CHAPTER 13
BASIC NUCLEAR PHYSICS AND WEAPONS EFFECTS

OVERVIEW

Nuclear weapons depend on the potential energy that can be released from the nuclei of atoms. The splitting apart of atoms, called fission, and joining together of atoms, called fusion, are nuclear reactions that can be induced in the nucleus. All current nuclear weapons use the basic approach of producing a very large number of fission events through a multiplying chain reaction and releasing a huge amount of nuclear energy in a very short period of time. This chapter provides an overview of nuclear physics, basic nuclear weapon designs, and the effects of nuclear detonations.

NUCLEAR PHYSICS

The fundamentals of nuclear weapons design and function include atomic structure, radioactive decay, fissile material, and nuclear reactions.

ATOMIC STRUCTURE

Matter is the material substance in the universe that occupies space and has mass. All matter in the observable universe is made up of various combinations of separate and distinct particles. When these particles (primarily protons, neutrons, and electrons) are combined to form atoms, they are called elements. There are more than 110 known chemical elements, each of which cannot be broken down further without changing its chemical properties. The number of protons in an atom's nucleus identifies the atomic element.

Atoms have a densely packed core—or nucleus—comprised of electrically neutral neutrons and positively charged protons (except for hydrogen whose nucleus contains only a single proton) that is surrounded by rings or shells of orbiting, negatively charged electrons as illustrated in Figure 13.1. Interactions with an atom's

electrons determine an element's chemical characteristics whereas interactions with an atom's nucleus determine an element's nuclear characteristics. Examples of chemical characteristics include the tendency of elements to combine with other elements (e.g., hydrogen and oxygen combine to form water), the ability to conduct electricity, and the ability to undergo chemical reactions, such as oxidation (e.g., iron and oxygen combine to form iron oxide or rust). Examples of nuclear characteristics include the tendency of a nucleus to split apart or fission, the ability of a nucleus to absorb a neutron, and radioactive decay where the nucleus emits a particle from the nucleus. An important difference between chemical and nuclear reactions is that there can neither be a loss nor a gain of mass during a chemical reaction; however, mass can be converted into energy in a nuclear reaction. This change of mass into energy is what is responsible for the tremendous release of energy during a nuclear detonation.

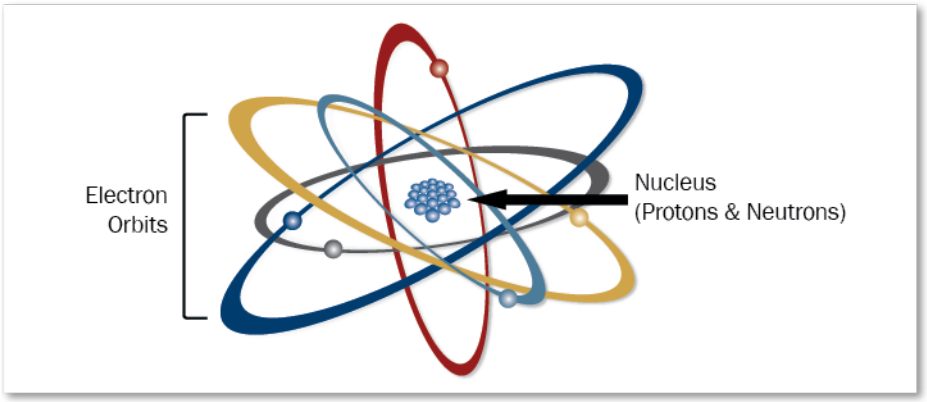

Figure 13.1 Diagram of an Atom

Isotopes are atoms of the same element that have identical atomic numbers (same number of protons) but a different atomic mass (also called atomic weight) due to a different number of neutrons in the nuclei. Isotopes are identified by their atomic mass, which is the sum of all protons and neutrons in the nucleus.

Different isotopes of the same element have different nuclear characteristics, e.g., uranium-235 (U-235) has significantly different nuclear characteristics than U-238. See Figure 13.2 for an illustration of two of the 23 currently known isotopes of uranium.

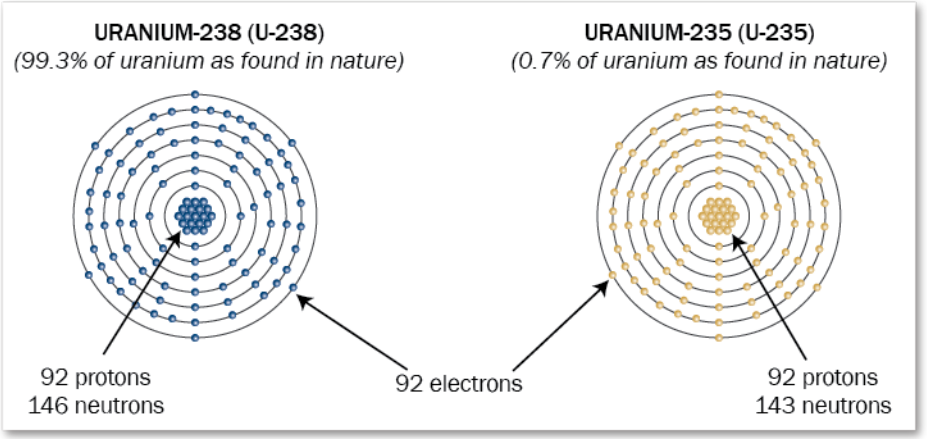

Figure 13.2 Isotopes of Uranium

RADIOACTIVE DECAY

Radioactive decay is the process of spontaneous nucleus breakdown and the resultant particle and/or energy release as the nucleus attempts to reach a more stable configuration. The nuclei of many isotopes are unstable and have statistically predictable timelines for radioactive decay. These unstable isotopes are known as radioisotopes. Radioisotopes have several decay modes, including alpha, beta, and gamma decay and spontaneous fission. The rate of decay is characterized in terms of "half-life," or the amount of time required for half of a given amount of the radioisotope to decay. Half-lives of different isotopes range from a tiny fraction of a second to billions of years. Rate of decay is also characterized as activity, or the number of decay events or disintegrations that occur in a given time.

FISSILE MATERIAL

Fissile material is material consisting primarily of atoms of *fissile isotopes*, i.e., those atoms of certain heavy elements that have a high probability of undergoing immediate fission of the nucleus by absorbing neutrons of any energy level.[1] Other isotopes whose atoms can undergo fission are called fissionable isotopes, but they are not fissile because they only have a high probability of fission when interacting with neutrons of some energy levels.[2]

NUCLEAR REACTIONS

Fission and fusion are key examples of nuclear reactions that can be induced in the nucleus. Fission occurs when a large nucleus, such as in a plutonium atom, is split into smaller fragments. Fusion occurs when the nuclei of two light atoms, each with a small nucleus, such as hydrogen, collide with enough energy to fuse two nuclei into a single larger nucleus.

Fission

Fission may occur spontaneously or when a subatomic particle, such as a neutron, collides with the nucleus and imparts sufficient energy to cause the nucleus to split into two or more fission fragments, which become the nuclei of lighter atoms and are almost always radioactive. Fission releases millions of times more energy than the chemical reactions that cause conventional explosions. The fission that powers both nuclear reactors and weapons is typically the neutron-induced fission of certain isotopes of uranium or plutonium. The neutrons produced by fission events, as shown in Figure 13.3, can interact with the nuclei of other fissile atoms and produce other fission events, referred to as a *chain reaction*.

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[1] All fissile material has a very small percentage of atoms that are non-fissile because all fissile isotopes are radioactive, and at any given time, a very small percentage of those atoms are decaying to other non-fissile, radioactive elements (also called daughter products). Some of these radioactive decay products may have a tendency to absorb neutrons which would reduce the efficiency of the fissile material, and are therefore considered impurities in the fissile material.

[2] Some references use the terms *fissile* and *fissionable* interchangeably. This chapter considers fissionable isotopes to be inadequate to be used as fissile material in a nuclear weapon.

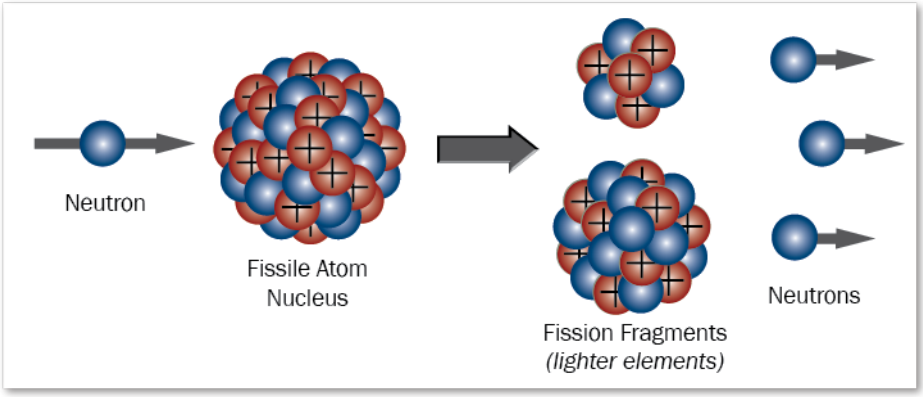

Figure 13.3 Fission Event

Criticality describes whether the rate of fission is increasing (supercritical), remaining constant (critical), or decreasing (subcritical). See Figure 13.4 for an illustration of a sustained chain reaction of fission events. In a highly supercritical configuration, the number of fission events increases very quickly, which results in the release of tremendous amounts of energy in a very short time, causing a nuclear detonation.

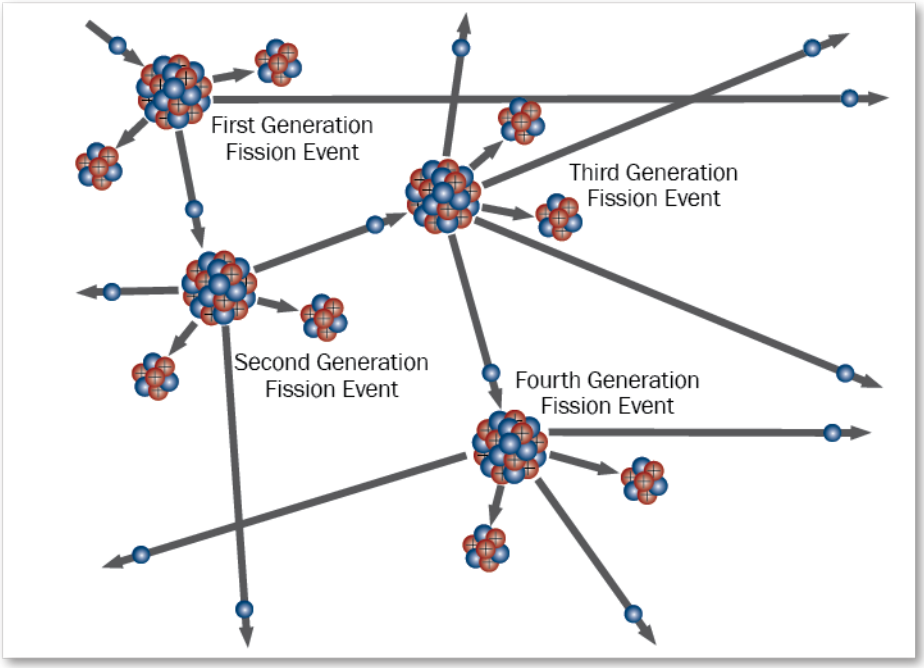

Figure 13.4 Chain Reaction of Fission Events

Fissile material is called a *subcritical mass*, or *subcritical component*, when the amount is so small and the configuration is so spread out that any fission event caused by a random neutron does not cause a sustained chain reaction of fission events. This is because almost all neutrons produced escape without producing a subsequent fission event. However, a *critical mass* of fissile material is the minimum amount of fissile material needed to support a self-sustaining nuclear chain reaction. Examples of fissile material are uranium-235, uranium-233, and plutonium-239.

Different types of fissile isotopes have different probabilities of fission when their nuclei are struck with a neutron and each fissile isotope produces a different average number of neutrons per fission event. These are the two primary factors in determining the material's fissile efficiency. Only fissile isotopes can undergo a multiplying chain reaction of fission events to produce a nuclear detonation. If the number of fission events is increasing with each generation of fission events, it is considered *supercritical*. There are seven factors affecting criticality:

- *Type of Fissile Material* – Isotopes with higher fissile efficiency can more readily achieve supercriticality.
- *Amount of Fissile Material* – Generally, the larger the amount of fissile material, the closer it is to approaching criticality if it is subcritical, and the more effectively it can sustain a multiplying chain reaction if it is supercritical.
- *Shape of the Mass of Fissile Material* – Fissile material in the shape of a sphere will be closer to a critical mass than the same material in a long thin strand because in the latter, more neutrons will escape the fissile mass without producing a subsequent fission event.
- *Density of the Fissile Material* – If a given amount of fissile material is subcritical in a spherical shape, it may become supercritical if that sphere is imploded, compressing the fissile material, causing the nuclei of fissile atoms to be closer together, and increasing the probability that any neutron produced by fission events will interact with another fissile nucleus and produce a subsequent fission event.
- *Enrichment* – The larger the percentage of fissile isotopes, the more readily that material can achieve criticality, and the more it is considered enriched.
- *Environment* – If a supercritical mass has neutron-reflecting material surrounding the outside edges, neutrons will be reflected back into the fissile mass to produce subsequent fission events that would not happen without the reflecting material.
- *Purity* – Any atoms of another element or isotope imbedded in the fissile material may cause a decrease in fissile efficiency by absorbing neutrons as the fissile material becomes supercritical. It is also possible that atoms of another element may cause a rearrangement of molecular structure, and thus a less efficient configuration for achieving criticality.

Fusion

Nuclear fusion is the combining of two light nuclei to form a heavier nucleus. For the fusion process to take place, two nuclei must be forced together by sufficient energy so that the strong, attractive, short-range, nuclear forces overcome the electrostatic forces of repulsion. Because the positively charged protons in the colliding nuclei repel each other, it takes a huge amount of energy to get the nuclei close enough to fuse. It is, therefore, easiest for nuclei with smaller numbers of protons, such as the isotopes of hydrogen, to achieve fusion.

In almost all cases, a fusion event will produce one high-energy free neutron (a neutron unattached to a nucleus), which can be used in a nuclear weapon to cause another fission event that would not occur without the fusion neutron.

Thus, with a relatively small amount of fusion gas in the middle of a supercritical mass, there may be a significant increase in yield (total energy released by the nuclear detonation) without any increase in the size or weight of the nuclear weapon. See Figure 13.5 for an illustration of a fusion event.

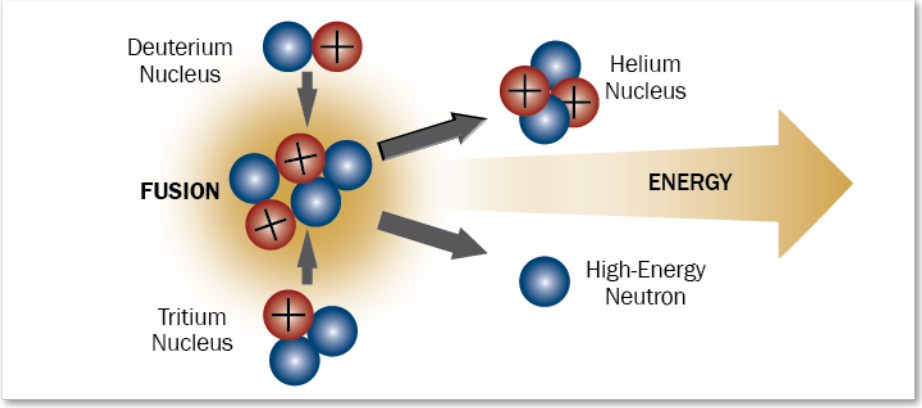

Figure 13.5 Fusion Event

BASIC NUCLEAR WEAPON DESIGNS

All current nuclear weapons use the basic approach of producing a very large number of fission events through a multiplying chain reaction and releasing a huge amount of nuclear energy in a very short period of time. Typically, dozens of generations of fission events in a nuclear detonation will take only approximately one millionth of a second.

The earliest name for a nuclear weapon was *atomic bomb* or *A-bomb*. This term has been criticized as a misnomer because all conventional explosives generate energy from reactions between atoms (i.e., the release of binding energy that had been holding atoms together as a molecule). However, the name is still associated with current nuclear weapons and is accepted by historians, the public, and even by some of the scientists who created the first nuclear weapons. A fission weapon is a nuclear weapon whose energy release is due to fission of the fissile atoms. Fusion weapons are nuclear weapons whose energy release is increased beyond that caused by fission alone because isotopes of hydrogen are used to achieve fusion that in turn causes additional fission events beyond those that occur without the added fusion. Nuclear weapons that include fusion are called hydrogen bombs or H-bombs (since the fusion is generated using isotopes of hydrogen) and are also referred to as thermonuclear weapons due to the high temperature and pressure required for the fusion reactions to occur.[3]

Achieving Supercritical Mass

To produce a nuclear detonation, a weapon must contain enough fissile material to achieve a supercritical mass and a multiplying chain reaction of fission events.

A supercritical mass can be achieved in two different ways. The first way is to have two subcritical components positioned far enough apart so any stray neutrons that cause a fission event in one subcritical component cannot begin a sustained chain reaction of fission events between the two components. At the same

[3] The term *thermonuclear* is also used to refer to a two-stage nuclear weapon.

time, the components must be configured in such a way that when the detonation is desired, one component can be driven toward the other to form a supercritical mass when they are positioned together.

The second approach is to have one subcritical fissile component surrounded with high explosives (HE). When the detonation is desired, the HE is exploded, with force pushing inward to compress the fissile component to a point where it goes from subcritical to supercritical, because the fissile nuclei become closer to each other with less space between them for neutrons to escape. This causes most of the neutrons produced to cause subsequent fission events and achieve a multiplying chain reaction. Both of these approaches can be enhanced by using a proper casing as a tamper to hold in the explosive force. By using a neutron reflecting material around the supercritical mass, and by using a neutron generator to produce a large number of neutrons at the moment the fissile material reaches its designed supercriticality, the first generation of fission events in the multiplying chain reaction becomes a larger number of fission events.

Currently, nuclear weapons use one of four basic design approaches: gun assembly, implosion, boosted, or staged. Figure 13.6 details the key characteristics of the basic types of nuclear weapons.

Weapon Type	Key Characteristics
Gun Assembly Weapon	• Propellant drives one subcritical mass into another subcritical mass, forming one supercritical mass and nuclear detonation • Less technically complex than other designs, but less efficient
Implosion Weapon	• Compression/implosion of one subcritical fissile component to achieve greater density and supercritical mass • More technically complex than gun assembly type and more efficient
Boosted Weapon	• Fusionable material (e.g., deuterium, tritium) placed inside core of fission device, producing large number of fusion events, thereby increasing yield • More technically complex than GA or implosion design and more efficient
Staged Weapon	• Boosted primary stage and secondary stage to produce significantly increased yield • Most technically complex; produces larger yields than other designs

Figure 13.6 Basic Types of Nuclear Weapons

Gun Assembly Weapons

Gun assembly (GA) weapons (Figure 13.7) rapidly assemble two subcritical fissile components into one supercritical mass. This assembly is structured in a tubular device in which a propellant is used to drive one subcritical mass into another, forming one supercritical mass and causing a nuclear detonation. In general, the GA design is less technically complex than other designs and is also the least efficient.

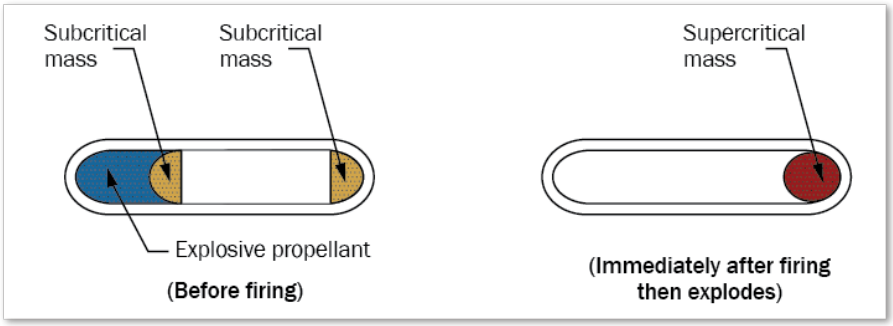

Figure 13.7 Unclassified Illustration of a GA Weapon
(Source: Joint DOE/DoD Topical Classification Guide for Nuclear Assembly Systems (TCG-NAS-2), March 1997)

Implosion Weapon

Implosion weapons (Figure 13.8) use the method of imploding one subcritical fissile component to achieve greater density and a supercritical mass. This compression is achieved by using high explosives surrounding a subcritical sphere of fissile material to drive the fissile material inward. The increased density achieves supercriticality due to the fissile nuclei being closer together, increasing the probability that any given neutron causes a subsequent fission event. In general, the implosion design is more technically complex than the GA design and more efficient.

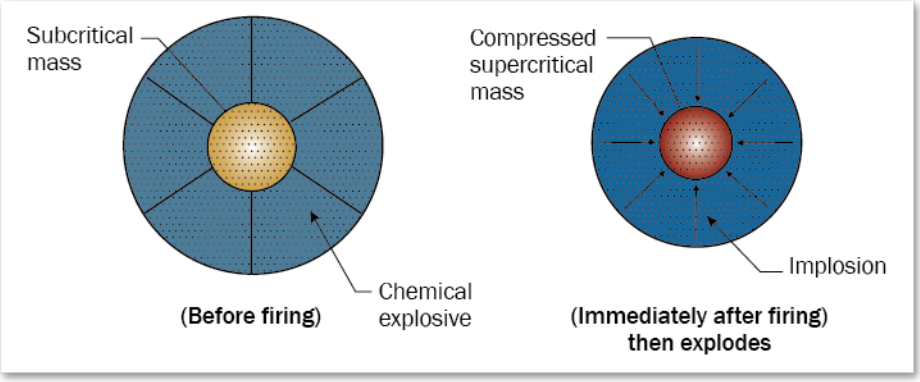

Figure 13.8 Unclassified Illustration of an Implosion Weapon
(Source: TCG-NAS-2, March 1997)

Boosted Weapons

A boosted weapon increases the efficiency and yield for a weapon of the same volume and weight when a small amount of fusionable material, such as deuterium or tritium gas, is placed inside the core of a fission device. The immediate fireball, produced by the supercritical mass, has a temperature of tens of millions of degrees and creates enough heat and pressure to cause the nuclei of the light atoms to fuse together. In this environment, a small amount of fusion gas, measured in grams, can produce a huge number of fusion events. Generally, for each fusion event, there is one high-energy neutron produced. These high-energy neutrons then interact with the fissile material, before the weapon breaks apart in the nuclear detonation, to cause additional fission events that would not occur if the fusion gas were not present. This approach to increasing yield is called “boosting” and is used in most modern nuclear weapons to meet yield requirements within size and weight limits. In general, the boosted weapon design is more technically complex than the implosion design and also more efficient.

Staged Weapons

A staged weapon (Figure 13.9) normally uses a boosted primary stage and a secondary stage to produce a significantly increased yield. In the first stage, a boosted fission device releases the energy of a boosted weapon, which includes a large number of X-rays. The X-rays transfer energy to the secondary stage, causing fusionable material in the secondary to undergo fusion, which releases large numbers of high-energy neutrons. These neutrons, in turn, interact with fissionable material in the secondary to cause a huge number of fission events, thereby significantly increasing the yield of the whole weapon. The two-stage weapon design is more technically complex than any other weapon design. For a given size, it can produce a much larger yield than any other design.

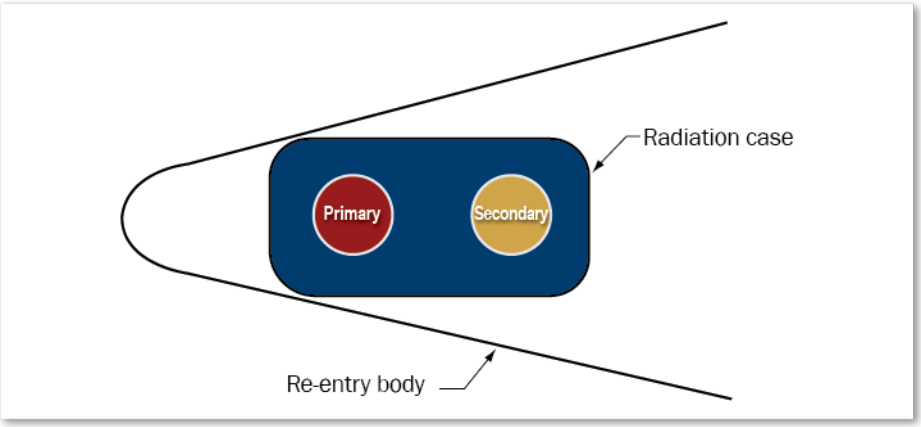

Figure 13.9 Unclassified Illustration of a Staged Weapon
(Source: TCG-NAS-2, March 1997)

EFFECTS OF NUCLEAR DETONATIONS

A nuclear detonation produces effects overwhelmingly more significant than those produced by a conventional explosive, even if the nuclear yield is relatively low. A typical nuclear detonation[4] produces energy that, weight for weight, is millions of times more powerful than that produced by a conventional explosion. It also produces an immediate large, hot nuclear fireball, thermal radiation, prompt nuclear radiation, air blast wave, residual nuclear radiation, electromagnetic pulse (EMP), interference with communications signals, and, if the fireball interacts with the terrain, ground shock. Figure 13.10 depicts the overarching energy distribution for a typical nuclear detonation.

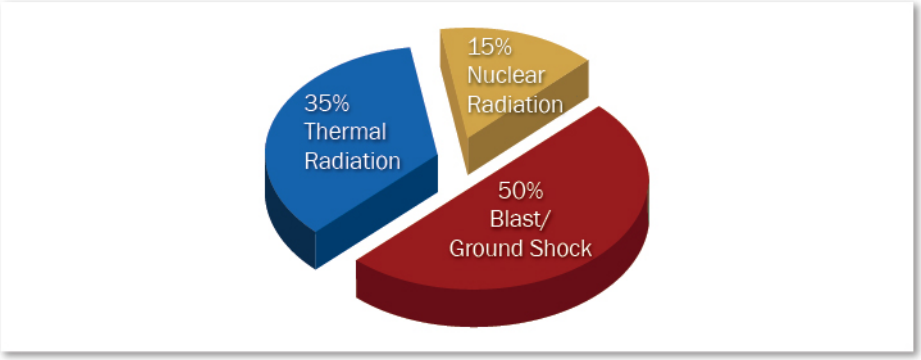

Figure 13.10 Energy Distribution for a Typical Nuclear Detonation

GROUND ZERO

Nuclear detonations can occur on, below, or above the Earth's surface. Ground zero (GZ) is the point on the Earth's surface closest to the detonation. The effects of a nuclear detonation can destroy structures and systems

[4] For the purposes of this chapter, a typical nuclear detonation is one that occurs on the Earth's surface or at a HOB low enough for the primary effects to cause damage to surface targets. Detonations that are exoatmospheric, high altitude, or deeply buried underground have different effects.

and can injure or kill exposed personnel at great distances from GZ. Figure 13.11 shows Hiroshima after the nuclear weapon detonation on August 6, 1945.

Figure 13.11 Hiroshima After the Nuclear Detonation

Nuclear detonation effects for people or objects close to GZ are devastating. However, the distances that effects can travel away from GZ are limited.

OVERALL EFFECTS

The yield of the weapon, measured in equivalent tons of TNT, is one of the most important factors in determining the level of casualties and damage. Other factors include the type and density of target elements near GZ, height of burst (HOB), terrain, or objects in the area that could interfere with various effects moving away from GZ as well as the weather patterns in the target area.

If effectively employed,[5] any one nuclear weapon should defeat any one military target. However, a few nuclear weapons with relatively low yields, such as the yields of any nation's first generation of nuclear weapons, would not defeat a large military force, such as the allied force in the first Gulf War. A single, low-yield nuclear weapon employed in a major metropolitan area would produce total devastation in an area large enough to produce tens of thousands or even hundreds of thousands of fatalities. Yet, it would not destroy the entire major metropolitan area. The survival of thousands of people who are seriously injured or exposed to a moderate level of nuclear radiation would depend on the response of various federal, state, and local government agencies and non-governmental organizations.

[5] Proper employment includes using the required yield at the required location with an effective HOB (e.g., a high-altitude detonation would not destroy a building or a bridge). Examples of single military targets include one or a group of structures in a relatively small area, special contents within a structure (e.g., biological agents), a missile silo or launcher position, a military unit (e.g., a single military ship, an air squadron, or even a ground-force battalion), a communications site, and a command post.

CASUALTY AND DAMAGE DISTANCES FOR POPULATED AREAS

A very low-yield, 1-kiloton (kt) detonation produces severe damage effects approximately one quarter of a mile from GZ. Within the severe damage zone, almost all buildings would collapse and 99 percent of persons become fatalities quickly. Moderate damage would extend approximately one half mile and would include structural damage to buildings, many prompt fatalities, severe injuries, overturned cars and trucks, component damage to electronic devices, downed cellphone towers, and induced radiation at ground level that could remain hazardous for several days. Light damage would extend out approximately 1.5 miles and include some prompt fatalities, some persons with severe injuries, and the effects on infrastructure as stated for medium damage. Some fatalities or injuries may occur beyond the light damage zone.

A low-yield, 10-kt detonation can produce severe damage effects approximately one half mile from GZ. Moderate damage can extend approximately one mile and light damage can extend to approximately three miles.

A high-yield, strategic 1-megaton (MT) detonation[6] can produce severe damage effects slightly beyond two miles from GZ. Moderate damage extends out beyond four miles and light damage occurs beyond 12 miles.

NUCLEAR FIREBALL

A typical nuclear weapon detonation can produce a huge number of X-rays, which heat the air around the detonation to extremely high temperatures, causing the heated air to expand and form a large fireball within a small fraction of a second. The size of the immediate fireball is a function of yield and the surrounding environment. Figure 13.12 shows the size of the immediate fireball for selected yields and environments.

Yield	Air Burst		Underground Burst	
	Radius	Diameter	Radius	Diameter
1 MT	560 m	1,120 m	315 m	630 m
10 kt	65 m	130 m	36 m	72 m
1 kt	30 m	60 m	17 m	34 m

Figure 13.12 Approximate Immediate Fireball Size

The immediate fireball is tens of millions of degrees (i.e., as hot as the interior of the sun). Inside the fireball, the temperature and pressure cause a complete disintegration of molecules and atoms. Current targeting procedures do not consider the fireball to be one of the primary weapon effects, but a nuclear fireball can be used to incinerate chemical or biological agents.

THERMAL RADIATION

Thermal radiation is electromagnetic radiation in the visible light spectrum that can be sensed as heat and light. Thermal radiation is maximized with a low-air burst and the optimum HOB increases with yield. Thermal radiation can ignite wood-frame buildings, vegetation, and other combustible materials at significant distances

[6] A 1-MT detonation releases the energy equivalent to one million tons of TNT.

from GZ. It can also cause burns to exposed skin directly or indirectly, if clothing ignites or the individual is caught in a fire ignited by the heat.

Anything that casts a shadow or reduces light, including buildings, trees, dust from the blast wave, heavy rain, and dense fog, provides some protection against thermal burns or the ignition of objects.

Flash blindness, or dazzle, is a temporary loss of vision caused when eyes are overwhelmed with intense thermal light. On a clear night, dazzle may last for up to 30 minutes and may affect people at distances beyond 10 miles. On a clear day, dazzle can affect people at distances beyond those for first degree burns, albeit it lasts for a shorter period of time. Because thermal radiation can be scattered and reflected in the air, flash blindness can occur regardless of whether an individual is looking toward the detonation. At distances where it can produce a first degree burn, thermal radiation is intense enough to penetrate through the back of the skull to overwhelm the eyes. Retinal burns can occur at great distances for individuals looking directly at the fireball at the moment of the nuclear detonation. Normally, retinal burns cause a permanent blindness to a small portion of the eye in the center of the normal field of vision. Figure 13.13 shows types of burns and approximate maximum distances for selected yields.[7]

			Approximate Distances (km)		
Degree	Affected Area	Description & Symptoms	1 kt	10 kt	1 MT
3rd	Tissue under skin	Charred skin; Extreme pain	0.7	1.7	11.1
2nd	All layers of skin	Blisters; Severe pain	0.9	2.3	13.7
1st	Outer layers of skin	Red/darker skin; Moderate pain	1.0	2.8	19.0

Figure 13.13 Thermal Radiation Burns

Because thermal radiation can start fires and cause burns at such great distances, if a nuclear weapon is employed against a populated area on a clear day, with an air burst at approximately the optimum HOB, it is likely the thermal effects would account for more casualties than any other effect. With a surface burst or if rain or fog are in the area, the thermal radiation effects would be reduced.

The effects of thermal radiation can be reduced with protective enclosures, thermal protective coatings, and the use of non-flammable clothing, tools, and equipment. Thermal protective coatings include materials that swell when exposed to flame, thus absorbing the heat rather than allowing it to penetrate through the material, and ablative paints, which act like a melting heat shield.

Materials like stainless steel, as opposed to temperature-sensitive metals like aluminum, are used to protect against thermal radiation. In order to reduce the amount of absorbed energy, light colors and reflective paints are also used. For effective thermal hardening, the use of combustible materials is minimized.

[7] The distances in Figure 13.12 are based on scenarios in which the weather is clear, there are no obstacles to attenuate thermal radiation, and the weapon is detonated as a low-air burst at the optimum HOB to maximize the thermal effect.

Finally, to mitigate the effects of thermal radiation, it is important to protect items prone to melting, such as rubber gaskets, O-rings, and seals.

AIR BLAST

In the case of surface and low-altitude air bursts, the fireball expands, immediately pushing air away from the point of the detonation, causing a dense wall of air to travel at great speed away from the detonation. Initially, this blast wave moves at several times the speed of sound, but quickly slows to a point at which the leading edge of the blast wave is traveling at the speed of sound and continues at this speed as it moves farther away from GZ. Shortly after breaking away from the fireball, the wall of air reaches its maximum density of overpressure, or over the nominal air pressure.[8] As the blast wave travels away from this point, the wall of air becomes wider, loses density, and the overpressure continues to decrease.

At significant distances from GZ, overpressure can have a crushing effect on objects as they are engulfed by the blast wave and subject to long-pulse pressure durations. In addition to overpressure, the blast wave has an associated wind speed as it passes any object. This can be quantified as dynamic pressure that can move, rather than crush, objects. The blast wave has a positive phase and a negative phase for both overpressure and dynamic pressure.

As the blast wave hits a target object, the positive overpressure initially produces a crushing effect. If the overpressure is great enough, it can cause instant fatality to an exposed person. Less overpressure can collapse the lungs and, at lower levels, can rupture the ear drums. Overpressure can implode a building. Immediately after the positive overpressure has begun to affect the object, dynamic pressure exerts a force that can move people or objects laterally at high speed, causing injury or damage. Dynamic pressure can also strip a building from its foundation.

As the positive phase of the blast wave passes an object, it is followed by a vacuum effect (i.e., the negative pressure caused by the lack of air in the space behind the blast wave). This is the beginning of the negative phase of dynamic pressure. The vacuum effect, or negative overpressure, can cause a building to explode, especially if the positive phase has increased the air pressure inside the building by forcing air in through broken windows. The vacuum effect then causes the winds in the trailing portion of the blast wave to be pulled back into the vacuum. This produces a strong wind moving back toward GZ. While the negative phase of the blast wave is not as strong as the positive phase, it may move objects back toward ground zero, especially if trees or buildings are severely weakened by the positive phase. Figure 13.14 shows the overpressure in pounds per square inch (psi) and the approximate distances associated with various types of structural damage.[9]

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[8] At a short distance beyond the radius of the immediate fireball, the blast wave would reach a density pressure of thousands of pounds per square inch.

[9] The distances in Figure 13.13 are based on an optimum HOB to maximize the blast effect and the existence of no significant terrain that would stop the blast wave (e.g., the side of a mountain). For surface bursts, the distances shown are reduced by approximately 30 to 35 percent for the higher overpressures and by 40 to 50 percent for 1 psi.

		Approximate Distances (km)		
Approx. Overpressure	Description	1 kt	10 kt	1 MT
7 - 9 psi	Concrete building collapse	0.5	1.1	5.1
6 psi	Shatter concrete walls	0.6	1.3	6.1
4 psi	Wood-frame building collapse	0.8	1.8	8.1
2 psi	Shatter wood siding panels	1.3	2.9	13.2
1 psi	Shatter windows	2.2	4.7	21.6

Figure 13.14 Air-Blast Damage to Structures

If the detonation occurs at ground level, the expanding fireball pushes into the air in all directions, creating an ever-expanding hemispherical blast wave, called the incident wave. As the blast wave travels away, its density continues to decrease. After some significant distance, it loses destructive potential and becomes a mere gust of wind. Yet, if the detonation is a low-air burst, a portion of the blast wave travels toward the ground and is then reflected off the ground. This reflected wave travels up and out in all directions, reinforcing the incident wave traveling along the ground. Because of this, air blast is maximized with a low-air burst rather than a surface burst.

If the terrain is composed of a surface that absorbs more thermal radiation than grass or soil, the thermal radiation leads to a greater than normal heating of that surface. The surface produces heat before the arrival of the blast wave. This creates a "non-ideal" condition that causes the blast wave to become distorted when it reaches the heated surface, resulting in an abnormal reduction in the blast wave density and pressure. Extremely cold weather (minus 50° Fahrenheit or colder) can lead to increased air-blast damage distances. If a surface burst occurs in a populated area or if there is rain and/or fog at the time of burst, the blast effect would probably account for more casualties than any other effect.

Structures and equipment can be reinforced to become less vulnerable to air blast. Nevertheless, any structure or piece of equipment will be destroyed if it is close enough to the detonation. High priority facilities that must survive a close nuclear strike are usually constructed underground and reinforced with strong materials, making them much harder to defeat.

Individuals who sense a blinding white flash and intense heat coming from one direction should immediately fall to the ground and cover their heads with their arms. This provides the highest probability the air blast passes overhead, without moving them laterally, and debris in the blast wave does not cause impact or puncture injuries. Exposed individuals who are very close to the detonation have no chance of survival. However, at distances where a wood-frame building can survive, exposed individuals significantly increase their chance of survival if they are on the ground when the blast wave arrives and remain on the ground until after the negative phase blast wave has moved back toward ground zero.

GROUND SHOCK

Given surface or near-surface detonations, the fireball's expansion and interaction with the ground causes a significant shock wave to move into the ground in all directions. This causes an underground fracture or

"rupture" zone. The intensity and significance of the shock wave and the fracture zone decrease with distance from the detonation. A surface burst produces significantly more ground shock than a near-surface burst in which the fireball barely touches the ground.

Underground structures, especially deep underground, are not vulnerable to the direct primary effects of a low-air burst. However, the shock produced by a surface burst may damage or destroy an underground target, depending on its structure and depth, the yield of the detonation, and soil or rock type. It is possible for a surface detonation to fail to crush a deep underground structure but have an effective shock wave that crushes or buries entrance or exit routes and destroys connecting communications lines. This could cause the target to be "cut-off" and render it, at least temporarily, incapable of performing its intended function. Normally, a surface burst or shallow sub-surface burst is used to attack deeply buried targets. As a rule of thumb, a 1-kt surface detonation can destroy an underground facility as deep as a few tens of meters. A 1-MT surface detonation can destroy the same target as deep as a few hundred meters.

Deeply buried underground targets can be attacked through the employment of an earth-penetrating warhead to produce a shallow sub-surface burst. Only a few meters of penetration into the earth is required to achieve a "coupling" effect, in which most of the energy that would have gone up into the air with a surface burst is trapped by the material near the surface and reflected downward to reinforce the original shock wave. This reinforced shock wave is significantly stronger and can destroy deep underground targets at distances usually two to five times deeper than those destroyed through the employment of a surface burst.[10] Ground shock is the governing effect for damage estimation against any underground target.

SURFACE CRATER

In the case of near-surface, surface, and shallow sub-surface bursts, the fireball's interaction with the ground causes it to engulf much of the soil and rock within its radius and remove the material as it moves upward. This removal of material results in the formation of a crater. A near-surface burst would produce a small, shallow crater. The crater from a surface burst, with the same yield, is larger and deeper, while the crater size is maximized with a shallow sub-surface burst at the optimum depth.[11] The size of the crater is a function of the yield of the detonation, depth of burial, and type of soil or rock.

For deeply buried detonations, such as those created with underground nuclear explosive testing, the expanding fireball creates a spherical volume of hot radioactive gases. As the radioactive gas cools and contracts, the spherical volume of space becomes an empty cavity with a vacuum effect. The weight of the heavy earth above the cavity and the vacuum effect within the cavity cause a downward pressure for the earth to give way. This can occur unpredictably at any time from minutes to months after the detonation. When it occurs, the cylindrical mass of earth collapsing down into the cavity forms a crater on the surface, called a subsidence crater (see Figure 13.15).

A crater produced by a recent detonation near the ground surface is probably radioactive. Individuals required to enter or cross such a crater could be exposed to significant levels of ionizing radiation, possibly enough to

[10] The amount of increased depth of damage is primarily a function of the yield and the soil or rock type.
[11] For a 1-kt detonation, the maximum crater size would have a burial depth between 32 and 52 meters, depending on the type of soil or rock.

cause casualties or fatalities. If a deep underground detonation has not yet formed the subsidence crater, it is very dangerous to enter the area on the surface directly above the detonation.

Normally, the wartime employment of nuclear weapons would not use crater formation to attack targets. Though at the height of the Cold War, NATO forces had contingency plans to use craters from nuclear detonations to channel, contain, or block enemy ground forces. The size of the crater and its radioactivity for the first several days produces an obstacle extremely difficult, if not impossible, for a military unit to cross.

A crater by itself does not present a hazard to people or equipment, unless an individual attempts to drive or climb into the crater. In the case of deep underground detonations, the rule is to keep away from the area where the subsidence crater could be formed until after the collapse occurs.

Figure 13.15 Subsidence Craters at Yucca Flats, Nevada National Security Site

UNDERWATER SHOCK

An underwater nuclear detonation generates a shock wave in a manner similar to a blast wave formed in the air. The expanding fireball pushes water away from the point of detonation, creating a rapidly moving dense wall of water. In the deep ocean, this underwater shock wave moves out in all directions, gradually losing its intensity. In shallow water, it can be distorted by surface and bottom reflections. Shallow bottom interactions may reinforce the shock effect.

If the yield is large enough and the depth of detonation is shallow enough, the shock wave ruptures the water's surface. This can produce a large surface wave that moves away in all directions. It may also produce a "spray dome" of radioactive water above the surface.

If a submarine is close enough to the detonation, the underwater shock wave is strong enough to rapidly move the vessel. This near-instantaneous movement could force the ship against the surrounding water with a force beyond its design capability, causing a structural rupture of the vessel. The damage to the submarine is a function of weapon yield, depth of detonation, depth of the water under the detonation, bottom conditions, and the distance and orientation of the submarine. People inside the submarine are at risk if the boat's structure fails. Even if the submarine structure remains intact, the lateral movement may cause injuries or fatalities to those inside the submarine.

Surface ships may be vulnerable to the underwater shock wave striking the hulls of the ships. If the detonation produces a significant surface wave, it can damage surface ships at greater distances. If ships move into the radioactive spray dome, the dome could present a radioactive hazard to people on the ship.

Both surface ships and submarines can be designed to be less vulnerable to the effects of underwater nuclear detonations. Yet, any ship or submarine can be damaged or destroyed if it is close enough to a nuclear detonation.

INITIAL NUCLEAR RADIATION

Nuclear radiation is ionizing radiation emitted by nuclear activity consisting of neutrons, alpha and beta particles, and electromagnetic energy in the form of gamma rays.[12] Gamma rays are high-energy photons of electromagnetic radiation with frequencies higher than visible light or ultraviolet rays.[13]Gamma rays and neutrons are produced from fission events. Alpha and beta particles and gamma rays are produced by the radioactive decay of fission fragments. Alpha and beta particles are absorbed by atoms and molecules in the air at short distances and are insignificant compared with other effects. Gamma rays and neutrons travel great distances through the air in a general direction away from ground zero.[14]

Because neutrons are produced almost exclusively by fission events, they are produced in a fraction of a second, and no significant number of neutrons is produced after that. Conversely, gamma rays are produced by the decay of radioactive materials and are produced for years after the detonation. Initially, these radioactive materials are in the fireball. For surface and low-air bursts, the fireball rises quickly and, within approximately one minute, is at an altitude high enough that none of the gamma radiation produced inside the fireball has any impact to people or equipment on the ground. For this reason, initial nuclear radiation is defined as the nuclear radiation produced within one minute post-detonation. Initial nuclear radiation is also called *prompt nuclear radiation*.

The huge number of gamma rays and neutrons produced by a surface, near-surface, or low-air burst may cause casualties or fatalities to people at significant distances. The unit of measurement for radiation exposure is the centigray (cGy).[15] The 450 cGy exposure dose level is considered to be the lethal dose for 50 percent of the population (LD50) with medical assistance. People who survive at this dose level would have a significantly increased risk of contracting mid-term and long-term cancers. Figure 13.16 shows selected levels of exposure, the associated near-term effects on humans, and the distances by yield.[16]

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[12] Ionizing radiation is defined as electromagnetic radiation (gamma rays or X-rays) or particulate radiation (e.g., alpha particles, beta particles, neutrons) capable of producing ions directly or indirectly in its passage through or interaction with matter.

[13] A photon is a unit of electromagnetic radiation consisting of pure energy and zero mass. The spectrum of photons includes AM and FM radio waves, radarwaves, microwaves, infrared waves, visible light, ultraviolet waves, X-rays, and gamma or cosmic rays.

[14] Both gamma rays and neutrons are scattered and reflected by atoms in the air, causing each gamma ray and neutron to travel a "zig-zag" path moving generally away from the detonation. Some neutrons and photons may be reflected so many times that, at a significant distance from GZ, travel back toward ground zero.

[15] cGy represents the amount of energy deposited by ionizing radiation in a unit mass of material and is expressed in units of joules per kilogram (J/kg).

[16] For the purposes of this chapter, all radiation doses are assumed to be acute (total radiation received within approximately 24 hours) and whole-body exposure. Exposures over a longer period of time (chronic), or exposures to an extremity (rather than to the whole body) could have less effect on a person's health.

		Approximate Distances (km)		
Level of Exposure	Description	1 kt	10 kt	1 MT
3,000 cGy	Prompt casualty; death within days	0.5	0.9	2.1
650 cGy	Delayed casualty; ~95% death in wks	0.7	1.2	2.4
450 cGy	Performance impaired; ~50% death	0.8	1.3	2.6
150 cGy	Threshold symptoms	1.0	1.5	2.8

Figure 13.16 Near-Term Effects of Initial Nuclear Radiation

Low levels of exposure can increase an individual's risk for contracting long-term cancers. For example, in healthy male adults ages 20 to 40, an exposure of 100 cGy increases this risk by approximately 10 to 15 percent and lethal cancer by approximately 6 to 8 percent.[17]

The ground absorbs more gamma rays and neutrons than the air. Almost half of the initial nuclear radiation resulting from a surface burst is quickly absorbed by the earth. In the aftermath of a low-air burst, half of the nuclear radiation travels in a downward direction. Much of that radiation is scattered and reflected by atoms in the air, adding to the amount of radiation traveling away from GZ. Because of this, initial nuclear radiation is maximized with a low-air burst.

Initial nuclear radiation effects can be predicted with reasonable accuracy. In this case, initial nuclear radiation is considered with air blast to determine the governing effect. Initial nuclear radiation is always considered for safety (if safety of populated areas or friendly troop personnel is a factor) and safety distances are calculated based on a "worst-case" assumption (i.e., there is a maximum initial radiation effect and objects in the target area will not shield or attenuate the radiation).

Individuals can do very little to protect themselves against initial nuclear radiation after a detonation has occurred because initial radiation is emitted and absorbed in less than one minute. DoD has developed an oral chemical prophylactic to reduce the effects of ionizing radiation exposure; however, the drug does not reduce the hazard to zero. Just as with most of the other effects, it is fatal if an individual is very close to the detonation.

Initial nuclear radiation can also damage the electrical components in certain equipment. Equipment can be hardened to make electronic components less vulnerable to initial nuclear radiation. Generally, structures are not vulnerable to initial nuclear radiation.

[17] Calculated from data in National Research Council, *Health Risks from Exposure to Low Levels of Ionizing Radiation: BEIR VII Phase 2* (Washington, D.C.: The National Academies Press, 2006), https:// doi.org/10.17226/11340.

RESIDUAL NUCLEAR RADIATION

Residual nuclear radiation consists of alpha and beta particles as well as gamma rays emitted from radioactive nuclei. There are types of residual nuclear radiation that result from a typical detonation. Residual radiation also results from a deep underground detonation, but the radiation remains underground unless radioactive gases vent from the fireball or residual radiation escapes by another means. An exoatmospheric detonation creates a cloud in orbit that could remain significantly radioactive for many months.

Induced Radiation on the Ground

Induced radiation on the ground is radioactivity caused by neutron absorption. With a detonation near the ground, neutrons are captured by light metals in the soil or rock near the ground surface.[18] These atoms become radioactive isotopes capable of emitting, among other things, gamma radiation. The induced radiation is generally created in a circular pattern that is most intense at GZ immediately after the detonation. The intensity decreases over time and with distance from GZ. In normal soil, it takes approximately five to seven days for induced radiation to decay to a safe level. In a populated area, the induced radiation could extend beyond building collapse, especially with a low-yield detonation. It is important for first responders to be trained to understand induced radiation and be aware of the radioactive hazard. Many first responders today have radiation detectors for this purpose.

Induced Radiation in the Air

Induced radiation in the air is caused by nitrogen absorbing neutrons producing carbon-14. Carbon-14 atoms can remain suspended in the air, are beta particle emitters, and have a long half-life (5,715 years). During the 1950s and 1960s, when four nuclear nations conducted aboveground nuclear testing, a 2 to 3 percent increase occurred in total carbon-14 levels worldwide. Gradually, the carbon-14 is returning to pre-testing levels. There are no known casualties attributed to the increase, but any increase in carbon-14 levels could be an additional risk.

Fallout

Fallout is the release of small radioactive particles that drop from the fireball to the ground. In most technical jargon, fallout is defined as the fission fragments from the nuclear detonation. The fireball contains other types of radioactive particles as well that fall to the ground and contribute to the total radioactive hazard. These include the radioactive fissile material that did not undergo fission, as no weapon fissions 100 percent of the fissile material, and material from warhead components induced with neutrons that have become radioactive. Residual gamma radiation is colorless, odorless, and tasteless and cannot be detected with the five senses unless an extremely high level of radiation exists.

If the detonation is a true air burst in which the fireball does not interact with the ground or any significant structure, the size and heat of the fireball causes it to retain almost all of the weapon debris, usually one or at most a few tons of material, as it moves upward in altitude and downwind. In this case, very few particles fall to the ground at any moment and no significant radioactive hot-spot on the ground is caused by the fallout. The fireball rises to become a long-term radioactive cloud. The cloud travels with the upper atmospheric winds and circles the hemisphere several times, over a period of months, before it dissipates completely. Most of the radioactive particles decay to stable isotopes before falling to the ground. The particles that reach the ground

[18] Neutrons induced into typical soil are captured primarily by sodium, manganese, silicon, and aluminum atoms.

are distributed around the hemisphere at the latitudes of the cloud travel route. Even though there would be no location receiving a hazardous amount of fallout radiation, certain locations on the other side of the hemisphere could receive more fallout, which is measurable with radiation detectors, than the area near the detonation. This phenomenon is called *worldwide fallout*.

If the fireball interacts with the ground or any significant structure (e.g., a large bridge or a building), the fireball has different properties. In addition to the three types of radioactive material, the fireball would also include radioactive material from the ground or structure induced with neutrons. The amount of material in the fireball would be much greater than the amount with an air burst. For a true surface burst, a 1-kt detonation would extract thousands of tons of earth up into the fireball, although only a small portion would be radioactive. This material would disintegrate and mix with the radioactive particles. As large and hot as the fireball is (1-kt detonation produces a fireball almost 200 feet in diameter and tens of millions of degrees), it has no potential to carry thousands of tons of material. Thus, as the fireball rises, it begins to release a significant amount of radioactive dust, which falls to the ground and produces a radioactive fallout pattern around GZ and in areas downwind. The intensity of radioactivity in this fallout area would be hazardous for weeks. This is called *early fallout*, caused primarily by a surface-burst detonation regardless of the weapon design. Early fallout would be a concern in the case of employment of a nuclear threat device during a terrorist attack.

Normally, fallout should not be a hazardous problem for a detonation that is a true air burst. Yet, if rain and/or snow occurs in the target area, radioactive particles could be "washed-out" of the fireball, creating a hazardous area of early fallout. If a detonation is a surface or near-surface burst, early fallout would be a significant radiation hazard around GZ and downwind.

Generally, a deep underground detonation presents no residual radiation hazard to people or objects on the surface. If there is an accidental venting or some other unintended escape of radioactivity, however, it could become a radioactive hazard to people in the affected area. The residual nuclear cloud from an exoatmospheric detonation could damage electronic components in some satellites over a period of time, usually months or years, depending on how close a satellite gets to the radioactive cloud, the frequency of the satellite passing near the cloud, and its exposure time and whether it is hardened against nuclear radiation.

There are four actions that provide protection against residual radiation. First, personnel with a response mission should enter the area with at least one radiation detector, and all personnel should employ personal protective equipment (PPE).[19] While the PPE does not stop the penetration of gamma rays, it will prevent the responder personnel from breathing any airborne radioactive particles. Second, personnel should only be exposed to radioactivity for the minimum time possible to accomplish a given task. Third, personnel should remain at a safe distance from radioactive areas. Finally, personnel should use shielding when possible to further reduce the amount of radiation received. It is essential for first responder personnel to follow the PPE principles of time, distance, and shielding.

[19] PPE for first responders includes a sealed suit and self-contained breathing equipment with a supply of oxygen.

BIOLOGICAL/MEDICAL EFFECTS OF IONIZING RADIATION

Ionizing radiation is any particle or photon that produces an ionizing event (i.e., strip an electron away from an atom), including alpha and beta particles, gamma and cosmic rays, and X-rays. Ionizing events cause biological damage to humans and other mammals. The greater the exposure dose, the greater the biological problems caused by the ionizing radiation. At medium and high levels of exposure, there are near-term consequences, including impaired performance that can cause casualties and death. Figure 13.17 lists the types of biological damage associated with ionizing events.

Ionized Objects	Resulting Problem
Ionized DNA molecules	Abnormal cell reproduction
Ionized water molecules	Creates hydrogen peroxide (H2O2)
Ionized cell membrane	Cell death
Ionized central nervous system molecules	Loss of muscle control
Ionized brain molecules	Loss of thought process & muscle control

Figure 13.17 Biological Damage from Ionization

At low levels of exposure, ionizing radiation does not cause any near-term medical problems. However, at the 75 cGy level, approximately 5 percent of healthy adults experience mild threshold symptoms (i.e., transient mild headaches and mild nausea). At the 100 cGy level, approximately 10 to 15 percent of healthy adults experience threshold symptoms and a smaller percentage experience some vomiting. Low levels of ionizing radiation exposure also result in a higher probability of contracting mid- and long-term cancers.

Figure 13.18 shows increased risk in healthy adults of contracting cancer after ionizing radiation exposure, by gender.

Level of Ionizing Radiation Exposure	Approximate Increased Risk of Cancer (percent)			
	Healthy Males, age 20-40		Healthy Females, age 20-40	
	Lethal	All Cancers	Lethal	All Cancers
100 cGy	6 - 8	10 - 15	7 - 12	13 - 25
50 cGy	2 - 3	4 - 6	3 - 5	5 - 10
25 cGy	1 - 2	2 - 3	1 - 2	2 - 5
10 cGy	< 1	1	1	1 - 2
1 cGy	< 1	< 1	< 1	< 1

Figure 13.18 Increased Cancer Risk at Low Levels of Exposure to Ionizing Radiation

Protection from ionizing radiation can be achieved through shielding. Most materials shield from radiation, but some materials need to be present in significant amounts to reduce the penetrating radiation by half. Figure 13.19 illustrates the widths required for selected types of material to stop half the gamma radiation, called "half-thickness," and to stop 90 percent of the radiation, called "tenth-value thickness."

Material	Half-Thickness	Tenth-Value Thickness
Steel / Iron	1.0	3.3
Concrete	3.3	11.0
Earth	4.8	16.0
Water	7.2	24.0
Wood	11.4	38.0

[values in inches]

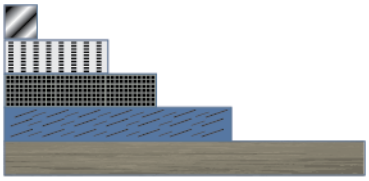

Figure 13.19 Radiation Shielding

ELECTROMAGNETIC PULSE

EMP is a very short duration pulse of low-frequency, or long-wavelength, electromagnetic radiation (EMR).

The source for all nuclear-generated EMP begins with the prompt nuclear radiation from the weapon which consists of neutrons, gamma rays, and X-rays. The most significant EMP effects are HEMP, for high-altitude EMP, SREMP, for source region EMP, and SGEMP, for system generated EMP. All forms of EMP require a symmetry-breaking condition or environmental disturbance in order for EMP to be generated—a requirement that is met in practice for all nuclear detonations but to varying degrees depending on HOB.

Detonations at altitudes above about 20 km are considered high-altitude bursts and give rise to HEMP. HEMP is the name for the effect that manifests itself on the ground due to radiated electromagnetic fields from EMP. High to exoatmospheric bursts also give rise to SGEMP which effects satellites and space-based systems. Surface and low-altitude bursts below about 5 km produce SREMP, while detonations ranging from about 5 km to 20 km altitude fall into a region of atmospheric and environmental conditions that generate a combination of HEMP and SREMP, but at weaker levels.

The symmetry-breaking mechanism responsible for generating HEMP is the Earth's geomagnetic field, without which no radiated EMP fields would escape the source region due to radial symmetry. The *source region,*[20] also known as the deposition region or conversion layer, is the region where the prompt gamma photons interact with air molecules primarily through the process of Compton scattering in which they scatter from electrons—deemed Compton electrons. The EMP[21] is created as the Compton electrons, traveling at close to the speed of light, accelerate and spiral along the Earth's magnetic field lines, creating transient electric fields and currents responsible for the electromagnetic pulse. The EMP, created with frequencies between about 100 KHz and 1 GHz, travels efficiently through the atmosphere. Because the detonation is high

[20] For high-altitude bursts, the source region is typically at altitudes of 15-40 km as this is the region where the atmosphere begins to be dense enough to produce significant Compton scattering. In the case of low-altitude and surface bursts, the source region (region of appreciable atmosphere) surrounds the detonation. Here the gammas begin to undergo Compton scattering immediately, unlike the high-altitude gammas which, depending upon their HOB, may traverse tens of kilometers before impinging upon the upper limits of the source region.

[21] The EMP signal from high-altitude detonations is broken down into three components: E1, the early time signal generated by prompt gammas; E2, the intermediate time signal generated by scattered gammas and neutrons; and E3, the late time signal generated by the effects caused from blast and heave of the Earth's atmosphere (as opposed to Compton Scattering). The long-wavelength, lower frequency E3 component is responsible for damage to transmission lines and long-underground conductors whereas the short-wavelength, higher frequency E1 component has the strongest electromagnetic fields and is responsible for electrical system/component upset and damage.

above the Earth's surface, the HEMP effect on the ground can cover large sweeping areas as well as affect targets or assets in flight such as planes and reentry vehicles. The large electric fields millivolt/meter (mV/m) associated with these EMP waves can have devastating consequences on electrical equipment that is not protected.

For surface or low-altitude detonations the symmetry-breaking mechanism that gives rise to SREMP is the non-uniformity of the air-ground boundary. The ground acts both as a radiation absorber and an electrical conductor. A target or asset on the ground close to GZ for a surface or low-altitude detonation will experience much greater electromagnetic fields than from a high-altitude detonation with the same weapon; however, the radiated fields from a surface or low altitude detonation affect a much smaller footprint on the ground and dissipate quickly with range from GZ.

For mid-altitude bursts, about 5 to 20 km, the effects of HEMP begin to taper off but still contribute depending on how much of the source region the prompt gammas actually travel through. Because the burst is lower in altitude, the footprint of the HEMP on the ground will also be smaller than that covered by a high-altitude burst. At mid-altitudes, the effect of SREMP begins to manifest the lower the HOB and, thus, it too contributes to the total electromagnetic field strength generated on the ground or experienced by assets in flight (planes and RVs).

Low energy X-rays from high-altitude detonations can give rise to SGEMP on satellites and space-based assets through the photoelectric effect by which the low energy X-rays are absorbed by the asset's surface materials and then liberate free electrons.[22] These liberated electrons move both inside and outside the space-based asset creating currents and inducing conductivity in dielectrics. The transient electron currents generated in this process create electromagnetic fields which can couple to nearby components that are part of the space-based asset. SGEMP energy can ultimately deposit in onboard electronic devices, causing upset (interruption, data loss) or damage from electrical overstress to unprotected electronics.

TRANSIENT RADIATION EFFECTS ON ELECTRONICS

Transient radiation effects on electronics (TREE) is damage to electronic components exposed to initial nuclear radiation gamma rays and neutrons. Gamma rays and neutrons moving away from GZ can affect electronic components and associated circuitry by penetrating deep into materials and electronic devices. Gamma rays can induce stray currents of electrons that generate electromagnetic fields similar to EMP. Neutrons can collide with atoms in key electronic materials causing damage to the crystal (chemical) structure and changing electrical properties. All electronics are vulnerable to TREE but smaller, solid-state electronics such as transistors and integrated circuits are the most vulnerable. Although initial nuclear radiation passes through material and equipment in a matter of seconds, the damage is usually permanent.

In the case of a high-altitude or exoatmospheric burst, prompt gamma rays and neutrons can reach satellites or other space systems. If these systems receive large doses of this initial nuclear radiation, their electrical components can be damaged or destroyed. If a nuclear detonation is a low-yield surface or low-air burst, the prompt gamma rays and neutrons could be intense enough to damage or destroy electronic components at

[22] SGEMP is driven by low-energy X-ray prompt radiation, whereas TREE is driven by the gamma and neutron prompt radiation.

distances beyond those affected by air blast. Because electronic equipment can be hardened against the effects of TREE, it is not considered in damage estimation.

Equipment designed to be protected against TREE is called "rad-hardened." Generally, special shielding designs can be effective, but TREE protection may include using shielded containers with a mix of heavy shielding for gamma rays and certain light materials to absorb neutrons. Just as with EMP hardening, it is always less expensive and more effective to design rad-hardening protection into the system during design and development.

BLACKOUT

Blackout is the interference with radio and radar waves resulting from an ionized region of the atmosphere. Nuclear detonations in the atmosphere generate a flow of gamma rays and X-rays moving away from the detonation. These photons produce a large number of ionizing events in the atoms and molecules in the air, creating a large region of ions with more positively charged atoms closer to the detonation, which can interfere with communications transmissions. Blackout does not cause damage or injuries directly. However, the interference with communications or radar operations could cause accidents indirectly, for example, the loss of air traffic control (due to either loss of radar capability or the loss of communications).

A high-altitude or exoatmospheric detonation produces a large ionized region of the upper atmosphere that could be as large as thousands of kilometers in diameter. This ionized region could interfere with communications signals to and from satellites and with AM radio transmissions relying on atmospheric reflection. Under normal circumstances, this ionized region interference continues for a period of time, up to several hours, after the detonation. The ionized region can affect different frequencies out to different distances and for different periods of time.

A surface or low-air burst produces a smaller ionized region of the lower atmosphere that could be as large as tens of kilometers in diameter. These bursts could interfere with Very High Frequency (VHF) and Ultra High Frequency (UHF) communications signals and radar waves that rely on line-of-sight transmissions. Normally, this low altitude ionized region interference would continue for a period of time, up to a few tens of minutes, after the detonation. There is no direct protection against the blackout effect.