Chapter 15

NUCLEAR ENERGY: ENVIRONMENTAL ISSUES

The State-Federal impasse on construction of a high-level nuclear waste repository, an impossibly cumbersome nuclear licensing process, and the loss of public confidence in our ability to manage civilian nuclear power technology have all contributed to the hiatus in the construction of new nuclear capacity. The National Energy Strategy proposes a number of measures to address these issues [...] Specifically, the National Energy Strategy will:

- reform the nuclear power licensing process;
- manage properly and dispose of high-level nuclear waste;
- develop new, passively safe designs.

(*National Energy Strategy, Executive Summary*, 1991/1992)

The Administration has made achieving the greatest possible degree of global nuclear safety a top priority. The Department of Energy will lead U.S. participation in international efforts to enhance nuclear safety in Russia, Ukraine, and the countries of Central and Eastern Europe to improve the safety of Soviet-designed reactors.
[…]

The Administration's policy is to expedite the characterization of a geological repository as a safe method for high-level waste disposal, and if determined to be safe, to build a geological repository to accept commercial nuclear waste.

(*Sustainable Energy Strategy*, July 1995)

The current situation in the nuclear power industry can best be summarized by saying that it probably has more problems than it deserves based on its *overall* track record. The principal reason for this is society's fear of radioactivity. Radioactivity can be viewed as a byproduct in the process of conversion of nuclear energy into heat. As in our discussion of pollution resulting from fossil fuel utilization, the environmental effects of nuclear energy utilization can best be judged if we quantify this nuclear pollution. We shall first see how much radioactivity is emitted from nuclear fuels. We shall then compare these quantities to the normal everyday radioactivity levels and to the tolerance levels in living organisms. This radiation is not released during normal operation of nuclear reactors, which are typically protected by thick concrete walls. It is released only during accidents, such as those at Three Mile Island and Chernobyl or during explosion of nuclear weapons.

Emission of Radioactivity

Certain nuclei have a tendency to emit radiation spontaneously. This radiation travels in the form of waves (x-rays, gamma rays) or particles (such as alpha and beta particles). It is very dangerous because it carries a lot of energy (see Figure 2-2). In fact, it carries so much energy that it is capable of altering the atoms in living cells and thus triggering a chain of events that can destroy these cells or make them function abnormally. For example, alpha particles, which carry a positive charge, can strip electrons from molecules of water or DNA. This destabilizes them and triggers a chain of events that may lead to the death of cells or to their abnormal reproduction. This is why such radiation is referred to as *ionizing radiation*; it can form ions (charged particles) from neutral atoms and molecules.

Exposure to different forms of radiation is an everyday experience for all of us. For instance, because of the sporadic disappearance of the ozone layer in the upper atmosphere, more and more ultraviolet radiation reaches the surface of the earth. Ultraviolet rays are not ionizing but over-exposure to them increases the chances of developing skin cancer. Similarly, when we take an intercontinental flight, we increase our exposure to the ionizing cosmic radiation. A dental check-up (with x-rays) or radiation therapy (with cobalt-60 isotope) is a source of ionizing radiation. The principal contributors to this ‘background’ radiation are shown in Figure 15-1.

In order to distinguish between these normal or background levels of radioactivity and levels that may be dangerous to our health, we need a radiation ‘yardstick’. The unit most commonly used to quantify radiation emitted from different sources is the *curie* (Ci), named after Marie and Pierre Curie (see Chapter 12).

$$1 \text{ curie} = 3.7 \times 10^{10} \text{ nuclear disintegrations per second}$$

A phenomenon that has recently attracted a lot of media attention, and some controversy (see, for example, “Some Scientists Say Concern Over Radon is Overblown by EPA,” NYT of 1/8/91), will be used to give us a feel for this unit of measurement. The reader is certainly aware of the possible presence of *radon* gas in our homes. Radon accounts for more than 50% of the background radiation (see Figure 15-1). It occurs naturally in the atmosphere because it is constantly produced by the radioactive decay of uranium in the soil. Wherever uranium exists – and it is quite widespread, in very small concentrations – radon is produced. During decay it emits harmful alpha particles as well as other radioactive atoms. The radon problem resides in the fact that, being a gas, it can accumulate within buildings. It is often detected in basements of houses located in the vicinity of uranium-rich soil or constructed of uranium-rich materials.

FIGURE 15-1
Natural and man-made sources of 'background' radiation.
[Source: *National Geographic*, April 1989, p. 403.]

According to many estimates, radon is the second principal cause of lung cancer (after tobacco smoking) and that it is responsible for 5,000-30,000 deaths every year. So the reader is urged to check his or her basement for radon concentration, using a test kit that can be bought at a local houseware store. The *Consumer Reports* magazine of July 1987 has reviewed the national radon-detection services and the ways to find out if your house has a radon problem. (In some areas of the country, you may not be able to sell your house without a radon test report.) The kit typically consists of a canister of charcoal that is left in the basement for about a week to absorb the radon and is then sent to a company for analysis. The Environmental Protection Agency (EPA) has issued *A Citizen's Guide to Radon*. If the radon emission level in your home is greater than $2x10^{-10}$ curies per liter of air (200 pCi/L), the EPA recommends immediate remedial action, which may include house remodeling; lifetime exposure to this much radon has been estimated to bear comparable risk to that of smoking 4 packs of cigarettes every day. If the radon level is greater than $2x10^{-11}$ curies per liter (20 pCi/L), there is reason for concern, but simple ventilation or sealing of cracks in basement walls may be sufficient to minimize the danger. Again, the EPA has issued a *Consumer's Guide To Radon Reduction* which discusses specific radon reduction techniques. If the level is less than 4 pCi/L, you are lucky; you don't have to do anything! If you are impatient and cannot wait for the results of the radon test in your home, check NYT of 9/6/94: in an article entitled “Studies Raise Doubts About Need to Lower Home Radon Levels,” it reproduces a county-by-county map of the U.S., prepared by the EPA, indicating areas that are likely (but not certain) to have more than 4 pCi/L.

Here again, as in the case of air pollution from fossil fuels, one of the key environmental issues is to define ‘acceptable’ (radiation) levels. But, in contrast to air pollution resulting from fossil fuel combustion, the undesirable effects of nuclear fuel utilization can be much more devastating and we need to quantify them more precisely.

Radioactivity is emitted as a result of the transformation of unstable nuclei into stable atomic nuclei. This decay process is governed by the same law that we encountered when we discussed population growth in Chapter 5. There we saw, for example, that the number of Earth's inhabitants grows exponentially with time. In other words, the increase in the number of future inhabitants is proportional to the number of present inhabitants. By analogy to population growth, in the process of radioactive decay the decrease in the number of radioactive nuclei is proportional to the number of unstable nuclei present at any given time. Therefore, in a manner exactly analogous to the concept of doubling time in the growth of population or energy consumption, radioactive decay is best characterized by the *half-life* of radioactive isotopes.

$$\text{Half-life} = \frac{0.7}{\text{Decay Constant}}$$

After one half-life, one half of a given amount of radioactive material is left; after two half-lives, one fourth of the same starting amount is left; after three half-lives, one eighth of this amount is left, and so on.

Table 15-1 shows the half-lives of a number of common radioactive isotopes, and Figure 15-2 illustrates the usefulness of this important and powerful concept.

A very important property of radioactivity is shown in Illustration 15-1. If the half-life is short, we must deal with the very intense radiation of ‘hot’ isotopes, or isotopes that have a very high rate of decay (high decay constant). These isotopes release large amounts of ionizing radiation in a short time, and are therefore very dangerous initially; however, they do decay rapidly and it is not necessary to store them for a very long time before they become harmless. At the other extreme, if the half-life of an isotope is long, the isotope has a small decay constant; its radiation is less intense, but we may have storage problems with them, because significant radioactivity persists over very long periods of time.

Illustration 15-1. In a hypothetical radiation leak there are 2 curies of radioactivity from krypton (Kr-89; half-life = 3 minutes) and 40 curies from rhodium (Rh-106; half life = 30 seconds). If a person is exposed to this much radiation for 3 minutes, how much radiation will he or she receive?

Solution.
The half-life of Kr-89 is 3 minutes; so, one half of its nuclei will have decayed in this period, releasing 1 curie of radiation.

For Rh-106, the half-life is 30 seconds. So after 30 seconds (one half-life), it will release 20 curies (leaving 20 behind); after 60 seconds (two half-lives), additional ten curies will be released (leaving ten behind); etc. After 3 minutes, 39.375 curies will have been released and 0.625 curies will remain (see Figure 15-2).

Therefore, this person will receive much more radiation from the isotope having a shorter half-life. After 3 minutes 40.375 curies of radioactivity will be released, of which 97.5% come from the isotope with a shorter half-life.

TABLE 15-1
Half-lives of selected radioactive isotopes

Isotope	Half-life
Uranium-238	4.5×10^9 years
Uranium-235	0.7×10^9 years
Plutonium-239	24,000 years
Carbon-14	5730 years
Lead-210	22 years
Tritium (H-3)	12.5 years
Cobalt-60	5.27 years
Polonium-210	140 days
Iodine-125	60 days
Bismuth-210	5 days
Radon-222	3.8 days
Polonium-218	3 minutes

For radioactive materials within a living organism, the decrease in radioactivity is the result of both radioactive decay and normal biological elimination of cells from the body. For example, it requires about 140 days for one half of the iodine atoms in a human thyroid to be eliminated through normal biological turnover. (These atoms are, of course, replaced by other iodine atoms, so the total number of iodine atoms required for normal functioning of the thyroid remains the same. Remember that isotopes are chemically identical atoms.) This is called the *biological half-life*. If atoms of iodine-125, a radioactive isotope with a half-life of 60 days, are incorporated in the thyroid, both biological turnover and radioactive decay act to eliminate them. The result is that the number of iodine-125 atoms is reduced to half of the initial amount in about 38 days, which is called the effective half-life for iodine-125 in the thyroid. For a radioactive isotope such as carbon-14, with a half-life of more than 5000 years, there is essentially no decrease in radioactivity during the time it spends within a living organism (except, perhaps, in trees and turtles, which live for hundreds of years); so the effective half-life is dependent only on biological elimination of the carbon-14 atoms. Upon death, however, only radioactive decay continues. This is then a powerful tool for archeological dating because its half-life is of the same order of magnitude as the age of ancient civilizations (see Review Question 15-1). A famous case of radioactivity-mediated detective work was the discovery that the shroud of Turin (presumably the Holy Shroud) was in fact a fake. Instead of being some 2000 years old, when Christ died, its C-14 to C-12 ratio revealed that it was made of cloth produced between 1260 and 1390 AD. (For more details on this fascinating story, see Britannica Online at http://www.eb.com, or www.cais.com/npacheco/shroud/turin.html.).

FIGURE 15-2. Illustration of the concept of half-life of radioactive isotopes.

Absorption of Radioactivity

Ionizing radiation is analogous, on a microscopic scale (that is, the scale of atoms and molecules), to the "presence of a bull in a china shop" (see C.E. Kobb, "Living with Radiation," *National Geographic*, April 1989). When it penetrates living tissue, and depending on its intensity, it can either kill quickly, or cause severe damage, or initiate cancers that may eventually result in death. The damage increases as the amount of energy deposited in the various organs increases. This quantity of energy retained (or absorbed) by the body is called the *dose*. It is measured in units called rads. One rad is equivalent to the energy of ten millijoules deposited in 1 kg of material:

$$1 \text{ rad} = 0.01 \frac{\text{joules}}{\text{kilogram}}$$

Illustration 15-2. Calculate the energy, in BTU, deposited in one gram of tissue by an exposure to a dose of 500 rad. If this dose is evenly distributed throughout the human body (75 kg), how much energy is deposited in the entire body?

Solution.
Remembering Table 2-2, we have:

$$500 \text{ rad} = (500 \text{ rad}) \left(\frac{0.01 \frac{\text{J}}{\text{kg}}}{1 \text{ rad}}\right) = \left(5 \frac{\text{J}}{\text{kg}}\right) = 5\text{x}10^{-3} \text{ J/g} =$$

$$= \left(5\text{x}10^{-3} \frac{\text{J}}{\text{g}}\right) \left(\frac{9.49\text{x}10^{-4} \text{ BTU}}{1 \text{ J}}\right) = 4.75\text{x}10^{-6} \text{ BTU/g}$$

So the amount of energy absorbed by the whole body is:

$$4.75\text{x}10^{-6} \text{ BTU/g} = \frac{4.75\text{x}10^{-3} \text{ BTU}}{1 \text{ kg}} \ (75 \text{ kg}) = 0.36 \text{ BTU}$$

The effect of ionizing radiation upon a given organ in a living organism may be related to factors other than the absorbed dose. In other words, equal doses of different forms of radiation produce different biological effects. The more intense the radiation is, the greater its penetrating power will be and part of it may not be retained by the body. For example, gamma rays are more energetic than alpha particles; a sheet of lead is necessary to stop them, while alpha particles can be stopped by skin. Yet their damaging effect is known to be about twenty times smaller. There is a simple way to take into account these differences.

A *quality factor* is defined for the various forms of ionizing radiation, as shown in Table 15-2. Their penetrating power is summarized in Table 15-3.

TABLE 15-2
Quality factors of common radiation types

Form of Radiation	Quality Factor, Q
X-rays	1
Beta particles	1
Gamma rays	1
Alpha particles	20
Protons	10
Neutrons	10

TABLE 15-3
Penetrating power of ionizing radiation emited by U-235 and Pu-239

Form of Radiation	Protection needed
Alpha particles	Skin
Beta particles	Aluminum
Gamma rays	Lead
Neutrons	Thick concrete

[Source: “Hide and Seek With a Nuclear Weapon,” NYT of 8/1/93.]

If we multiply the value of the absorbed dose by this quality factor, the resulting *dose-equivalent* represents well the inflicted damage, regardless of the origin of radiation. The special unit for dose-equivalent is the *rem*.

$$1 \text{ rem} = 1 \text{ rad} \times Q$$

The rem units are used in the legislation that regulates the exposure to radiation of persons working with radioactive materials or the public in general. Table 15-4 summarizes this legislation. Expressed in these units, exposure levels from natural (background) radiation are typically less than 0.2 rem/year. Average exposure levels from medical x-rays are less than 0.1 rem/year. Table 15-5 summarizes the acute (immediate) biological effects of human exposure to high levels of radiation. Delayed effects, such as induced cancers, are also possible and important; they are the subject of intense research and controversy.

TABLE 15-4
U.S. legislation on radiation exposure

Population Group	Maximum permissible dose (whole body exposure)
Job-related exposure	1.25 rem per calendar quarter (5 rem per calendar year)
Fertile female limit	0.5 rem per 9 consecutive months
General public (individual)	0.5 rem per year
General public (large groups)	0.17 rem per year

TABLE 15-5
Acute biological effects of exposure to ionizing radiation

Dose, rem	Effect
~100	Radiation sickness (flu-like symptoms, recovery likely)
200-1000	Bone marrow syndrome (death may result in 10-30 days)
1000-10000	Gastro-intestinal syndrome (death may result in 3-5 days)
>10000	Central-nervous-system syndrome (death may result in hours to days)

Nuclear Accidents

Much has been written about the nuclear accidents at Three Mile Island (near Harrisburg, PA) and Chernobyl (near Kiev, Ukraine). We have briefly discussed their technical aspects in Chapter 13. Now that we know the acceptable levels of radiation in the atmosphere, we can assess their environmental impact. It should be mentioned that, apart from these two much-publicized accidents, there have been a number of other instances when minor accidental exposure to radiation occurred (see for example “The Hidden Files,” *NYT Magazine* of 11/19/89).

At Three Mile Island, it is estimated that approximately 17 curies of radioactivity were emitted to the environment. The dose-equivalent readings in the surrounding areas never surpassed 2 millirem per person. Besides much panic, both warranted and unwarranted, no significant increase in cancer incidence has been reported as a result of this accident. The cleanup lasted for more than a decade (at a cost that exceeded a billion dollars); the removal of the fuel was completed in early 1990, but the evaporation of the accident-generated radioactive water continued for several years thereafter. It took so long because the exposure of the cleanup crew was as high as 15 mrem/hour. Under these circumstances, workers could not afford to stay in the contaminated area for more than 3-4 hours at a time. In 1987, for example, the average dose in the reactor was 0.71 rem per person.

At Chernobyl, it is estimated that more than 50 million curies of radiation were emitted to the environment and spread throughout Europe. In fact, the accident was first reported to the world by Swedish scientists. About 13,000 square miles of agricultural land are contaminated today with radioactivity at levels of 5 or more curies per square kilometer (see *NYT Magazine* of 4/14/91, p. 28). The official death toll was thirty one. These deaths occurred immediately after the accident, mostly from overexposure to radiation. Hundreds of people suffered radiation injuries. Eleven out of nineteen people that received bone marrow transplants died. Much has been written about the increase in cancer-induced fatalities as a result of the exposure of a large population to high levels of radiation. The evacuation of more than 100,000 people from the contaminated area was not made until a week after the accident. In the authoritative report by the International Atomic Energy Agency it is concluded, perhaps surprisingly, that "future increases over the natural incidence of cancers or hereditary effects would be difficult to discern." Moreover, "there were no health disorders that could be attributed directly to radiation exposure" (cited from *Chemical & Engineering News*, May 27, 1991, p. 5). Conflicting reports continue to appear in the media. For example, in an article entitled "Chernobyl and Cancer: New Study," NYT of 11/21/95 reports a 100-fold increase in thyroid cancer in children from the most exposed areas. Today, the reactor is surrounded by a 'sarcophagus'; this ancient Egypt-style concrete tomb is supposed to prevent further release of radiation from the damaged reactor, in whose interior the radiation levels are so high that constant vigil will be required for the next 100,000 years or so (see Illustration 15-4).

However enormous the human and material losses from these accidents may be, there is no question that – in the long run – the greatest loss is that of public confidence in the safety of nuclear energy. The consequences of this loss were illustrated in Figure 13-1. Whether and how this confidence can be restored is unclear. Newspaper and magazine pages in the 1990s, ever since the global warming issues took center stage in the late 1980s, are full of speculations regarding an impending 'comeback' of the nuclear industry. Here are some representative examples that illustrate such views (with a few exceptions):

•*Next Generation of Nuclear Reactors: Dare We Build Them? Worried about global warming and future energy crises? The answer, proponents of a nuclear option say, is a new generation of fission power plants, safer, simpler, and more economical than current reactors. But the nuclear industry's troubled past makes most environmentalists skeptical – Popular Science, April 1990.*

Illustration 15-3. Compare the background radiation level of 5 curies per square kilometer existing in the northern Ukraine today with a case of serious radon accumulation in the basement of a house in Pennsylvania (2×10^{-10} curies per liter of air).

Solution.
The measurement of radon concentration is given per unit volume and those of the radiation levels in the northern Ukraine are given per unit area. Let us convert the volume into area in the radon case by assuming that the typical size of a basement (where, presumably, this concentration has been measured) is 10 meters (length) by 10 meters (width) by three meters (height). So the volume of the basement is 300 m^3 and the area covered by it is 100 m^2. The total concentration of radon is:

$$\left(2\times10^{-10}\ \frac{\text{curies}}{\text{liter}}\right)\left(\frac{1000\ \text{liters}}{1\ \text{m}^3}\right)(300\ \text{m}^3) = 6\times10^{-5}\ \text{curies}$$

The surface concentration of radon is then:

$$\frac{6\times10^{-5}\ \text{curies}}{100\ \text{m}^2} = 6\times10^{-7}\ \text{curies/m}^2 = 0.6\ \text{curies/km}^2$$

This is only one order of magnitude (a factor of ten) less than the residual radioactivity in northern Ukraine after the accident at Chernobyl.

•*Energy from Nuclear Power. Atomic energy's vast potential can be harnessed only if issues of safety, waste and nuclear-weapon proliferation are addressed by a globally administered institution – Scientific American, September 1990.*

•*Barriers are Seen to Reviving Nuclear Industry. Experts agree on one crucial step: The public's trust must be regained – NYT, 10/8/90.*

•*Is Nuclear Winter Giving Way to Nuclear Spring? With global warming, research on safer reactors and the need for more energy all converging, advocates of nuclear power see signs that the industry is overcoming years of public criticism and doubt – NYT, 5/12/91.*

•*Our Electric Future: A Comeback for Nuclear Power? – National Geographic, August 1991.*

•*Nuclear Power: Losing Its Charm. It was once seen as the energy of the future. Now nuclear power looks to many countries riskier and more expensive than old-fangled alternatives – Economist, 11/21/92.*

•The Future of Nuclear Power. Scientists forget to remind people of the huge differences in technological possibilities between nuclear and fossil fuels – Environmental Science & Technology, June 1992.

•The Future of Nuclear Power. America will choose nuclear power only if demand for electricity accelerates, nuclear costs are contained and global-warming worries grow – American Scientist, January-February 1993.

•Nuclear Power's Dim Future. The percentage of the nation's electricity produced by nuclear power will decline – Environmental Science & Technology, June 1993.

•Outgoing N.R.C. Head Sees Nuclear Industry Revival. But Next Few Years Will Be Tough, He Says. Heady predictions for an industry that has not seen them in a long time – NYT, 6/30/95.

•The Nuclear Legacy: 50 years after the bomb. The technology unleashed by bomb builders was supposed to bring us cheap, clean energy. But operating nuclear power plants has become so expensive that many are quietly mutating into radioactive waste dumps – Popular Science, August 1995.

•Meltdown. The worst industrial accident ever to befall humanity left a wound that has not healed with time. Now, the nuclear power industry appears to be wearing out its welcome on the planet - and opening the door wider to renewables – World Watch, May/June 1996.

The design of a new generation of "inherently safe" reactors is nuclear industry's attempt to regain credibility. The new reactor designs are intended not to allow the possibility of a meltdown, as in the modular high-temperature-gas-cooled reactor (MHTGR). If they do allow such a possibility, they eliminate the 'active' water-cooled safety system, with its pumps and valves that can fail. Instead of these mechanical devices, which have failed at Three Mile Island and elsewhere, they would use 'passive' water cooling, relying on gravity. (Nature hardly ever fails.) In case of an accident, storage tanks filled with water, placed above the reactor, would flood it and prevent meltdown. Indeed, the MHTGR is claimed by nuclear energy advocates to be 'idiot-proof'. In the core, there are no metal parts that can melt. All the components of the core (graphite-coated uranium grains imbedded in billiard-ball-size graphite pebbles) can thus withstand a very high temperature (1800 °C) and, to be on the even safer side, the amount of fuel in the core is so small that these high temperatures cannot be reached.

Like in the radon story above (where we work hard to insulate our home to keep our energy bills as low as possible and may end up keeping not only warm air inside the house but the radioactive radon too), there are two sides to the coin here as well. Abundant evidence exists that the accident at Three Mile Island has served one useful purpose. The number of emergency situations that require reactor 'scrams' has been decreasing, despite the fact that the number of reported incidents – which can range from tools left in the wrong place to a flawed reactor – is about the same. Indeed, some analysts even argue that the

Three Mile Island accident was a demonstration of safety of nuclear reactors in the United States. So many things went wrong on that spring day in 1979, half of the core melted, and yet the reactor did not get completely out of control, as it did at Chernobyl.

Disposal of Nuclear Waste

Even when a nuclear reactor operates normally (that is, nearly all the time, of course), its managers are faced with the increasingly alarming problem of nuclear waste disposal. In Chapter 13 we saw that not all the nuclear fuel is consumed in the reactor. It is taken out of the core while still emitting large amounts of radioactivity. And it will continue to be dangerously radioactive for decades, centuries, and even millenia.

In most cases, the spent fuel rods, also referred to as *high-level radioactive waste*, are left on site. Only in France and Great Britain do significant reprocessing facilities exist, in which uranium and plutonium are separated for reuse.

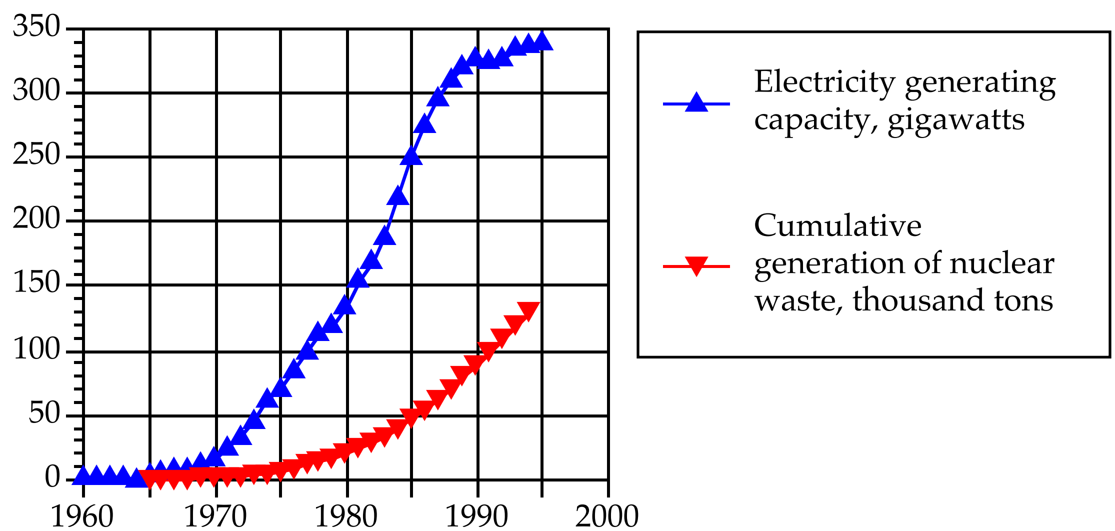

FIGURE 15-3. World electricity generating capacity of nuclear power plants and accumulation of spent fuel at the 431 commercial nuclear reactors.
[Source: Vital Signs 1995, 1996, Worldwatch Institute.]

Published statistics on the storage capacity of U.S. power plants (see, for example, *USA Today*, March 21, 1989) indicate that by the year 2000, most of the 110 operating plants will have nowhere to store their spent fuel rods. This nuclear waste must be sent to a more permanent repository.

No new nuclear power plants have been built in the U.S. in almost two decades. The growth of nuclear power in the world has levelled off, as shown in Figure 15-3. Despite these facts, the accumulation of high-level waste continues; this is also illustrated in Figure 15-3. Some 25% of the 130,000 tons of spent fuel rods, with a total radioactivity of 26 billion curies, has piled up in the United States.

Illustration 15-4. How many years are needed for the isotopes of polonium-210, tritium, and plutonium-239 to decay to a level five hundred times lower than that of their initial activity.

Solution.
From Illustration 15-1, it can be verified easily that

$$N = \frac{N_o}{2^n}$$

where N is the number of radioactive nuclei at time t, N_o is the initial number of radioactive nuclei and n is the number of half-lives. Consequently, we have:

$$\frac{N}{N_o} = \frac{1}{2^n}$$

In this problem, we have:

$$\frac{N}{N_o} = \frac{1}{500} = \frac{1}{2^n}$$

or n = 9, approximately. Therefore, the time required for this decay of activity will be approximately 200,000 years for plutonium-239, 110 years for tritium and 3.5 years for polonium-210.

The issue of where to build a high-level repository has been in the headlines for years now and no resolution is yet in sight. The Department of Energy has been working on the construction of an underground storage facility at Yucca Mountain in Nevada, about 100 miles northwest of Las Vegas. The early plans were to have it operational by 2003. Environmental groups, Nevada citizens and others are opposed to having it there – for various reasons, not the least of which is the NIMBY syndrome (see Chapter 18). More recent and perhaps optimistic estimates of the facility's opening date are by the year 2010, if the “current candidate [in the Yucca Mountain] is found suitable” (see *National Energy Strategy*, p. 115). Because plutonium-239 is one of the main ingredients of high-level waste, it is difficult to ascertain the ‘suitability’ of a waste site for the next 100,000 years or so (see Illustration 15-4).

Nuclear Weapons

During the first four decades of the post-World War II era, the so-called Cold War, whenever the presidents of the two superpowers met, they talked about limiting the testing and deployment of nuclear weapons. The media headlines were then invaded by terms such as launchers, warheads and megatons. Today – after the dissolution of the Soviet Union and the signing of various international treaties on arms reduction and test bans – such headlines have been displaced by those that question the security and the fate of the nuclear weapons that are being dismantled. Here are a few typical headlines from newspapers and magazines:

•*Want to Buy the Bomb? No Problem. Tighten export controls on strategic technologies – NYT, 11/25/92.*

•*How To Steal an Atom Bomb. Did you stop worrying about nuclear obliteration when the cold war ended? Start again. To make an atomic bomb, a terrorist or a would-be-proliferator would need to get hold of only 5 kg of weapon-grade plutonium or 15 kg of weapon-grade uranium, less than you would need to fill a fruitbowl - Economist, 6/5/93.*

•*Surplus Plutonium Called Big Threat. A report seeks ways to make the world safer – NYT, 1/25/94.*

•*The Plutonium Racket. The panic in Germany about Russian plutonium smuggling – understandable though it may be – may perversely make safeguarding nuclear material harder – Economist, 8/20/94.*

•*Formula for Terror. The former Soviet arsenal is leaking into the West, igniting fears of a new brand of nuclear horror – Time, 8/29/94.*

•*Peaceful Plutonium? No Such Thing. The growing peril from commerce in spent nuclear fuel – NYT, 1/25/95.*

•*Tracing a Nuclear Risk: Stolen Enriched Uranium. A growing fear that terrorists can buy the makings of a nuclear bomb – NYT, 2/15/95.*

•*Deadly Nuclear Waste Piles Up With No Clear Solution at Hand – NYT, 3/14/95.*

The analysis of these issues is beyond the scope of our textbook. But we can make one key point here. We saw in Chapter 13 that nuclear reactors and nuclear weapons are inextricably linked by the production of plutonium. If you have a nuclear reactor, you have the means to produce nuclear weapons. So *nuclear proliferation* is a problem that may block the conversion of nuclear energy into an important (and nondepletable) energy source. It is necessary therefore to summarize here just the basic facts about how nuclear weapons are made and give the reader a sense of their destructive power.

There is no question that we are living today in the longest period of worldwide peace in recent history. (Localized wars fought with conventional weapons continue to be a problem, of course.) Whether this is because or in spite of the existence of nuclear weapons – which could blow the world apart in a hurry – is something that historians will debate for a long time to come.

Many books have been written and movies have been made about the Manhattan Project, code name for the development of the atomic bomb in the United States. More recently, interesting and readable accounts of Soviet and German nuclear weapons programs have been published (see Further Reading, p. 459). Even though the optimistic predictions of the early days – that nuclear power use for electricity generation will make electricity too cheap to meter – did not materialize, widespread public support existed for the rapid development of both military and civilian nuclear capabilities in the period 1945-1979.

In Chapter 13 we emphasized the fact that the ability to control the chain reaction in the fission process makes the difference between a nuclear reactor and a bomb. In an atomic bomb, no attempt is made to control the number of neutrons produced within the fissionable material. The reproduction constant is greater than one and a runaway condition is created when the "critical mass" of fissionable material is assembled. The *critical mass* is the minimum quantity of nuclear fuel necessary for the bomb to explode. Current thresholds of danger are 8 kg of plutonium and 25 kg of enriched uranium-235 (25% or more). Two ways in which a critical mass can be achieved are illustrated in Figure 15-4.

The first man-made chain reaction was achieved in a squash court under the football stadium at the University of Chicago on December 2, 1942. It wasn't long thereafter that the first atomic bomb was assembled (at Los Alamos, NM) and tested (at the Trinity site near Alamogordo, NM, on July 16, 1945). The nuclear weapons were first used at Hiroshima and Nagasaki. This brought Japan to the capitulation table and brought a quick end to World War II. The recent fiftieth anniversary was another opportunity to reexamine these tragic events and to second-guess one more time the fateful decisions of President Truman to use the bombs. A sample of media headlines is listed below:

•*Hiroshima: A Controversy That Refuses to Die – NYT, 1/31/95.*

•*Was It Necessary? – Parade Magazine, 7/4/95.*

•*Behind Truman's Decision on the Atomic Bomb. Peter Jennings Reporting on Hiroshima: Why the Bomb Was Dropped – NYT, 7/27/95.*

•*Dissecting a Decision That Shook the World. Fifty years after the United States dropped The Bomb on Hiroshima, some historians say President Truman believed much more was at stake than ending the war - USA Today, 7/27/95.*

•*Television: Hiroshima-To Drop the Bomb – WSJ, 7/31/95.*

•*Shock Wave: "My God, what have we done?" – USNWR, 7/31/95.*

•*The Nuclear Legacy: 50 years after the bomb – Popular Science, 8/95.*

•*Beliefs: Fifty years later, the debate over dropping the atomic bomb has widened – NYT, 7/29/95.*

(a)

(b)

FIGURE 15-4. Two possible ways of assembling the critical mass in a nuclear bomb. [From "Energy and Problems of a Technical Society," by J.J. Kraushaar and R.A. Ristinen. Copyright © 1988 by John Wiley & Sons. Reproduced with permission.]

The "Little Boy" was dropped on Hiroshima on August 6, 1945; it was 28 inches in diameter and 10 feet long and it weighed about 4.5 tons. The explosive 'yield' of its uranium fuel was rated at about 13,000 tons of TNT. The term TNT stands for trinitrotoluene, a substance that is used to make conventional explosives. In other words, it released the same energy as 13,000 tons (or 13 kilotons) of TNT. In more conventional energy units:

$$1 \text{ ton of TNT} = 4.3 \times 10^9 \text{ joules}$$

The "Fat Man" was dropped on Nagasaki a few days later; it was 5 feet in diameter and 128 inches long. It weighed 5 tons and the explosive yield of its plutonium fuel was 22 kilotons of TNT. More than 200,000 people died immediately as a result of the bombings, and many others contracted cancer.

Today's nuclear weapons are much more sophisticated and even deadlier. For example, Minuteman II, an intercontinental ballistic missile (ICBM), has a yield of 1 megaton, or a destructive power that is about 50 times greater than that of the World-War-II bombs. Similarly, an SS-11 Russian missile has a yield of 1.5 megatons.

Illustration 15-5. Calculate the quantity of energy released, in tons of TNT, when 1 kg of fissionable material (e.g., U-235) is converted into energy.

Solution.

We showed in Illustration 13-1 that the fission of 1 kg of U-235 releases about $6.9\text{x}10^{10}$ BTU of energy. Using the information provided in Table 2-2, we then have:

$$\text{Energy released} = \left(\frac{6.9\text{x}10^{10} \text{ BTU}}{1 \text{ kg U-235}}\right)\left(\frac{2.38\text{x}10^{-10} \text{ tons TNT}}{1 \text{ J}}\right)\left(\frac{1 \text{ J}}{9.48\text{x}10^{-4} \text{ BTU}}\right) =$$

$$= 1.7\text{x}10^4 \text{ tons TNT/kg U-235} \quad \text{(17 kilotons).}$$

Recognized nuclear weapons production capability exists today in quite a few countries, mostly in the industrialized world, but more recently also in some of the less developed countries (for example, India, Pakistan, South Africa, Brazil). This is the result of the facts discussed in Chapter 13. Plutonium-239 produced from uranium-238 in nuclear power plants, or in breeder reactors, can be separated easily from the spent fuel, much more easily than U-235 from U-238 in the conventional nuclear fuel cycle. As little as 8 kilograms or so of this highly enriched material (>90%), accumulated in this way, is sufficient to achieve the critical mass and make a bomb (see "A Smuggling Boom Brings Calls For Tighter Nuclear Safeguards," NYT of 8/21/94). This is why the International Atomic Energy Agency (IAEA) has a mandate to keep an inventory of nuclear fuel in all commercial reactors of the 141 nations signatories of the 1970 Nuclear Non-Proliferation Treaty (NPT). The main charter of this institution (formed in 1956 and headquartered in Vienna) is to detect on time the diversion of significant quantities of nuclear material from peaceful activities to the manufacture of nuclear weapons. The NPT signatory countries have agreed that they will not supply weapons, nor the means to fabricate them, to non-nuclear nations;

the non-nuclear nations in turn have agreed not to receive or acquire such devices or technology. The development of advanced fuel reprocessing and enrichment facilities in some countries has recently made IAEA's life more difficult. Stronger reliance on site inspection visits is necessary, and that is not always possible or easy. At the time of this writing, there is much speculation and controversy in the media – and among experts – over North Korea's atomic bomb capabilities. Some years ago, a similar controversy existed over Iraq's capabilities and intentions. Tougher safeguards have been adopted recently (see “Making It Easier to Uncover Nuclear Arms,” NYT of 6/16/95) but, as IAEA's director put it, we live in a world of sovereign states and cannot parachute in or shoot our way into suspicious facilities.

With the demise of the Soviet Union and the end of the “Cold War,” many nuclear weapons are in the process of being dismantled (see Investigations 13-4 and 15-20). The United States has dismantled close to 4000 warheads over the past three years and will continue to dismantle more if Russia does as much. But hundreds of ICBMs, submarine-launched missiles and bombers still remain, and this is probably enough to blow up much of the world.

Future of Nuclear Energy: Summary

The future of conventional fission-based nuclear reactors does not depend on the resolution of major technical problems. Even the underestimated but difficult economic issues take the back seat when compared to the socio-political issues. These all stem from understandable reluctance to accept the construction of a nuclear power plant or a waste repository in one's ‘backyard’. (This is the so-called NIMBY syndrome, “not in my backyard;” see Chapter 18.) However, this is mostly an emotional rather than an informed judgment. Whether or not the nuclear industry will indeed “stage a comeback” on the world scene, and in the U.S. in particular, depends primarily on the issues presented in this chapter. It is probable that the new designs of nuclear power plants will provide a greater degree of safety and will decrease the likelihood of major accidents. It is unlikely, however, that a completely failsafe reactor will ever be designed. After all, accidents like those at Three Mile Island and Chernobyl were considered ‘impossible’ until they happened. Society will have to weigh the effect of potential nuclear pollution against the problems brought about by increasing use of fossil fuels (see Chapter 11). In this analysis, we must avoid the often displayed irrational *a priori* rejection of the nuclear option. The material covered in this chapter and in particular its quantitative aspects, which are not difficult to grasp, should be a good starting point for such analysis.

REVIEW QUESTIONS

15-1. While digging in your backyard, you find a piece of decomposed human bone. You analyze it for isotope content and find that its ratio of carbon-14 to carbon-12 is $0.8x10^{-12}$ to 1. Assume that the ratio of C-14 to C-12 in living bones is $1.3x10^{-12}$ to 1. When did this person live in your neighborhood?

15-2. The decay constant of a radioactive isotope (see p. 268) is its decay rate, analogous to the growth rate or interest rate in exponential growth (see Chapter 5). Show that the decay rate of a fresh 1-gram sample of carbon-14 is 15.0 decays/min, while that of a 2000-year old sample is 11.7 decays/min. Assume the same C-14/C-12 ratio as in 15-1 above.

15-3. Cobalt-60 (Co-60) is often used for cancer treatment. If 5 grams of a fresh Co-60 source are used, how much remains after 10 half-lives? How long will it take until only 1 gram of Co-60 is left?

15-4. Find the radioactivity (in curies) of one gram of radium, element discovered by Marie Sklodowska-Curie, whose half-life is 1622 years.

15-5. The NYT of 11/3/91 has reported that the radiation levels of cesium-137 surrounding the Chernobyl power plant exceed 40 curies per square kilometer.
(a) Compare this with the radioactivity level of found in your basement of 40 pCi/L.
(b) How long will it take until exposure to this isotope becomes less dangerous. The half-life of cesium-137 is 30 years; assume that 10 half-lives is sufficient for this condition to be satisfied.

15-6. Indicate whether the following statements are true or false:
(a) Radioactive isotopes are unstable elements that release energy spontaneously in order to become more stable.
(b) Emission of radiation is measured by the half-life of a radioactive isotope .
(c) Spent fuel rods from nuclear reactors are referred to as low-level radioactive waste.
(d) By 1995 more than 100,000 tons of high-level nuclear waste had accumulated in the world.
(e) The longer the half-life of a radioactive isotope is, the more intense (and dangerous) its radiation will be.
(f) An aluminum sheet is sufficient protection from exposure to gamma rays.
(g) Man-made sources account for more than 50% of ‘background’ nuclear radiation.

15-7. Fill in the blanks: The quantity of _______________ retained (or absorbed) by the body is called the dose. Shortly after the accident at ________________, more than 30 people died as a consequence of an overdose. During the accident at _________________, no such deaths were reported.

15-8. Explain briefly the radon problem.

INVESTIGATIONS

15-1. Investigate the unique position that France has on nuclear energy issues. What percentage of its electricity is generated using nuclear power? Have there been any reports of accidents at French nuclear power plants? Has France signed the nuclear non-proliferation treaty? (If not, why not?) When was the last time France conducted a nuclear weapons test? Check, for example, the following sources: “France Promises to Follow The '68 Nuclear Agreement” in NYT of 8/4/92; “Dangerous Nuclear Tests” in NYT of 7/5/95; “Nuclear Test Plan Tarnishes France's Image in Pacific” in NYT of 9/1/95; “France, Despite Wide Protests, Explodes a Nuclear Device” in NYT of 9/6/95; “France Ending Nuclear Tests That Caused Broad Protests” in NYT of 1/30/96; “French Nuclear Tests Spark International Protest” in WSJ of 7/13/95; “France: Test and shout,” *Economist* of 9/9/95.

15-2. What fraction of its electricity does Japan produce using nuclear power? Have there been any recent nuclear reactor accidents in Japan? What is Japan's position regarding plutonium? Check the following sources: “Japan Nuclear Accident May Impede Push for Plants,” NYT of 2/11/91; “A Crack in Japan's Nuclear Sangfroid,” NYT of 2/17/91; “Japan's Nuclear Dilemma,” *Technology Review* of 10/91; “Japan's Plan to Ship Plutonium Has Big and Little Lands Roaring,” NYT of 10/5/92; “No Fear. The Plutonium Is Safe,” NYT of 10/27/92; “Japan: Off Course on Plutonium,” NYT of 11/10/92; “Japan bets on plutonium,” *Baltimore Sun* of 11/22/92; “Japan's Nuclear Fiasco,” NYT of 12/20/92; “Ship Carrying Plutonium Arrives in Japan in Largest Sea Shipment,” NYT of 1/5/93; “Japan, Bowing to Pressure, Defers Plutonium Projects,” NYT of 2/22/94; “Effort to Solve Energy Woes Clashes With Nuclear Safety,” NYT of 8/20/94; “U.S., Criticized for Helping Japan Over Plutonium, Will Stop,” NYT of 9/9/94; “Japan: Curse of the Pacific Pintail,” *Economist* of 4/29/95; “Nuclear Waste Cargo Reaches Japan and Rough Political Waters,” NYT of 4/26/95; “Accident At A-Plant Leads Japan To Debate,” NYT of 12/17/95; “Japanese Suicide Linked To Nuclear Plant Leak,” NYT of 1/14/96; “Reactor Accident in Japan Imperils Energy Program,” NYT of 2/24/96.

15-3. By the end of the 1980s, Asia had 62 operating nuclear reactors (more than 50% of them in Japan) and 26 in construction (close to 50% in Japan). Has this changed in the early 1990s as the continent makes huge economic progress? See “Energy-Hungry, Asia Embraces Nuclear Power,” NYT of 4/23/95; “Asia's energy temptation,” *Economist* of 10/7/95.

15-4. (a) Review and summarize some of the recent media reports on the health effects of the Chernobyl disaster. See “Chernobyl–One Year Later,” *National Geographic* of 5/87; “Five Years Later, Chernobyl: The Danger Persists,” *NYT Magazine* of 4/14/91; “Who Knows How Many Will Die?,” *Time* of 4/29/91; “Chernobyl: Nuclear reactor tragedy left scars on land, lives and ‘will never be over’,” *USA Today* of 9/17/91; “Chernobyl Said to Affect Health of Thousands in a Soviet Region,” NYT of 11/3/91; “Child Cancers Found

to Rise Near Chernobyl," WSJ of 9/3/92; "Chernobyl Death Toll Continues to Climb," NYT of 11/1/93; "The nuclear legacy in Ukraine, Kazakhstan, Lithuania and Armenia," PI of 6/13/94; "Living with the Monster: Chernobyl," *National Geographic* of 8/94; "The truly wild life around Chernobyl," USNWR of 7/17/95; "A Haven for the Ailing Children From Chernobyl," NYT of 10/6/95; "Chernobyl and Cancer: New Study," NYT of 11/21/95; "Chernobyl Trust Fund Depleted as Problems of Victims Grow," NYT of 11/29/95; "Chernobyl, cancer and creeping paranoia," *Economist* of 3/9/96; "10 Years Later, Through Fear, Chernobyl Still Kills in Belarus," NYT of 3/31/96; "Ten Years of the Chernobyl Era," *Scientific American* of 4/96.
(b) Summarize the current state of the Chernobyl nuclear power plant. Is it still operating? See "The Chernobyl Cover-Up," *Time* of 11/13/89; "A New Arena for Soviet Nationalism: Chernobyl," NYT of 12/30/90; "Chernobyl Within the Barbed Wire: Monument to Innocence and Anguish," NYT of 4/23/91; "Ukraine to Keep Chernobyl in Operation," NYT of 10/22/93; "Ukraine to Close Chernobyl Plant," NYT of 4/10/94; "Russia's rising nuclear peril," PI of 6/12/94; "Chernobyllions," *Economist* of 7/2/94; "Chernobyl closing requires $12 billion, Ukraine says," PI of 11/17/94; "Ukraine Votes to Become a Nuclear-Free Country," NYT of 11/17/94; "Agreement is Reached on Replacing Chernobyl," NYT of 5/28/95; "Chernobyl's Future: What to do with Reactor 4?," USNWR of 7/17/95; "Chernobyl: If You Can Make It Here ...," BW of 3/30/98.

15-5. Investigate Sweden's situation regarding nuclear energy. The Swedes said 'No' to nuclear power in a 1980 referendum. Have they changed their mind since then? See the *Economist* of 4/20/96 ("Tilting at nuclear windmills").

15-6. Find out more about the storage of high-level nuclear waste and the most recent status of the Yucca Mountain repository. See "A Nuclear Dump: The experiment begins," *Discover* of 3/89; "No Home for Hot Trash," *Time* of 12/11/89; "A Mountain of Trouble," *NYT Magazine* of 11/18/90; "Experts Clash on Risk At Nuclear Waste Site", NYT of 12/3/91; "Wasting Away: a $1.3 billion tomb for nuclear waste in New Mexico remains unused...," *NYT Magazine* of 8/30/92; "State Pressure on U.S. Over Nuclear Waste," NYT of 10/20/92; "Nuclear Industry Seeks Interim Site To Receive Waste," NYT of 8/27/93; "Out of Sight, Out of Our Minds," *NYT Magazine* of 3/6/94; "Lethal garbage: nuclear waste," USNWR of 11/7/94; "By Default and Without Debate, Utilities Ready Long-Term Storage of Nuclear Waste," NYT of 2/15/95; "Scientists Fear Atomic Explosion of Buried Waste," NYT of 3/5/95; "Theory on Nuclear Dump Peril is Disputed," NYT of 3/8/95; "Nuclear waste: Down a highway near you," *Economist* of 4/22/95; "For our nuclear wastes, there's gridlock on the road to the dump," *Smithsonian* of 5/95; "The Nuclear Legacy," *Popular Science* of 8/95; "A Nuclear Problem Keeps Growing," *Washington Post* of 12/31/95; "Factory is Set to Process Dangerous Nuclear Waste," NYT of 3/13/96; "Nuclear waste: One big dump," *Economist* of 4/20/96; "Nuclear waste with nowhere to go," BW of 6/10/96; "Can Nuclear Waste Be Stored Safely at Yucca Mountain?", *Scientific American* of June 1996.

15-7. Throughout the early 1990s, the U.S. Council for Energy Awareness (Washington, D.C.) has had the following advertisement headlines in many newspapers and magazines:
•Every day is Earth Day with nuclear energy
•Foreign oil: the kiss of death? Nuclear energy means more energy independence
•Foreign oil: dangerously unpredictable. Nuclear energy means more energy independence
•The growing returns on America's investment in nuclear energy
•Nuclear energy helps slow the flow of foreign oil
•Citizens for nuclear energy: Nuclear energy for energy independence and a cleaner Earth
•Our need for more nuclear energy is up in the air: nuclear energy means cleaner air
What kind of an institution is this? Summarize the arguments that it uses to support this position. Do you ‘buy’ these arguments? See for example *Time* of 8/20/90, 10/29/90 and 3/1/93; WSJ of 9/26/90; *Esquire* of 11/90; *National Geographic* of 9/93.

15-8. More recently, the Nuclear Energy Institute (Washington, D.C.) is paying for similar advertisements. Check out their arguments. Do you ‘buy’ them? See “Putting Nuclear Energy In a Whole New Light," NYT of 8/2/94; “Nuclear Energy Helps Us All Breathe A Little Easier,” NYT of 4/18/95.

15-9. Why did India vote against the recent Comprehensive Nuclear Test Ban Treaty? How many countries voted as India did? See “India Vetoes Pact To Forbid Testing of Nuclear Arms,” NYT of 8/21/96; “Approve the Test-Ban Treaty,” NYT of 9/10/96; “U.N. Endorses a Treaty to Halt All Nuclear Testing,” NYT of 9/11/96; “India: Nuclear poker,” *Economist* of 12/23/95; “India and Pakistan: Going critical,” *Economist* of 5/4/96.

15-10. Summarize the most recent events regarding the extension of the Nuclear Non-Proliferation treaty (NPT). See “Between the bomb and a hard place,” *Economist* of 3/25/95; “U.N. Council Seeks Support for Nuclear Pact,” NYT of 4/6/95; “Critical Mass,” USNWR of 4/17/95; “A Good Nuclear Example” and “Discord Over Renewing Pact on Spread of Nuclear Arms,” NYT of 4/17/95; “Mushroom clouds and mushrooms spawn,” *Economist* of 4/22/95; “Nuclear Pact May Continue by Consensus,” NYT of 5/9/95; “Nuclear proliferation: Almost in the bag,” *Economist* of 5/13/95; “India and Pakistan: Going critical,” *Economist* of 5/4/96.

15-11. Safety issues at the Indian Point 3 nuclear power plant in New York have been in the news for quite a while. What was (is) the problem? See NYT of 10/9/90 (“2 Hot Bundles Hang Perilously At Nuclear Site”), 10/17/90 (“Fuel Rods Dropped at Indian Point But Tests Show No Radiation Leak”), 10/18/90 (“At Indian Point, No Second Guessing After a Nuclear Fuel Mishap”), 12/11/90 (“2 at Indian Point Facing Charges From U.S. Panel”), 4/21/93 (“Federal Inspector Criticizes Indian Point Nuclear Plant for Lapses on Safety”), 9/26/94 (“Cost and Safety Threaten Indian Point 3”), 9/27/94 (“Atom Plant Is Assessed At a Hearing”), 3/30/95 (“Indian Point A-Plant's Safety Doubted on Eve of U.S. Visit”), and 10/18/95 (“U.S. Calls Operations At A-Plant Still Flawed”). Check also the Internet at http://www.nrc.gov.

15-12. The Yankee Rowe nuclear plant in Massachusetts was closed several years ago. What is its status now? See NYT of 10/2/91 (“A Plant to Close Over Safety Issue”), 10/6/91 (“Turning Off the Juice”), 11/4/94 (“Officials Raise by $123 Million Estimate of Dismantling Reactor”); PI of 10/2/91 (“Safety concerns force shutdown of oldest nuclear plant”); WSJ of 9/12/91 (“Aging Nuclear Plants Become a Hot Issue As Relicensings Near”), 10/2/91 (“Massachusetts Nuclear Plant Is Closed After Regulators Voice Safety Concerns”); BW of 9/23/96 (“Giving New Life to Aging Nuclear Plants”). Check also the Internet at http://www.nrc.gov.

15-13. Several nuclear reactors at the Tennessee Valley Authority were scheduled for shutdown. Why? What is their status now? See NYT of 12/13/94 (“T.V.A. to Stop All Work on 3 Reactors”), 12/15/94 (“End of a Nuclear Generation”). Check also the Internet at http://www.nrc.gov.

15-14. The most notorious case of a troubled nuclear power plant is that of Shoreham, Long Island. It was built at a cost of $5.5 billion and was sold to the state of New York for $1. Investigate its history. See WSJ of 3/27/89 (“NRC Nears Licensing Lilco Nuclear Plant Despite State Pact”); NYT of 10/23/91 (“Court Says Shoreham A-Plant Can Be Closed”), 10/25/91 (“At Shoreham, a Somber Beginning of the End”), 2/19/92 (“Pitching a Nuclear Plant at Shoreham”), 9/23/92 (“Shoreham's Nuclear Fuel May Be Headed Abroad”), 12/13/92 (“Shoreham Fuels Nuclear Proliferation”), 4/22/93 (“Nuclear Fuel to Be Moved Through Populous Areas”), 10/13/94 (“Dismantling of the Shoreham Nuclear Plant Is Completed”); PI of 9/28/93 (“A suspenseful journey begins from Long Island”), 10/3/93 (“The nuclear fuel got through; and the city is still in one piece”); *Economist* of 1/4/97 (“Lilco's nuclear waste”).

15-15. Investigate which countries belong to the “Nuclear Club” (group of nations that have acknowledged or are believed to have nuclear weapons). See NYT of 3/25/93 (“South Africa Says it Built 6 Atom Bombs”) and 3/29/95 (Atom Powers Want to Test Despite Treaty”); *Time* of 6/21/93 (“Fighting Off Doomsday”). See also an article about the cost of keeping and destroying nuclear weapons: “Costing a bomb” in the *Economist* of 1/4/97.

15-16. On the occasion of the 10th anniversary of the Three Mile Island accident, many reports on nuclear reactor safety have been published. Summarize some of them. Review *Newsweek*, *Time*, etc. for relevant articles. See also NYT of 3/23/89 (“10 Years After Three Mile Island”), 3/27/89 (“Nuclear Safety Goals Are Not Met”), 3/28/89 (“Three Mile Island: The Good News”), *USA Today* of 3/21/89 (“How nuclear power plants are faring”), and 3/27/89 (op-ed page), PI of 3/26/89 (“A decade after the accident, TMI still holds...”).

15-17. Summarize the problems with nuclear power plants that are still operating in Russia and eastern Europe, in the light of what happened at Chernobyl. See the *Economist* of 8/15/92 (“Chernobyls-in-waiting” and “Eastern Europe's nuclear reactors: Too little...”) and 7/24/93 (“Eastern Europe's Nuclear Power: Buying peace of mind”); NYT of 10/13/91

("Eastern Europe's Reactors Don't Seem So Distant Now"), 10/16/91 ("A Peril-Ridden A-Plant: It's a Frightening Legacy"), 3/22/92 ("40 Chernobyls Waiting to Happen"), 3/25/92 ("Nuclear Power: Safety at Risk"), 11/8/92 ("Russia Will Keep Using Notorious Nuclear Reactors"), 1/29/93 ("Major Powers Back a Fund For Soviet-Design Reactors"), 9/22/94 ("40 Nations Agree to Shut Down Nuclear Plants Deemed Unsafe"); PI of 6/12/94 ("Russia's rising nuclear peril"); BW of 6/8/92 ("Preventing Chernobyl II"); *Time* of 12/7/92 ("Nuclear Time Bombs"); USNWR of 8/9/93 ("Radiation in Russia").

15-18. "Newcastle had coal, Liechtenstein had sausage skins, Hanford had plutonium." These are all motherhood-and-apple-pie statements. For the first one, see Investigation 7-7. We won't worry about the second one here. But do find out more about Hanford, its plutonium, its past and its present. See *Economist* of 8/15/92 ("Nuclear Clean-ups: Repent at leisure") and *Time* of 7/23/90 ("There Was Death in the Milk").

15-19. Find out more about the link between low-level radiation exposure (to radon, for example) and incidence of cancer. See "Study Finds No Increased Risk of Cancer Deaths Near Nuclear Sites," NYT of 9/20/90; "Some Scientists Say Concern Over Radon Is Overblown by E.P.A.," NYT of 1/8/91; "Study Links Cancer Deaths And Low Levels of Radiation," NYT of 3/20/91; "New Study Questions Hiroshima Radiation," NYT of 10/13/92; "Pioneer in Radiation Sees Risk Even in Small Doses," NYT of 12/8/92; "E.P.A. Proposes Costly Rules to Curb Radon Health Threat in New Houses," NYT of 4/7/93; "Radon? Dangerous? Maybe less than feared," PI of 10/17/93; "Radon Tied To 30% Rise In the Risk Of Cancer," NYT of 1/25/94; "Studies Raise Doubts About Need to Lower Home Radon Levels," NYT of 9/6/94.

15-20. The idea to use plutonium from dismantled nuclear weapons in commercial power plants sounds like killing two birds with one stone. But is it really a win-win solution? It certainly has caused quite a stir in the media. Summarize the basic facts and issues surrounding this "hot potato"? See "Quietly, U.S. Converts Uranium Into Fuel for Civilian Reactors," NYT of 6/19/95; "Nuclear Deal With Russia Is Reshaped," NYT of 7/9/95; "Uranium Deal: Is Russia Delivering?," NYT of 1/29/96; "Plan for Managing Nuclear Arms Leaves a Tough Issue Unresolved," NYT of 2/29/96; "Profit Motive Clouding Effort To Buy Up A-Bomb Material," NYT of 8/28/96; "U.S. Set to Allow Reactors to Use Plutonium From Disarmed Bombs," NYT of 11/22/96; "Agency To Pursue 2 Plans To Shrink Plutonium Supply," NYT of 12/10/96; "Controlling the Risks of Plutonium," NYT of 12/11/96; "Groups Protest a Proposal For Disposing of Bomb Fuel," NYT of 12/23/96.

15-21. A related issue, and equally hot, is the privatization of uranium enrichment operations in the U.S. What are the basic facts and issues here? See "A Company for Uranium," NYT of 7/1/93; "An Endangered Nuclear Bargain," NYT of 6/13/95; "U.S. Goals at Odds In a Plan to Sell Off Nuclear Operation," NYT of 7/25/95; "Morgan Stanley Gets Big Role In Privatizing Uranium Unit," NYT of 11/9/95.