CHAPTER 4

BIOLOGICAL EFFECTS OF A NUCLEAR EXPLOSION

SECTION I - GENERAL

401. Introduction.

Chapter 3 described the physical characteristics of nuclear explosions. This chapter will consider the biological effects of blast and thermal radiation. The material to be presented is intended to supplement the material on the clinical aspects of blast and thermal injuries described in Chapter 6. The basic scientific aspects of radiation injury will be discussed in Chapter 5.

SECTION II - BLAST INJURY

402. General.

a. The basic physical effects of a blast wave are described in Chapter 3 along with how the wave is formed. There are two basic types of blast forces which occur simultaneously in a nuclear detonation blast wave. These are: direct blast wave overpressure forces, measured in terms of atmospheres of overpressure; and indirect blast wind drag forces, measured best in terms of the velocities of the wind which cause them. The most important blast effects, insofar as production of casualties requiring medical treatment is concerned, will be those due to the blast wind drag forces. Direct overpressure effects do not extend out as far from the point of detonation and are frequently masked by drag force effects as well as by thermal effects.

b. However, direct blast effects can contribute significantly to the immediate deaths and injuries sustained close to the point of detonation and, therefore, do constitute an important total casualty producing effect in the large area of lethal damage associated with a given nuclear detonation. Personnel in fortifications or heavy vehicles such as tanks who are protected from radiation and thermal and blast wind effects may be subjected to complex patterns of direct overpressures since blast waves can enter such structures and be reflected and reinforced within them.

403. Direct Blast Injury.

a. When a blast wave is incident upon a target, the nature and probability of damage will depend upon a number of variables in the characteristics of the blast wave and of the target. Important variables of the blast wave include: the rate of pressure rise at the blast wave front, the magnitude of the peak overpressure, and the duration of the blast wave. Those of the target include: size, mass, density, resistance to deformity, etc. If the target is human, then additional factors such as age, physical condition, and the presence of disease or other injury become important.

b. When the blast wave acts directly upon a resilient target such as the human body, rapid compression and decompression result in transmission of pressure waves through the tissues. These waves can be quite severe and will result in damage primarily at junctions between tissues of different densities (bone and muscle) or at the interface between tissue and air spaces. Lung tissue and the gastrointestinal system, both of which contain air, are particularly susceptible to injury. The resulting tissue disruptions can lead to severe hemorrhage or to air embolism, either of which can be rapidly fatal. Perforation of the ear drums would be a common but a minor blast injury.

c. The range of overpressures associated with lethality can be quite variable. It has been estimated that overpressures as low as 193 kPa (1.9 atm) can be lethal, but that survival is possible with overpressures as high as 262 kPa (2.5 atm). Atypical range of probability of lethality with variation in overpressure is summarized in Table 4-I. These are rough estimates based on selected experimental data, and there will be some differences between these figures and tabulations based upon other experimental work. In addition these numbers apply only to unreinforced, unreflected blast waves. When blast waves are complicated by reinforcement and reflection, estimation or measurement of the overpressures associated with specific injuries becomes quite complex. The significant thing shown by the data in Table 4-I is that the human body is remarkably resistant to static overpressure, particularly when compared with rigid structures such as buildings. Shattering of an unreinforced cinder block panel, for example, will occur at 10.1 -20.2 kPa (0.1-0.2 atm).

Table 4-I. Range of Lethality at Peak Overpressure

Lethality (approximate %)	Peak overpressure (k Pa)
1	160 - 230
50	230 - 400
100	400 +

d. Overpressures considerably lower than those listed in Table 4-I will cause injuries which are not lethal. Lung damage and eardrum rupture are two useful biomedical parameters to use as examples, since one is a relatively serious injury, usually requiring hospitalization even if not lethal, while the other is a minor injury, often requiring no treatment at all.

(1) The threshold level of overpressure which is estimated to cause lung damage is about 68.9 kPa for a simple unreinforced, unreflected blast wave. There will be considerable variation in this value with differing conditions of exposure.

(2) The threshold value for eardrum rupture is probably around 22 kPa (0.2 atm) and that overpressure associated with a 50% probability of eardrum rupture ranges from 90 to 130 kPa (0.9 to 1.2 atm).

e. From this it can be seen that casualties requiring medical treatment from direct blast effects could theoretically be produced by overpressures greater than 70 kPa. However, direct blast injuries will not occur by themselves; and in general, other effects, such as indirect blast injuries and thermal injuries are so severe at the ranges associated with these overpressures that patients with direct blast injuries will comprise a very small part of the patient load.

404. Indirect Blast Wind Drag Forces.

a. *Blast Winds.* The drag forces of the blast winds are proportional to the velocities and duration times of those winds, which in turn vary with distance from the point of detonation, yield of the weapon, and altitude of the burst. These winds are relatively short in duration but are extremely severe. They can be much greater in velocity than the strongest hurricane winds and may reach several hundred kilometers per hour. Considerable injury can result, due either to missiles or to the physical displacement of human bodies against objects and structures in the environment.

b. *Probability of Indirect Blast Injury.* The distance from the point of detonation at which severe indirect injury will occur is considerably greater than that for equally serious direct blast injuries. It is difficult to give precise ranges at which these indirect injuries are likely to occur because of the marked effect of variations in the environment. However, that range at which the peak overpressure is about 20.3 kPa (0.2 atm) is a reasonable reference distance at which the probability of serious indirect injury is high. Injuries can occur at greater ranges, and casualties will be generated at greater ranges, but not consistently.

405. Missile Injury.

The probability of injury from a missile depends upon a number of factors.

a. *The Number of Missiles.* The number of missiles which can be generated by the blast winds depends to some extent upon the environment. Certain terrain, such as desert, is particularly susceptible to missile forming effects of winds. However, the drag forces of the blast winds produced by nuclear detonations are so great that almost any form of vegetation or structure will be broken apart or fragmented into a variety of missiles. As a result, large numbers and a great variety of missiles will be generated in almost any environment. Single missile injuries will be rare and multiple, varied missile injuries will be common. As a result, the overall severity and significance of missile injuries is greatly increased. Table 4-II gives an indication of the ranges out to which significant missile injuries would be expected.

b. *The Kinetic Energy and Shape of the Missiles.* Several separate factors are involved here, but a detailed discussion of complex missile ballistics is beyond the scope of this handbook. The major factor in how missiles are accelerated depends upon the wind velocity and the size and weight of the missiles. The wind velocity is the maximum, since objects cannot be made to go faster than the winds themselves. Therefore, all these missiles will be low velocity in nature. None will be high velocity, such as is produced with small arms fire. The weight or mass of an object and the duration times of the winds determine whether or not that object will be accelerated maximally. Light objects will be accelerated rapidly up to the maximum possible velocity, whereas heavy objects may not be. The velocity is important because the probability of a penetrating injury increases with increasing velocity, particularly for small, sharp missiles such as glass fragments. Table 4-III shows typical experimental data for probability of penetration related to size and velocity of glass fragments of various weights. The table also lists the kinetic energy associated with each weight and velocity. The progression in energy is reversed, and it can be seen that heavier objects require higher kinetic energies to penetrate, at least in this particular experimental system. Heavy blunt missiles will not penetrate but can result in significant injury, particularly fractures. For example, a velocity of about 4.6 meters/see is a threshold velocity for skull fracture for a 4.5 kg missile.

*Table 4-II. Ranges for Different Probabilities of Injury from Small Missiles**

Yield (Kt)	Range for 1% probability of serious injury	Range for 50% probability of serious injury	Range for 99% probability of serious injury
1	0.28 km	0.22 km	0.17 km
10	0.73 km	0.57 km	0.44 km
20	0.98 km	0.76 km	0.58 km
50	1.4 km	1.1 km	0.84 km
100	1.9 km	1.5 km	1.1 km
200	2.5 km	1.9 km	1.5 km
500	3.6 km	2.7 km	2.1 km
1000	4.8 km	3.6 km	2.7 km

* Incidence of head injury based on incidence of perforation of skin and tissue. Missiles used were 10 gm in weight.

*Table 4-III. Probability of Penetration of Glass Fragments and Associated Kinetic Energy Related to Size and Velocity**

Mass of glass fragments (grams)	1%	50%	99%
	Impact velocity (m/sec)**/Kinetic energy (joules)***		
0.1	78/0.3	136/0.9	243/3.0
0.5	53/0.7	91/2.1	161/6.5
1.0	46/1.1	82/3.4	143/10.2
10.0	38/7.2	60/18.0	118/70.0

* The penetrating injury example here is for the abdominal cavity.
** Impact velocity is in m/sec. Conversion to cm/sec is necessary to determine kinetic energy in joules.
*** Kinetic energy is expressed by $1/2mv^2$, in which m = mass in grams and v = velocity in cm/sec. The basic unit of kinetic energy is the erg, which is equivalent to gm^2/sec^2.

406. Crush and Translational Injuries.

The drag forces of the blast winds are strong enough to displace even large objects such as vehicles or to cause collapse of large structures such as buildings. These can result in very serious crush injuries. Humans themselves can become a missile and be displaced a variable distance and at variable velocities depending upon the intensity of the drag forces and the nature of the environment. The resulting injuries sustained are termed translational injuries. The probability and the severity of injury are functions of the velocity of the human body at the time of impact. If a representative displacement distance of 3.0 meters is assumed, the impact velocities which would be associated with various degrees of injury can be calculated. These are shown in Table 4-IV. The table shows terminal or impact velocities associated with significant but nonlethal blunt injury. It also shows those velocities which are associated with a probability of lethality. The velocities in Table 4-IV can be equated against yield, and the ranges at which such velocities would be found can be calculated. These are given in Table 4-V.

Table 4-IV. Translational Injuries

Velocity*(m/sec)	Probability of blunt injuries & fractures	Probability of fatal injuries
2.6	>1%	-
6.6	~50%	>1%
17.0	99%	~50%
44.5	-	99%

*Velocities are based on solid impact with a nonyielding surface.

Table 4-V. Ranges for Selected Impact Velocities of a 70-kg Human Body Displaced by Blast Wind Drag Forces for Different Yield Weapons

Weapon yield (Kt)	Velocities*(m/sec)		
	2.6	6.6	17.0
1	0.38 km	0.27 km	0.19 km
10	1.0 km	0.75 km	0.53 km
20	1.3 km	0.99 km	0.71 km
50	1.9 km	1.4 km	1.0 km
100	2.5 km	1.9 km	1.4 km
200	3.2 km	2.5 km	1.9 km
500	4.6 km	3.6 km	2.7 km
1000	5.9 km	4.8 km	3.6 km

* These velocities are selected from those listed in Table 4 -IV. Data account for ground friction and consider only prone personnel.

SECTION III - THERMAL INJURY

407. Mechanism of Injury.

The thermal radiation emitted by a nuclear detonation causes burns in two ways, by direct absorption of the thermal energy through exposed surfaces (flash burns) or by the indirect action of fires caused in the environment (flame burns). The relative importance of these two processes will depend upon the nature of the environment. If a nuclear weapon detonation occurs in easily flammable surroundings, indirect flame burns could possibly outnumber all other types of injury.

408. Thermal Effects.

a. Thermal radiation travels in a straight line from the fireball, and the amount of energy which is available to act upon a given target area decreases rapidly with distance. The thermal flux in watts per square centimeter decreases approximately with the square of the distance from the point of detonation. This attenuation with distance varies somewhat with the nature of the environment and the weather, since thermal radiation is easily reflected. However, the attenuating effect of even a heavy cloud cover is surprisingly small. Since thermal radiation travels in straight lines, objects between the fireball and any targets will tend to shield and protect them.

b. Close to the fireball the thermal output will be so great that all objects will be incinerated. Immediate lethality obviously would be 100% within this range and to some extent beyond. The actual range out to which overall lethality would be 100% will vary with yield, position of burst, weather, the environment and how soon those burned can receive medical care. The mortality rate among the severely burned is much greater without early resuscitative treatment.

409. Thermal Energy and Burns to Exposed Skin.

Two factors determine the degree of burn injury in a given situation. The amount of thermal energy per square centimeter and the duration of the thermal pulse. The dose of thermal radiation to exposed skin required to cause a flash second-degree bum will vary from less than 16.7 joules/cm^2 to more than 29.3 joules/cm^2 depending on the yield of the weapon (Table 4-VI). A larger dose is required with larger yield weapons because of the nature of the pulse. Megaton weapons have much longer thermal pulses with much more gradual rates of increase. There is time for the skin to dissipate some of the thermal energy; and therefore, more is required to produce a given degree of injury. However, it must be realized that the same degree of injury from a megaton weapon is seen at a much greater range and over a much greater area than would be the case with kiloton weapons. The difference in dose required to produce a given burn injury is not a significant factor when compared with the increase in overall probability of injury associated with increasing yield.

Table 4-VI. Factors for Determining Probability of Second-Degree Burns to Bare Skin

Yield of weapon	1 Kt	10 Kt	100Kt	1Mt	10 Mt
Range in kilometers for production of second-degree burns on exposed surfaces (air burst)*	0.78	2.1	4.8	9.1	14.5
Duration of thermal pulse (sec)**	0.2	0.6	1.6	4.4	12.0
Joules/cm^2 required to produce second-degree burns on exposed skin	16.7	18.8	22.1	26.3	29.3

* Ranges calculated considering a 10-km visibility.
** Time for delivery of 70% of thermal energy.

410. Flash Burns Under Clothing.

While most thermal injury predictions are referred to exposed skin, it is important to remember the protection from burn that can be achieved with clothing. That protection, however, is not absolute. At temperatures below those required to ignite clothing, it is possible to transfer sufficient thermal energy across clothing to the skin to produce flash burns. The amount of heat energy conducted across clothing is a function of the energy absorbed by and the thermal conducting properties of the clothing. It will also be a function of whether the clothing is tight fitting or loose. Two uniform combinations have been specifically tested to determine the incident thermal exposure necessary to produce second-degree burns to skin under clothing. Table 4-VII summarizes the thermal burn criteria for skin under the U.S. Army summer uniform and the U.S. Army chemical protective overgarment. As can be seen by comparison with Table 4-VI, clothing significantly reduces the effective range to produce second-degree burns, thus affording significant protection against thermal flash burns. It should be noted that, because of the modifying effect of the uniforms, the exposures necessary to cause second-degree burns beneath the uniforms are yield independent.

*Table 4-VII. Incident Exposure Necessary to Cause Second-Degree Burns Under Clothing**

Clothing**	All yields - joules/cm^2
U.S. Army summer uniform (fatigue uniform and undershirt)	62.7
U.S. Army chemical protective overgarment (battledress overgarment, fatigue uniform, and undershirt)	129.7

* This is based on a 3mm separation between clothing and skin.
** The U.S. fatigue uniform is made from 50% cotton and 50% nylon. The battledress overgarment shell is 50% nylon and 50% cotton, and the lining is 100% synthetic material impregnated with a charcoal slurry. Fluence required to produce second-degree burns under uniforms remains constant as yield varies.

411. Flame Burns.

Indirect or flame burns result from exposure to fires caused by the thermal effects in the environment, particularly from ignition of clothing. This could be the predominant cause of burns depending on the number of and characteristics of (e.g., man-made fibers) flammable objects in an environment. This is particularly true for the large yield weapons, which can cause conflagrations and fire storms over extensive areas. Complications arise in the treatment of skin burns which have been created, in part, by melting man-made fibers; therefore, it may be advisable for clothing made of natural fibers to be worn next to the skin. The probability of flame burns cannot be quantified with range as well as can flash burns. The variables of environmental flammability are too great to allow prediction of either incidence or severity. The burns themselves will be far less uniform in degree and will not be limited to exposed surfaces. For example, the respiratory system may be exposed to the effects of hot gases produced whenever extensive fires occur. Respiratory system burns are associated with severe morbidity and high mortality rates. Depending on the flammability of the material, blast winds may extinguish or fan the burning material.

412. Eye Injuries.

The effects of thermal/visual radiation on the eyes fall into two main categories, temporary flash blindness and permanent retinal scarring.

a. *Flash Blindness.*

(1) Flash blindness is caused by the initial brilliant flash of light produced by the nuclear detonation. More light energy is received on the retina than can be tolerated, but less than is required for irreversible injury. The retina is particularity susceptible to visible and short wavelength infrared light, since this part of the electromagnetic spectrum is focused by the lens with concentration of energy at the retinal surface. The result is bleaching of the visual pigments and temporary blindness.

(2) During the daylight hours, flash blindness does not persist for more than about 2 minutes, but generally is of the order of seconds. At night, when the pupil is dilated for dark adaptation, flash blindness will affect personnel at greater ranges and will last for longer periods of time (Figure 4-I). Partial recovery, such that personnel could function in lighted areas, may be expected within 3 to 10 minutes. Impairment of dark adaptation and night vision will persist for longer periods, however, and may seriously reduce combat effectiveness. It may require 15-35 minutes for recovery of night adaptation, depending upon the amount of light energy absorbed.

(3) Figure 4-I illustrates flashblindness and retinal burn safe separation distances for an observer on the ground, as a function of explosion yield, for burst heights of 3,000 meters at night and on a clear day. Safe separation distances are those distances beyond which persons on the ground would not receive incapacitating eye injuries.

b. *Retinal Scarring.* A retinal burn resulting in permanent damage from scarring is also caused by the concentration of direct thermal energy on the retina by the lens. It will occur only when the fireball is actually in the individual's field of vision and would be a relatively uncommon injury. Retinal burns, however, may be sustained at considerable distances from the explosion (Figure 4-I). The apparent size of the fireball, a function of yield and range will determine the degree and extent of retinal scarring. The location of the scar will determine the degree of interference with vision, with a scar in the central visual field being potentially much more debilitating. Generally, a limited visual field defect, which will be barely noticeable, is all that is likely to occur.

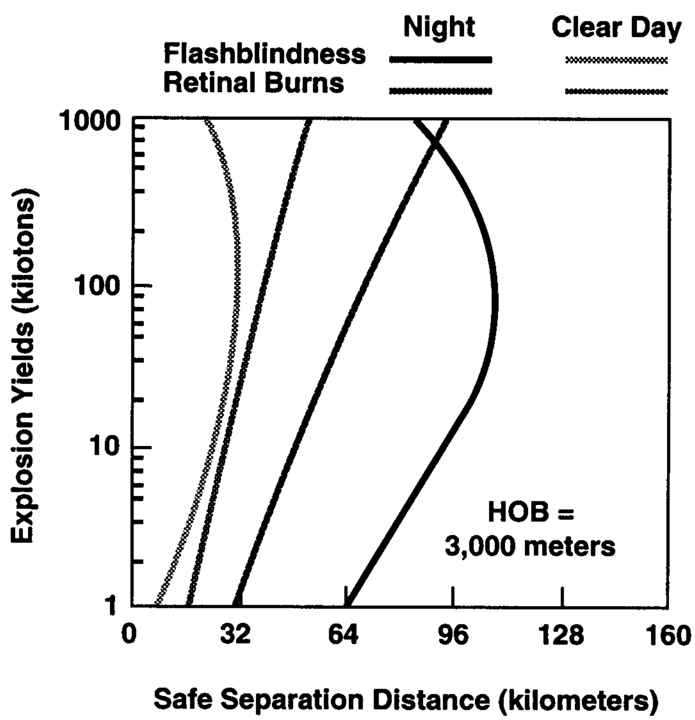

Figure 4-I. Flashblindness and Retinal Burn Safe Separation