5

Nuclear and Radiological Hazards

These atomic bombs which science burst upon the world that night were strange even to the men who used them.

H.G. Wells, *The World Set Free*, 1914

That is the biggest fool thing we have ever done.
The atomic bomb will never go off, and I speak as an expert in explosives.

Admiral William D. Leahy, commenting to President Harry S. Truman, 1945

Malicious acts involving nuclear or other radioactive material are a continuing worldwide threat.

IAEA Annual Report 2008

INTRODUCTION

Nuclear weapons are by far the most powerful of all weapons of mass destruction (WMDs). The detonation of a nuclear device by a terrorist group would result in catastrophic physical effects, including blast overpressure, thermal effects and radiation contamination, and also cause tremendous psychological impacts worldwide.

During the Cold War between the United States and the Soviet Union (late 1940s to early 1990s), the nations of the world lived with the constant threat of nuclear war. With the end of the Cold War came the hope that the nuclear arsenals stockpiled by these and other countries would eventually be dismantled. Unfortunately, however, international terrorist organizations have been attempting to gain access to WMDs, including nuclear weapons, by trying to acquire nuclear materials, and recruit nuclear weapon scientists. In addition, certain nuclear nations still pose a military threat to others.

NUCLEAR WEAPONS

Nuclear weapons are designed and constructed based on two unstable materials, uranium and plutonium.

The uranium-based weapons are not manufactured directly from this metal; the naturally occurring mineral must be enriched before it is usable in a weapon. Enrichment processes are costly and extremely complex; therefore, only large national institutes or industries possess the resources needed to carry out these processes. In other words, a terrorist group is unlikely to engage in such activities without being detected. Plutonium does not exist in nature and is only produced within a nuclear reactor, another complex technology limited solely to large-scale enterprises.

Because of these limitations, a terrorist organization can acquire a nuclear weapon only by limited means, including the following:

- Obtaining an intact nuclear weapon from a national stockpile
- Obtaining fissile material from stocks that were produced in industrial facilities and then converting the fissile material into a nuclear weapon

The most important and effective steps for reducing the threat of nuclear terrorism are therefore to secure, consolidate, reduce, and, where possible, eliminate nuclear weapons and fissile material. Programs to implement such measures are under way in many countries but are far from reaching their goals (NTI, no date).

HISTORY OF NUCLEAR AND RADIOLOGICAL WEAPONS

Early in the 20th century the science of physics had achieved remarkable advances; much was discovered regarding the nature of atoms and

their behavior. In the late 1800s at the University of Wurzburg (Germany), Wilhelm Konrad Roentgen conducted experiments involving high voltage currents in vacuum tubes and in 1895 discovered x-rays. In 1898, Pierre and Marie Skladowska Curie discovered a new substance occurring within pitchblende (an ore of uranium), which emitted massive amounts of energy (this energy was later to be termed **radioactivity**). The work of the Curies led to the discovery of polonium in 1896 and radium in 1897. Different types of radioactive emissions were soon identified; in 1899, Henri Becquerel found that some radiation emissions were electrically charged. British Chemist and Physicist Ernest Rutherford went on to distinguish two types of charged emissions—alpha and beta. He demonstrated that alpha particles were actually helium atoms minus their planetary electrons. In 1900, Paul Villard, a French Physicist, identified gamma rays, which were determined to be uncharged waves of electromagnetic radiation.

Experiments by Rutherford in 1911 indicated that the vast majority of an atom's mass is concentrated within the center, or nucleus, and is composed of protons surrounded by a cloud of electrons. In 1932, James Chadwick discovered that the nucleus contained another fundamental particle, later termed the *neutron* because of its lack of electrical charge.

In 1932, John Cockcroft and Ernest Walton (English and Irish physicists, respectively) were the first scientists known to have split the atom, and by late 1933, Hungarian physicist Leo Szilard conceived the idea of using a "chain reaction" of neutron collisions with atomic nuclei to release energy. He also realized the potential of using this chain reaction to make bombs. In 1934 Szilard received a patent for the atomic bomb, although he had no intentions of pursuing such a weapon; rather, his intent was to protect the concept of the bomb to prevent its destructive use. He offered his theory to the British government so that it could be made classified and protected under British secrecy laws. The British War Office rejected Szilard's offer; however, a few months later in February 1936, he succeeded in getting the British Admiralty to safeguard the new discovery (Atomicarchive, 2008a).

Nuclear **fission** was documented in December 1938, when German chemists Otto Hahn and Fritz Strassmann reported that they had detected the element barium after bombarding uranium with neutrons (Hahn and Strassmann, 1939). On January 25, 1939, a research team at Columbia University conducted the first nuclear fission experiment in the United States (Anderson et al., 1939).

World War II

With the start of World War II many of Europe's most distinguished physicists fled the continent. Scientists now understood that nuclear fission could be employed in a weapon; however, no one had yet determined how this could be accomplished. There was alarm among scientists of the Allied nations that Nazi Germany might develop its own project to create fission-based weapons. Urgent research began in the United States and Britain with the intention of beating Hitler in the race to construct the bomb. By 1942, the U.S. nuclear program was placed under the supervision of a military team led by General Leslie Groves and became known as the Manhattan Project. Led by the American physicist J. Robert Oppenheimer (Figure 5.1), the project brought together top scientific minds, including many European exiles. The United States and Britain agreed to combine their resources for the project; however, the Soviet Union, the other major Allied power, was not informed of plans for the bomb. In the early years of the war, physicists halted all publishing on the topic of nuclear fission to prevent Nazi Germany (and the Soviets, whom the United States and Britain did not trust) from gaining any advantage in nuclear weapons development.

Figure 5.1 Physicist J. Robert Oppenheimer (right, with General Leslie Groves) led the Manhattan Project, the Allied atomic weapons program. (http://www.cfo.doe.gov/me70/manhattan/images/GrovesOppenheimerLarge.jpg.)

The U.S. government invested enormous energy and resources into wartime research for the project, which was distributed across more than 30 sites in the United States and Canada. Scientific knowledge was centralized at a secret laboratory named Los Alamos near Santa Fe, New Mexico. On December 2, 1942, Enrico Fermi achieved the world's first controlled and sustained nuclear chain reaction in the first "atomic pile" (i.e., a crude nuclear reactor) at the University of Chicago. At the same time, large reactors were secretly being constructed in eastern Washington State at what is now known as the Hanford Site, to manufacture weapons-grade plutonium.

By early 1943 Oppenheimer determined that two weapons projects should be given highest priority: the so-called Thin Man (a plutonium gun) and Fat Man (a plutonium implosion device). Development of the latter bomb was given top priority. A gun-type uranium bomb was next in line for development.

Germany surrendered on May 8, 1945, thus closing the European Theater of the war. A team of Allied scientists followed Allied troops into Europe to assess the status of the German nuclear program. This effort was also designed to prevent the Soviets, marching in from the east, from discovering any nuclear materials or locating scientists. It was eventually discovered that, in early 1945, a Nazi scientific team had been directed by physicist Kurt Diebner to develop a primitive nuclear device in Ohrdruf, Thuringia (Furlong, 2005; Karlsch, 2005). However, while Germany had been developing its own atomic bomb program, it was far from becoming operational.

The Manhattan Project was still months away from having a working weapon available. In April 1945, after the death of U.S. President Franklin Roosevelt, Vice President Harry Truman was first informed about the secret wartime project. On July 16, 1945, the first nuclear test, code-named "Trinity," took place in the desert north of Alamogordo, New Mexico. The detonation released the equivalent of 19 kilotons (kt) of TNT, far greater than any weapon ever used before. While observing the massive fireball, Manhattan Project Director Robert Oppenheimer quoted *The Bhagavad Gita*, a Hindu holy book:

> If the radiance of a thousand suns
> were to burst at once into the sky,
> that would be like the splendor of the Mighty One ...
> I am become Death,
> the shatterer of Worlds.

After considering arguments from scientists and military officers over the possible use of atomic weapons against Japan, President

Truman ordered dropping them on to Japanese cities with the hope that these weapons would stun the Japanese government to the point of their country's capitulation. Initial proposed targets of the first atomic bomb included Tokyo but this suggestion was dropped. The Target Committee recommended Kyoto, Hiroshima, Yokohama, and a weapons depot at Kokura as possible targets. On August 6, 1945, a uranium-based weapon, "Little Boy," was dropped on Hiroshima (Figure 5.2). Three days later, a plutonium-based weapon, "Fat Man," was dropped onto Nagasaki. The two bombs, specifically the blast wave, heat, and radiation that were generated, killed at least 100,000 Japanese immediately, most of them civilians. Tens of thousands died later of radiation sickness and cancer.

Truman threatened to destroy Japanese cities one by one until Japan accepted unconditional surrender. Japan surrendered on August 15. Truman's threat was actually a bluff, since the United States had no more atomic bombs in its arsenal at the time (Rhodes, 1996).

Postwar

The Soviet Union was not privy to intelligence about the U.S. atomic bomb program; however, a substantial coterie of Soviet spies was

Figure 5.2 Aftermath of the atomic bombing of Hiroshima, 1945. (http://en.wikipedia.org/wiki/File:AtomicEffects-Hiroshima.jpg.)

directly involved with the Manhattan Project and regularly forwarded detailed plans about Allied weapons development to their home country. One of the most notorious moles was Klaus Fuchs, a German émigré physicist who had participated in the early British nuclear program. During the war Fuchs went on to work with the U.K. division at Los Alamos (Figure 5.3). Fuchs was closely involved in the development of the plutonium weapon and passed on detailed cross sections of the device to his Soviet contacts. The diverted information, in combination with the Soviet's own nuclear program led by physicist Yuli Khariton, provided that country with the necessary resources for developing a tactical nuclear weapon.

Soon after the war, the Soviets became acutely focused on the development of their own atomic weapons. Early on, however, the Soviet program stalled due to insufficient nuclear fuel resources; little data was available regarding potential uranium deposits within the Soviet Union. The United States had already made progress in monopolizing the largest known and highest quality uranium reserves in the Belgian Congo. The USSR decided to mine uranium deposits in Czechoslovakia, which was now under its control. They eventually discovered new domestic deposits as well.

On August 29, 1949, the USSR tested its first fission bomb (dubbed "Joe-1" by the United States) at its test site in Kazakhstan, years ahead of predictions by American scientists. The news of the first Soviet detonation

Figure 5.3 Klaus Fuchs. (http://www.cfo.doe.gov/me70/manhattan/espionage.htm.)

was announced to the world by the United States, which had detected nuclear fallout from reconnaissance aircraft patrolling near the Arctic Circle. The U.S. response to the Soviet test was one of apprehension and alarm. In early 1950, President Truman announced the development of a crash program to develop a nuclear **fusion** device—a **hydrogen bomb** or **thermonuclear bomb**—a far more powerful weapon than those dropped on Japan during the war. At this point, however, the mechanisms and design of a nuclear fusion weapon were unknown. It was agreed, however, that the goal of this project was to construct a device that would harness the same reactions as those that powered the Sun.

A number of scientists, including several who had developed the first atomic bombs for the Manhattan Project, were vehemently opposed to the concept of creating a weapon thousands of times more powerful. Technical issues were raised; for example, it seemed impossible to be able to generate sufficiently high temperatures to support a nuclear fusion reaction. Scientists also presented moral objections: such a powerful weapon could not be used solely on military targets; large civilian populations would inevitably be annihilated. This weapon therefore seemed to serve only as a weapon of genocide.

The first fusion bomb, code-named "Mike," was tested by the United States in *Operation Ivy* on November 1, 1952, at Eniwetok Atoll of the Marshall Islands (Figure 5.4). The device was very large, standing more than 20 feet tall and weighing more than 60 tons. The detonation yielded 10.4 megatons (Mt) of energy, almost 500 times the power of the bomb dropped onto Nagasaki—obliterating the atoll and leaving an underwater crater 6200 feet wide and 160 feet deep. On January 7, 1953, President Truman announced the development of the hydrogen bomb to the world.

The Soviet Union detonated its first thermonuclear device, designed by physicist Andrei Sakharov, on August 12, 1953. The Soviet device was cause of great concern within U.S. government and military agencies because, unlike "Mike," the Soviet device was a deliverable weapon, which the United States did not yet have. Although its yield was not in the megaton range, it was nonetheless a powerful propaganda tool for the Soviet Union. On February 28, 1954, the United States detonated its first deliverable thermonuclear weapon during the *Castle Bravo* test at Bikini Atoll in the Marshall Islands. The yield of the device was 15 Mt, over twice its expected energy. This detonation also became the worst radiological disaster in U.S. history. The exceptionally large blast combined with poor weather conditions caused a cloud of radioactive nuclear fallout to contaminate more than 7000 square miles, including Marshall Island natives and the crew of a Japanese fishing boat.

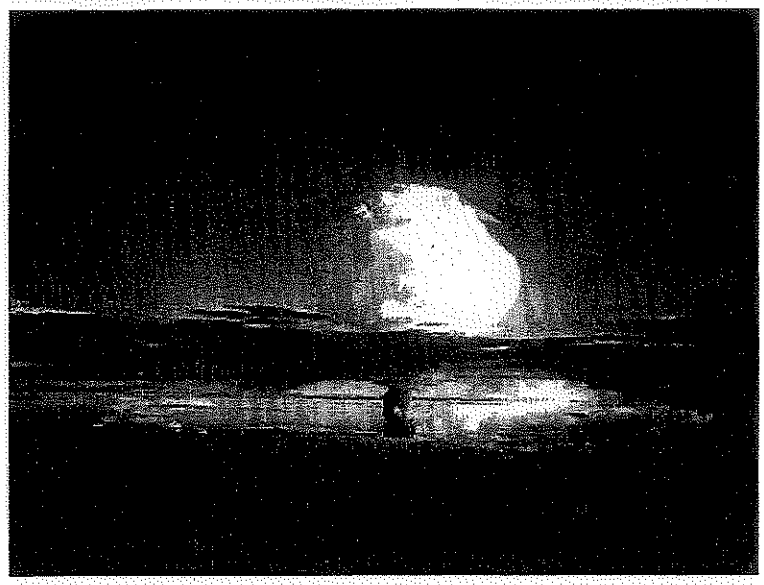

Figure 5.4 The "Mike" test in 1952 ushered in the age of fusion weapons. (http://www.cfo.doe.gov/me70/manhattan/images/IvyMikeWhiteLarge.jpg.)

As the Cold War intensified during the 1950s a program of nuclear testing was undertaken to improve the U.S. nuclear arsenal. The Nevada Test Site, located 90 miles north of Las Vegas in the Nevada desert, became the primary location for all U.S. nuclear testing (Figure 5.5). In the USSR, the Semipalatinsk Test Site in Kazakhstan served as the primary nuclear test site (NTI, 2001). Tests by the United States were divided into two primary categories, that is, weapons-related (verifying the feasibility of a new weapon) and weapons effects (observing how weapons behaved under selected conditions).

Early during U.S. and Soviet nuclear programs most nuclear tests were conducted either above ground ("atmospheric tests") or under water. Concerns began to be raised about the safety of the tests, which were now known to release nuclear fallout to the atmosphere. Several prominent scientists and leaders called for an outright ban on nuclear testing. In 1958 the U.S., U.S.S.R., and the U.K. (which had recently become a nuclear state) declared a temporary testing moratorium for both political and public health reasons. In 1961 the Soviet Union renounced the moratorium and both the U.S.S.R. and the U.S. began testing their latest devices with greater urgency and frequency.

The Soviets tested the massive Tsar Bomba, the largest-ever nuclear weapon, in October 1961. The device was detonated in a reduced state

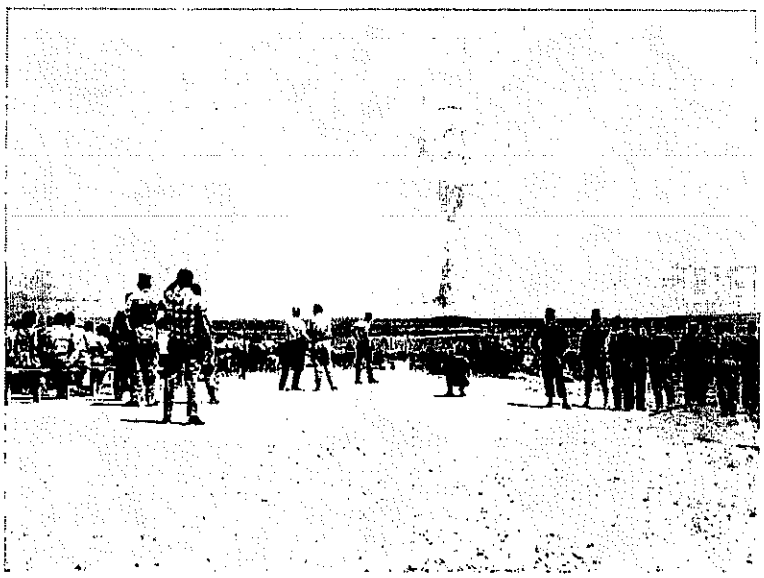

Figure 5.5 Hundreds of nuclear tests, both above- and below-ground, were conducted at the Nevada Test Site. (http://ndep.nv.gov/boff/atomic.jpg.)

with a yield of about 50 Mt; had the full detonation occurred it was estimated to have had a yield of approximately 100 Mt. There was nevertheless concern by the weapon's designers that the nuclear reaction might "run away" and cause damage on an even greater scale. The weapon was impractical for actual military use; however, it was hot enough to induce third-degree burns at a distance of 62 miles (100 km) away (Adamsky and Smirnov, 1994; *Time Magazine*, 1961).

In 1963 all nuclear and many nonnuclear states signed the Limited Test Ban Treaty, pledging to refrain from testing nuclear weapons in the atmosphere, under water, or in outer space. The treaty permitted underground tests, however. Most tests were devoted to increasing the efficiency and power of detonations or to reducing the size of the weapons so that they could be more easily transported. This latter modification prompted the installation of nuclear warheads into missiles. The first nuclear-tipped rockets such as the MGR-1 Honest John, first deployed by the United States in 1953, were surface-to-surface missiles with relatively short ranges (about 15 miles) with yields about twice that of the Hiroshima-era weapons. The limited range of these weapons meant that they could only be used for tactical purposes (i.e., in small-scale military situations) (Figures 5.6 and 5.7).

Figure 5.6 Honest John nuclear-tipped rocket. (http://www.redstone.army.mil/history/archives/missiles/honest_john_02.jpg.)

Figure 5.7 The Davy Crockett was the smallest and lightest nuclear weapon ever deployed by the U.S. military. It was designed for use in Europe against Soviet troop formations. (http://en.wikipedia.org/wiki/File:DavyCrockettBomb.jpg.)

For strategic weapons (i.e., those which would serve to threaten an entire country), long-range bombers were the only vehicles initially capable of penetrating deep into enemy territory. In the United States the Strategic Air Command (SAC) was created in 1946, a system of bombers directed by General Curtis LeMay. The SAC kept a number of nuclear-armed planes in the sky at all times, ready to attack Moscow upon command from Washington DC (Figure 5.8). By the 1960s both the U.S. and the USSR developed intercontinental ballistic missiles (ICBMs), which could be launched thousands of miles from their target (Figure 5.9). In addition, submarine-launched ballistic missiles had a shorter range but could be launched very close to the target without any radar warning.

By the 1950s and 1960s other nations became members of the "nuclear club" In 1952, British Prime Minister Winston Churchill announced that the United Kingdom had an atomic bomb; a successful test took place in October of that year. Early U.K. weapons were free-fall bombs, soon followed by missiles, for example, "Blue Steel," and later by submarine-based ballistic missiles. In the 1950s a French civil nuclear research program began, which eventually generated plutonium as a by-product but also as a potential nuclear fuel. A successful nuclear test, called *"Gerboise bleue"* (blue jerboa) took place on February 13, 1960, in the French Sahara. On October 16, 1964, China's first atomic bomb was successfully tested at Lop Nur. A hydrogen bomb became operational less than 3 years later, in

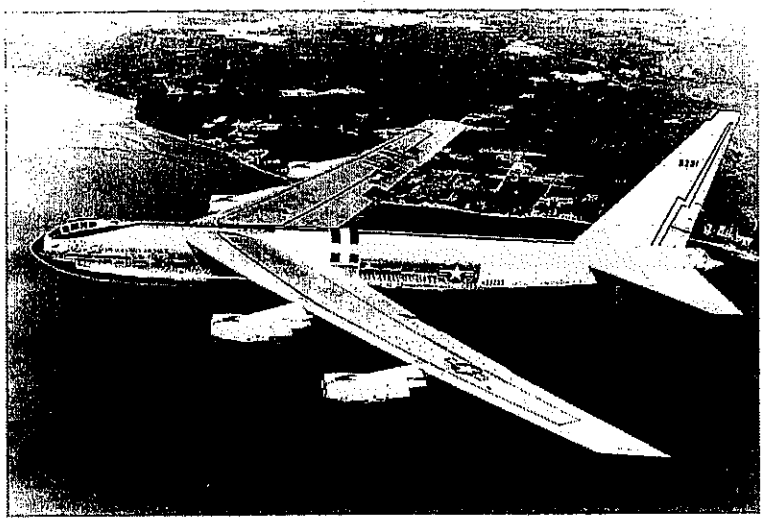

Figure 5.8 Long-range bomber aircraft, such as the B-52 Stratofortress, allowed for a wide range of strategic nuclear forces to be deployed. (http://en.wikipedia.org/wiki/File:YB-52sideview.jpg.)

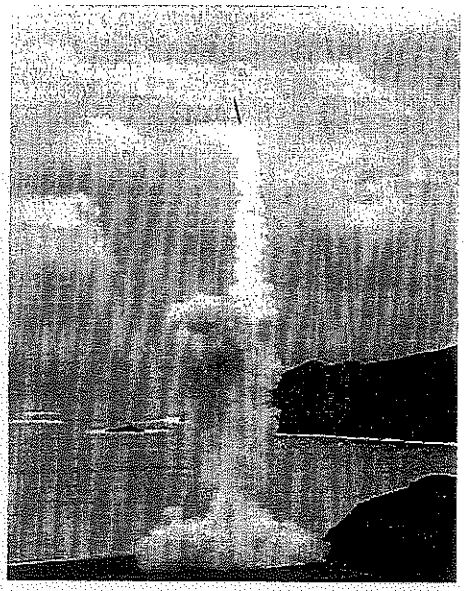

Figure 5.9 Intercontinental ballistic missile, the Minuteman-III. (http://en.wikipedia.org/wiki/File:YB-52sideview.jpg.)

June 1967. It is believed that Chinese warheads had been improved and miniaturized using designs obtained by espionage from the United States. The current number of Chinese nuclear weapons is unknown; however, it is thought that up to 2000 warheads may have been produced.

On January 27, 1967, more than 60 nations signed the Outer Space Treaty, banning the use of nuclear weapons in space. Twenty-five years later, in a dramatic move after the end of the Cold War, Russian President Boris Yeltsin announced in 1992 that Russia would stop targeting U.S. cities with nuclear weapons. All former Soviet bloc nations housing nuclear weapons including Ukraine, Belarus and Kazakhstan, returned their warheads to Russia by 1996.

Nuclear proliferation among lesser powers began with the end of the Cold War (Bracken, 2003). In 1974, India tested its first atomic weapon, named "Smiling Buddha," which it described as a "peaceful nuclear explosion." India tested fission and perhaps fusion devices in 1998. Its neighbor Pakistan successfully tested fission devices also in 1974, raising concerns of a nuclear conflict between the two hostile nations. South Africa had an active program to develop nuclear weapons; however, the effort was scrapped in the 1990s. There is no firm evidence of a nuclear test on South African soil, though it later claimed to have constructed several crude devices which it eventually dismantled. Israel has never officially

confirmed or denied the presence of a nuclear program; however, Israel is believed to possess an arsenal of possibly up to several hundred nuclear warheads.

Terrorist Use of Nuclear/Radiological Materials

Terrorist activities are more of a possibility with radiological dispersal devices (RDDs) ("dirty bombs"), rather than nuclear weapons. Since the September 11, 2001, terror attacks, concerns of terrorist groups using dirty bombs have increased markedly. Two cases of cesium-containing dirty bombs (neither of which were detonated) have been reported. The first attempt was carried out in November 1995 by a group of Chechen separatists who concealed a cesium-137 source wrapped in explosives at Izmaylovsky Park in Moscow. Chechen rebel leader Shamil Basayev alerted the media and the bomb was removed by security forces.

In December 1998 a second attempt at radiological terror was announced by the Russian-backed Chechen Security Service, who discovered a container filled with radioactive materials attached to an explosive mine. The Security Service safely defused the bomb. The location of the discovery—in a suburban area 10 miles east of the Chechen capital of Grozny, where a Chechen rebel group is known to operate an explosives workshop—led nuclear specialists to suspect Chechen rebels' involvement in the incident. Shamil Basayev, the rebel leader who phoned in the dirty-bomb threat in Moscow 3 years earlier, had been closely associated with the explosives workshop (NOVA, 2003).

On October 14, 2001, Israel is reported to have arrested a man linked to al-Qaeda who was trying to enter the country from the West Bank city of Ramallah with a radiological bomb hidden in his backpack (Huessy, 2007).

In November 2002, the Director of Russia's nuclear regulatory agency, Yuri Vishnyevsky, announced that small amounts—"a few grams here and there"—of weapons-grade and reactor-grade uranium was missing from his country's atomic facilities. Vishnyevsky did not provide details on when and how the materials disappeared. A few grams of weapons-grade uranium would not be sufficient to construct an effective nuclear device; however, it could constitute adequate material for a dirty bomb. Moreover, small amounts of reactor-grade uranium can be enriched to weapons-grade (NOVA, 2003).

In January 2004, Pakistani nuclear scientist Abdul Qadeer Khan confessed to his participation in illicit trafficking of nuclear materials,

BOX 5.1 U.N. RESOLUTION 1718

United Nations Security Council Resolution 1718 was adopted unanimously by the U.N. Security Council on October 14, 2006. The resolution imposes a number of economic and commercial sanctions on North Korea (the Democratic People's Republic of Korea) in the aftermath of their nuclear test of October 9, 2006.

information, and equipment from Pakistan to Libya, Iran, and the Democratic People's Republic of Korea (North Korea). In 2003 North Korea announced that it had constructed several nuclear devices. The first detonation of a nuclear weapon by North Korea took place in 2006, resulting in the adoption of U.N. Resolution 1718 (Box 5.1). In mid-2009 North Korea continued nuclear testing, in violation of Resolution 1718.

In Iran on August 9, 2005, Ayatollah Ali Khamenei issued a fatwa forbidding the production, stockpiling, and use of nuclear weapons. The full text of the fatwa was released in an official statement at the meeting of the International Atomic Energy Agency (IAEA) in Vienna (Mathaba.net, 2005). Despite this, however, there is mounting concern in many nations about Iran's refusal to halt its domestic nuclear energy program, which many fear is an attempt to obscure weapons development activities.

PROPERTIES OF THE ATOM

The tremendous power of nuclear weapons originates from reactions occurring within atomic nuclei. In nuclear reactions matter is converted to energy. The amount of energy generated is many orders of magnitude greater than that available from any chemical reaction.

Elements and Atomic Structure

A total of 92 elements are known to occur naturally; hydrogen (H) is the lightest (having 1 proton) and uranium (U) the heaviest, with 92. There are also at least 25 artificially created elements, termed **transuranic** (i.e., "beyond uranium") elements, used in research and industry. These elements make up all matter on earth.

The **atom** is the simplest structural unit of any element that can exist, while still retaining the unique chemical and physical characteristics of the element. An atom is composed of a central nucleus containing most of its mass, with **electrons** orbiting in shells around the nucleus. The nucleus consists of two fundamental particles, **protons** and **neutrons** (Figure 5.10). The proton is a particle that possesses a positive charge. The neutron is an uncharged particle with mass similar to that of the proton. Electrons are negatively charged particles of extremely low mass.

Isotopes

Atoms of different elements possess unique numbers of protons in their nuclei. The term **atomic number** describes the number of protons in a nucleus. A single element may contain varying numbers of neutrons in its nucleus, however. The total number of protons plus neutrons in a nucleus is termed **atomic mass**. When atoms have the same number of protons but different numbers of neutrons, they are still the same element, but are termed isotopes (Table 5.1). Some isotopes are known to be quite unstable. This instability is termed radioactivity, which is truly the cornerstone of our discussion of nuclear science (and nuclear weapons).

If we refer to the Periodic Table of the Elements, the element with atomic number 92 is uranium, chemical symbol U. The atomic mass

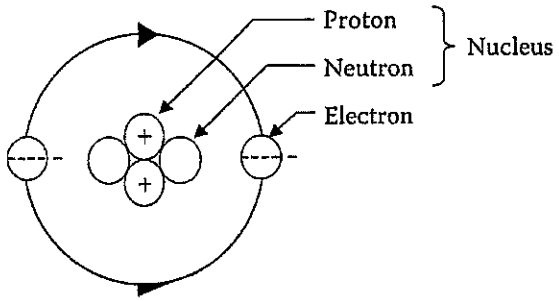

Figure 5.10 Generic structure of an atom.

Table 5.1 Selected Isotopes of Uranium

Isotope	Abundance (%)	Protons	Neutrons	Electrons
Uranium-238	99.3	92	146	92
Uranium-235	0.7	92	143	92

number 235 identifies a uranium isotope having 92 protons and 143 neutrons (235–92 = 143) in its nucleus. To identify the individual isotopes of a given element, the following notation is used:

$$^{A}_{Z}X$$

Where:

X = chemical symbol of the element
Z = atomic number (number of protons)
A = atomic mass number (protons + neutrons).

An example of the standard notation would be

$$^{235}_{92}U$$

The atomic number is often deleted and an isotope will then be represented by its mass number and chemical symbol, for example, ^{235}U.

RADIOACTIVITY

The nuclei of certain naturally occurring isotopes, and of others produced artificially, contain excess energy, that is, they are unstable. To attain stability, those energetic nuclei emit that energy in the form of nuclear radiation. Isotopes that emit ionizing radiation from their nuclei to achieve stability are termed **radioactive**. Radioactive isotopes are also referred to as **radioisotopes** or **radionuclides**. Each radioisotope has its own unique radioactive **decay scheme**. A decay scheme identifies the types of ionizing radiation emitted, the range of energies of the radiation emitted, and the half-life of the decaying radioisotope (Figure 5.11).

The **half-life** of a radioisotope is the time required for half the atoms of a sample to decay to nonradioactive forms. Half-life values range from fractions of a second to thousands of years, depending on the isotope. The concept of half-life is extremely important in discussions of soil, structures, and debris contaminated by radiation, and **radioactive fallout**. Radioactive decay can be plotted in linear or semilogarithmic form (Figure 5.12). These line forms are used to determine, by simple inspection, an isotope's activity at a specific time.

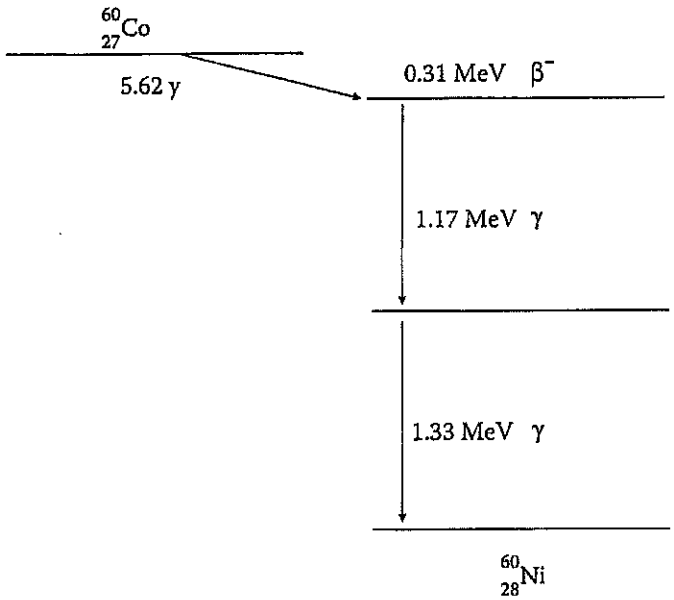

Figure 5.11 Radioactive decay scheme for ^{60}Co. Note that, after several stages of decay, cobalt has been converted to nickel.

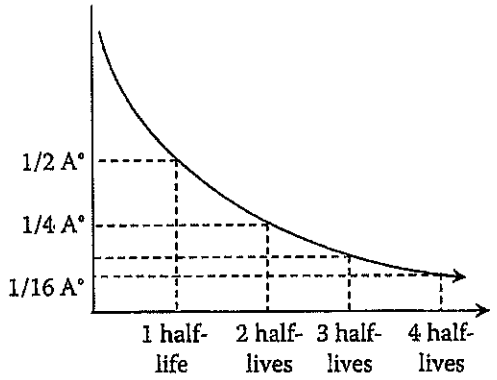

Figure 5.12 Plot of radioactive decay of an isotope.

IONIZATION: WHEN RADIATION INTERACTS WITH MATTER

Why is radiation such a significant hazard to the human body and all biota? It is well established that ionizing radiation greatly increases the risk of certain forms of cancer. There are conflicting reports regarding the potential for radiation to increase the risk of birth defects, however. Let's

look at the root cause of the concern to emergency responders, health-care officials, and the public as regards radiation.

Ionizing radiation results in the deposition of energy in living tissue. Radioactive particles or waves (alpha, beta, gamma radiation, and neutrons, discussed below) all possess significant energy. The transfer of energy to the atoms of a recipient material (in this discussion, human tissue) may occur by several mechanisms (U.S. Army, Navy, Air Force, 1996):

Excitation. This process involves the addition of energy to an atom, thereby elevating it from its stable state (**ground state**) to an excited state. Excitation occurs when relatively small amounts of energy are transferred. Depending upon the type of interaction, either the nucleus of the atom or one of its electrons will absorb the excitation energy. The excited atom or electron will not retain this higher energy but tends to return to its original energy level either by transferring the excess energy to other atoms or by emitting it as electromagnetic radiation, often in the form of x-rays.

Ionization. Ionization will occur if incoming radiation transfers sufficient energy to dislodge one or more electrons from the outer orbitals of the recipient atom. Ionization thus creates an ion pair consisting of a free electron and a **cation**, that is, the positively charged remainder of the atom (Figure 5.13).

The ionization process is especially significant in DNA, the genetic repository that codes for structure, physiology, and behavior of an organism. It is accepted that random mutation of DNA is a natural process (and is, in fact, the basis for natural selection and evolution); however, when living tissue is bombarded with radioactive particles or waves, the incidence of DNA mutation is greatly increased. DNA chains have a significantly greater chance of fragmenting and recombining, resulting in the coding

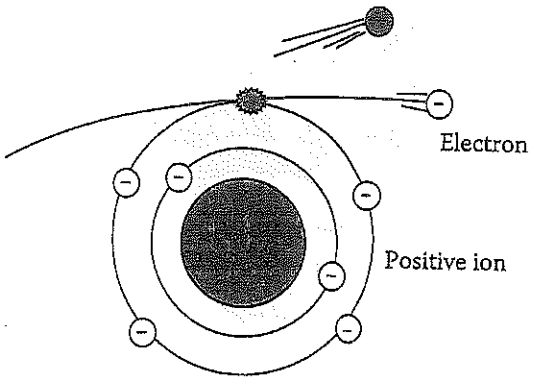

Figure 5.13 Ionization of an atom resulting from bombardment by radiation.

of new, undesirable and possibly detrimental changes in the affected organism (e.g., development of **carcinomas**).

FORMS OF RADIATION

There are four types of ionizing radiation that can be emitted from radioactive elements. All are potentially hazardous to organisms and include the following:

- Alpha particles
- Beta particles
- Gamma/x-rays
- Neutrons

Alpha Radiation

When large, unstable nuclides such as uranium or radium decay, they may emit several forms of radiation. One common form is a particle composed of two protons and two neutrons, essentially the nucleus of a helium atom minus its planetary electrons (Figure 5.14). This form is termed **alpha** radiation. Alpha radiation is relatively heavy, of relatively low energy, and carries a net positive charge.

Alpha travels only a few centimeters in air and has little penetrating power. Most alpha radiation is stopped by one to two inches of air or a sheet of paper or cloth. Alpha cannot even penetrate the outer layer of dead skin on the body. For this reason alpha is considered an **internal**

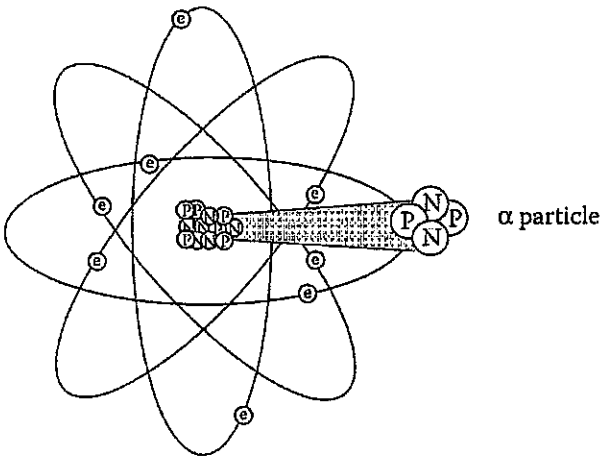

Figure 5.14 Alpha radiation.

hazard only, that is, it must enter the body to cause biological damage. For example, if radon gas (an alpha emitter) is inhaled, the alpha particles can reach the live cells deep in the lungs and deposit large amounts of energy in a small volume of unprotected tissue. Radon gas is therefore known to increase the risk of lung cancer.

Sources of alpha radiation include the following:

- Uranium (nuclear power plant fuel and nuclear weapons)
- Plutonium (nuclear weapons)
- Americium (smoke detectors)
- Thorium (tungsten welding rods, coatings on large lenses of telescopes)

Beta Radiation

Beta radiation is essentially an electron minus an electrical charge, ejected from the nucleus at high energy (Figure 5.15). Given its small size, beta particles have extremely low mass. At high exposures beta-emitting radionuclides can cause injury to the skin and surface body tissues. Otherwise they present mostly an internal hazard. Ionization of matter occurs due to the beta particle scattering electrons from recipient atoms.

Beta radiation has a limited penetrating ability; its range in air is about 10 feet. Most beta radiation can be shielded by about 1/4 inch of plastic sheeting, aluminum foil, thick clothing, or safety glasses. Externally, beta radiation is potentially hazardous to the skin and eyes. Beta particles cannot penetrate through all skin layers to damage the internal organs, however. Beta radiation becomes an internal hazard if the beta emitter is

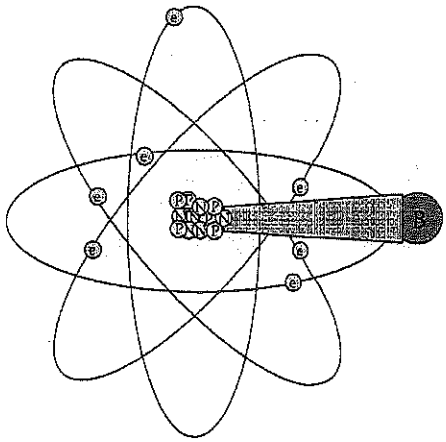

Figure 5.15 Beta radiation.

ingested or inhaled; in such cases the source of the beta radiation must be in proximity to body tissues and can deposit energy over a small area.

Beta particles are emitted from the following:

- Used nuclear reactor fuel and nuclear weapons fallout (e.g., as strontium-90)
- Some industrial radioactive sources such as cesium
- Tritium in glow-in-the-dark EXIT signs, watch dials, night-sights on firearms
- Radioactive nickel in chemical agent detectors

Gamma Radiation/X-Rays

Gamma rays and x-radiation have no mass and no charge; they are composed of electromagnetic energy, not matter. Gamma radiation is illustrated in Figure 5.16.

Because gamma and x-ray radiation have no charge and no mass, they have very high penetrating power. Gamma rays travel great distances in air (thousands of yards to miles) at the speed of light. They are considered a whole body hazard (internal and external). Gamma radiation can be extremely destructive to living tissue via ionization. A single gamma ray may ionize many thousands of atoms along its path of travel. The more electrons it removes (ionizes), the less energy remains. Eventually the gamma radiation gives up the last of its energy and disappears.

Gamma radiation and x-rays must be shielded by very dense materials such as concrete (6 inches or more), lead (1 inch or more), water

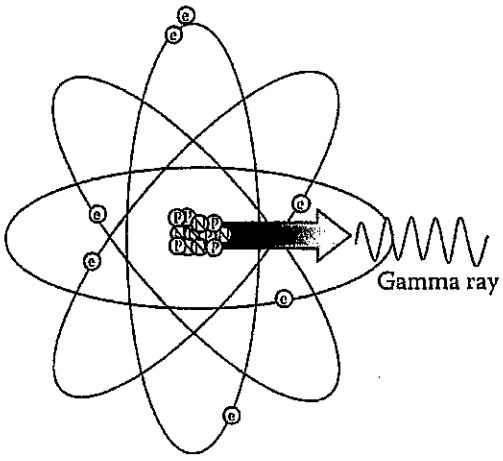

Figure 5.16 Gamma/x-ray radiation.

(1 foot or more), soil (1 foot or more), or thick steel (several inches). The thicker the shielding, the greater the success in blocking the radiation.

Sources of gamma radiation include the following:

- Uranium, plutonium, radioactive cobalt and cesium
- Industrial radiation sources
- Medical sources and cancer treatment machines

Many beta emitters are also known to emit gamma radiation.

Neutron Radiation

As mentioned earlier, neutrons are one of the fundamental subatomic particles occurring within an atom's nucleus. A neutron has mass, but no electrical charge. Emission of a neutron particle is illustrated in Figure 5.17.

Ionization of matter occurs as the result of collisions between neutrons and nuclei of target atoms. The neutrons continue on, smashing into other atoms until they dissipate all of their energy. Neutron radiation has a high penetrating ability—they are difficult to shield and stop. The range for neutrons in air is very far—up to several miles. It follows that neutron radiation is a whole body hazard (internal and external)—it easily penetrates body tissues and is quite destructive to tissue.

Neutron radiation is best shielded by materials with high hydrogen content such as water or thick plastic (6–10 inches or more). In addition, thick concrete (1 foot or more), water (several feet), and soil (several feet) are very effective for neutron shielding.

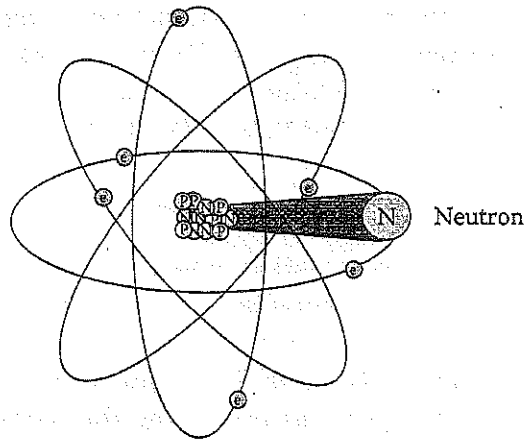

Figure 5.17 Neutron radiation.

Sources of neutrons include the following:

- Nuclear fuels within a nuclear reactor
- The pulse of radiation from an exploding nuclear weapon (discussed below)
- Plutonium, californium, and americium

MEASUREMENT OF RADIATION

Measurement of radiation emitted from a source is critical for safety and correct response actions; likewise, the amount of radiation absorbed by victims will give an indication of possible degree of harm. Units of radiation will vary as a function of whether it is being emitted or being absorbed.

Most scientists in the international community measure radiation using the System Internationale (SI), a protocol that evolved from the metric system. In the United States, however, the conventional system of measurement is still widely used.

Measuring Emitted Radiation

The amount of radiation being emitted by a radioactive source is measured using the **curie** (Ci), named for Marie Curie, or the SI unit **becquerel** (Bq). The Ci or Bq express the number of disintegrations of radioactive atoms over a period of time. For example, one Bq is equal to one disintegration per second. One Ci is equal to 37 billion (37×10^9) disintegrations per second; therefore, one Ci is equal to 37 billion (37×10^9) Bq. These units may be used to refer to the amount of radioactive materials released into the biosphere. For example, during the Chernobyl nuclear accident that took place in the former Soviet Union in 1986, an estimated 81 million Ci of radioactive cesium was released (U.S. CDC, 2003).

Measuring Radiation Dose

When a human is exposed to radiation, energy is deposited in the body's tissues. The amount of energy deposited per unit weight of human tissue is termed the absorbed dose. Absorbed dose is measured using the conventional **rad** or the SI unit gray (**Gy**). One Gy is equal to 100 rad. The biological risk of exposure to radiation is measured using the conventional unit **rem** or the SI unit **sievert** (Sv). The amount of rems received from exposure to a radioactive source can be correlated with possible harm (Table 5.2).

Table 5.2 Estimated Effects on Human Health as a Function of Radiation Dose

Dose (rem)	Effects
5–20	Possible latent effects (cancer), possible chromosomal aberrations
25–100	Changes in blood chemistry
More than 50	Fatigue; temporary sterility in males
100	Hemorrhage; double the normal incidents of genetic defects
100–200	Vomiting, diarrhea, reduction in infection resistance, possible bone growth retardation in children
200–300	Serious radiation sickness, nausea
More than 300	Permanent sterility in females
300–400	Bone marrow and intestine destruction; possible death
400–1000	Acute illness and early death (usually within days)
2000	Damage to central nervous system, loss of consciousness, death in minutes to days

Source: U.S. Environmental Protection Agency. 2010. Radiation protection. Health effects. http://www.epa.gov/rpdweb00/understand/health_effects. html; U.S. Nuclear Regulatory Commission. 2010. Fact sheet on biological effects of radiation. http://www.nrc.gov/reading-rm/doc-collections/fact-sheets/bio-effects-radiation.html.

NUCLEAR REACTIONS

Fission

The fission process, whether in a commercial nuclear power plant or a nuclear weapon, relies on the inherent instability of certain naturally occurring and artificially produced elements. The nuclei of some heavy isotopes, in particular uranium-235 (^{235}U) and plutonium-239 (^{239}Pu), can split when they are bombarded by outside neutrons. This splitting is termed nuclear fission.

As illustrated in Figure 5.18, a free neutron smashes into the nucleus of a fissionable atom, resulting in splitting of the unstable nucleus. This results in the production of two or more fission products, more free neutrons, and a tremendous amount of energy in the form of heat and light.

When nuclear materials are tightly packed such as in nuclear reactors and nuclear weapons, such a process will cascade, resulting in a virtual avalanche of neutrons being released which go on to split more and more nuclei. Each generation of neutrons released can generate a tremendous number of fissions. This phenomenon is the so-called **nuclear chain**

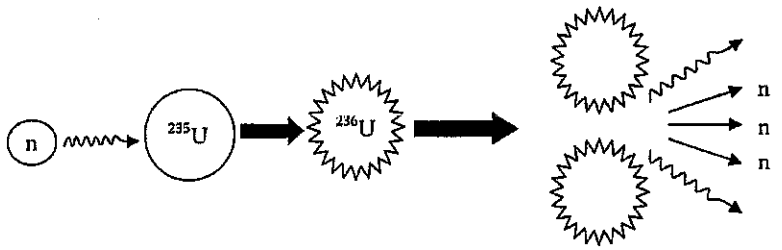

Figure 5.18 Nuclear fission of U-235 showing generation of daughter nuclei and additional neutrons.

reaction, or self-sustaining reaction. Ultimately, the energy recovered from such a process may be extremely large.

In theory, a single neutron could initiate a chain reaction of nuclear fissions that could result in the splitting of each fissionable atom in a fuel mass. In reality, however, not all the neutrons produce more fission reactions. Many escape from the fissionable mass; others may be removed by nonfission reactions. Both these effects were significant practical problems affecting the development of the first atomic bombs.

In commercial nuclear reactors the fission chain reaction takes place slowly and in a controlled manner. The resulting energy can, therefore, be used to generate electricity. In contrast, in a nuclear detonation, the chain reaction occurs at an extremely rapid and uncontrolled rate.

Isotopes capable of fission are termed **fissionable isotopes**. The most common fissionable isotope is uranium-238 (^{238}U). Large quantities of U-238 exist in nature; however, U-238 does not readily undergo fission and therefore cannot be used in a nuclear detonation. Some isotopes such as uranium-235 (^{235}U) or plutonium-239 (^{239}Pu) undergo fission relatively easily and are termed **fissile isotopes**. Because of this capability, fissile isotopes are valuable for generating energy in nuclear reactors. This fissile capability is also important to cause a nuclear detonation.

Fissile isotopes are extremely rare in nature. Natural uranium consists of 99% U-238 but less than 0.7% U-235 (see Table 5.1). Plutonium-239 does not occur naturally. Highly complex industrial processes are needed to isolate and concentrate sufficient quantities of U-235 and to generate Pu-239; these activities are considered to be beyond the capabilities of terrorist organizations. To initiate a chain reaction, sustain the reaction sufficiently long to build up the explosive energy, and confine the released energy for as long as possible to maximize the weapon's explosive effect, requires that a variety of important requirements be fulfilled (U.S. Army, Navy, Air Force, 1996). Some are discussed below.

Critical Mass

The first requirement for generating a fission detonation is that sufficient fuel material be present and in the proper configuration so that successive generations of neutrons can cause greater numbers of fission reactions. The quantity of fuel capable of sustaining a chain reaction is termed a **critical mass.** A tremendous number of fissions is required for the release of such catastrophic amounts of energy as occurs in a nuclear detonation. One of three types of chain reactions may occur for a given mass of fissionable fuel (U.S. Army, Navy, Air Force, 1996):

- *Subcritical chain reaction.* A reaction in which the number of neutrons decreases in succeeding generations, thus not sustaining itself.
- *Critical chain reaction.* A reaction in which the number of neutrons remains constant in succeeding generations.
- *Supercritical chain reaction.* A reaction in which the number of neutrons increases in succeeding generations.

To initiate a nuclear detonation, a weapon must be equipped with an amount of uranium or plutonium that exceeds the mass necessary to support a chain reaction, that is, a **supercritical mass** of fissionable material. Several methods can be used to make a mass of fissionable material supercritical (Rhodes, 1996; U.S. Army, Navy, Air Force, 1996):

- The material is purified to eliminate unwanted impurities that might absorb neutrons and attenuate the chain reaction.
- Fissionable material is enriched, that is, the amount of ^{235}U compared to ^{238}U is increased.
- The material is machined into the most efficient shape. A spherical shape provides the greatest volume with the least surface area, thereby reducing the probability of neutron loss.
- Moderators are used to slow down fission neutrons, increasing the probability of their producing fissions.
- Neutrons that escape the fissile fuel are reflected back into the mass using suitable reflector materials. Reflectors can also physically delay the expansion of the exploding material, allowing more fission to occur, thereby resulting in increased explosive energy.

When constructing a nuclear weapon it is essential to keep fuel materials below critical mass; otherwise, the critical or supercritical mass may melt or possibly explode. Before detonation, therefore, the fuel must be separated into several pieces of fissionable material, all below critical

mass. At the time of detonation, the mass is made supercritical by changing its shape or configuration (see below).

Fusion

Under extreme heat and pressure the nuclei of two isotopes of hydrogen (deuterium and tritium) can fuse together to form a single atom of helium. This process is known as nuclear fusion. For the fusion process to occur, the two nuclei must be forced together by enough energy so that the strong, attractive, short-range nuclear forces overcome the electrostatic forces of repulsion (U.S. Army, Navy, Air Force, 1996). Nuclear fusion occurs in the Sun and is responsible for producing light, heat, and other energy forms.

The two conditions required for fusion are (1) extremely high temperatures (to accelerate the nuclei) and (2) high pressure density (to increase the probability of interaction). For the development of a weapon, the only practical means to attain the required temperatures and pressures is by means of a fission detonation. Consequently, fusion weapons must contain a fission component. The energy released in the detonation of a fission-fusion weapon originates from approximately equal amounts from fission and fusion processes (U.S. Army, Navy, Air Force, 1996).

Nuclear fusion has been applied to nuclear weapons, but methods for using fusion to produce energy in commercial reactors (e.g., to generate electricity) have not yet been feasible.

NUCLEAR WEAPON DESIGNS

Nuclear weapons are explosive devices that rapidly release the energy generated from the fission or fusion of atomic nuclei. Nuclear devices are thousands of times more powerful than any known chemical explosive. The explosive power, or **yield**, of nuclear weapons is typically expressed in terms of the quantity of TNT that would release an equivalent amount of energy, often measured in thousands of tons of TNT (kilotons, kt). For the most powerful weapons, however, yield is measured in millions of tons of TNT (megatons, Mt). The first of the fission bombs (July and August, 1945) had yields in the range of 10–20 kt. Substantially greater yields have since been designed for fission weapons.

Fission weapons are designed to rapidly assemble a supercritical mass of fissile material to create an uncontrolled fission chain reaction.

The energy of this reaction is released within a fraction of a second, resulting in a powerful detonation. Fission weapons are the only type of nuclear weapon ever used in wartime. Since August, 1945, no nuclear weapon of any type has been used in combat.

There is concern that terrorist organizations could build fission weapons if they could acquire sufficient fissile material (either **highly enriched uranium, (HEU)** or plutonium). Terrorists could also obtain fission weapons from nations storing them in their nuclear arsenals. The most difficult challenge for a terrorist organization attempting to construct an **improvised nuclear device (IND)** is obtaining the fissile material.

Highly enriched uranium has been processed to increase the proportion of the U-235 isotope to more than 20%, which is required for the construction of a **gun-type** nuclear device (see below). The greater the proportion of U-235 (i.e., the greater the degree of enrichment), the less material is needed for a nuclear detonation. **Weapons-grade** uranium refers to uranium enriched to at least 90%; however, material of far lower enrichment levels, found in both fresh and spent nuclear fuel, can be used to create a nuclear device (NTI, no date).

HEU Production

The process of generating HEU begins with mining natural uranium, a fairly widespread element in the Earth's crust. Uranium is mined primarily from sandstone ores in which the uranium occurs at concentrations of 0.03%–0.2% by weight, but it is also found in lower concentrations in shales and granites. Uranium-bearing rocks are extracted from underground mines or open pits. The ore is crushed and placed in an acid bath that leaches the uranium into solution. The dissolved metal is then extracted as uranium oxide, U_3O_8.

The uranium-235 isotope must then be separated from the more abundant U-238 form. The goal is to concentrate U-235 well above its value of 0.7% in natural uranium. In a chemical sense, different isotopes of uranium behave identically; therefore, most separation methods rely on physical rather than chemical means, based on the slight difference in mass between the U-235 and U-238 isotopes. The primary approaches to separation involve first converting the natural uranium to uranium hexafluoride gas (UF_6), followed by physical separation of the lighter $^{235}UF_6$ molecules from the slightly heavier $^{238}UF_6$ molecules.

The best-known technologies for accomplishing this separation are (NTI, no date)

- *Gaseous diffusion*, which takes advantage of the difference in diffusion rates of the lighter and heavier molecules through a cascade of thousands of porous barriers.
- *Centrifugation*, which uses thousands of sophisticated, ultra-high-speed, gas centrifuge instruments to separate the molecules based on their differing masses.

Plutonium Production

In a commercial or defense nuclear reactor, the nuclear fuel will never be pure U-235 and will contain substantial contamination by the U-238 isotope. This contamination is not necessarily detrimental to the overall process, as usable plutonium can be generated. Any nuclear reactor that contains U-238 in its fuel produces Pu-239 in the course of operation as a result of the absorption of some of the fission neutrons by this uranium isotope:

$$_{92}U^{238} + n \rightarrow {}_{92}U^{239} \rightarrow {}_{93}Np^{239} + {}_{-1}e^{0} \quad (5.1)$$

$$_{93}Np^{239} \rightarrow {}_{94}Pu^{239} + {}_{-1}e^{0} \quad (5.2)$$

Some of the newly produced Pu-239 undergoes fission in the course of the continuing chain reactions in the reactor, and some undergoes successive absorption of further neutrons to become the heavier plutonium isotopes Pu-240, Pu-241, and Pu-242.

Types of Nuclear Weapons

At the time of detonation, the nuclear fuel is made supercritical by changing its shape or configuration. Two general methods have been developed for rapidly converting a subcritical mass into a supercritical one.

Gun Type

The simplest type of nuclear weapon is the so-called gun type. Two pieces of fissionable material, each below critical mass, are rapidly brought together to form a single, supercritical unit. The gun-type assembly (Figure 5.19) is achieved in a tube in which a high explosive blasts a subcritical piece of fissionable material from one end into a second subcritical piece held at the opposite end. When the two masses collide, they form a supercritical mass that results in a nuclear detonation. Although the gun-type weapon

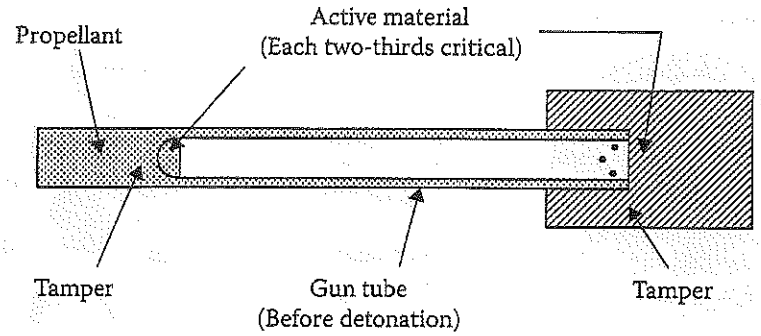

Figure 5.19 Gun-type nuclear weapon assembly.

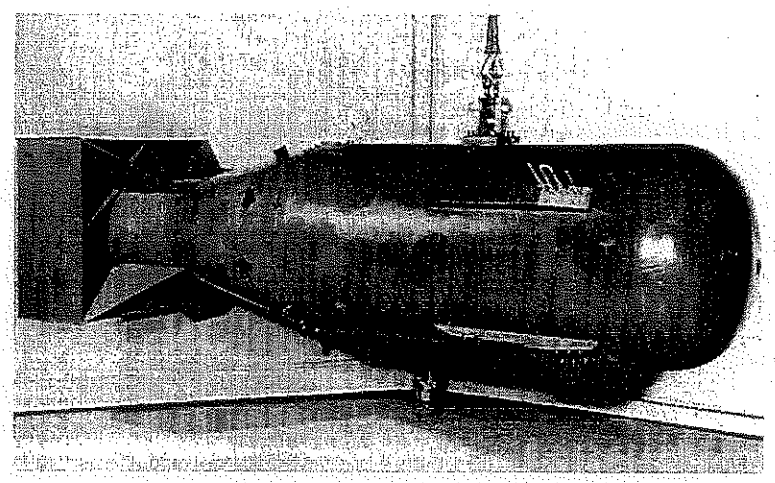

Figure 5.20 Little Boy gun-type nuclear weapon. (http://www.cfo.doe.gov/me70/manhattan/early_bomb_design.htm.)

is the simplest of the nuclear weapon types to design and construct, they typically require more fissile material than do other designs such as the implosion design (see below).

Depending upon the sophistication of the design, at least 25 to 50 kg (55 to 110 lbs) of HEU enriched to 90% U-235 is needed to build a gun-type nuclear device. The "Little Boy" bomb dropped on Hiroshima during World War II was a gun-type fission weapon containing 64 kg of 80% enriched uranium with an explosive yield of 14 kt (Figure 5.20).

Implosion Weapons

An implosion fission weapon is a significantly more sophisticated device compared with the gun-type design. In the implosion assembly method

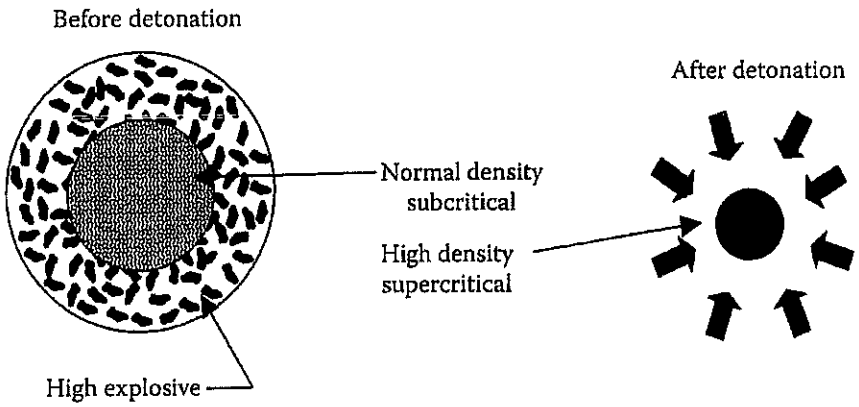

Figure 5.21 Implosion method for nuclear detonation.

(Figure 5.21) a subcritical mass of ^{235}U or ^{239}Pu is compressed to produce a supercritical mass.

Compression is achieved by the detonation of many specially positioned high explosives around a subcritical sphere of fissionable material. When the high explosive is detonated, implosion occurs. The imploding blast wave compresses the sphere of fissionable material, thus making the mass supercritical. Once compressed, the mass will undergo a rapid chain reaction.

The first nuclear weapon ever exploded, at the "Trinity" test near Alamogordo, New Mexico on July 16, 1945, was an implosion-type weapon. The "Fat Man" bomb used against Nagasaki in World War II was an implosion-type weapon, with an explosive yield of about 21 kt (Figure 5.22).

Implosion-type weapons are much more difficult to design and construct than are gun-type weapons; the explosive components and fusing systems are highly complex. Implosion-type weapons typically require much less fissile material than gun-type weapons. An implosion weapon requires only about 8 kg (18 lbs) of highly enriched uranium or 4 kg (9 lbs) of plutonium. This means that implosion weapons can be relatively small and lightweight.

Thermonuclear Weapons

Thermonuclear weapons derive their explosive yield from the combined power of nuclear fission and fusion. An initial fission reaction with plutonium fuel generates the extreme temperatures needed to trigger a secondary fusion reaction. The fission component relies upon implosion of the plutonium fuel. Radiation from the fission detonation heats and

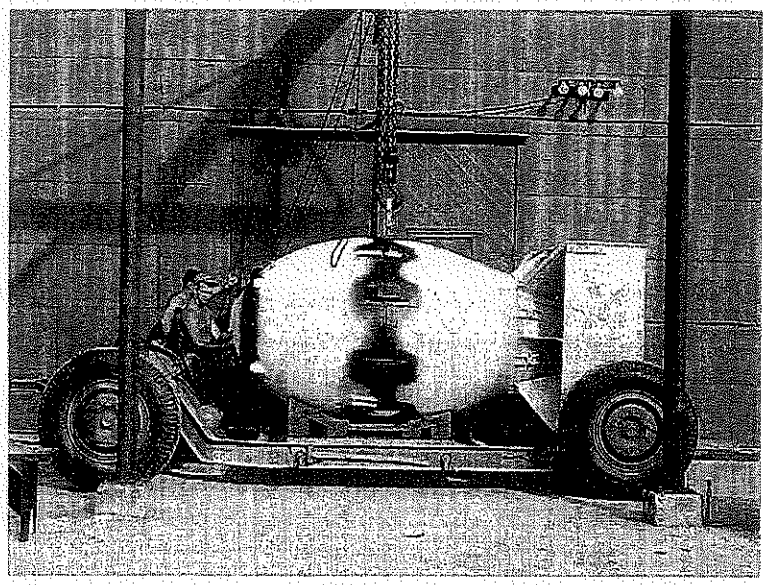

Figure 5.22 "Fat Man" nuclear device on transport carriage. (http://en.wikipedia.org/wiki/File:Fat_Man_Assembled_Tinian_1945.jpg.)

BOX 5.2 DEUTERIUM AND TRITIUM

Hydrogen (^{1}H) has an atomic mass of one, due to the presence of one proton and no neutrons in its nucleus. **Deuterium** (^{2}H), also called *heavy hydrogen*, is a stable isotope of hydrogen having one proton and one neutron (atomic mass = 2). **Tritium** (^{3}H) is another radioactive isotope of hydrogen with a nucleus containing one proton and two neutrons (atomic mass = 3).

compresses a separate core of deuterium and tritium, which undergoes fusion. In thermonuclear weapons, the key fusion reaction is known as the D-T reaction. Using the heat and pressure of fission, deuterium (^{2}H), fuses with tritium (^{3}H) (Box 5.2), to form helium-4 (^{4}He) plus one neutron (η) and energy (Glasstone and Dolan, 1977):

$$^2D + {}^3T \rightarrow {}^4He + \eta + 17.6\ MeV \qquad (5.3)$$

The fusion reaction generates additional explosive energy, but more importantly, releases more neutrons within the core. These neutrons will bombard more of the fissile material in the weapon, causing it to undergo

fission rather than being dispersed by the detonation. This boosting process significantly reduces the quantity of fissile material that might have been wasted.

Both deuterium and tritium occur naturally on earth; however, their concentrations are extremely small.

Thermonuclear weapons are significantly more difficult to design, build, and maintain than are fission weapons (Figure 5.23). Thermonuclear weapons can be extremely powerful, with yields measured in megatons.

Improvised Nuclear Devices

An IND is essentially a "home-made" weapon designed to cause a nuclear detonation. These devices may be fabricated in a completely improvised manner or may be a modification to a weapon already present in a national nuclear stockpile.

The destructive capability of an IND depends on the explosive yield of the weapon and location of the detonation. The possibility exists that an IND could generate a substantial yield, as might be expected for a tactical nuclear weapon; however, the more likely scenario would be a low-yield device of 5 kt or less that could be easily concealed and transported.

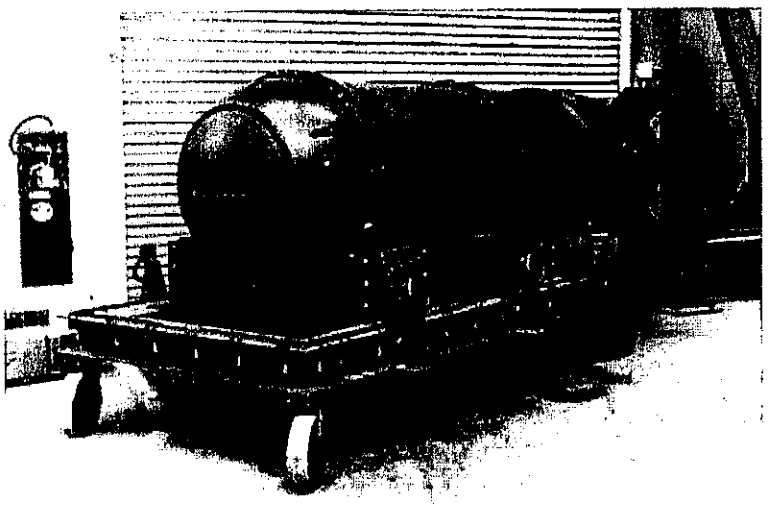

Figure 5.23 The Mk-15 thermonuclear device. (http://en.wikipedia.org/wiki/File:Mk15.jpg.)

In the case of detonation of a low-yield weapon, damage would be much greater than that of the largest high explosive devices deployed in truck bombs. Radiation released from the blast may injure large numbers of people who may exhibit no symptoms for hours. The spread of radioactive fallout will create panic among the general public. It is possible that substantial radiation exposure would affect first responders working at ground zero.

The potential for terrorist use INDs will be discussed in some detail later in this chapter.

EFFECTS OF NUCLEAR DETONATIONS

The energy released by a nuclear detonation will result in extensive damage to buildings, infrastructure, and humans and other biota. As noted above, nuclear detonations can potentially release millions of times more force than the largest conventional explosions (e.g., TNT).

Both nuclear weapons and conventional explosives rely on the destructive force of the blast or shock wave. However, the temperatures reached in a nuclear detonation are markedly higher than that in a conventional explosion, and a large proportion of the energy is released in the form of heat and light. Nuclear detonations are also accompanied by radiation, **fallout**, and **electromagnetic pulse** (EMP). Blast, thermal radiation, and **prompt ionizing radiation** occur within seconds or minutes of the detonation. Delayed effects, including radioactive fallout, inflict damage over hours to years. The relative distribution of these effects depends on the yield of the weapon, the location of the detonation, and the characteristics of the blast environment.

Yield

For a low-altitude atmospheric detonation of a 20 kt weapon, it is estimated that the energy is distributed approximately as follows:

- 50% as blast (overpressure and high winds).
- 35% as thermal radiation, composed of a wide range of the electromagnetic spectrum, including infrared, visible, and ultraviolet light, as well as **soft x-rays**.

- 15% as nuclear radiation, including 5% as initial ionizing radiation composed of neutrons and gamma rays emitted within the first minute after detonation, and 10% as residual nuclear radiation. Residual radiation is the hazard in fallout.

Blast

The major proportion (approximately 50%) of energy from a nuclear weapon detonated either on the Earth's surface or within the atmosphere is released in the form of blast and shock waves. At the instant of a nuclear detonation the heat from the fireball produces a high-pressure wave that moves outward. The front of the blast wave (**the shock front, shock wave**, or incident shock wave) is a moving wall of highly compressed air that travels rapidly away from the fireball, sharply increasing air pressure. The pressure can crush structures and create hurricane-force winds of hundreds of miles per hour. These winds in turn create pressure against objects facing the blast. When this shock wave comes into contact with a solid object, it will either move the object in the direction of the wave propagation or shatter it, depending upon the strength of the shock wave and the characteristics of the recipient object (Figure 5.24). The **overpressure** reaches its maximum value upon the arrival of the shock wave (see Box 5.3). It

Figure 5.24 Effects of a blast wave on a typical wood frame house. (http://www.nv.doe.gov/library/photos/upshot.aspx.)

BOX 5.3 OVERPRESSURE

When a detonation occurs, a shock wave is generated by the rapidly expanding air heated by reaction, whether nuclear or chemical. The term overpressure refers to the increase in atmospheric pressure as a result of the detonation. Blast effects are usually measured by amount of overpressure, that is, the pressure in excess of the normal atmospheric value, in pascals (Pa) (metric system) or pounds per square inch (psi) (English system).

Different influences at the time of the incident (e.g., surface versus air burst, urban area versus open area) make it difficult to accurately predict the magnitude of damage produced by different blast intensities. A general guide is given in Table 5.3.

Shock waves from a nuclear detonation occurring on or below-ground can destroy buildings in a manner similar to that of an earthquake (U.S. Army, Navy, Air Force, 1996). Urban, built-up areas are completely destroyed by overpressures of 5 psi, with heavy damage extending out to at least the 3 psi contour. Overpressures of 2 psi will seriously damage frame and composite houses. The blast from a nuclear weapon equivalent in yield to that dropped on Hiroshima (about 14 kt) would flatten all wooden or un-reinforced masonry structures within 1 mile (1.6 km) from ground zero. No structure can withstand 10–12 psi overpressure. Industrial facilities might survive 5 psi, but most houses will be destroyed (Figure 5.24).

Location of the Blast

The magnitude of a nuclear blast effect is related to the height of the burst above ground level. For any detonation (nuclear or chemical) there is an optimum burst height that will produce the greatest change in air pressure (overpressure). A detonation on the surface produces the greatest overpressure at very close ranges, but less overpressure over longer ranges than an air burst.

Some scientists believe that a Hiroshima-sized weapon detonated at ground level in an urban environment would show modified blast effects; a tremendous amount of damage would be expected, but the blast damage could be significantly less than what would occur from an equivalent yield weapon detonated high above a city's skyline. The Hiroshima bomb detonation height was set at 2000 feet to maximize the blast damage.

Table 5.3 Physical Effects of Overpressure on Humans and Structures

Overpressure (psi)	Wind Speed (mph)	Physical Effects
1	38	Residential structures collapse; serious injuries occur, and fatalities may occur
2	70	Windows and doors blown down; humans injured by flying debris
5	163	Most buildings collapse; injuries are universal, fatalities are widespread
10	294	Reinforced concrete buildings are severely damaged or destroyed; most people are killed
20	502	Heavily built concrete structures are severely damaged or demolished; fatalities approach 100%

Source: U.S. Centers for Disease Control and Prevention. No date. Explosions and Refuge Chambers. Zipf, R.K., and K.L. Cashdollar. Effects of blast pressure on structures and the human body. http://www.cdc.gov/niosh/docket/pdfs/NIOSH-125/125-Explosions%20and%20Refuge%20Chambers.pdf, No date; Glasstone, S., and Dolan, P., *The Effects of Nuclear Weapons*, Third Edition. U.S. Dept of Defense and U.S. Dept of Energy, Washington, DC, 1977.

then decays over a period ranging from a few tenths of a second to several seconds, depending on the blast strength and the weapon's yield (Figure 5.25) (Atomicarchive, 2008b).

The Mach Stem

If the nuclear detonation occurs aboveground, the expanding blast wave will quickly strike the surface of the Earth. This wave is immediately reflected from the surface to form a second shock wave traveling behind the first. This reflected wave travels faster than the first, or incident, shock wave since it is traveling through air already moving at high speed due to the passage of the incident wave. The reflected blast wave merges with the incident shock wave to form a single wave, known as the **Mach stem.** The overpressure at the front of the Mach wave is generally about twice as great as that of the direct blast wave front (Figure 5.26). At first the height of the Mach Stem wave is small, but as the wave front continues to move outward, the height increases

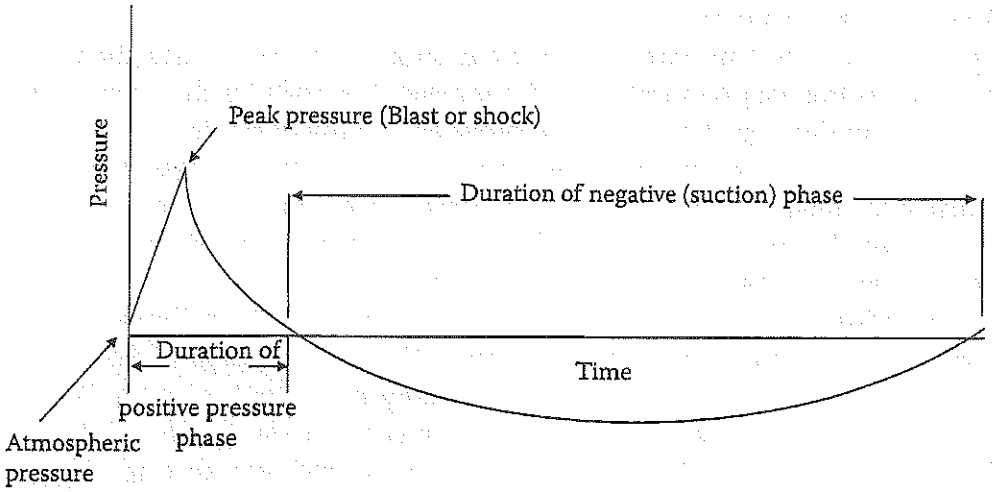

Figure 5.25 Representation of shock front and overpressure following a detonation.

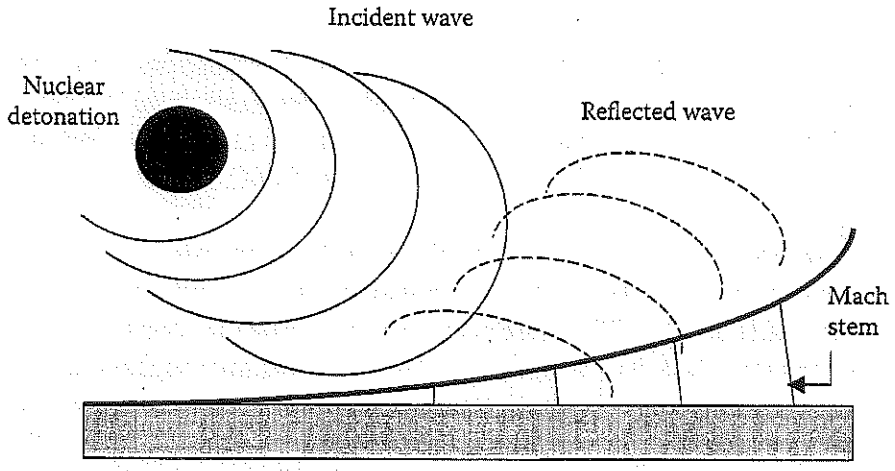

Figure 5.26 The Mach effect.

steadily. At the same time, however, the overpressure, like that in the incident wave, decreases because of the continuous loss of energy and the increasing area of the advancing front. When the Mach front from a 1-Mt nuclear weapon is 10 miles from ground zero (after approximately 40 seconds) the overpressure will have decreased to roughly 1 psi (Glasstone and Dolan, 1977).

Blast Effects on Humans

Upon contact with humans, the nuclear shock wave will push the person in the direction of propagation and compress the body as the wave passes, resulting in damage ranging from burst eardrums to destruction and liquefaction of internal organs, depending upon the amount of overpressure (Langford, 2004). At overpressures of 1 psi, people can be knocked down; at 5 psi eardrums are ruptured. Pressures of more than 40 psi are sufficient to cause lethal effects.

An added danger from overpressure comes from the collapse of structures. Urban areas contain many objects that can become airborne, and the destruction of buildings generates many more such objects. The collapse of structures can crush persons caught inside. Serious injury or death can also occur from impact after being thrown through the air. The blast also magnifies thermal radiation burn injuries by tearing away severely burned skin. This creates raw open wounds that may become infected.

Thermal Effects

Approximately 35% of the energy of a nuclear detonation is released as heat, reaching temperatures at the moment of detonation of 180,000,000°F (100 million °C). In contrast, the temperature due to explosion of a conventional chemical explosive (e.g., TNT or RDX) is only a few thousand degrees.

Such temperatures are as hot as those of the sun, and are so extreme that about one-third of the energy is converted into electromagnetic radiation (specifically x-rays). This electromagnetic radiation, consisting mostly of soft x-rays (see Box 5.4), is absorbed by the local atmosphere at ground zero, heating it to very high temperatures and forming an extremely hot sphere of air and gaseous weapon residues, the so-called **fireball** (Figure 5.27). The surface temperature of the fireball is about 14,400°F (8000°C). At these very high temperatures the nonfissioned components of the weapon are vaporized. The heat obviously incinerates all matter over a large distance.

Depending on environmental factors such as building materials and weather conditions at the site of detonation, the blast heat can also create a firestorm. This storm of flames and air is heated to more than 1000°C and is hot enough to melt glass and many metals. In a Hiroshima-sized explosion, such a firestorm could incinerate everything within about 1.9 km (1.2 miles) from ground zero.

BOX 5.4 HARD X-RAYS AND SOFT X-RAYS

X-rays are commonly defined in terms of the energy they carry, in units of thousands of electron volts (keV). X-rays have energies ranging from less than 1 keV to greater than 100 keV. **Hard x-rays** are the highest energy x-rays, typically those with energies greater than 10 keV; the lower energy x-rays are referred to as **soft x-rays.**

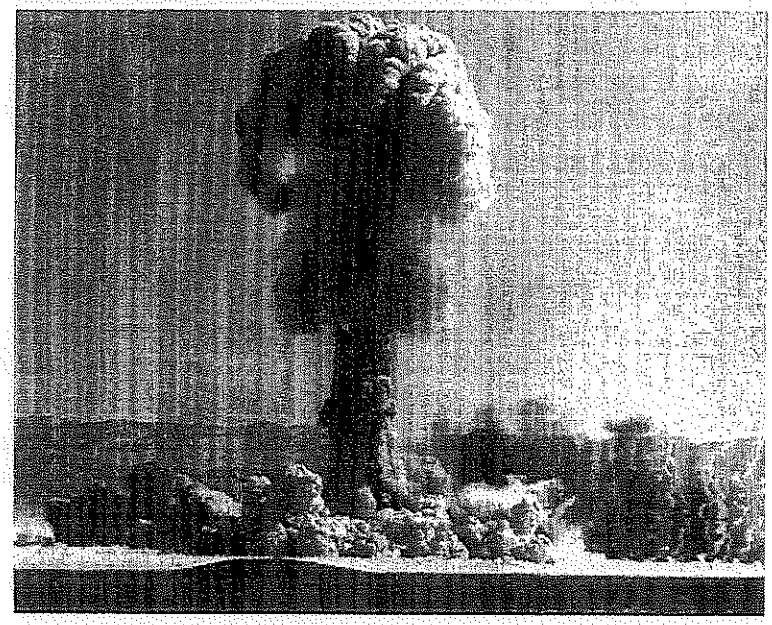

Figure 5.27 Fireball and mushroom cloud following detonation at the Nevada test site. (http://ndep.nv.gov/boff/upshot.jpg.)

Prompt Radiation

About 15% of the energy released from a nuclear detonation occurs as various types of radiation. The initial nuclear radiation comprises about one-third of this total. Initial nuclear radiation, also termed prompt radiation, is defined as that produced within about 1 minute following detonation. Prompt radiation is quite destructive and is composed mainly of neutrons, gamma rays, x-rays, and alpha and beta particles. Although prompt radiation lasts for only about 1 minute it is lethal to all life within

a few thousand yards. At these distances blast and thermal effects are also lethal.

The electromagnetic radiation (chiefly, gamma rays) interacts with the molecules in the air (and debris) so that its intensity is eventually reduced. The intensity and effects of such radiation follow the inverse-square law (Box 5.5).

The prompt radiation from a Hiroshima-sized explosion would expose people within about 2 km (1.3 miles) of ground zero to a 500 rem dose of radiation, creating a 50% chance of death from radiation sickness, radiation burns, and other health effects within days to weeks (see Table 5.2). The actual radiation exposure a person receives depends on the amount of time exposed, the distance from the radiation source, and the amount of shielding. For instance, in a large, modern city such as New York, the dense array of structures should significantly reduce the amount of prompt radiation exposure to human populations.

Health Effects

Radiation adversely affects the structure and function of cells. Two general mechanisms of radiation damage are known in biological systems: direct action and indirect action mechanisms. The **direct action mechanism** occurs because of direct attack on a molecule by ionizing radiation and the consequent destruction of the molecule. Thus, radiation damages cells by changing the structure of organic molecules such as DNA, ribonucleic acid (RNA), and enzymes. For example, the molecular structure of a specific enzyme that is essential to substrate metabolism in a cell is altered by radiation. As a consequence cell metabolism is disrupted and energy can no longer be generated. This disruption causes the cell to die.

BOX 5.5 THE INVERSE-SQUARE LAW

This law states that the intensity from a radioactive source decreases in relation to the square of the distance.

For example, if the radiation at 10 meters is 500 R, at twice that distance or 20 meters, it is 125 R ($500/2^2$).

At 30 meters (about 100 feet), radiation intensity is only about 56 R ($500/3^2$), and so on.

The **indirect action mechanism** occurs when water in the cell is irradiated. The water molecule is split and the resulting free radicals subsequently damage the cell. A **free radical** is an atom or molecule that has a single unpaired electron in one orbit (as compared to most electron orbits, which have pairs of electrons). The splitting of water occurs when radiation strikes a water molecule. The following reactions show the processes involved in the breakdown of the water molecule. H° symbolizes the hydrogen radical and OH° denotes the hydroxyl radical.

Radiation

$\downarrow\downarrow\downarrow$

$H_2O \rightarrow H^{\circ} + OH^{\circ}$	Free radicals
$H^{\circ} + H^{\circ} \rightarrow H_2$	Hydrogen gas
$H^{\circ} + OH^{\circ} \rightarrow H_2O$	Water
$OH^{\circ} + OH^{\circ} \rightarrow H_2O_2$	Hydrogen peroxide (toxic)
$H^{\circ} + O_2 \rightarrow HO_2^{\circ}$	Peroxyl radical (toxic)

Free radicals hydrogen peroxide and the peroxyl radical are extremely harmful to a living cell. The formation of the highly toxic hydrogen peroxide from recombined free radicals is referred to as the "Poison Water Theory."

Radiation effects are generally classified as early (or **acute**) and late (or **chronic**). The terms "early" and "late" refer to the length of the latency period after exposure. The **latency period** is the time interval between dose and detection of symptoms. Acute radiation health effects are those clinically observable effects on health that are manifested within two or three months after exposure (U.S. FEMA, no date). Their severity depends on the radiation dose received. Examples of acute radiation effects include skin burns, loss of appetite, nausea, fatigue, and diarrhea. Late effects can occur years after exposure; examples include cancer, leukemia, cataracts, and genetic effects. Radiation damage can be repaired if the dose received is not too high and if the dose is received over a long period of time.

Electromagnetic Pulse

The radiation from a nuclear detonation creates a powerful electromagnetic pulse, or EMP. Radiation from a nuclear detonation ionizes air molecules, imparting an electric charge to them. These ionized air

molecules interact with the earth's magnetic field to create a surge of electromagnetic energy. The EMP effect is similar to the electrical surge caused by lightning, but about 100 times faster and thousands of times stronger. The EMP from some very large nuclear detonations can cause surges of 25,000–50,000 volts per meter. This surge is strong enough to destroy unprotected electronic equipment, shut down power grids and communications networks, and completely erase the memory on a computer hard drive. The EMP can also cause arcing in electronic equipment.

If a nuclear weapon detonates close to the ground surface the EMP is generated over a relatively small area. However, an EMP could be conducted by buried electric lines, resulting in loss of electrical power beyond the immediate zone of destruction. Depending on the weapon's yield, EMP effects could radiate significantly beyond the zone of heaviest blast damage, potentially leading to loss of electrical communications equipment for emergency responders stationed within miles of ground zero, unless this equipment was electrically shielded in advance. In case of a high-altitude nuclear detonation, a tremendous flux of gamma rays from the nuclear device occurs. These gamma rays produce high-energy free electrons, typically at altitudes between 12 and 24 miles above the Earth's surface (Langford, 2004). The high-energy electrons become trapped in the earth's magnetic field, generating an oscillating electric current which creates a rapidly rising electromagnetic field, resulting in a significant EMP. The pulse can cover a radius of hundreds of miles, spanning entire continents, affecting electrical and electronic systems (NTI, no date).

The first recorded EMP incident accompanied a U.S. high-altitude nuclear test over the South Pacific, resulting in power system failures as far away as Hawaii. It is highly unlikely that a high-altitude detonation could be achieved by terrorists.

Induced Radiation

Many atoms can be converted into radioactive isotopes by **neutron activation**. In the process, a nonradioactive atom absorbs a **slow neutron** (i.e., one whose kinetic energy is below about 1 keV) and becomes a radioactive isotope having one additional mass unit. The new atom can emit radiation as alpha, beta, or neutron particles, or x-rays, or gamma rays. Building materials, water, and soil can undergo neutron activation and thus become radioactive. Most isotopes created by neutron activation have short half-lives and decay rapidly. Thus, the intensity of induced radioactivity decreases rapidly.

Fallout

About 10% of the total energy from a nuclear blast occurs in fallout, that is, fine particles of radioactive dust that settle back to earth over a period of minutes to years. This radiation is largely due to the radioactivity of the fission products present in weapon debris, plus irradiated soil and moisture from the detonation. It is estimated that the radioactivity from detonation of a fission-type nuclear weapon results from about 300 different radionuclides representing about 40 different elements. As an example, U-235 can split in many different ways with numerous products. Equation 5.4 shows one possible fission reaction, where U-235 is converted to strontium-95 (^{95}Sr), xenon-139 (^{139}Xe), and two neutrons (η), plus energy (Glasstone and Dolan, 1977):

$$^{235}U + \eta \rightarrow {}^{95}Sr + {}^{139}Xe + 2\eta + 180\ MeV \qquad (5.4)$$

During the 1960s public health officials expressed concern that strontium isotopes from fallout, being chemically similar to calcium, were becoming incorporated into cow's milk and stored in human tissue.

Radioactive materials blasted high into the atmosphere by the force of a nuclear detonation can travel hundreds of miles before falling to earth, depositing radioactive contamination across thousands of square miles. The intensity and duration of contamination from fallout vary with the yield of the nuclear weapon and how close to the ground it had detonated.

Ground Blast

Weapons detonated close to ground level generate the greatest quantities of fallout. A significant hazard results from soil particles irradiated by the nuclear detonation and lifted into the sky. The radioactive particles that rise only a short distance (i.e., those in the "stem" of the mushroom cloud) will fall back to Earth within a matter of minutes, landing close to ground zero. Such particles are unlikely to cause many deaths, as they will fall in areas where most people have already been killed.

Immediately after fallout is deposited near the blast site, radiation intensities will be very high as the short-lived isotopes decay. For 2 days after a Hiroshima-sized detonation at ground level, persons within about 1.5 miles of ground zero could be exposed to a 500 rem radiation dose from fallout carried by low-altitude winds. This level of radiation could result in a 50% chance of death. This intense radiation will decrease relatively quickly. The intensity will fall by a factor of 10 after 7 hours, a factor of 100 after 49 hours and a factor of 1000 after 2 weeks (OTA, 1979).

Regardless, however, without extensive decontamination radiation within the area may not decay to safe levels for 3–5 years. The radioactivity that remains will create difficulties for response and rescue, and also for eventual reconstruction of the affected area.

Air Burst

The fallout from air bursts poses long-term health hazards, but they are relatively minor compared to other consequences of the nuclear blast. The radioactive particles that rise high in the atmosphere will be carried significant distances by the wind before returning to Earth, and hence the area and intensity of the fallout is strongly influenced by local weather conditions. Much of the material is simply blown downwind in a long plume. A number of attempts have been made to mathematically model the possible path of a fallout plume following a nuclear detonation (Figure 5.28).

The map shown in Figure 5.28 illustrates the plume expected from a 1-Mt surface burst in Detroit if winds were blowing to the northeast, that is, toward Canada. The model assumes that the winds were blowing at a uniform speed of 15 mph over the region. The plume would be longer and narrower if wind speeds were greater, and broader if the winds were slower. The areas in the plume would become safe (by peacetime standards) in 2–3 years for the outer ellipse, and in about 10 years for the inner ellipse.

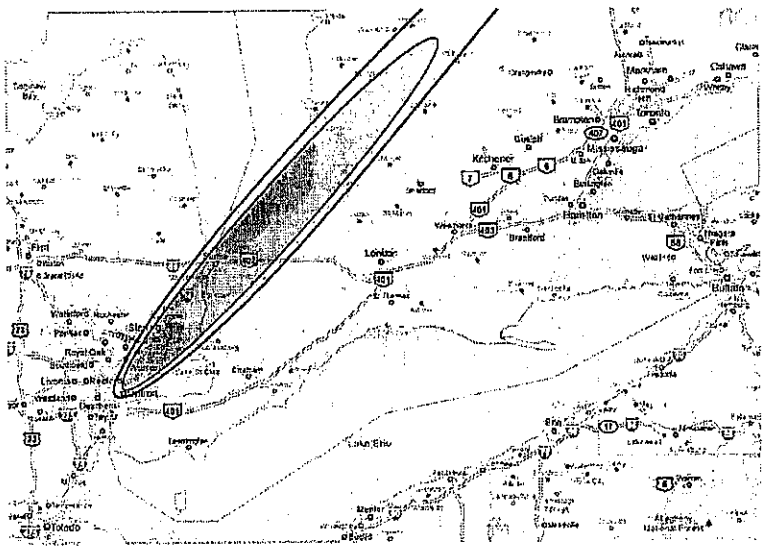

Figure 5.28 Model showing a plume of radioactive fallout over Detroit following a hypothetical detonation. (From U.S. Congress Office of Technology Assessment [OTA].)

Wind direction will make a significant difference in radiation intensity on affected populations. Rainfall will also have a significant influence on the deposition of radiation from weapons, since rain will carry contaminated particles directly to earth. The areas receiving such contaminated rainfall would become "hot spots," having greater radiation intensity than their surroundings (OTA, 1979).

The amount of radiation produced by fallout will decrease with time as the radioactive materials decay. Each isotope decays at a characteristic rate. Some radioactive particles that have been thrust into the stratosphere may not return to earth for years. In this case only the long-lived particles pose a threat, and they are dispersed around the world over a range of latitudes. Some fallout from United States and Soviet weapons tests in the 1950s and early 1960s can still be detected. There are also some particles in the immediate fallout (notably strontium-90 and cesium-137) that remain radioactive for years.

The biological effects of fallout radiation are similar to those from direct radiation. Persons exposed to significant amounts of fallout radiation may die; those exposed to lesser amounts may become ill. Areas receiving such fallout must be evacuated or decontaminated; otherwise, survivors would have to be sheltered for months until the most intense radiation is dissipated.

TIMELINE OF A NUCLEAR DETONATION

A suggested timeline for a blast resulting from a 1-Mt explosion in air is as follows:

Time = 0. Detonation caused by runaway chain reaction. Fireball expands rapidly and rises due to its low density.

1 millisecond after detonation. Diameter of fireball is about 150 meters (450 feet).

10 seconds. The fireball has attained its maximum size (approximately 5700 feet across) and the shock front is about 3 miles from ground zero. The fireball had increased at the rate of 100 meters per second (300 feet per second). The initial rapid expansion of the fireball severely compresses the surrounding atmosphere, producing the powerful blast wave. As the fireball expands toward maximum diameter, it cools.

50 seconds. The fireball is no longer visible. The blast wave has traveled about 12 miles; it is traveling at about 780 miles per hour, slightly faster than the speed of sound at sea level.

60 seconds. The temperature decreases so that the fireball no longer emits significant thermal radiation. The combination of upward movement

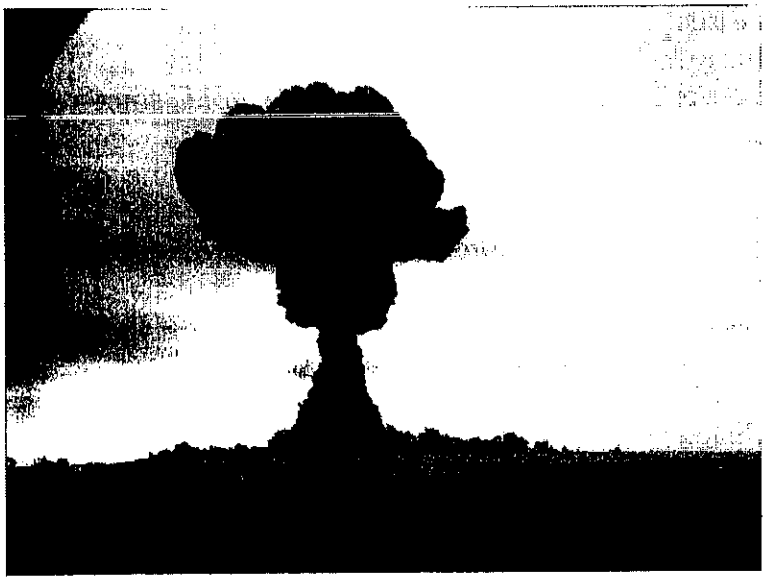

Figure 5.29 Soviet test of "Joe 1," detonated on the ground surface, showing dirty cloud due to soil incorporation. (http://www.cfo.doe.gov/me70/manhattan/images/Joe1SovietTest.jpg.)

and the cooling of the fireball induce the formation of the characteristic mushroom cloud. As the fireball cools, the vaporized materials within condense to form a cloud of solid and liquid particles. Following an air burst, condensed droplets of water impart a white cloud-like appearance to the fireball. In the case of a surface burst, this cloud will also contain large quantities of soil and other debris that are vaporized when the fireball touches the earth's surface or are drawn up by the strong updrafts, giving the cloud a dirty gray-brown appearance (Figure 5.29).

The soil and other debris become contaminated with the radioisotopes generated by the detonation or activated by neutron radiation and return to earth as fallout.

Varying times. Radioactive fallout lands close to ground zero; debris drawn higher into the atmosphere will travel great distances and may be deposited thousands of miles from ground zero.

EMERGENCY RESPONSE TO A NUCLEAR DETONATION

The detonation of a nuclear device will clearly overwhelm emergency response efforts in any community. Many emergency responders stationed near ground zero may die or be injured by the initial blast. First responders

will be contaminated with soil and dust from the detonation before any personnel with the capability of monitoring for radiation arrive on scene.

Victims could overwhelm first responders before a decontamination plan could be established. Many victims may self-admit to local clinics and hospitals before those facilities were aware of the incident and the potential for contamination. Once it is determined that radioactive contamination is present, decisions have to be made rapidly concerning rescue efforts.

The presence of radiological contamination will result in a high degree of physical and psychological stress on those responders attempting to recover victims from the debris. Because of brief work shifts (to limit exposure to radiation) and decon requirements for the responders, it may be difficult to maintain a sufficient number of trained rescue personnel on-scene immediately following the incident. The psychological impact on emergency responders will also be significant. They would not only be concerned about their own safety but that of loved ones who may have been affected by the incident.

In the aftermath of a nuclear detonation, mass decontamination will be needed. Exposure to radiological materials typically indicates no immediate symptoms; thus, it will be difficult to manage large numbers of civilians who have no idea that they have been contaminated. If mass decontamination is established, there will likely be a shortage of monitoring equipment and trained personnel to determine if victims have been successfully decontaminated.

TERRORISM AND NUCLEAR DEVICES

The possible use of INDs by terrorist groups is a growing concern. The ability of terrorists to obtain fissile material is a closely related issue, given the fall of the Soviet Union and subsequent black market operations.

Global Nuclear Inventories

Today, more than two decades since the end of the Cold War, more than 22,000 assembled nuclear weapons exist worldwide (Table 5.4). Nine countries possess these weapons; the five nations possessing the largest number are also state parties to the Nuclear Non-proliferation Treaty: Russia, the United States, France, China, and the United Kingdom. The United States and Russia own the majority (about 95%) of these weapons (Bunn

Table 5.4 Status of World Nuclear Forces

Country	Strategic	Nonstrategic	Operational	Total Inventory
Russia	2600	2050	4650	12,000
United States	1968	500	2468	9600
France	300	n.a.	~300	300
China	180	?	~180	240
United Kingdom	160	n.a.	<160	225
Israel	80	n.a.	n.a.	80
Pakistan	70–90	n.a.	n.a.	70–90
India	60–80	n.a.	n.a.	60–80
North Korea	<10	n.a.	n.a.	<10
Total	~5400	~2550	~7700	~22,600

Source: FAS.org, 2010. (http://www.fas.org/programs/ssp/nukes/nuclearweapons/nukestatus.html.)

and Zenko, 2007). In addition, U.S. nuclear weapons are also located in six other countries: the United Kingdom, and five nonnuclear-weapon states (Germany, the Netherlands, Belgium, Italy, and Turkey) (Norris and Kristensen, 2006).

HEU and plutonium-239 have both military and civilian uses. With few exceptions, HEU is no longer used in commercial (civilian) nuclear reactors. However, HEU continues to be widely used in civilian research reactors as well as for medical isotope production and in naval reactors, among other uses. It is estimated that 140 research reactors in more than 40 countries continue to operate with HEU as their fuel (Bunn and Zenko, 2007). Many civilian nuclear facilities, for example fuel fabrication plants, possess sufficient nuclear material on site for construction of a nuclear device. It is estimated that 128 research reactors or associated facilities possess at least 20 kilograms of HEU (U.S. GAO, 2004).

There are an estimated 1900 tons of HEU in civilian use worldwide (Albright and Kramer, 2005a). Of the 1830 tons of plutonium in stocks worldwide at the end of 2003, about 1675 tons were in civilian stocks, and 155 tons were devoted to nuclear weapons. The amount of civilian plutonium increases annually at a rate of about 70 tons (Albright and Kramer, 2005b).

Many countries reprocess plutonium from spent reactor fuel and recycle it as plutonium-uranium mixed oxide fuel in civilian reactors. These activities result in the processing, use, and transport of many tons of weapons-usable plutonium annually (Bunn and Zenko, 2007).

Transport of HEU, particularly military-grade material, takes place on a massive scale. Nuclear weapons are dismantled and HEU is shipped from dismantlement facilities to storage facilities. In some countries excess HEU is shipped to other facilities for blending to low enriched uranium (LEU) (i.e., that having less than 20% U-235) (U.S. GAO, 1999). In contrast, the scale of shipments of civilian HEU is relatively small. However, hundreds of kilograms of HEU are shipped each year for fuel for research reactors and for medical isotope production—primarily within the United States and Russia. These also pose risks of theft and use by terrorists (Mendelsohn, 2005).

Transport of military-grade plutonium currently occurs at a much smaller scale than transport of military HEU (Bunn and Zenko, 2007). In the United States and Russia, plutonium from dismantled weapons is stored at the site of dismantling. Final management, including reprocessing and/or disposal of excess plutonium, has not been initiated. Large quantities of weapons-usable separated plutonium are transported every year in the civilian sector. Approximately 20 tons of plutonium is reprocessed from spent fuel and about half of that is fabricated into fuel for use in nuclear reactors. Roughly 100 commercial plutonium shipments occur per year, most of which contain more than 100 kg of weapons-usable plutonium per single shipment (Albright, 2007).

Nuclear Smuggling

There is ample evidence which documents that both terrorist groups and states hostile to the United States have sought stolen nuclear weapons or weapons-usable nuclear materials; many have furthermore attempted to recruit scientists and engineers with expertise in the construction of nuclear weapons (Bunn et al., 2005). In 2003, a Russian businessman offered $750,000 for stolen weapons-grade plutonium for sale to a foreign client. He went on to make contact with residents of the closed city of Sarov, site of one of Russia's top nuclear weapons research and development centers, to attempt to close the deal (Bunn and Wier, 2003; RIA-Novosti, 2003). There is evidence of groups carrying out reconnaissance at nuclear weapon storage sites and on nuclear weapon transport trains in Russia, whose locations and schedules are state secrets (Associated Press, 2001; Koryashkin, 2001). Finally, there are reports that nuclear materials have simply disappeared from some countries' inventories. In 1998, Russian Army Lieutenant General Lebed was ordered to account for 132 suitcase-size nuclear weapons that the Soviet Union had manufactured during the

1970s and 1980s. He could only locate 48. He explained, "We do not know what the status of the other devices is, we just could not locate them . . . ." The Soviet devices, built by the KGB for sabotage purposes, have an explosive charge of roughly 1 kt of TNT.

Many less developed countries had nuclear research reactors built in the 1950s under the Eisenhower administration's "Atoms for Peace" program. The thinking of the time was that making reactors available to these countries would make them more receptive to U.S. influence. At this time the USSR was also actively marketing its research reactors in a similar attempt to draw countries into its sphere of influence (Daly et al., 2005).

In 1958, construction of a research reactor began at the edge of the University of Kinshasa campus outside the capital city of the Congo. In 1959, the reactor went critical and was acknowledged as a symbol of progress for the Congo and for Africa in general. The first reactor was retired in 1970, and a newer and larger design began operation in 1972.

In the mid- to late 1970s, two of the reactor rods in storage at the Kinshasa facility disappeared (Daly et al., 2005; Kinshasa Digitalcong, 2002). The location of the rods was unknown for over two decades until 1998. It had been suggested that Congo President Mobutu, overthrown in 1997, took the rods with him as a potentially valuable asset. At the same time allegations were made of Italian criminal smuggling rings attempting to sell nuclear material from the country. In July, 1996, a Portuguese businessman offered to make available a bar of uranium-235 from Zaire worth 7 billion Italian lira. Eventually, two Portuguese citizens involved in the plot admitted to criminal activity. An Italian involved in the plot claimed to be working for the Russian Secret Service. Although one of the rods was recovered, the second was not. An IAEA official responded to this issue by stating that it was probably "lost in the jungle" (Wrong, 1999).

In 2001, U.S. intelligence agencies concluded that the al-Qaeda terrorist network may have made greater strides than previously thought toward obtaining plans or materials to make a crude nuclear weapon. Osama bin Laden and al-Qaeda have openly attempted to obtain nuclear weapons for use against the United States and its allies. Bin Laden has labeled the acquisition of weapons of mass destruction a "religious duty." Al-Qaeda communications reportedly have referred to inflicting a "Hiroshima" on the United States (Risen and Engelberg, 2001). An al-Qaeda spokesman, Sulaiman Abu Ghaith, has asserted that the group "has the right to kill 4 million Americans—2 million of them children," in retaliation for

the deaths the group believes the United States and Israel have inflicted on Muslims (Bunn et al., 2005). For over a decade al-Qaeda has been attempting to purchase stolen nuclear weapons or nuclear material, and to recruit nuclear expertise (Albright, 2002; Albright et al., 2002).

In 2005, the U.S. intelligence community assessed that al-Qaeda was capable of fabricating at least a "crude" nuclear device if it could obtain the requisite nuclear material, that is, HEU or separated plutonium. Michael Scheuer, of a CIA team focused on Osama bin Laden, wrote in 2004 to the House and Senate Intelligence Committees that his unit "acquired detailed information about the careful, professional manner in which al-Qaeda was seeking to acquire nuclear weapons." He continued, "there could be no doubt after this date that al-Qaeda was in deadly earnest in seeking nuclear weapons" (Atlantic, 2004). The CIA Counterterrorist Center judged in November 2001 that al-Qaeda "probably had access to nuclear expertise and facilities and that there was a real possibility of the group developing a crude nuclear device."

Osama bin Laden, Mamdouh Mahmud Salim and others have made efforts to obtain the components of nuclear weapons (CNS, 2001). The best documented case was an attempt in 1993 to purchase HEU for a nuclear weapon in the Sudan, which has been described in some detail in court testimony of Jamal Ahmad al-Fadl, the al-Qaeda operative charged with several key steps in the transaction (McCloud and Osborne, 2001).

In addition to the 1993 attempt, there have been repeated reports regarding al-Qaeda attempts to purchase nuclear materials or nuclear weapons in the former Soviet Union (Bunn et al., 2005; McCloud and Osborne, 2001). Al-Qaeda and its allies have also actively attempted to recruit individuals with nuclear weapons expertise.

For example, Osama bin Laden and his deputy Ayman al-Zawahiri met with two senior Pakistani nuclear weapons experts, both Taliban sympathizers with extreme Islamic views, and pressed them for information regarding the manufacture of nuclear weapons. Pakistani intelligence officials told the *Washington Post* that the two had provided bin Laden with detailed technical information, in violation of Pakistan's secrecy laws (Albright and Hunter, 2003). In 2000, an official of Russia's National Security Council announced that the Taliban regime of Afghanistan attempted to recruit a nuclear expert from a Russian facility (Radio Free Europe, 2000). In 1998, a scientist at one of Russia's nuclear weapons laboratories was arrested for spying for both the Taliban and Iraq (Bunn et al., 2005).

Other terrorist organizations have been documented as having ambitions to obtain or construct a nuclear weapon. Aum Shinrikyo, the Japanese doomsday cult associated with the 1995 Tokyo sarin attacks, recruited nuclear physicists from Moscow. It was also determined that the group tried to mine its own uranium in Australia and to purchase Russian nuclear warheads (Willman and Miller, 2001).

TERRORISM AND RADIOLOGICAL DISPERSAL DEVICES

This chapter has thus far presented phenomena associated solely with nuclear detonations, that is, engineered reactions occurring within nuclei of atoms to release extremely large quantities of energy. In contrast, a **radiological dispersal device (RDD)** or "dirty bomb" occurs as a simple improvised device consisting of explosives such as black powder or dynamite in combination with radioactive material. When the explosives are detonated, the blast disperses radioactive debris into the local area.

The U.S. Department of Defense (DOD) defines an RDD as

> any device, including any weapon or equipment, other than a nuclear explosive device, specifically designed to employ radioactive material by disseminating it to cause destruction, damage, or injury by means of the radiation produced by the decay of such material.

Terrorists would employ an RDD to scatter radioactive debris, thereby contaminating a wide area. The threat from an RDD not only includes the blast wave and fragmentation from the explosive, but also radiation exposure from the radioactive material, and fear and panic that would spread among the target population. Depending on the type and strength of radiation involved, RDDs could render a great deal of property unusable for an extended period unless costly remediation practices were undertaken. However, most probable radioactive sources in an RDD would be incapable of releasing sufficient radiation to cause severe illness or death. The explosives contained in the device would likely have more immediate lethal effect than would the radioactive material.

An RDD is far easier for terrorists to construct, conceal, and detonate as compared with a true nuclear weapon. Unlike the HEU or plutonium required for a nuclear device, the radioactive material for a dirty bomb exists at thousands of locations worldwide. In other words, the probability of a dirty bomb attack is substantially higher than the probability of

BOX 5.6 EXPOSURE VERSUS CONTAMINATION

It is important to appreciate the difference between exposure to radiation and contamination with radioactive material. Health effects and countermeasures differ significantly for each.

Radiation exposure (irradiation) occurs when radiation penetrates tissue, for example, when a patient undergoes a diagnostic x-ray. A person can be irradiated without physically contacting radioactive material. Radiation can occur in materials (e.g., a radioactive source), in the air or on the ground.

Radioactive contamination involves the placement of radioactive material in random, unintentional places. Contamination can be external (outside of the body) or internal (within the body) or both. External contamination is defined as radioactive material occurring on a person's clothes, skin, or hair. Internal contamination includes radioactive material that has entered the body by inhalation, ingestion, or absorption through skin or wounds.

a terrorist attack with a nuclear weapon. However, the consequences of a dirty bomb attack would be far less than those for a nuclear weapon (Bunn, 2010) (Box 5.6).

Radionuclides of Concern

Almost any radioactive material can be used to construct an RDD, including fission products, spent fuel from nuclear reactors, and relatively low-level materials such as medical, industrial, and research waste. Millions of radioactive sources have been manufactured and distributed worldwide since the end of World War II, with hundreds of thousands currently is use, storage, and production. Many of these sources are weakly radioactive and pose little radiological risk (IAEA, 2002).

Worldwide, the IAEA has documented more than 20,000 operators of significant radioactive sources; for example, more than 10,000 radiotherapy units for medical care are in use; about 12,000 industrial sources for radiography are supplied annually; and about 300 irradiator facilities containing radioactive sources for industrial applications are in operation (IAEA, no date).

The most probable radionuclides used in an RDD include cesium, cobalt, americium, and iridium (U.S. DHHS, 2010a); however, others may

also be used. Multiple agents may be combined in a single detonation. The isotopes of interest for RDDs are shown in Table 5.4.

Cs-137, Co-60, and Ir-192 (Table 5.5) are all strong gamma emitters, which make these isotopes valuable for commercial and medical applications, including sterilization of equipment, irradiation of tumors, and evaluation of high-integrity welds. They are also used in industrial gauges. If exposed, these nuclides could pose a whole body hazard to victims.

Strontium-90 emits beta particles and has important commercial uses, a major one being in radioisotope thermal generators (RTGs). Approximately one thousand RTGs occur in Russia, most being used as power sources for lighthouses and navigation beacons. All Russian RTGs have long exhausted their designated service periods and are in need of dismantling (Figure 5.30). The importance of this issue is emphasized by three recent

Table 5.5 Possible Isotopes for Use in RDDs

Nuclide	Primary Radiation Type (Half Life)	Primary Form	Possible Radiation per Source (Curies)	Application
^{90}Sr	Beta (28.6 years)	Ceramic ($SrTiO_3$)	300,000	Large radioisotopic thermal generator (RTG) (Russian IEhU-1)
^{137}Cs	Beta + Ba-137 m Gamma (30.17 years)	Salt (CsCl)	200,000	Irradiator
^{60}Co	Beta, gamma (5.27 years)	Metal	300,000	Irradiator
^{238}Pu	Alpha (87.75 years)	Ceramic (PuO_2)	300,000	RTG used for the Cassini Saturn space probe
^{241}Am	Alpha (432.2 years)	Pressed ceramic powder (AmO_2)	20	Single well logging source
^{252}Cf	Alpha (2.64 years)	Ceramic (Cf_2O_4)	20	Several neutron radiography or well-logging sources
^{192}Ir	Beta, gamma (74.02 days)	Metallic	1000	Multiple industrial radiography units
^{226}Ra	Alpha (1600 years)	Salt ($RaSO_4$)	100	Old medical therapy sources

Source: Argonne National Laboratory. 2005c. *Radiological Dispersal Device (RDD).* EVS Human Health Fact Sheet, August; U.S. Department of Health and Human Services, 2010b. Radiological dispersal devices. http://www.remm.nlm.gov/rdd.htm (accessed October 27, 2010).

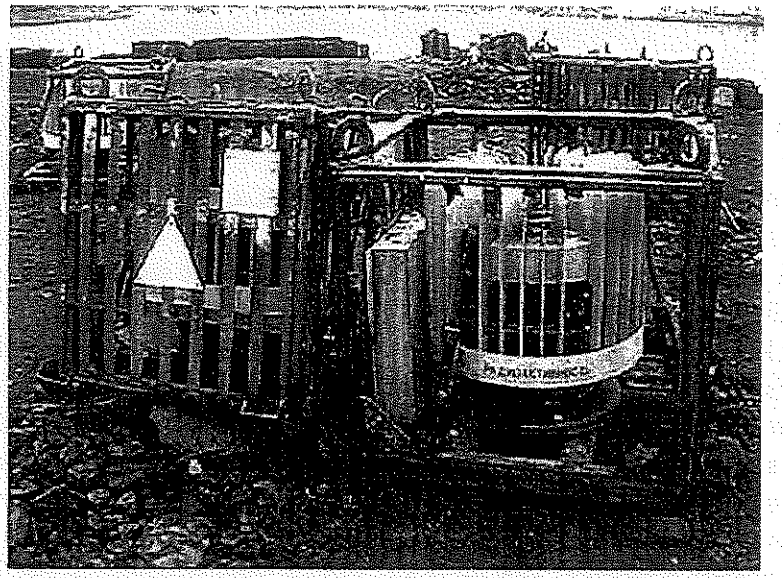

Figure 5.30 Abandoned RTGs on the Kola Peninsula, Russia. (http://www.bellona.no/imagearchive/72029f025e5aa2e80c543023d7f1590b.)

incidents mostly involving vandalism, with these dangerous sources in 2003—on the shore of the Baltic Sea, and in the Kola Bay (Alimov, 2003). The poor accountability for Soviet-era RTGs has been widely publicized. RTGs pose a considerable threat because they may contain tens of thousands of curies of Sr-90. Initial radiation levels have declined substantially in older RTGs due to radioactive decay, but levels in newer units could exceed 10,000 Ci. Beta emitters such as Sr-90 are primarily an internal health hazard if ingested or inhaled.

A number of isotopes in Table 5.5, for example, Am-241, Cf-252, Po-210, Pu-238, and Ra-226, are primarily alpha emitters. Alpha particles are easily shielded with minimal layers of protective material, so they do not pose a significant external health hazard. Rather, their health significance relates to ingestion or inhalation. In addition, Am-241 is commonly mixed with beryllium to produce a neutron-emitting source. Similarly, Cf-252 emits neutrons through spontaneous fission. Neutron emitters represent both an external and internal health hazard. Alpha or neutron emitters have been used in soil moisture gauges, medical pacemakers, and well logging gauges used in the petroleum industry.

Dispersal of Radioactive Material

One key consideration relating to radiation hazard of RDDs involves the ability of radioactive debris to disperse in the local environment. This ability to disperse is a function of the physical and chemical properties of the material employed in the RDD. Solid metallic forms would be difficult to disperse, while powder forms could be dispersed readily. Cobalt, iridium, and polonium typically occur in solid metallic forms and are hence not readily dispersible (U.S. EPA, 2009). Several others, however, including americium, californium, and plutonium, tend to occur as oxides that could exist as a powder (Argonne, 2005a; 2005b). Cesium is often prepared as cesium chloride, which is a powder and is highly soluble in water. Radium and strontium are used in various forms. Strontium fluoride in certain sealed sources is **sintered** such that it is essentially insoluble and nondispersible.

Ultimately, however, the original radioactive material used by a terrorist could be chemically or physically altered to enhance dispersal (Zimmerman, 2006). Finally, detonation of a chemical explosive would also physically and chemically alter the radioactive materials to produce oxides as well as nitrates (from the explosives) occurring over a range of particle sizes (Argonne, 2005c).

Accidents with Radioactives

Numerous events have been documented regarding the effects of uncontrolled radioactive contamination. Possibly the worst-case example of a radiological accident is that which occurred in Goiânia, Brazil. In September 1987, a radiotherapy clinic, formerly owned by the Instituto Goiano de Radioterapia in Goiânia, moved to a new location and left its radiation cancer therapy unit behind. Metal scavengers entered the abandoned clinic and removed a teletherapy source capsule containing cesium-137. The cesium had an activity of 50.9 T Bq (approximately 1400 Curies) (IAEA, 1988). Cesium-137 has a half-life of 30.1 years, and beta-decays to metastable barium-137. The Ba-137m has a half-life of 2.55 minutes and emits gamma radiation.

The sealed radioactive source capsule was set in a source wheel manufactured of lead and stainless steel. The source was brought to one scavenger's home in attempts to disassemble and eventually sell for scrap metal. Later that day the two men handling the source experienced signs

of acute radiation illness; both were vomiting and one had a swollen hand (edema) and diarrhea.

Several days later, one of the men punctured the 1-mm thick window of the capsule and removed some of the cesium chloride powder. Thinking it might be gunpowder, he attempted to ignite it (there was no reaction). In the evening, noticing that the powder glowed blue in the dark, he brought it home, and pieces were distributed to family and friends. There were several instances of people daubing the radioactive powder on their skin, as they might with the glitter used at carnival time. The 6-year-old daughter of one of the scavengers handled the source while eating her meal by hand.

Contamination by cesium powder of citizens, homes, and businesses continued for about two weeks, resulting in an increasing number of adverse health effects. Early diagnoses were attributed to allergic reaction, food poisoning, or tropical disease. Almost 2 weeks later, hospital staff recognized symptoms of acute radiation syndrome in the victims. By this time 249 people were contaminated, 151 exhibited both external and internal contamination of which 20 people were seriously ill and 4 died (IAEA, 1988).

The panic that followed caused more than 112,000 people—10% of the population—to request radiation surveys to determine whether they had been exposed. At a makeshift facility in the city's Olympic Stadium, 250 persons were found to be contaminated. Twenty-eight had sustained radiation-induced skin injuries (burns), while fifty had ingested cesium. For the latter victims there is concern that the internal deposition may result in an increased risk of cancer over their lifetime (IAEA, 1988).

Once the correct diagnosis of acute radiation sickness was made the proper precautions were put into procedure. A local response agency had considered throwing the source into a nearby river; however, they were dissuaded at the last moment. Local citizens were persuaded to vacate the contaminated area, which by this time covered more than forty city blocks. Of the 85 homes found to be significantly contaminated, 41 were evacuated and 7 were demolished. It was also discovered that through routine travels within that short time, people had contaminated houses nearly 100 miles away. It is relevant to note that cesium chloride's high solubility contributed to the extensive contamination of persons, property, and the environment.

Various remedial actions were undertaken in the affected area such as decontamination of property, collection of contaminated clothing, removal of contaminated soil, and placing of restrictions on home-grown

produce near the area. Cleanup generated 3500 m^3 of radioactive waste at a cost of $20 million.

The impacts of this incident also included psychological effects such as fear and depression for a large proportion of the city's inhabitants. Frightened by the possibility of radioactive contamination, neighboring provinces isolated Goiânia and boycotted its products. The price of their manufactured goods dropped 40%. Tourism, a primary industry, collapsed. Total economic losses were estimated at hundreds of millions of dollars (Argonne, 2005c).

The accident in Goiânia was one of the most serious radiological accidents to have ever occurred. However, it has similarities with a number of other accidents, such as those in Mexico City (1962), Algeria (1978), Morocco (1983) and Ciudad Juarez in Mexico (1983). The Ciudad Juarez event was remarkably similar to the accident in Goiânia (Combs, 2008).

The Goiânia incident to some extent predicts the radiation contamination pattern during an event involving an RDD if it is not immediately realized that the explosion spread radioactive material, and also how hazardous even small amounts of ingested radioactive powder can be (Zimmerman and Loeb, 2003). Such information could be highly useful for responders in the event of an RDD attack.

A Variation on the Dirty Bomb: The "Smoky Bomb"

In November 2006, former KGB spy Alexander Litvinenko died from acute radiation syndrome after his food was poisoned with polonium-210. In contrast to Cs-137, Po-210 is an alpha emitter.

As stated in earlier in this chapter, alpha particles are fast-moving helium nuclei ejected during the radioactive decay of certain isotopes, including polonium-210. Alpha radiation cannot travel far and can be easily shielded—for example, by the outer layer of skin, a few sheets of paper or a layer of aluminum foil. According to terrorism analysts, alpha radiation could not injure a person as long as the source stayed outside their body. Mr. Litvinenko was apparently killed by polonium that he ate or drank or inhaled. Mr. Litvinenko's death implies that "smoky bombs," where alpha emitters are attached as fine particulate matter to airborne dust and other debris from fires or explosions, could be inhaled and/or ingested.

Polonium-210 is a common element. It is used by industry in devices that eliminate static electricity, for example, in certain applications of the photographic and textile industries (Zimmerman, 2006). It is used

to control dust in "clean rooms" where computer chips and hard drives are manufactured. The goal for radiological terrorists may be to get the alpha-emitting material inside the bodies of their victims, where it will do the most harm. Because alpha particles travel such short distances, they deposit all of their energy in a relatively small number of cells, killing them or causing them to mutate, increasing the long-term risk of cancer. "Smoky bombs" based on alpha emitters might easily be just as dangerous as beta- or gamma-emitting dirty bombs. The terrorist's solution lies in getting very finely divided polonium into the air where people can breathe it. A smoky bomb exploded in a packed theater or in a crowded downtown could possibly kill hundreds.

QUESTIONS

1. Check various web sites and published sources to obtain data on the overpressure from a nuclear detonation. What range of pressure can be generated from a 10-kT detonation? A 1-Mt detonation? Compare this data with that from detonations of conventional chemical explosives provided in the next chapter.
2. Define: isotope; half-life; fissile; critical mass; soft x-rays; Compton scattering; EMP.
3. List three natural sources of background radiation. What are the most common naturally occurring radioactive elements? In what materials do they occur?
4. Nuclear weapons are designed and constructed based on which two isotopes? Could other radioisotopes be used, for example, thorium? Discuss.
5. How is uranium processed before it is usable in a weapon? Describe the processes involved.
6. List the hazards to humans and structures from a thermonuclear explosion. The relative distribution of the effects depends on which factors?

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