Chapter 9

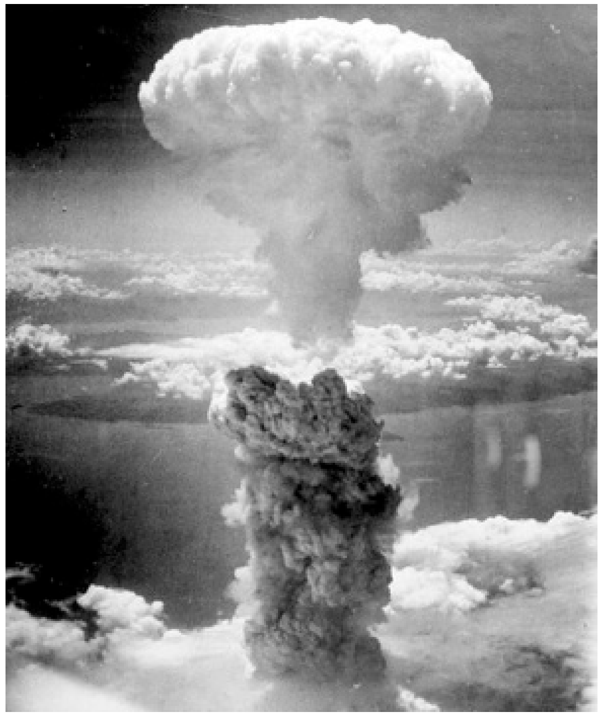
Nuclear Energy

Chapter Objectives:

1. Define and discuss key terms.
2. Define half-life and be able to calculate the amount of a radioactive element left after a given number of half-lives have past.
3. Discuss nuclear fusion and nuclear fission.
4. Discuss the process of nuclear chain reactions.
5. Discuss the general design of light and heavy water reactors. Discuss the roles of control rods and water in them.
6. Outline and discuss the nuclear fuel cycle and the resulting radioactive wastes.
7. Discuss the nuclear accidents that occurred at Three Mile Island and Chernobyl.
8. Discuss the environmental impact of nuclear power generating plants.

The Nucleus

Almost any phrase that has the word "nuclear" in it has a bad reputation. The term conjures up images of mushroom clouds and radioactive mutants. It is interesting to note that in the 1940's and 50's, the term that applied to energy derived from the decay radioactive material was atomic energy. This term was somewhat correct, since the energy was coming from the breakdown of the atom. It was not until later that the more appropriate term nuclear energy was used as more people began to understand that the energy was coming from the breakdown of the nucleus of the atom.



The picture in Figure 1 is a popular image of the atom found throughout the literature. It shows a central nucleus comprised of protons and neutrons with electrons whizzing around it in circular orbits. Unfortunately, this image is not a true depiction of an actual atom. While we are pretty sure that the positively-charged protons and the neutrally-charged neutrons are together in a central nucleus, the fact is that we have no idea as to what the electrons are doing as they traverse the atom. Electrons are incredibly small (mass is 9.1×10^{-31} kg), and any effort on our part to determine the path that they take will cause them to be knocked to the other side of the universe. Although it is not completely accurate, the image does convey the basics of an atom. The negatively-charged electrons, which are small, are attracted to the net positive charge of the nucleus, where the proton and neutrons are relatively huge (1.7×10^{-27} kg each) compared to the electrons. Since experimental evidence shows that the electrons are not in the nucleus, we know that they must be moving around in some type of orbit around it, and a graphical depiction of them moving in circles is okay, as long as one understands that this is just a model and is not necessarily what is actually happening.

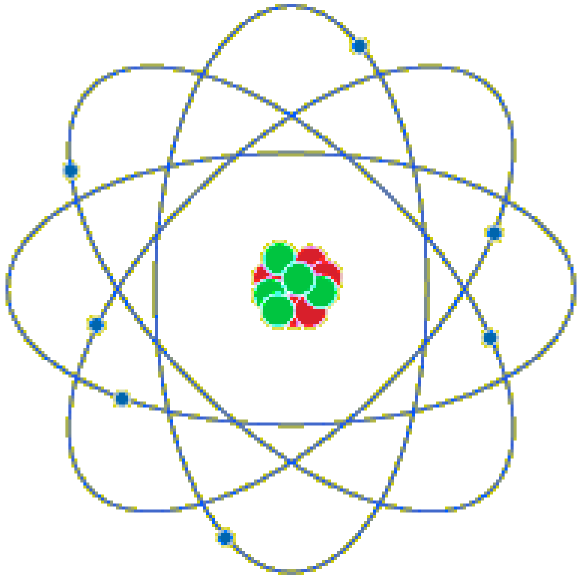


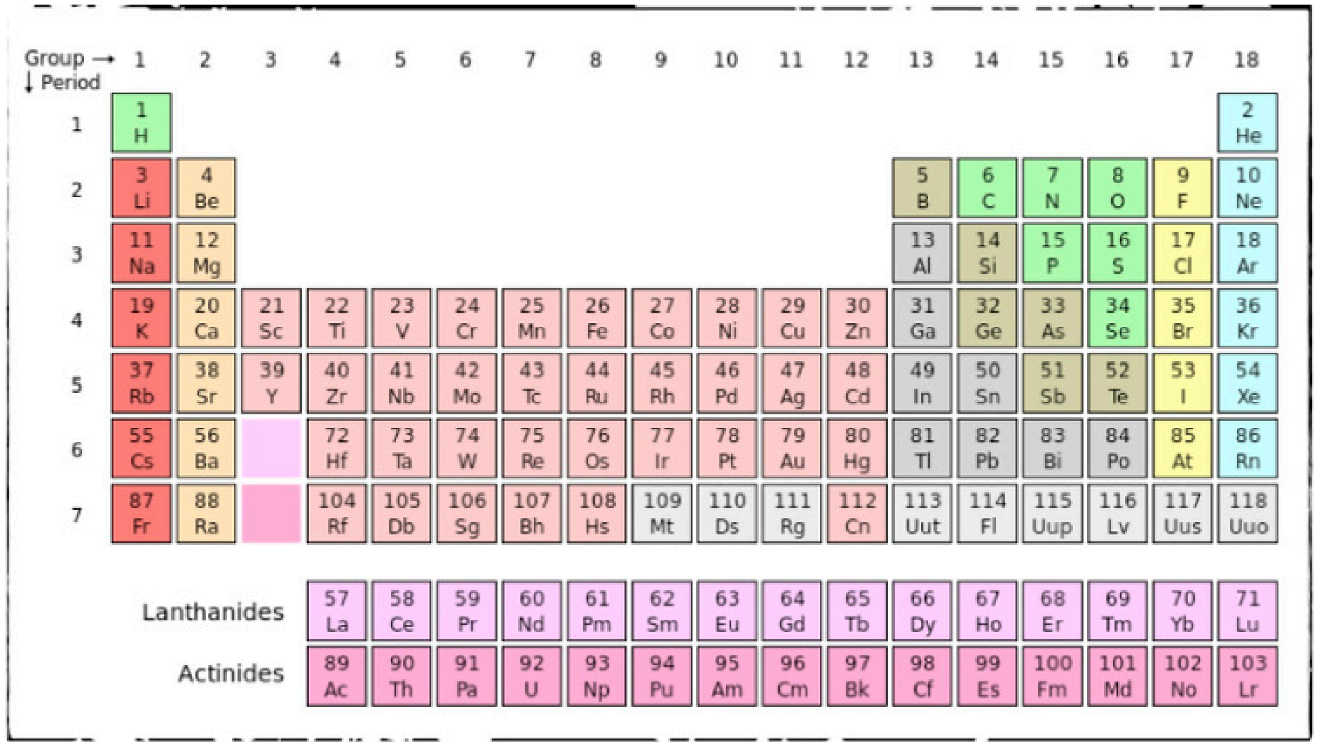
Fig. 1: simplified diagram of an atom

In introducing the topic of atoms, most textbooks talk about the opposite charges on electrons and protons as being the reason for the atoms existence. This type of introduction completely ignores an obvious problem: what is holding the nucleus together? If there is more than one proton in the nucleus, the electrostatic force should cause it to fly apart, as protons repel protons with an incredibly strong force (see Chapter Three). Furthermore, what is keeping the neutrons in the atom, as there is no force whatsoever between them and the protons. What textbooks rarely discuss is the presence of the strong and weak nuclear forces, which are responsible for the nucleus existence.

The most likely reason for this is that the formulae that define these two forces are incredibly advanced and would take too long to explain. Unlike the electrostatic force, which is relatively simple to explain (like charges repel and unlike attract), the strong and weak nuclear forces are rather complicated, in that the discussion of them involves the interactions between quarks, gluons, and vector bosons. However, intimate knowledge of these forces is not required in order to understand nuclear energy, and therefore, we will leave it to the reader to research this subject as they desire. For the purposes of this discussion, we will merely note that the forces do exist, that they are important over very short distance scales (10^{-15} m and less), and that they bind nucleons together under certain conditions. The short distance nature of these forces will be very important to our later discussions of radioactive decay.

Before going any further, though, it should be pointed out that the number of protons in the nucleus defines what element a particular atom is. Hydrogen is hydrogen because it has one proton, whereas carbon is defined by having six protons in the nucleus. If a carbon atom were to lose a proton, it would stop being carbon and would become boron, which is defined as five protons in the nucleus. The number of protons in an atom is referred to as the **atomic number**, and it defines an atom’s location on the periodic table of elements.

This does not mean that the number of electrons in an atom is irrelevant. If an atom is to be neutral, it must have the same number of electrons as it does protons, i.e. the total amount of negative charge must equal the total amount of positive charge. If it has a different number of electrons and protons, the atom is called an *ion*. Depending upon whether it has more electrons than protons, or vice versa, it will be called a negative or a positive ion. The chemical nature of an ion is much different from that of a neutral atom, as an ion is much more likely to react with other atoms to form molecules. The reason for this is simple: the net charge on the ion means that it will be drawn to particles with a net charge that is opposite of the ion. As an example, if an electron is removed from a sodium atom, it becomes a positive ion and will become very attractive to any negative ions, such as a chlorine atom that has gained an extra electron.



Group → ↓ Period	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1 H																	2 He
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	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
5	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
6	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
7	87 Fr	88 Ra		104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Uut	114 Fl	115 Uup	116 Lv	117 Uus	118 Uuo
Lanthanides				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
Actinides				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

Isotopes

The number of neutrons in an atom is also not irrelevant. However, the complicated nature of the strong and weak nuclear forces plus the numerous configurations that could be used for storing protons and neutrons in a nucleus means that there is no given rule for the numbers of neutrons an element has. In fact, most elements have multiple numbers of neutrons that can be stored in the nucleus. Atoms that have the same number of protons, but different numbers of neutrons, are known as **isotopes** of an element.

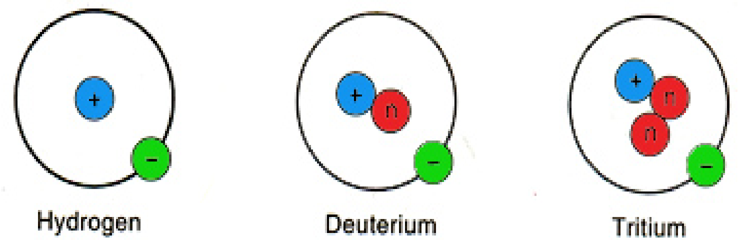


Figure 1: Bohr models of hydrogen, deuterium, and tritium

Not all of these isotopes are stable configurations, though, which can result in an atom decaying into some other form. For most naturally occurring elements, there is at least one isotope that is stable. Figure 2 shows three different isotopes of hydrogen. The first of these, which is what we normally think of as hydrogen, is called hydrogen-1 or protium and is stable. The other two isotopes are called hydrogen-2 (deuterium) and hydrogen-3 (tritium). Deuterium, which is found in nature in about 1 in every 6500 atoms of hydrogen, is stable, whereas tritium, which is much rarer, is unstable and will undergo radioactive decay, if given enough time. Other examples of isotopes with which you might be familiar are carbon-12 (6 protons and 6 neutrons), which is stable, and carbon-14 (6 protons and 8 neutrons), which is unstable. Carbon-14 is one of the radioactive isotopes that is used to determine the age of biological fossils. There are some elements for which there are no stable isotopes. An example of this would be uranium. If given enough time, all forms of these elements will decay.

Isotopes of a particular element behave the same chemically. That is to say, molecular compounds that can be made with one isotope of an element can be made in the same way with any other isotope of that same element. For example, water (H_2O) can be constructed using hydrogen-1, hydrogen-2, or hydrogen-3. The water molecules made from each of these will all look, taste, and feel like water. The only physical difference between them will be that water molecules made with deuterium and tritium will be heavier and denser than the one made with hydrogen-1. That is, the atomic mass (the sum of the mass of protons and neutrons, usually represented in atomic mass units or AMU, which is the mass of a single proton) of the different isotopes are different, and is one way to distinguish between them. The ones made with tritium will differ in one other way: they will also be radioactive.

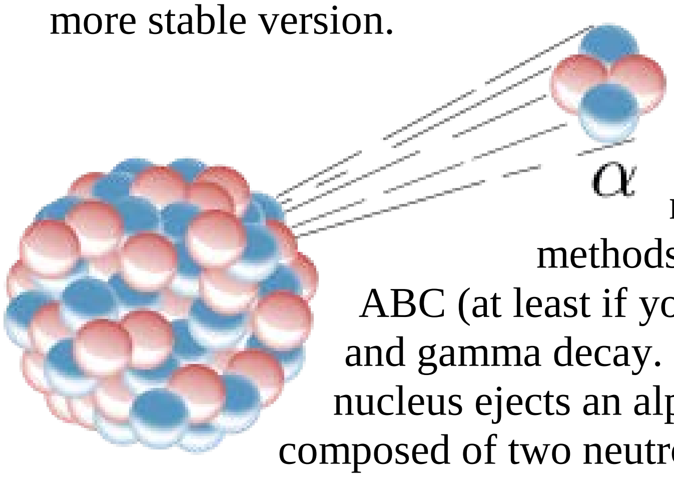
Methods of Decay

The intricacies of the strong and weak nuclear forces lead to configurations of protons and neutrons that are not stable. As we stated previously, these two forces are very short-range forces, being on the order of 10^{-15} meters. At those distances, the electrostatic force is incredibly strong. Two protons that are this far apart will exert a repulsive force on each other of (see Equn 3.1)

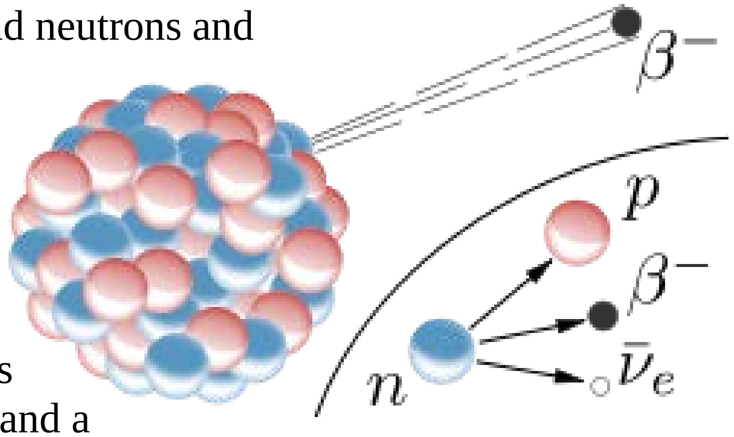
$$F = (9 \text{ x } 10^{9} \text{ N m}^{2}/\text{C2})(1.67 \text{ x } 10^{-19} \text{ C})(-1.67 \text{ x } 10^{-19}\text{C})/ (1.0 \text{ x } 10^{-15} \text{ m})^{2}$$

$$F = 250 \text{ N}$$

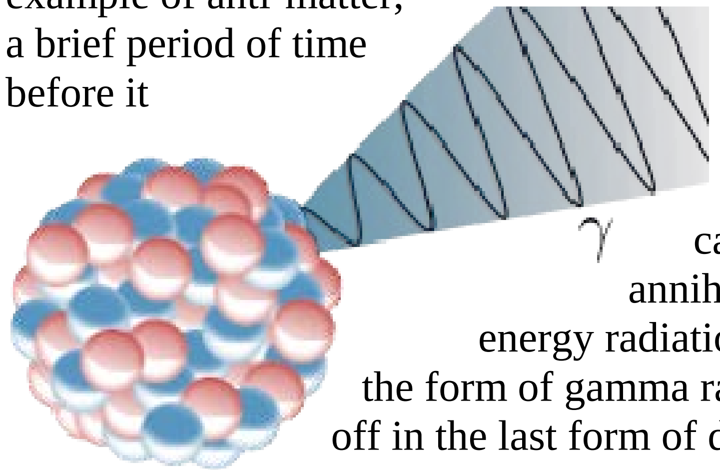
While this seems like a medium-sized force, the fact that it is operating on a particle that has a mass of 1.7 x 10^{-27} kg means that it would result in an acceleration on the order of 10^{29} m/s^2. To overcome this and hold the nucleus intact, the strong and weak nuclear forces have got to be huge. In certain configurations of protons and neutrons, the forces are just not strong enough to do this, and the nucleus will eventually change in order to form a more stable version.



When an atom decays, it can do so via one of three natural methods. These methods are as easy to remember as ABC (at least if you know Greek): alpha, beta, and gamma decay. In **alpha decay**, the unstable nucleus ejects an alpha particle, which is composed of two neutrons and two protons. Another way of stating this is that the nucleus decays by ejecting a helium-4 nucleus. Thus, the particle that is emitted is a positive helium ion. Because of its size, this particle cannot penetrate very deep into any substance even if it has a large amount of kinetic energy. An alpha particle can be effectively blocked with a sheet of paper. As an aside, it should be pointed out that this form of decay is responsible for all helium found on Earth. Helium, which is both light and chemically non-reactive, leaks out of the atmosphere soon after it enters it. The helium that we use in commercial, manufacturing, and entertainment industries all comes from mines of igneous rocks in which radioactive particles are undergoing alpha decay and releasing it.



In **beta decay**, the nucleus ejects a beta particle, which is either an electron (beta minus) or a positron (beta plus). At first glance, this would seem to be problematic, as a nucleus is comprised of protons and neutrons and contains no electrons or positrons. If they are not in the nucleus initially, where do they come from? They are produced in the nucleus whenever a neutron decays into a proton, an electron, and a neutrino or a proton decays into a neutron, a positron, and a neutrino. In either case, the proton or neutron is left behind, while the neutrino (which does not interact well with matter) and the electron or positron fly off. The electron given off in beta minus decay will be able to penetrate further into material than an alpha particle, but not by much. Electrons can be blocked with a short stack of paper or a plate of glass even at high kinetic energies.



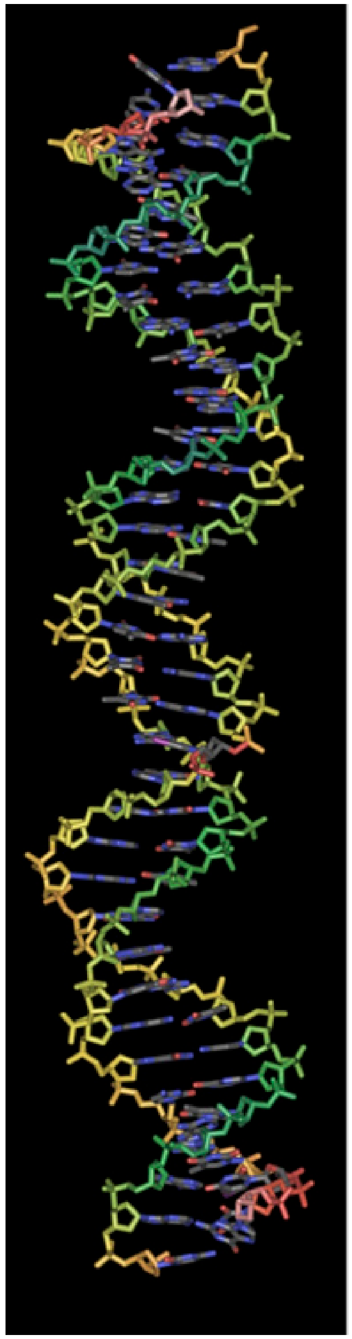
Stopping a positron is a harder proposition. A positron is an example of anti-matter, and it will exist for only a brief period of time in our matter universe before it eventually comes in contact with an electron (its matter twin) and causes both particles to annihilate, giving off high energy radiation. This radiation is in the form of gamma rays, which is also given off in the last form of decay. When a nucleus

decays via **gamma decay**, the only thing emitted is high energy electromagnetic radiation as the protons and neutrons become more tightly bound. Because gamma rays do not interact with matter well, they can penetrate material very deeply. In order to effectively block gamma rays, several inches of lead or several feet of lighter materials are required.

There is another way for a nucleus to decay, though this method usually involves the actions of humans. A nucleus can be forced to break apart if it is hit by particles from outside of the nucleus. This was discovered by Ernest Rutherford in the early 1900's when he bombarded nitrogen-14 (7 protons, 7 neutrons) with alpha particles (helium-4) to produce oxygen-17 (8 protons, 9 neutrons) and a proton. The easiest method for doing this type of decay is to bombard the nucleus with neutrons. Since the neutrons have no net charge, they are not repelled electrostatically away from the nucleus like a proton would be, and thus, do not require large energies in order to strike it. This will be important when we discuss the operation of a nuclear power plant.

Results of Decay

When an atom decays, at least three things occur that we need to discuss. The first is that the atom does not disappear. Instead, it can either stay the same element or change into a new one. An atom undergoing alpha decay changes its atomic mass by 4 AMU (the mass of a helium nucleus) and its atomic number by 2. Thus, a uranium atom (92 protons) that undergoes alpha decay will turn into thorium (90 protons). An atom undergoing beta decay does not change its mass, but it will increase its atomic number by one if it undergoes beta minus or decrease its atomic number by one if it undergoes beta plus. An atom that undergoes gamma decay does not change either its atomic mass or its atomic number. The atom into which the original atom decays is called the daughter isotope. This by-product of the decay might itself be radioactive.



The second thing is that the particles or radiation released have a strong ability to ionize atoms and molecules in their surroundings. Both the alpha and beta particles that are released have a net charge, as well as a considerable amount of kinetic energy. If they slam into any neutral atoms, they have a high likelihood of stripping charge from that atom, thus ionizing the atom. **Gamma radiation** can have a similar effect on atoms that absorb it, as the amount of energy in gamma radiation is more than enough to free electrons in an atom. The net effect of this ionizing radiation can be severe if the atoms that are ionized happen to be located in key positions inside an organic life form. In particular, if the atom forms part of the DNA molecule in a cell, then ionizing the atom might cause it to react with other atoms, thereby changing the DNA. If this change does not cause the cell to die, then when it divides, this change in the DNA will be passed on to the next generation of cells, thereby producing a mutation. While the odds of this mutation being benign are good, there is the possibility that this change will result in a harmful side effect, such as uncontrolled growth, which is what we call cancer.

This is a reason that the penetrating ability of the different decay methods is important. However, equally important is the location of the decay in relationship to an organism. If the decay occurs outside of the body, then you would like the radiation to not penetrate very well, as this would limit any damage to the exterior surface of the organism where it can be detected. If the decay occurs inside of the organism, then the radiation needs to be able to penetrate a great length, as it will be more likely to travel all of the way through the organism without doing any harm. This is why radon exposure is so potentially harmful. Radon, an alpha emitter, is a radioactive gas that filters up through the ground from natural decay in rocks. If you breathe in the radon, and it decays in your lungs, then you are almost assured that the alpha particles will ionize some atom on the surface of your lungs.

The third thing to be noted is that energy is no longer conserved in a traditional sense. As we learned in Chapter Two, the First Law of Thermodynamics states that the energy in a system can only be changed by doing work or adding heat. The particles and/or radiation emanating from the nucleus have kinetic energy that came from neither of these two sources. Instead, the energy released is as a result of mass loss in the nucleus, i.e. the mass of the initial nucleus is greater than the mass of the daughter isotopes plus the particles released. As postulated by Albert Einstein in 1905, this difference in mass results in an energy gain in the system, as energy and mass are just different manifestations of the same thing. Einstein was able to quantify the relationship between the two with the famous equation $E = mc^2$.

Half-Life Versus Activity

The natural decay process occurs in an exponential fashion. That is, given a large enough quantity of an isotope, the same percentage of nuclei will decay in the same amount of time. This means that in a given year, the number of isotopes that decay, divided by the number of isotopes at the beginning of the year, will be the same quantity. Rather than listing this fraction for isotopes, though, we often turn the issue on its head and discuss the length of time it takes for a certain fraction of the material to decay. In particular, we list the amount of time that it takes for half of the isotopes to decay, which is called the half-life of the substance. For example, iodine-131 has a half-life of 8 days. If one were to start with 100 kg of it, after 8 days, they would only have 50 kg of I-131, as the other 50 kg is now some other element. After another 8 days, they would have 25 kg left, and so on and so forth. Eventually, the amount of iodine-131 would become so small that it would no longer obey exponential decay, at which time we would have no way of determining when a particular amount of the substance would decay.

This is not to imply, though, that the fraction of the substance that will decay in a given time period is not important. It is very important, as this quantity is related to the activity, which is the number of decays that occurs per unit time. It is just that the activity and the half-life are inversely related, which means that knowledge of the half-life allows one to calculate the activity using the equation

(Equn. 8.1)

Activity = 0.69 * number of isotopes/half-life

While the half-life gives you some indication of how long a radioactive substance will be around, the activity tells you how much radiation it is currently emitting. This relationship often confuses people. For instance, a lot of people will look at a substance that has a half-life of a billion years as a bad thing. They fixate on how long the substance will be around. However, a very long half life is a good thing from a radiation standpoint, as it means that you would need an enormous quantity of the substance in order for there to be any appreciable activity. Another way to think of it is that stable isotopes, the substances that are not radioactive, have an extremely long half-life; it is infinite.

As we mentioned before, the daughter isotope of a decay might also be radioactive. In fact, a situation might exist where the granddaughter, great-granddaughter, and a whole line of descendent isotopes of a particular radioactive atom might also be radioactive. At some point, an isotope will be reached that is not radioactive, but that might take some time to reach. The chart above shows a possible radioactive decay chain for uranium-238. As you can see, the uranium-238 decays into thorium-234, which is radioactive and decays into protactinium-234. The isotopes that result keep being radioactive until lead-206 is reached, at which point the decaying stops. This is one of the primary problems with radioactive waste from a nuclear reactor. The material stays active

TABLE 1: U-238 DECAY CHAIN
IN DESCENDING ORDER OF DAUGHTER PRODUCTS

ISOTOPE	HALF-LIFE	DECAY MODE
Uranium-238	4.5 billion years	alpha
Thorium-234	24.1 days	beta, gamma
Protactinium-234	1 minute	beta, gamma
Uranium-234	245,000 years	alpha, gamma
Thorium-230	76,000 years	alpha, gamma
Radium-226	1,600 years	alpha, gamma
Radon-222	3.8 days	alpha
Polonium-218	3 minutes	alpha
Lead-214	27 minutes	beta, gamma
Bismuth-214	20 minutes	beta, gamma
Polonium-214	160 microseconds	beta, gamma
Lead-210	22 years	beta, gamma
Bismuth-210	5 days	beta, gamma
Polonium-210	138 days	beta, gamma
Lead-206	stable	-

for a long period time, with both long and short half-life isotopes, as a succession of radioactive materials is produced and decayed.

See Section 2: Additional Reading & Internet Exercises of this chapter to learn more about half-life and decay chains.

Fusion

While energy is released when a nucleus spontaneously decays, energy can also be released when nuclei are combined. The reason for this is because the force of attraction per nucleon is greater in these configurations. For example, two deuterium nuclei can come together to form a helium-4 nucleus. If you measure the force between the two protons and two neutrons in the helium-4 nucleus, you will find that it is greater than that of the force between the proton and neutron in the deuterium nucleus. Because these particles are more tightly bound in the helium isotope, it means that the potential energy of the system is lower, i.e. the potential energy of the deuterium nuclei is higher than that of the helium-4 nucleus. Thus, energy must be given up in order to form the helium nucleus.

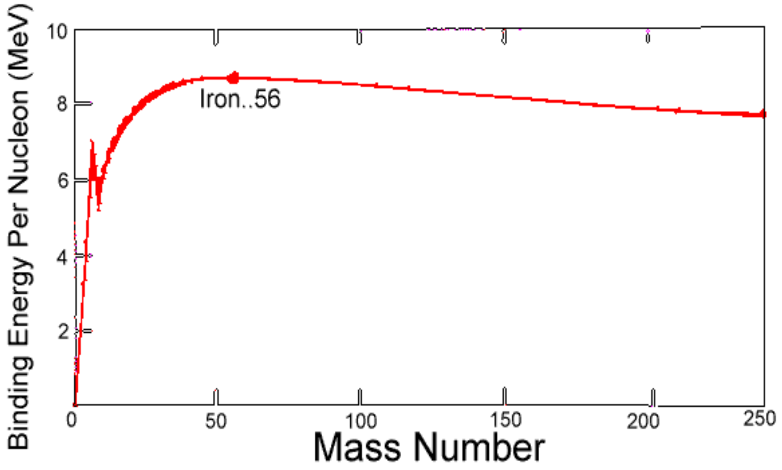


Fig. 3: Binding energy curve

Figure 3 shows a plot of the average binding energy per nucleon plotted against the mass number. It shows that the most tightly bound nucleus per nucleon is iron-56. This means that this nucleus has the lowest potential energy, and that if one wanted to either decay an Fe-56 isotope (fission) or put together two Fe-56 isotopes (fusion), one would have to add energy to the system, as there is no lower potential state to which to go. Mass numbers to either side of this isotope have lower binding energy, which means that they can give off energy by moving closer to it. Nuclei with mass numbers below iron-56 must do this by fusing together, such as when two deuterium atoms merge to form helium. Nuclei with mass numbers above iron-56 do this by fissuring, such as when an iodine-131 decays via an alpha particle.

While fission occurs quite naturally in unstable nuclei, fusion is much harder to achieve. The reason for this is that the nuclei have a net positive charge. As we discussed earlier, the strong and weak nuclear forces are very short-range forces. Before nuclei get close enough such that these two forces will be strong enough to cause them to fuse, they must overcome the huge force of repulsion. This can be done if the nuclei are moving incredibly fast, i.e. they have a lot of kinetic energy. The normal way to do this is to put the nuclei in a high temperature environment. The temperature needs to be in the million Celsius range, which is hotter than any containment vessel we can build on Earth. This is why the only way that we have been able to achieve this is in a modern nuclear bomb. These bombs fuse tritium nuclei by heating them up with a uranium nuclear bomb. Of course, nature also has fusion taking place. This is what is providing our sunlight, as the temperature and pressure at the center of the Sun are high enough to fuse hydrogen into helium.

Nuclear Power Plants: Energy

As we discussed in the section above, energy is released when isotopes decay. This energy can either be in the form of electromagnetic radiation or the kinetic energy of the nuclear fragments. The important question for us is, “How can this energy be converted into a useful form like electricity?” The most obvious thing to do is to allow either of these forms of energy to be absorbed by a substance in order to increase its internal energy and thus, increase its temperature. As the substance warms up above its surroundings, a temperature difference is created, and allows for any one of a number of heat engines to be placed between the two and convert some of the heat into useful energy.

Radioisotope thermoelectric generators create electricity from this heat difference by use of the Seebeck effect. Discovered in 1821 by Thomas Seebeck, a potential difference or voltage will be created across the juncture of two unlike metals whenever there is a temperature difference applied across the juncture. This potential difference will act as a current source if it is connected to a circuit. These types of generators are quite reliable, as there are no moving parts and the decay of the nuclear material is quite predictable. They have been used extensively in the NASA deep space probe programs, as solar energy is not usable for satellites that are going far away from the Sun. The picture in Figure 9 is the diagram of one of the RTG’s that was placed in the Cassini spacecraft that was sent to Saturn.

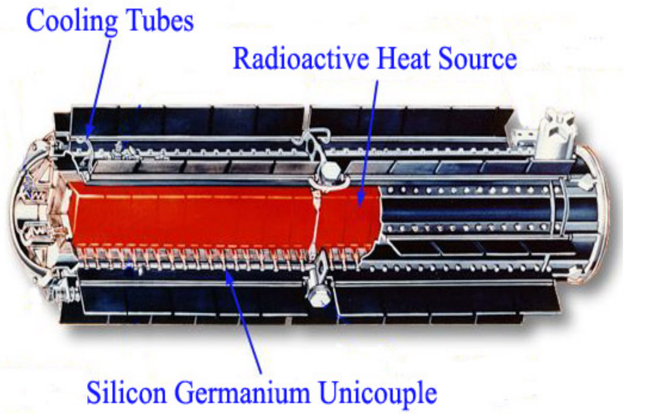


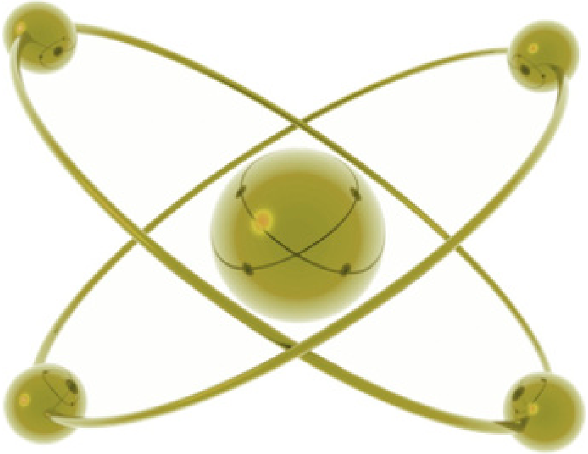
Figure 5: Diagram of the Cassini Spacecraft RTG

The efficiency of these radioisotope thermoelectric generators is not very good, being in the 6-8% range1. For a deep-space mission where the primary objective is reliability, this level of efficiency is okay. For applications here on Earth that need to produce large quantities of electrical energy, we need something that is competitive with other forms of generation. One such method would be to use the absorbed energy to boil water for use in a steam turbine. The steam turbine is the basis behind the majority of the electricity generated in the U.S., with most power plants of this type having efficiencies in the 30-40% range. Of course, to get efficiencies in this range, water temperatures above 600 °F must be reached.

Limitations on Nuclear Materials

In order to generate this level of thermal activity and to sustain it, power plants need a source that produces a tremendous amount of energy in a short period of time. For a nuclear power plant, this corresponds to having an amount of radioactive material that can fit in the plant that has a high activity. As shown in Equation 8.1, a high activity requires either a large amount of a radioactive substance and/or an isotope with a short half-life. The physical limits on the amount of available isotopes and on the size of the power plant put constraints on the amount of material that can be used. Therefore, to get the required level of activity, a substance with a relatively short half-life is needed.

This presents a problem, as substances with short half-lives are rarely found in nature in large abundance. This should not be surprising. Given the fact that Earth is approximately 5 billion years old, any short half-life material that was originally present would have completely decayed by now. New isotopes are being created all of the time, as discussed above, and some of these might have a short half-life. However, by the time that the material is found, mined, refined, and put into a power plant, a significant fraction of the material will have decayed.



Thus, using the natural decay of radioactive isotopes is not a very useful means for running a nuclear power plant. Instead, one could use bombardment of nuclei in order to break the isotopes apart and generate energy. The easiest method for achieving this is to bombard the nuclei with neutrons, as their electrostatic neutrality means that there will be no force of repulsion from the protons in the nuclei. This does solve the problem of having enough nuclear material with a high enough activity to run the plant, as we can break apart even stable isotopes with this method. But it does create another problem. In order to bombard the material, we will have to input energy (separating neutrons from other material and accelerating a beam of them onto the nuclear material), which means that our overall efficiency will be less than what we desire.

Chain Reactions

We could get around this problem if we had a substance that produced free neutrons as a result of its being bombarded with neutrons. In other words, we need a substance that produces the catalyst (bombarding neutrons) from a reaction that was caused by the catalyst. It turns out that we are in luck, in this regard, as there is one naturally occurring isotope that is abundant enough to run a power plant that fits this criteria. When uranium-235 (U-235) is bombarded with low energy neutrons, its nucleus will fragment into several parts, with neutrons being amongst them. A typical reaction for U-235 (one of many possibilities, all of which produce neutrons) is

neutron + uranium-235 ⟶
barrium-144 + krypton-89 + 3 neutrons + 173.3 MeV of energy

The three neutrons that are released by this reaction are free to bombard three other uranium-235 nuclei, which would then decay into barium and krypton fragments with up to 9 more neutrons and about three times the amount of energy being released.

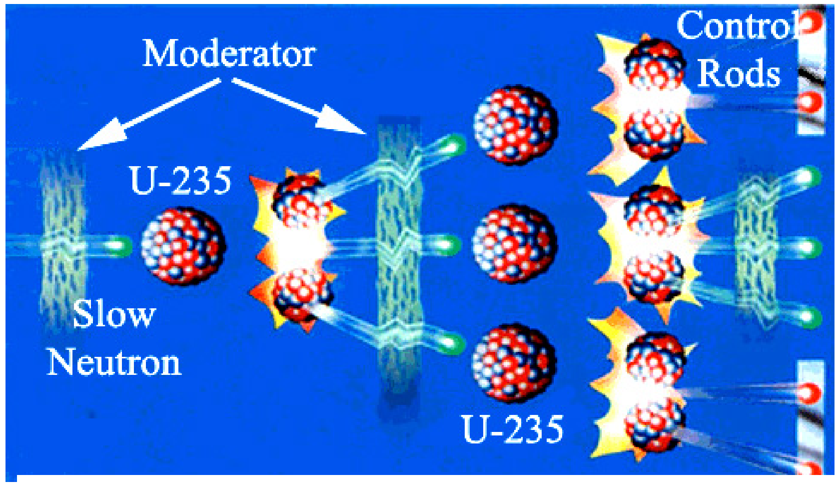


Figure 4: U-235 undergoing a chain reaction

This chain reaction would look something like the picture to the right. There are two features about this chain reaction that require further discussion. The first of these is that it is only slowly moving neutrons that have a high probability of interacting with the uranium-235 nuclei and causing a reaction. Therefore, a neutron moderator, which slows the neutrons down, is needed in a nuclear power plant in order to keep the chain reaction occurring. The second feature has to do with the number of neutrons that will be present after several different decays. While there are many different possible decay reactions that could take place, the uranium-235 nucleus will average about 2.5 neutrons released in each one. This means that each reaction will produce more neutrons than what were there initially, causing more reactions to take place at the next stage. If this is allowed to go on for some time, there will be so many neutrons around ready to react that too many decays will start taking place, which will release too much energy and cause the material to melt down. For this reason, control rods, which are made from materials that readily absorb neutrons, need to be in the system in order to limit the number of reactions that can take place at any given time.

Basic Reactor Design

Besides having neutron moderators and some method for controlling the number of neutrons in the reactor, a nuclear power plant also has to have some way of transferring the thermal energy of the nuclear material to water in order to create steam to power a turbine. This can be done in a number of ways, depending upon how safe you wish to make the reactor and how much energy you wish to create. In the U.S., we have two basic designs for reactors. A boiling water reactor (BWR) places the hot nuclear material directly in the water where steam is created. This expanding steam is used to turn a turbine, which is connected to a generator that creates electricity. After the steam has passed through the turbine, it is cooled by a heat exchanger until it condenses back to hot water, and is then pumped back into the reactor chamber. A pressurized water reactor (PWR) looks similar to a BWR, except that the reactor is sitting in water that gets extremely hot, but is not allowed to turn to steam by the pressure applied to the chamber. This extremely hot water is used to heat another chamber of water where steam is generated. A diagram of a PWR is shown in Figure 5.

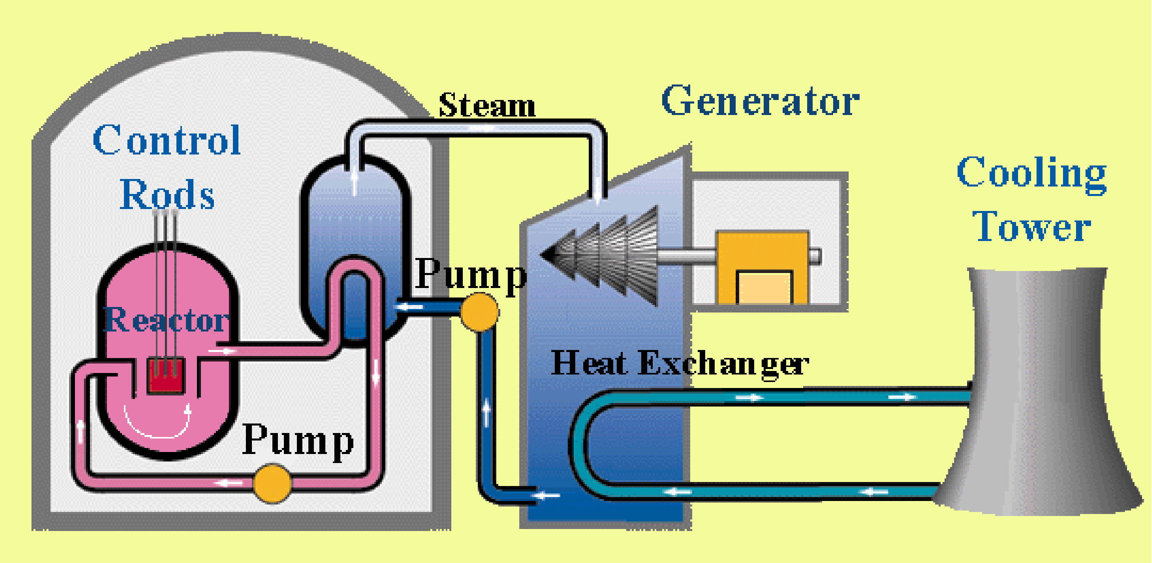


Figure 5: Schematic of pressurized water reactor

While these are the two designs used in the U.S., they are far from being the only nuclear reactor designs. Other countries have experimented with different designs, with varying degrees of success. For instance, the former Soviet Union used an RMBK design that had carbon as its neutron moderator and water as a coolant that was passed through the reactor chamber in pipes, i.e. the fuel rods were not sitting in water. This reactor was the one that was involved in the famous accident at Chernobyl. To learn more about the different styles of reactors, check out the Nuclear Tourist link in the Additional Reading section.

Production

The production of electricity via nuclear energy has been stagnant for more than a decade (Figure 6). Since 2000, we have produced about 800 billion kilowatt-hours of electricity from nuclear power plants, with variations year-to-year due to down time at particular plants for maintenance and other general production issues. The reason for this stagnation is simple: we have not brought a new nuclear reactor online in that entire time period. Without any new plants, the only way to increase production would be to run the plants at full capacity all of the time, which we cannot do, especially with our aging fleet of plants that will soon reach the end of their licensed lifespans.

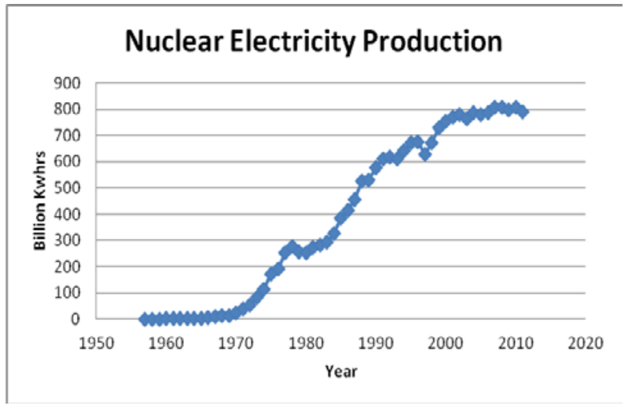


Figure 6: Historical Electricity Production

Of course, saying that we have not built any new plants does not get at the real reasons for the stagnation of production. As we will see below, several accidents involving nuclear energy in the 1970’s and 1980’s caused the general public to lose faith in the safety of nuclear energy. Fear of the potentially large impact of a nuclear disaster caused protests against the licensing of any new plants. Even plants that were already licensed to be built were put on hold, as local citizens mobilized to keep plants from being built near them. Nuclear energy never has lived up to its initial promise of being very cheap, and this fact, along with the fear of accidents, caused many plants that were already approved to be converted to either coal or natural gas plants.

Accidents

After a period of time, different parts of the reactors, such as the control rods, the reactor vessel, and the water, will become radioactive from both bombardment and from dissolving of radioactive elements by water. To prevent the releasing of radioactivity from the facility, these different designs for reactors have different safety features built into them. For example, the extra loop in the PWR means that there would need to be holes in both the reactor and the heat exchanger loops simultaneously for radiation to get into the cooling tower for release into the atmosphere. The odds of this happening are very slim. The control rods are suspended over the reactor by electromagnets in both PWR and BWR designs. Should there be a loss of electricity for running the plant, the electromagnets will cease holding the control rods, and they will drop into place, shutting down the reactions completely. If there is a water leak in the reactor chamber, and the fuel rods are exposed and no longer cooled by the water, the reaction will begin to slow down, as the water is also the neutron moderator. This prevents the reactor from getting too hot and melting a hole all the way through the reactor chamber floor, which has been reinforced with over 10 feet of concrete.

While safety can be designed into the reactor, there is still a possibility for accidents, as there is with any human endeavor. In the U.S., these have been few and far between. The most famous one was the partial core meltdown in Unit 2 at the Three Mile Island facility in 1979, which effectively galvanized public sentiment against nuclear energy enough to stop the granting of licenses for new nuclear plants for the next 30 years. This accident was caused by poor training of staff and the overriding of safety features in the plant during previous maintenance. A loss of cooling fluid caused the control rods to scram (be inserted into the reactor core) to shut down the reactions. Residual heat caused the temperature of the core to increase, which triggered the computers to add more cooling water from auxiliary sources. However, the valve to these sources had been tied shut during previous maintenance, which prevented the water from entering the chamber and causing the pile to partially melt. To prevent an explosion of hydrogen gas that had accumulated in the chamber, the air in the chamber was vented to the outside, releasing radioactive steam into the environment. While the amount of radiation released was well below that which could have caused illness, the panic that ensued did create unnecessary fear and tension that possibly did cause an increase in illnesses and miscarriages. The panic was amplified by the release of the movie, “The China Syndrome”, just 12 days before the accident.

The RBMK design discussed above has a much worse track record when it comes to safety. The reason for this is that 1) there is little to no containment built around the reactor, 2) water is used only to remove heat from the core and does not act as a moderator, and 3) the core contains carbon, a flammable substance, to act as a partial moderator. Due to the lack of openness and transparency in the former Soviet Union, we do not know exactly the extent of damage done by accidents at RBMK facilities, although there have been stories that have come out since the fall of the USSR. The one accident that we do know about is the massive release of radioactive material from the Chernobyl facility in 1986. That accident was the result of engineers at the plant running unauthorized tests to see how bad the situation could get and still have the safety features prevent an accident. Unfortunately, they found out.

The test that was being performed was to see if the momentum of the turbines could keep electricity running to the water pumps to cool the core in the event of a plant shutdown. Normally, diesel generators kick in to produce the electricity if there is a problem, but there was a time delay between when the plant had a problem and when the diesels produced enough electricity to run the pumps. The only way to run this test was to turn off most of the safety features on the reactor, and this proved fatal. The spindown of the turbines was not enough to keep the electricity going to the pumps to cool the core, and it became super heated and melted. The carbon in the core ignited, and pressure built up in the core that caused an explosion. The lack of a containment vessel meant that this explosion blew the roof of the unit, sending radioactive material high into the atmosphere and allowing the subsequent fire to continue to pump radioactive materials into the surrounding atmosphere. The fire was eventually put out by the local firemen, but costs almost all of them their lives, as the radiation levels were above the lethal dose at the reactor. The Soviet authorities did not begin evacuating people for another day, which resulted in many people being exposed to high levels of radiation, particularly iodine-131, which can be very fatal. Western authorities did not find out about it until several days later when radioactive particles started raining out of the atmosphere in Eastern Europe.

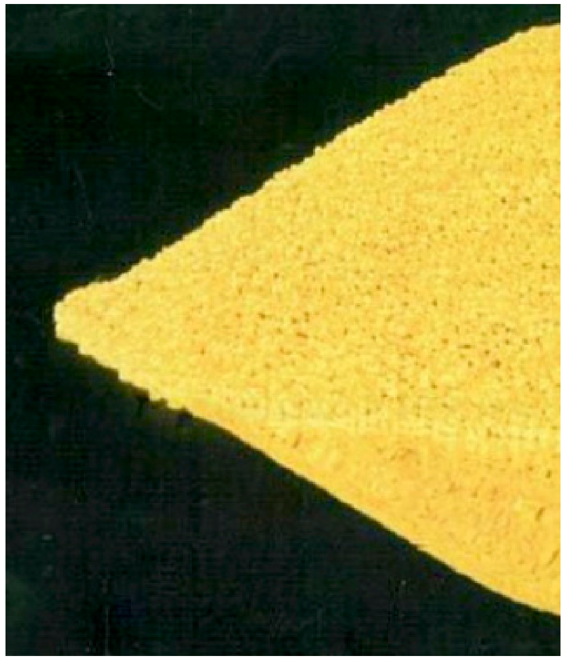
If Three Mile Island started the process of not allowing new nuclear reactors to be built in the U.S., the Chernobyl disaster cemented it. This accident killed hundreds of people immediately and possibly resulted in the deaths of thousands of others due to exposure. The Soviet government created a 30 km radius exclusion zone around the reactor, and removed all of the citizens to other locations. To this day, no one has been allowed back into the region to stay, although it is possible to visit there.

With time, though, people begin to forget about these dangers. In recent years, fears of global warming from the burning of fossil fuels had caused some to begin talking once again of increasing the number of reactors in the U.S. Several companies drew up plans for new reactors and began the process of getting them licensed. In 2011, though, the horrors of nuclear power plant accidents came back into the public mind in full force with the disaster at the Fukushima Daiichi plant in Japan. On March 11, 2011, a 9.0 earthquake occurred off the coast of Northwestern Japan along a major thrust fault. This resulted in a huge tsunami that forced water over 14 meters high to swamp the plant which was built along the coast. Generators that were designed to cycle cooling water over the nuclear piles were disabled, which lead to partial meltdowns of the cores in several of the reactors there. The creation of hydrogen gas from the exposed piles caused explosions, which exposed the reactors to the outside world. Eventually, sea water had to be pumped in to cool the cores, but not before large amounts of radioactive material was released over a broad area and creating a non-habitable zone similar to that at Chernobyl. Scientists are still in the process of assessing the amount of damage at the area, and we are not likely to know the full impact for years or decades. However, the response internationally has been one of reversing course on increasing nuclear energy, with some countries like Germany announcing plans to abandon it altogether in about a decade.

Fuel Cycle

The fuel for a nuclear reactor both starts and ends its cycle of usability as radioactive. In between, it goes through a series of steps that take it from a mineral ore in the ground to a concentrated waste in search of a final resting place. Each of these stages requires a great deal of care and has an impact on the environment. The five major steps in this fuel cycle are mining, enrichment, fuel rod, reprocessing, and disposal.

Uranium-235 starts out as a mineral ore in rocks such as carnotite and uraninite. The concentration of uranium in such rocks is usually fairly low, comprising less than 1% of the total volume of the ore. Of this uranium, the overwhelming majority (99%) of it is in the form of uranium-238. This means that usable uranium-235 is in very low concentrations in the ore. In order to have enough material for use in a nuclear power plant, this low concentration results in a large amount of ore that must be mined. The rock is extracted by either conventional open pit mining or sub-surface



mining, although some mines in the U.S. employ in-situ leaching methods that drill wells into the rock, pump a leaching fluid through the rock, and then recover the leachate through the wells. In either case, a fair amount of environmental damage is done, as the processed rock contains other heavy metals which are brought to the surface and exposed either in a tilling pile or a slag heap.

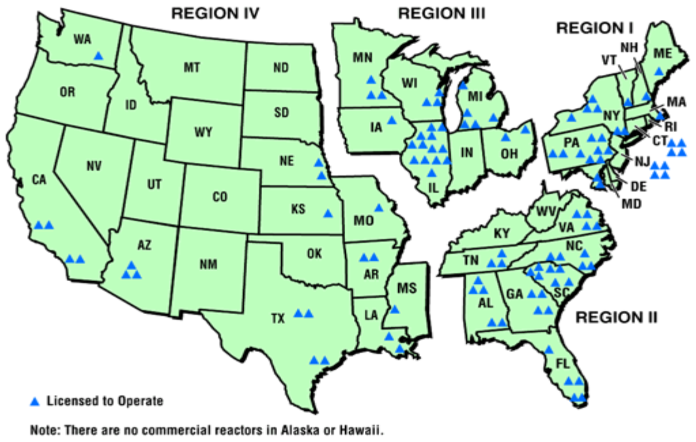
The uranium is leached from the ore in the form of uranium oxide, which must be converted to uranium hexafluoride for the second stage: enrichment. In American reactors, the fuel cells need to be at least 3% uranium-235 in order to operate. Since both U-235 and U-238 are chemically the same, there is no chemical process that can be used to separate the two. Instead, a slight separation is accomplished by taking advantage of the mass difference between the two isotopes. This is done by converting the uranium hexafluoride into a gaseous phase and then using a method, such as spinning tubes in a high-precision centrifuge, to give a slight separation between the isotopes. The material that is highest in concentration will go on to become fuel in a reactor, while the lower concentration material will go on to be used as **depleted uranium** in other applications, such armor-piercing shells for military use.

From the enrichment process, the uranium hexafluoride is converted to uranium dioxide so that it can be manufactured into ceramic pellets. These pellets are loaded into metallic tubes and sealed to prevent any leakage of the material. These tubes are called fuel rods, and they form the heart of a reactor core. Depending upon the type of reactor, these rods are formed into bundles that have the rods spaced very precise distances apart. Once completed, the fuel is now ready for use in a reactor.

The reactor core is made up of hundreds of these fuel bundles. As the reaction continues over time, the amount of uranium-235 in the individual fuel rods will be depleted. Because of the concentration of neutrons will vary across the fuel assembly, the rate of depletion will not be uniform across the core, which means that some bundles will deplete faster than others. To maintain optimal efficiency, the bundles are moved around during the operation of the plant, with depleted bundles being removed and new bundles being added in different places.

Once a bundle is no longer operating efficiently due to its uranium-235 levels being so low, it is removed for disposal. However, it does not necessarily go directly to this process. Besides the fact that there is still some U-235 in the bundle, there is also another fuel source that can sustain a chain reaction in the rods: plutonium-239. This isotope is created during the normal operation of a reactor core from the uranium-238 in the fuel pellets. While slow moving neutrons interact with uranium-235 to keep the reaction going, fast moving neutrons interact with the uranium-238 to make uranium-239. This isotope has a fairly short half-life, decaying by beta-minus to neptunium-239. This isotope, too, decays in a very short time period via beta-minus to form plutonium-239.

This man-made isotope will support a sustained chain reaction, just like the uranium-235. Better yet, since this is a completely different element, it can be more easily separated from the uranium-238, meaning that fuel pellets can be much of a much higher purity than a uranium reactor core. However, using plutonium requires a completely different setup, as the core must run at higher temperatures. Most of the test facilities for plutonium reactors use liquid sodium as the coolant, which comes with its own special problems (sodium will undergo spontaneous combustion when it comes in contact with water). Because of this, there are no operating plutonium reactors in the U.S. The plutonium is still used in nuclear bombs, as the higher purity means that you can make the nuclear bombs smaller than a uranium nuclear bomb.



Note: There are no commercial reactors in Alaska or Hawaii.

Fig. 7: Nuclear reactor sites (DOE)

Once the spent fuel rod has had any usable isotopes from it during the re-processing step, the remainder is ready for disposal. This is where the biggest problem in the nuclear industry lies. Because of the half-lives and toxicity of the isotopes that are left, the material will be dangerous for many years to come. Most people do not want this material deposited for safekeeping anywhere near them. In France and Germany, the materials are stored in barrels in abandoned mines and salt domes and constantly monitored. In the U.S., the decision was made during the 1970’s and 1980’s to bury the waste from commercial U.S. plants in the Yucca Mountains in Nevada. This location was chosen as it was far from people, had a very low water table, and was made of volcanic rock that would provide significant shielding in the case of a spill.

The facility for handling this waste was supposed to be built by the mid 1990’s. A tax was placed on nuclear energy that generated the funds to do this. However, protests, studies, Congressional hearings, and the like have delayed the construction of this facility. While part of it has been built, funding was eliminated in 2011, and construction has terminated. In the interim, all of the waste is stored on site at the commercial reactors that produced it. This means that nuclear waste is currently stored in over 100 sites around the country, with the majority of them being east of the Mississippi River. Figure 7 shows a map that has the general location of all nuclear power plants in the U.S. For the last decade, some reactor operators have looked at a short-term solution to the storage until a facility is finished. Since most governors and state legislators will not even discuss the option of bringing that much waste into their state, the most discussed option is to negotiate a deal with a Native American tribe that has a reservation. Since reservations only have to follow federal law and not state laws, they would be able to take the waste without getting the okay of any governor or legislature. To date, no deal has been made.

Discussion Questions & Problems

1. Iodine-131 has a half life of 8 days. If 10 kg of it is allowed to sit undisturbed for 24 days, how much iodine-131 is left after this time period?
2. A proton has a positive electrostatic charge; a neutron, no charge. What holds a nucleus together?

3. What is the most stable atomic nucleus? Why?

4. Why is uranium-235 used in nuclear power plants? Are any other radioactive nuclei feasible to use? Why or why not?

5. What is the current plan for commercial radioactive waste storage in the U.S.? Is there a plan for federal radioactive waste?

6. Could a Chernobyl-like accident occur in the U.S.? Why or why not?

7. What is the worst form of radiation: alpha, beta, or gamma?

8. You are given a choice of burying 100 kg of two different radioactive isotopes in your backyard. One has a half-life of 3 months; the other, 1 million years. Which do you bury in your yard?

9. Can barium-144 decay into a carbon isotope? Why or why not?

10. A coal-burning power plant emits more radiation into the atmosphere than a nuclear power plant. Why do we fear nuclear power plants more than coal ones?

References

1.http://www.llnl.gov/seaborginstitute/training/radiation_misuse_2.pdf, June 9, 2003.

Additional Reading

The following website leads to the U.S. Nuclear Regulatory Commission, which seeks to protect the public health and safety, as well as the environment, from the effects of nuclear reactors, materials, and waste products. This site provides information on reactors that are in operation in the U.S. and on the materials and waste that are involved in the process.

Nuclear Regulatory Commission

Topic: U.S. Nuclear Regulatory Commission

Summary: Links to information about U.S. reactors, nuclear materials, and nuclear waste

Link: http://www.nrc.gov/

The next website is a privately owned website that is maintained by Joseph Gonyeau, a consulting nuclear engineer for the IAEA and the DOE. This site contains a wealth of information and links regarding the entire fuel cycle process. Of particular interest is the information on the various nuclear reactor designs found around the world.

Virtual Nuclear Tourist

Topic: Nuclear Reactor Designs

Summary: Private informational website about nuclear energy. Check under Plant Designs for information about different reactor types.

Link: http://www.nucleartourist.com/

Half-life: The following link will open up a new window that contains an interactive Java applet that simulates the decay of a quantity of radioactive isotopes into daughter products. As this decay occurs, the applet plots the activity (energy released) and the number of radioactive isotopes left. Some of the sample isotopes decay directly into stable daughters; some decay into unstable daughters that then decay into stable isotopes. In particular, try using carbon-10, carbon-15, oxygen-20, oxygen-22, and fluorine-23 in the simulation, and note the concentrations and activity levels as the decays proceed.

Physics 2000

Topic: Radioactive Half-life

Summary: Tutorial on the relationship between half-life and activity from the University of Colorado’s Physics 2000 website.

Link:http://www.colorado.edu/physics/2000/isotopes/radioactive_decay3.html

Decay Chains: The next link opens up a new window that contains an interactive Java applet that shows possible decay chains for most known isotopes. Note that some isotopes have more than one decay chain, such as uranium-238. Isotopes that might be of particular interest are hydrogen-3 (H-3), carbon-14 (C-14), radon-222 (Rd-222), uranium-235 (U-235), and uranium-238 (U-238). Note the number of daughter products that are produced from each of these. Is there a general difference between the lighter and heavier isotopes?

Link:http://www.nucleonica.net/Applet/Decay/radioactive_decay.aspx