiation.

Blast and thermal effects occur to some extent in all types of explosions, whether conventional or nuclear. The release of ionizing radiation, however, is a phenomenon unique to nuclear explosions and is an additional casualty producing mechanism superimposed on blast and thermal effects. This radiation is basically of two kinds, electromagnetic and particulate, and is emitted not only at the time of detonation (initial radiation) but also for long periods of time afterward (residual radiation). Initial or prompt nuclear radiation is that ionizing radiation emitted within the first minute after detonation and results almost entirely from the nuclear processes occurring at detonation. Residual radiation is defined as that radiation which is emitted later than 1 minute after detonation and arises principally from the decay of radioisotopes produced during the explosion.

*Table 3-III. Approximate Radient Exposures for Ignition of Fabrics for Low Air Burst**

Material	Wt (g/m²)	Color	Effect on material	Ignition Exposure 35 kilotons ground Joules sq cm	Range** (km)	Ignition Exposure 20 megatons ground Joules sq cm	Range** (km)
a. Clothing Fabrics:							
Cotton	298	White	Ignites	134	2.1	355	20.9
		Khaki	Tears on flexing	71	2.7	142	33.2
		Khaki	Ignites	84	2.5	163	30.9
		Olive	Tears on flexing	38	3.4	88	42.1
		Olive	Ignites	58	2.9	88	42.1
		Dk Blue	Tears on flexing	46	3.2	71	46.9
		Dk Blue	Ignites	58	2.9	88	42.1
Cotton corduroy	298	Brown	Ignites	46	3.2	92	41.2
Cotton denim, new	372	Blue	Ignites	50	3.1	184	29.1
Cotton shirting, new	112	Khaki	Ignites	58	2.9	117	36.5
Cotton-nylon mixture	186	Olive	Tears on flexing	33	3.6	71	46.9
		Olive	Ignites	50	3.1	222	26.5
Wool	298	White	Tears on flexing	58	2.9	109	37.9
		Khaki	Tears on flexing	58	2.9	142	33.2
		Olive	Tears on flexing	38	3.4	79	44.5
		Dk Blue	Tears on flexing	33	3.6	75	45.7
	744	Dk Blue	Tears on flexing	58	2.9	109	37.9
Rainware (double neoprene-coated)	335	Olive	Begins to melt	21	4.4	54	53.8
Nylon twill		Olive	Tears on flexing	33	3.6	92	41.2
b. Drapery Fabrics:							
Rayon gabardine	223	Black	Ignites	38	3.4	109	37.9
Rayon-acetate	186	Wine	Ignites	38	3.4	117	36.5
Rayon gabardine	260	Gold	Ignites	***		#117	36.5
Rayon twill lining	112	Black	Ignites	29	3.8	104	38.8
Rayon twill lining	112	Beige	Ignites	54	3.0	117	36.5
Acetate-sheeting	112	Black	Ignites	#42	3.3	#146	32.7
Cotton heavy drapes	484	Dark	Ignites	63	2.8	142	33.2
c. Tent Fabrics:							
Canvas (cotton)	446	White	Ignites	54	3.0	213	27.1
Canvas	446	O. Drab	Ignites	50	3.1	117	36.5
d. Other Fabrics:							
Cotton chenille bedspread		Lt Blue	Ignites	***		63	49.8
Cotton venetian blind tape, dirty		White	Ignites	42	3.3	92	41.2
Cotton venetian blind tape		White	Ignites	#54	3.0	#130	34.7
Cotton muslin window shade	298	Green	Ignites	29	3.8	79	44.5

* Radient exposures for indicated responses (except where marked#) are estimated valid to +25% under standard laboratory conditions. Under typical field conditions, values are estimated within +50% with a greater likelihood of the higher than lower values. For materials marked #, ignition levels are estimated to be valid within +50% under laboratory conditions and within 100% under field conditions.

** Ground ranges calculated for good visibility conditions.

*** Data not available or appropriate scaling not known.

318. Initial Radiation.

About 5% of the energy released in a nuclear air burst is transmitted in the form of initial neutron and gamma radiation. The neutrons result almost exclusively from the energy producing fission and fusion reactions, while the initial gamma radiation includes that arising from these reactions as well as that resulting from the decay of short-lived fission products. The intensity of initial nuclear radiation decreases rapidly with distance from the point of burst due to the spread of radiation over a larger area as it travels away from the explosion, and to absorption, scattering, and capture by the atmosphere. The character of the radiation received at a given location also varies with distance from the explosion. Near the point of the explosion, the neutron intensity is greater than the gamma intensity, but with increasing distance the neutron-gamma ratio decreases. Ultimately, the neutron component of initial radiation becomes negligible in comparison with the gamma component. The range for significant levels of initial radiation does not increase markedly with weapon yield and, as a result, the initial radiation becomes less of a hazard with increasing yield. With larger weapons, above 50 Kt, blast and thermal effects are so much greater in importance that prompt radiation effects can be ignored.

319. Residual Radiation.

The residual radiation hazard from a nuclear explosion is in the form of radioactive fallout and neutron-induced activity. Residual ionizing radiation arises from:

a. *Fission Products.* These are intermediate weight isotopes which are formed when a heavy uranium or plutonium nucleus is split in a fission reaction. There are over 300 different fission products that may result from a fission reaction. Many of these are radioactive with widely differing half-lives. Some are very short, i.e., fractions of a second, while a few are long enough that the materials can be a hazard for months or years. Their principal mode of decay is by the emission of beta and gamma radiation. Approximately 60 grams of fission products are formed per kiloton of yield. The estimated activity of this quantity of fission products 1 minute after detonation is equal to that of 1.1×10^{21} Bq (30 million kilograms of radium) in equilibrium with its decay products.

b. *Unfissioned Nuclear Material.* Nuclear weapons are relatively inefficient in their use of fissionable material, and much of the uranium and plutonium is dispersed by the explosion without undergoing fission. Such unfissioned nuclear material decays by the emission of alpha particles and is of relatively minor importance.

c. *Neutron-Induced Activity.* If atomic nuclei capture neutrons when exposed to a flux of neutron radiation, they will, as a rule, become radioactive (neutron-induced activity) and then decay by emission of beta and gamma radiation over an extended period of time. Neutrons emitted as part of the initial nuclear radiation will cause activation of the weapon residues. In addition, atoms of environmental material, such as soil, air, and water, may be activated, depending on their composition and distance from the burst. For example, a small area around ground zero may become hazardous as a result of exposure of the minerals in the soil to initial neutron radiation. This is due principally to neutron capture by sodium (Na), manganese, aluminum, and silicon in the soil. This is a negligible hazard because of the limited area involved.

320. Fallout.

a. *Worldwide Fallout.* After an air burst the fission products, unfissioned nuclear material, and weapon residues which have been vaporized by the heat of the fireball will condense into a fine suspension of very small particles 0.01 to 20 micrometers in diameter. These particles may be quickly drawn up into the stratosphere, particularly so if the explosive yield exceeds 10 Kt. They will then be dispersed by atmospheric winds and will gradually settle to the earth's surface after weeks, months, and even years as worldwide fallout. The radiobiological hazard of worldwide fallout is essentially a long-term one due to the potential accumulation of long-lived radioisotopes, such as strontium-90 and cesium-137, in the body as a result of ingestion of foods which had incorporated these radioactive materials. This hazard is much less serious than those which are associated with local fallout and, therefore, is not discussed at length in this publication. Local fallout is of much greater immediate operational concern.

b. *Local Fallout.* In a land or water surface burst, large amounts of earth or water will be vaporized by the heat of the fireball and drawn up into the radioactive cloud. This material will become radioactive when it condenses with fission products and other radiocontaminants or has become neutron-activated. There will be large amounts of particles of less than 0.1 micrometer to several millimeters in diameter generated in a surface burst in addition to the very fine particles which contribute to worldwide fallout. The larger particles will not rise into the stratosphere and consequently will settle to earth within about 24 hours as local fallout. Severe local fallout contamination can extend far beyond the blast and thermal effects, particularly in the case of high yield surface detonations. Whenever individuals remain in a radiologically contaminated area, such contamination will lead to an immediate external radiation exposure as well as a possible later internal hazard due to inhalation and ingestion of radiocontaminants. In severe cases of fallout contamination, lethal doses of external radiation may be incurred if protective or evasive measures are not undertaken. In cases of water surface (and shallow underwater) bursts, the particles tend to be rather lighter and smaller and so produce less local fallout but will extend over a greater area. The particles contain mostly sea salts with some water; these can have a cloud seeding affect causing local rainout and areas of high local fallout. For subsurface bursts, there is an additional phenomenon present called "base surge." The base surge is a cloud that rolls outward from the bottom of the column produced by a subsurface explosion. For underwater bursts the visible surge is, in effect, a cloud of liquid (water) droplets with the property of flowing almost as if it were a homogeneous fluid. After the water evaporates, an invisible base surge of small radioactive particles may persist. For subsurface land bursts, the surge is made up of small solid particles, but it still behaves like a fluid. A soil earth medium favors base surge formation in an underground burst.

c. *Meteorological Effects.* Meteorological conditions will greatly influence fallout, particularly local fallout. Atmospheric winds are able to distribute fallout over large areas. For example, as a result of a surface burst of a 15 Mt thermonuclear device at Bikini Atoll on March 1, 1954, a roughly cigar-shaped area of the Pacific extending over 500 km downwind and varying in width to a maximum of 100 km was severely contaminated. Snow and rain, especially if they come from considerable heights, will accelerate local fallout. Under special meteorological conditions, such as a local rain shower that originates above the radioactive cloud, limited areas of heavy contamination may be formed.