# Appendix B
## *The Effects of Nuclear Weapons*

## B.1 *Overview*

A nuclear detonation produces effects that are overwhelmingly more significant than those produced by a conventional explosive, even if the nuclear yield is relatively low for a nuclear weapon. A nuclear detonation differs from a conventional explosion in several ways. The characteristics of a typical nuclear detonation include:

a) weight for weight, the energy produced by a nuclear detonation is millions of times more powerful than a conventional explosion;
b) a very large, very hot nuclear fireball is produced instantaneously;
c) an electromagnetic pulse (EMP) is generated instantaneously that can destroy or disrupt electronic equipment;
d) a larger percentage of energy is transmitted in the form of heat and light within a few seconds, which can produce burns and ignite fires at great distances from the detonation;
e) highly-penetrating, prompt nuclear radiation is emitted in the first minute after the detonation, which can be harmful to human and animal life, and can damage electronic equipment;
f) an air blast wave is created (if the detonation is in the lower atmosphere) that can cause casualties or damage at significant distances from the detonation;
g) a shock wave can destroy underground structures (if the detonation is a surface or near-surface burst[1]);
h) residual nuclear radiation will be emitted over an extended period of time, which may be harmful to humans if the detonation is close to the ground, or may damage electronic components in satellites if the detonation is exo-atmospheric; and
i) some of these mechanisms may cause interference to communications signals for extended periods.[2]

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[1] A near-surface burst is a detonation in the air that is low enough for the immediate fireball to touch the ground.

[2] For the purposes of this appendix, a "typical" nuclear detonation is one that occurs on the Earth's surface, or at a height of burst low enough for the primary effects to cause damage to surface targets. Detonations that are exo-atmospheric, high altitude, or deeply buried underground have different effects.

Figure B.1 Nuclear "Mushroom" Cloud

Figure B.1 is a photograph of the nuclear fireball and "mushroom" cloud produced by the 14 kiloton (kt) test device "Buster Charlie" on October 30, 1951 at the Nevada Test Site.

Understanding the effects of nuclear weapons is important for two reasons. First, as a part of the responsibility for maintaining the U.S. nuclear deterrent, the U.S. must have trained specialists that are knowledgeable and capable of advising senior leaders about the predictable results and the uncertainties associated with any employment of U.S. nuclear weapons, regardless of how important the target. Second, because potential adversary nations have nuclear weapons capabilities, we must have an understanding of how much and what types of damage might be inflicted on a U.S. populated area or military unit by an enemy use of one or more nuclear weapons.

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 weapon detonation can destroy unprotected or unhardened structures and systems and can harm or kill exposed personnel at great distances from the point of detonation, thereby affecting the successful outcome of a military mission or producing a large number of casualties in a populated area. Figure B.2 shows a picture of Hiroshima after being attacked with a nuclear weapon on August 6, 1945.

Figure B.2
Hiroshima After the Nuclear Detonation

This appendix provides a description of each of these effects and their impact on people, materiel equipment and structures, with example distances for selected effects, and certain weapon yields. It is written with the goal of remaining technically correct, but using terms and descriptions that can be understood by people without an academic education in physical sciences, engineering, or mathematics. A greater level of technical detail can be found in the more definitive documents on the subject such as the Defense Nuclear Agency *Effects Manual Number 1* (DNA EM-1) published by the forerunner organization to the current Defense Threat Reduction Agency (DTRA), or *The Effects of Nuclear Weapons*, 1977, by Samuel Glasstone and Philip Dolan. See Appendix

C, *Nuclear Weapons Effects Survivability and Testing*, for a discussion on the programs to increase the overall survivability of U.S. nuclear deterrent forces and to harden other military systems and equipment against the effects of nuclear weapons.

For people or objects that are very close to GZ, the effects are devastating. People and objects will survive at various distances depending on several factors, especially the yield of the weapon. If employed properly, any one nuclear weapon should defeat any one military target.[3] However, a few nuclear weapons with relatively low-yields (such as the yields of any nation's first generation of nuclear weapons) will not defeat a large military force (such as the allied force that operated in the first Gulf War). A single, low-yield nuclear weapon employed in a major metropolitan area will produce total devastation in an area large enough to produce tens of thousands of fatalities. It will not "wipe-out" the entire major metropolitan area. Survival of thousands of people who are seriously injured, or exposed to a moderate level of nuclear radiation, will depend on the response of various federal, state, and local government agencies.

## B.2 General Concepts and Terms

An explosion of any kind generates tremendous force by releasing a large amount of energy into a limited amount of space in a short period of time. This sudden release of energy increases the temperature and pressure of the immediate area to such a degree that all materials present are transformed into hot compressed gases. As these gases seek equilibrium, they expand rapidly outward in all directions, creating a shock wave or *blast wave* that has tremendous destructive potential. In a conventional explosion, almost all of the energy goes into producing the blast wave; only a small percentage of the energy produces a visible thermal radiation flash.

A typical nuclear detonation will produce both blast and thermal radiation, but it will also include a release of nuclear radiation. The distribution of energy is primarily a function of weapon design, yield, and height of burst (HOB). A nuclear weapon's output can be tailored to increase its ability to destroy specific types of targets, but a detonation of a typical fission-design weapon at or near the ground will result in approximately: 50 percent of the energy producing air blast, ground shock, or both; 35 percent producing thermal radiation (intense light and heat); and 15 percent producing nuclear radiation. Figure B.3 depicts this energy distribution.

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[3] Examples of single military targets include: one or a group of structures in a relatively small area; special contents (e.g. biological agents) within a structure; 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 command post; a communications site, etc.

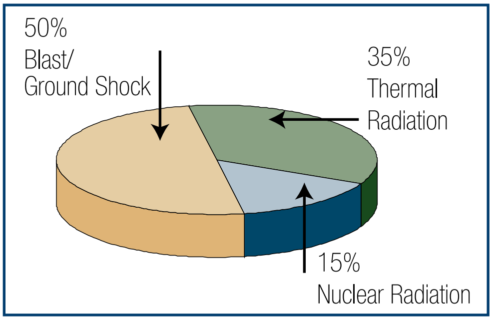


Figure B.3
Energy Distribution for a Typical Nuclear Detonation

The yield of a nuclear detonation is normally expressed in terms of an equivalent amount of energy released by a conventional explosive. A one kiloton (kt) nuclear detonation releases the same amount of total energy as 1,000 tons (two million pounds) of the conventional explosive trinitrotoluene (TNT), or approximately $10^{12}$ calories of energy. A one megaton (MT) nuclear detonation releases the same amount of energy as one million tons of TNT.

## B.3 *The Nuclear Fireball*

A typical nuclear weapon detonation will 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 forming 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 B.4 shows the size of the immediate fireball for selected yields and environments.

| Yield | Air Burst | | Underground Blast | |
|---|---|---|---|---|
| | 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 B.4 Approximate Fireball Size

The immediate fireball reaches temperatures in the range of tens of millions of degrees, i.e., as hot as the interior temperatures of the sun. Inside the fireball, the temperature and pressure cause a complete disintegration of molecules and atoms. While current targeting procedures do not consider the fireball to be one of the primary effects, a nuclear fireball could be used to defeat special types of target elements, e.g., to incinerate chemical or biological agents.

In a typical nuclear detonation, because the fireball is so hot, it begins to rise in altitude immediately. As it rises, a vacuum effect is created under the fireball, and air that had been pushed away from the detonation rushes back toward the fireball, causing an upward flow of air and dust that follows the fireball moving upward. This forms the stem of a mushroom-shaped cloud.

As the fireball moves up, it will also be blown downwind. Most of the dust and other material that had been in the stem of the mushroom-shaped cloud will drop back to the ground around GZ. If there is a strong wind, some of this may be blown downwind. After several minutes the cloud will reach an altitude where its vertical movement slows, and after approximately ten minutes, it will reach its stabilized cloud height, usually tens of thousands of feet in altitude.[4] After reaching its stabilized cloud height, the cloud will gradually expand laterally over a period of hours to days causing the cloud to become much less dense, but much larger. The top of the cloud could have some material drawn to higher altitudes. After a period of weeks to months, the cloud will have dispersed to the extent that it covers a very large area and will have very little radioactivity remaining.

## B.4 *Thermal Radiation*

*Thermal radiation* is electromagnetic radiation in the visible light spectrum that can be sensed as heat and light. A typical nuclear detonation will release thermal radiation in two pulses. For low-yields, the two pulses occur too quickly to be noticeable without special sensor equipment. For very large yields (one megaton or more) on clear days, the two pulses would be sensed by people at great distances from the detonation (a few tens of kilometers), and the second pulse would remain intense for ten seconds or longer. Thermal radiation is maximized with a low-air burst; the optimum height of burst to maximize the thermal effect increases with yield.

### B.4.1 Thermal Radiation Damage & Injury

Thermal radiation can ignite wood frame buildings and other combustible materials at significant distances from the detonation. It can also cause burns to exposed skin directly, or indirectly if clothing ignites, or if the person is caught in a fire ignited by the thermal radiation. Anything that casts a shadow (opaque material) or reduces light, including buildings, trees, dust from the blast wave, heavy rain, and dense fog, would provide at least some protection from thermal burns or ignitions to objects within the shadow. Transparent materials, such as glass or plastic, will attenuate thermal radiation only slightly. Figure B.5 shows the different types of burns and approximate maximum distances for selected yields.[5]

4 A large-yield detonation would have a hotter fireball, and would rise to a higher altitude than a low-yield detonation. A one megaton detonation would rise to an altitude of between 60,000 and 70,000 feet.

5 The distances in Figure B.5 are based on clear weather, no obstacles to attenuate the thermal radiation, and a low-air burst at the optimum height of burst to maximize the thermal effect.

| | | | Approximate Distances (km) | | |
|---|---|---|---|---|---|
| Degree | Affected Area | Description & Symptoms | 1 kt | 10kt | 1MT |
| 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 B.5 Thermal Radiation Burns

Flash blindness, or "dazzle," is a temporary loss of vision caused by the eyes being overwhelmed by the intense thermal light. On a clear night, dazzle can affect people at distances of tens of kilometers and may last for up to 30 minutes. On a clear day, dazzle can affect people at distances well beyond the distances for first degree burns but should last for a shorter period of time. Flash blindness can occur regardless of whether a person is looking toward the detonation because the thermal radiation can be scattered and reflected in the air. At distances where it can produce a first degree burn, it is so intense that it can penetrate through the back of the skull to overwhelm the eyes.

For people looking directly at the fireball at the moment of the detonation, retinal burns can occur at great distances. If the yield is large enough, and the duration of the second thermal pulse is more than one second, some people would look toward the detonation and receive retinal burns. Normally, retinal burns would cause a permanent blindness to a small portion in the center of the normal field of vision. A surface burst would reduce the incidence of both temporary blindness and retinal burns.

### B.4.2 Thermal Radiation Employment Factors

For thermal radiation to cause ignition or burns, the person or object must be in direct line-of-sight from the detonation, without anything opaque in between. For this reason, thermal radiation is maximized with a low-air burst rather than a surface burst because the higher height of detonation provides direct line-of-sight out to much greater distances.

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

### B.4.3 Thermal Radiation Protection

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 the use of materials that swell when exposed to flame (absorbing the heat rather than allowing it to penetrate through the material), as well as ablative paints, which act like a melting heat shield. Materials like steel, as opposed to temperature-sensitive metals like aluminum, are used to protect against thermal radiation. Similarly, higher-temperature resins are used in forming fiberglass structures. 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. 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—from direct exposure.

## B.5 *Air Blast*

For surface and low-air bursts, the fireball expands, pushing air or ground soil/rock/water immediately away from the point of the detonation.[6] Above the ground, a dense wall of air breaks away from the immediate fireball, traveling at great speed. Initially, this blast wave moves at several times the speed of sound, but quickly slows to a point where the leading edge of the blast wave is traveling at the speed of sound (mach one), and it 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 (over the nominal air pressure).[7] As the blast wave travels away from this point, the wall of air becomes wider and wider in width, and loses density (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. In addition to overpressure, the blast wave has an associated wind speed as the blast wave 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. Figure B.6 shows the result of air blast damage to buildings.

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[6] For a one kiloton, low-air burst nuclear detonation, the immediate fireball would be approximately 30 meters (almost 100 feet) in radius and approximately 60 meters (almost 200 feet) in diameter.

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

| | | Approximate Distances (km) | | |
|---|---|---|---|---|
| Approx. Overpressure | Description | 1 kt | 10kt | 1MT |
| 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 B.6 Air Blast Damage to Structures

### B.5.1 Air Blast Damage & Injury

As the blast wave hits a target object, initially the positive overpressure produces a crushing effect on the object. If the overpressure is great enough, it could cause instant fatality. Less overpressure could collapse the lungs, and at lower levels, could rupture the ear drums. Overpressure can implode a building. Immediately after the positive overpressure has begun to affect the object, the dynamic pressure exerts a force that can move people or objects laterally very rapidly, causing injury or damage. It can also strip a building from its foundation, blowing it to pieces moving away from GZ.

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 (negative overpressure) could cause a wood-frame 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 cause objects to be moved back toward GZ, especially if trees or buildings are weakened severely by the positive phase. Figure B.6 shows the overpressure in psi and the approximate distances associated with various types of structural damage.[8]

[8] The distances in Figure B.6 are based on an optimum height of burst to maximize the blast effect, and 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 one psi.

## B.5.2 Air Blast Employment Factors

If the detonation occurs at ground level, the expanding fireball will push 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, until after some significant distance, it no longer has destructive potential and becomes a mere gust of wind. However, if the detonation is a low-air burst, a portion of the blast wave travels down toward the ground and is reflected off the ground. This reflected wave travels up and out in all directions, reinforcing the incident wave traveling along the ground. Figure B.7 shows the sequence of the incident wave moving away from the fireball, the reflected wave "bouncing" off the Earth's surface, and the formation of the reinforced blast wave. Because of this factor, air blast is maximized with a low-air burst rather than a surface burst.

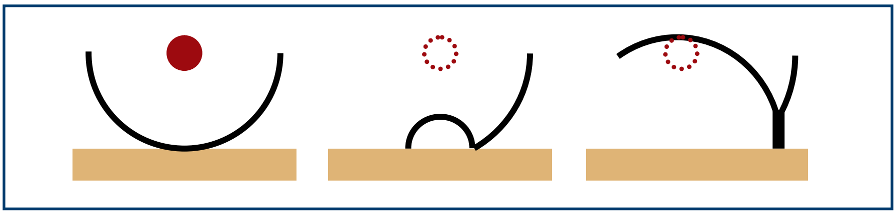

Figure B.7 Low-Air Burst Reinforced Blast Wave

If the terrain has a surface that will absorb thermal radiation more than grass or normal soil (e.g., sand, asphalt, etc.), the thermal radiation will heat the surface more than normal, giving off heat prior to the arrival of the blast wave. This is a "non-ideal" condition that will cause the blast wave to become distorted when it reaches the heated surface, causing an abnormal reduction in the density of the blast wave and abnormally reduced psi. Extremely cold weather (-50° F or colder) could cause increased air blast damage distances for some equipment and structures. For surface bursts against a populated area, or if there is rain or fog in the area, the blast effect would probably account for more casualties than any other effect.

## B.5.3 Air Blast Protection

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

People who sense a blinding white flash and intense heat coming from one direction (the thermal radiation) should fall to the ground immediately and cover their head with their arms. This will provide the highest probability that the air blast will pass overhead without moving the person laterally or having debris in the blast wave cause impact or puncture injuries. Exposed people that are very close to the detonation have no chance of survival. However, at distances where a wood frame building can survive, an exposed person would significantly increase their chance of survival if they are flat on the ground when the blast wave arrives, and remain on the ground until after the negative phase blast wave has moved back toward GZ.

## B.6 Ground Shock

For 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 will produce significantly more ground shock than a near-surface burst where the fireball barely touches the ground.

### B.6.1 Ground Shock Damage & Injury

Underground structures, especially ones that are very 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 the yield of the detonation, the soil or rock type, the depth of the target, and its type of structure. It is possible for a surface detonation to fail to crush a deep underground structure but to have an effective shock wave that crushes or buries entrance/exit routes and destroys connecting communications lines. This could cause the target to be "cut-off" and, at least temporarily, incapable of performing its intended function.

### B.6.2 Ground Shock Employment Factors

Normally, a surface burst or shallow sub-surface burst is used to attack deeply buried targets. As a simple rule of thumb, a one kt surface detonation can destroy an underground facility as deep as a few tens of meters. A one MT surface detonation can destroy the same target as deep as a few hundreds of meters.

Deeply buried underground targets can be attacked by employing 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, where 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 to distances that are usually between two and five times deeper.[9] Ground shock is the governing effect for damage estimation against any underground target.

### B.6.3 Ground Shock Protection

Underground facilities and structures can be buried deeper to reduce their vulnerability to damage or collapse from a surface or shallow sub-surface detonation. Facilities and equipment can be built with structural reinforcement or other unique designs to make them less vulnerable to ground shock. As a part of functional survivability, the requirement for entrance/exit routes must be considered, as well as any communications lines that must connect to equipment at ground level.

## B.7 *Surface Crater*

For 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 that material as it moves upward. This evacuation 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 would be larger and deeper; crater size is maximized with a shallow sub-surface burst at the optimum depth.[10] The size of the crater is a function of the yield of the detonation, the depth of burial, and the type of soil or rock.

For deeply buried detonations, such as those created with underground nuclear 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 this cavity and the vacuum effect within the cavity cause a downward pressure for the earth to fall in on the cavity. 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 will form a crater on the surface, called a subsidence crater. Figure B.8 shows the *Sedan* crater formed at the Nevada Test Site by a 104 kt detonation at an optimum depth of 193.5 meters (635 feet). The *Sedan* subsidence crater is approximately 390 meters (1,280 feet) in diameter and 98 meters (320 feet) deep.

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[9] The amount of increased depth of damage is primarily a function of the yield and the soil or rock type.

[10] For a one kt detonation, the maximum crater size would have a depth of burial between 32 and 52 meters, depending on the type of soil or rock.

Figure B.8 Sedan Subsidence Crater

### B.7.1 Surface Crater Damage & Injury

If a crater has been produced by a detonation near the surface within the last several days, it will probably be radioactive. People who are required to enter or cross such a crater could be exposed to significant levels of ionizing radiation, possibly enough to cause casualties or fatalities.

If a deep underground detonation has not yet formed the subsidence crater, it would be very dangerous to enter the area on the surface directly above the detonation.

### B.7.2 Surface Crater Employment Factors

Normally, the wartime employment of nuclear weapons does not use crater formation to attack targets. 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, would produce an obstacle that would be extremely difficult, if not impossible, for a military unit to move over it.

### B.7.3 Surface Crater Protection

A crater by itself does not present a hazard to people or equipment, unless the person tries to drive or climb into the crater. For deep underground detonations, the rule is to keep away from the area where the subsidence crater will be formed until after the collapse occurs.

## B.8 *Underwater Shock*

A nuclear detonation underwater generates a shock wave similar to the way a blast wave is 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, but surface interaction will generally mitigate the shock effect.

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

### B.8.1 Underwater Shock Damage & Injury

If a submarine is close enough to the detonation, the underwater shock wave will be strong enough to move the vessel rapidly. 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.

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

### B.8.2 Underwater Shock Employment Factors

Normally, nuclear weapons are not used to target enemy naval forces.

### B.8.3 Underwater Shock Protection

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

## B.9 *Initial Nuclear Radiation*

*Nuclear radiation* is ionizing radiation emitted by nuclear activity, consisting of neutrons, alpha and beta particles, as well as electromagnetic energy in the form of gamma rays.[11] Gamma rays are high-energy photons of electromagnetic radiation with frequencies higher than visible light or ultraviolet rays.[12] Gamma rays and neutrons are produced from fission events. Alpha and beta particles, as

[11] Ionizing radiation is defined as electromagnetic radiation (gamma rays or X-rays) or particulate radiation (alpha particles, beta particles, neutrons, etc.) capable of producing ions (electrically charged particles) directly or indirectly in its passage through matter.

[12] A photon is a unit of electromagnetic radiation consisting of pure energy and zero mass; the spectrum of photons include AM radio waves, FM radio waves, radar- and micro-waves, infrared waves, visible light, ultraviolet waves, X-rays, and gamma/cosmic rays.

well as 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 GZ.[13]

Because neutrons are produced almost exclusively by fission events, they are produced in a fraction of a second, and there are no significant number of neutrons produced after that. Conversely, gamma rays are produced by the decay of radioactive materials and will be produced for years after the detonation. Most of these radioactive materials are initially in the fireball. For surface and low-air bursts, the fireball will rise quickly, and within approximately one minute, will be at an altitude high enough that none of the gamma radiation produced inside the fireball would have 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 after the detonation. Initial nuclear radiation is also called *prompt nuclear radiation*.

### B.9.1 Initial Nuclear Radiation Damage & Injury

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. For a description of the biological damage mechanisms, see the section on the Biological Effects of Ionizing Radiation below. The unit of measurement for radiation exposure is the centi-Gray (cGy).[14] Figure B.9 shows selected levels of exposure, the associated prompt effects on humans, and the distances by yield.[15] The 450 cGy exposure dose level is considered to be the lethal dose for 50 percent of the population (LD50). People who survive at this dose level would have a significantly increased probability of contracting mid-term and long-term cancers, including lethal cancers.

Low levels of exposure can increase a person's risk for contracting long-term cancers. For example, for healthy male adults age 20 to 40, an exposure of 100

[13] Both gamma rays and neutrons will be scattered and reflected by atoms in the air, causing each gamma photon and each 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 the GZ, they will be traveling back toward the GZ.

[14] One cGy is an absorbed dose of radiation equivalent to 100 ergs of ionizing energy per gram of absorbing material or tissue. The term centi-Gray replaced the older term radiation absorbed dose (RAD).

[15] For the purposes of this appendix, 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 impact to a person's health.

| | | Approximate Distances (km) | | |
|---|---|---|---|---|
| Level of Exposure | Description | 1 kt | 10kt | 1MT |
| 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 B.9 Prompt Effects of Initial Nuclear Radiation

cGy will increase the risk of contracting any long-term cancer by approximately 10 to 15 percent, and for lethal cancer by approximately 6 to 8 percent.[16]

Initial nuclear radiation can also damage the electrical components in certain equipment. See the section on Transient Radiation Effects on Electronics (TREE) below.

## B.9.2 Initial Nuclear Radiation Employment Factors

The ground absorbs both gamma rays and neutrons much more than air can absorb them. A surface burst will have almost half the initial nuclear radiation absorbed quickly by the earth. A low-air burst will also have half the nuclear radiation traveling in a downward direction, but much of that will be scattered and reflected by atoms in the air and can add to the amount of radiation traveling away from GZ. For this reason, initial nuclear radiation is maximized with a low-air burst rather than a surface burst. Generally, the effects of initial nuclear radiation for lower yield weapons are more significant, compared with other effects, than they are with higher-yield weapons.

Initial nuclear radiation effects can be predicted with reasonable accuracy. Some non-strategic targets, or theater, may have personnel as one of the primary target elements. 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., that there will be maximum initial radiation effect, and that objects in the target area will not shield or attenuate the radiation.

[16] Calculated from data in *Health Risks from Exposure to Low Levels of Ionizing Radiation: BEIR VII - Phase 2*, National Academy of Sciences, Committee to Assess Health Risks from Exposure to Low Levels of Ionizing Radiation, 2006.

### B.9.3 Initial Nuclear Radiation Protection

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

Generally, structures are not vulnerable to initial nuclear radiation. Equipment can be hardened to make electronic components less vulnerable to initial nuclear radiation.

## B.10 *Residual Nuclear Radiation*

Residual nuclear radiation consists of alpha and beta particles and gamma rays emitted from the nuclei during the decay of radioactive material. For a typical detonation, there are two primary categories of residual nuclear radiation: induced radiation and fallout. A deep underground detonation would have the same categories, but the radiation would remain deep underground, unless there were a venting of radioactive gases from the fireball, or if other residual radiation escaped by another means, e.g., through an underground water flow. An exo-atmospheric detonation would create a cloud that could remain significantly radioactive in orbit for many months.

For typical surface or low-air burst detonations, there will be two types of induced radiation. The first type is neutron-induced soil on the ground, called an "induced pattern." Neutrons emitted from the detonation are captured by light metals in the soil or rock near the ground surface.[17] These atoms become radioactive isotopes capable of emitting, among other things, gamma radiation. The induced radiation is generally created in a circular pattern around the GZ. It is most intense at GZ and immediately after the detonation. The intensity decreases with distance from GZ, and it will also decrease over time. For normal soil, it would take approximately five to seven days to decay to a safe level.

Another type of induced radiation is the production of carbon-14 by the absorption of fission neutrons in nitrogen in the air. The carbon-14 atoms can remain suspended in the air, are beta particle emitters, and have a long half-life (5,715 years).

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

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. However, the fireball will contain other types of radioactive particles that will also fall to the ground contributing to the total radioactive hazard. These include the radioactive fissile material that did not undergo fission (no weapon is so efficient to fission 100 percent of the fissile material), and material of the warhead components that have been induced with neutrons and have become radioactive.

Residual gamma radiation is colorless, odorless, and tasteless. Unless there is an extremely high level of radiation, it cannot be detected with the five senses.

### B.10.1 Residual Nuclear Radiation Damage & Injury

Usually, 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, that could become a radioactive hazard to people in the affected area. The residual nuclear cloud from an exo-atmospheric 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.

If a nuclear device is detonated in a populated area, it is possible that the induced radiation could extend to distances beyond building collapse, especially with a low-yield device. This could cause first responders who are not trained to understand induced radiation to move toward GZ intending to help injured people, and to move into an area that is still radioactively hot. Without radiation detectors, the first responders would not be aware of the radioactive hazard.

Between the early-1950s and 1962, when the four nuclear nations were conducting above ground nuclear testing, there was a two to three percent increase in total carbon-14 worldwide. Gradually, the amount of carbon-14 is returning to pre-testing levels. While there are no known casualties caused by the carbon-14 increase, it is logical that any increase over the natural background level could be an additional risk. If nuclear-capable nations were to return to nuclear testing in the atmosphere, carbon-14 could become a hazard for the future.

Normally, fallout should not be a hazardous problem for a detonation that is a true airburst. However, if rain or snow is falling in the target area, radioactive particles could be “washed-out” of the fireball, causing 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.

## B.10.2 Residual Nuclear Radiation Employment Factors

If the detonation is a true air burst, where the fireball does not interact with the ground or any significant structure, the size and heat of the fireball will cause 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 there is no significant radioactive hot-spot on the ground caused by the fallout. The fireball will rise to become a long-term radioactive cloud. The cloud will travel with the upper atmospheric winds, and it will circle the hemisphere several times over a period of months before it dissipates completely. Most of the radioactive particles will decay to stable isotopes before falling to the ground. The particles that reach the ground will be 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 radiation (measurable with radiation detectors) than the area near the detonation. This is called worldwide fallout.

If the fireball interacts with the ground or any significant structure (e.g., a large bridge or a large building), the fireball would have different properties. In addition to the three types of radioactive material mentioned in the previous paragraph, the fireball would also include radioactive material from the ground (or from the structure) that has been 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 one 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 (for a one kt, almost 200 feet in diameter and tens of millions of degrees), it has no potential to hold up and carry thousands of tons of material. Thus, as the fireball rises, it would begin to release a significant amount of radioactive dust, which would fall to the ground and produce a radioactive fallout pattern around GZ and moving downwind. The intensity of radioactivity in this fallout area would be hazardous for weeks. This is called early fallout. It is caused primarily by a surface burst detonation regardless of the weapon design.

## B.10.3 Residual Nuclear Radiation Protection

There are four actions that are the primary 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).[18] While the PPE will not stop the penetration of gamma rays, it will prevent the responder personnel from breathing in any airborne radioactive particles. Second, personnel should remain 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 principles of PPE, time, distance, and shielding.

Equipment may be designed to be "rad-hard" if it is a requirement. See Appendix C, *Nuclear Weapons Effects Survivability and Testing*, for a discussion of the U.S. survivability program.

## B.11 Biological Effects of Ionizing Radiation

*Ionizing radiation* is any particle or photon that can produce an ionizing event, i.e., stripping one or more electrons away from their parent atom. It includes alpha particles, beta particles, gamma rays, cosmic rays (all produced by nuclear actions), and X-rays (not produced by nuclear actions).

### B.11.1 Ionizing Radiation Damage & Injury

Ionizing events cause biological damage to humans and other mammals. Figure B.10 shows the types of life-essential molecular ionization and the resulting biological problem. Generally, the greater the exposure dose, the greater the biological problems caused by the ionizing radiation.

| Ionized Objects | Resulting Problem |
|---|---|
| Ionized DNA molecules | Abnormal cell reproduction |
| Ionized water molecules | Creates hydrogen peroxide ($H_2O_2$) |
| Ionized cell membrane | Cell death |
| Ionized central nervous system molecules | Loss of muscle control |
| Ionized brain molecules | Loss of thought process & muscle control |

Figure B.10 Biological Damage from Ionization

At medium and high levels of exposure, there are near-term consequences, including impaired performance, becoming an outright casualty, and death. See Figure B.9 for a description of these problems at selected dose levels. People who survive at this dose level would have a significantly increased probability of contracting mid-term and long-term cancers, including lethal cancers.

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

At low levels of exposure, there are no near-term medical problems. However, at 75 cGy, approximately five percent of healthy adults will experience mild threshold symptoms, i.e., transient mild headaches and mild nausea. At 100 cGy, approximately 10-15 percent would experience these threshold symptoms, with a smaller percentage experiencing some vomiting. It is also possible that some people could experience near-term psychosomatic symptoms, especially if they respond to inaccurate reports by the news media or others. Low exposure levels also result in some increased probability of contracting mid-term and long-term cancers, including lethal cancers. Figure B.11 shows the increased probability for healthy adults, by gender.

| Level of Ionizing Radiation Exposure | Approximate Increased Risk (Probability) 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 B.11 Increased Risk - Low Level Exposure

### B.11.2 Ionizing Radiation Protection

Shielding can be achieved with most materials, however, some require much more material; to reduce the penetrating radiation by half. Figure B.12 shows 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").

## B.12 *ElectroMagnetic Pulse (EMP)*

Electromagnetic Pulse (EMP) is a very short duration pulse of low-frequency (long-wavelength) electromagnetic radiation (EMR). It is produced when a nuclear detonation occurs in a non-symmetrical environment, especially at or near the Earth's surface or at high altitudes.[19] The interaction of gamma rays, X-rays, and neutrons with the atoms and molecules in the air generates an instantaneous flow of electrons, generally in a direction away from the detonation. These electrons immediately change direction (primarily because of

[19] EMP may also be produced by conventional methods.

| Material | Half-Thickness (inches) | Tenth-Value Thickness (inches) |
|---|---|---|
| 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 |

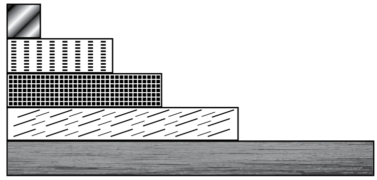

Figure B.12 Radiation Shielding

the Earth's magnetic field) and velocity, emitting low frequency EMR photons. This entire process occurs almost instantaneously (measured in millionths of a second) and produces a huge number of photons.

### B.12.1 EMP Damage & Injury

Any unprotected equipment with electronic components could be vulnerable to EMP. A large number of low-frequency photons can be absorbed by any antenna of any component that acts as an antenna. This energy moves within the equipment to any unprotected electrical wires or electronic components and generates a flow of electrons. The electron flow becomes voltage within the electronic component or system. Modern electronic equipment using low voltage components can be overloaded with a voltage beyond its designed capacity. At low levels of EMP, this can cause a disruption of processing, or a loss of data. At increased EMP levels, certain electronic components will be destroyed. EMP can damage unprotected electronic equipment, including computers, vehicles, aircraft, communications equipment, and radars. EMP will not produce structural damage to buildings, bridges, etc.

EMP is not a direct hazard to humans. However the indirect effects of electronics failing instantaneously in vehicles, aircraft, life-sustaining equipment in hospitals, etc., could cause injuries or fatalities.

### B.12.2 EMP Employment Factors

A high-altitude detonation, or an exo-atmospheric detonation within a certain altitude range band, will generate an EMP that could cover a very large region of the Earth's surface, as large as 1.000 kilometers across. A surface or low-air burst would produce local EMP with severe intensity, traveling through the air out to distances that could go beyond the distances of building collapse (hundreds of meters). Generally, the lower the yield, the more significant is the EMP compared with air blast. Again, within this area, unprotected electronic components would be vulnerable. Electrical lines and telephone wires would carry the pulse to much greater distances, possibly ten kilometers, and could destroy any electronic device connected to the power lines.

Because electronic equipment can be hardened against the effects of EMP, it is not considered in traditional approaches for damage estimation.

### B.12.3 EMP Protection

Electronic equipment can be EMP-hardened. The primary objective of EMP hardening is to reduce the electrical pulse entering a system or piece of equipment to a level that will not cause component burnout or operational upset. It is always cheaper and more effective to design the EMP protection into the system during design development. Potential hardening techniques include using certain materials as radio frequency shielding filters, using internal enclosed protective "cages" around essential electronic components, using enhanced electrical grounding, shielded cables, keeping the equipment in closed protective cases, or keeping the equipment in an EMP-protected room or facility. Normally, the hardening that permits equipment to operate in intense radar fields (e.g., helicopters that operate in front of a ship's radars) also provides a significant degree of EMP protection.

Because the EMP is of such short duration, home circuit-breakers, typical surge-protectors, and power strips are useless against EMP. These devices are designed to protect equipment from electrical surges caused by lightning, but they cannot defend against EMP because it is thousands of times faster than the pulse of lightning.

## B.13 *Transient Radiation Effects on Electronics (TREE)*

Transient Radiation Effects on Electronics (TREE) is the damage to electronic components by initial nuclear radiation gamma rays and neutrons.

### B.13.1 TREE Damage & Injury

The gamma rays and neutrons produced by a nuclear detonation are transient initial nuclear radiation which 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 harmful 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. While all electronics are susceptible to the effects of TREE, smaller, solid-state electronics such as transistors and integrated circuits are most vulnerable to these effects.

Although initial nuclear radiation may pass through material and equipment in a matter of seconds, the damage is usually permanent.

### B.13.2 TREE Employment Factors

With a high-altitude or exo-atmospheric 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 distances beyond air blast damage to that equipment. Because electronic equipment can be hardened against the effects of TREE, it is not considered in traditional approaches to damage estimation.

### B.13.3 TREE Protection

Equipment that is designed to be protected against TREE is called "rad-hardened." The objective of TREE hardening is to reduce the effect of the gamma and neutron radiation from damaging electronic components. 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 cheaper and more effective to design the EMP protection into the system during design development.

## B.14 *Black-Out*

Black-out is the interference with radio and radar waves due to an ionized region of the atmosphere. Nuclear detonations, other than those underground or far away in outer space, will generate the flow of a huge number of gamma rays and X-rays, moving in a general direction away from the detonation. These photons will produce a large number of ionizing events in the atoms and molecules in the air, creating a very large region of ions. A large number of electrons are stripped away from their atoms, and move in a direction away from the detonation. This leaves a large number of positively charged atoms closer to the detonation, creating an ionized region with positively charged atoms close to the detonation and negatively charged particles farther from the detonation.

### B.14.1 Black-Out Damage & Injury

Blackout cannot cause damage or injuries directly. The interference with communications or radar operations could cause accidents indirectly, e.g., the loss of air traffic control, due to either loss of radar capability or the loss of communications, could affect several aircraft simultaneously.

## B.14.2 Black-Out Employment Factors

A high-altitude or exo-atmospheric detonation would produce a very 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 that rely on atmospheric reflection if those signals have to travel through or near the ionized region. Under normal circumstances, this ionized region interference would continue 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 would produce a smaller ionized region of the lower atmosphere that could be as large as tens of kilometers in diameter. This ionized region could interfere with VHF and UHF communications signals and with radar waves that rely on pin-point line-of-sight transmissions if those signals have to travel through or near the ionized region. Under normal circumstances, this low altitude ionized region interference would continue for a period of time up to a few tens of minutes after the detonation. Again, the ionized region can affect different frequencies out to different distances and for different periods of time.

## B.14.3 Black-Out Protection

There is no direct protection against the black-out effect.