PDHonline Course E337 (4 PDH)

Nuclear Power Volume I - The Nuclear Power Industry

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Nuclear Power Volume I
The Nuclear Power Industry

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Cover photograph: Courtesy U.S. Nuclear Regulatory Commission (NRC).

Preface

This is the first in a series of three courses about the nuclear power industry. The series covers the nuclear industry from the physics of nuclear reactions to the types of plants in operation today as well as the potential of the next generation of nuclear power plants that are likely to appear in the first half of the 21st century.

The complete series includes three courses:

1. Volume I – The Nuclear Power Industry
2. Volume II – Nuclear Power Plants
3. Volume III – The Future of Nuclear Power

The first course, *Volume I – The Nuclear Power Industry*, gives a broad overview of the nuclear power industry. This course goes into the details of nuclear reactions and the physics of nuclear power. The prime fuel source, uranium, is covered too.

The second course, *Volume II – Nuclear Power Plants*, reviews the classifications of nuclear power plants and the basic components of a nuclear power plant. The course covers the design and operation of the current generation of nuclear power plants in operation today.

The third course, *Volume III – The Future of Nuclear Power*, gives an overview of the types of plants that are being considered for the next generation of power plants. Some of the designs covered are already operating in experimental stages, some are modifications of current designs, and others are radical new concepts that have not been commercially validated.

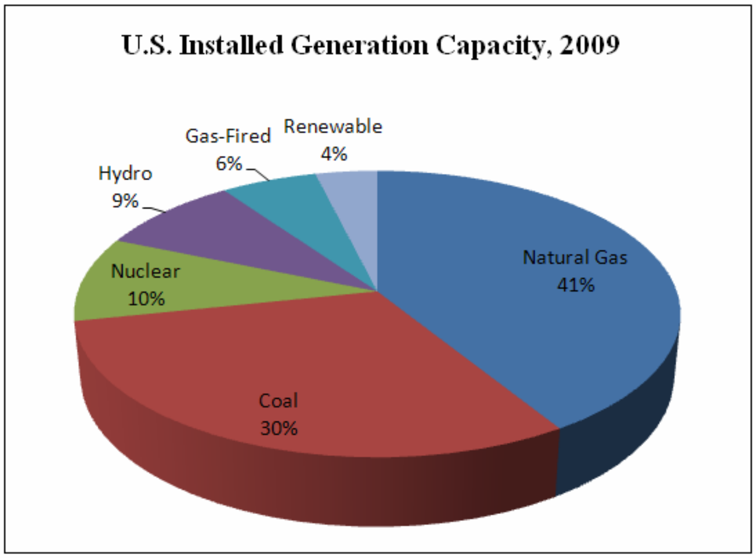
It is not necessary to take the courses in sequence. However, for the best comprehensive it is suggested that the courses be taken in the order presented.

Introduction

A modern technological society requires substantial use of energy to function. While there is currently a lot of talk about energy conservation and renewable energy, the fact is energy consumption is growing and – for electrical base load power – the only practical alternatives are coal, gas, and nuclear energy. Each of these has issues; Coal has environmental issues with carbon dioxide, natural gas is subject to price volatility, and nuclear is expensive. As energy consumption continues to grow – and it will – all three of the traditional base load power sources must be considered to meet our energy needs. This course looks at nuclear power and how it is generated and discusses some of the issues facing the nuclear power industry today.

Meeting the future energy demand requires building many large power-plants over the next few years. If we do not do this and our energy demand grows as expected, we will be faced with large scale blackouts. This is not just an issue for the United States. The rest of World's use of energy is rising too, especially in former third-world nations. The inevitable consequence of the development in places like China and India is a tremendous demand for electricity. Almost all Third World countries (and certainly China and India) intend to raise their standard of living to Western levels. Both these Countries have populations of around 1 billion people and such developments will more than double the world demand for energy. Note that this will happen. The developing world will use energy at a rate comparable to what we did before the end of the 21st Century. China has identified nuclear power as an important component of its future energy mix. India has long-term plans to develop a nuclear power program to meet its own vast energy needs.

It is quite possible to utilize nuclear power to provide the vast majority of an entire country's need for electricity. For instance, in France nuclear power provides 77% of the nation's need for electricity. France generates a surplus of electricity which it exports to neighboring countries.



From a *capacity* standpoint, nuclear is only about 10% of the total electrical generation in the U.S. See the chart on the right. Natural gas is the largest segment of the installed generation in the U.S. at 41%, followed by coal at 30%, and nuclear at 10%. Renewables make up less than 4% of installed capacity (and an even smaller amount of energy consumption.)

From a consumption – or *energy* - standpoint, nuclear power is responsible for approximately 19% of the electrical energy in the United

States. The total generation is approximately 3,800 thousand gigawatt-hours. For comparison purposes, nuclear generation accounts for the following of the total electrical production in some other countries: 77% in France, 46% in Sweden, 43% in Ukraine, 39% in South Korea, 30% in Germany, and 30% in Japan. There are currently 104 licensed commercial nuclear power plants in the United States and 439 worldwide.

The current electrical energy consumption for the entire planet is approximately 1517 gigawatts (GW) of continuous power. The installed nuclear capacity is 371 GW which provides 16% of the electrical power production of the world. The United States produces the most nuclear energy, with nuclear power providing 19% of the electricity it consumes, while France produces the highest percentage of its electrical energy from nuclear reactors—77% as of 2006.

Unlike the coal and oil plants that supply most of the electrical power in the United States, a nuclear power plant, like the one shown on the right, releases virtually no pollution or greenhouse gases into the Earth's atmosphere, and therefore doesn't contribute to global warming. The white stuff puffing out of this plant is non-radioactive water vapor. Although nuclear power plants generate long-lived nuclear waste, this waste arguably poses much less of a threat to the biosphere than greenhouse gases would.

Photo Credit: Nuclear Regulatory Commission

Nuclear power is power produced from controlled nuclear reactions. Commercial plants use nuclear fission reactions. Electric utility reactors heat water to produce steam, which is then used to generate electricity. When an atom undergoes fission it splits into smaller atoms, other particles, and releases energy. It turns out that it is possible to harness the energy of this process on a large enough scale for it to be a viable way of producing energy.

The fundamental point about nuclear energy is that the energy content of one gram of Uranium is equivalent to approximately three tons of coal. This means that we need to consume about three million times less material with nuclear power compared to using coal or any other fossil fuel. This substantially reduces the volumes of fuel and waste of nuclear power compared to fossil fuels.

An alternative to nuclear fission is nuclear fusion. Nuclear fusion reactions are widely believed to be safer than fission and appear potentially viable, though technically quite difficult. Fusion power has been under intense theoretical and experimental investigation for many years and the interest in this concept as waned somewhat in recent years.

Ernest Rutherford is credited as the father of nuclear physics for first splitting the atom in 1917. He split the atom by bombarding nitrogen with naturally occurring alpha particles from radioactive material and observed a proton emitted with energy higher than the alpha particle. Other scientists built on his research and soon discovered that when uranium was bombarded by neutrons the relatively tiny neutron split the nucleus of the massive uranium atoms into two roughly equal pieces. Later, scientists discovered that if fission reactions released additional neutrons, a self-sustaining nuclear chain reaction could result.

Electricity was generated for the first time by a nuclear reactor in 1951 at the 100 kW EBR-I experimental station in Idaho. Incidentally, in 1955, this reactor was also the first to experience partial meltdown. In 1956, the 50MW Calder Hall nuclear power station in the United Kingdom was the world's first nuclear power station to produce electricity in commercial quantities. The Shippingport Atomic Power Station in Pennsylvania was the first commercial reactor in the United States and was opened in 1957.

In 1954, the chairman of the United States Atomic Energy Commission made the famous statement that “nuclear power generated electricity will be too cheap to meter." Of course, this is not true, but the idea took hold that nuclear power could be used to economically generate electric power and installed nuclear capacity initially rose relatively quickly, rising from less than one gigawatt in 1960 to approximately 366 GW by 2005. Most of this growth occurred in the 1970’s and 1980’s. More than two-thirds of all nuclear plants ordered after 1970 were eventually cancelled. A total of 63 nuclear units were canceled in the United States between 1975 and 1980.

A general movement against nuclear power arose during the last quarter of the 20th century, based on the fear of a possible nuclear accident as well as the history of accidents, fears of radiation as well as the history of radiation of the public, nuclear proliferation, and on the opposition to nuclear waste production, transport and lack of any final storage plans. Perceived risks on the citizens' health and safety, the 1979 accident at Three Mile Island, and the 1986 Chernobyl disaster played a part in stopping new plant construction in many countries.

The economics of nuclear power plants are primarily influenced by the high initial investment necessary to construct a plant. In 2009, estimates for the cost of a new plant in the United States ranged from $6 to $10 billion. Therefore it is most economical to run them as long as possible, or construct additional reactor blocks in existing facilities. New nuclear power plant construction costs are rising faster than the costs of other types of power plants.

The first chapter of this course is an overview of the nuclear power industry. The next chapter delves into the physics of nuclear power, followed by a chapter on nuclear fuel.

Chapter 1
Overview of the Nuclear Power Industry

In an electrical generator, a magnet (rotor) revolves inside a coil of wire (stator), creating a flow of electrons inside the wire, which produces electricity. There must be a mechanical device to provide the motive force to turn the rotor. This mechanical device is known as the *prime mover* and the most common prime movers are water turbines, steam turbines, and gas engines. A wind turbine is also a form of prime mover.

When a turbine is attached to the electrical generator, the kinetic energy of the falling water, or steam pushes, against the fan-type blades of the turbine, causing the turbine, and therefore, the attached rotor of the electrical generator, to spin and produce electricity.

Types of Power Plants

In a hydroelectric power plant, water, flowing from a higher level to a lower level, travels through the metal blades of a water turbine, causing the rotor of the electrical generator to spin and produce electricity. See Figure 1 for a view of a hydro power plant.

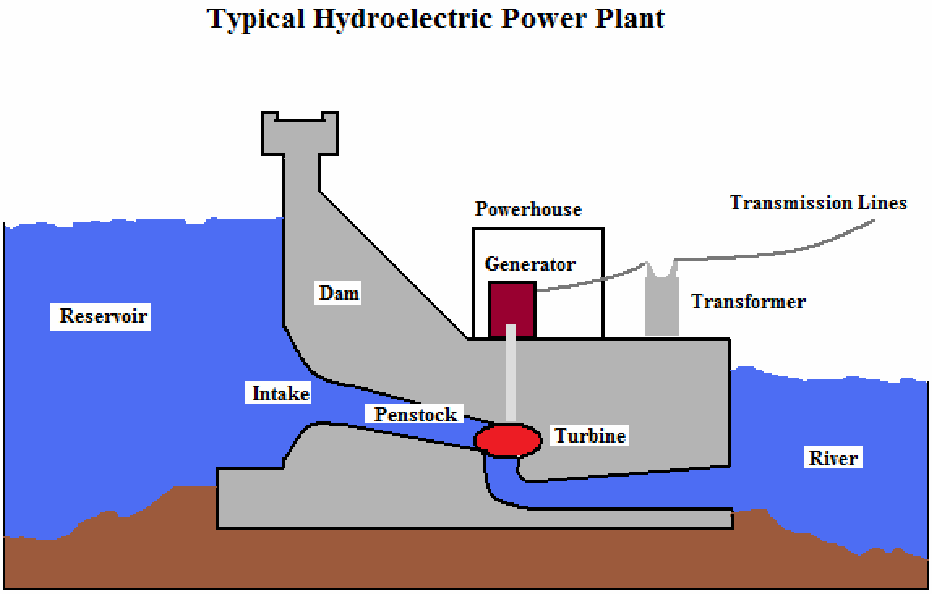

Typical Hydroelectric Power Plant

Figure 1

In a fossil-fueled power plant, heat, from the burning of coal, oil, or natural gas, converts (boils) water into steam, which is piped to the turbine. In the turbine, the steam passes through the blades, which spins the electrical generator, resulting in a flow of electricity. After leaving the turbine, the steam is converted (condensed) back into water in the condenser. The water is then pumped back to the boiler to be reheated and converted back into steam. See Figure 2.

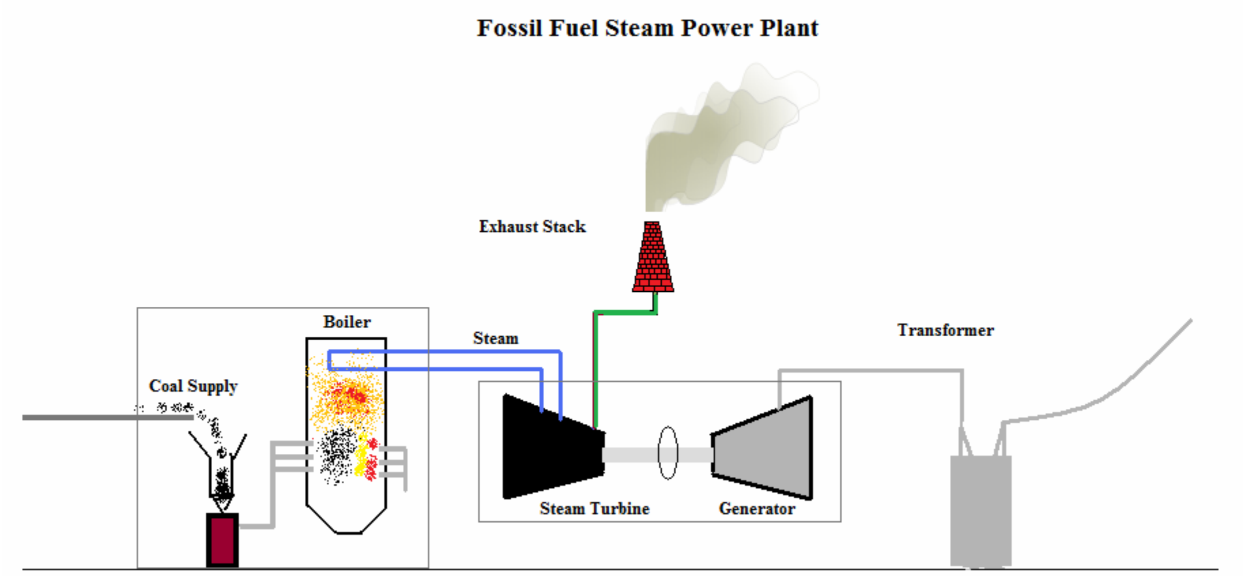


Figure 2

In a nuclear power plant, many of the components are similar to those in a fossil-fueled plant, except that the steam boiler is replaced by a Nuclear Steam Supply System (NSSS). The NSSS consists of a nuclear reactor and all of the components necessary to produce high pressure steam, which will be used to turn the turbine for the electrical generator. See Figure 3.

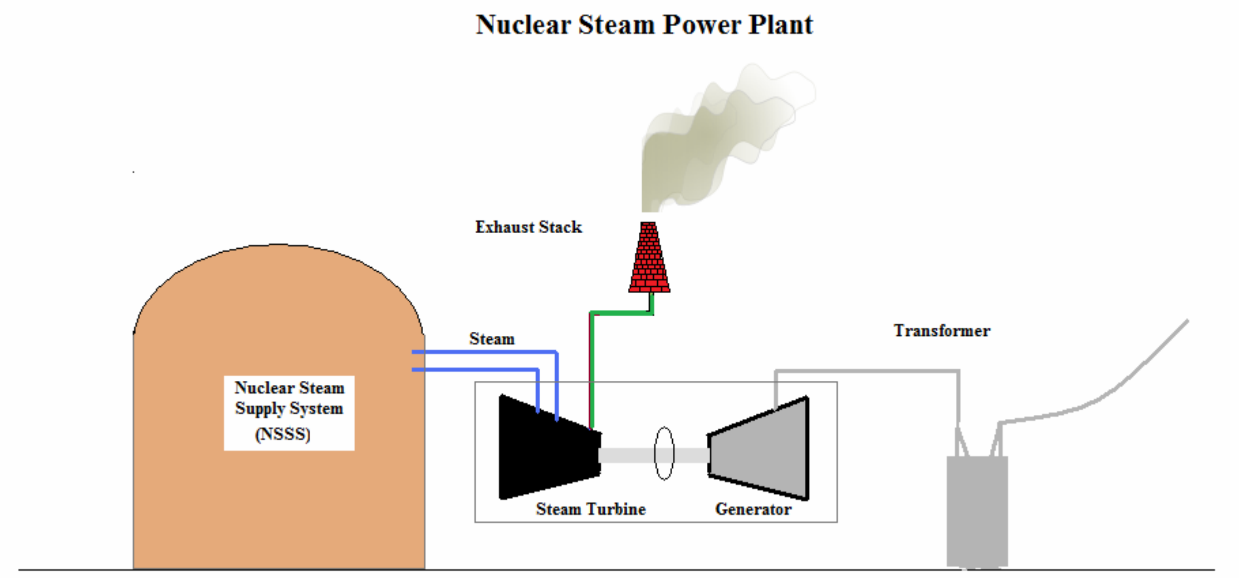


Figure 3

Like a fossil-fueled plant, a nuclear power plant boils water to produce electricity. Unlike a fossil-fueled plant, the nuclear plant’s energy does not come from the combustion of fuel, but from the *fissioning* – or splitting - of fuel atoms.

Nuclear power is produced when a nucleus absorbs a neutron and splits into two lighter nuclei. When a relatively large fissile atomic nucleus (usually uranium-235 or plutonium-239) absorbs a neutron, a *fission* of the atom often results. Fission splits the atom into two or more smaller nuclei with kinetic energy and also releases gamma radiation and free neutrons. A portion of these neutrons may later be absorbed by other fissile atoms and create more fissions, which release more neutrons, and so on. This releases enormous amounts of energy which in turn produces heat. Nuclear reactors harness the heat which is produced from the energy released when the atom splits and convert it into electrical energy. Nuclear reactors produce radioactive waste including long lived radioactive atoms. These radioactive particles are a product of the splitting of the atom. The waste of nuclear reactors is highly radioactive and long lived, and as a consequence must be isolated from humans for many years. The current consensus is that nuclear waste should be disposed in secure containers and placed deep underground. Future technology promises to turn the long lived radioactive particles into shorter lived atoms.

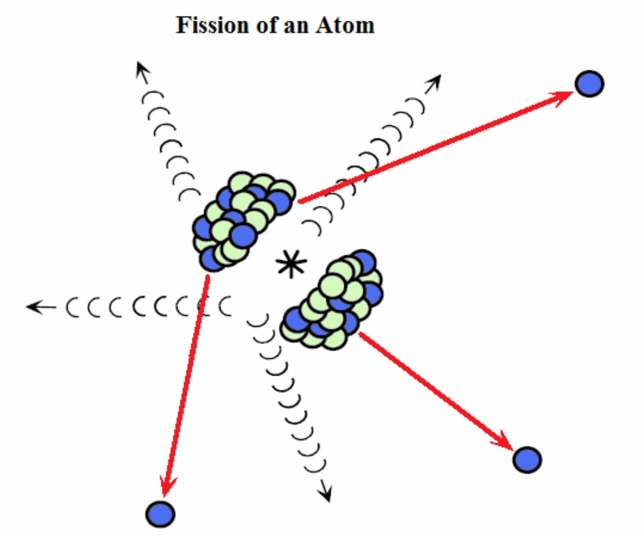

Fission of an Atom

Figure 4

The nuclear fuel cycle begins when uranium is mined, enriched, and manufactured into nuclear fuel, which is delivered to a nuclear power plant. After usage in the power plant, the spent fuel is delivered to a reprocessing plant or to a final repository for geological disposition. In reprocessing 95% of spent fuel can be recycled to be returned to usage in a power plant.

The most common fuel for the electrical producing reactor plants in the United States is uranium. The uranium starts out as ore (as shown in the photograph on the right), and contains a very low percentage (or low enrichment) of the desired atoms (U-235). The U-235 is a more desirable atom for fuel, because it is easier to cause the U-235 atoms to fission (split) than the much more abundant U-238 atoms. Therefore, the fuel fabrication process includes steps to increase the number of U-235 atoms in relation to the number of U-238 atoms (enrichment process).

A nuclear reactor is only part of the life-cycle for nuclear power. The process starts with mining. Uranium mines are underground, open-pit, or in-situ leach mines. The uranium ore is extracted, usually converted into a stable and compact form such as yellowcake, and then transported to a processing facility. Here, the yellowcake is converted to uranium hexafluoride, which is then enriched using various techniques. At this point, the enriched uranium, containing more than the natural 0.7% U-235, is used to make rods of the proper composition and geometry for the particular reactor that the fuel is destined for. Once the fuel has been enriched, it is fabricated into ceramic pellets. The pellets are stacked into 12-foot long, slender metal tubes, generally made of a zirconium alloy. The tube is called the *fuel cladding*.

When a tube is filled with the uranium pellets, it is pressurized with helium gas, and plugs are installed and welded to seal the tube. The filled rod is called a *fuel rod*. The fuel rods are bundled together into *fuel assemblies* or *fuel elements*. The completed assemblies are now ready to be shipped to the plant for installation into the reactor vessel. The fuel rods will spend about three operational cycles – about six years - inside the reactor, generally until about 3% of their uranium has been fissioned, then they will be moved to a spent fuel pool where the short lived isotopes generated by fission can decay away. After about five years in a cooling pond, the spent fuel is radioactively and thermally cool enough to handle, and it can be moved to dry storage casks or reprocessed.

Nuclear Power Plant Reactor Types

There are two broad categories of power plant reactors: Fast reactors and slow reactors. In fast reactors, neutrons emitted in the fission of uranium have a lot of kinetic energy and are moving very fast. A *fast reactor* uses these neutrons by letting them be absorbed directly by the next uranium atom. A problem is that the isotope U-238 (which is not part of the power producing reaction) absorbs these fast neutrons with higher probability than U-235 (which produces the power). To get around this problem, the fuel for fast reactors must be enriched with a much larger fraction of U-235.

A *slow reactor*, also known as a *thermal reactor*, slows down the neutrons produced in the uranium fission to the same speed as the unused fuel. This allows the neutrons to be more readily absorbed by the correct uranium isotope, U-235. There are two basic types of slow or *thermal* reactor plants being used in the United States to produce electricity, the boiling water reactor (BWR) and the pressurized water reactor (PWR). These units are covered in detail in Volume II of this series. Here is a brief overview of BWR's and PWR's.

Boiling Water Reactor (BWR)

The *boiling water reactor* operates in essentially the same way as a fossil-fueled generating plant. Inside the reactor vessel, a steam/water mixture is produced when very pure water - reactor coolant - moves upward through the core absorbing heat. The major difference in the operation of a boiling water reactor as compared to other nuclear systems is the steam void formation in the core. The steam/water mixture leaves the top of the core and enters two stages of moisture separation, where water droplets are removed before the steam is allowed to enter the steam line. The steam line, in turn, directs the steam to the main turbine, causing it to turn the turbine and the attached electrical generator. The unused steam is exhausted to the condenser where it is condensed into water. The resulting water condensate is pumped out of the condenser with a series of pumps and back to the reactor vessel. The recirculation pumps and the jet pumps allow the operator to vary coolant flow through the core and to change reactor power. Boiling water reactors comprise about one-third of the power reactors in the United States.

The major *fuel assembly* components are the fuel rods, the spacer grids, and the upper and lower end fittings. The fuel rods contain the ceramic fuel pellets. The fuel rods are approximately 12 feet long and contain a space at the top for the collection of any gases that are produced by the fission process. These rods are arranged in a square matrix of 8 x 8 for boiling water reactors.

The spacer grids separate the individual rods with pieces of sprung metal. This provides the rigidity of the assemblies and allows the coolant to flow freely up through the assemblies and around the fuel rods. Some spacer grids may have flow mixing vanes that are used to promote mixing of the coolant as it flows around and though the fuel assembly. The upper and lower end fittings serve as the upper and lower structural elements of the assemblies. The lower fitting (or bottom nozzle) will direct the coolant flow to the assembly through several small holes machined into the fitting. There are also holes drilled in the upper fitting to allow the coolant flow to exit the fuel assembly. The upper end fitting will also have a connecting point for the refueling equipment to attach for the moving of the fuel with a crane.

At the nuclear power plant, the fuel assemblies are inserted vertically into the reactor vessel, which is a large steel tank filled with water with a removable top. The fuel is placed in a precise grid pattern known as the *reactor core*.

Pressurized Water Reactor (PWR)

The *pressurized water reactor* (PWR) differs from the boiling water reactor in that steam is produced in the steam generator rather than in the reactor vessel. Both boiling water reactor and pressurized water reactor fuel assemblies consist of the same major components, except that the rods are arranged in a 17x17 square matrix. For pressurized water reactor fuel, there will also be guide tubes in which the control rods travel. The guide tubes will be welded to the spacer grids and attached to the upper and lower end fittings. The guide tubes provide a channel for the movement of the control rods and provide for support of the rods. The upper end of the control rod will be attached to a drive shaft, which will be used to position the rod during operations. The pressurizer keeps the water that is flowing through the reactor vessel under very high pressure (more than 2,200 pounds per square inch) to prevent it from boiling, even at operating temperatures of more than 600F. Pressurized water reactors make up about two-thirds of the power reactors in the United States.

To operate properly, all steam plants, whether nuclear or fossil-fueled, need a circulating water system to remove excess heat from the steam system in order to condense the steam, and transfer that heat to the environment. A cooling system removes heat from the reactor core and transports it to another area of the plant, where the thermal energy can be harnessed to produce electricity or to do other useful work. Typically the hot coolant will be used as a heat source for a boiler, and the pressurized steam from that boiler will power one or more steam turbine driven electrical generators. The circulating water system pumps water from the environment (river, lake, and ocean) through thousands of metal tubes in the plant’s condenser. Steam exiting the plant’s turbine is very rapidly cooled and condensed into water when it comes in contact with the much cooler tubes. Since the tubes provide a barrier between the steam and the environment, there is no physical contact between the plant's steam and the cooling water. Because a condenser operates at a vacuum, any tube leakage in this system will produce an "inflow" of water into the condenser rather than an "outflow" of water to the environment.

Power plants located on the ocean will often discharge their circulating water directly back to the ocean under strict environmental protection regulations. Water is taken from the ocean, pumped through the thousands of small tubes in the condenser to remove the excess heat, and is then discharged back into the ocean. The expected temperature increase from circulating water inlet to outlet is about 5 to 10 degrees Fahrenheit.

Most nuclear power plants that are not located on the ocean need cooling towers to remove the excess heat from the circulating water system. One type of cooling tower is the forced draft cooling tower like the Canton, France plant shown in the photo on the right. The circulating water is pumped into the tower, after passing through the condenser, and allowed to splash downward through the tower, transferring some of its heat to the air. Several large electrical fans, located at the top of the cooling tower, provide forced air circulation for more efficient cooling. The taller hourglass shaped, natural convection cooling towers do not require fans to transfer the excess heat from the circulating water system into the air. Rather, the natural tendency of hot air to rise removes the excess heat as the circulating water splashes down inside the cooling tower. These towers are typically several hundred feet tall.

The steam vented from the top of a cooling tower is really lukewarm water vapor and is not radioactive. As the warm, wet air from inside the cooling tower contacts the cooler, dryer air above the cooling tower, the water vapor which cannot be held by the cooler air forms a visible cloud. This is because the colder the air is, the lower its ability to hold water. The released cloud of vapor will only be visible until it is dispersed and absorbed by the air.

In the next chapter we delve into more of the physics of nuclear power plants.

Chapter 2
Physics of Nuclear Reactions

The earth, and all living things on it, is constantly bombarded by radiation from space. Charged particles from the sun and stars interact with the earth's atmosphere and magnetic field to produce a shower of radiation. This dose of cosmic radiation varies in different parts of the world due to differences in elevation and to the effects of the earth's magnetic field.

Radioactive material is also found throughout nature. It is in the soil, water, and vegetation. Low levels of uranium, thorium, and their decay products are found everywhere. Some of these materials are ingested with food and water, while others, such as radon, are inhaled. The dose from terrestrial sources also varies in different parts of the world. Locations with higher concentrations of uranium and thorium in their soil have higher dose levels. The major isotopes of concern for terrestrial radiation are uranium and the decay products of uranium, such as thorium, radium, and radon.

In addition to the cosmic and terrestrial sources, all people also have radioactive material, such as potassium-40, carbon-14, lead-210, and other isotopes inside their bodies from birth. The variation in dose from one person to another is not as great as the variation in dose from cosmic and terrestrial sources.

In addition to naturally occurring sources, we are exposed to man-made radiation from medical procedures, such as diagnostic X-rays, nuclear medicine, and radiation therapy. We are also exposed to radiation from consumer products, such as tobacco, building materials, combustible fuels, ophthalmic glass, televisions, luminous watches and dials, airport X-ray systems, smoke detectors, road construction materials, electron tubes, fluorescent lamp starters, lantern mantles, etc.

Of lesser magnitude is exposure to radiation from the nuclear fuel cycle, which includes the entire sequence from mining and milling of uranium to the actual production of power at a nuclear plant. The final source of exposure is the shipment of radioactive materials and residual fallout from nuclear weapons testing and accidents, such as Chernobyl.

Chemical Elements

Atoms consist of an electron cloud and a nucleus. The electrons each have the same mass and the same negative electric charge therefore, the mass of an atom is given almost entirely by the nucleus which consists of protons and neutrons. Protons have a positive electric charge and neutrons have no electric charge. The chemical properties of atoms are governed by the number of electrons in the cloud. These match the number of protons in the nucleus and the electric charge of the electron and proton balance exactly. Therefore, atoms are composed of positively charged protons in the nucleus and negatively charged electrons orbiting the nucleus. The simplest atom is hydrogen, composed of one proton and one electron. Its atomic number - which is equal to the number of protons - is one.

More complex atoms have more protons and electrons, but each unique combination of protons and electrons represents a different chemical element. Helium, for example, with two protons, two neutrons, and two electrons, has an atomic number of two. See Figure 5.

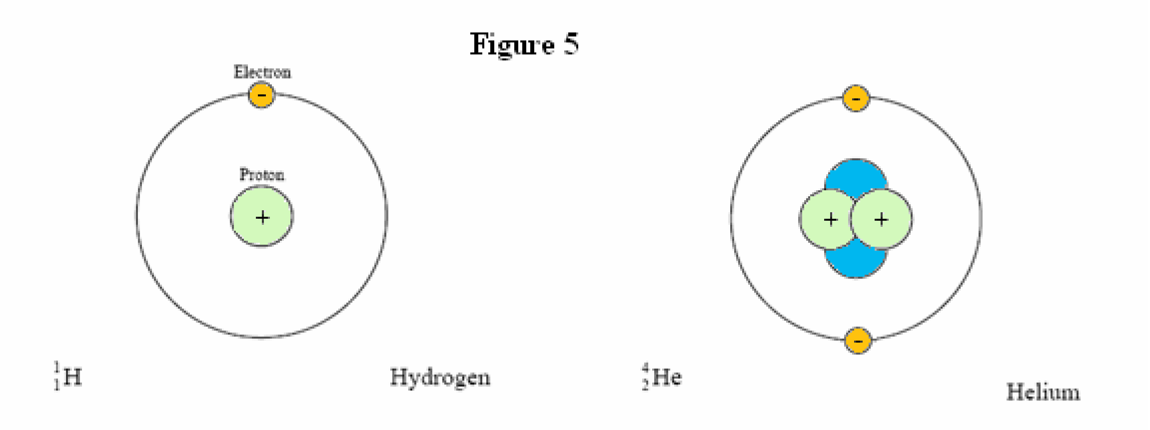
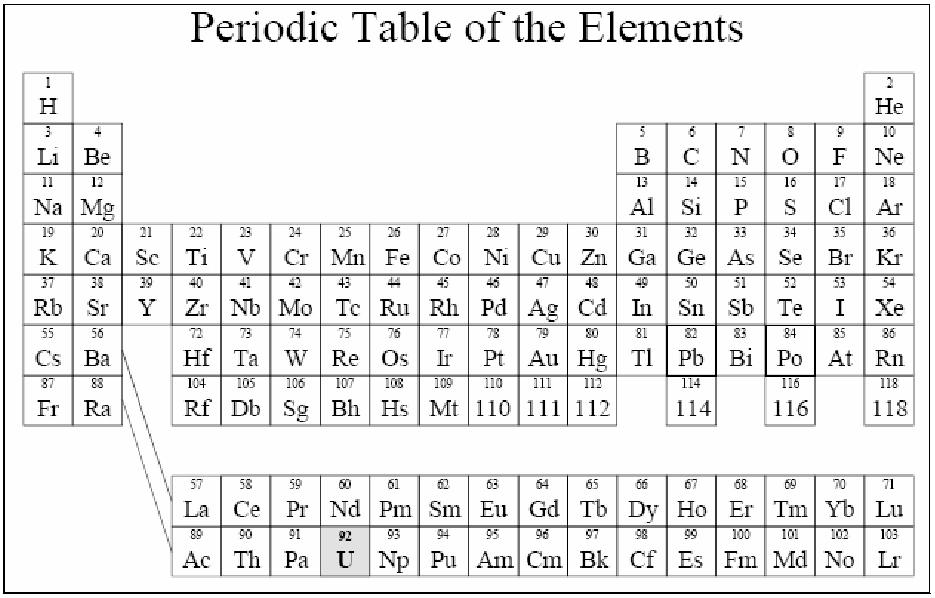


Figure 5

Each element has a chemical symbol. Elements are listed by increasing atomic number and grouped by similar chemical characteristics in the Periodic Table of the Elements as shown below.


Periodic Table of the Elements

1 H																	2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba		72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra		104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 110	111 111	112 112		114 114		116 116		118 118
			57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
			89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

Since all protons are positively charged, and since like charges repel, electrostatic force tends to push protons away from each other. See figure 6.

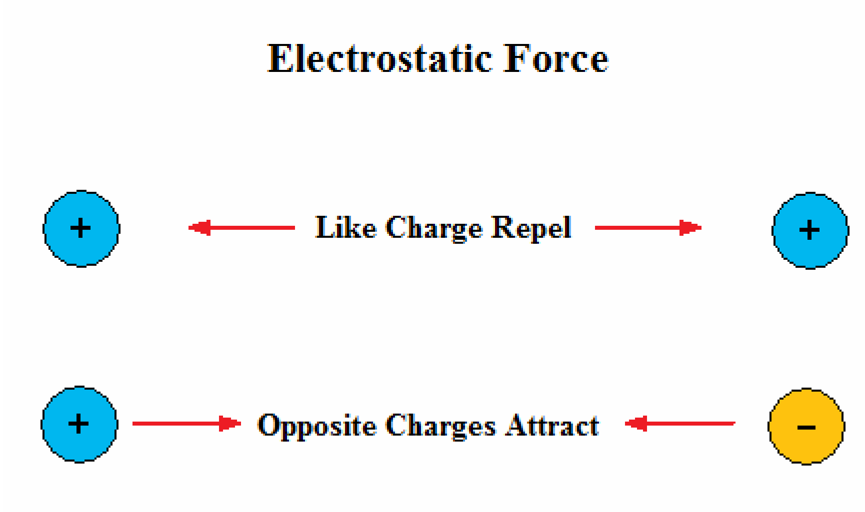


Figure 6

Neutrons, with no electrical charge, provide the attractive nuclear force to offset the electrostatic repulsive forces and hold atoms together. All atoms found in nature, except the basic hydrogen atom, have one or more neutrons in their nuclei.

A chemical element can have several different combinations of protons and neutrons in its nuclei. Hydrogen has three naturally occurring combinations, which are known as *isotopes*. They are:

1. Basic hydrogen (one proton, one electron, and no neutrons),
2. Deuterium (one proton, one electron, and one neutron), and
3. Tritium (one proton, one electron, and two neutrons).

Figure 7 shows the isotopes of Hydrogen.

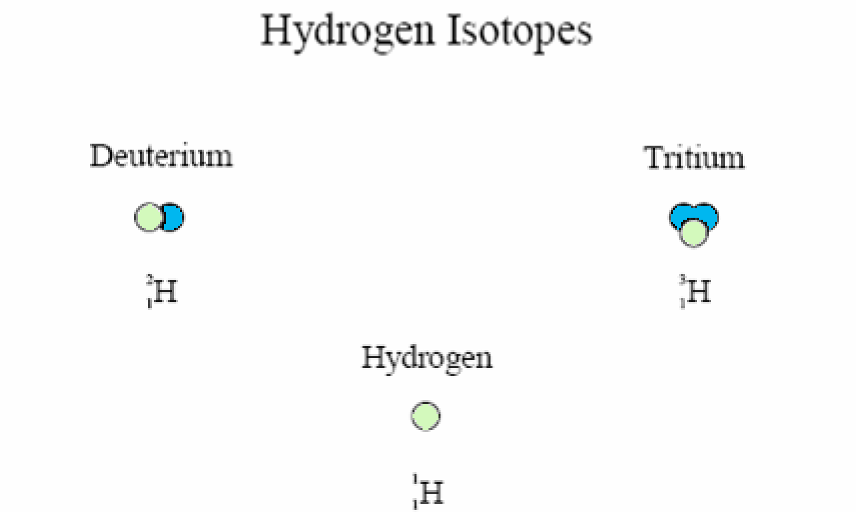


Figure 7

The number of protons an element has (atomic number) determines its chemical characteristics. Atomic numbers are always related to the same element (hydrogen-1, cobalt-27, uranium-92). When used in technical literature, the atomic number is usually written to the lower left of the chemical symbol. Often, the atomic number for an element will be omitted since this number will never change for the element under discussion.

Since chemical elements can have different numbers of neutrons, the use of isotopic numbers (or mass numbers) is necessary to distinguish one isotope from another. Naturally occurring isotopes of the element carbon are shown below. The isotopic number (shown to the upper left hand of the chemical symbol) is the sum of the number of protons and the number of neutrons in the nucleus of an atom.

Naturally Occurring Carbon

$^{12}_{6}C$	$^{13}_{6}C$	$^{14}_{6}C$
6 Protons 6 Neutrons	6 Protons 7 Neutrons	6 Protons 8 Neutrons

Although the placement of the isotopic number in the upper left is technically correct, many variations are encountered. For example, all of the following refer to the same isotope of copper.

Copper-63 **Cu-63** $^{63}_{29}Cu$ $^{63}\mathrm{Cu}$ Cu^{63}

Radiation

Radioactive material contains atoms which are *unstable* and attempt to become more stable by ejecting particles, electromagnetic energy (photons), or both. When a radioactive atom ejects particles and/or photons, the atom undergoes a process called *disintegration* (or decay).

Radiation is the term given to the particles and/or energy emitted by radioactive material as it disintegrates (see Figure 8.) *Radioactivity* is a term which indicates how many radioactive atoms are disintegrating in a time period and is measured in units of *curies*. One curie is defined as that amount of any radioactive material that will decay at a rate of 37 billion disintegrations per second (based upon the disintegration rate of one gram of radium-226).

Unstable atoms have excess energy in their nuclei.

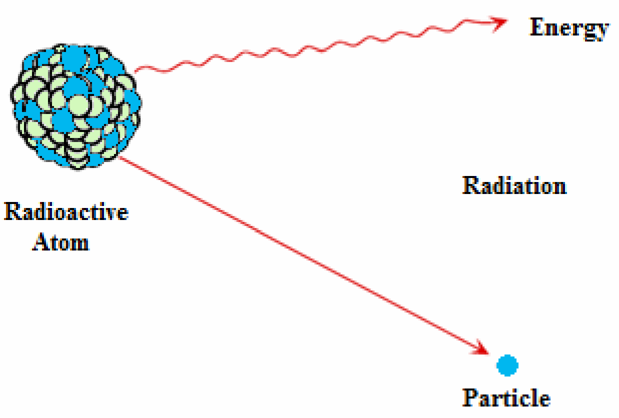


Figure 8

One nucleus will spontaneously transform into a different nucleus if the final state nucleus is more stable and if the laws of physics allow the transformation. This process is usually accompanied by the release of ionizing radiation and is often called *radioactive decay*. Nuclei that exhibit this behavior are said to be unstable or *radioactive*. Most of the matter found naturally on Earth is stable and does not undergo this transformation. Some examples of common radioactive isotopes found naturally that have this property are Potassium-40 which is present in seawater and many salts, Carbon-14 and Uranium and Thorium.

Radiation emitted by radioactive material can produce *ionizations* and, therefore, is called *ionizing radiation*. Ionization is the process of stripping, knocking off, or otherwise removing electrons from their orbital paths, creating free electrons and leaving charged nuclei. The negatively charged electrons and positively charged nuclei may interact with other materials to produce chemical or electrostatic changes in the material where the interactions occur. If chemical changes occur in the cells of our bodies, some cellular damage may result.

An *alpha particle* is an ionizing radiation that consists of two protons and two neutrons. The neutrons and protons give the alpha particle a relatively large mass as compared to other ionizing radiation particles. Because of this large size, the alpha particle has a relatively low speed and low penetrating distance (one or two inches in air). The particle tends to travel in a straight line, causing a large number of ionizations in a small area.

Alpha particles are easily stopped by a thin sheet of paper or the body's outer layer of skin. Since they do not penetrate the outer layer of skin, they present little or no hazard when they are external to the body. However, alpha particles are considered to be an *internal hazard*, because they can be in contact with live tissue and have the ability to cause a large number of ionizations in a small area.

Internal and **external** hazards refer to whether the radioactive material is inside the body (internal) or outside the body (external).

A *beta particle* is a high speed ionizing radiation particle that is usually negatively charged. The charge of a beta particle is equal to that of an electron (positive or negative), and its mass is equal to about 1/1800th of that of a proton or neutron. Due to this relatively low mass and charge, the beta particle can travel through about ten feet of air and can penetrate very thin layers of materials such as aluminum. However, clothing will stop most beta particles. The beta particle can penetrate into the live layers of the skin tissue and is considered both an internal and an external hazard. Beta particles can also be an external hazard to the lens of the eye. Beta particles are best shielded by thin layers of light metals and plastics.

A *gamma ray* is an ionizing radiation in the form of electromagnetic energy similar in many respects to visible light, but far more energetic. Due to the high energy gamma rays can travel thousands of feet in air and can easily pass through the human body.

Because of their penetrating capability, gamma rays are considered both an internal and external hazard. The best shielding materials for gamma rays are very dense materials such as lead, concrete, and uranium. Note: X-rays are similar to gamma rays in penetration and damage potential. X-rays, however, are produced by changes in electron orbit position rather than by nuclear decay or fission.

The *neutron particle* is an ionizing radiation emitted by nuclear fission and by the decay of some radioactive atoms. Neutrons can range from high speed, high energy particles to low speed, low energy particles (called thermal neutrons). Neutrons can travel hundreds of feet in air and can easily penetrate the human body.

Neutrons are considered both an internal and external hazard, although the likelihood of an internal, neutron emitting, radioactive material is extremely unlikely. The best shielding materials for neutrons would be those that contain hydrogen atoms, such as water, polyethylene, and concrete.

As previously mentioned, the nucleus of a hydrogen atom contains a proton. Since a proton and a neutron have almost identical masses, a neutron hitting a hydrogen atom gives up a great amount of its energy, and therefore, the distance traveled by the neutron is limited. This is like a cue ball hitting another billiard ball. Since they are the same size, the cue ball can be made to stop and the other ball will start moving. But, if a ping pong ball is thrown against a bowling ball, the ping pong ball will bounce off with very little change in velocity, only a change in direction. Therefore, heavy atoms, like lead, are not good at stopping neutrons.

An atom that is radioactive will decrease its radioactivity in time and eventually decay. How fast the radioactivity decreases depends on the half-life. The *half-life* is defined as the time it takes for half of the radioactivity to decay. Hence an isotope with a short half-life will decay quickly. The half-life is also inversely proportional to the intensity of radioactivity. Therefore, the higher the intensity of radioactivity the shorter the half-life.

The approximate half-lives of some of the isotopes in the spent nuclear fuel are listed in Table 1 below:

Table 1
Half-Lives

Isotope	Half-Life
Strontium-90	28 years
Caesium-137	30 years
Plutonium-239	24,000 years
Caesium-135	2.3 million years
Iodine-129	15.7 million years

The rate of nuclear decay is measured in terms of half lives. The half life of any radioactive material is the length of time necessary for one half of the atoms of that material to decay to some other material. During each half life, one half of the atoms which started that half life period will decay. Figure 9 shows the decay curve in half-lives.

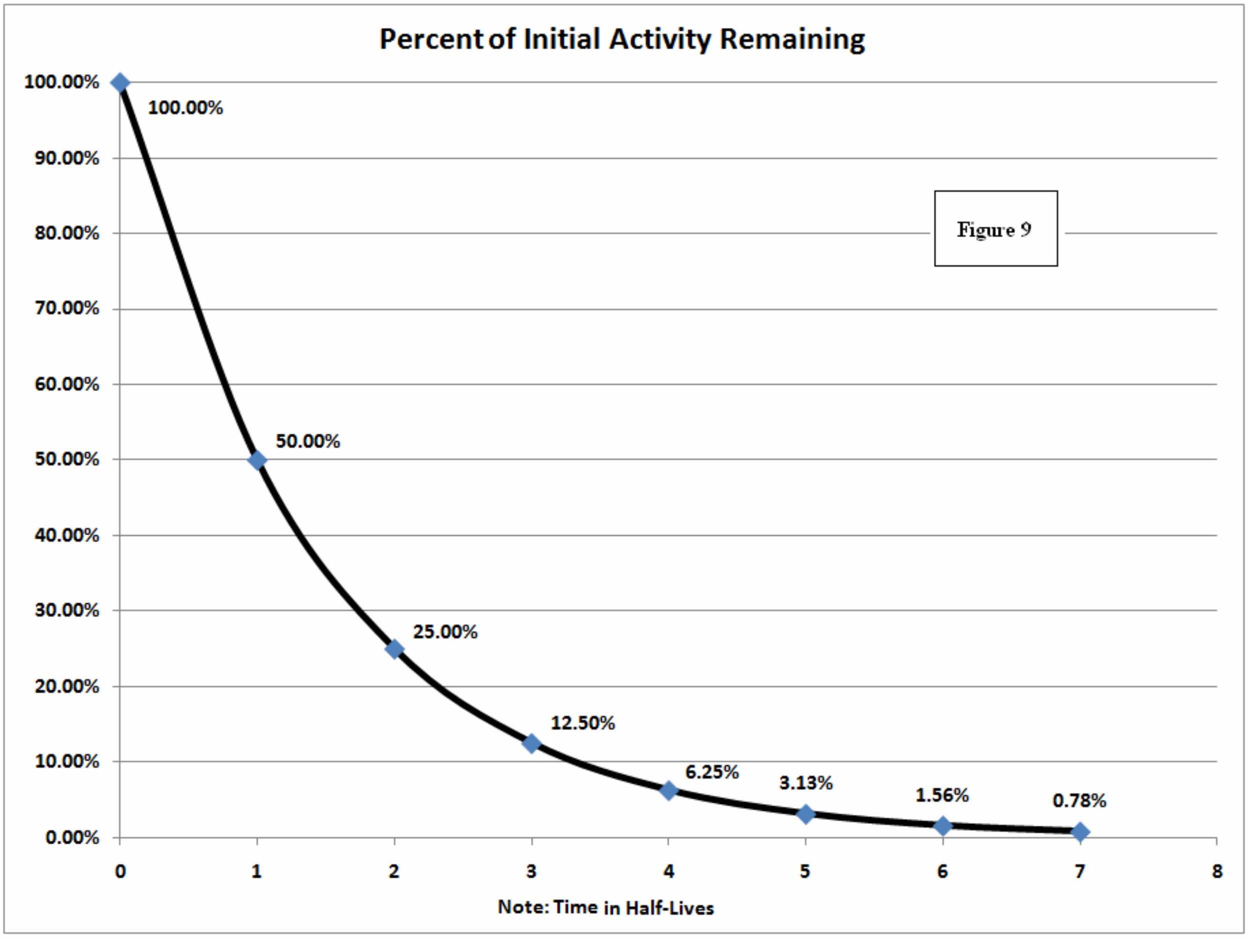


Figure 9

Half lives range from millionths of a second for highly radioactive fission products to billions of years for long-lived materials (such as naturally occurring uranium). No matter how long or short the half life is, after seven half lives have passed; there is less than 1 percent of the initial activity remaining.

Fission

Nuclear Fission energy is released when a very heavy atomic nucleus absorbs a neutron and splits into two lighter fragments. The energy release in this process is enormous. It is 10 million times greater than the energy released when one atom of carbon from a fossil fuel is burned. As this process happens, heat is produced which is converted into electricity via conventional steam and gas turbines. A uranium isotope is the fuel used in electric generating nuclear reactors. Natural uranium consists of three isotopes:

- Uranium-238
- Uranium-235
- Uranium-234

Uranium isotopes are radioactive. The nuclei of radioactive elements are unstable, meaning they are transformed into other elements, typically by emitting particles (and sometimes by absorbing particles). This radioactive decay generally results in the emission of alpha or beta particles from the nucleus. It is often also accompanied by emission of gamma radiation, which is electromagnetic radiation, like X-rays. These three kinds of radiation have very different properties in some respects but are all ionizing radiation--each is energetic enough to break chemical bonds, thereby possessing the ability to damage or destroy living cells.

Uranium found in nature consists largely of two isotopes, U-235 and U-238. The production of energy in the form of heat in nuclear reactors is from the `fission' or splitting of the U-235 atoms. Natural uranium contains 0.7% of the U-235 isotope. The remaining 99.3% is mostly the U-238 isotope which does not contribute directly to the fission process.

Table 2

Summary of Uranium Isotopes

Isotopes	**Naturally Occurring (Percent)**	**Protons**	**Neutrons**	**Half-Life (years)**
Uranium – 238	99.284%	92	146	4.46 billion years
Uranium – 235	0.711%	92	143	704 million years
Uranium - 234	0.0055%	92	142	245,000 years

As you can see from Table 2, Uranium-238, the most prevalent isotope in uranium ore, has a half-life of about 4.5 billion years; that is, half the atoms in any sample will decay in that amount of time. Uranium-238 decays by alpha emission into thorium-234, which itself decays by beta emission to protactinium-234, which decays by beta emission to uranium-234, and so on. The various decay products, form a series starting at uranium-238. After several more alpha and beta decays, the series ends with the stable isotope lead-206.

Uranium-235 and U-238 are chemically identical, but differ in their physical properties, particularly their mass. The nucleus of the U-235 atom contains 92 protons and 143 neutrons, giving an atomic mass of 235 units. The U-238 nucleus also has 92 protons but has 146 neutrons - three more than U-235, and therefore has a mass of 238 units.

Uranium is enriched in U-235 by gaseous diffusion or centrifuge technology. Both of these processes work on the principle of separating the lighter U-235 from the heavier U-238, when in the form of uranium hexafluoride gas.

Uranium-238 emits alpha particles which are less penetrating than other forms of radiation, and weak gamma rays as long as it remains outside the body, uranium poses little health hazard. If inhaled or ingested, however, its radioactivity poses increased risks of lung cancer and bone cancer. Uranium is also chemically toxic at high concentrations and can cause damage to internal organs, notably the kidneys.

Uranium-235 is the fuel for most power reactors in the United States. Uranium-235 is useful as a reactor fuel because:

1. It will readily absorb a neutron to become the highly unstable isotope U-236.
2. U-236 has a high probability of fission (about 80% of all U-236 atoms will fission).
3. The fission of U-236 releases energy (in the form of heat) which is used to produce high pressure steam and ultimately electricity.
4. The fission of U-236 releases two or three additional neutrons which can be used to cause other fissions and establish a chain reaction.

See Figure 10 for an illustration of neutron absorption and fission.

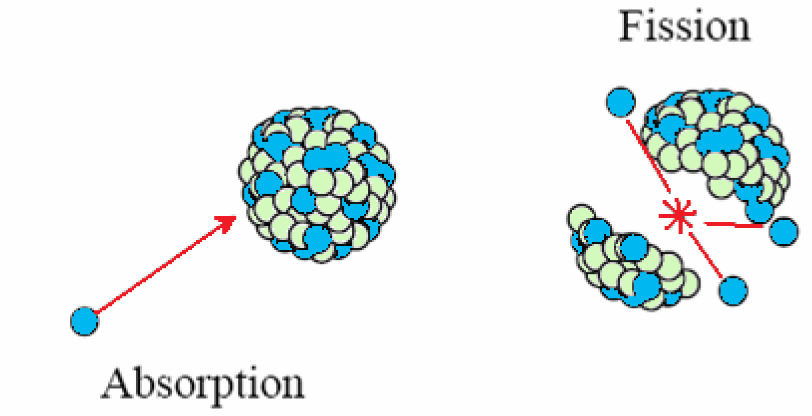


Figure 10

U-235 has a high probability of absorbing a neutron. However, the probability increases even more if the neutron is moving slower. Therefore, in the reactor, it is desired to slow the neutrons down and then let the U-235 absorb them. This slowing down process is accomplished by the same water that is used to remove the heat from the fuel. Therefore, the water circulating through the reactor (called the reactor coolant system) has two important functions. First, the water carries the heat from the reactor core to produce the steam used in the turbine. This prevents the fuel from becoming too hot, which could lead to fuel damage. Second, the water is used to control the fission process by slowing the neutrons down and by acting as a reflector to bounce back any high energy neutrons that try to escape. This conserves the neutrons so that even more fissions may occur. The slowing down process is called *thermalization* or *moderation*.

Every fission releases a tiny amount of heat. Trillions of fissions per second are necessary to produce the high temperature, high pressure steam for the production of electricity. The rate at which the uranium atoms are fissioned determines the rate at which heat is produced. Remember,

Fissions = Heat

And

Controlling Fission Rate = Controlling Heat Production Rate

Since neutrons are necessary to cause the fission event, and since each fission releases neutrons, there is the potential to set up a self-sustaining chain reaction. For this to occur, there must be sufficient material capable of fissioning, and the material must be arranged such that the neutrons will reach other fuel atoms before escaping.

If the conditions in the core allow, the chain reaction will reach a state of being self-sustaining. At this point, for every fission event that occurs, a second event occurs. This point of equilibrium is known as *criticality*. This just means that the number of neutrons produced by the fission events is equal to the number of neutrons that cause fission plus the number of neutrons that do not cause fission. Therefore, the reactor has reached a state of equilibrium. That is, the amount of power, and therefore heat, being produced is constant with time. See Figure 11.

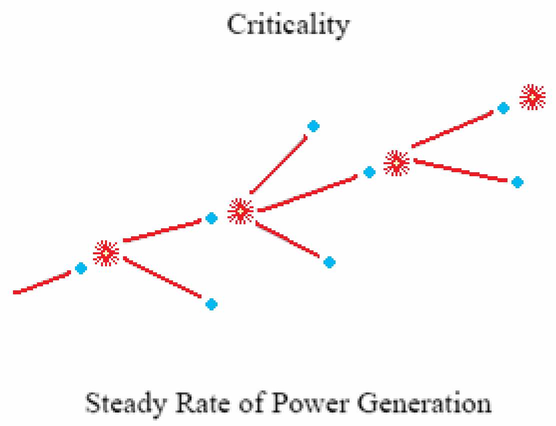


Figure 11

Because all neutrons that are produced by the fission process do not end up causing subsequent fissions, enough neutrons must be produced to overcome the losses and to maintain the critical balance needed for a constant power level. The neutrons that are lost to the fission process either "leak out" of the fuel area (escape) or are absorbed by materials that do not fission. The materials that absorbed neutrons and do not fission are called *neutron poisons*.

Some of the neutrons released by fission will leak out of the reactor core area to be absorbed by the dense concrete shielding around the reactor vessel. All the neutrons that remain in the core area will be absorbed by the materials from which the various core components are constructed (U-235, U-238, steel, control rods, etc.).

Any material that absorbs neutrons and does not fission is a *poison* to the fission process. The reactor vessel, structural components, and the reactor coolant all absorb neutrons. Several fission products (the elements that are formed from the splitting of the large U-235 nucleus) absorb neutrons. Uranium-238 sometimes fissions after absorbing a fast neutron. When it does not, it acts as a neutron poison. These neutron poisons are uncontrollable by the operator. Some of the poisons include:

- Control Rods
- Soluble Boron
- Fission Products
- Uranium-238
- Structural Components

Reactor operators can manipulate the total amount of poisons in the reactor by adjusting the position of the control rods. Also, in a pressurized water reactor, the operator can adjust the amount of boron that is dissolved in the reactor coolant. The control rods and the soluble boron are called *controllable neutron poisons*.

Control rods are concentrated neutron absorbers, or poisons, which can be moved into or out of the core to change the rate of fissioning in the reactor. Rod insertion adds neutron poisons to the core area, which makes fewer neutrons available to cause fission. This causes the fission rate to decrease, which results in a reduction in heat production and power. Pulling the control rods out of the core removes poisons from the core area allowing more neutrons to cause fissions and increasing reactor power and heat production.

The use of water as a neutron moderator helps produce a steady rate of reactor power by slowing the neutrons down that will be absorbed by the U-235 and by reflecting many of the neutrons that try to leak out of the reactor back into the core. The water can also remove neutrons from the fission chain.

Water has a limited capacity to absorb neutrons, thus acting as a neutron poison. But an even greater effect is the changing of the moderator temperature. If the reactor coolant temperature increases, the water becomes less dense. This means that the water becomes less effective at slowing the neutrons down and more will leak out of the core. Conversely, if the coolant temperature decreases, the water becomes a better moderator, and the number of neutrons available for fission will increase. If the only action to occur was a change in the temperature of the moderator, power would also change. This moderator temperature effect is a major factor in the control of the fission process and heat production of the reactor.

Since the moderator density plays such an important part in the control of the fission rate and the power production in the reactor, the formation of steam bubbles, or *voids*, must also be considered. A steam bubble is an area of very low density water.

In a boiling water reactor, the conversion of water into steam produces a dramatic change in the density of the water from the bottom to the top of the core. Water at the bottom of the core is far denser than the water steam mixture at the top. Therefore, neutron moderation is much better towards the bottom of the core. In a pressurized water reactor, the high pressure of the reactor coolant will prevent all but just a very minimum amount of steam bubbles from being formed. Therefore, the effects of voids on the power production in a pressurized water reactor are very minimal.

Because of the unique properties of the nuclear fuel, there are some byproducts of the heat producing process. *Fission products* are the smaller atoms produced when the larger uranium atoms are split during the fission process. Some of these fission products are neutron poisons, and therefore, must be compensated for by removing some of the controllable poisons (such as the control rods for boiling water reactors or control rods or boron for pressurized water reactors) as they are produced. The fission products are usually very highly radioactive. They emit a large amount of radiation, and therefore, must be contained within the plant. A system of “barriers” has been developed to prevent these atoms from escaping into the environment. These barriers are the fuel pellet and cladding, the reactor coolant system pressure boundary, and the containment.

Another problem with the fission products is the generation of decay heat. See Figure 12. When an atom decays, it gives off energy or particles to become more stable. The energy or particles then interact with the surroundings to generate heat. This heat will be collected inside the fuel pellet area. If this decay heat is not removed, it could possibly cause damage to the fuel pellets or other parts of the “barrier” system. Therefore systems are designed to remove this heat after the plant is shut down.

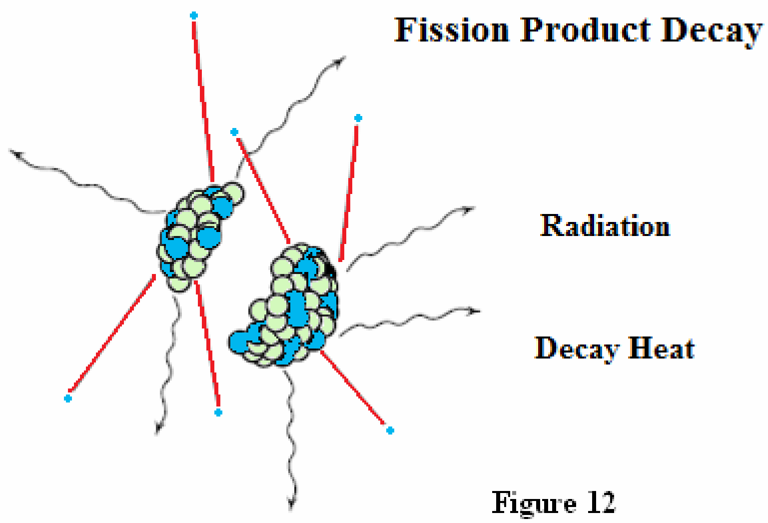


Figure 12

The approximate temperatures of the fuel centerline, pellet surface, cladding surface, and coolant, when a reactor is operating at full power, are shown Figure 13 below.

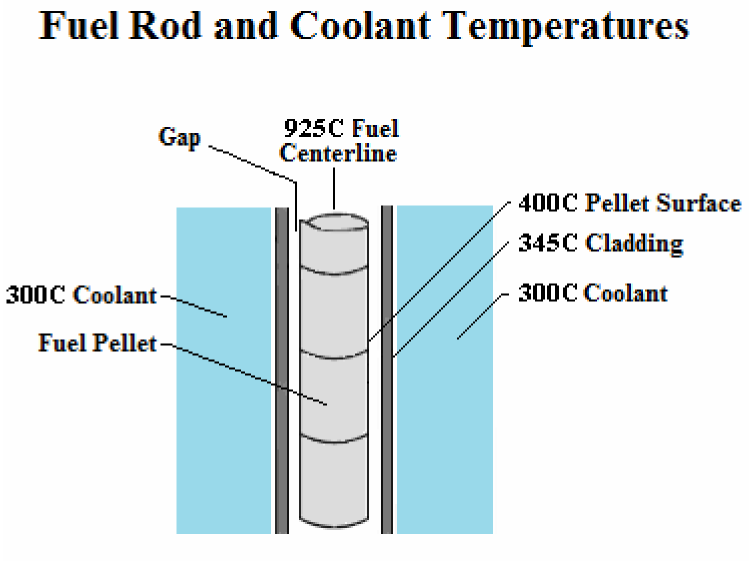


Figure 13

The average fuel pellet temperature under normal operating conditions is about 750C. The melting temperature of the ceramic fuel is approximately 2,850C. The fuel cladding can be damaged by temperatures in excess of 975C. Significant fuel damage can be expected at sustained temperatures above 1,200C.

Nuclear generating plant systems - both normal operating and emergency - must be designed to maintain the fuel temperature low enough to prevent fuel damage. For example, if conditions approach an operating limit, the reactor protection system will rapidly insert the control rods to shut down the fission chain, which removes a major heat production source. This rapid insertion of rods into the core is called a reactor trip or scram. A reactor *scram* is the rapid insertion of the control rods into the core to stop the fission chain reaction. Even though all of the fissioning in the core is not stopped, the chain reaction is broken down, which causes a significant decrease in reactor power in just a few seconds. When the reactor is shut down, with all rods inserted, the amount of heat being generated due to the fissions which are not stopped and the decay heat is much less than that which can be removed by the plant systems. Therefore, the fuel can be protected from an over-temperature condition.

In a boiling water reactor, the control rods are inserted from the bottom of the reactor vessel into the core. In a pressurized water reactor, the control rods are inserted from the top of the reactor vessel into the core.

Radiation Measurement Terms

The commonly used units in the United States for radiation exposure and dose measurements are:

- Roentgen
- RAD
- REM

The *Roentgen* (R) is a measure of exposure to X-ray or gamma ray radiation. One roentgen is that amount of X-ray or gamma radiation that will deposit enough energy to strip about two billion electrons from their orbits (called one electrostatic unit) in one cubic centimeter of dry air. The roentgen technically applies only to ionization in dry air from X-ray or gamma radiation and does not apply to damage to body tissues.

The *Radiation Absorbed Dose* (RAD) is a measure of the absorbed dose in a material. One RAD is the deposition of one hundred *ergs* of energy in one gram of any material due to the ionization from any type of radiation.

Erg: One erg of energy is equal to about one ten billionth of a BTU, or about one ten millionth of a watt.

The *REM* is a measure of the biological damage caused by ionization in human body tissue. It is a term for dose equivalence and equals the biological damage that would be caused by one RAD of dose. The REM accounts for the fact that not all types of radiation are equally effective in producing biological change or damage. That is, the damage from one RAD deposited by beta radiation is less than that caused by one RAD of alpha radiation. The REM is numerically equal to the dose in RADs multiplied by a *quality factor*, which accounts for the difference in the amount of biological damage caused by the different types of radiation. The *quality factor* converts the absorbed dose in RAD to the dose equivalent in REM. Quality factors are highest for the alpha radiation, which deposits its energy within the smallest volume.

Gamma ray radiation provides the consistency among the units of exposure and dose. One Roentgen of exposure of gamma or X-ray radiation is approximately equal to one RAD of absorbed energy (dose), which equals one REM of biological damage in humans (dose equivalent).

Particulate ionizing radiation (alpha and neutron) has been found to cause more biological damage than electromagnetic radiation (gamma and X-ray), even when the same amount of energy has been deposited. For example, one RAD of alpha radiation can be expected to cause about twenty times the damage caused by one RAD of gamma radiation. This difference in ability to cause damage is corrected for by a quality factor (Q).

The *dose rate* is the rate at which a person receives a radiation dose. It is a measure of radiation dose intensity and includes some unit of time (e.g., hour, week, or day). The *dose* is equal to the strength of the radiation field (dose rate) multiplied by the length of time spent in that field. For example, if a person has a dose rate of 50 mREM per hour and is exposed for thirty minutes, the dose is,

$$\textbf{Dose} = \textbf{Dose Rate} * \textbf{Time}$$

$$\text{Dose} = 50\ \text{mREM} * .5\ \text{hrs}$$

$$\text{Dose} = 25\ \text{mREM}$$

Stay time is an exposure control value equal to the length of time a person can remain in a radiation field before exceeding some dose limit.

$$\textbf{Stay Time} = \frac{\text{Dose Limit}}{\text{Dose Rate}}$$

Suppose a dose limit of 100 millirems has been established. With a dose rate of 50 millirems/hour, the stay time is calculated to be two hours by dividing the dose limit by the dose rate.

Table 3 and the material that follows describe the units of measurement for radioactivity in both traditional and SI units.

Table 3

Relationship between Traditional and SI Units

Traditional Units	SI Units	Conversion Factor
Curie	Becquerel	1 Becquerel = $2.7*10^{-11}$ Curie
RAD	Gray	1 Gray = 100 RADs
REM	Sievert	1 Sievert = 100 REMs

One *curie* is defined as the amount of any radioactive material that decays at the rate of 37 billion disintegrations per second. The SI unit for activity is the Becquerel. It is equal to one disintegration per second. Therefore, one curie equals 37 billion Becquerel's.

1 Gray = 100 RADs

The *Gray* is the SI unit of absorbed dose. A Gray is equal to 0.1 Joule of energy deposited in one kilogram of matter. Therefore, one RAD is equivalent to 1/100 of a gray, and one gray is equal to 100 RADs.

1 Sievert = 100 REM

The S*ievert* is the SI unit of dose equivalent. In the same way that converting from the absorbed dose (RAD) to the dose equivalent (REM) involved the use of quality factors, the conversion of grays to Sieverts also uses quality factors.

Chapter 3
Uranium as a Fuel Source

First discovered in the 18th century, uranium is an element found everywhere on Earth, but mainly in trace quantities. Uranium is the principal fuel for nuclear reactors and the main raw material for nuclear weapons.

In the last fifty years uranium has become one of the world's most important energy minerals. It is used almost entirely for making electricity, though a small proportion is used for the important task of producing medical isotopes.

The property of uranium important for nuclear power is its ability to fission, or split into two lighter fragments when bombarded with neutrons releasing energy in the process. Of the naturally-occurring uranium isotopes, only uranium-235 can sustain a chain reaction - a reaction in which each fission produces enough neutrons to trigger another - so that the fission process is maintained without any external source of neutrons. In contrast, uranium-238 cannot sustain a chain reaction, but it can be converted to plutonium-239, which can.

The conversion of uranium into a nuclear fuel involves the following steps:

1. Ore is **mined** to recover uranium
2. Ore is **milled** to extract yellowcake
3. Yellowcake is **converted** into uranium hexaflouride
4. Uranium is **enriched**
5. Fuel is **fabricated** into a product suitable for consumption in a nuclear power plant

Let's look at each of these steps from the extraction and conversion to fabrication of uranium fuel, starting with mining.

Uranium Mining

Uranium averages about 2.8 parts per million of the earth's crust. Traces of it occur almost everywhere. It is more abundant than gold, silver or mercury, about the same as tin and slightly less abundant than cobalt, lead or molybdenum. Vast amounts of uranium also occur in the world's oceans, but in much lower concentrations.

There are many uranium mines operating around the world, in some twenty countries, though more than two thirds of world production comes from just ten mines. Most of the uranium ore deposits present in these mines have average grades in excess of 0.10% of uranium. In the infancy of nuclear power, this would have been seen as a respectable grade, but today some Canadian mines have huge amounts of ore up with average grades of up to 20% uranium. Other mines however can operate successfully with very low grade ores.

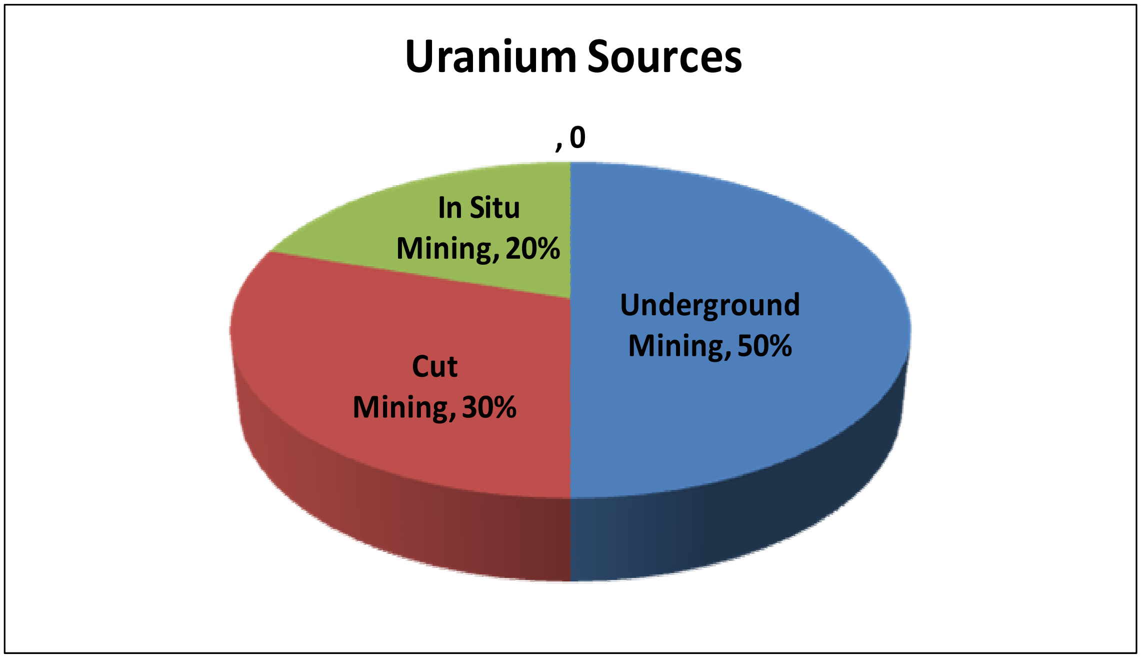
Some uranium is also recovered as a by-product with copper, or as by-product from the treatment of other ores, such as the gold-bearing ores of South Africa. In these cases the concentration of uranium may be as low as a tenth of that in ore bodies mined primarily for their uranium content.

Uranium mining is no different from other kinds of mining unless the ore is very high grade. Where ore bodies lie close to the surface, they are usually accessed by open cut mining, involving a large pit and the removal of overburden as well as waste rock. Where ore bodies are deeper, underground mining is usually employed, involving construction of access tunnels and shafts but with less waste rock removed and less environmental impact. In either case, grade control is usually achieved by measuring radioactivity as a surrogate for uranium concentration. Underground mines have relatively small surface disturbance and the quantity of material that must be removed to access the ore is considerably less than in the case of an open pit mine.
In the case of underground uranium mines, special precautions, consisting primarily of increased ventilation, are required to protect against airborne radiation exposure.

Traditionally, uranium has been extracted from open-pits and underground mines. In the past decade, alternative techniques such *in-situ leach mining*, in which solutions are injected into underground deposits to dissolve uranium, have become more widely used. Some ore bodies lie in groundwater in porous unconsolidated material and may be accessed simply by oxygenating that groundwater and pumping it out - this is called *in situ leach* (ISL) mining. ISL mining means that removal of the uranium minerals is accomplished without any major ground disturbance.

Weakly acidified or alkaline groundwater with a lot of oxygen injected into it is circulated through an enclosed underground aquifer which holds the uranium ore in loose sands. The leaching solution with dissolved uranium is then pumped to the surface treatment plant.

Uranium can be roughly categorized as coming from one of these three mining sources as shown in the following pie chart.



After the uranium ore has been mined it is milled. *Milling*, which is generally carried out close to a uranium mine, extracts the uranium from the ore. Most mining facilities include a mill, although where mines are close together, one mill may process the ore from several mines At the mill, the ore is crushed and ground to a fine slurry. Sulfuric acid or a strong alkaline solution is used to dissolve the uranium to allow the separation of uranium from the waste rock. It is then recovered from solution and precipitated as uranium oxide (U_3O_8) concentrate. The milling (refining) process extracts uranium oxide (U_3O_8) from ore to form *yellowcake*, a yellow or brown powder that contains about 90% uranium oxide.

Conventional mining techniques generate a substantial quantity of *mill tailings* waste during the milling phase, because the usable portion is generally less than one percent of the ore. (In-situ leach mining leaves the unusable portion in the ground; it does not generate this form of waste). The total volume of mill tailings generated in the U.S. is over 95 percent of the volume of all radioactive waste from all stages of the nuclear power production. While the hazard per gram of mill tailings is low relative to most other radioactive wastes, the large volume and lack of regulations until 1980 have resulted in widespread environmental contamination. Moreover, the half-lives of the principal radioactive components of mill tailings, thorium-230 and radium-226 are long, being about 75,000 years and 1,600 years respectively. The most serious health hazard associated with uranium mining is lung cancer due to inhaling uranium decay products. Uranium mill tailings contain radioactive materials, notably radium-226, and heavy metals such as manganese and molybdenum, which can leach into groundwater. Near tailings piles, water samples have shown levels of some contaminants at hundreds of times the government's acceptable level for drinking water.

Most mines in the U.S. have shut down and imports account for about three-fourths of the roughly 16 tons of refined uranium used domestically each year. The following Figure shows the countries with the largest known recoverable reserves of Uranium.

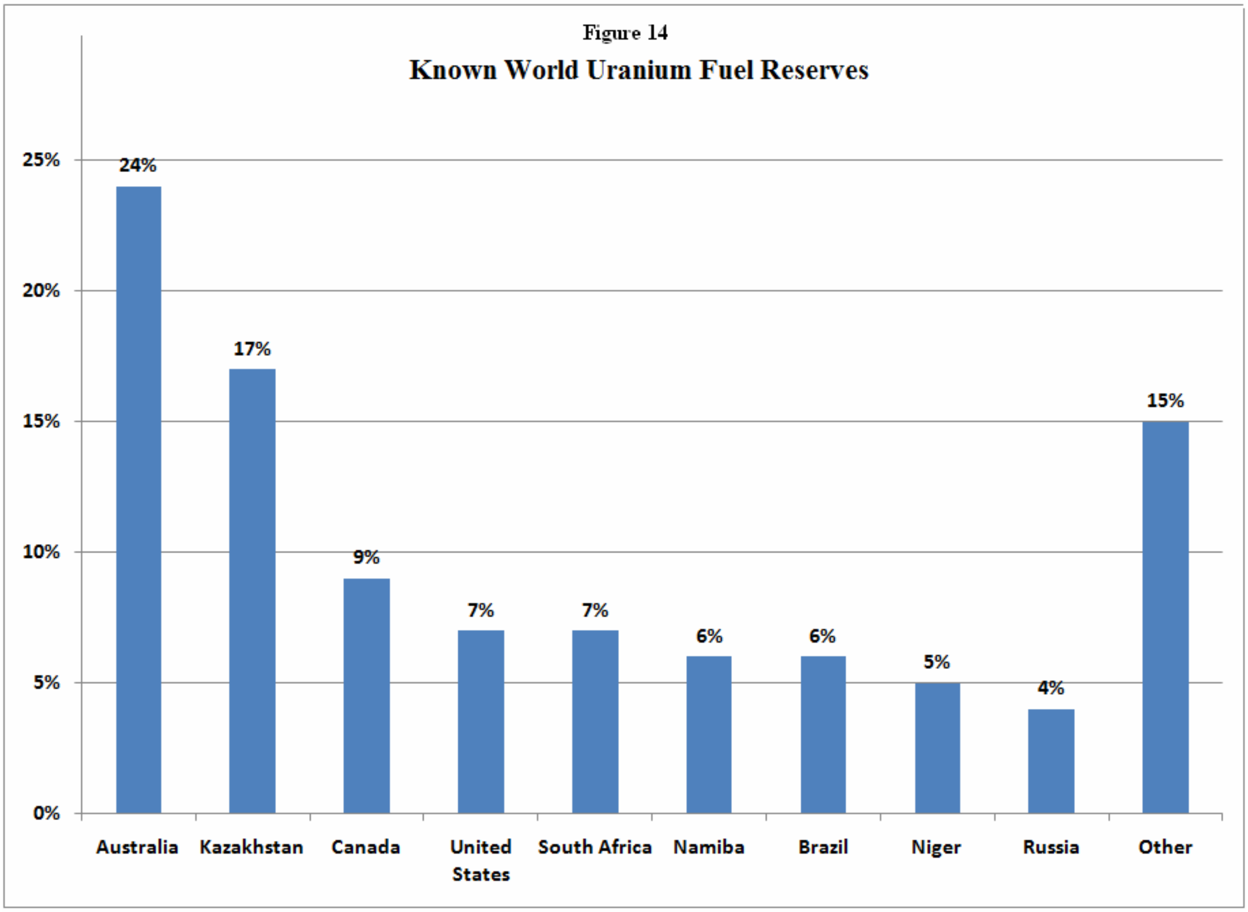


Figure 14

Known World Uranium Fuel Reserves

As you can see from the chart above, Australia, Kazakhstan, and Canada make up 50% of the known world uranium reserves.

Uranium Enrichment

Most reactors use fuel enriched in the U-235 isotope. The solid uranium oxide from the mine is converted into the gas UF_6, which is then enriched in the U-235 isotope by one of two physical methods of enrichment. *Diffusion* enrichment, works by exploiting the different speeds at which U-235 and U-238 pass through a membrane. *Centrifuge* enrichment, works by passing the gas through spinning cylinders, the centrifugal force moving the heavier U-238 to the outside of the cylinder, leaving a higher concentration of U-235 on the inside.

Uranium is generally used in reactors in the form of uranium dioxide (UO_2). Production of uranium dioxide requires chemical processing of yellowcake. Further, most civilian and many military reactors require uranium that has a higher proportion of uranium-235 than present in natural uranium. The process used to increase the amount of uranium-235 relative to uranium-238 is known as *uranium enrichment*. Nuclear power plants typically use 3 to 5 percent uranium-235. Military and research reactors use "highly enriched uranium" (HEU) with over 90 percent uranium-235.

Uranium enrichment requires the material to be in gaseous form. The product of a uranium mine (yellowcake) is not directly usable and the uranium oxide must be converted into uranium hexafluoride (UF_6) which is a gas at relatively low temperature. In a fuel fabrication plant, enriched UF_6 gas is converted to uranium dioxide (UO_2), which is formed into ceramic fuel pellets by baking it at a high temperature (over 1400°C).

The *diffusion process* involves forcing uranium hexafluoride gas under pressure through a series of porous membranes. As U-235 molecules are lighter than the U-238 molecules they move faster and have a slightly better chance of passing through the pores in the membrane. The UF_6 which diffuses through the membrane is thus slightly enriched, while the gas which did not pass through is slightly depleted in U-235.

This process is repeated many times in a series of diffusion stages called a cascade. The enriched UF_6 product is withdrawn from one end of the cascade and the depleted UF_6 is removed at the other end. The gas must be processed through some 1,400 stages to obtain a product with a concentration of 3% to 4% U-235.

At present the gaseous diffusion process accounts for about 40% of world enrichment capacity. However, because they are old and energy inefficient, most gaseous diffusion plants are being phased out over the next five years and the focus is on energy-efficient centrifuge enrichment technology which will replace them.

Like the diffusion process, the *centrifuge process* uses UF_6 gas as its feed and makes use of the slight difference in mass between U-235 and U-238. The gas is fed into a series of vacuum tubes, each containing a rotor. The rotors are spun rapidly, at 50,000 to 70,000 rpm and centrifugal force causes the heavier molecules with U-238 increase in concentration towards the cylinder's outer edge. There is a corresponding increase in concentration of U-235 molecules near the center.

The enriched gas forms part of the feed for the next stages while the depleted UF_6 gas goes back to the previous stage. Eventually enriched is drawn from the cascade at the desired concentration and depleted uranium is removed for storage.

A major hazard in both the uranium conversion and uranium enrichment processes comes from the handling of uranium hexafluoride, which is chemically toxic as well as radioactive. Moreover, it reacts readily with moisture, releasing highly toxic hydrofluoric acid. Conversion and enrichment facilities have had a number of accidents involving uranium hexafluoride.

Fuel Fabrication

Most nuclear reactors use fuel made comprising of pellets of uranium dioxide encased in metal tubes, which are arranged in fuel assemblies. Uranium dioxide fuels are used in Pressurized Water Reactors (PWR's), Boiling Water Reactors (BWR's), and CANDU reactors.

The pellets are then encased in metal tubes, usually made of zirconium alloy (zircalloy) or stainless steel, to form fuel rods. The rods are then sealed and assembled in clusters to form fuel assemblies for use in the core of the nuclear reactor.

Fuel for pressurized water reactors consists of cylindrical rods of Zircalloy tubes filled with UO_2 pellets put into bundles. There are between 179 and 264 fuel rods per fuel bundle and about 121 to 193 fuel bundles, about 4 meters in length, are loaded into a reactor core. Control rods are inserted through the top directly into the fuel bundle.

In boiling water reactors (BWR), the fuel is similar to PWR fuel except that the bundles are "canned". That is there is a thin tube surrounding each bundle. In BWR fuel bundles, there are about 500-800 fuel rods per assembly. Each BWR fuel rod is back filled with helium to a pressure of about three atmospheres.

CANDU fuel bundles consist of sintered (UO_2) pellets in Zirconium tubes, welded to Zirconium end plates. A typical core loading is on the order of 4,500 bundles. Current CANDU designs do not need enriched uranium to achieve criticality (due to their more efficient heavy water moderator); however, some newer concepts call for low enrichment to help reduce the size of the reactors.

The bulk of waste from the enrichment process is *depleted uranium*, so-called because most of the uranium-235 has been extracted from it. Depleted uranium has been used by the U.S. military to fabricate armor-piercing conventional weapons and tank armor plating.

Uranium Waste Management

When uranium and other fissile atoms in nuclear fuel split - or fission - they form new, lighter elements, known as *fission fragments* or *fission products*. With time, the concentration of fission fragments and *transuranics* formed in fuel will increase to the point where it is no longer practical to continue to use the fuel. So after 12 to 24 months the used fuel is removed from the reactor.

Transuranics are elements with atomic numbers greater than 92 (i.e. above uranium in the periodic table.) There are at least 20 transuranics including neptunium and lawrencium. All transuranics are unstable, decaying radioactively, with half-lives that range from tens of millions of years to mere fractions of a second.

When removed from a reactor, a fuel bundle will be emitting both radiation - principally from the fission fragments - and heat. Used fuel is unloaded into a storage pond immediately adjacent to the reactor to allow the radiation levels to decrease. In the ponds the water shields the radiation and absorbs the heat.

Used fuel can be stored safely in these ponds for long periods. It can also be dry stored in engineered facilities, cooled by air. However, both kinds of storage are intended only as an interim step before the used fuel is either reprocessed or sent to final disposal. The longer it is stored, the easier it is to handle, due to decay of radioactivity.

There are two alternatives for spent fuel:

- Reprocessing to recover the usable portion of it
- Storage and final disposal without reprocessing

Reprocessing separates uranium and plutonium from waste products (and from the fuel assembly cladding) by chopping up the fuel rods and dissolving them in acid to separate the various materials. Used fuel is about 95% U-238, 1% U-235 that has not fissioned, about 1% plutonium and 3% fission products, which are highly radioactive, with other transuranic elements formed in the reactor. Reprocessing enables recycling of the uranium and plutonium into fresh fuel, and produces a significantly reduced amount of waste (compared with treating all used fuel as waste). The remaining 3% of high-level radioactive wastes can be stored in liquid form and subsequently solidified.

The uranium recovered from reprocessing can be used in mixed oxide (MOX) fuel or it can be returned to the conversion plant for conversion to uranium hexafluoride and subsequent re-enrichment. It can then be used in fresh uranium oxide fuel, although it does need special handling because it has a different isotopic mix than uranium oxide made from fresh uranium. The plutonium can be blended with uranium to produce a mixed oxide (MOX) fuel, in a fuel fabrication plant. In reactors that use MOX fuel, plutonium substitutes for the U-235 in normal uranium oxide fuel. Typically reactors will use a combination of MOX fuel assemblies and uranium oxide fuel assemblies, although it is possibly to fuel a reactor using just MOX fuel.

If used fuel is not reprocessed it can be disposed of as waste. At the present time used fuel not destined for reprocessing is stored in interim storage facilities. Because of political quagmire in Washington, there is not a final disposal facility in operation in which used fuel can be placed. Utilities have paid millions of dollars to the Federal government to develop suitable long-term nuclear waste storage. Yucca Mountain, Nevada is the current site being considered for long-term storage. In any event, the longer used fuel is in interim storage the easier it is to handle, due to the progressive diminution of radioactivity. There is also a reluctance to dispose of used fuel because it represents a significant energy resource which could be reprocessed at a later date to allow recycling of the uranium and plutonium.

A number of countries are carrying out studies to determine the optimum approach to the disposal of used fuel, as well as wastes from reprocessing. The waste forms envisaged for disposal are vitrified high-level wastes sealed into stainless steel canisters, or used fuel rods encapsulated in corrosion-resistant metals such as copper or stainless steel. The general consensus favors its placement into deep geological repositories, initially recoverable. Many geological formations such as granite, volcanic tuff, salt or shale will be suitable.

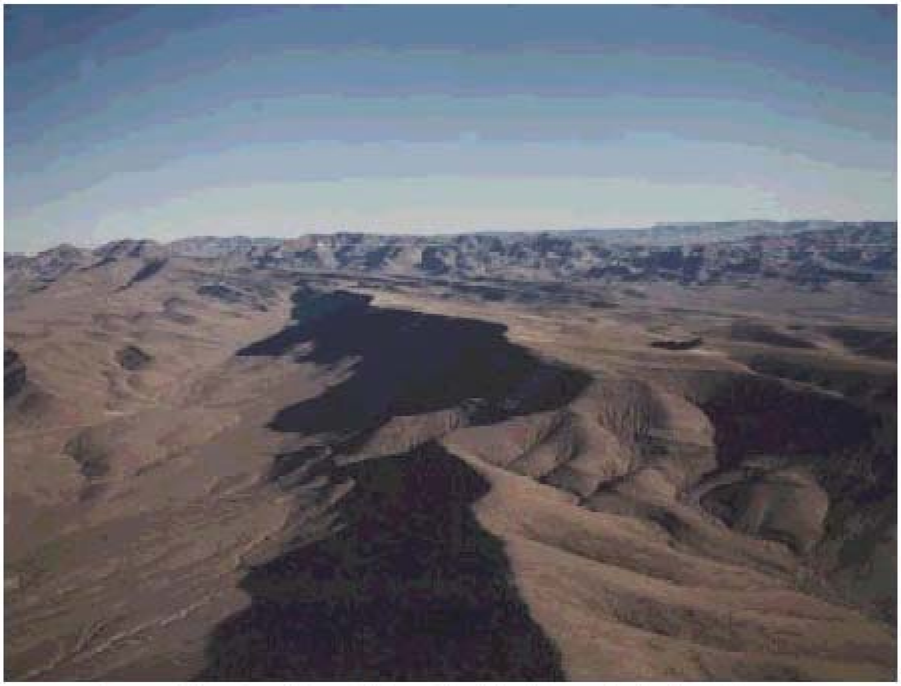


Image Courtesy Yucca Mountain Site Characterization Process

Summary

Proponents of nuclear energy contend that nuclear power is a sustainable energy source that does not create air pollution, reduces carbon emissions and increases energy security by decreasing dependence on foreign oil. The operational safety record of nuclear plants in the Western world is far better when compared to the other major types of power plants. With the exception of Chernobyl, no radiation-related fatalities have ever occurred because of a commercial nuclear power plant. Optimists point out that the volume of radioactive waste is very small, and claim it can be stored safely deep underground. Future designs of reactors are promised to eliminate almost all waste.

Critics believe that nuclear power is a potentially dangerous energy source, with decreasing proportion of nuclear energy in production. They claim that radioactive waste cannot be stored safely for long periods of time, that there is a continuing possibility of radioactive contamination by accident or sabotage, and that exporting nuclear technology to other countries might lead to the proliferation of nuclear weapons. The recent slow rate of growth of installed nuclear capacity is said to indicate that nuclear reactors cannot be built fast enough to slow down climate change.

What is certain is that the United States – and the World – will need a significant amount of base load generation in the first half of the 21st Century and nuclear power is one of only a few viable technologies to meet this demand.

The next volume in this series reviews the basic operation of the current fleet of nuclear plants in operation today.

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