Nuclear Power

Technology

Chapter 4

4.1 INTRODUCTION

The history of nuclear power dates back to the World War II era, and it was inextricably linked to the development of atomic (actually nuclear) weapons. Thus, this chapter will discuss nuclear weapons as well as nuclear power. Only after the war, simultaneous with a significant expansion of the U.S. arsenal during the Cold War with the Soviet Union, was the "Atoms for Peace" slogan coined to broaden the focus to include commercial nuclear power. During that period, one commissioner of the old U.S. Atomic Energy Commission, Admiral Lewis Strauss, optimistically proclaimed that nuclear power would prove to be "too cheap to meter," meaning that it soon would be supplied at no charge to consumers (Pfau, 1984). Although Strauss' prediction was very far from the truth, the fact remains that despite concerns some people have had about nuclear power, it currently generates 20 times the electricity produced by solar power and 20% of all electricity produced in the United States, a figure that is close to the world average. Moreover, as with wind and solar and other renewable forms of energy, nuclear power contributes virtually no greenhouse gases during operation of the plants, which is one reason it is now being looked on more favorably, including by some environmentalists especially in nations such as France (Figure 4.1).

Apart from contributing a negligible amount of greenhouse gases (neglecting the contribution associated with the construction of a nuclear plant), nuclear does share a number of other properties with renewable forms of energy, which arguably allows us to consider nuclear to be a form of renewable energy. Whether or not you believe this controversial assertion or the claim that new generations of nuclear reactors are expected to lack many of the problems with earlier ones, the inclusion of nuclear power in a book on renewable energy can be easily justified, because in making the case for renewable energy we need to consider the relative merits of all energy sources. Moreover, nuclear has a property that it shares with no other energy source—namely, an extraordinary high energy density. Specifically, the energy liberated in nuclear reactions is roughly a million times greater per unit mass of fuel than that liberated in any chemical process. It is this extraordinary energy density that makes nuclear potentially simultaneously attractive as an energy source and dangerous if not carefully controlled. In this chapter, the primary focus will be on nuclear fission—the splitting of the atomic nucleus—but some attention will be given to the other prospective way of extracting nuclear energy, namely, nuclear fusion. Nuclear fusion, the combining of light nuclei, has been an active field of research for many years, but at the time of this writing, no

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Figure 4.1 Nuclear power plant and the reactor cooling towers in France—a nation that leads the world in the percentage of its electricity generated by nuclear power at 78%. The large plumes emitted from the reactor cooling towers consist of water vapor.

commercial fusion reactors exist—nor are they likely to exist for at least several decades according to most estimates.

4.2 EARLY HISTORY

Nuclear fission was discovered just before the outbreak of World War II in Nazi Germany by Otto Hahn, Lise Meitner, and Fritz Strassmann (Hahn and Strassmann, 1939; Meitner and Frisch, 1939). Meitner, who was Jewish, barely escaped Germany with her life after foolishly remaining there until 1938. After taking up residence in Stockholm, Meitner continued a secret collaboration with her former colleague Hahn who performed difficult experiments to find chemical evidence for fission. Hahn was baffled by his results, and he relied on Meitner to explain them. Politically, however, it was by then impossible for them to coauthor a publication on their results, and Hahn therefore published with Strassmann, with Hahn receiving the lion's share of the credit. As a result, Meitner was unjustifiably overlooked by the Nobel Committee when they later awarded the Nobel Prize to Hahn for discovering fission. Although Meitner soon thereafter realized the potential for using fission to build an enormously destructive weapon, she was not the first to do so. That idea had come to the remarkable Hungarian refugee Leo Szilard in 1933, a full 5 years before the discovery of fission. Szilard conceived the concept of a nuclear chain reaction in a bolt out of the blue that struck him one day while waiting for a London traffic light (Figure 4.2). He was granted a patent on the idea and later also received a patent with Enrico Fermi on the idea of a nuclear reactor to release nuclear energy in a controlled manner.

Figure 4.2 Physicist Leo Szilard conceived the idea of a nuclear chain reaction while crossing a London street in front of the Imperial Hotel. (Image courtesy of Brian Page.)

After the actual confirmation that fission could occur by German scientists on the eve of World War II, Szilard wanted to alert the U.S. government to the possibility of building a nuclear weapon, lest Germany do so first. He enlisted Albert Einstein in the effort on the grounds that a U.S. president would be more likely to pay attention to the world's most famous physicist than an unknown Hungarian refugee. Szilard, however, actually drafted the letter to President Roosevelt for Einstein to sign, which he did in August 1939, and the top secret U.S. project to build the bomb (the innocuous sounding "Manhattan Project") was the eventual outcome (Figure 4.3).

BOX 4.1 EINSTEIN AND THE BOMB

Although Einstein's relativity, specifically $E = mc^2$, was the theoretical underpinning behind nuclear energy, and his famous letter to Roosevelt may have started the U.S. project to develop the bomb, he played no role in its actual development. In fact, Einstein had long regarded himself as a pacifist—a position he no longer held to absolutely once Hitler assumed power in Germany in 1933. Nevertheless, Einstein later deplored the bomb's use against Japan, and toward the end of his life he noted: "I made one great mistake in my life… when I signed the letter to President Roosevelt recommending that atom bombs be made; but there was some justification—the danger that the Germans would make them" (Clark, 1953). Given that understandable fear it is ironic that Germany's progress in developing a nuclear weapon during the war was negligible, in part perhaps due to its well-documented disdain for Einstein's "Jewish physics" (Lenard, 1930).

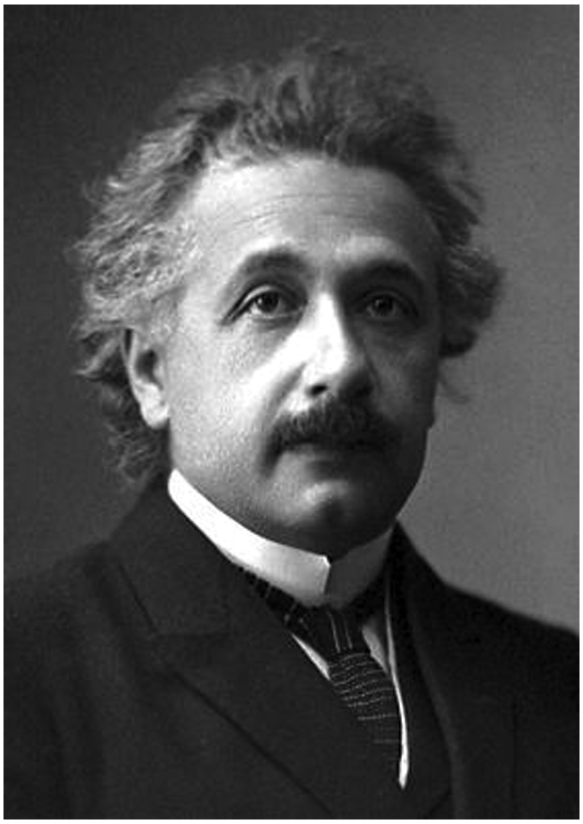

Figure 4.3 Albert Einstein, official 1921 Nobel Prize in Physics photograph. (Public domain image.)

4.3 CRITICAL MASS

Szilard's idea of a chain reaction is quite easy to understand, given (a) the existence of nuclear fission and (b) the emission during fission of two to three neutrons—neither of which had been empirically demonstrated when he conceived the idea! Suppose we imagine that two of the emitted neutrons in a fission are absorbed by other fissionable nuclei, and as a result they undergo fission and each also emit 2–3 neutrons, two of which are again absorbed creating further fissions. Clearly, as this process continues from one generation to the next the number of nuclei undergoing fission would grow exponentially, reaching 2^n after n generations have elapsed. If the time between generations (the time between neutron emission and subsequent absorption) is extremely short, the result would be a gigantic explosion.

You might wonder what is to prevent a mass of fissionable material from exploding all the time. It all depends on whether or not a mass of fissionable material exceeds a value known as the critical mass. In general, we may define f as the fraction of emitted neutrons that are absorbed by other nuclei causing them to fission, and N_0 as the average number of neutrons emitted per fission—typically, a number from 2 to 3 depending on the isotope. Those neutrons that fail to cause fissions escape the mass of material before they are absorbed by a fissionable nucleus. We, thus, have for the number of fissions in the nth generation

$$N_n = (fN_0)^n \tag{4.1}$$

Clearly, in order to have exponential growth over time it is necessary that $f > 1/N_0$—which is one way to define the condition of criticality. What will influence the actual value of f for a mass of fissionable material? The main variable would be the mass of material present, since the larger the mass, the less likely it is that emitted neutrons will escape before being absorbed, and the larger f will be. However, there are many variables besides mass itself that determine whether criticality is reached, and an explosion will occur. These include the density, geometric shape, and the level of "enrichment" in the fissionable isotope. The first of these factors should be obvious if we consider a fixed mass in the shape of either a thin pancake versus a sphere. In the case of a pancake, a much larger fraction of emitted neutrons would leave the surface of the material and not cause subsequent fissions. The importance of the "enrichment" level is also easy to understand, because the greater the percentage of a fissionable isotope, the less distance neutrons have to travel before causing a fission—and the less likely they will leave the surface of the material before doing so.

4.3.1 Neutron Absorption by Uranium Nuclei

In order to understand the manner in which neutrons are absorbed in passing through some thickness of uranium it is easiest to start with a very simple geometry: a parallel beam of neutrons incident on a very thin slab of uranium—see Figure 4.4. Define the intensity of the beam to be I (which is simply the number of neutrons per second per unit area). Let the slab have a unit area and a thickness dx that is so small that the chances of a neutron being absorbed in traveling the distance dx through it are negligible.

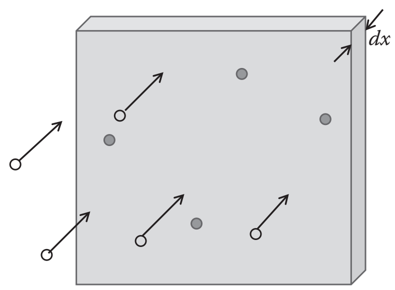

Figure 4.4 Thin slab of uranium of thickness *dx* on which a parallel beam of neutrons is incident. Open circles are the approaching neutrons, and closed circles are a few of the uranium nuclei in the slab.

By the definition of the total cross section for neutron absorption σ, only neutrons incident on an area this size will be absorbed by the nucleus. Suppose that the uranium slab has n nuclei per m^3 so that the number of nuclei inside the slab will be ndx. Thus, the chance that one incident neutron is absorbed in the total cross section of all the nuclei in the slab is σndx. Remember, however, that we are not dealing with just one neutron but I neutrons per second incident on the unit area slab, making the absorbed intensity also proportional to I and hence the intensity loss is $dI = -\sigma nIdx$, from which we find

$$\frac{dI}{I} = -\sigma ndx \tag{4.2}$$

Finally, if we have a thick slab of width x (which we imagine consisting of many thin slabs), we can easily find the total absorbed intensity by integrating Equation 4.2 and then expressing the result as

$$I = I_0 e^{-\sigma n x} \tag{4.3}$$

where I_0 is the initial intensity before striking the slab. We can rewrite Equation 4.3 as

$$I = I_0 e^{-x/d} \tag{4.4}$$

where the quantity d, known as the "mean free path," satisfies

$$d = \frac{1}{\sigma n} \tag{4.5}$$

It can be shown that physically the mean free path represents the mean distance neutrons will travel before being absorbed.

4.3.2 Why Does Density Matter in Determining Critical Mass?

The importance of the density of the material in determining the critical mass of a piece of uranium requires a bit more explanation. The distance d that a neutron will travel before having a 50% chance of being absorbed by a fissionable nucleus is given by Equation 4.5, and notice that it varies inversely with the density of fissionable nuclei per unit volume, Recall that whether a sphere of this fissionable material of radius R is critical or not depends on the ratio d/R being sufficiently small. Let us suppose that a sphere has a radius R so that the d/R ratio is just above the critical value. If the sphere were compressed to a fraction f of its original radius, the density of the sphere n would increase to nf^{-3} so that the mean free path for neutron absorption would decrease to df^3 and the ratio of the mean free path to the radius would then become $f^2(d/R)$.

Thus, if d/R was initially just above the critical value, a relatively small compression factor f would be needed to cause the sphere to become critical. Detonating a nuclear bomb by compressing a subcritical sphere can be achieved by surrounding the core of the bomb with shaped explosive charges that when detonated cause the sphere to implode and increase its density. However, the detonations must occur virtually simultaneously and the charges must be precisely shaped, otherwise the implosion will not be symmetrical and no detonation will occur if the compressed material becomes significantly nonspherical.

4.3.2.1 Example 1: Estimation of Critical Mass The cross section for absorption of a neutron having MeV energies in ^{235}U is on the order of a few "barns," where 1 barn = 10^{-28} m^2. Estimate the mean free path for neutron absorption and the critical mass for a spherical shape.

Solution

As you can easily verify by considering the units of each quantity, the number of nuclei per cubic meter in uranium or any other element can be expressed in terms of its density ρ, atomic weight A, and Avogadro's number N_A:

$$n = \frac{\rho N_A}{A} \tag{4.6}$$

which here yields $n = 4.9 \times 10^{28}$ nuclei per m^3. Using Equation 4.5, we find a mean free path of around 0.1 m = 10 cm. If two neutrons were emitted during a fission occurring at the center of a sphere having a 10 cm radius, the chances of zero, one, or two being absorbed before leaving the sphere would be 0.25, 0.5, and 0.25, respectively. Thus, the average number of neutrons absorbed in this case is one. This implies that 10 cm is roughly the radius of a sphere having the critical mass—in this case around 80 kg. In contrast, the critical mass listed in the open literature for this isotope is listed as 52 kg, which is significantly less because we have made a number of simplifying assumptions in arriving at the 80 kg estimate.

As noted earlier, the critical mass depends strongly on the level of enrichment, so that with only 20% ^{235}U it would be over 400 kg, which is generally considered the minimum enrichment level needed for a "crude" nuclear weapon. Our preceding list of ways to achieve criticality through changes in the mass, shape, density, and enrichment level are not exhaustive. Two other methods applying to nuclear reactors but not bombs would include (a) the introduction of a medium known as a moderator to slow neutrons down or alternatively (b) the presence or absence of so-called control rods made of a material that absorbs neutrons.

BOX 4.2 THE ESSENTIAL DIFFERENCE BETWEEN NUCLEAR BOMBS AND REACTORS

The essential difference between bombs and reactors concerns the critical mass. In a bomb you wish to be able to achieve the critical mass as quickly as possible, so as to have a rapidly rising exponential growth in energy released. If the critical mass is not achieved quickly, the bomb would detonate prematurely and the result would be a "dud," i.e., it would blow itself apart from the heat released before a large fraction of the nuclei fission. In a reactor, the goal is to never exceed the critical mass. However, for maximum power generation it would be desirable to approach the critical mass as closely as possible.

4.4 NUCLEAR WEAPONS AND NUCLEAR PROLIFERATION

The link between nuclear power and nuclear weapons established in World War II continues to this day, because exactly the same technology to produce enriched uranium is needed in both cases, although the level of enrichment required in the case of fuel for a nuclear reactor is only around 4% (up from the 0.7% found in nature for ^{235}U)—far less than the 90% required for a military-grade weapon. Another fissionable isotope that can be used in both reactors and bombs is ^{239}Pu, although unlike ^{235}U it is not found in nature.

Given the common enrichment technology for creating fuel for reactors and bombs, it is not surprising that among the eight "declared" nuclear weapons states, several have developed nuclear weapons under the pretense of developing a nuclear power or a nuclear research program.* One nation (Israel) not included in the eight declared weapons states has chosen not to confirm that it has a nuclear arsenal, but no informed observer doubts that fact. Of the eight declared nuclear weapons states only two have developed them since the mid-1970s: Pakistan (in 1998) and North Korea (in 2006)—giving some hope to the notion that the spread of nuclear proliferation can be slowed or halted. However, this relatively slow pace of nuclear proliferation could change abruptly if (or more likely when) Iran develops a nuclear arsenal in the volatile Middle East, since at least four other nations in that region almost certainly could build a nuclear arsenal if they so chose. The general rule of thumb is that any nation that has an engineering school could build the bomb.

BOX 4.3 HOW SECURE IS THE WORLD'S NUCLEAR WEAPONS MATERIAL?

There is much speculation about the highly enriched nuclear material in certain nations being diverted and either stolen or deliberately sold. A 2012 report by a nonprofit advocacy group (the Nuclear Threat Initiative) has ranked 32 countries based on their levels of nuclear security (NTI, 2012). A nation needs to have at least a kilogram of highly enriched uranium or plutonium to be included on the list. Nuclear security is evaluated based on the degree to which procedures and policies exist to prevent theft, as well as societal factors, e.g., those affecting the government's degree of corruption and stability, which could undermine security. Not surprisingly, this last factor places North Korea, Pakistan, and Iran at the bottom of the list of 32 nations. According to the NTI report, the top countries in terms of nuclear security are Australia, Hungary, Czech Republic, Switzerland, and Austria, with the United States not showing up until 13th place. The United States would have ranked in second place were it not for its large quantity of highly enriched material and the number of locations where it is stored—both of which contribute to vulnerability to theft.

* The eight declared weapons states in order of which they first conducted a nuclear test are United States, Russia, United Kingdom, France, China, India, Pakistan, and North Korea.

Following World War II, the United States began to amass a very large nuclear arsenal as a means of deterring the Soviet Union, in a possible conventional conflict in Europe. At the peak in the mid-1960s, the U.S. arsenal numbered over 30,000 nuclear weapons. The Soviets who started their nuclear arsenal later (with the help of some spies in the U.S. and U.K. programs) eventually amassed an even larger number of weapons. Although both arsenals have been scaled back considerably, the numbers of nuclear weapons in the U.S. and now Russian arsenals are still believed to dwarf those of any other country. A question that continues to divide many analysts concerned with national security is the optimum (and the minimum) number of weapons a nation needs to protect itself and deter threats against it.

There are many nations who are quite capable of building a large nuclear arsenal if they so choose, but who have concluded that this optimum number is exactly zero. Whether that choice will ever be realistic for the world as a whole is a matter that is tied to such controversial questions as world government, and/or the prevention of war as an instrument of national policy. Clearly, in our present-day world, where nations need to deter not so much threats from conventional nation states, but also terrorist groups, the relevance of a large nuclear arsenal becomes less certain, apart from discouraging collaborations between rogue nations led by rational leaders and terrorists.

BOX 4.4 WHAT IF THE WORST HAPPENS?

The “worst” used to be defined in terms of an all-out nuclear exchange between the United States and its superpower rival the U.S.S.R. Nowadays, it is considered much more likely that if nuclear weapons are used the threat would involve either a rogue state or terrorist group, so it is instructive to consider what would happen in such a case. In 2004, the Rand Corporation did a study for the U.S. Department of Homeland Security involving the detonation of a 10 kton bomb brought in a shipping container to the port of Long Beach, California. Such a bomb would be about two thirds the size of the Hiroshima bomb, and would be within the capabilities of a rogue state to produce. According to the study, the result would be around 60,000 short-term deaths—a horrific number. However, the study also found that an additional 150,000 people would be at risk from fallout carried by the wind. The “good news” of the study if one can call it that is that many deaths in that latter group could be avoided with some simple precautions, such as taking shelter for a few days in an ordinary basement if one were available.

BOX 4.5 INTERNATIONAL NUCLEAR AGREEMENTS

The most important international agreement for controlling the spread of nuclear weapons is the Nuclear Nonproliferation Treaty (NPT). The NPT with 189 nations participating in it is essentially a bargain between most of the nuclear weapons states and those nations not possessing them. In accordance with the NPT, the weapons states agree to help the nonweapons states with the peaceful applications of nuclear technology, and in return the nonweapons states promise not to pursue their own weapons program. In addition, the weapons states promise to work toward eventual nuclear disarmament. Unfortunately, however, three states with nuclear weapons (Pakistan, India, and Israel) never signed the treaty, one state that had signed chose to withdraw and develop a weapon (North Korea), and several other states that had signed were found to be in noncompliance with the treaty (Iran and Libya). Thus, it is clear that regardless of treaties controlling the spread of nuclear weapons, nations will pursue what they regard to be in their national interest. Only one nation (South Africa) has at one time developed nuclear weapons on its own, and later chosen to dismantle them. Presumably, however, should it ever feel the need to reconstitute an arsenal and withdraw from the NPT, this option would remain open. Another important international agreement, the Atmospheric Test Ban Treaty in force since 1963, bans testing of nuclear weapons aboveground, where the amount of radioactivity released to the atmosphere is significantly greater than in underground tests.

Many technologies exist for enriching uranium, but fortunately they tend to be expensive and time consuming, since they all rely on the very small mass differences between isotopes. A common one used by many nations involves ultrahigh-speed centrifuges filled with uranium hexafluoride, a gaseous compound of uranium (UF^6). If the gaseous centrifuge is spun at extremely high speed, the slightly lighter ^{235}U isotope tends to concentrate closer to the spin axis on average than ^{238}U. The operation of the centrifuge is illustrated in Figure 4.5a. UF^6 enters from the left, slightly enriched gas and slightly depleted gas exits through separate pipes as the centrifuge spins. The spin rate is so high that the walls of the rotor are

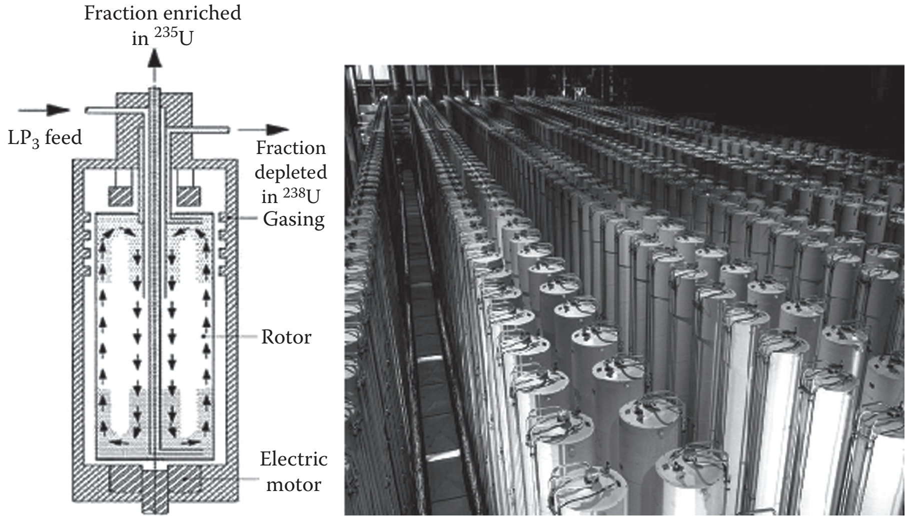

Figure 4.5 (a) Cross-sectional drawing of a gaseous centrifuge for uranium enrichment. (Image courtesy of U.S. Nuclear Regulatory Commission, Lay Road Delta, PA is in public domain.) (b) Cascade of many gas centrifuges. (Image courtesy of U.S. Department of Energy, Washington, DC.)

moving at almost the speed of sound, which requires it to be made from an extremely strong type of material, and the casing containing the rotor must be evacuated of air to avoid frictional losses. Since the degree of concentration from one pass through the centrifuge is extremely small, either the gas must be run through the centrifuge many times, or else many of them must be used in series with the very slightly enriched gas from one being piped to the next. A single centrifuge might produce only 30 g of highly enriched uranium per year, so the usual practice is to use many in series. A cascade of 1000 centrifuges of them operating continuously might yield 30 kg per year, enough for one weapon. During the World War II Manhattan Project, the race to amass enough fissionable material for several bombs was pursued by all available means including gaseous centrifuges, but these were abandoned during the project in favor of using a reactor (the world's first) to "breed" plutonium from uranium.

4.5 WORLD'S FIRST NUCLEAR REACTOR

In 1938 after receiving the Nobel Prize for work on induced radioactivity, Enrico Fermi fled his native Italy to escape the dictatorship of fascist Italy that was then allied with Nazi Germany and took a position at the University of Chicago, where he led the effort to design and build an "atomic pile"—essentially the world's first nuclear reactor (Figure 4.6). The purpose of the first nuclear reactor was to breed plutonium (^{239}Pu).

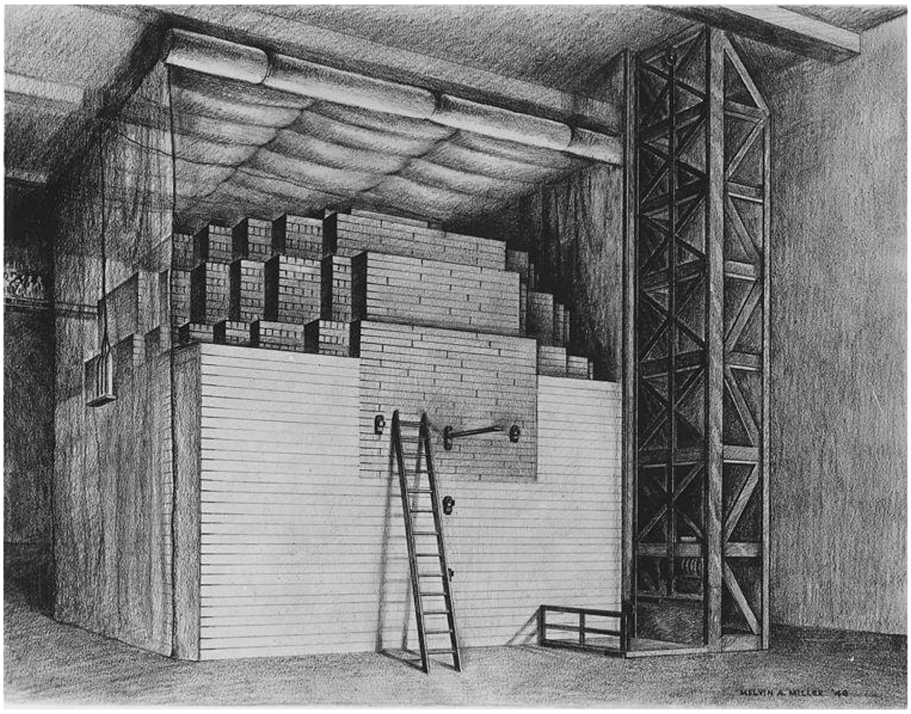

Figure 4.6 Drawing of the first nuclear reactor was erected in 1942 in the West Stands section of Stagg Field at the University of Chicago. On December 2, 1942 a group of scientists achieved the first self-sustaining chain reaction and thereby initiated the controlled release of nuclear energy. (Image courtesy of the U.S. Department of Energy, Washington, DC, is in the public domain.)

This fissionable isotope has a much smaller critical mass than ^{235}U, which is a considerable advantage in creating a bomb that is easily deliverable. Fermi's atomic pile was constructed secretly under the stands at Stagg field at his University. However, unlike almost all reactors built since then, Fermi's design had neither radiation shielding to protect the researchers, nor a cooling system to prevent a runaway chain reaction. As the neutron absorbing control rods were withdrawn and the power level increased, the reactor came ever closer to the point of criticality. Fermi, however, was sufficiently confident in his calculations that he was given the go ahead to conduct what could have been a potentially disastrous experiment in the midst of one of the nation's largest cities! After the happily successful result, he reported the outcome using the previously agreed upon coded phrase that the "Italian navigator has landed in the New World." In terms of power produced, in its first run Fermi's reactor produced a meager 50 W—although power production was not its intended purpose of course.

There are several other reasons for building nuclear reactors aside from the obvious ones of producing electric power or breeding fuel for bombs. These include conducting nuclear research, and as propulsion systems (Figure 4.7). The first nuclear powered submarine was, for example, built in 1954—the *USS Nautilus*. The twin advantages of nuclear power for propulsion in subs is their ability to stay submerged for much longer times—given the long period before the reactors need to be refueled, and their much quieter operation than diesel-powered subs. The United States even at one time considered building a nuclear powered aircraft, and perhaps strangest of all was the project considered by the Ford Motor Company to build a nuclear powered car, the Nucleon. Readers will need to find pictures of this vehicle on the web because the Ford Motor Company, perhaps understandably, declined to respond to my request for permission to use a picture of this vehicle in this book.

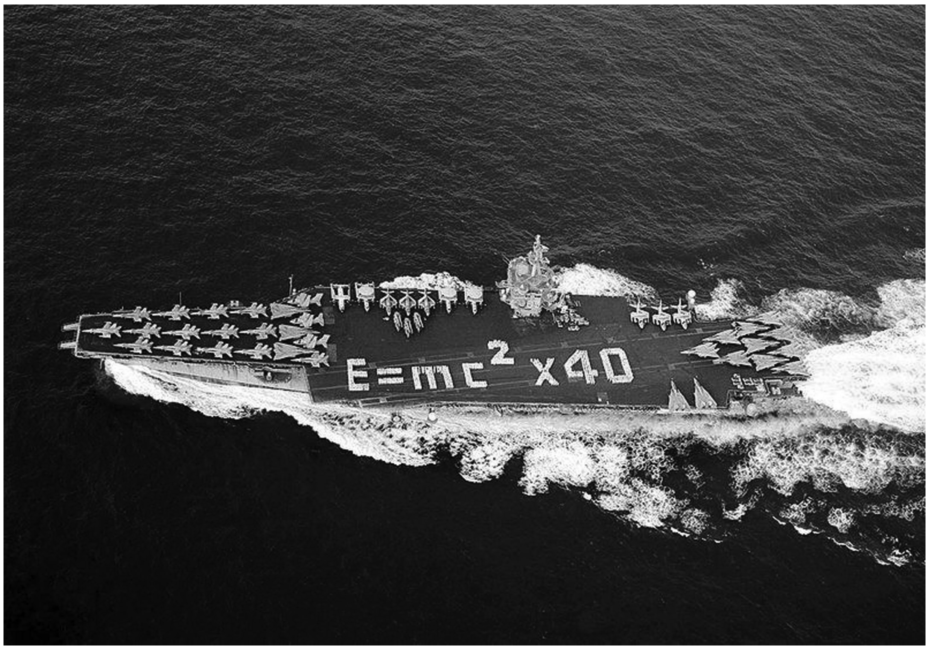

Figure 4.7 Sailors aboard USS Enterprise spell out "$E = mc^2 \times 40$" on the carrier's flight deck to mark 40 years of U.S. Naval nuclear power. (Image courtesy of the U.S. Navy is in the public domain.)

4.6 NUCLEAR REACTORS OF GENERATIONS I AND II

The first nuclear reactor ever built for the purpose of generating electricity (which produced a meager 100 kW) was not constructed until 1951—6 years after the end of World War II. Nuclear reactors built over the next two decades were the early generation I prototypes. These later led to the generation II reactors currently still in use today in the United States and many other nations. Although the current generation II reactors are more sophisticated and safer than the early prototypes they also have had their problems over the years, including some very serious ones.

A nuclear reactor used for producing electricity begins with creating heat—a result of the enormous energy release during fission. Once the heat is generated, the rest of the process for creating electricity is very similar to what occurs in many fossil fuel power plants: the heat boils water to produce steam, which drives a turbine that runs a generator producing the electricity. Thus, the components of the most common type of existing reactor that are exclusively nuclear are in the reactor vessel that is normally placed within a containment structure with thick concrete walls—the last line of defense in case of a severe reactor accident.

Inside the reactor vessel itself is the core of the reactor consisting of fuel (usually in the form of rods filled with pellets[Figure 4.8]) and the neutron-absorbing control rods that can be partially withdrawn to bring the reactor closer to criticality and increase the power level. The water that flows through the reactor core serves three purposes: (a) it prevents the

Figure 4.8 Around 20 fuel pellets for a nuclear reactor shown together with a section of a fuel rod into which they are inserted. One of those tiny pellets contains the energy equivalent of nearly a ton of coal. (Image courtesy of the U.S. Department of Energy, Washington, DC, is in the public domain.)

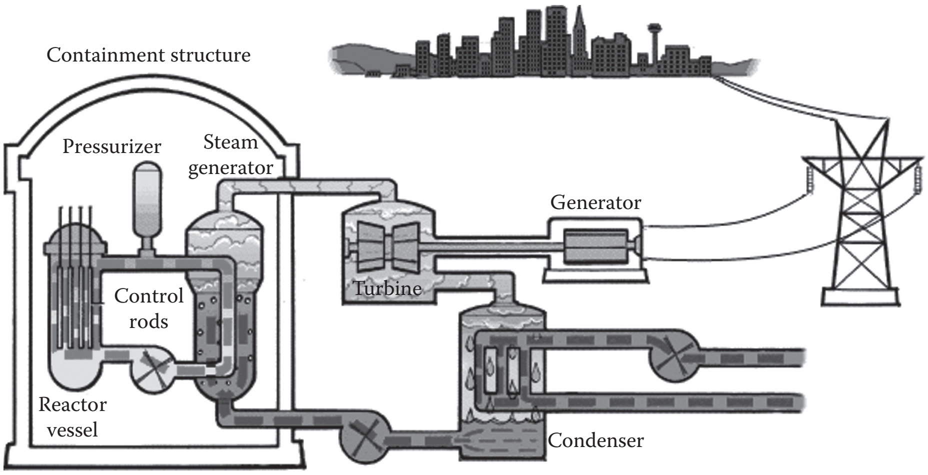

Figure 4.9 Main components of a pressurized water reactor. (Image courtesy of the U.S. Nuclear Regulatory Commission, is in the public domain.)

reactor from overheating, (b) its heat creates the steam used to power the turbine, and (c) it acts as a "moderator" whose function is to slow down the neutrons emitted in fission and thereby increase their cross section for absorption. Notice that the water that actually flows through the reactor vessel (and becomes radioactive) never comes into contact with the steam turbine, because there are two separate closed water loops that are connected only through a heat exchanger (Figure 4.9).

4.7 EXISTING REACTOR TYPES

Although upward of 85% of today's reactors are of the light water variety—some of which (5%) use a graphite moderator—a number of other types are also in use around the world, including 9% that use heavy water. Light water, of course, is not something dieters should drink! Light and heavy water are distinguished according to whether the hydrogen nucleus in the water molecules is a single $A = 1$ proton (light) or an $A = 2$ deuteron (heavy). Water found in nature consists of 99.97% of the light variety and 0.03% heavy. In addition to reactors cooled by light or heavy water, there are 5% that are cooled by gas rather than water, and 1% that are so-called fast breeders. These various reactor types will be discussed in the following sections based on the choice of moderator, fuel, and coolant.

4.7.1 Choice of Moderator

The reason that most reactors have a "moderator" such as water has to do with the dramatic variation of neutron absorption cross section with energy (Figure 4.10). Neutrons emitted in fission have energies on the order of MeV, where their cross section is around a barn. As neutrons make elastic collisions with the nuclei in the moderator, they transfer a fraction of their energy to those nuclei and gradually slow down. This has the effect of increasing their absorption cross section, and making it much more likely they will be absorbed by a fissionable ^{235}U nucleus they encounter. The section of the plot in Figure 4.10 between around

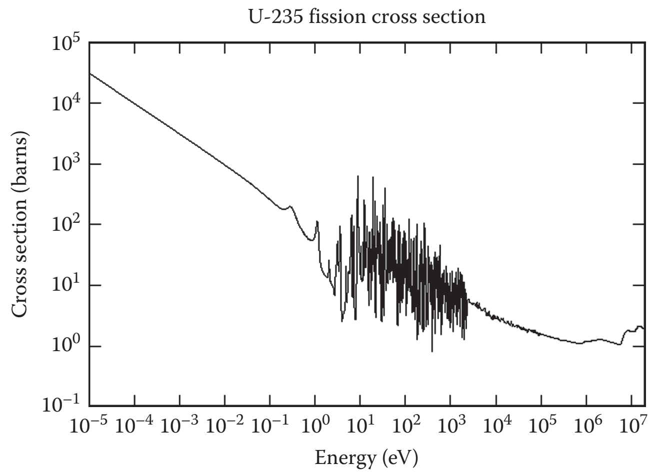

Figure 4.10 Neutron absorption cross section in barns for ^{235}U versus neutron energy in eV. A barn is a unit of area equal to 10^{28} m^2. (Image courtesy of the U.S. Department of Energy, Washington, DC, is in the public domain.)

1 eV and 1 keV where the cross section fluctuates wildly is the resonance region. In this region there are large variations in absorption cross section depending on whether the neutron energy matches spacing between the energy levels in the nucleus. At energies below around 1 eV the cross section resumes its steady rise, reaching around 1000 barns at the energy 0.025 eV which is in thermal equilibrium with the environment. Neutrons having energies near 0.025 eV are therefore known as thermal neutrons, and reactors that have moderators that slow neutrons to these energies are known as thermal reactors. The importance of a large cross section cannot be overstated, because it means the mean free path for fission-inducing absorption is correspondingly less, and the amount of fuel needed to achieve a critical mass is therefore also less.

One reason that water is often chosen as a moderator is because it has hydrogen, and therefore the proton nuclei being of almost the same mass as the neutrons are particularly effective in slowing them in elastic collisions. In contrast, if we imagine a neutron elastically colliding with a heavy nucleus, that nucleus would recoil with only a small fraction of the neutron's energy. Water also has other advantages, namely, that it is an effective coolant and that it is nonflammable—unlike graphite, for example, which increased greatly the environmental consequences at the Chernobyl disaster.

4.7.1.1 Example 2: How Much Energy Does A Neutron Lose On Average During Elastic Collisions? Suppose we had an elastic collision between a neutron of energy E and a stationary atomic nucleus of a moderator having atomic mass A. Consider the two extreme types of collisions (a) where the scattering angle of the neutron is very close to zero and (b) where it is 180°. In the first case, the energy lost by the neutron is essentially zero. In the second case, if $A > 1$ the neutron recoils backward. Let the neutron's original momentum be p and assume the nucleus it hits is initially at rest. After impact, let p' be the neutron's recoil momentum so that $q = p + p'$ is that of the recoiling nucleus. Using the equations of conservation of momentum and energy it can easily be shown that the ratio R of the kinetic energy of the recoiling nucleus to that of the original neutron is given by

$$R = \frac{4A}{(A+1)^2} \tag{4.7}$$

Recall that this result applies in the case of a 180° scattering, where the neutron loses the maximum amount of energy. Thus, since all scattering angles are possible, to obtain an approximate estimate we shall assume all angles are equally likely, and furthermore that for the average collision angle a neutron would lose half this much energy. Clearly, the smaller the A value of the nucleus, the greater the R will be, meaning that the neutron loses more energy in the collision. Note that when A = 1, R also is 1—why is that?

BOX 4.6 FOUR TYPES OF NEUTRON INTERACTIONS WITH MATTER

So far we have been considering three sorts of neutron interactions: (1) where a neutron is absorbed by a fissionable nucleus, such as ^{235}U and causes it to undergo fission; (2) where a neutron elastically scatters off nuclei of the moderator, which slows them down and makes fission more likely, due to the dependence of fission cross section on energy; and (3) where neutrons are absorbed by certain materials that "poison" the chain reaction by removing them. A fourth type of neutron reaction that occurs in breeder reactors is where a neutron is absorbed by a "fertile" nucleus that it converts into a fissionable one. One example of this process is the three-step reaction of neutron absorption followed by two beta decays: $n + {}^{238}U_{92} \rightarrow {}^{239}U_{92} \rightarrow \beta^- + \bar{\upsilon} + {}^{239}Np_{93} \rightarrow \beta^- + \bar{\upsilon} + {}^{239}Pu_{94}$. It is important to realize that the likelihood of each of the four neutron processes occurring depends on the nuclear cross section for the process, which in general will vary with the neutron's energy, and the particular nuclear isotope it encounters.

4.7.2 Choice of Fuel

Nuclear reactor designers also need to decide what fuel to use. The most common choice is uranium, which has been enriched to around 3%–5% of the fissionable isotope ^{235}U. A noteworthy exception is the Canadian CANDU reactor, which was originally designed to use natural (unenriched) uranium, since Canada at the time lacked enrichment facilities. CANDU is a trademarked abbreviation standing for "CANada Deuterium Uranium" and unlike most reactors it uses heavy water as its moderator and coolant. The reason for the heavy water is that in a normal light water reactor, while the water may be a very effective moderator in slowing neutrons to energies where they cause fission, it also has the unfortunate side effect of sometimes absorbing neutrons and decreasing the probability that they will reach ^{235}U nuclei and cause fissions.

Heavy water—a much poorer neutron absorber, but still an excellent moderator—avoids this problem and allows a reactor to operate at the enrichment level of 0.7% found in nature. Despite its capability, however, CANDU reactors now do operate using enriched uranium, which allows them to operate at higher power levels.

Another choice of fuel in some reactors is plutonium, especially in breeder reactors. However, unlike uranium, plutonium is not found in nature. Rather it needs to be created in nuclear reactions when, for example, a reactor core is surrounded by a blanket or layer of a so-called fertile isotope such as ^{238}U or ^{232}Th. By definition, fertile isotopes can be converted to fissionable ones by neutron absorption. During the operation of a breeder reactor more fissionable material is created than is consumed. In addition, one of the fissionable isotopes that is bred (^{239}Pu) itself fissions afterward, and contributes to the reactor power generated. Moreover, the portion of the ^{239}Pu that is not consumed can be reprocessed afterward (removed from the reactor waste), and then mixed with natural uranium to refuel the reactor.

The great advantage of breeders is that by breeding new fuel they allow reactors to use a far greater fraction of the original uranium, whereas other reactors make use of only the 0.7% that is ^{235}U. After a number of breeders were built in the United States and other nations several decades ago, they fell out of favor. One reason was that breeders imply waste fuel reprocessing, which was considered to have a significant risk of diversion of plutonium that could lead some nations to stockpile it for bomb making. In addition, during that period uranium was cheap and abundant, and there seemed to be no need for breeders. Currently, however, there is renewed interest in them—and a number of nations (India, Japan, China, Korea, and Russia) are all committing substantial research funds to further develop fast breeders. Fast breeders use neutrons having MeV energies to cause fission rather than thermal neutrons, and hence have no need for a moderator.

One final fuel choice briefly discussed here is thorium. Like uranium, thorium is a fissionable isotope found in nature (unlike plutonium, which is not). The chief advantages of thorium as a reactor fuel are twofold. First all thorium is a single isotope and is fissionable, unlike uranium where only 0.7% is. Second, thorium is three times as naturally abundant as uranium. Taking both of these factors into account, a ton of thorium can produce as much energy as 200 tons of uranium. But the advantages of thorium do not stop there. Thorium also has better physical and nuclear properties when made into a reactor fuel, it has greater proliferation resistance (since the waste is "poisoned" for bomb making), and it has a reduced volume of nuclear waste. At the moment, thorium reactors are being researched in a number of nations including the United States, and one commentator has suggested that thorium-fueled reactors would "reinvent the global energy landscape… and an end to our dependence on fossil fuels within three to five years," and he has called for a Manhattan Project scale effort to implement this vision (Evans-Pritchard, 2010).

4.7.3 Choice of Coolant

Whether a water-cooled reactor uses heavy or light water as a coolant would make almost no difference in terms of its cooling properties, since they both have the same specific heat. On the other hand, the pressure at which the reactor core operates does make a difference. Two common types of light water reactors are the boiling water reactor (BWR) and the pressurized water reactor (PWR). In the BWR, the cooling water has a pressure of about 75 atm, and a boiling point of about 285°C, and it is allowed to boil so as to produce steam, which then drives a turbine. In contrast, in the PWR the higher pressure of about 158 atm increases the boiling point enough so that boiling does not occur in the primary water loop.

An alternative liquid coolant to water in some advanced reactors is liquid metal, which has the advantage of higher power density for a given reactor size, and greater safety owing to the lack of need to operate the reactor under high pressure. It also has some significant disadvantages, including having a coolant that may be corrosive to steel—depending on the choice of metals. Given the higher power densities of liquid metal cooled reactors, an early application was in submarine propulsion systems, and both the U.S. and Soviet fleets have used them. Liquid metal coolant reactors tend to be of the fast neutron variety, because they need to have a lower neutron absorption cross section in view of their high energy density. In other words, if thermal neutrons were used, their power level would skyrocket, and the reactor could not operate safely. The earliest liquid metal used in a reactor was mercury; however, mercury has the disadvantage of being highly toxic and emitting highly poisonous vapor at high temperatures, and even at room temperature. Two other choices that have suitable low melting points and suitably high boiling points are lead (327°C, 1749°C) and sodium (98°C, 883°C). However, these choices also have their problems. Sodium, for example, undergoes violent reactions with both air and water, and it also emits explosive hydrogen gas. Nevertheless, despite their problems, liquid-metal-cooled reactors have enough advantages to be planned for many advanced "generation IV" reactor designs.

Another advanced design built in Britain in 1983 is the advanced gas cooled (AGR) reactor, which used high pressure CO_2 (40 atm) as its coolant. Gas cooling results in higher temperatures of operation and hence higher thermal efficiency. In addition, since a significant fraction of the cost of water-cooled reactors is in the cooling system, gas-cooled reactors should be much more economical. The graphite-moderated AGR, while not using water as a coolant, still relies on it to generate the steam needed to drive the turbines. Unfortunately, the British AGRs took far longer than expected to build due to their complexity, and the cost overruns led them to prove uneconomical, although seven of them continue to operate. They are also being planned for some "generation IV" reactor designs.

It should be obvious that "very bad things" can happen to a reactor should it lose its coolant. However, unlike your car, where a loss of coolant at the worst will result in fatal damage to the engine, for a reactor a loss of cooling accident (LOCA) is potentially devastating for the environment. While it may be true that reactors are incapable of a nuclear explosion, they can (and have) had meltdowns, and released a very large amount of radioactivity to the environment.

BOX 4.7 WHAT IS A MELTDOWN?

A meltdown has a large number of meanings in English, but as applied to a nuclear reactor it refers to the core of the reactor partially melting due to the extreme heat generated (particularly if there should be a loss of coolant), or the reactor momentarily becoming critical. Even in the extreme case, however, in which an explosion occurs due to the rapid buildup of energy, the reactor core will blow itself apart before a very significant fraction of the core undergoes nuclear reactions, and hence the explosion would be nonnuclear. In the Chernobyl disaster, it has been estimated that 0.01% of the fissionable ^{235}U reacted during the meltdown, in contrast to the much larger fraction in the event of a nuclear bomb detonation.

4.8 REACTOR ACCIDENTS

The seriousness of nuclear accidents is rated on a scale of 1–7, by the International Atomic Energy Agency (IAEA), with the two most serious categories being 6 = "serious" and 7 = "major," based on the impacts on people and the environment. There have been two major accidents in the nuclear age: Fukushima in 2011 and Chernobyl in 1986, as well as one "serious" one at Mayak in the former Soviet Union in 1957, which many people in the West may never have heard about. On the same rating scale the accident at Three Mile Island (TMI) in the United States in 1979 was rated as a five based on the amount of released radiation qualifying as being in the "limited" category. In the following sections, we discuss the three accidents TMI, Chernobyl, and Fukushima, starting with the last one, which is probably the most familiar to the majority of readers.

4.8.1 Fukushima

The accident at Fukushima was a direct result of the earthquake and tsunami that hit Japan on March 11, 2011. These led to a series of nuclear meltdowns among some of the reactors at that six-reactor complex. Although the reactors operating at the time shut down automatically when the earthquake occurred, there was a loss of power both from the grid as well as that from backup generators (due to flooding). These power failures caused a loss of coolant to the shut down reactors, which triggered meltdowns in three of the six reactors. The meltdowns were followed by hydrogen gas explosions and fires with releases of radioactivity to the environment both locally, and eventually over a much wider area. The released radiation led to an evacuation of Japanese living in a 20 km radius around the plant. Fukushima will certainly cause long-term health, environmental, and economic problems for the Japanese for years to come, and it has already led to their decision to phase out their reliance on nuclear power. Nevertheless, the following facts about Fukushima need to be considered to put the accident in perspective:

- There were zero deaths or serious injuries from direct radiation exposures, even though 300 plant workers are judged to have experienced "significant" radiation exposures. The few plant workers that did die were killed as a result of the earthquake.
- Most of those residents in the mandatory evacuation zones are estimated to have received "annualized" doses of perhaps 20 mSv, which is the dose that would have been received had there been no evacuation. However, since most residents left this zone after perhaps no more than 2–3 days, their actual dose received was perhaps 0.2 mSv, which is equivalent to 6% of what is received from background radiation each year.
- Some residents were not evacuated for up to a month, and not evacuated very far, thus definitive assessments of the doses received cannot yet be made. Despite this word of caution, for most people living in Fukushima their total radiation exposure was relatively small and unlikely to result in any observable increase in the long-term cancer death rate.
- The total amount of radiation released from the Fukushima accident has been estimated as being about 1/10th that which was released by the Chernobyl accident.
- The total number of Japanese killed by the tsunami and earthquake was 28,000.

4.8.2 Chernobyl

The Swedes are reputed to be a very safety conscious society, and yet they heavily depend on nuclear power for 45% of their electricity—a fact that speaks either to the safety of nuclear power when carefully controlled or the hubris of the Swedes, depending on your point of view. On April 27, 1986 the alarms triggered by high levels of radiation went off at the Swedish Forsmark nuclear plant prompting concerns of a leak. However, the source of the radiation was found not to be at the Forsmark plant, but rather it was wind-borne fallout originating 1100 km to the Southeast—from one of the Chernobyl reactors in the town of Pripyat in Ukraine.

Initially, the Soviet Union (to which Ukraine then belonged) tried to cover up what had happened, but after the Swedes reported their detection the Soviets finally had to acknowledge to the world that a nuclear catastrophe had taken place, and only then they belatedly ordered an evacuation of Pripyat a full 36 h after the April 26 disaster—and only after the town's citizens had received the early (most intense) radiation exposures. The Swedish radiation detectors were triggered a day after the disaster, because it took that long for the radioactive dust cloud to reach them.

The total radioactivity released by Chernobyl into the atmosphere has been estimated to be 50–250 million Curies, which is about the equivalent of that released by between 100 and 400 Hiroshima bombs. Apparently, 70% of this radioactivity was deposited in the neighboring country of Belarus, whose border is 7 km from the Chernobyl site. People living in the immediate area would have received extremely high doses before they were evacuated, and for people at a considerable distance the dose received would depend on their distance, but even more strongly on whether they happened to be in the path of the wind-borne radioactive dust cloud, and whether any precipitation occurred over them. As of December 2000, over 350,000 people had been evacuated from the most severely contaminated areas and resettled.

The number of fatalities in the immediate aftermath of Chernobyl includes 57 workers who met an agonizing (often slow) death from radiation sickness, and an estimated 9 children who died from thyroid cancer—the one cancer where the increase due to the radiation exposure is most evident—see Figure 4.11. Thyroid cancer, however, is rarely fatal, with a 5 year survival rate of 96%. The eventual death toll from other cancers over time has been estimated to be 4,000 among the 600,000 persons receiving more significant exposures, plus perhaps another equal amount among 5 million people in the less contaminated areas (UNSCEAR, 2010). Both of these estimates are based on the linear no-threshold model. However, since cancer has a long latency period, and since the number of spontaneously occurring cancers will eventually number in the tens or hundreds of millions, the actual percentage rise in the cancer death rate will be very modest, and almost certainly not detectable, making a test of the model impossible.

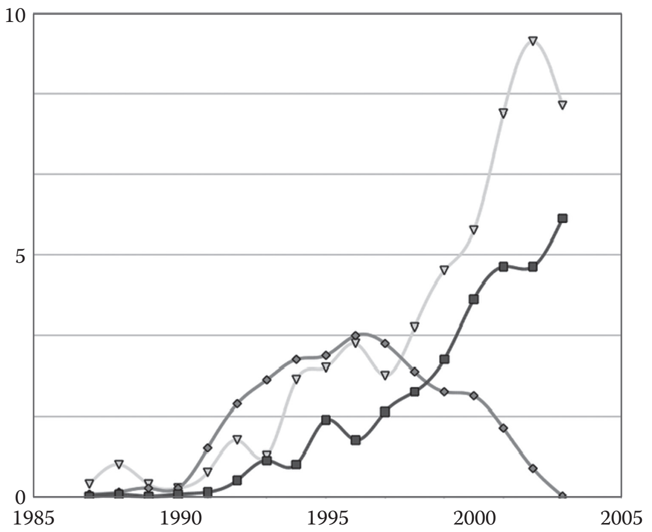

Figure 4.11 Thyroid cancer incidence in children and adolescents from Belarus after the Chernobyl accident per 100,000 persons. Triangle: Adults (19–34), Square: Adolescents (15–18), Circle: Children (0–14). (From Demidchik, Y.E. et al., *Int. Congr. Ser.*, 1299, 32, 2007; Cardis, E. et al., *J. Radiol. Prot.*, 26, 127, 2006; and has been released to the public domain.)

4.8.2.1 Causes of Chernobyl It may be inaccurate to call Chernobyl an "accident," because it was probably bound to occur sooner or later for this reactor design, so if it was an accident it was one that was "waiting to happen." The catastrophe occurred during a systems test that had not been properly authorized at a time when the reactor's chief engineer was home asleep, and the man in charge was Anatoly Diatlov. The test's purpose was to see if the reactor could safely be shut down if there was a loss of power from the grid to the pumps that supplied the reactor with cooling water. In principle, emergency diesel generators should automatically come on in such an event to supply the needed 5.5 MW of power to run the pumps. However, there was an unacceptable 60 s time delay between the signal that grid power had been lost and the emergency generators coming on and reaching their full power. The engineers thought that the residual rotational momentum of the massive turbines might be enough to bridge the bulk of that 60 s gap, and the purpose of the test was to check this idea—even though three previous tests had given a negative result.

During the start of the test, owing to an error (inserting the reaction quenching control rods), the reactor power level had dropped precipitously to 30 MW—a near-total shutdown and only 5% of the minimum safe power level to conduct the test. Below the authorized level of 700 MW, owing to a known design defect, reactors of the Chernobyl design were unstable and prone to a runaway chain reaction, whereby a small increase in power leads to a still larger increase. Anatoly Diatlov, however, was unaware of this fatal design flaw, and against the advice of others in the control room, he ordered that the test proceed anyway. In an attempt to raise the power level back up to the mandated 700 MW, nearly all the neutron absorbing control rods were raised out of the reactor also in violation of standard operating procedure. This action essentially disconnected the reactor's "brakes."

After some minutes had elapsed the power in the reactor was rising steadily and the cooling water began boiling away, leading to a number of low water level alarms going off. These were foolishly ignored by a crew all too used to false alarms, and the power level rose still further as less and less water was cooling the core. When the crew finally realized what was happening, and they tried to slam on the brakes, the control rods descended far too slowly taking a full 20 s to reach the core after being activated—another design flaw. Moreover, those same control rods, which never should have been fully removed in the first place, had a further flaw. Their graphite tips (the first part to enter the core) actually caused an increase in the reaction rate not a decrease. With their insertion, the power level in the reactor increased at one point to over 100 times its normal level, and the result was an immense pressure buildup followed by a series of massive explosions, and the destruction of the reactor.

To compound matters even further, the use of a graphite core, a reactor roof made of combustible material, and the absence of a containment dome (standard in all U.S. reactors) led to a fire that burned for days and the release of much of the reactors radioactive core into the environment. The firemen who were called in to put out the fire and many of the other emergency workers had no idea what they were dealing with, and many of them died from radiation sickness. Here is how one French observer sums up the accident in terms of an analogy with a bus careening down a mountain road:

> To sum up, we had a bus without a body careening down a mountain road with a steering wheel that doesn't work and with a brake system that speeds up the vehicle for a few seconds and then takes 20 seconds to apply the brakes, that is, well after the bus has slammed into the wall or gone off into the ravine (Frot, 2001).

Remarkably, after Chernobyl, Ukraine continued to run the other reactors at Chernobyl for many years, and the last one was not shut down until the year 2000.

BOX 4.8 HOW MUCH RADIOACTIVITY WAS RELEASED BY CHERNOBYL?

The amount of radioactivity released has been a subject on which a wide range of opinions has been offered. One estimate is 3 billion Curies, which corresponds to a third of the total radioactivity in the reactor core. Despite such an incredibly large release, however, it is noteworthy that the more "slow motion" release that occurred over the years during the period of atmospheric nuclear testing of the 1950s and 1960s was actually about a thousand times greater! However, even those atmospheric tests during their most intense period of 1963 increased the worldwide background radiation level by only 5% (Thorne, 2003).

4.8.3 Reactor Accidents: Three Mile Island

Although the accident that occurred at the Three Mile Island paled besides Chernobyl in terms of its seriousness (Table 4.1), and its impact on the growth of nuclear power worldwide (Figure 4.12), it was the most serious on American soil. In the minds of many Americans, it is probably considered on a par with Chernobyl given its location in the United States near Harrisburg, Pennsylvania. The accident began on March 28, 1979, as a result of a stuck-open pilot-operated relief valve. The open valve allowed

Table 4.1 Comparison of Effects of Chernobyl and Three Mile Island

Consequence	Chernobyl	TMI
Radioactivity released	Up to 3 billion Curies	Up to 13 million Curies
Impact on immediate area	Immediate area uninhabitable	0.3% Rise in background
Global fallout	Much of Europe and Asia contaminated	Zero
Health effects (short term)	56 deaths	Psychological distress
Health effects (long term)	Est 4000 excess cancer deaths	<1 excess cancer death

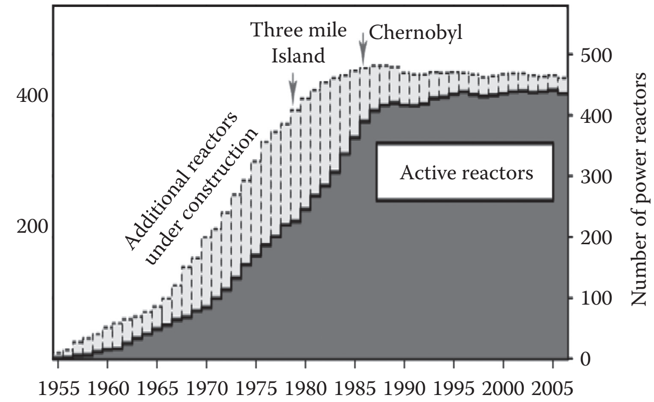

Figure 4.12 Number of reactors worldwide versus time. The impact of the TMI and Chernobyl accidents on the growth of nuclear power is evident from this graph. (This image was created by Robert A. Rohde for the Global Warming Art project. It is licensed under the Creative Commons Attribution-Share Alike 3.0 Unported license, http://en.wikipedia.org/wiki/File:Nuclear_Power_History.png)

a significant loss of coolant, which went unrecognized by the operators for some time. Eventually, the reactor was brought under control, but not before a small (nonnuclear) explosion occurred and up to 13 million Curies of radioactive gases were released to the atmosphere. The main reason for the absence of global fallout is that the release from TMI was in the form of radioactive gases, not dust, and hence it did not return to ground level.

4.9 FRONT END OF THE FUEL CYCLE: OBTAINING THE RAW MATERIAL

Deposits of uranium ore can be found in many nations, and the world supply has been estimated to be quite abundant. At the current mining costs and ore grades presently mined, there is about 100 years' worth, but this estimate is misleading because there is much more uranium available if we go to less economical lower grade ores. Even though they may be more expensive (on a per unit energy basis) lower grade ores would have a negligible impact on the cost of nuclear energy, given that the cost of fuel is a very small contributor to the total cost (mainly personnel, construction, and maintenance). At present, the three countries that supply the largest share of uranium are Australia, Canada, and Kazakhstan, which between them account for 63% of uranium production in 2010. During the twentieth century, the United States was the leading producer of uranium in the world, but given that the best high-grade ores in known deposits have been depleted in the United States, it is cheaper to import from other nations. However, it is worth emphasizing that relying on imports of uranium is quite a different proposition than relying on imported oil, since if the need arose, the United States could use its domestic reserves to satisfy its needs with only a negligible impact on cost, and having Australia and Canada as our main suppliers is less worrisome than relying on oil imports from the Middle East.

Uranium mining tends to be similar to many other hard rock mining operations, and it is extracted either in open pits or underground mines—the latter being more hazardous to miners' health, given the concentrations of radon gas and radioactive dust. In the past, especially during the early period of the 1950s, there was an increase in the cancer death rate among uranium miners due to their exposure to radon. Of course, underground mining of any sort is a dangerous occupation, which continues to get safer over the years. For example, in 1907 there were over 900 deaths among U.S. coal miners due to mine disasters plus many more deaths due to long-term exposure—which is a far cry from the experience of recent years even though accidents continue to happen. Of the various types of mining and drilling to provide energy—both fossil fuel and nuclear, nuclear is certainly the safest on a per kilowatt-hour generated. The reason is that due to the extremely high energy density, much less uranium is needed than any fossil fuel—recall the equivalence of one tiny uranium pellet and a ton of coal.

A particularly intriguing method of obtaining uranium involves mining the oceans. The world's oceans have a staggering amount of uranium—about 1000 times what is found on land, but in exceedingly low concentrations, of about three parts per billion. There has been considerable work demonstrating the feasibility of such ocean extraction since the mid-1990s, particularly by Japanese and U.S. scientists. The method is more costly to implement by a factor of 5–10 than mining on land, given the much lower uranium concentration in the oceans. Such a high cost would essentially make it out of the question to extract uranium in this manner, were it not for the fact that the cost of the uranium fuel, as previously noted, is a small fraction of the cost of the energy being generated (see Problem 15). Thus, the existence of this uranium supply in the oceans reminds us that the world has a supply that will last 1000 times longer than can be provided by land-based reserves, even though it is cheaper not to extract it from the oceans for now. Interestingly, even that factor of 1000 greater abundance severely understates the amount of uranium available! It is believed that the crust of the Earth and the sea tend to be in equilibrium chemically, so that as uranium is extracted from the sea it would tend to be replenished by uranium in the Earth's crust (that is not accessible to mining)—40 trillion tons worth. On the basis of such continued ocean replenishment, it has been suggested that a source of uranium will be available for billions of years.

4.10 BACK END OF THE FUEL CYCLE: NUCLEAR WASTE

A major concern of many people who worry about nuclear power is the waste that reactors generate. This "high level" (intensely radioactive) waste consists of many different radioisotopes having many different half-lives, and the radioactivity, therefore, does not decay according to the simple radioactive decay law. Most nuclear waste is classified as "low level," in terms of its radioactivity, but the waste generated by nuclear reactors is much more radioactive, and considered "high level." Although it is sometimes noted that given the very long half-lives of some fission products, high-level wastes will remain hazardous in some cases for hundreds of thousands of years, such statements ignore the fact that after such time spans the magnitude of the danger is negligible, since the wastes will have decayed to well below the level of radioactivity of the original ore and be equivalent to a small rise in background radiation. Decay of high-level waste to the level of the radioactivity in the original ore requires about 7000 years, but when "transuranic" (elements with $A > 92$) are first removed, the remaining waste decays to the level of the original ore in around 500 years. As a consequence, prior extraction of the transuranic elements that can provide fuel for breeder reactors could simplify the waste disposal problem, given the much shorter decay times of the remaining wastes.

The three main approaches for dealing with high-level nuclear wastes depending on the length of time after being removed from a reactor are (1) isolation often in water-filled pools for some years when they are initially most radioactive, (2) later storage in casks onsite (often in the open) at the power plant, and (3) final eventual geological disposal underground in a nuclear waste repository. The third and final stage remains hypothetical (at least in the case of the United States), because the Yucca Mountain repository, which has been constructed and approved by Congress in 2002, has been blocked for some time based on various concerns, including geologic stability of the site and the hazards associated with shipping high-level wastes across country by truck or rail. Moreover, all work on Yucca has been halted since 2009, after $15 billion has been spent on the facility. Meanwhile, the imperative to do something with the high-level waste that continues to accumulate (at 2000 ton per year) onsite at the nation's reactors has most recently been recognized by a 2012 Presidential Commission, but the identification of an alternative site remains elusive. Of course, it is also possible that Yucca (the officially designated repository) could be reactivated under a Republican Senate and President.

The actual means of storage envisioned would be in a vitrified form in which the wastes become bonded into a glass matrix, which should be highly resistant to water—thus eliminating the possibility of the wastes finding their way into groundwater—a method in use in several countries. For this reason some observers consider the nuclear waste disposal problem essentially a political one rather than a technical one. Whether it is essentially a political problem or not, the failure of the U.S. government to resolve the impasse surrounding the Yucca Mountain waste repository also causes both the general public and many potential investors in nuclear power to question its viability.

While there continues to be NIMBYism on the part of some citizens toward all things nuclear, opposition toward a long-term nuclear waste repository site anywhere nearby tends to be especially strong compared to public opposition toward a new nuclear power plant. The reasons are understandable, since nuclear power plants bring many more jobs than would a waste repository, and if there is only one in the nation why put it in ***MY*** backyard? Given this reality, the lesson of Sweden—a nation much more dependent on nuclear power than the United States—is instructive. In the past, the Swedes had been rather opposed to nuclear power. However, in 2009 the government, despite some continuing opposition, lifted a 30 year ban on new nuclear plants. In addition, a number of small towns changed their attitude toward a nuclear waste repository in their area from NIMBY to PIMBY ("Please in my backyard!") when they became convinced that the facility planned was not a hazard to their health, or at least that the financial incentive the government offered was more than worth the risk.

4.10.1 Shipping Nuclear Waste

Quite apart from the issue of storing nuclear waste in a permanent repository, many people are much more concerned with the matter of getting it there, especially since that would often involve shipping it cross-country, and possibly right through their own town. If or when the nuclear waste repository in the United States should start being used, there might be perhaps 600 cross-country shipments by rail or 3000 by truck annually—up from the present 100. On the other hand, on a worldwide basis there have been more than 20,000 such shipments annually involving high-level wastes (amounting to over 80,000 tons) and over millions of kilometers by rail, road, or ship. In none of these shipments was there an accident in which a container (always in a very sturdy and fire resistant) filled with highly radioactive material has been breached, or has leaked.

The steel and lead containers carrying the high-level wastes are protected by armed guards and are designed to withstand serious crashes and fires, but an accident that breached them cannot be ruled out. According to the U.S. Department of Energy, in such a "worst case" scenario occurring in a major city there might be as many as 80 deaths from a year's exposure to the radiation—although why someone would remain in a high radiation area for a full year is unclear. It is instructive to compare the nuclear situation with that of certain other dangerous cargoes—especially chlorine, which is a highly poisonous gas (used in combat in World War I), and for which 100,000 shipments are made annually. The Naval Research Laboratory has done a study that concluded that

> The scenario of a major chlorine leak caused by a terrorist attack on a rail car passing through Washington, D.C. could produce a chlorine cloud covering a 14-mile (23-km) radius that would encompass the White House, the Capitol, and the Supreme Court, endangering nearly 2.5 million people, and killing 100 people per second (NRL, 2004).

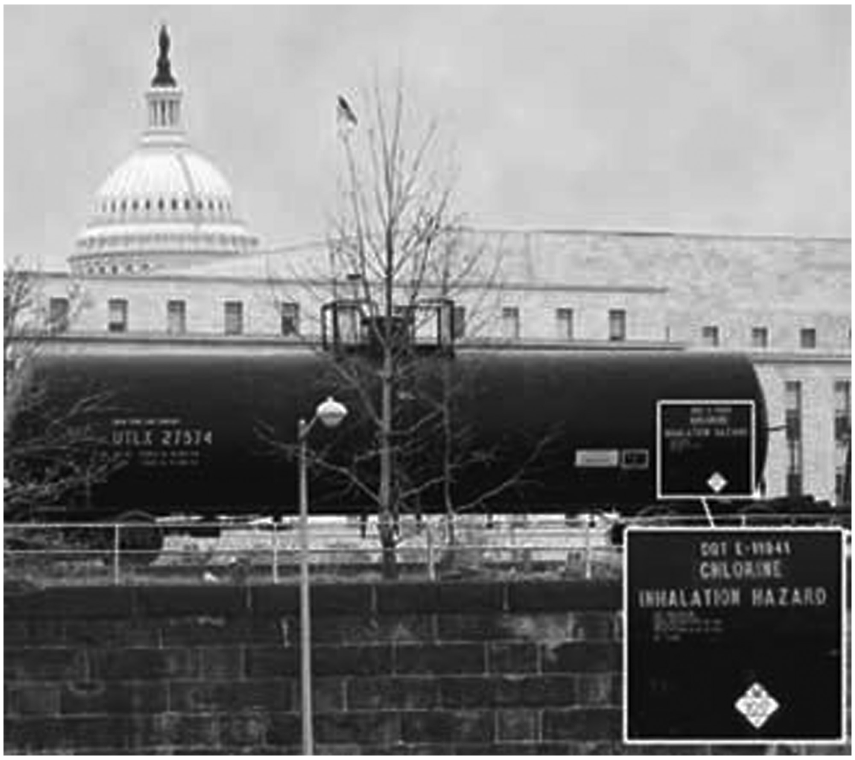

Figure 4.13 Shipment of a 90 ton pressurized chlorine gas rail tank within four blocks of the Capitol building in Washington, DC. Helpfully (to terrorists), the nature of the cargo is clearly labeled with a sign on the side, and there are no obvious armed guards onboard. (Photo courtesy of Jim Dougherty, Sierra Club, 2004.)

At that rate within the first half hour before any evacuation got underway there could be 50,000 deaths. Moreover, unlike the case of nuclear waste shipments, aside from predictions of models, there have been real fatalities in some very serious accidents involving chlorine shipments. Note that chlorine being heavier than air tends to stay near ground level where most people are, rather than drift away. Surely, no city, especially Washington, DC would be so foolish as to permit such cargo to transit the city!

After taking the photo in Figure 4.13, Mr. Dougherty, a lawyer, wrote and lobbied for passage of a law that the Washington, DC Council later adopted restricting movement of ultrahazardous rail cargo through the center of Washington, DC. This law was subsequently challenged by the federal government on the grounds that states and localities cannot interfere with interstate commerce. Mr. Dougherty helped defend the DC law in court, and the DC law was upheld. However, since there is no federal law on the books (as of 2007), such ultrahazardous cargo is not prohibited from moving through cities generally.

The main point of this "apples and oranges" comparison (nuclear waste versus chlorine shipments) is that as a society we seem to insist on a level of safety in the former case that goes far beyond what we insist on in other categories that actually involve far greater risks and consequences.

4.11 ECONOMICS OF LARGE-SCALE NUCLEAR POWER

Many opponents of nuclear power believe that apart from any environmental or safety issues, it simply makes no sense economically. The opponents could be right, since electricity from nuclear power is currently more expensive than either coal or gas. However, one can also find studies making the opposite claim made depending on whether one is speaking about existing reactors or new reactors. The obvious question is then why is there so much uncertainty regarding the economics of nuclear power relative to other ways to generate electricity?

There are four categories of cost for electricity generation from nuclear reactors: (a) construction, (b) operating and maintenance (including fuel cost), (c) decommissioning, and (d) waste disposal. In the United States, eventual nuclear waste disposal costs are funded by a charge to the utility of a 0.1 cent/kWh. The cost of the fuel alone is a small fraction of the total—amounting to about 0.5 cent/kWh, and the cost to decommission a reactor tends to be around 15% of the construction—also a relatively small contribution of the total. The main costs of nuclear power are for construction of the plant, which typically range from 70% to 80% of the total. In part, the higher relative fraction of costs for construction for nuclear plants is a reflection of a much lower cost for the fuel owing to the enormous energy density of nuclear, but it is also a consequence of the higher construction costs for nuclear power. Capital construction costs for nuclear tend to be higher than for other energy sources for many reasons, including the higher skill level needed for construction workers, and the need for more stringent safety precautions, but the two main reasons have to do with the length of the construction time and the discount or interest rate paid to borrow the money used to construct a plant.

In the United States, in particular, there have been unexpected changes in licensing, inspection, and certification of nuclear plants that have lengthened construction time (in some cases by many years) and increased costs, due to the interest paid on borrowed money. Additionally, the interest rate for these projects tends to be higher than for other capital projects owing to either the perceived greater risks or the greater uncertainties, which in some cases have been created by unwise policies. For example, the U.S. Nuclear Regulatory Commission (NRC) used to approve new nuclear plants in a two-step process: first, granting approval to begin construction, and then only after completion, granting approval to begin operation of the plant. Investors who loan money for the capital construction phase had no guarantee that the completed plant would ever be allowed to operate. Understandably, this uncertainty might lead investors to demand a higher interest rate particularly after the Shoreham reactor met a fate of exactly this kind! As one incentive to promote nuclear power in the United States, the Congress passed in 2005 a program of loan guarantees for new clean energy plants, making nuclear power potentially more attractive to lenders. Regrettably, the funds for such loan guarantees tends to dry up in bad economic times, which impacts not only nuclear, but large-scale initial investments in various renewable energy technologies, such as solar–thermal plants.

BOX 4.9 THE FATE OF THE SHOREHAM REACTOR

Shoreham was built on highly populated Long Island, NY, between 1973 and 1984, a construction period of 11 years. Such a long construction time obviously led to skyrocketing costs. The delay, in part, was due to the intense public opposition to the reactor (located only 60 miles from Manhattan), particularly after the 1979 TMI accident in nearby Pennsylvania. The public opposition eventually led to the Governor of the state refusing to sign the mandated evacuation plan for the surrounding area. This action then led the NRC to deny the utility a permit to operate the reactor, which was then taken over by the state, and later decommissioned in 1994.

Subsequent to Shoreham, the NRC wisely changed its policy on the two-step process and it now grants permission both to start construction and operate the completed reactor in a single step. It has also put in place other rule changes that permit for a more logical and streamlined approval process without compromising safety. Most importantly, each reactor that had been built in the United States was done so as a one-of-a-kind design, and it had to be approved individually. Following the long-term practice in France, as of 1997 the NRC finally approved applications for standardized designs, with four different approved designs (by two companies) as of 2010.

Regardless of national policies, however, construction of nuclear plants (assuming they are funded by private investors not a government) are always likely to be higher than nonnuclear plants because of their greater complexity, longer construction times, and the likely higher interest rates paid for loans. In addition, nuclear plant construction costs have escalated dramatically in recent years, as a result of such factors as a lack of experience in building plants with the recently approved designs, and a strong worldwide competition for the resources and manufacturing capacity to build such plants. Thus, whether nuclear is economically favorable depends entirely on what one assumes about the (a) construction cost, (b) interest rate for loans, and (c) construction time.

Based on Table 4.2, the range in electricity costs for new nuclear plants spans an enormous range—a range that is large enough for optimists to say it compares quite favorably with other alternatives, and pessimists to make the contrary claim.

No one can predict the future, but unless memories of Fukushima fade fairly quickly the nuclear pessimists seem more likely to be correct.

Table 4.2 Cost of Electricity in Cents/kW-h Based on Construction Costs of $5 Billion and $2.5 Billion, Interest Rates from 5% to 10%, and Construction Times from 3 to 7 Years

Construction Cost	$5 Billion				$2.5 Billion			
Interest Rate (%)	3 Years	4 Years	5 Years	7 Years	3 Years	4 Years	5 Years	7 Years
5	5.8	6.1	6.5	7.6	3.7	3.9	4.2	4.9
6	6.6	7.1	7.6	9.2	4.1	4.4	4.8	5.9
7	7.5	8.1	8.9	11.3	4.6	4.9	5.5	7.2
8	8.5	9.4	10.5	14.2	5.0	5.5	6.3	9.0
9	9.5	10.7	12.4	18.2	5.6	6.3	7.4	11.7
10	10.7	12.3	14.7	24.1	6.2	7.1	8.6	16.1

Source: http://nuclearinfo.net/Nuclearpower/WebHomeCostOfNuclearPower

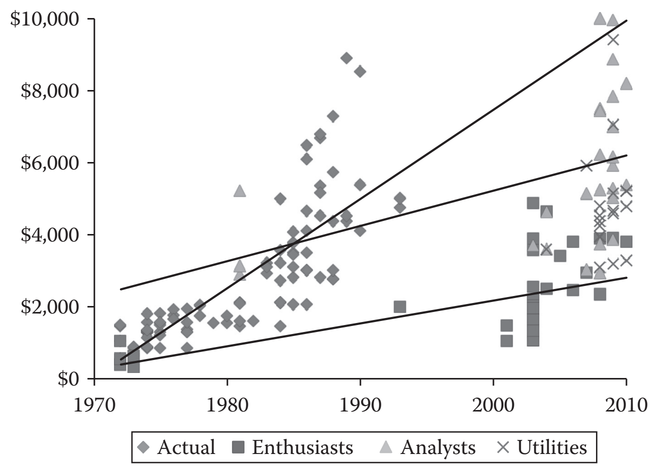

Figure 4.14 Actual costs and cost projections in 2009 dollars per kilowatt for new U.S. nuclear reactors. The cost projections are identified by their source. Note that estimates for other nations particularly China and France tend to be lower than for the United States. (From Cooper, M., *Nucl. Monitor*, August 28, 692, 2009. With permission.)

In fact, the actual costs of new reactors have tended to be far greater than the cost projections of the "enthusiasts," as seen in Figure 4.14. Moreover, it is worth noting that virtually all the 31 new plants that had been proposed in the United States by 2009 have been shelved due to the confluence of low gas prices, high costs of nuclear power, and weak demand for new electricity capacity. The 33 year long stoppage has been apparently ended by two new reactors being planned in Georgia—a project that undoubtedly will be closely watched by utilities around the country. Nevertheless, there are also grounds for some optimism if you are a proponent of nuclear power. According to the Nuclear Energy Institute, worldwide 150 nuclear energy projects are either in the licensing or advanced planning stage as of 2012, and 63 reactors are under construction (NEI, 2012).

4.12 SMALL MODULAR REACTORS

While the economics of traditional nuclear power plants remains uncertain and highly subject to one's choice of assumptions, that for a new type of reactor—the small modular reactor—appears to be much more favorable, because it is not subject to escalating onsite construction costs. Although nuclear power is a contentious issue politically, it is interesting that the polarization on the nuclear issue tends to be more correlated with gender than politics (Bisconti, 2010). In fact, there was one nuclear-energy-related proposal by President Obama in 2011 that met a very different fate in Congress than almost all his other proposals—energy-related or not. The President, calling for a "new generation" of nuclear power plants, proposed money for research and loan guarantees to help build SMRs. That request for funding was approved by the U.S. Senate by a vote of 99 to 1 with not a single Democrat or Republican opposed.

As of 2010, there are at least 8 nations developing SMRs according to 16 different designs. One example is the 25 MW reactor being built by Hyperion Power Generation in the United States, based on designs developed at Los Alamos National lab (Figure 4.15). This small liquid-metal-cooled reactor would produce enough power for around 20,000 homes. The reactor has no moving parts, and has a sufficiently small amount of fuel that a meltdown is said to be impossible. In fact, Hyperion envisions that the reactors would be made at the factory, shipped in one piece to the site where they will be used, and then buried underground, where they would run with little or no human intervention required during the 10 years for the fuel to burn up.

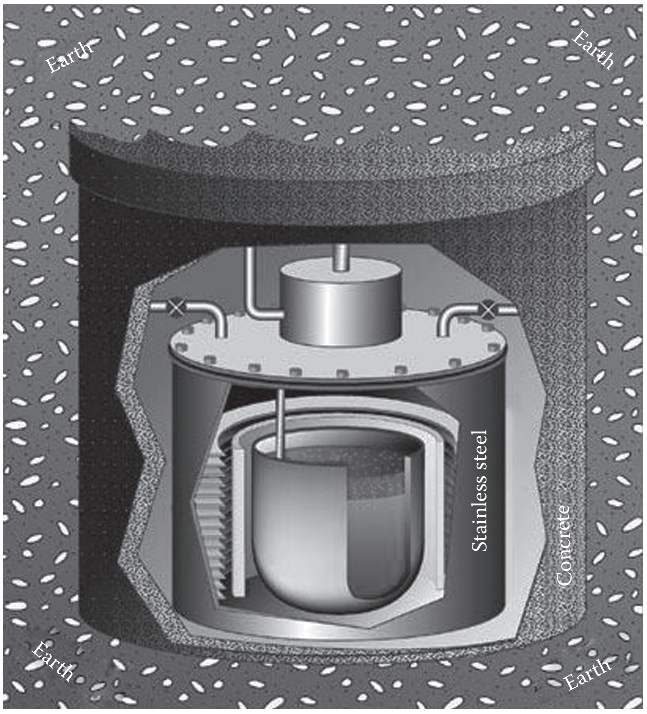

Figure 4.15 Conceptual drawing of the Hyperion "nuclear battery" (the central component of its power generating plant), which stands about the height of a man. (Courtesy of U.S. Los Alamos National Lab, a public domain image.)

After that period of time, a reactor would be shipped back to the factory perhaps on a flatbed truck to have the spent fuel replaced. The goal of the company is to produce power for under 15 cents per kWh, which while not competitive with grid parity in most areas of the United States would be highly competitive for remote off-grid communities and government installations.

Another somewhat higher power reactor (165 MW) of a very novel design is the Pebble Bed Modular Reactor (PBMR), first developed in Germany and now being pursued mainly by the United States and China (Figure 4.16). The PBMR is cooled by helium gas, and its fuel is in the form of spherical pellets about the size of tennis balls. Each pellet consists of the nuclear fuel, surrounded by a fission product barrier, and graphite moderator. Simply piling in enough pebbles will allow the reactor to approach criticality. The pellets, because of their size and composition never get hot enough to melt, so that a meltdown is said to be impossible. In fact, should there be a coolant failure, the effect would be to slow the reaction rate and cause the reactor to shut down. This passive safety feature is diametrically opposite to the unfortunate design feature of Chernobyl-type reactors, which become more reactive when they heat up. In the PBMR, at any one time the reactor vessel contains around 450,000 of the pellets, with new ones continually entering from above and spent ones leaving from the bottom of the reactor vessel. Thus, the reactor is continually being refueled online, and costly shutdowns for refueling are never necessary. Defects in the production of pebbles can, however, cause problems, and in fact an accident at a German PBMR in 1986 resulting from a jammed pebble did cause a shutdown and resulted in a small release of a small amount of radioactivity.

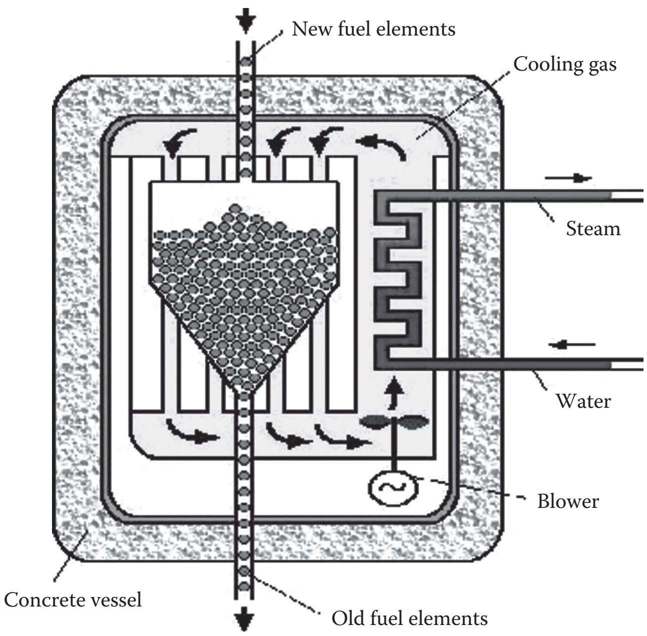

Figure 4.16 Pebble bed modular reactor. (Image created by Picoterawatt and released to the public domain; http://en.wikipedia.org/wiki/Pebble_bed_reactor)

Other types of SMRs are of a more conventional light water reactor design (such as those made by NuScale Power and by Babcock and Wilcox) that better lend themselves to being scalable so as to provide large amounts of power when a number of them are added as the demand grows. Virtually all the SMR designs rely on "passive" safety features (no operator intervention required) to maintain safe operation and prevent a catastrophic melt down. Passive safety features, in general, rely either on the laws of physics, the properties of particular materials, and the reactor design to prevent accidents. In addition to passive safety systems, simplicity of operation and (perhaps) lower cost, modular nuclear reactors have many other advantages. They can also be placed very close to the need—thus requiring smaller transmission costs, and fewer new power lines. Effectively, modular reactors can be thought of as "nuclear batteries" having an energy density millions of times greater than normal batteries that can also provide backup to intermittent renewable energy sources.

The future of small modular reactors does indeed look bright, but they will probably not come on line for another decade (2020) due to the lengthy NRC approval process required. This process is necessary for usage either in the United States or in other nations in order to comply with IAEA safeguards. Although the U.S. Navy has had a long experience with small reactors for propulsion, the fuel configuration and enrichment levels required for civilian commercial use are quite different, which is the reason that a lengthy process of evaluating new designs is necessary. Moreover, when considering the economics of SMRs, we should remember that many new technologies fail to live up to initial expectations. Recall that large-scale nuclear power, initially thought to be too cheap to meter, may turn out to be too expensive to compete, so one cannot be certain about either the economics or the public acceptance of modular reactors until they meet the realities of the marketplace.

4.13 NUCLEAR FUSION REACTORS

Nuclear fusion, should it prove technically and economically feasible, would be an ideal energy source for many reasons, including an inexhaustible supply of energy in the hydrogen in the world's oceans, and the lack of any long-lived fission decay products. The main technical difficulty is (a) achieving the high temperatures needed for controlled nuclear fusion and (b) confining the fuel for a long enough time for self-sustaining ignition to occur. In the core of the sun, gravity is able to provide the confinement, but on Earth the only two known means of achieving confinement are either to a magnetic field, or inertial confinement. In the latter case, pellets of fuel are bombarded by powerful lasers from many directions, and the pellet heats up so fast that the inertia of its parts prevents it from blowing itself apart before its temperature is raised to the ignition point. In the other technique pioneered by the Russians in their Tokamak reactor, a diffuse plasma is confined using a magnetic field of a toroidal geometry, which keeps it away from the walls of the vessel while energy is added to heat it. Although considerable progress has been made since the first Tokamak, we are still decades away (if ever) from a commercially viable fusion reactor. The usual way to measure progress in this field is based on the ratio

$$Q = \frac{power\_produced}{power\_input}$$

where

- Q = 1 represents the break-even point
- Q = 5 is the point for a self-sustaining reaction, i.e., where power input equals power produced plus power lost
- Q = 22 is what is considered necessary for "reactor conditions"

A simplified way for measuring how close a given design is to these Q values is based on the Lawson criterion, i.e., the triple product of the plasma density, temperature, and confinement time. For ignition, i.e., Q = 1 to occur with the *dt* (deuterium-tritium) fusion reaction, the Lawson criterion is

$$nT\tau > 10^{21}\ \mathrm{keV\ s/m^3} \quad (4.8)$$

where the temperature T is chosen to have its optimum value. Currently, a seven-nation $15 billion effort is taking place involving an international collaboration known as International Thermonuclear Experimental Reactor (ITER) based in France. It is hoped that ITER will come quite close to the self-sustaining point for a time of 10 s by the year 2018. There are also competing (or complementary) efforts—one known as Ignitor using a "riskier" design originating at MIT that might beat ITER at its own game at only 2% of the cost. Although research continues on fusion using inertial confinement as well, the inertial approach currently appears further from reaching a commercially feasible reactor.

It will be seen from Figure 4.17 that the Lawson criterion (Equation 4.8) is not the whole story in deciding how close we are to achieving ignition, since if it were, curves for constant Q would be shown as horizontal lines rather than the parabolas they appear to be. In other words, the temperature variable T is unlike the other two in Equation 4.8, in that we cannot say the higher the better, since above some optimum value there becomes a decreased chance of ignition—can you think of a reason for this strange fact?

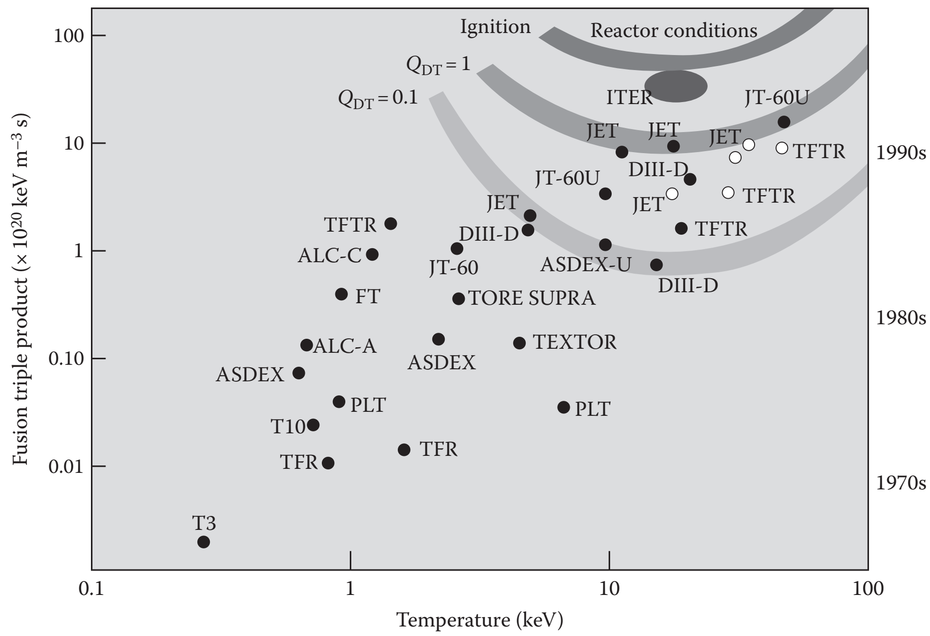

Figure 4.17 Progress toward achieving a fusion reactor: plots of the Lawson triple product (Equation 4.8) versus temperature. The thick curves correspond to particular *Q*-values, and the points show the performance of various designs. (From *Physics World*, March 2006. With permission from Institute of Physics Publishing.)

BOX 4.10 UNDERSTANDING THE LAWSON CRITERION: BUILDING A CAMPFIRE

Imagine that you are camping outdoors on a cold evening. There are at least four things you need to build a camp fire: (a) a suitable source of kindling (with a low enough ignition temperature), (b) enough fuel gathered in one place, (c) an initial spark or source of heat allowing the fuel to reach the ignition temperature, and (d) a long enough interval of time without a wind strong enough to snuff the fire out. Each of these four conditions corresponds closely to what is needed to create a self-sustaining nuclear fusion reaction, namely, a choice of light nuclei that can be made to fuse without too high an ignition temperature; a high enough density of the fuel, n; a high enough temperature to which the fuel is heated, T; and a long enough time, t, the fuel is confined before ignition is reached. In fact, it should not surprise us that the product of these three variables needs to exceed some critical value for a self-sustaining ignition to occur—hence the basis of the Lawson criterion.

4.14 SUMMARY

This chapter traced the history of nuclear technology beginning with the World War II era, when the main goal was developing nuclear weapons, not power. Only after the War was the goal broadened to include nuclear power, which has become an important contributor to the generation of electricity in many nations—roughly 20% of all electricity generated.

Following several high-profile nuclear accidents, including TMI and especially the much more serious Chernobyl and Fukushima accidents, public opinion has moved sharply away from new nuclear reactors. Many citizens now consider them more of a hazard than coal plants, which by objective measures is demonstrably false. Still, so far only Germany and Japan plan to phase them out, which could prove quite costly to those nations. Although the economic feasibility of large new nuclear plants remains highly uncertain, that for abandoning working reactors is also extremely steep. The economics of small modular reactors could be much more promising than those of the 1000 MW variety. Independently, research continues on nuclear fusion reactors, although their timetable is further in the future, and their economic feasibility remains highly uncertain.

PROBLEMS

1. Using Equation 4.4 show that *d* represents the mean distance neutrons travel before being absorbed.
2. Derive Equation 4.7 using conservation of momentum and energy.
3. Discuss the specific simplifications made in Example 1 that led to a too high a value of the critical mass, and indicate whether each simplification leads to a value that is too high or too low.
4. Show that if the smallest critical mass for ^{235}U is 52 kg and that if the enrichment level is only 20%, the critical mass rises to over 200 kg.
5. Using Equation 4.7, quantify how effective hydrogen versus carbon would be as a moderator.
6. Approximately how many elastic collisions would a 1 MeV neutron need to make with nuclei of a moderator in order to have its energy reduced to thermal energies? Do the calculation for light water (A = 1), heavy water (A = 2), and graphite (A = 12) as moderators.
7. The most abundant form of uranium, ^{238}U, fissions spontaneously, so why is it not suitable as a reactor fuel?
8. The specific heat of carbon dioxide at constant pressure is about 1200 J/kg-K. Advanced gas-cooled reactor uses CO_2 at 40 atm pressure as its coolant. How much does its temperature rise if the reactor is putting out 2000 MW of heat when operating and the flow rate of the CO_2 through the reactor is 1000 kg/min?
9. Suppose a beam of neutrons containing 10^{15} particles per second is incident on a gold foil. The cross-sectional area of the beam is 1 cm^2. Assume a total cross section for neutron absorption of 10^{-24} m^2, and a foil thickness of 0.2 mm. What percentage of the neutrons in the beam will be stopped by the foil?
10. The walls of the rotor in a gaseous centrifuge spin at almost the speed of sound. If the rotor has a diameter 0.5 m, how fast does it spin?
11. Explain clearly how you would empirically determine the total cross section for some process.
12. The section on the causes of Chernobyl compares the accident with a bus careening down a mountain road. Explain each of the features of the analogy.

13. Given that Chernobyl is estimated to cause 4000 cancer deaths long term, and the radioactivity released at TMI was 250 times less, one might have expected the long-term cancer deaths caused by TMI to be around 4000/250, i.e., around 16, not less than one as stated in Table 4.1. Explain.
14. Suppose that the intensity of a neutron beam is reduced by 10% when passing through a 10 cm thickness of lead. (a) Find the mean free path for neutrons in lead. (b) If lead atoms are 500 pm apart, find the total cross section for absorption of neutrons by a lead nucleus.
15. Suppose that nuclear plants produce electricity at 7 cents/kW-h, and that the cost of nuclear fuel is 0.7 cents/kW-h, of which 35% is the cost of the ore. Now suppose that ocean extraction of uranium proves to be 10 times as costly as mining the ore. How much would the cost of electricity rise as a result?
16. Suppose the mean free path for neutron absorption in concrete is 0.5 m. How large a thickness slab of concrete would you need between you and the reactor so that no more than one neutron out of a hundred coming out of a nuclear reactor reaches you?
17. Do some searching on the web to ascertain the following data: the number of nuclear plants that Germany now has, and their average power rating and age. Assume that nuclear plants have an average lifetime of 30 years, make a model to calculate the cost to Germany to terminate their reliance on nuclear power assuming they choose to build new renewable power plants based on solar or offshore wind and that they do it (a) on an immediate basis or (b) on a phased basis as existing nuclear plants reach the end of their assumed 30 year lifespan.
18. If a 1000 MW nuclear plant is 35% efficient, how many gallons of water would need to flow through the reactor per minute if the water temperature is raised by 10°F?
19. Explain why there is an "optimum" temperature to achieve fusion (see Figure 4.17), i.e., why you need to have a larger triple product (Equation 4.8) if the actual temperature is either lower or higher than the optimum. What does the optimum appear to be for the *dt* reaction from Figure 4.17?
20. Find the loss in mass of the nuclear fuel in a 35% efficient 1000 MW reactor running for 1 year.
21. Assume that a 35% efficient 1000 MW reactor has its fuel rods replaced with new ones after about 12 years. U-235 has an energy density of 80×10^{12} J/kg, and typical nuclear fuel has 4% enrichment in this isotope. Find the fraction of the original energy that has been removed from the fuel rod during its 12 years in the reactor, assuming only 10% reactor downtime during that period.
22. Prove the correctness of Equation 4.6 from the units on each quantity.
23. If your view of nuclear power is that it is too risky to be pursued, look up some sources that support this view and in a one-page description see if you can find any flaws in the arguments. Do the same if your view happens to be that nuclear power should be pursued.

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