Chapter 4

The World Adapts to Nuclear Energy

To Be or Not to Be…

The first forty-five years of the 20th century had two world wars where new technology, combined with energy from coal and then oil, was used to kill approximately ninety-two million people. At the very end of WW II, a form of energy became available that was a million times more powerful than coal or oil. The future of human civilization depended upon how it would be used. For the first time in history, people had technologies based on a source of energy that was so great that it could kill almost everyone unless the urge for domination and intolerant behavior could be controlled. Like Hamlet, humankind faced the question of destroying ourselves. In this unit, you learn about the potential of nuclear energy technology to destroy or to energize civilization.

Why Do I Need to Know This?

Even though nuclear energy has the potential to destroy civilization, provide enormous amounts of clean energy, and create or cure cancer, the basics of nuclear physics are not included in the curriculum of most American students. This chapter is your chance to learn enough about nuclear energy to understand these vital issues that affect the energy future of the country, the potential of going to war to prevent some countries from building nuclear weapons, and the diagnosis of a disease that you or a loved one might have.

1 Physics of the Nucleus

Learning Objectives

1. Identify the difference between elements and isotopes of the same element. [4.1.1]
2. Identify the four types of radiation from the nucleus. [4.1.2]
3. Identify the relationship between types of ionizing radiation, harm to humans, and shielding thickness. [4.1.3]
4. Describe the concept of background radiation. [4.1.4]
5. Identify types of transmutation and how they affect the atomic number of an atom. [4.1.5]
6. Identify the factors that must be present for a nuclear chain reaction. [4.1.6]
7. Identify the factor that racial and ethnic intolerance played in the development of nuclear bombs. [4.1.7]

Let's begin by reviewing what you learned about nuclear energy in the first unit. Recall that the energy of the sun comes from combining hydrogen atoms to form helium atoms where the resulting atoms have slightly less mass which is converted into heat and light in a process called nuclear fusion. Because nuclei are positively charged, they repel and it is very difficult to force them together. Nuclear fusion occurs inside the sun because of the tremendous force of its gravity but it is very hard to do outside of the sun. There is another type of nuclear reaction that releases similar amounts of energy but before we discuss it, you need more background information.

Isotopes

Recall that the nucleus of an atom has positively charged particles called protons and equally massive neutral particles called neutrons. The number of protons in the nucleus determines the amount of positive charge on the nucleus and the number of electrons that it attracts which in turn determines its chemical behavior. Each type of atom is called an element. For example, hydrogen, carbon, and oxygen are elements. If an atom has one proton in its nucleus it is hydrogen, if it has six it is carbon, and if it has eight it is oxygen.

The number of neutrons in the nucleus is usually about the same as the number of protons but this proportion can vary without affecting the chemical behavior of an atom. For example, carbon always has six protons in the nucleus and most carbon atoms have six neutrons. However, some carbon atoms have seven neutrons and others have eight. The mass of an atom's nucleus is measured in atomic mass units where protons and neutrons each have a mass that is very close to 1. The atomic mass number is the sum of the number of protons and neutrons. The notation used to indicate the atomic mass of an atom places the atomic mass number above and to the left of the atom's letter and the number of protons (atomic number) below and to the left. For example, ${}^{12}_{6}C$is the most common type of carbon and ${}^{14}_{6}C$ is a less common type. They have the same number of protons, attract the same number of electrons (6) and therefore have the same chemical properties. If atoms have the same number of protons, we say they are the same type of atom. The term for this is isotope which means same-type. This is like brothers in the same family who all have the same last name. They have different personalities but they share one important characteristic. Isotopes of the same element have different mass but the same chemical properties. To determine the number of neutrons in the nucleus of an isotope, subtract the atomic number from the mass number. For example the number of neutrons in ${}^{14}_{6}C$ is 8.

Refer to figure 4.1. It shows three elements and isotopes of each.

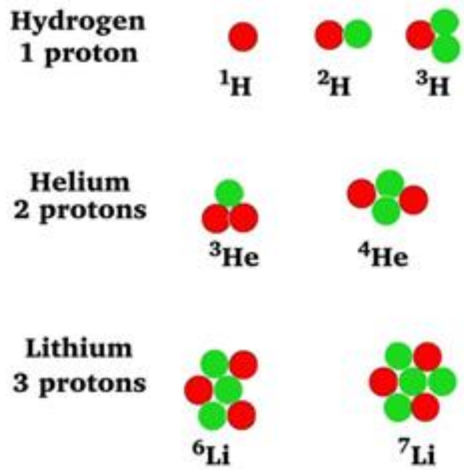

Figure 4.1. First three elements by atomic number and examples of isotopes of each element

Radiation from the Nucleus

Although isotopes of the same element have the same chemical properties they can differ greatly in how the nucleus behaves. In the first three decades of the 20th century, physicists discovered some very unusual properties of the nucleus. They discovered that very energetic charged particles and photons of light were emitted from some types of nuclei. At first they didn't know what these emissions were so they just labeled them with the first three letters of the Greek alphabet; alpha, beta, and gamma. Refer to Figure 4.2 for a table of Greek letters.

Figure 4.2. Greek letters are often used as labels in science.

These emissions radiated outward from the samples being studied and became known as nuclear radiation. (A fourth type of radiation, neutrons, went undetected.)

Because any type of emission that radiates outward from a central source can be called radiation, the term is easily confused. For example, the heating unit in a house is called a radiator because it emits heat in the form of infrared light but this light does not come from the nucleus. Similarly, when you go to the dentist, he or she might use an x-ray machine that emits photons of high-energy invisible light that casts shadows of your teeth on film. X-rays are also called radiation but they don’t come from the nucleus either.

Later studies determined the nature of alpha, beta, and gamma radiation and they were puzzling.

- Beta radiation turned out to be electrons that came from the nucleus. The theory of the day had to be revised because they had no idea of how a negative electron could come out of a positive nucleus.
- Gamma radiation is high energy photons of light that are similar to x-rays but they come from the nucleus.
- Alpha radiation turned out to be a clump of two protons and two neutrons. When the alpha particles slowed down, they attracted electrons from other nearby atoms and turned into helium atoms, ${}^{4}_{2}He$.

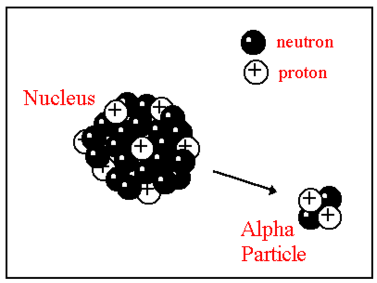

Figure 4.3 Alpha particles turned out to be helium nuclei.

Radiation and Shielding

The alpha, beta, and gamma radiations come from the nucleus with a lot of energy. When they collide with other atoms, they can knock electrons from the outer layers of those atoms or they can break the covalent bonds that hold molecules together. Either of these actions creates ions. The result is a trail of ions along the path of the radiation. Radiation that has enough energy to knock off electrons or break apart molecules is called ionizing radiation.

To protect humans from the effects of large amounts of ionizing radiation all that needs to be done is to place non-living material between them to absorb the energy. This type of material is called shielding. The different types of radiation require differing amounts of shielding that are inversely proportional to the amount of ionization that the radiation causes, as shown in Figure 4.4.

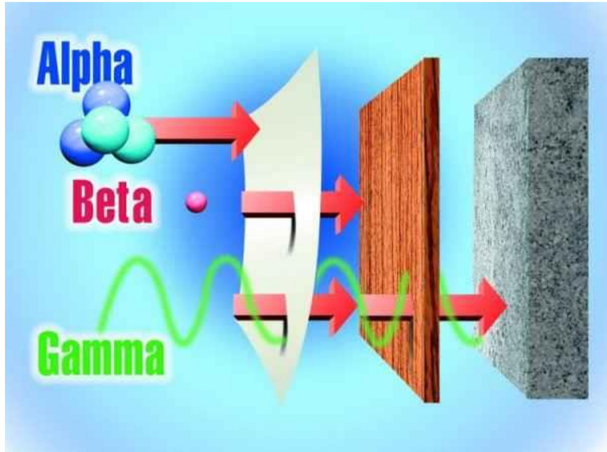

Figure 4.4 The amount of shielding needed is inversely proportional to the ionization

- Alpha particles have a relatively large mass and two positive charges. They ionize many atoms along their path but they transfer their energy quickly. A few inches of air or even the layer of dead skin on your hand is enough to stop them. They only hurt living organisms if the source material is taken internally. Alpha particles are only emitted from large atoms and almost all of them are solids (with the exception of Radon) so the main concern is to prevent a source of alpha particles from entering the body as dust in the lungs or ingested in food.
- Beta particles are negatively charged electrons. They ionize less but travel further. A thin layer of metal or a few inches of wood, water or concrete is sufficient to block them.
- Gamma rays are photons of light that are similar to x-rays. They ionize less than alpha or beta but penetrate further. Several feet of water or a few feet of concrete is adequate to block them.
- Neutrons do not cause ionization and interact less with materials which requires more shielding. Shielding from neutrons is only needed near nuclear reaction cores where neutrons are emitted.

Detection

Pierre and Marie Curie used a device invented by Pierre that detected ionizing radiation by how fast it caused an object to lose a static charge. The Curies introduced the term radioactive to describe materials that had this property. A German, Hans Geiger, invented an electrical device to detect and count ionizing radiation, like the one shown in Figure 4.5.

Figure 4.5 Geiger counter detects ionizing radiation

The device has a tube that has charged plates at either end with just enough electric force on them to make a small amount of electricity flow. When ionizing radiation passes through the tube, the resulting path of ions has less resistance and a surge of current flows briefly. The result is a brief pulse of current that can be counted or fed into a speaker where it sounds like a click. The average number of events can be shown on a dial.

Half-Life

It is impossible to predict when an individual atom will emit radiation. The best we can do is to predict the behavior of large numbers of atoms. Fortunately, a few ounces of any material contain a large number of atoms so these predictions are useful. Each isotope that is radioactive, has a characteristic type of emission (alpha, beta, gamma, or neutron) and a likelihood of how long it will be before it emits that radiation. The time period is called the half-life because approximately half of the atoms will emit radiation during that period. For example, the isotope of carbon that has 6 protons and 8 neutrons, ${}^{14}_{6}C$, emits beta particles and has a half-life of 5730 years. (Korea Atomic Energy Research Institute 2000) This means that if you start with a sample of Carbon 14, half of it will emit a beta particle and transmute into Nitrogen 14 in 5730 years. However, it will take another 5730 years for half of the remaining Carbon 14 to emit their betas and so on. Another way to look at it is that if you have a radioactive isotope, its activity will drop to half in one half-life and then to one-quarter (half of a half) in two lifetimes, and then one-eighth (half of a half of a half) in three lifetimes. A chart of isotopes is called a chart of the nuclides, as shown in Figure 4.6.

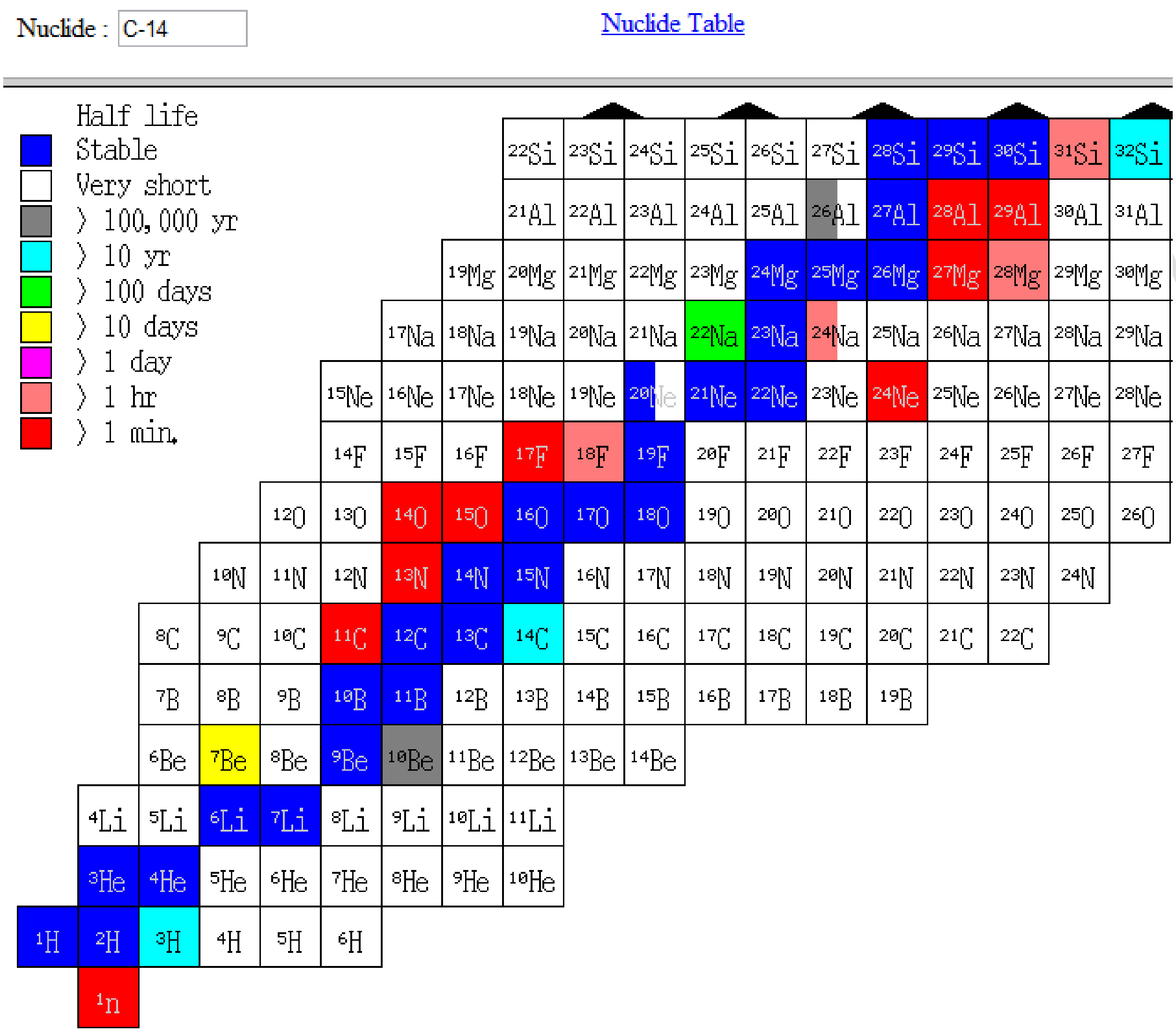

Figure 4.6 Chart of the Nuclides

If an isotope has a short half-life it implies that it is very radioactive but will not exist for long. If it has a long half-life, it is much less radioactive but it will be around a long time. After about ten half-lives the activity is too low to measure separately from other surrounding sources.

Radiation and Nature

When you hear some people talk about radiation, they talk as if nuclear radiation was unusual and it is not normally present. In fact, all elements have isotopes that emit alpha, beta, or gamma radiation. For example, the isotope of carbon that has eight neutrons ${}^{14}_{6}C$ is present in the atmosphere and in all living plants and is being constantly regenerated by cosmic rays in the upper atmosphere so its concentration is fairly stable in the atmosphere. This isotope of carbon emits about 14,000 beta particles each minute for each kilogram (2.2

lbs.) of carbon. When a plant dies and it stops taking in carbon dioxide from the atmosphere, the amount of radiation it emits decreases with time. We know how old a wooden artifact is by how much *less* radioactive it is than when the tree was alive. Nuclear radiation is part of nature—nothing is more *natural* than radiation. A certain amount of ionizing radiation is always present. It is called background radiation. There are several sources of background radiation including the sun, other stars, plants, people, and minerals in rocks so the actual amount of background radiation varies depending on where you are. Humans have lived in this environment of background radiation throughout their entire existence.

Transmutation

When the number of protons in the nucleus is changed, the atom becomes a different element. Changing something from one element into another was the dream of early alchemists who tried to turn lead into gold and is called transmutation. The alchemists never got it to work because chemistry involves the outer layers of electrons—not the nucleus. Transmutation can be achieved in three ways that affect the number of protons in the nucleus. Two of them are spontaneous and one is artificial.

Alpha Emission

When an alpha particle is emitted from a large nucleus, the nucleus loses two protons and two neutrons. The loss of two protons changes the atom into another element. For example when radium $^{226}_{88}Ra$ emits an alpha, $^{4}_{2}HE$, the atomic number of the remaining nucleus is reduced by two and its atomic mass by four and it becomes Radon, $^{222}_{86}Rn$. Radon is also an alpha emitter and when it emits an alpha it turns into Polonium, $^{218}_{84}Po$. This process continues until a stable isotope of lead is formed.

Beta Emission

When beta emissions were identified as electrons from the nucleus, it was hard to explain. In 1932, it was discovered that a neutron could transform into a proton and emit an electron. When a nucleus emits a beta and a neutron transforms into a proton, the atomic number (the number of protons) increases by one and the atomic mass (protons plus neutrons) stays the same. For example, when carbon-14, $^{14}_{6}C$, emits a beta it turns into nitrogen-14, $^{14}_{7}N$.

Neutrons Added to the Nucleus

If neutrons are projected into a material, some of them will be absorbed by the nuclei of that material and the atomic mass number increases by one. If the additional neutron causes the nucleus to emit a beta, the proton is left which increases the atomic number by one. Uranium, $^{238}_{92}U$, is the largest atom that is found in the earth today. It has a half-life of about 4.5 billion years. Because this is the approximate age of the earth, we would expect about half of the original amount to remain. All of the larger atoms have much shorter half-lives and if any of them existed on earth billions of years ago, they have transmuted by alpha emissions into smaller atoms by now. They can be recreated by transmuting Uranium. The Uranium is bombarded with neutrons that emit beta particles. One of the first elements to be made using this method as named Plutonium. It is created by adding a neutron to Uranium 238 ${}^{238}_{92}U$ which causes two neutrons to emit beta particles and turn into protons. The result is Plutonium 239 ${}^{239}_{94}P$ which has a half-life of 24,000 years. About nineteen elements larger than Uranium have been created using this method.

Neutrons can also be absorbed by any other type of atom. This can cause previously non-radioactive materials to become radioactive isotopes and can change the chemical and structural characteristics of a material. For example, some types of steel will become brittle after years of exposure to large amounts of neutron radiation because the elements added to the steel to make it stronger change into other elements. Construction of devices that handle large amounts of neutrons must take this effect into account.

Fission and Chain Reactions

In the late 1800s and early 1900s Germany had some of the best chemists and physicists in the world. One of them was Lise Meitner who was born to a Jewish family in Vienna, Austria (see Figure 4.7)

Figure 4.7 Lise Meitner and Otto Hahn discovered fission

She was the second woman to earn a doctorate in physics from the University of Vienna. When Hitler came to power in 1933, she was acting director of the Institute for Chemistry. Unlike other Jews in high academic position, she was allowed to keep her job because she was an Austrian instead of a German. She worked with Otto Hahn on an experiment that attempted to use neutrons to transmute uranium into larger elements. In 1938, she fled Germany with just what she could carry and a diamond ring that Hahn gave her to use in case she had to bribe a border guard. Hahn continued the experiment with Uranium and shared the findings with Meitner in a series of letters. Instead of creating new elements beyond Uranium, his sample was unexplainably contaminated with other elements that were a about half the size of Uranium. Hahn did not recognize the significance of the data from the experiment but Meitner did. She realized that some of the uranium atoms were splitting—nuclear fission—instead of transmuting. A single neutron could be absorbed by the nucleus which made it unstable. Instead of emitting a beta, many of the Uranium atoms would split approximately in half plus three more neutrons and a huge amount of energy due to the missing mass. The atoms that are roughly half the size of Uranium are called daughter products. Daughter products tend to be radioactive isotopes. Meitner further realized that under the right conditions, if one or more of the neutrons released by the fission caused other fissions, there would be a chain reaction where many atoms would fission quickly releasing nuclear energy that is millions of times more powerful than chemical explosives. Hahn published the results of his chemical experiment in 1939 and Meitner published her explanation two months later where she named the process nuclear fission. Hahn received the Nobel Prize in chemistry for the discovery of nuclear fission but Meitner did not. Hitler's persecution of Jews caused many of the best physicists in Europe to flee to other countries which reduced the effectiveness of their research in this new field.

Key Takeaways

The number of protons in a nucleus determine the element. The number of neutrons in the nucleus determine which isotope it is. [4.1.1]

The nucleus can emit four types of radiation

Alpha – a helium nucleus with two protons and two neutrons

Beta – an electron

Gamma – a photon of light that is similar to an x-ray

Neutron – a neutral particle similar in size to a proton but with no charge. [4.1.2]

Ionizing radiation is radiation that can break the bonds between molecules or atoms and their electrons producing charged particles (ions). These ions change the chemistry of those molecules which can be damaging to living cells. The amount of damage a type of radiation does to living cells is proportional to the amount of ionization. The greatest is alpha, then beta, and finally gamma. Neutrons do not cause ionization. The shielding necessary to stop them is inversely proportional to their ionization. Alpha takes the least (about a quarter-inch of air), followed by beta and gamma. [4.1.3]

We are surrounded by sources of radiation from space, rocks, and other living things. The typical amount of radiation that is naturally present is called background radiation. [4.1.4]

Atoms can be transmuted from one element into another if they emit a charged particle that affects the number of protons in the nucleus. If an alpha is emitted, the number of protons is decreased by two. If a neutron in the nucleus splits and emits a beta, an extra proton is left which increases the number of protons by one. If an extra neutron is absorbed and then emits a beta, the result is one more proton. [4.1.5]

A chain reaction happens when a large atom like Uranium absorbs a neutron and then splits into smaller atoms and two or more neutrons that have less total mass which is converted to energy. The neutrons can cause more Uranium atoms to split resulting in a sequence of splits that release large amounts of energy. [4.1.6]

The Nazis persecuted Jews and Gypsies. Many of the best physicists in Germany and Italy came to the U.S. for this reason where they convinced the President to build a nuclear bomb before the Nazis did. [4.1.7]

2 People and Radiation

Learning Objectives

1. Identify how ionizing radiation causes radiation sickness. [4.2.1]
2. Identify the method used for predicting the health effects of exposure to small additional amounts of radiation. [4.2.2]
3. Identify the medical uses of x-rays. [4.2.3]
4. Identify the similarities and differences between x-rays and gamma rays. [4.2.4]
5. Identify the mechanism by which certain isotopes are concentrated in certain human organs. [4.2.5]

Ionizing radiation can be harmful and helpful to humans depending on the amount and type of exposure.

Harmful Effects of Radiation on Humans

Ionizing radiation creates ions and ions behave differently than neutral atoms. If there are too many ions created within a single cell of a plant or animal, the cell's chemistry is altered too much and the cell can die. It is normal for cells to die from many different causes and plants and animals deal with this in normal ways and stay healthy. If more cells are killed than the plant's or animal's system can handle, it can become sick or even die which is called radiation sickness. Radiation sickness becomes apparent hours after exposure to large amounts of ionizing radiation. It is like a having a sunburn throughout the body.

When people are exposed to large amounts of radiation, it causes illness and death and the amount of illness and death is roughly proportional to the exposure. If that trend is extrapolated—extended—downward to much smaller amounts of additional exposure a small amount of additional illness or death would be expected. If a large population were exposed, this method would predict a small percentage of additional deaths which would still be thousands of people. After the nuclear accidents at Three-mile Island (TMI) in the U.S. in 1980 and Chernobyl in the Ukraine in 1986, this method was used to predict that that there would be thousands of additional cancer deaths during the lifetimes of those exposed. (World Health Organization 2005) After thirty years, those predictions of higher than normal amounts of cancer have yet to be seen so it is most likely that this method of prediction is not accurate when extrapolated to levels of radiation that are close to the normal amount of background radiation. (U.S. NRC 2011), (World Nuclear Association 2011)

Diagnostic X-rays Used in Health Care

Photons of light that have enough energy to cause ionization but which are created outside the nucleus are called X-rays in English speaking countries and Roentgen rays in Germany. These rays of photons are like gamma rays but usually have less energy and they do not come from the nucleus. Because they are similar to gamma rays and they cause ionization like nuclear radiation, they are included in this discussion.

These rays are created by sending a stream of electrons to collide with a metal plate. When the electrons stop suddenly, they give off these high-energy photons. X-rays can penetrate soft tissue but are blocked by bone and metal. If a source of X-rays is placed on one side of a person's body, and a photographic film or digital photo detector is placed on the other, the bones in the body cast shadows. The resulting image shows the outline of the bones including large breaks or cavities in teeth, as shown in Figure 4.8.

Figure 4.8 Dental x-ray

If lower energy is used to make the x-rays, the photons can be stopped by softer tissue. This type of x-ray is used for breast examinations and is also known as a mammogram, as shown in Figure 4.9.

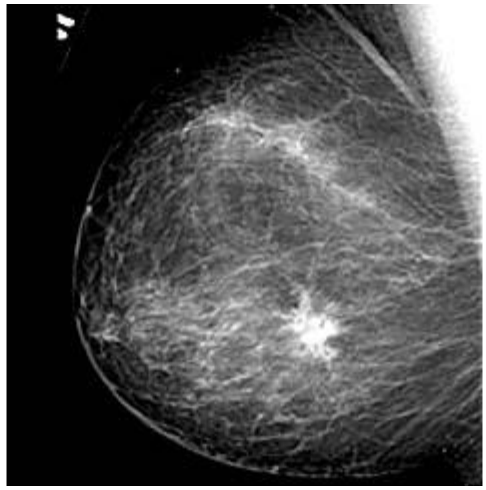

Figure 4.9 Breast x-ray also known as a mammogram

The controversy over the effects of low levels of ionizing radiation affects the use of radiation as a diagnostic tool. Because physicians are not sure if low amounts of radiation cause harm, they choose to err on the side of caution unless the benefit outweighs the perceived risk. Dental technicians leave the room after they place an apron with lead shielding over the person's body. Some doctors are reluctant to use x-rays for breast examinations on all women because they are concerned that exposing large numbers of women to ionizing radiation would cause some cancers.

Multiple x-rays can be taken of a narrow region of the body from different angles. This process is called X-ray Computed Tomography (CT) or Computer Aided Tomography (CAT). The process of taking the multiple images of a narrow region is called a scan.

Digital detectors are used instead of film and this data is fed into a computer. The computer constructs an image that appears to be a slice across the body, as shown in Figure 4.10.

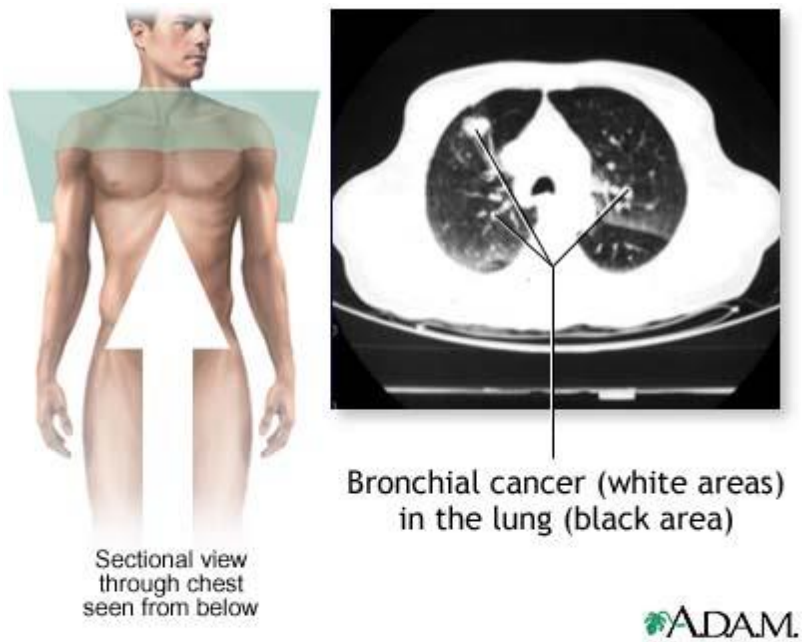

Figure 4.10 CT Scan

New technologies in x-ray detection replace film with arrays of detectors like those in a digital camera that are more sensitive than film and require smaller amounts of radiation. This allows doctors to take scans of many layers and then use a computer to construct a three-dimensional image, such as Figure 4.11.

Figure 4.11 Three dimensional image constructed from multiple CT scans

If the power is increased to the electron beam, the x-rays cause enough ionization to kill cells. A beam of high-energy x-rays is directed through the cells of a tumor to kill it. Computers, robots, imaging x-rays and high-energy x-rays can be used together in a system that is designed to target hard to reach areas or parts of the body that are in constant motion to kill tumors, as shown in Figure 4.12.

Figure 4.12 Imaging x-rays used to target tumors that are destroyed by high-energy x-rays

X-rays are a form of ionizing radiation similar to gamma rays but they do not come from the nucleus. Because they are commonly used for medical imaging, exposure to nuclear radiation is often compared to them. For example, the amount of radiation exposure that people who lived near Three-Mile-Island was comparable to a chest x-ray.

Biological Concentration

The human body extracts certain chemicals from food or water and concentrates them in particular organs. For example, iodine is concentrated in the thyroid gland in the neck and calcium is concentrated in the bones. If a radioactive isotope of one of these elements that emits gamma rays is ingested, it will be transported and concentrated in a particular part of the body. The gamma radiation from the isotopes can be detected outside the body to form an image that is similar to an x-ray. Recall that an x-ray image is essentially a shadow. A an image created from radioactive isotopes is like seeing tiny sources of light inside the body where the isotopes are biologically concentrated.

The most severe result of the Chernobyl accident beyond the immediate vicinity of the plant was the effect of the radioactive isotope of iodine that was released. The iodine was deposited on grass which was eaten by cattle that produced milk which was consumed by children. The iodine was biologically concentrated in the thyroid glands of the children which caused approximately 4000 cases of thyroid cancer.

Fortunately, this type of cancer is highly treatable by removing the thyroid gland and few deaths resulted.

Key Takeaways

- Ionizing radiation breaks chemical bonds in molecules and knocks electrons from atoms. The resulting ions behave differently in a cell and might cause the cell to die. If enough cells die over a short period of time, a person becomes ill which is known as radiation sickness. It is like having a sunburn throughout the body. [4.2.1]
- A known relationship between high doses of radiation and resulting cancers is extrapolated to low levels. When this method is applied to large populations, predictions of thousands of additional cancers result. These predictions have not be supported by evidence twenty and thirty years after TMI and Chernobyl except for the thyroid cancers where the Iodine was biologically concentrated. [4.2.2]
- X-rays penetrate soft tissue but are stopped by dense tissue and bones. An x-ray source casts a shadow on film or photo detectors that show the bones and denser tissue. Computers can be used to interpret multiple x-rays to make an image that looks like a slice through a person or a complete 3-D model. [4.2.3]
- X-rays and gamma rays are both photons of light. X-rays are produced by machines using a beam of electrons and gamma rays are emitted from the nucleus of atoms. The machines can produce a range of x-rays with different amounts of energy that are often less than gamma rays. [4.2.4]
- Body organs extract certain elements from the bloodstream to do their jobs. If radioactive isotopes of those elements are in the body, they will be concentrated in those organs. [4.2.5]

3 Nuclear Reactor Design

Learning Objectives

1. Identify percentages of U-238 and U-235 that are normally found in Uranium. [4.3.1]
2. Identify how the percentage of U-235 is increased and what percentages are used in fuel rods and in weapons. [4.3.2]
3. Identify the steps of a chain reaction. [4.3.3]
4. Identify the role of a moderator in a chain reaction and the elements that are used as moderators. [4.3.4]
5. Identify the parts of a nuclear reactor that generates electricity. [4.3.5]
6. Identify the purpose of a breeder reactor. [4.3.6]

After Hahn and Meitner discovered that Uranium could fission and potentially create a chain reaction that could release millions of times more energy than a chemical reaction, several countries set about to build devices that could sustain a nuclear chain reaction. This turned out to be very difficult.

Uranium Enrichment

Uranium, like most other elements, is a mixture of isotopes. By far the most common isotope (99.28%) is

$^{238}_{92}U$. Unfortunately, this isotope doesn't fission easily or frequently enough to support a chain reaction. In every sample of uranium, less than one percent (.7%) is $^{235}_{92}U$. This isotope will fission if it absorbs a neutron that is not traveling too fast. In a normal sample of uranium, the U-238 gets in the way and absorbs the neutrons without splitting. To sustain a chain reaction where at least one of the neutrons emitted by the fission causes another fission, the percentage of U-235 must be increased from less than 1% to between 3% and 5%. This is a very difficult problem to solve because both isotopes are chemically identical so none of the usual chemical methods work. To create a chain reaction that releases the energy from almost all of the U-235 at once in an explosion, the percentage must be about 90%.

The only thing the physicists could work with was the very small difference in the mass of U-238 and U-235. The most successful device for separating the two isotopes due to the difference in their mass is the centrifuge. The uranium is turned into a gas which is placed in a spinning cylinder. The more massive U-238 collects near the walls forcing the less massive U-235 toward the center where it is drawn off. This process is repeated thousands of times in rows of spinning tubes to slowly increase the percentage of U-235, as shown in Figure 4.13.

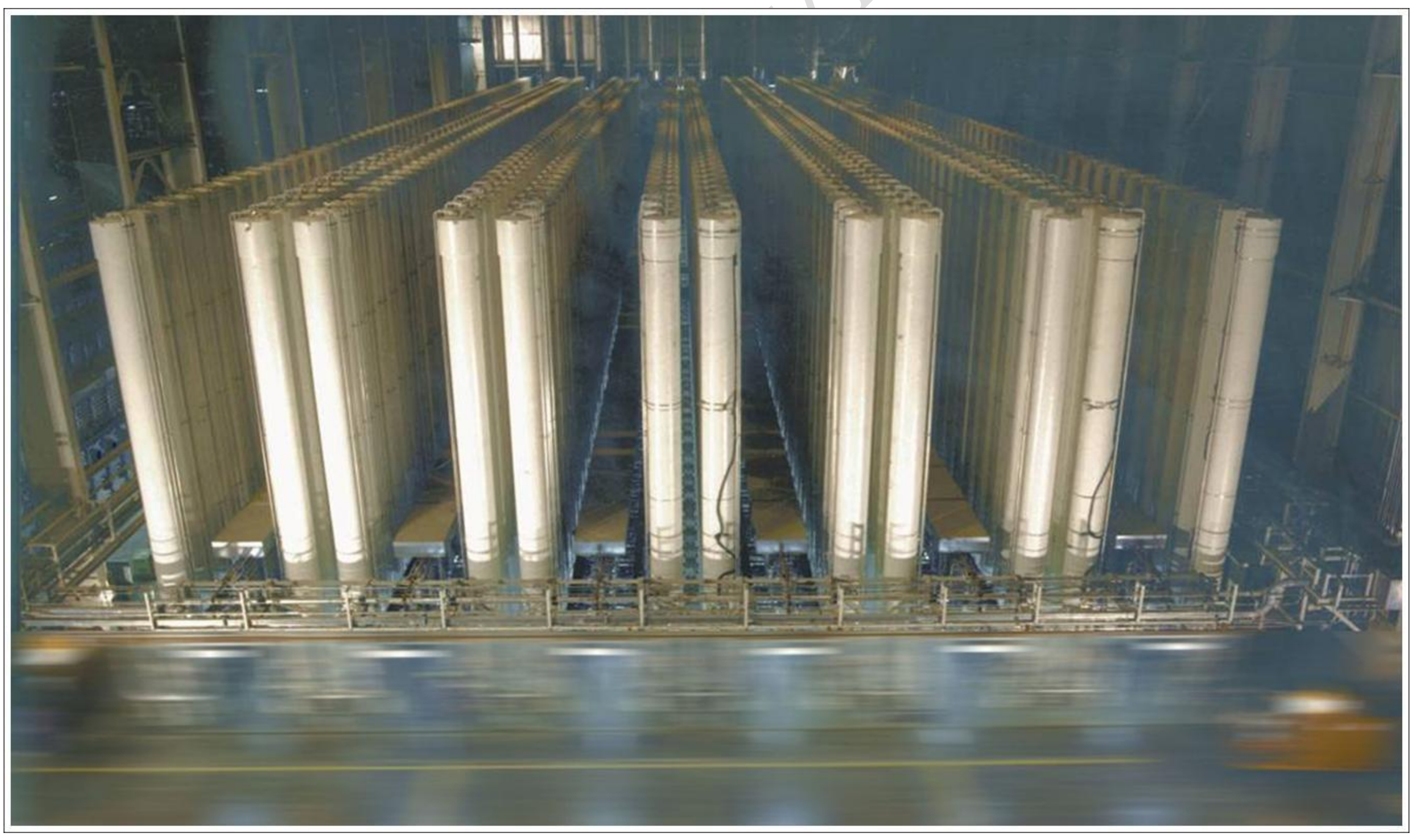

Figure 4.13 Spinning centrifuge tubes separate U-235 from U-238

The left-over Uranium that has a lower than normal percentage of U-235 is called depleted uranium and is used for armor-piercing bullets because it is more massive than lead.

Moderators

A controlled chain reaction can be maintained with lower concentrations of U-235 if the efficiency is improved. When the nucleus splits, the parts fly off at very high speed. It was discovered that the neutrons were more likely to cause another U-235 nucleus to split if they were slowed down so they could be absorbed. To accomplish this, the neutrons are allowed to collide with the atoms of a material that will absorb their energy without absorbing the neutrons themselves. This type of material is called a moderator. An ideal moderator would have atoms whose nuclei are about the same size as a neutron but which don't absorb the neutrons. Early experiments identified the following materials as possible moderators:

> Hydrogen gas: The most common isotope of hydrogen has one proton in the nucleus. Collisions between a neutron and a proton transfer the most energy like a pool ball that stops when it strikes another ball of the same mass squarely. Unfortunately, hydrogen gas isn't very dense and the neutron can stick to the proton instead of bouncing off. It gets hot in the process and will explode if oxygen is present.
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> Paraffin: Paraffin is a hydrocarbon that has a lot of hydrogen atoms in a denser arrangement because it is a solid instead of a gas. It will also catch fire and burn if oxygen is present.
>
> Carbon: Pure carbon in the form of graphite is a decent moderator but it will also burn if oxygen is present.
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> Light Water: Water has two hydrogen atoms and is denser than hydrogen gas or solid paraffin. It is a good moderator with the added benefit that it can be pumped and if allowed to turn into steam, it can turn a turbine. Some of the neutrons will be absorbed by the single protons in the hydrogen atoms.
>
> Heavy Water: The problem of absorption can be reduced if the hydrogen atoms in the water already have a neutron in the nucleus. Normally, water is H_2O where each hydrogen is the isotope ${}^{1}_{1}H$ and the Oxygen isotope is ${}^{16}_{8}O$ so the molecule has a total mass of 18 (16 +1+1). If one of the hydrogen atoms is a heavier isotope, ${}^{2}_{1}H$, the total mass of the molecule is 19. This type of water absorbs fewer neutrons so it is a better moderator and a lower concentration of U-235 is needed. Because of its slightly greater mass (19 vs. 18) it is called heavy water. Water with the more common isotopes of hydrogen is called light water.

Reactor Design

A nuclear reactor uses the heat of fission in fuel rods to boil water into steam. The expanding steam spins a turbine that spins a generator to make electricity. The steam is cooled and condenses back into water which returns to the fuel rods to start the cycle again, as shown in Figure 4.14. The water serves as a moderator and as a source of steam.

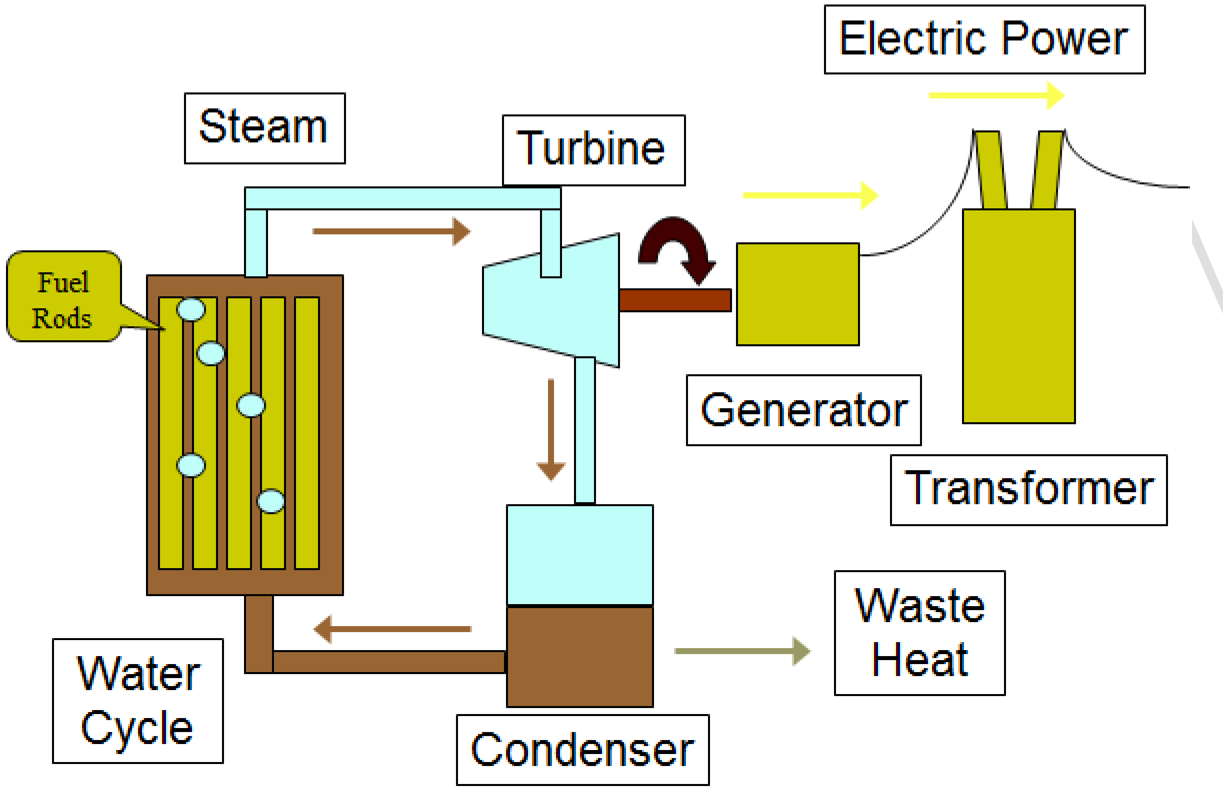

Figure 4.14 Nuclear reactor design

The fuel consists of enriched uranium pellets inside of metal rods. The heat of the fission reaction and the radioactivity of the fission daughter products is enough to melt the metal rods if they are not kept immersed in water. The fuel rods are enclosed in thick metal containment vessel. A fuel rod will produce heat efficiently for several years but it produces less each year as the percentage of U-235 diminishes. After three or four years, the fuel rods are removed and placed in a pool of water for storage, as shown in Figure 4.15.

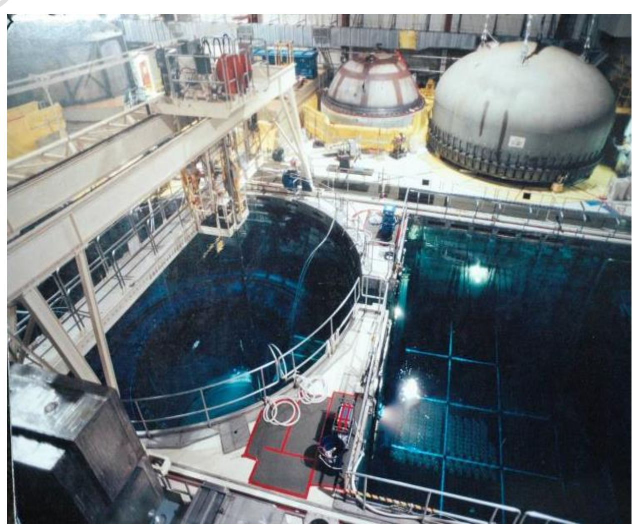

Figure 4.15 Fuel rods being moved from the reactor vessel at left into a storage pool.

These fuel rods still contain a much higher percentage of U-235 than unrefined Uranium which can be recycled. They have daughter products that are very radioactive and still produce heat. Water is circulated in the storage pool to keep them cool. After a few years and several half-lives of the more radioactive daughter products, they can be moved to dry storage in concrete bunkers. In the U.S., the fuel rods are simply stored in pools next to the reactor or in dry storage on the reactor property.

The steam is condensed using cool water from a lake or river. The heated water is evaporated to transfer the heat to the atmosphere and then recycled to cool more steam. Most nuclear reactors use cooling towers like the one shown in Figure 4.16 to cool water that is used to cool the steam.

Figure 4.16 Reactor, generator building, and cooling towers

The white cloud coming from a cooling tower is water vapor. It is not smoke and it does not contain carbon dioxide or any of the other contaminants that are typical of a coal or natural gas powered plant. It does not contain any additional radioactive material from the reactor. All the commercial nuclear power plants in the U.S. use water as a moderator and as a source of steam.

Breeder Reactors

Recall that fission was discovered accidentally while scientists were trying to transmute Uranium into larger atoms like Plutonium. In a reactor, some of the faster neutrons are absorbed by the U-238 and transmuted into Plutonium. The transmutation process uses fast neutrons while the fission of U-235 needs slower neutrons. Recall that the purpose of the moderator is to slow down the neutrons to increase the efficiency of the fission process. If a different moderator, such as carbon or liquid sodium, is used along with a more enriched fuel, there are enough neutrons of both speeds to sustain the chain reaction and to transmute U-238 into Pu-239. The advantage of this process is that Pu-239 fissions as well as U-235. Because this type of reactor design produces usable fuel (Pu-239) it is called a breeder reactor. Because more than 99% of the Uranium found in the earth is U-238, a breeder reactor makes it possible to use it for fuel by converting it to Plutonium.

Key Takeaways

- Uranium found in the earth is 99.28% U-238 and .7% U-235. [4.3.1]
- The Uranium is turned into a gas and placed in a spinning tube called a centrifuge. The small difference in mass causes an increase in the concentration of the lighter isotope, U-235, near the center. The gas is drawn from the center and fed to another spinning tube. This process is repeated thousands of times to increase the percentage of U-235. Fuel rods are about 3% to 5% and a bomb must be at least 90%. [4.3.2]
- A relatively slow neutron is captured by a nucleus of U-235 or Pu-239 which makes it unstable. The nucleus can split into two daughter atoms and three neutrons. Each neutron can cause another fission resulting in a sequence or chain of fissions called a chain reaction. [4.3.3]
- The neutrons coming from a fission are traveling too fast to be efficient at causing other atoms to fission. To increase the likelihood of causing more fissions, the neutrons must be slowed down. If they collide with another material such as water, hydrogen, or carbon they will be slowed down. These materials are called moderators because they moderate the speed of the neutrons. A good moderator slows down neutrons without absorbing them. [4.3.4]
- Fuel rods in a reactor vessel get hot when fission takes place within them. Water between the rods acts as a moderator and it turns into steam. The steam turns a turbine that turns a generator to make electricity. The steam goes into a condenser where it is cooled back into liquid water that is fed back into the reactor vessel. [4.3.5]
- Fast neutrons tend to cause transmutation of U-238 into fissionable Pu-239. Breeder reactors are designed with moderators that slow enough neutrons to keep the chain reaction going but still have enough fast neutrons to transmute or breed Pu-239 from the relatively useless U-238. [4.3.6]

4 Nuclear Reactor Operation

Learning Objectives

1. Identify the advantages of nuclear power compared to coal and oil regarding air pollution. [4.4.1]
2. Compare the rate of accidental deaths from using Uranium versus coal for generating electricity in the U.S. [4.4.2]
3. Identify the applications where nuclear reactors have an advantage over coal or oil in transportation. [4.4.3]

4. Identify the contents of a used fuel rod that can be recycled and those that are waste. [4.4.4]

5. Compare the methods used in the U.S. and in France to deal with used fuel rods and the percentage of electricity generated by nuclear energy in each country. [4.4.5]

6. Identify sources of low-level radioactive waste and how they are handled. [4.4.6]

The U.S. gets about 20% of its electricity from nuclear reactors and all of its submarines and aircraft carriers use nuclear power. When operating normally, they do not release radioactive isotopes or radiation. Because each atom releases a million times more energy than coal or oil, the waste products are far less and are not released into the atmosphere. Nuclear reactors do not emit carbon dioxide or gasses that cause acid rain or lung problems. One of the biggest drawbacks to nuclear power is the risk of accidental release of radioactive daughter products of the fission process.

Reactor Accidents

In the decades of operation since nuclear power plants have been used to produce electricity, there have been three accidents that were severe enough to expose the population to additional radiation that was enough to cause illness and death.

The accident in the U.S. at Three Mile Island in 1980 was the result of a loss of cooling water which allowed some of the fuel rods to melt. The containment vessel and surrounding building did their job and almost all of the radioactive daughter products were contained with the exception of some gasses that leaked out through a vent. The local population was exposed to the equivalent of a chest x-ray of additional radiation and there was no discernable increase in the cancer rates in that area in the thirty years following the accident.

The worst accident on record was the explosion and fire at the Chernobyl reactor in the former Soviet Union in 1986. The Chernobyl reactor was a breeder reactor that used carbon as a moderator. It did not have a thick metal containment vessel. When it accidentally exploded, the carbon caught fire which spread the daughter products, such as Iodine-131 into the atmosphere. About fifty people were killed on site and several thousand cases of thyroid cancer were detected and treated. The population was evacuated from the area near the plant.

The most recent significant accident occurred in 2011 in Fukushima, Japan. A tsunami—surge of water caused by an earthquake—damaged the reactor and its backup power supply. The technicians who were trained to control the reactor did not have power to run pumps or even to run the sensors to tell them what was going on in the reactor. As a result, explosive gasses built up inside the building and when they exploded, they did further damage to the water circulation system. The fuel rods were exposed in the reactor vessels and in the storage pools. As a result, the fuel rods melted and released daughter products into the atmosphere. Fortunately, the prevailing winds at the time blew most of the material out over the Pacific Ocean where it dissipated. Minute amounts of radioactive daughter products can be detected over a wide area but they are not concentrated enough to increase the amount of natural background radiation. Because the daughter products continue to produce heat in the fuel rods, cooling is needed for months even after the fission process is stopped. Because the people in Japan already consume food with abundant amounts of Iodine, there is less risk of thyroid cancer and parents in the area were warned to restrict intake of milk and other foods that might be contaminated with Iodine-131. Predictions of the impact of the additional radiation on the population vary greatly depending on whether the extrapolation model is used. Based on what has been observed in the twenty-five years following the Chernobyl accident, there will be few future fatalities.

In the fifty-year history of nuclear power in the U.S., no one has died. By comparison, 33 coal miners die each year in the U.S. (Coal Fatalities by State 2008) [Link] and thousands die in wars fought for oil.

In 1954, the Soviets began operating a nuclear power plant to generate 5 megawatts of electricity. This was followed in 1956 by a 50 megawatt nuclear power plant in England and in 1957 by a 60 megawatt plant in the U.S. Nuclear power plants are used in many countries to generate electricity. In the U.S. approximately 20% of the electricity is generated this way. The country with the highest percentage of its power produced from nuclear energy is France. The French recognized that they didn't have a lot of coal or oil so they chose nuclear power for electrical generation. Today, France has 60 nuclear power plants which produce 79% of its electricity. France exports electricity to Italy, Britain, and Germany and has the lowest cost of electricity in Europe.

Reactors for Transportation

Like the British navy before WWI, the American navy recognized the advantage of using a new energy source to power its ships. Because nuclear energy is a million times greater per atom than chemical energy, a controlled nuclear chain reaction using U-235 or Pu-239 produces great amounts of energy for years without refueling. Because it is not a chemical reaction like burning oil, a ship that is powered by nuclear energy does not need to take in oxygen. In 1954, the U.S. Navy launched the world's first nuclear powered submarine which does not have to surface at all.

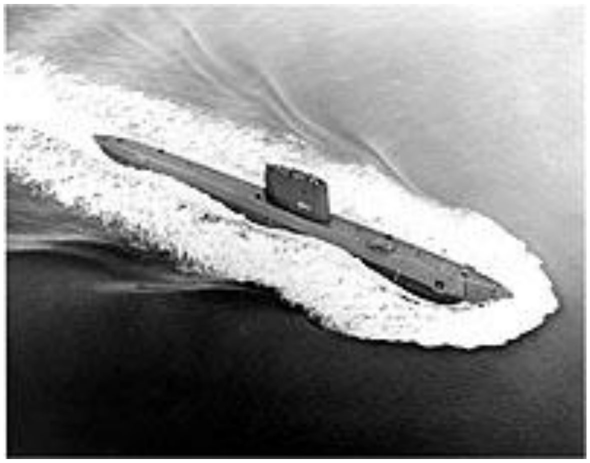

Figure 4.17 Nuclear powered submarine

The U.S. Navy uses nuclear power for all of its aircraft carriers with 11 currently in service. The reactors in the carriers deliver about 280,000 horsepower to move the ships at about 33 knots (38 mph).

Figure 4.18 Nuclear powered aircraft carrier

By 1989, the navies of the U.S., the Soviet Union, the British and the French had 400 nuclear powered submarines in use. Because of the accident at Three-mile Island, the U.S. stopped building civilian power reactors but continued to build them for the U.S. Navy. These relatively small reactors could be used for civilian electric power production.

Nuclear Waste Recycling and Disposal

Used fuel rods are highly radioactive because they contain the daughter products of fission. However, they also contain U-238, U-235, and Pu-239 in higher concentrations that are found in nature. The fuel in the rods can be recycled by chemically removing the highly radioactive daughter products. France produces 78% of their electric power with nuclear fuel and they have a reprocessing plant shown in Figure 4.19

Figure 4.19 Nuclear fuel reprocessing plant in France

The highly radioactive materials are mixed with molten glass and allowed to solidify. This greatly reduces the volume of waste and makes it safe to store or bury. In the U.S., the used fuel rods are stored on the plant site. Originally, the plan was to create a central storage location underground in Nevada, near the old bomb testing site at Yucca Mountain. Politicians could not agree on this solution so the fuel rods are still on-site at most power plants. Older fuel rods that no longer need constant cooling will probably be moved to dry storage inside concrete bunkers.

Recall that neutrons can cause transmutation. Prolonged exposure to neutrons can create radioactive isotopes in materials that are exposed to the reactor core. For example, some of the hydrogen in the water, ${}_{1}^{1}H$, absorbs two neutrons and is transmuted to ${}_{1}^{3}H$ which is also known as Tritium. Periodically, some of the water from the reactor is replaced to keep the level of Tritium down. The water is slightly more radioactive than background and since it is not biologically concentrated, it is quickly dispersed in larger bodies of water like lakes.

Materials that are slightly more radioactive than normal due to exposure to neutrons or contamination by processing daughter products are called low-level waste. They can be stored safely in dry storage in concrete casks or underground with a moderate amount of shielding.

Key Takeaways

- Nuclear power plants do not emit combustion gasses like carbon dioxide or cause acid rain. When operated normally, they occasionally release small amounts of tritium that is diluted in local bodies of water. [4.4.1]
- There have been no accidental deaths from the use of nuclear power for generating electricity in the U.S. On average, about 33 coal miners die each year. [4.4.2]
- The extended range of a nuclear powered ship makes nuclear reactors ideal for naval vessels and the ability to operate underwater without air makes the ideal for submarines. The steam generating system makes them too heavy for use in individual vehicles or planes. [4.4.3]
- Used fuel rods contain U-238, U-235, and Pu-239 that can be extracted and used in new fuel rods. They also contain the daughter products that are highly radioactive that can be separated and stored behind shielding such as concrete or underground. [4.4.4]
- The U.S. stores used fuel rods next to the main reactor in pools of water or in concrete casks after they cool enough so they don't need constant cooling. The French reprocess the fuel rods at a central facility. The U.S. gets about 20% of its electricity from nuclear while France gets about 78% [4.4.5]
- Neutrons can transmute hydrogen into tritium in the water that can be periodically released into larger bodies of water. It is not biologically concentrated. Solid materials like the steel of the containment vessel and used fuel rod casings are stored behind shielding or underground. [4.4.6]

5 Nuclear Explosives

Learning Objectives

1. Describe the process of a nuclear fission explosion and how the power is rated. [4.5.1]
2. Describe the historical context of the first use of nuclear weapons against civilian targets. [4.5.2]
3. Identify the key components of a hydrogen bomb and compare its power to fission-only bombs. [4.5.3]
4. Describe the concept of Communism and the reasons for a cold war instead of direct conflict between the U.S and the Soviet Union. [4.5.4]
5. Identify the countries that have nuclear weapons and roughly how many they have. [4.5.5]
6. Identify the reasons for maintaining control of used fuel rods when selling nuclear

power plants. [4.5.6]

7. Identify the three countries that have about half of the world's uranium ore deposits compared to the percentage in the U.S. [4.5.7]

Recall that a chemical explosive is a material whose molecules release their stored energy quickly. The same is true of a nuclear explosive but the energy is coming from the fission or fusion of nuclei. The problem with chemical explosives like nitroglycerine is that they tend to explode easily. The opposite is true of a nuclear explosion using fissionable atoms like U-235 or Pu-239. To release the energy from a lot of the atoms in a very short time, a sufficient number of fissionable nuclei—a critical mass—must be close together long enough for the nuclei to exchange neutrons.

The challenge is to keep the critical mass together while the energy released by the first atoms to fission is blowing it apart. To achieve this, nuclear bombs are made of pieces of enriched Uranium or Plutonium—each of which is less than the critical mass—surrounded by chemical explosives that drive the pieces together in a symmetric implosion. Timing the detonation of the chemical explosives is critical. If the implosion isn't a perfect sphere only part of the material will fission resulting in a much less powerful explosion called a squib. Proper design of a bomb is an important engineering accomplishment but it is the type of information that can be shared easily.

The Manhattan Project

The Manhattan project produced enriched Uranium and Plutonium that was used to make nuclear bombs. By the time the bombs were ready, Germany had surrendered but the President of the U.S. decided to use the bombs to force Japan to surrender. As a result, Japan had fewer civilian casualties than might have otherwise occurred. Germany and Japan had approximately the same size civilian populations but Germany had 1.6 million civilian deaths compared to .6 million civilian deaths in Japan.

The world was introduced to nuclear energy first as a weapon of destruction. To compare the energy of nuclear weapons to chemical bombs, they are compared to tons (2000 lbs) of TNT. The first nuclear bomb used against Japan (see Figure 4.20) converted less than a gram of mass into energy, releasing as much energy as 15,000 tons (15 kilotons) of TNT which destroyed the city of Hiroshima and killed approximately 100,000 people on August 6, 1945.

To place this event in context of the war, Hiroshima was not the first city that was destroyed in one attack during the war where large numbers of civilians were killed. The allies used a method of setting an entire city on fire at once causing a firestorm where the rising hot air creates its own wind of over 100 mph. This technique was used against major cities in Germany and Japan;

- The German city of Hamburg was attacked on July 27, 1943 where 739 bombers killed approximately 50,000 people
- In the German city of Dresden in February 1945, 1,300 bombers killed approximately 32,000 people. The Germans surrendered twelve weeks later.
- In Japan, on the night of March 9–10 1945, 279 B-29s dropped approximately 1,700 tons of bombs on Tokyo that were designed to start fires. Approximately 16 square miles of the city was destroyed and over 100,000 died in the resulting firestorm.

Firebombing was used against sixty-seven Japanese cities resulting in approximately 500,000 deaths but this was not enough to force surrender. The fact that was most striking about the use of a nuclear weapon was that an entire city was destroyed by one plane with one bomb. Japanese physicists had some idea of how hard it would be to enrich enough uranium to make a bomb. Some of them thought that the U.S. might not have enough for a second bomb and they advised the government of this opinion. They were almost right.

Once the Manhattan Project had enough enriched uranium to sustain a controlled chain reaction, they used the neutrons to breed plutonium. Because plutonium is a different element with different chemical characteristics, it is far easier to separate and concentrate it to make smaller, more powerful bombs. The first atomic bomb used plutonium and it was tested in Nevada. The second plutonium bomb was used against the Japanese city of Nagasaki where it killed approximately 80,000 people and it became apparent to the Japanese that the U.S. could produce many more. See Figure 4.21. Six days later, the Japanese surrendered. The explosive power of the plutonium bomb was equal to 21,000 tons of TNT (21 kilotons).

Figure 4.20 Replicas of the nuclear bombs used on Japan. Uranium bomb is in front.

Hydrogen Bomb

Research continued after WWII to develop more powerful bombs. Another Jewish scientist who fled the Nazis in Hungary and came to the U.S. was Edward Teller. Teller recognized that the tremendous heat and pressure emanating from a fission explosion was strong enough to force hydrogen nuclei together similar to the sun's heat and gravity. Teller worked with Stanislaw Ulam, who was a mathematician originally from a Jewish family in Poland. They designed a bomb they called *the super* that used a fission bomb at the core and placed a hydrogen compound around to it. The blast from the fission bomb caused the hydrogen to fuse and release more energy. The energy released from the hydrogen fusion increased the amount of energy by a factor of a thousand. The new hydrogen bomb released as much energy as millions of tons of TNT. Most nuclear bombs produced by the U.S. after 1952 were hydrogen bombs whose power was rated in megatons of TNT. To grasp the magnitude of this number, consider that a typical pickup truck can carry about a half-ton of payload in the back. If it were stacked with cases of high-explosive it would take two million of these trucks to carry one megaton of chemical explosives.

Figure 4.21 First hydrogen bomb in 1951 had a fireball three miles wide. It was rated at 10 megatons.

The Cold War

The axis powers of Germany, Italy, and Japan sought to use the energy from coal and oil to create large empires. They used traditional concepts of racial superiority to justify their actions. Their defeat marked the end of an era. The next challenge the world had to face was an idea—communism.

The idea of a commune is not new. For example, early Christians in Greece lived together and shared what they had. The idea became stronger in response to the abuse of power by individuals who controlled the new industries and cities and who did not share their wealth. People who borrow money (capital) and use it to make products which they sell for a profit are capitalists. People like John D. Rockefeller used their money to impose their will on smaller capitalists and individual workers and amassed great fortunes. The average person witnessed the enormous wealth that a few people had and resented some of the tactics they used. In some countries, the power of the individual capitalists was counter balanced by the power of popularly elected officials, a bill of rights of individuals, a court system, and labor unions. In countries where the average worker did not have these rights, such as in the oil fields of Baku, the workers became increasingly angry.

In the mid-1800s Karl Marx (see Figure 4.22) and Frederick Engles gave this anger a voice and published the communist manifesto.

> Modern Industry has converted the little workshop of the patriarchal master into the great factory of the industrial capitalist. Masses of laborers, crowded into the factory, are organized like soldiers. As privates of the industrial army, they are placed under the command of a perfect hierarchy of officers and sergeants. Not only are they slaves of the bourgeois class, and of the

bourgeois state; they are daily and hourly enslaved by the machine, by the overlooker, and, above all, in the individual bourgeois manufacturer himself. The more openly this despotism proclaims gain to be its end and aim, the more petty, the more hateful and the more embittering it is. … abolition of the bourgeois relations of production, an abolition that can be affected only by a revolution… (Marx and Engels 1848) [Link]

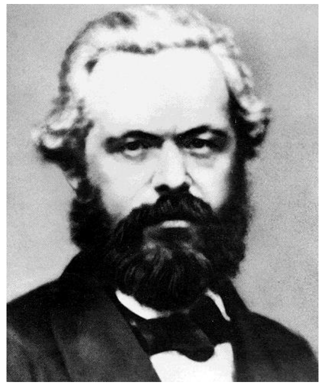

Figure 4.22 Karl Marx called for revolution where the workers took control

In 1917, the communists lead a revolution in Russia and created a new communist country, the Soviet Union. The Soviets defeated the Germans in WWII and captured half of Europe including many Nazi scientists. There were many people in the U.S. and Great Britain who were sympathetic to the Soviet ideals and who passed the secrets of nuclear weapons to the Soviets. The Soviets rapidly developed their own nuclear bomb and tested it successfully in 1949.

The Soviet Union and the U.S. proceeded to build and test new bombs. The radiation from these tests spread throughout the atmosphere until both sides recognized they were damaging the environment and agree to limit testing in 1963 to underground tests.

The Soviets and Americans built thousands of hydrogen bombs using Plutonium for fission that could be delivered by plane or by rocket. They had so many, that each side could completely destroy the other. The Soviets built a 50 megaton bomb that was designed to destroy the U.S. strategic Air Command center even though it is underground. See Figure 4.23.

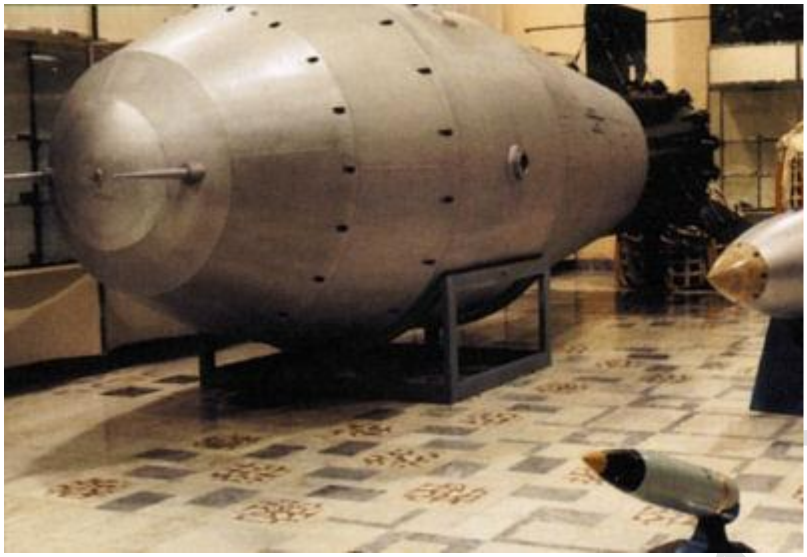

Figure 4.23 Largest nuclear bomb of the cold war built by the Soviets

This policy was ironically referred to as Mutually Assured Destruction (MAD). As a result, the Soviets and Americans chose not to use their weapons. Instead of direct confrontation with nuclear weapons, they chose to fight using conventional weapons in other countries such as Vietnam and Afghanistan. Because there was no direct conflict, the period from the end of WW II in 1945 to the collapse of the Soviet Union in 1991 was called the cold war.

Weapons Proliferation

Because of their ability to destroy an entire city, nuclear bombs are very dangerous. The countries that have the ability to make them and who already have many of them are attempting to reduce the number of bombs. One option is to recycle the fissionable Plutonium and use it for fuel in nuclear reactors.

There are nine countries thought to have nuclear weapons. (Federation of American Scientists 2011) They are:

Country	Estimated Number of Bombs
Russia	11,000
United States	8,500
France	300
China	240
United	225

Kingdom	
India	80
Pakistan	80
Israel (not declared)	80 to 150
North Korea	10

Figure 4.24 Countries with Nuclear Bombs

The minimum enrichment needed to make a chain reaction that is fast enough to make an explosion is about 20%, compared to a few percent for a fuel rod. This is a significant barrier to making nuclear weapons. A shortcut is to set up a breeder reactor that uses the low enriched Uranium as a source of neutrons to breed (transmute) U-238 into Pu-239. Even though the initial concentration of Pu-239 is low in a used fuel rod, it can be extracted and concentrated using standard chemical methods.

As many emerging countries choose to buy nuclear power plants to provide electric power, the key issue is what will be done with the used fuel rods. Even civilian power plants produce some Plutonium in the fuel rods. If those used fuel rods are not returned to the country that provided the plant, the Plutonium can be extracted and a few Plutonium bombs made.

Because breeder reactors can potentially use all of the uranium fuel instead of just the .7% that is U-235, developing countries favor buying breeder reactors. Access to Plutonium that can be chemically concentrated would give them the option of making nuclear weapons simply by increasing the concentration from fuel rod (5%) to 20% or higher. This conflict between efficient use of U-238 and the risk of weapons proliferation is important to understand and to resolve as part of any agreements to provide nuclear power plants to countries that do not already have nuclear weapons.

Uranium Deposits

Uranium ore is found in many countries including the U.S., (World Nuclear Association 2007) as shown in Figure 4.25. This is a table of known recoverable resources as of 2007.

	tonnes U	percentage of world
Australia	1,243,000	23%
Kazakhstan	817,000	15%
Russia	546,000	10%
South Africa	435,000	8%

	tonnes U	percentage of world
Canada	423,000	8%
USA	342,000	6%
Brazil	278,000	5%
Namibia	275,000	5%
Niger	274,000	5%
Ukraine	200,000	4%
Jordan	112,000	2%
Uzbekistan	111,000	2%
India	73,000	1%
China	68,000	1%
Mongolia	62,000	1%
other	210,000	4%
World total	**5,469,000**	

Figure 4.25 Countries with Uranium Ore

Key Takeaways

- Pieces of enriched Uranium or Plutonium are forced together by a chemical explosion called an implosion. If there is enough fissionable atoms near enough to each other to form a critical mass, the chain reaction rapidly releases energy from many atoms at once resulting in an explosion. [4.5.1]
- Jewish scientists who had escaped Nazi persecution in Germany convinced the president to develop nuclear weapons before the Nazis did. The war in Germany ended before the bomb was ready but the U.S. was still at war with Japan. For various reasons, including reducing the loss of life of invading Japan, the President chose to use the bombs on Japanese cities that forced them to surrender. [4.5.2]
- A hydrogen bomb uses a fission bomb as a detonator. The shock wave from the fission explosion compresses the hydrogen that surrounds the fission bomb so that it fuses together. Recall that fusion of hydrogen is the nuclear reaction that provides energy in the sun. [4.5.3]
- Communism is the belief that the workers should own the means of production instead of being virtual slaves to the capitalists who own the factories. They also believed that armed revolution was the only way to gain control. The Soviet Union was founded on the principle of communism and began to spread its revolutionary ideas. The Soviets and the U.S. both had thousands of nuclear bombs and they both knew that an exchange of explosions would destroy both sides. Instead, they fought each other in countries like Vietnam and Afghanistan using local troops and conventional weapons. [4.5.4]
- The U.S. and Russia have thousands; France, China and the U.K have two or three hundred; India, Pakistan and Israel have about a hundred, and North Korea has about ten. [4.5.5]
- Used fuel rods contain some Plutonium that has been transmuted from U-238. It can be extracted

chemically and concentrated into bomb-grade material. If the reprocessing of used fuel rods is left to a country that does not have nuclear weapons, they can make them from the used fuel rods. [4.5.6]

- Of world Uranium deposits, Australia has 23% followed by Kazakhstan at 15% and Russia at 10%. The U.S. has 6%. [4.5.7]

Key Terms

Atomic mass number

the sum of the number of protons and the number of neutrons

Atomic number

the number of protons in the nucleus

Background radiation

naturally occurring nuclear radiation

Breeder reactor

fission reactor designed to use some of the neutrons to convert U-238 to fissionable fuel

Capitalists

people who make money by investing in production and selling the products for a profit

Centrifuge

device used to separate mixtures of liquids or gasses based on the difference in mass by spinning them

Chain reaction

each fission causes the fission of at least one other nucleus

Cold war

contest with communist countries that did not involve direct fighting

Communism

political system that was intended to empower the common worker where the means of production would be owned by all the people

Computed Tomography (CT) or Computer aided Tomography (CAT)

composite image created by a computer from multiple x-ray images

Critical mass

minimum concentration and configuration of fissionable atoms to support a chain reaction

Daughter products

atoms about half the size of uranium produced during fission

Depleted uranium

mixture of uranium isotopes that has less than the normal percentage of U-235

Element

each unique kind of atom determined by the number of protons in its nucleus

Extrapolate

extend a trend forward or backward beyond the known data to predict unmeasured values

Half-life

length of time it takes for half of a sample of radioactive material to emit radiation

Heavy water

water molecules have at least one hydrogen isotope that is more massive than the more common hydrogen atom

Hydrogen bomb

derives most of its energy from the fusion of hydrogen but triggered by a fission explosion

Implosion

an inwardly directed release of energy

Ionizing radiation

can break up atoms into ions

Isotope

family of atoms that are the same element but have different mass due to differing numbers of neutrons

Light water

water molecules that has the a mass of 18 (16 for oxygen and one each for hydrogen)

Mammogram

x-ray of the breast

Moderator

material that slows neutrons without absorbing too many of them

Mutually Assured Destruction (MAD)

policy of maintaining enough nuclear bombs to destroy both sides if either started a war

Nuclear fission

splitting of the nucleus

Nuclear radiation

class of particles and photons coming from the nucleus

Radiation sickness

illness due to more dead cells killed by radiation than the body can dispose of

Radioactive

emits ionizing radiation

Scan

image of a narrow slice of an object or the process of building an image from multiple narrow images

Shielding

material used to absorb radiation

Squib

a partial explosion

Transmutation

process of changing to a different element

Tritium

radioactive isotope of hydrogen with two neutrons and an atomic mass of 3

Works Cited

Coal Fatalities by State. 1 14, 2008. http://www.msha.gov/stats/charts/coalbystate.asp (accessed 1 29, 2008).

Federation of American Scientists. *Status of World Nuclear Forces.* 2011. http://www.fas.org/programs/ssp/nukes/nuclearweapons/nukestatus.html (accessed June 17, 2011).

Korea Atomic Energy Research Institute. *Table of Nuclidec.* 2000. http://atom.kaeri.re.kr/ton/nuc1.html (accessed June 15, 2011).

Marx, Karl, and Frederick Engels. *Manifesto of the Communist Party.* 1848. http://www.marxists.org/archive/marx/works/1848/communist-manifesto/ch01.htm (accessed Jan 27, 2008).

U.S. NRC. *Backgrounder on the Three Mile Island Accident.* March 15, 2011. http://www.nrc.gov/reading-rm/doc-collections/fact-sheets/3mile-isle.html (accessed June 15, 2011).

World Health Organization. *Chernobyl: the true scale of the accident.* September 5, 2005. http://www.who.int/mediacentre/news/releases/2005/pr38/en/index.html (accessed June 15, 2011).

World Nuclear Association. *Chernobyl Accident 1986.* April 2011. http://www.world-nuclear.org/info/chernobyl/inf07.html (accessed June 15, 2011).

—. *World Uranium Mining.* January 1, 2007. http://www.world-nuclear.org/info/inf23.html (accessed June 19, 2011).

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