Nuclear Power: Villain or Victim?

OUR MOST MISUNDERSTOOD SOURCE OF ELECTRICITY

SECOND EDITION

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To my wife, Phyllis

FOREWORD

Oh, the things we think we know
that are not so.
Anonymous

Making electricity from nuclear energy is a fascinating process. How in the world can we generate electricity to operate a microwave oven from the nuclei of atoms — specks of matter so tiny that 10,000 billion of them would still be invisible to the naked eye? This book is about nuclear power — electricity made from specks of uranium and plutonium.

Nuclear power is important to Americans for jobs, a high standard of living, and clean air. Because it emits no pollutants to the atmosphere, it is estimated to save thousands of lives every year in the United States alone; it could save tens of thousands more. It may be crucial for preventing catastrophic consequences of global warming and for preventing wars over the world's supply of petroleum.

Polls indicate that a majority of Americans support nuclear power, but a vocal minority has opposed it. That minority includes people who are sincere and well-meaning; people who do not understand it; environmental groups, some of which use opposition to it as a fund-raising tool; and antinuclear groups that oppose both advanced technology and large industry in general.

A lack of understanding of nuclear power is a major cause of opposition. Some people believe radiation from nuclear energy is new and man-made, although the earth has been bathed in it since the dawn of time. The public has feared radiation since the two atomic bombings in Japan in 1945; however, although the radiation effects were severe, radiation accounted for only 20% of the deaths there. The mass media contribute to misunderstanding through the use of frightening headlines, frequently to attract readers or listeners. A New York newspaper headlined *'2000 die' in Nukemare* shortly after the Chernobyl nuclear power plant failure in Ukraine in 1986, although the number of known deaths from radiation today is about 50. Individuals make outrageous statements. Ralph Nader has said that one pound of plutonium could kill eight billion people; however, 10,000 pounds have been released into the earth's atmosphere from weapons tests in the last 50 years — enough by his estimate to kill all the people on earth several thousand times.

There is also misunderstanding about nuclear waste. Antinuclear groups and some political leaders state repeatedly that the nuclear waste disposal problem is unsolved, and the public comes to believe this. However, most of the scientific and engineering community believes the waste can readily be disposed of by deep-underground burial — where it will be harmless. Even if the waste-disposal statement were true, it could be quite misleading; it is intended to imply that other technologies do not have significant waste-disposal problems. The groups opposing nuclear power rarely mention that there is no solution for handling the several million tons of carbon dioxide that every large coal and natural gas power plant discharges each year — other than to release the gas to the atmosphere where it becomes a major contributor to the greenhouse effect and climate change. Nor do we have a practical solution for handling particulate pollutants that coal plants discharge into the atmosphere — where they are estimated to cause tens of thousands of deaths yearly.

This book's major goal is to present facts about nuclear power and to eliminate as much misunderstanding about it as possible. The book is addressed to adults who have forgotten their high school science courses and to ninth and tenth grade high school students who haven't; brighter students in grades as early as the fourth or fifth will also understand it. Each of you will learn more about the subject than most scientists, engineers, government leaders, and representatives of industry and environmental groups know. The book doesn't provide the intricate details of the design and operation of a nuclear plant because that takes years of study. Nevertheless, it gives "the big picture" on which decisions are made about the use of nuclear energy.

We will compare nuclear power with its alternatives, just as everybody compares alternatives in real-life situations. If you intended to buy a car, you would compare prices, styles, gas mileages, trade-in values, and colors of different makes and models. You wouldn't simply walk to the nearest automobile dealer and buy the first car you saw in the window. Similarly, we must make comparisons in deciding the best ways to make electricity. The primary alternatives are to make it by burning fossil fuels — coal, natural gas, and oil (petroleum).

I will present considerable data for making comparisons. This is partly because most readers don't have time to find the needed information by themselves — the data have to be dug out from many books and technical magazines. A second reason is that those books and magazines are not easily available to most people. Some data will surprise (shock?) you, and you may doubt the accuracy of some statements. Good. I invite you to challenge any factual assertion you believe to be incorrect, and a Suggested Reading list is given at the end of the book to help. Your public or school libraries should be able to obtain these references.

Chapters 1 through 10 cover the following:

- What is nuclear power and why is it important?
- What is nuclear energy?
- What is a nuclear reactor and how does it work?
- How is electricity made from nuclear energy?
- What are the health effects of radiation?
- Are nuclear power plants safe?
- How do we dispose of radioactive waste?
- What is the possibility of theft of uranium or plutonium by terrorist groups to make explosives?
- What kind of advanced reactors are being developed?
- What is the cost of nuclear power?

Chapter 11 describes the enormous benefits that nuclear energy promises the world. Chapter 12 gives recommendations on what we can do to help realize those benefits.

ACKNOWLEDGMENTS

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CONTENTS

Chapter 1

WHY IS NUCLEAR POWER IMPORTANT?

There's really no mystery about what nuclear power is. It is simply electricity produced using a nuclear reactor, a turbine, and an electrical generator. There is nuclear energy in uranium, and we can release this energy in a reactor. We then convert the energy to heat and use the heat to boil water and make steam. Finally, we can cause the steam to turn a turbine wheel, which is attached to a coil of copper wires located inside a magnet. We call this the generator. If we do everything properly, electricity is produced as the wires turn inside the magnet.

Electricity is obviously important for many reasons. One is that it helps maintain and increase our standard of living as our population grows. Another is that it allows our factories to increase their efficiency. Low-cost electricity is vital for industry to compete internationally and to provide jobs. Our electricity use has risen continuously for the last 50 years, and the Department of Energy predicts we will need the equivalent of 275 large new coal or nuclear power plants by 2025 — 19 years from now. This new capacity includes the replacement of inefficient, older plants. The total will cost hundreds of billions of dollars.

The need for electricity is even greater outside the United States. Today, there are over six billion people in the world, and almost two billion of them have no electricity. In 50 years, there will likely be about 10 billion people on the planet.

A logical question is: Why is nuclear energy important for making electricity? The answer is that it is a clean, safe, and inexpensive way to produce electricity. Nuclear energy is especially important for *clean air.* Most electricity produced in the world today comes from burning coal, natural gas, or oil, including about 70% of that in the United States. Burning these fossil fuels releases carbon dioxide (CO_2) into the atmosphere. It is estimated that two billion tons of CO_2 per year are released into our air from generating electricity. China releases 50% more than the United States does, and its burning of coal may double in 25 years. CO_2 is responsible for about two-thirds of the "greenhouse effect" and potential global warming; many scientists predict this warming will cause disastrous climate changes in parts of the world. CO_2 is released when any fossil fuel is burned, including natural gas that releases about half as much as coal in making electricity. *In contrast, no* CO_2 *is released from a nuclear power plant.* Coal plants also release sulfur and nitrogen compounds that cause acid rain, *whereas nuclear plants do not.*

Nuclear energy is also important to *save lives.* *Nuclear power is safe;* except for the Chernobyl event in Ukraine in 1986, there have been no known deaths among the public caused by the world's four hundred plus nuclear plants during their 45 years of operation. In contrast, the burning of fossil fuels, such as coal, diesel oil, and gasoline, releases tiny particles or particulates into the atmosphere; breathing these particulates is estimated to cause tens of thousands of deaths each year in the United States alone. *Nuclear plants release zero particulates.* Because 20% of our electricity comes from nuclear power, the 100-plus nuclear plants operating in the United States today are probably saving thousands of lives every year. Increased substitution of nuclear power for coal power would save thousands more lives each year.

The Chernobyl event was a very serious accident, and its eventual toll from radiation is predicted to be a few hundred deaths by optimistic estimates or a few thousand by more pessimistic ones. Most of these deaths will result from cancer, with individual deaths coming 20 or 30 years after radiation exposure. In addition, there were other serious effects; 350,000 people faced a traumatic relocation experience; many people in the area have undergone severe mental health problems; and the economic costs are estimated in the tens (possibly hundreds) of billions of dollars. However, the Chernobyl accident was unique. The reactor was of an extremely dangerous design; such a reactor could not and would not have been built in the U.S. or elsewhere in the Western world. It was operated by incompetent management; some managers had almost no training in and understanding of nuclear reactor operation. The national safety regulatory system (such as the U.S. has) was woefully deficient. *For all practical purposes, there is zero chance that an accident of the magnitude of the Chernobyl event will ever occur outside the former USSR.* Moreover, with the modifications that have been made to the half-dozen or so still-operating Chernobyl-type reactors, there is little chance of a repeat of the original accident even there.

The only proven methods to generate large amounts of electricity at *competitive costs* in new power plants are to burn fossil fuels or to use uranium. Our American dam sites for hydroelectric power have largely been put to use, as have our geothermal sites. Electricity generation from wind, biomass, solar energy, or other "renewable" sources has not been demonstrated on a large scale, and it is uneconomic for base-load power. The average cost of producing electricity from wind in the U.S. in 2004 was over twice that for coal and uranium, with that from biomass and solar being more costly yet. Power from controlled fusion is at least 40 years away. In new plants, the cost of electricity from uranium may be a few percent higher than the cost from coal; *it will be below the cost from coal if needed restrictions are placed on releasing carbon dioxide to the atmosphere.* Further, the nuclear energy in a pound of uranium is three million times the energy released in burning a pound of coal; the long-range potential cost of generating electricity from uranium is considerably lower than from any fossil fuel.

> Note: Not all nuclear power plants produce electricity. Navy nuclear plants propel ships directly without using generators or electricity. However, we will continue to discuss nuclear power as electricity produced with reactors. Electricity can also be produced on a small scale from nuclear energy without a reactor. This is done on space satellites, using a different kind of nuclear process.

Chapter 2

WHAT IS NUCLEAR ENERGY?

To understand nuclear power, we need to understand what nuclear energy is and where it comes from. According to Einstein's famous equation, $E = mc^2$, mass (m) can be converted into energy (E) in a nuclear process. (In the equation, c is the speed of light.) Therefore, the more mass we use up, the more energy we get. It is easy to convert uranium into energy.

As you may recall from your science classes, there are 90 elements that occur in nature, and almost everything in the world is made up of those individual elements or combinations of them. When we study the elements in science or chemistry, they are listed in a periodic table, with hydrogen as number one, helium as number two, and so on until we reach 92, which is uranium. (The 43rd element, technetium, and the 61st element, promethium, do not exist naturally.) If you held a chunk of uranium metal in your hand and were able to crumble it into very tiny pieces, you would find that it is made up of billions of individual particles called "atoms." The atoms for each element have a nucleus at the center and a unique number of electrons outside the nucleus; hydrogen, helium, and uranium atoms are illustrated in Figs. 1 through 3.

Electrons are tiny bits of electricity, and if we try to bring two of them together, we would find that they repel one another. Protons are much bigger (but still tiny) particles, and they, too, repel one another. However, if we bring an electron and a proton close together, we would find that they attract each other; it would be difficult to keep them apart. Neutrons are similar in size to protons, and they attract protons and other neutrons but not electrons.

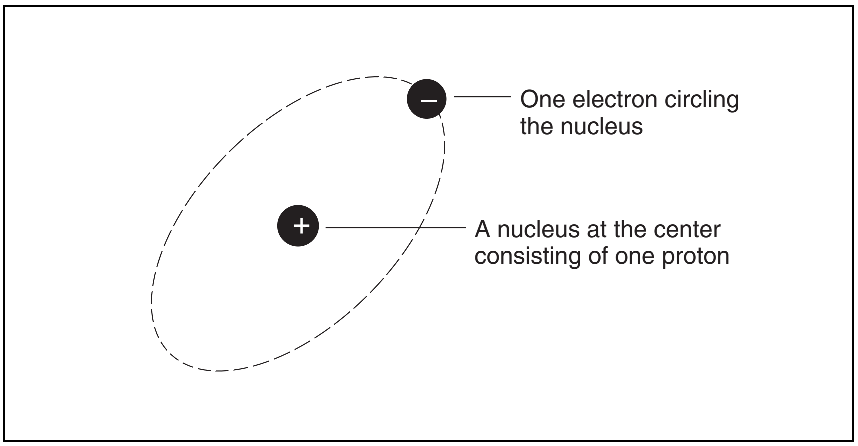

Figure 1: Hydrogen Atom

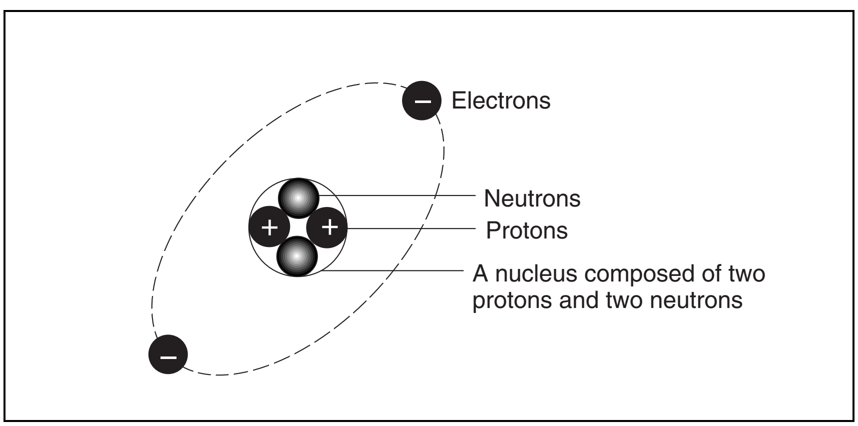

Figure 2: Helium Atom

No one has ever seen an atom, an electron, a proton, or a neutron, nor has anyone counted the number of protons or neutrons in a nucleus. They are all too small. However, scientists (particularly physicists and chemists) have been studying atoms for over 200 years and have developed models to explain the results of the thousands of experiments they have run.

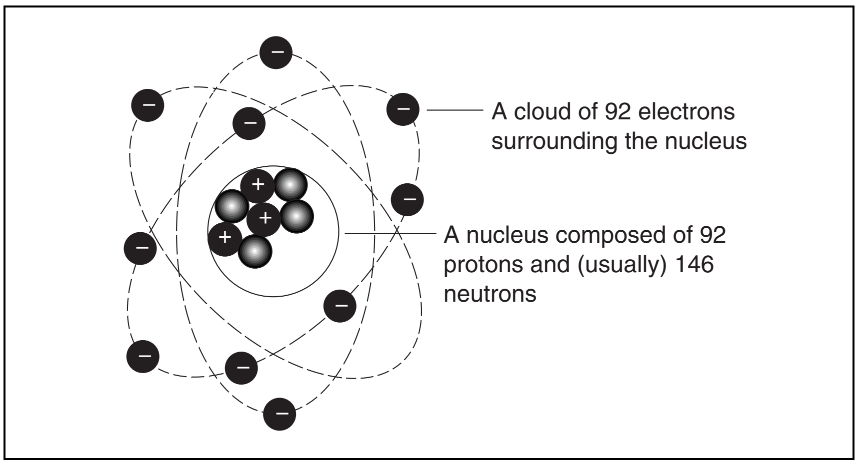

Figure 3: Uranium Atom

Our model tells us that uranium nuclei are unstable and some are continually breaking up or disintegrating and emitting neutrons. Further, the model and experiments show that, if one of these neutrons hits and is absorbed in the nucleus of another uranium atom, the nucleus may split into two fragments; it will also release two or three neutrons, and give off energy. We term this splitting process "fissioning," and the energy is termed "nuclear" energy because it comes from a reaction in the nucleus. The model is illustrated in Fig. 4.

The energy results from some of the mass in the nucleus being converted to energy as in Einstein's equation; if we could weigh the fission fragments and neutrons that result from splitting the nucleus, we would find that they weigh less than the original nucleus and neutron. The difference in weight has gone into energy. (For the purposes in this book, we will use mass and weight interchangeably, although they are not exactly the same.)

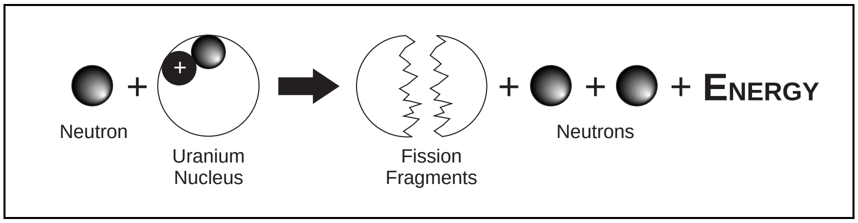

Figure 4: Fission Process

We say there are two kinds of energy — kinetic and potential. Kinetic energy is the energy of motion — the energy of a body or object that results from its motion. A moving automobile and a bullet fired from a gun have kinetic energy. Potential energy is energy that can be converted to kinetic energy, and it results from location or structure. A rock sitting on top of a hill has potential energy; it could roll down the hill and its potential energy would be converted to kinetic energy.

Kinetic energy can be converted easily to heat. If I swing a heavy hammer (which has kinetic energy because it is moving) and strike a piece of iron, the hammer will lose part of its energy, the iron will absorb that energy, and the iron will rise in temperature. A similar happening occurs if you rub one stick against another to start a fire — kinetic energy is converted to heat, which raises the temperature of the wood.

The energy given off when a uranium nucleus absorbs a neutron and fissions is kinetic energy; the two fission fragments each travel at a high speed. They will be slowed down and stopped as they strike surrounding atoms, and the piece of uranium will be heated.

Nuclei are very tiny, and the amount of energy given off in an individual fission event is extremely small. However, huge numbers of fission events (typically ten million trillion) can be made to occur every second in a nuclear reactor power plant, and large amounts of energy can be released.

One important aspect of fissioning uranium has not been mentioned so far. There are several kinds of uranium atoms, each called an *isotope* of uranium. The isotope pictured in Fig. 3 with 92 protons and 146 neutrons in the nucleus is called uranium 238 or U-238. (Note that 92 + 146 = 238.) If you were to dig up a piece of uranium ore in Colorado, you would find that about 99.3% of the uranium atoms would be U-238. Most of the remaining 0.7% would be uranium 235 atoms, with 92 protons but only 143 neutrons in each nucleus. There is an important difference between the two isotopes: it is easy to cause a U-235 nucleus to capture a neutron, to fission, and to release energy, whereas this is difficult with U-238. In the electricity-generating reactors used around the world today, little fissioning takes place in U-238 nuclei, and we will ignore it in this book.

U-238 nuclei are important though because they can absorb neutrons to form the element plutonium, that does not occur in nature except in minute quantities. Most nuclei of plutonium will fission and release energy just like U-235. Plutonium is produced in commercial power reactors during normal operation, and about 40% of the electricity comes from it.

In summary, the term “nuclear energy” as used in this book is the kinetic energy of the fragments that result from the fissioning or splitting of U-235 and plutonium nuclei when they absorb neutrons. The kinetic energy is converted to heat as the fragments are slowed, and the heat is converted to electricity as described later.

In passing, it should be noted that nuclear energy can also be released by fissioning in a process involving thorium, the 90th element in the periodic table. However, thorium is seldom used and will not be discussed further in this book.

Actually, there are two processes by which nuclear energy is released — fission and fusion. The energy given off by our sun is another form of nuclear energy; it comes from the fusion process. In this, the nuclei of atoms combine or fuse together, and mass is lost in the process. The mass is converted into energy, also in accordance with Einstein’s equation. Fusion is much more difficult to achieve here on earth than fission; this is partly because it occurs at temperatures around 100 million degrees. Scientists and engineers have been working since 1950 to learn how to make power from fusion, but they have not yet been successful. We probably will not have fusion electricity for at least 40 years, and because our need for clean energy is *now*, fusion will not be discussed further.

Chapter 3

WHAT IS A NUCLEAR REACTOR?

A "nuclear reactor" is a machine built to release energy from uranium and plutonium. The energy is converted to heat and used to heat water* and make steam. (The steam is used to make electricity as described later.) In some reactors, the steam is made inside the reactor; in others, very hot water is piped outside the reactor to form steam there.

A typical reactor consists of four main parts: uranium or uranium and plutonium; water; devices to control the rate at which fission occurs; and a radiation shield, which is discussed in Chapter 6. The water is used to: a) cool the uranium, b) make steam, and c) slow down the neutrons as follows.

Suppose we take a block of pure uranium metal. As discussed previously, we would find that some nuclei are continuously breaking up, with neutrons being released in the

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* Helium, carbon dioxide, a type of water called heavy water, and the metal sodium (in liquid form) are substituted individually for ordinary water in some reactors. In particular, Canadian reactors use heavy water and some British reactors use carbon dioxide. Sodium reactors are discussed later.

process. These neutrons would fly off in all directions at very high speed. Some would strike nearby U-235 nuclei and cause fissioning to take place. However, this is an inefficient process because the neutrons travel too fast (about 40 million miles per hour); many of them would escape from the block and be lost. To improve the efficiency, let us shape the uranium into a large number of small rods, each about one-half inch in diameter and several feet long. Let us also arrange the rods vertically and insert water between them to slow down the neutrons. The neutrons slow down (to perhaps 7,500 miles per hour) because they lose energy as they strike the nuclei of hydrogen in the water. They then more easily cause fission of U-235 nuclei. In a typical reactor, the rods are separated from each other by about one-eighth inch of water.

The water has two other purposes, as well. First, it is pumped past the uranium rods to carry away the heat. Unless the uranium is cooled, it would melt. Second, the heated water forms steam to generate electricity as described later.

The fission rate must be controlled or the reactor could be destroyed. This is done by control rods. At least two neutrons are released in each fission event, and the number of neutrons in the reactor could multiply to an undesirably high level. In fact, it could rise so high that the water would be incapable of carrying the heat away and the uranium rods would melt. To prevent this, we insert an additional material into the reactor to absorb "excess" neutrons and control the fission rate. The element boron is frequently used because it absorbs neutrons readily. By moving the boron into or out of the uranium region, we can easily control the rate of fissioning. Of course, if we insert too much boron, the neutron population drops rapidly. This is the way the reactor is shut down.

A "boiling water reactor" and a "pressurized water reactor" are illustrated in Figs. 5 and 6. In the boiling water reactor, water enters the reactor and turns to steam as it passes through.

In the pressurized water reactor, hot water under very high pressure leaves the reactor and is passed through tubes in a "heat exchanger"; here, heat from the reactor water passes through the walls of the tubes and boils a separate supply of water outside the tubes.

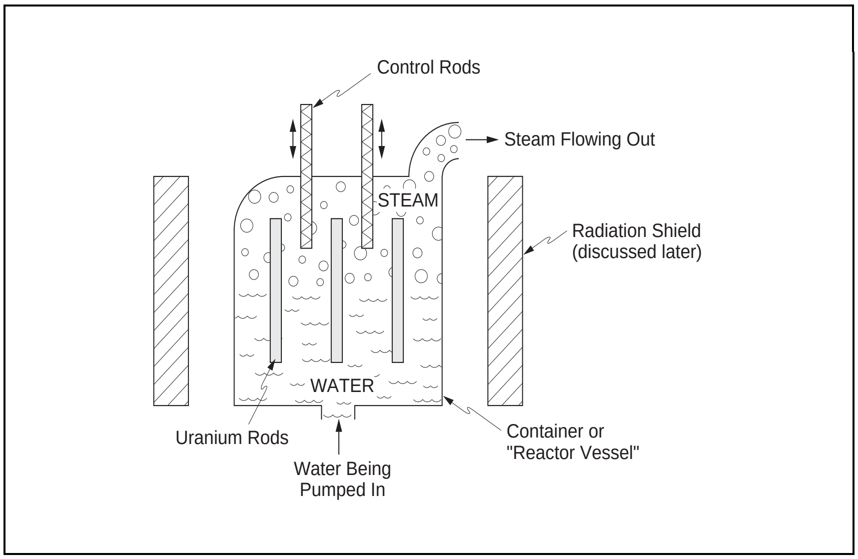

Figure 5: Boiling Water Reactor

And that is all a reactor is; it can be a very simple device. In fact, nature created one in what is now the African nation of Gabon about two billion years ago. There was enough uranium and water in the ground for fissioning to occur intermittently for several hundred thousand years. The water slowed the neutrons and served as a control device. With water present, the neutrons would be slowed and fissioning would occur; if the water boiled away, the reactor would shut down until rain replenished the supply. Then, fissioning would begin again. Of course, nature didn't care about collecting steam to generate electricity.

How do we know this happened? Because the fragments given off in fissioning of U-235 nuclei are effectively "fingerprints," and the fingerprint evidence at the site is overwhelming. In addition, the fingerprints can be dated to tell when the event occurred. Could such reactors have occurred elsewhere in the world? Yes, and they probably did.

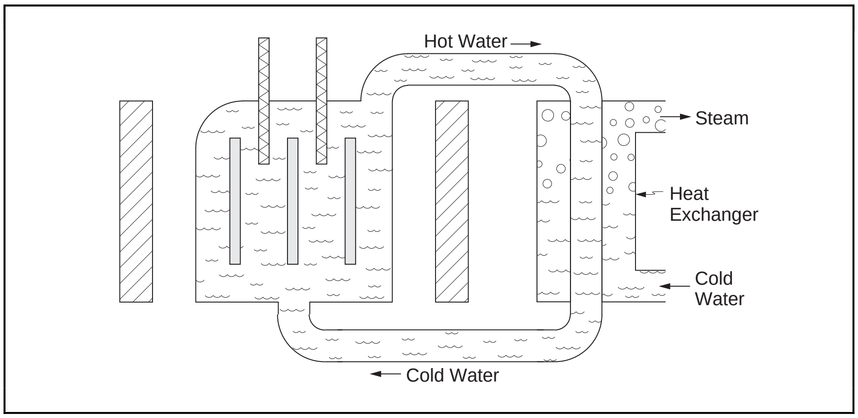

Figure 6: Pressurized Water Reactor

Chapter 4

WHAT IS A NUCLEAR POWER PLANT?

So far in our story, we have a reactor with steam being produced. How do we make a power plant — how do we generate electricity?

Let us discuss the last component of a power plant — the electrical generator. The discovery of how to build such a machine was made 150 years ago. If you wind copper wire into a circular coil and rotate the coil inside a magnet, you can generate electricity. Stationary brushes rub against the coil and carry the electricity away. A sketch of a simplified generator is shown in Fig. 7.

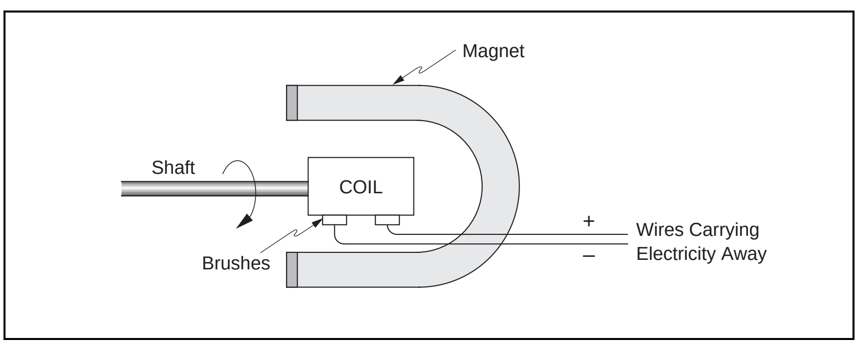

Figure 7: Electrical Generator

How can we couple the reactor to the generator to make electricity? The answer is by using a machine called a turbine. A turbine is like a windmill that you may have seen in a farmer's field. It is basically a big wheel with many "cups" at the edge; it turns when steam (or air in the case of the windmill) blows on the cups, as shown in Fig. 8. It has a steel shaft in the center of the wheel that is connected to the coil of copper wire in the electrical generator. Therefore, the steam turns the turbine wheel; the shaft at the center of the wheel turns the coil of wires; and electricity is produced when the coil turns inside the magnet. The wires forming the coil are connected to transmission lines via brushes that carry the electricity to homes and factories.

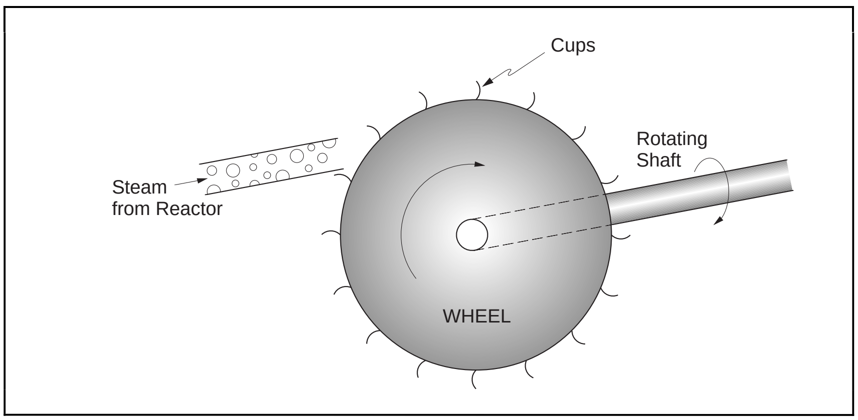

Figure 8: Steam Turbine

Now, the turbine wheel won't turn unless the steam from the reactor is flowing at a high speed. The final question to be answered, then, is why the steam from the reactor is flowing rapidly. Let's use a tea kettle to explain.

If you heat a tea kettle on a stove, the temperature of the water inside will rise to the boiling temperature. Steam will be formed, and the steam will push the spout open and "shoot out" or escape. This happens because, as the water turns to steam, its volume expands about 1,000 times. This expansion causes the pressure to build up in the kettle, and the pressure forces the steam out at high speed. If you held your finger on the spout so the steam couldn't escape, the pressure inside would build up and the kettle would rupture. (Don't try this; you might get hurt.)

A reactor behaves in a similar manner. As the reactor water is boiled, its volume increases, and the steam escapes at high speed through the outlet piping. The piping is designed so the steam strikes the cups on the turbine wheel; the wheel spins and its shaft turns the copper coil in the electrical generator.

A complete nuclear power plant is illustrated in Fig. 9.

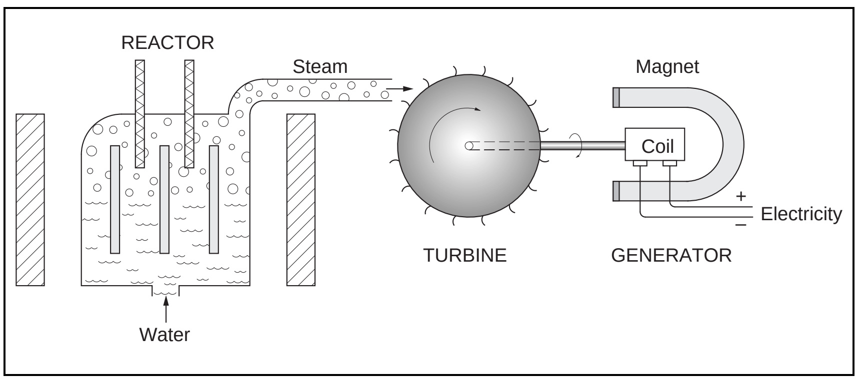

Figure 9: Boiling Water Reactor Nuclear Power Plant

There is one more component, in particular, that must be mentioned. We would like to reuse the steam after it leaves the turbine; very pure water is used in the reactor, and it is more economical to reuse the steam than to continuously purify replacement water. Liquid water can be pumped but steam cannot. Consequently, we must condense the steam back to liquid water after it leaves the turbine; this necessitates removing heat from the steam. This can be accomplished in a "condenser" as shown in Fig. 10.

The Kewaunee and Point Beach Nuclear Power Plants in Wisconsin are located on Lake Michigan; they take water from the lake, use it for condensing steam, and return it to the lake. In the condenser, the lake water flows inside metal tubes and the steam flows on the outside of the tubes. Heat passes through the tube walls from the steam to the lake water. The steam condenses as it loses heat, and the lake water is warmed as it receives heat. Thus, the water is a few degrees warmer when it returns to the lake than when it left. Many fish like warm water and congregate at the condenser outlet; fishermen frequently have great success there. It should be recognized that the lake water is kept totally separated from the reactor water; the two supplies of water never mix, and the lake water never comes near the reactor.

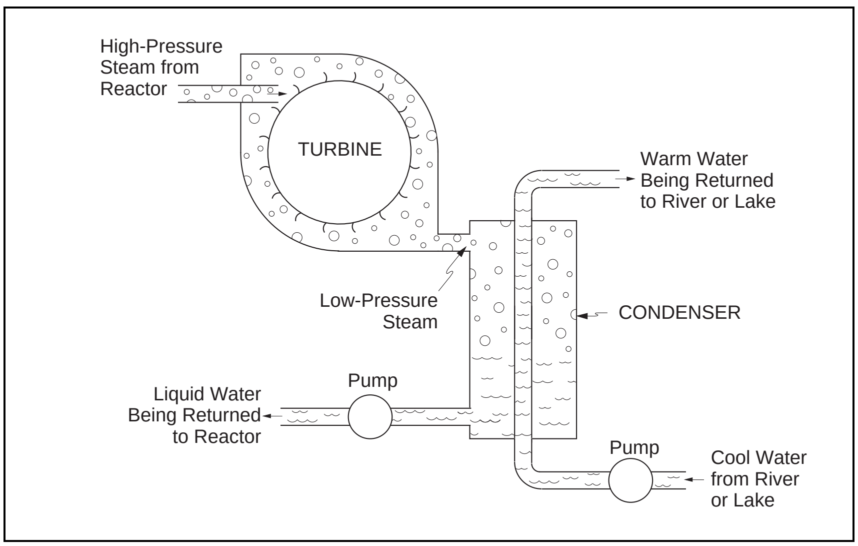

Figure 10: Turbine and Condenser

When power plants cannot be located near lakes or large rivers, another method of providing cooling water for the condenser is required. "Cooling towers" are frequently used, and they substitute for a lake. This system is shown in Fig. 11.

Cold water is pumped through the condenser and is heated as the steam condenses. This warm water is then sprayed downward from the top of the cooling tower. At the same time, cooler air rises upward inside the tower because of natural convection. As the air and water pass each other, the air cools the water. The air and a little water vapor are discharged to the atmosphere; it is the vapor or “steam” that you see from a distance. The cooled water is pumped back through the condenser. As Fig. 11 shows, the water is re-circulated continuously through the condenser and the cooling tower. The water is heated in the condenser as it absorbs heat from the steam, and it is cooled by the air in the cooling tower. Fresh water must be added continuously to replace the water lost as vapor, of course. Note that this cooling tower water is entirely separate from the reactor water; as before, the cooling tower water never gets near the reactor. These towers are large structures, many about 500 feet tall. They can be seen from a considerable distance from nuclear plants that use them.

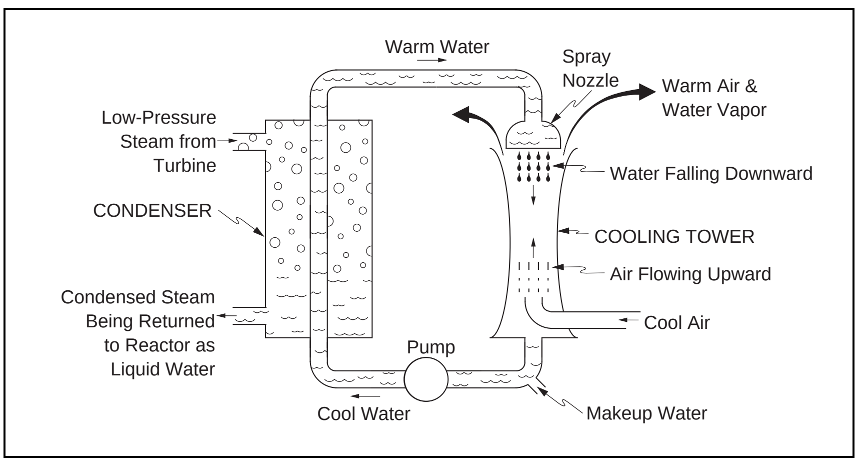

Figure 11: Cooling Tower

It is worth noting that about two-thirds of the nuclear energy released in the uranium and plutonium is lost through the condenser cooling water to the lake or atmosphere; the plant has a “thermal efficiency” of about 33%. Some advanced reactors show promise of achieving 50% efficiency. It is unfortunate that such a small fraction of the released energy is converted to electricity. However, this process is the most practical energy-conversion technique we have for large-scale electricity production.

A coal-burning power plant is somewhat more efficient, but it operates much the same way. Coal is currently the predominant fuel for electricity generation in the United States. A coal plant is shown in Fig. 12.

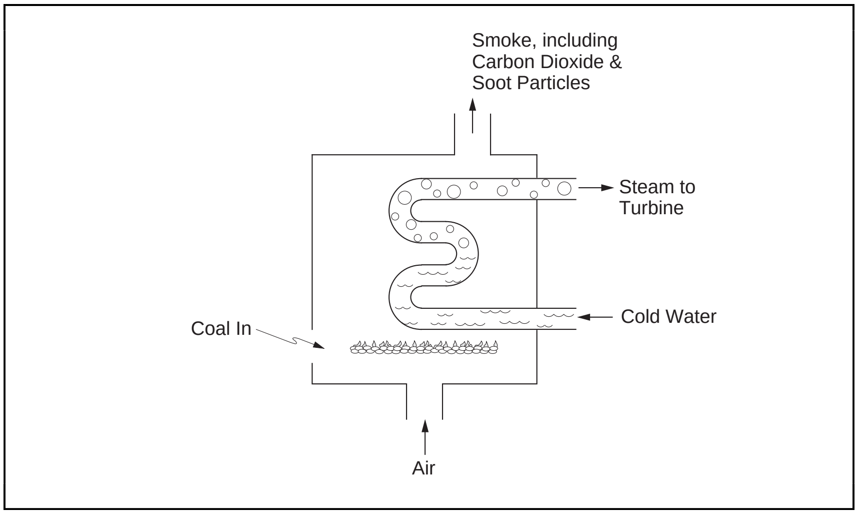

Figure 12: Coal Plant Furnace

When coal is burned, the carbon (C) in the coal combines with oxygen (O_2) from the air to form CO_2, and chemical energy is released. (This is truly “atomic” energy; atoms of carbon and oxygen combine chemically to form CO_2. The nuclei of these atoms are unchanged and play no role here.) The CO_2 is discharged to the atmosphere as part of the “smoke.” The remainder of the system, including the turbine, electrical generator, condenser, and cooling tower, is basically the same as for the nuclear plant. Heat is also lost when the steam from the turbine is condensed. The thermal efficiency in a coal plant is usually somewhat higher than in a nuclear plant; efficiencies above 40% are typical in new coal plants.

Plants burning oil or natural gas are quite similar to coal plants, with carbon and oxygen again combining to release energy. As with coal, the CO_2 is discharged to the atmosphere.

Chapter 5

RADIATION AND HEALTH EFFECTS

What Is Radiation?

Although there are many similarities between nuclear and fossil plants, there are also several unique differences; one is that there are much larger amounts of radiation associated with nuclear than fossil units. We will explore radiation in this chapter.

Everyone has heard of radiation, but what is it? There are many kinds, but our discussion will center on four types:

- the electrons and neutrons discussed in Chapter 2,
- the "alpha particle," which is the nucleus of the helium atom (two protons and two neutrons, as shown in Fig. 2), and
- gamma rays.

Gamma rays are tiny bundles or packets of energy that are weightless. They are very similar to X-rays and the bundles of energy that make up ordinary sunlight. Gamma rays and X-rays have more energy than a sunlight bundle, and this extra energy makes them invisible to us. Thus, the radiation of importance in this book consists primarily of three particles (electrons, neutrons, and alpha particles) and little packets of energy (gamma rays).

Where Does Radiation Come from?

Radiation is natural; life evolved in a sea of radiation. It is in our bodies; our food; and in the soil, water, and air. The radiation level now is about one-tenth of what it was when life began billions of years ago. Sunlight is radiation.

There are two sources of radiation that are important to us in this discussion: natural and man-made. From nature, each of us receives radiation termed "background radiation." It comes from the sun and outer space; from materials such as uranium and thorium in the soil and in our buildings; and from radon, a radioactive gas found in the soil which leaks into our homes. Everyone on earth receives this type of radiation. It is mostly alpha and gamma radiation. It is invisible, although it is very easy to detect and measure with instruments or even photographic film. The amount we each receive varies, depending primarily on where we live. Much of the radiation that strikes a person's body simply passes through without "touching" us; it has no effect. However, a small amount is absorbed and may have an effect. The terms used by scientists to express quantities of absorbed radiation are confusing. Therefore, we will discuss radiation in terms of the amount the average American absorbs each year and call that amount *one year of background radiation*. For the reader who wishes to refer to other books, this amount of radiation is defined as 3 mSv (milliSieverts) per year or 300 mrem (millirems) per year.

Man-made radiation comes primarily from medical X-rays. A small amount comes from various devices such as nuclear reactors and smoke detectors. Our interest will center on radiation produced in the reactors (by fissioning uranium and plutonium nuclei). There are three categories. First, when a uranium or plutonium nucleus captures a neutron and splits apart (fissions), electrons, gamma rays, and neutrons are emitted instantaneously. The second category comes from the fragments into which the uranium or the plutonium nuclei split. Nearly all of these so-called “fission fragments” emit radiation. Some release their radiation almost immediately; others release theirs over a period of hundreds or thousands of years. Most of this radiation consists of electrons and gamma rays.

The third category of radiation related to fission comes from ordinary materials that absorb neutrons and subsequently emit radiation. For example, there is a relatively common metal called cobalt; it is important in making inks, paints, and stainless steel. If we put a piece of cobalt in a nuclear reactor, many of its nuclei will absorb neutrons. These nuclei will each eventually emit one electron and two gamma rays, and we say the cobalt has become *radioactive*. This is how the radioactive cobalt used in hospitals to treat cancer is made. Many materials can be made radioactive by exposing them to neutrons. The iron used in the structural supports inside reactors becomes radioactive. Most radioactive materials made this way will emit electrons and gamma rays, but some will emit neutrons.

What Are the Health Effects of Large Amounts of Radiation?

Much radiation is beneficial to us. Over 100 million Americans have a total of about a billion X-rays each year; 10 million Americans are diagnosed using radioactive medicine yearly; and a quarter million cancer patients are treated with radiation each year — many have their cancers cured. The medical use of radiation saves thousands of lives every year.

Some radiation has no detectable effect on us. For example, there is always radioactive potassium (element 19) in the food we eat, and some of this is stored in our bodies. About 18 million potassium nuclei disintegrate in the body of a typical adult and emit radiation every hour. The released radiation strikes billions of our cells every hour. It does no apparent harm. About an equal number of radioactive carbon nuclei emit electrons in our body.

However, many scientists believe that very large amounts of radiation to prospective parents can genetically harm their children and grandchildren; large doses of radiation have been shown to produce harmful mutations in all plant and animal systems studied. Further, very large doses can cause sickness or death. Let us examine these effects individually.

About 70 years ago, scientists discovered that high doses of radiation damage both the chromosomes and their genes in fruit flies; this damage causes mutations and abnormal genetic effects in the offspring. The scientists assumed that similar results will occur in humans. However, no such effects have been found. Our main source of information comes from studies of children of the survivors of atomic bomb blasts in World War II (1945). The bomb released at Hiroshima, Japan (made of U-235) and the one at Nagasaki, Japan (made of plutonium) derived their tremendous energy from nuclear fission. They emitted huge quantities of radiation. *However, extensive studies of 30,000 children born to parents who were exposed to radiation in the blasts have found no evidence of genetic effects.* This result is not surprising; the frequency of mutations is so low that they would likely be detectable only in a much larger group of children. In addition, the parents would have had to receive considerably more radiation than did the bomb survivors. It should also be noted that studies of the Chernobyl accident discussed below have also found no evidence of decreased fertility or of increases in birth defects in the surrounding population.

The situation is different with regard to non-genetic effects; if the body absorbs very large amounts of radiation in a few minutes or hours, sickness or death can result. These are termed *acute* doses — doses received in a short time period. Our main source of information on these effects also comes from the 1945 explosions. About 400,000 civilians were present in Hiroshima and Nagasaki at the time of the explosions; 175,000 of them died instantly or within four months. Most of the deaths (80%) were due to blast and heat, but the other 20% (35,000) were caused by radiation, as stated earlier. Information has also come from medical personnel who use X-ray machines and from patients treated by radiation. There have also been a few laboratory accidents in which people received large, acute doses of radiation.

From all the evidence, we know that about half the people who absorb 1,500 times as much radiation in a few minutes as we normally do from background in a full year will die within a month. An acute dose equal to about 650 years of background radiation will cause sickness, but nearly all the people will recover; there will be almost no early deaths if proper medical care is received. We also know that acute doses of radiation below 650 years of background radiation will increase the chance of cancer. Information on the latter effects also comes from bomb survivors and is discussed in the next section below.

Lower doses of radiation received over an extended period of time will also cause cancer. Our primary information on this effect comes from studies of workers who used radium to make luminous watch dials; radium is radioactive and emits alphas, electrons, and gamma rays. From 1915 to about 1960, thousands of (mostly) young women were hired in factories to paint radium solutions on dials, and they did this with tiny paintbrushes. Unfortunately, they sharpened the tips of the brushes by touching the brushes to their tongues. Radium entered their bodies, and about 2% (85 out of about 4,000) of the painters died from bone cancer many years later. No one who started work after 1925 died of radiation-induced cancer; beginning in that year, workers were forbidden from touching the brushes to their tongues.

What Are the Health Effects of Small Amounts of Radiation?

The amount of radiation that the public receives from nuclear power plant operation is *thousands of times below the levels discussed above* that cause sickness or death. It is also *several hundred times below background radiation levels.* During normal operation, the amount of radiation leaving a plant site is so small it is almost immeasurable. Releases during accidents are also minimal. There has been only one major accident in the United States in nuclear power's 45-year history — at Three Mile Island (TMI) in Pennsylvania in 1979. No member of the public received more than the equivalent of one-third year of background radiation from it; at worst, not more than one person will die from it. Expressed differently — the average person living near the accident site received less radiation in 1979 than every person in Denver did that same year. This was because the background level in Denver is higher than that in Pennsylvania. Denver has more uranium in its soil. It is also at a higher elevation than the TMI area, which allows more cosmic radiation. The people in Denver receive this high level of background radiation every year of their lives, of course.

What do we know about the health effects of small quantities of radiation? Fortunately, quite a bit. First, no study has ever shown a harmful effect of acute doses less than 65 times as much radiation as we normally receive from background in a full year. Scientists at the *Radiation Effects Research Foundation* in Hiroshima, Japan have studied about 86,000 Japanese bomb survivors since 1950. They found that some survivors who received large doses of radiation developed cancer later in life. However, they have found no meaningful evidence of cancer formation among the 75,000 survivors who received 65 years of background radiation or less. There were cancer deaths, but they were so few that the scientists couldn't tell whether any resulted from bomb radiation. In contrast, among a group of 6,308 people who received larger doses (between 65 and 165 years of background radiation), there were enough deaths that the scientists could conclude many were caused by bomb radiation. There were 659 deaths between 1950 and 1990, whereas only 567 deaths would have been expected if the people had not been exposed to bomb radiation. Thus, it appears that bomb radiation caused about 92 deaths; this is also evidence that harmful effects become observable somewhere in the range of 65 to 165 years of background radiation.

There is less certainty about the effects of acute doses of radiation below 65 years of background radiation. Many genetic and cancer specialists believe that, if a large amount of radiation will cause 100 cancer deaths, half that amount will cause 50, one fourth the amount will cause 25, and so on. They have carried this extrapolation down to zero radiation exposure and believe that any amount of radiation is harmful, no matter how small. Their theory is called the *linear, no-threshold theory,* and formal support for the theory has come from a committee established by the National Academies of Science and Engineering and the Institute of Medicine which issued a report in 1990 "Biological Effects of Ionizing Radiation V" (BEIR V). The theory is accepted by the National Council on Radiation Protection and Measurements (NCRP), a Congressionally chartered non-profit organization that helps advise the government on radiation safety. U.S. governmental agencies use the theory to estimate the cancer deaths that will result from radiation accidents.

However, the BEIR V report is being updated, and a current Prepublication Copy/Uncorrected Proofs of BEIR VII-Phase 2, June 2005 has been printed. The latter is not in final, official form. However, it tentatively reduces the predicted cancer deaths caused by a dose of radiation below 33 years of background radiation. The reduction is about one-third, and it is accomplished by applying a correction factor. The theory itself is retained. If BEIR VII becomes officially accepted, governmental agencies will be expected to use this one-third reduction in estimating cancer deaths from radiation accidents.

The reduction of predicted cancer deaths from small radiation exposures in BEIR VII is supported by other studies, although some investigators call for a more drastic reduction. For example, France's Académie des Sciences and Académie Nationale de Médecine released a report in March 2005 stating that the use of the linear, no-threshold theory could greatly overestimate the risks of small amounts of radiation. It expressed concern that this may have a detrimental effect on public health by discouraging physicians and patients from performing important radiological examinations such as a mammography or a chest X-ray. The Academies believe that recent, basic radiobiological data indicate very low doses have either: a) effects far below what the theory would indicate, or b) no harmful effects at all. It advises that use of the theory for assessing risks of radiation below about seven times the background radiation we typically receive in a year is unjustified and should be discouraged. (Note: The radiation from a single chest X-ray is typically about 5% to 10% of our yearly background dose.)

A second group supporting reduced predictions of cancer-death risk is the United Nations Scientific Committee on the Effects of Atomic Radiation. It issued a report in 1994 that officially declared its belief that low levels of radiation exposure are not only not harmful but actually beneficial. In the words of a former chair of the Committee, the report "dispels the common notion that even the smallest dose of radiation is harmful."

Thus, there is not agreement on the precise effects of exposures to small amounts of radiation. However, there is no doubt that they are very small, and many scientists around the world believe them to be beneficial rather than harmful.

What can we conclude about the practical effects of exposure to small amounts of radiation such as members of the public would receive from a nuclear power plant accident? Our best knowledge comes from a study of the Chernobyl accident in Ukraine in 1986. As described earlier, the reactor caught fire and spewed radioactive material into the atmosphere for days. The reactor was of an extremely poor design found only in the former USSR, and a more devastating nuclear power plant accident is almost impossible to imagine. 200,000 emergency and recovery operation workers received excessive amounts of radiation during the 1986-87 period, with those from Russia receiving an average of 35 years of background radiation. Five million people currently living in areas of Belarus, Russia, and Ukraine received radiation exposure in lower doses over a period of several years, and many in Europe received still lower doses. Tens of thousands of deaths were predicted from radiation exposure.

However, a new study released in September 2005 predicts a much smaller total of 9,000 to 10,000 eventual deaths from radiation. This study was performed by an international team of more than 100 scientists from eight United Nations agencies including the World Health Organization and the International Atomic Energy Agency. An estimated 2,200 of the 9,000 to 10,000 predicted deaths are expected from among the emergency and recovery operation workers, with the remaining approximately 7,000 to 8,000 coming from among the general public. Predicted deaths among the public will typically result from cancer many years after the accident.

Even so, as of 2005, fewer than 50 known deaths have been attributed to radiation from the accident.

It should be noted that the linear, no-threshold theory was used in arriving at the figures in the UN report. If the BEIR VII correction factor were applied, the total predicted deaths would fall to the 6,000-7,000 range. Moreover, many studies have shown that a given amount of radiation delivered at a high rate in a single exposure causes up to ten times as much biological damage as the same amount of radiation delivered at a lower rate over a longer period of time. Most cells in our bodies have internal repair systems, and many tissues can replace damaged cells at the same time they are being irradiated. Since most individuals involved at Chernobyl received their radiation exposures over several months, application of this factor would reduce the Chernobyl casualty predictions considerably further.

Why Do People Have an Excessive Fear of Radiation?

Contrary to the above evidence, however, many people have an excessive fear of radiation. There are many reasons for this. For one, there is a legacy from the atomic bomb. This devastating weapon was made possible by “atomic energy” and radiation, but most people do not realize that most Japanese casualties resulted primarily from heat and blast rather than radiation — reason enough to fear the bomb, certainly, but that is a different topic.

In addition, the mass media frequently distort the significance of radiation. A harmless radiation release from a nuclear plant will frequently receive much more publicity than an accident involving several deaths in another industry. For example, The Christian Science Monitor referred to nuclear power a few years ago as “the most dangerous technology ever devised”, yet, less than 50 people worldwide are known to have died from nuclear power radiation. Separately, the media frequently refer to “deadly” radiation although no deaths occur; it rarely refers to “deadly” electricity although many people die yearly from accidental electrocution or to “deadly” water although many people drown.

Still another reason may be that, when an accident occurs, grossly unrealistic casualty figures can be headlined by the media, whereas equal publicity is seldom given to corrected figures.

Finally, people tend to be much more fearful of a single event in which a large number of people are killed than many small events in which the same total number dies. For example, there would likely be much more public outcry if two or three airliners crashed and killed 1,000 people in the U.S. this year than there is when approximately 40,000 people die yearly a few at a time from auto-related accidents. And people may not yet be comfortable with the concept of radiation. Some fear it because they can't "see, feel, or smell it", not remembering that the same situation exists with respect to the air we breath.

Summary

In summary, we must treat radiation with respect. At the high levels associated with nuclear weapons, it can be quite harmful. At the low levels associated with nuclear power, its effects are uncertain but certainly small and possibly even beneficial. Low levels are not a cause for excessive or abnormal fears.

Comparison with Alternate Electricity Sources

Radiation is not involved in making electricity from fossil fuels. However, people living near coal plants typically receive 100 times as much radiation as those living near a nuclear plant. This is because coal has uranium, thorium, and other radioactive materials mixed in with it. When the coal is burned, the radioactive materials go out the smokestack; a relatively harmless amount of radiation is spread downwind from the stack.

Harmful Results of This Fear of Radiation

The exaggerated fear the public has of radiation is harmful in many ways. It has led to greatly increased costs for nuclear electricity. It apparently led to tens of thousands of unneeded abortions following the Chernobyl accident. It prevents widespread acceptance of food sterilized by radiation; experts believe this sterilization could prevent hundreds or thousands of deaths each year in the United States caused by food contamination.

This exaggerated fear will also contribute to widespread public alarm if terrorist groups succeed in introducing “dirty” bombs in the U.S. Radiation levels received by the public would likely be very low, and depending on the type of radiation, the anticipated alarm would probably be largely unwarranted. This author believes that organizations such as the National Council on Radiation Protection and Measurements and the Department of Homeland Security should be aggressive in educating the public on the minimal effects of radiation before potentially chaotic conditions develop.

Chapter 6

NUCLEAR POWER PLANT SAFETY

As stated previously, the radiation released from a nuclear plant is small. However, there are large amounts of radioactive materials within the reactor. This necessitates that engineers design the plant carefully for worker and public safety. Let us examine that topic in this chapter.

As noted, the fragments resulting from fissioning the uranium and plutonium nuclei are radioactive; some emit radiation instantly, while others release their radiation over a period of minutes or years. During operation and for a considerable period after reactor shutdown, this radioactivity level is very intense. The uranium and plutonium in a reactor are located at the center in a volume about 12 feet high and 15 feet or larger in diameter; this is called the "core" of the reactor. An individual standing at the edge of the core during reactor operation would receive a lethal dose in a fraction of a second. (It is impossible to stand there.) If a large fraction of the material could somehow escape from the reactor, it could be harmful to the public as happened at Chernobyl.

The structural materials inside the reactor also become radioactive when they absorb neutrons; however, they are a much smaller source of radiation than the fuel and will be ignored in this book.

Plant workers are protected against the radioactivity in the core by massive shields made of materials such as lead, iron, and concrete. These materials surround the core and absorb most of the radiation. They are shown in Fig. 5.

There is a scenario by which radioactive material might escape from the reactor. The fuel rods that make up the core consist of the uranium, plutonium, and fission fragments in solid form; each rod is also clad or coated with an alloy of the metal zirconium. Very little radioactive material can escape as long as the rods are in this form. However, during reactor operation, heat is generated in each rod, and it is continuously removed by cooling water. If the water flow were to be interrupted, the temperature of the rods would rise; if the reactor weren't shut down, the rods might melt. The molten fuel could then melt its way through piping and walls and might reach the outside of the building that surrounds the reactor. Radioactive material could be blown off the site by the wind.

Another possibility is for the heat generation rate in the rods to increase beyond the ability of the water to remove the heat. Again, melting could occur.

Fuel rod melting could also take place even if the reactor is shut down. This is because heat is generated by the radiation coming from the fission fragments; as noted earlier, some of this radiation is not emitted until days or even years after fission takes place. Melting would take place more slowly with the reactor shutdown, but it would still be a possibility, especially in the first few hours after shutdown.

Consequently, the focus of nuclear power plant safety is simply: a) to keep the reactor running at a steady level while in operation, and b) to keep adequate water flowing over the fuel rods so they stay cool and solid, both during operation and after shutdown. Attention is also given to preventing the release of radioactive material outside the plant boundary even if fuel melting should somehow occur.

The approach taken to assure plant safety is called *defense-in-depth:* several consecutive safety features are provided for important functions rather than just single ones. For example, to protect against loss of water flow and subsequent fuel melting,

- High-quality water pumps are used,
- Backup pumps and several supplies of water are installed to provide cooling in case the regular pumps or the normal water supply fail for some reason,
- Because the pumps are driven by electric motors, several sources of electricity are provided. One source is the plant itself. If the plant shuts down, electricity can be obtained from at least two separate sources outside the plant. If a hurricane destroys the power lines from both offsite sources, electricity is obtained from an emergency, diesel-motor-operated electrical generator located on the plant site. This generator is always housed in a bunker built to withstand storms, earthquakes, floods, fires, and so on. If that generator fails, there is a second and sometimes a third that can be called upon.
- In some newer plants, cooling water will be stored in tanks where it can flow by gravity (in the event of total pump failure) and provide cooling for several hours while the pumps are being repaired.

The entire plant is designed with this defense-in-depth concept in mind; there is backup instrumentation; there are multiple shutdown systems; there are multiple fire barriers; and so on. Duplicate safety systems are designed so that no common component could cause both to fail.

However, engineers recognized that failures can occur even in the best-designed plants; the possibility of rod melting is not ignored. Several physical barriers are provided to prevent the spread of radioactive material beyond the plant in the event of melting. These include the cladding around the fuel, which is made of a high-melting-point material, and a several-inch-thick steel vessel in which the core is located. Each reactor is further enclosed in a building designed to contain any radioactive material that might escape from the reactor. These buildings or domes are airtight and have several-feet-thick walls made of steel-reinforced concrete; they are designed to protect the reactor against tornadoes with 300 mile-per-hour winds, earthquakes, direct hits by large aircraft, and so on. These domes are familiar structures at plant sites. The barriers for a representative pressurized-water-reactor plant are shown in Fig. 13.

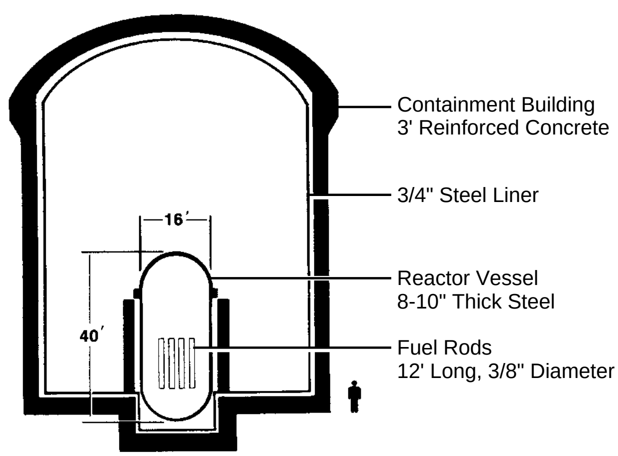

Figure 13: Pressurized-Water-Reactor Containment Barriers
(Credit: Westinghouse Electric Company)

Plant operation is equally important to design. Quality personnel are employed, and they receive extensive and continuing training. The reactor operators must each pass repeated, periodic exams monitored by the U.S. Nuclear Regulatory Commission and be licensed continuously by that agency.

The effectiveness of our nuclear power plant safety efforts can be shown by citing our actual experience. In the 45 years of commercial nuclear power plant operation in the United States involving about 120 reactors, there has been only one major accident — at the Three Mile Island plant in Pennsylvania in 1979. The reactor was destroyed. However, as stated earlier, the amount of radiation released from the plant was so small that no member of the public was harmed by it.

Both industry and the federal government deserve credit for this superb record. Industrial designers have incorporated many safety features in their plants. Utility organizations have established competent operating groups and have set up a strong organization (the Institute for Nuclear Power Operations) to continuously improve their operation. The Congress formed the Nuclear Regulatory Commission (NRC) to establish and enforce safety standards for design, construction, training, and operation throughout the entire industry.

The majority of the plants that have been built worldwide have been based on American designs and safety standards. There have been no accidents in any of these plants where members of the public have been harmed. Many other non-U.S. designs have been equally safe.

The only major accident in nuclear power's 45-year history, besides that at Three Mile Island, occurred at Chernobyl. As stated previously, the reactor failed catastrophically; much of the radioactivity in the rods was released outside the plant as airborne dust — its most dangerous form. A low level of radiation was spread over parts of the former Soviet Union and several European countries; millions of people were exposed to the radiation. It is hard to imagine a worse nuclear plant accident.

That reactor and similar ones built in the former Soviet Union are of a unique design; they are much inferior to those used in most power plants throughout the world. For example, if an American-type reactor loses its cooling water due to an accident, it shuts down; a Chernobyl-type reactor will “speed up.” If an American pressurized water reactor heats up and the cooling water boils, it tends to shut down; in the Chernobyl type, the reactor speeds up when the water begins to boil. Chernobyl-type reactors are unstable, and an extremely dangerous safety problem can exist when one of them is at a low power level. The Chernobyl reactor was at such a level when the accident occurred. American industry would not design such a reactor. The Nuclear Regulatory Commission would not allow it to be built in the United States.

The plant manager, who had no nuclear training, was also a major cause of the Chernobyl accident. In his desire to run an experiment on the turbine and generator, he totally ignored the advice of the reactor staff. He further insisted the reactor be run at the low level where it was unstable and unsafe. Finally, he ordered that several control devices be manually disconnected; these devices automatically shut the reactor down when unsafe situations arise. The results were predictable; it was not an accident. Rather, it was a predictable event. The reactor was destroyed. For a host of reasons, American industry would not operate a reactor in such a foolish, irresponsible fashion, and the NRC certainly would not allow it.

The Chernobyl reactor was not enclosed in a containment building like U.S. reactors are. However, this may not have mattered much. There was a very unique steam explosion when the accident occurred, and normal containment buildings are not designed to withstand such exceptional explosions.

Some Chernobyl-type reactors still operate in and around Russia, and modifications have been made to improve their safety, although they do not reach American safety levels. That type of reactor is no longer built, and existing units are slowly being phased out. Current Russian models are much more similar to American designs, and they are also built with suitable containment buildings.

Sabotage and Terrorism at Nuclear Power Plants

You may wonder if it would be easy for a saboteur or terrorist group to damage a power plant and cause radioactive material to be released. The answer is "No".

Several steps are taken to protect against sabotage. For example,

- All new employees must pass a variety of tests and checks. These include drug and alcohol screening tests and psychological evaluation. They also include a check of employment records, criminal records through the FBI, and credit histories. All plants have a formal program under which the behavior of all employees is monitored continually; the aim is to detect any unusual or erratic behavior.
- Access to important areas of nuclear plants is controlled by security officers who search entering vehicles and people. Individuals entering a plant must pass through metal and explosive detectors.
- All plants have well-armed and highly trained security forces that are routinely drilled and tested.
- Plant design automatically helps protect against sabotage. The defense-in-depth design approach provides backup systems that require multiple failures before damage occurs.

Terrorist organizations would also have great difficulty in damaging a plant enough to harm public health. For example,

- The NRC requires that all plants have massive vehicle barriers to protect against truck bombs. The barriers also keep intruders from entering the plant.

- The NRC continuously consults the FBI and other intelligence agencies and continually evaluates potential threats. One such threat under study involves the spent fuel pools at power plants. After the spent fuel rods are discharged, they are stored in a deep, underground pool of water adjacent to the reactor/containment building for a year or more; the rods continue to emit heat, and cooling is required to prevent overheating, melting, and potential failure of the fuel cladding by burning. Fire would allow radioactive material to escape from the pool building into the atmosphere. It has been postulated that a terrorist group might be able to breach the steel-reinforced concrete walls of a pool, cause drainage of the cooling water, and prevent cooling from being restored for several hours — time for the rods to heat and catch fire. This author cannot prejudge the results of the study, but the possibility of draining an underground pool and preventing the restoration of cooling at a heavily-guarded plant does not seem likely.

In September 2002, 19 members of the National Academy of Engineering released a report on possible terrorist attacks at nuclear power plants. Most of the members were retired, all had had extensive experience in the nuclear field, and all had held high-level, responsible positions. The following is quoted from the report: "We read that airplanes can fly through the reinforced, steel-lined 1.5-meter-thick concrete walls surrounding a nuclear reactor (Author note: The dome we see at nuclear plants.) and inevitably cause a meltdown resulting in 'tens of thousands of deaths' ... . However, there seems to be no credible way to achieve that result. No airplane, regardless of size, can fly through such a wall. This has been calculated in detail and tested … . And inside the containment wall are additional walls of concrete and steel protecting the reactor."

They also stated: "Is it possible to cause a nuclear reactor core to melt down some way? Answer: Yes, as happened at Three Mile Island in 1979. … Suppose it happens through terrorist action; what then? … Answer: Even if the TMI containment (the dome) had been severely breached when the core melted there, little radioactivity would have escaped. Few, if any, persons would have been harmed."

And also: "To test how far the 10 to 20 tons of molten reactor core penetrated the five inch thick bottom of the reactor vessel at TMI, samples were obtained and exampled. It was found that the molten core mass penetrated only about 0.2 inches. This result confirmed tests in Germany and Idaho that the "China syndrome" is not a credible possibility.

Thus, it would be very difficult for a saboteur or terrorist group to harm the public by damaging a reactor. One cannot say it is impossible, but this author has reasonable confidence that it should not be a major worry.

Summary

In summary, nuclear power is safe; no member of the public has ever been killed from the operation of American-type plants. Chernobyl-type plants cannot be built or operated in the United States; all Chernobyl-type plants will likely be phased out within a few years.

It appears that no deaths will result worldwide from nuclear power's first 45 years of history — except at Chernobyl. This is a truly phenomenal safety record for a new technology.

Comparison with Alternate Electricity Sources

A document issued by the Natural Resources Defense Council (NRDC) in May 1996 helps provide a comparison with other energy sources. The NRDC analyzed data obtained primarily from a Harvard School of Public Health study reported by Dr. Douglas W. Dockery and co-workers and an American Cancer Society-Harvard Medical School study reported by Professor C. Arden Pope and co-workers. Both studies dealt with the effect on our health from tiny particles of matter in the air we breathe. Burning fossil fuels including coal, natural gas, oil, diesel fuel, gasoline, and wood is the largest single source of these small particles. Coal-fired power plants are the worst offenders by far. The NRDC estimated that approximately 64,000 people may have been dying prematurely each year in 239 U.S. metropolitan areas due to the particles. The latter cause heart and lung disease, and lives are shortened by an average of one to two years in the most polluted areas. One-third of the deaths were estimated to result from discharges from electricity generating power plants.

The particles are very small; some have diameters of 2.5 microns, which means that 10,000 side-by-side would be shorter than an inch. Thirty side-by-side would be about as wide as a human hair.

The NRDC believed tens of thousands of premature deaths could be prevented yearly by reducing particulate emissions. It recommended switching from coal to natural gas for generating electricity; natural gas plants emit only a fraction of the particles that coal plants emit.

Nuclear plants would reduce those premature deaths even more; *nuclear plants do not emit such particles.*

The U.S. Environmental Protection Agency (EPA) set standards in 1997 to restrict the emission of the larger of these particles. However, according to EPA estimates, particle pollution still killed about 20,000 Americans yearly and hospitalized many more. EPA increased the restrictions slightly in 2006; but 20 of 22 members of the EPA's Clean Air Scientific Advisory Council and the American Medical Association urged significantly tighter restrictions. Worldwide figures for yearly deaths are not available, but they are no doubt much higher than for the U.S. alone, considering the coal-burning air pollution in countries such as China and Poland. These numbers are much higher than those for the Chernobyl accident, even as horrendous as the latter are.

Nuclear power thus saves thousands of lives each year. Twenty percent of our electricity comes from nuclear energy; coal provides 50% but would likely provide 70% if not for nuclear power. Nuclear power has thus held down the amount of pollution from coal and saved lives accordingly. The data indicate that replacing all our coal plants with nuclear plants would save thousands of additional lives yearly.

It is interesting to note that wood, a renewable energy resource, presents considerable health hazards. Residential wood burning releases more of some kinds of particles to the atmosphere than do coal-burning power plants. Aspen, Colorado and Klamath Falls, Oregon recently failed to meet EPA clean-air standards because of wood smoke.

There are other risks related to power production. For example, 15,000 people died when the Gujarati hydroelectric dam in India failed in 1979. Close to 90,000 miners were killed in coal mine accidents in the United States in the last century, and 31 were killed in the first five month of 2006. 1,440 people were killed in natural gas accidents (fire, explosion) between 1969 and 1986 according to a recent study, and 2,070 people were killed in oil accidents (refinery fires, transportation) in the same period.

Chapter 7

HIGH-LEVEL WASTES

As with any system, nuclear plants have wastes that must be discarded; some of this waste involves radioactivity. In some materials, the level of radioactivity is trivial; the materials are harmless and can be discharged to rivers or to the atmosphere.

Other material is too radioactive to discharge in that manner but is only moderately hazardous. It is buried underground along with similar wastes from hospitals and radiochemical laboratories. Because this material (called low-level waste) does not represent a health hazard when properly disposed of, it will not be discussed further.

A third class of wastes, the used or “spent” fuel rods from a nuclear reactor, presents a greater challenge; the rods become intensely radioactive during their three- to five-year residence in the reactor. They must be disposed of by long term isolation after they are discharged. Because of its high radioactivity, the material in the spent fuel is termed *high-level waste* or *HLW*.

HLW Disposal Methods

When spent fuel rods are discharged from a reactor, they are first stored in water-filled concrete pools similar to deep swimming pools at the reactor site. This is a satisfactory storage method for several years, and the rods can later be moved to above-ground, on-site, air-cooled concrete casks. These casks provide suitable storage for many decades or possibly centuries, but a different method is required for longer-term storage.

Many methods for long-term disposal of HLW have been suggested. They include burying it 100 feet or so below the ocean floor where it would be isolated from mankind; burying it near the South Pole where (since it emits heat) it would melt its way down through several thousand feet of ice; and shooting it into outer space on rockets. However, the best approach appears to be to bury it beneath the surface of the earth in a stable geological formation. Burial could be in volcanic, salt, granite, or other layers of material. Most nations are pursuing this approach. Sweden is considering granite layers, Germany salt layers, and the United States volcanic layers at Yucca Mountain (YM) in Nevada. Congress passed a law in 1982 requiring the U.S. Department of Energy (DOE) to handle the burial of HLW from commercial nuclear plants. Burial was to begin in 1998, but the program is a decade behind schedule. DOE may be required to provide temporary storage in above-ground casks before burial begins.

Composition of HLW

Spent fuel material inside the cladding is composed typically of 95% uranium, 1% plutonium, 3.65% fission fragments, and 0.35% of other elements that are heavier than uranium. There is also oxygen in the material, but it is unimportant in our discussion.

As you will recall, uranium occurs in nature, and fission fragments are formed when nuclei split during fissioning. You will also recall that plutonium is made when U-238 nuclei capture neutrons; plutonium, in turn, will usually fission when it captures a neutron. However, sometimes it will simply absorb the neutron and form the next-heavier element, americium. The latter, in turn, can absorb a neutron and form the still-heavier element, curium, and so on. This process — the conversion of one element into another — is called "transmutation." There are about a dozen of these man-made, heavier-than-uranium elements; plutonium is one of them. They are called transuranic elements. These elements are similar to those in the periodic table; all have nuclei composed of protons and neutrons that are surrounded by electrons. However, none exists in nature beyond trace amounts. All will fission like U-235.

Hazards of HLW

The composition of the spent fuel (uranium, fission fragments, plutonium, and other transuranic elements) determines the difficulty of HLW disposal. Uranium is only a relatively small health hazard and can be buried with little concern.

The fission fragments are intensely radioactive when formed and when the rods are discharged from the reactor. However, there is something special about all radioactive substances — *they all lose their radioactivity as time passes.* This makes it easier to dispose of the fragments. Let us examine this special feature.

Natural Decrease of Radioactivity Levels

Assume that a radioactive material is giving off 2,000 particles of radiation each minute. Now, if we watch it, we will find that the level will fall in half (to 1,000 particles per minute) eventually; we say the radiation level *decays.* Maybe it took four years for the level to fall in half. Let us call that four years the *half-life* of the material. If we keep watching, we will find that the level will fall in half again or to 500 particles per minute in another four years. In four more years, the level will fall to 250 particles per minute. And so on. In 10 half-lives or 40 years, the level will decrease by a factor of 2 x 2 x 2 … (10 times) = 1,024 or to about two particles per minute.

Note: When many materials decay by radiation emission, they become new elements. A new element may be stable (that is, not radioactive) and will exist forever, or it may be radioactive. If it is radioactive, it, too, will decay. This process will continue until a stable element is reached. This explains why transuranic elements exist only in trace amounts. Many existed when the earth was formed, but they were all radioactive. Consequently, all have decayed into new elements among the 90 stable elements in the periodic table. The main isotope of plutonium has a half-life of 24,600 years, but the earth is a few billion years old. Therefore, for all practical purposes, natural plutonium does not exist. (Traces exist from a process that will not be discussed here and from U.S. and USSR weapons testing.)

Different fission fragments have different half-lives. Some have half-lives of fractions of seconds; others have half-lives of a few days or as much as thousands of years. However, all the fission fragments together have an effective half-life of about 30 years; their activity will decrease by a factor of about 1,000 in 300 years. Their total activity would not be a serious health hazard at that time. Further, it would not be difficult to develop practical burial methods to isolate these materials for that period of time. Two fission fragments, technetium-99 and iodine-129, have half-lives over 200,000 and 15,000,000 years, respectively, but they are present only in very small quantities.

Hazards of Plutonium and Other Transuranic Elements

The third component of HLW, plutonium, presents a more serious disposal problem. As stated previously, the most plentiful isotope of plutonium, Pu-239, has a half-life of 24,600 years, and it is a health hazard under some conditions.

Plutonium decays by emitting alpha particles; they travel less than 1.5 inches in air, and they will not penetrate the skin. Therefore, plutonium is not a hazard as long as it remains outside the body.

If plutonium gets inside the body, its alpha particles lose all their energy in a very short distance; the particles can be very damaging to sensitive tissues nearby. In significant quantities, plutonium can cause injury if it remains within the body, including cancer many years later.

Plutonium can enter the body through the mouth (food, water), nose (breathing airborne particles), or cuts and wounds. Studies indicate that small quantities taken in through the *mouth* pass through the digestive tract with very little being absorbed. Some Japanese scientists state publicly that solutions of plutonium can be drunk without harm. Bernard L. Cohen, Emeritus Professor of Physics and Radiation Health at the University of Pittsburgh, has offered to eat about a gram of plutonium to demonstrate that eating it is no more dangerous than eating the same quantity of caffeine. Plutonium and radium act similarly inside the body; plutonium is about one-sixth as poisonous as radium on a weight basis. It was noted earlier that only about 2% of the radium-dial painters who ingested large quantities of radium died later from cancer.

Studies on dogs indicate that *breathing* airborne plutonium can be serious; very small amounts administered to beagles consistently caused lung cancer. However, these studies do not seem to apply to humans.

Humans appear to be less harmed by plutonium than animals, although human data are limited. Many workers in the Manhattan ("Atomic Bomb") Project in the 1940s got plutonium into their nostrils; however, they apparently developed no more lung cancer than the rest of the population. Twenty-six men inhaled plutonium (or absorbed it through cuts) at the Los Alamos National Laboratory in the mid-1940s. At their examination in the early 1990s, seven of the 26 had died; this is less than the 13 deaths that would have been expected normally. Plutonium still showed up in the urine of the 19 survivors and always will. Separately, eighteen seriously ill hospital patients were injected with small doses of plutonium in the 1945-1947 period; five of the subjects were still alive almost 30 years later, and no ill effects of the plutonium were observed. Thus, plutonium in large quantities will surely cause some cancer deaths just as radium does; however, *there has never been a known case of death resulting from plutonium.*

Because of plutonium's health effects, HLW containing large amounts of the element must be isolated from humans. One effective way to do this is to bury the waste deep underground.

Many of the other transuranic elements also have long half-lives and emit potentially harmful radiation. In particular, neptunium-237 has a half-life of 2,140,000 years and americium-243 has a half-life of 7,370 years; both are alpha emitters like plutonium. Although small, the quantities of such transuranic elements are large enough to warrant disposal methods similar to those for plutonium.

Burial of HLW

As stated earlier, current U.S. plans are to bury the HLW underground, and Congress assigned the Department of Energy the responsibility for: a) accepting the spent fuel from nuclear power plants by January 1998, b) building an underground disposal facility, and c) accomplishing the burial. The DOE is currently studying Yucca Mountain to show that that site is suitable for HLW burial, and present planning calls for the spent fuel elements to be loaded into massive concrete and steel casks that will be buried about 1,000 feet below the surface of the Mountain. A 1990 report of the National Research Council (which is administered by the most prestigious scientific and engineering bodies in the United States) states:

> "There is a worldwide scientific consensus that deep geological disposal, the approach being followed in the United States, is the best option for disposing of high-level radioactive waste (HLW). *There is no scientific or technical reason to think that a satisfactory geological repository cannot be built*." (Emphasis added by this author.)

This DOE burial program is behind schedule for many reasons. DOE has had difficulty developing a convincing case that YM is indeed a satisfactory storage site; this case must meet U.S. Nuclear Regulatory Commission (NRC) requirements before the latter will issue a permit to begin waste burial. Political leaders in Nevada do not want the wastes buried there — possibly because of the "not in my backyard" syndrome. It is also easy for any group opposed to burial or to the use of nuclear power in general to stall the program; delay is readily accomplished by challenges through our court system. These reasons have delayed the initiation of waste burial by a decade.

It is interesting to note that the plutonium formed in the ground in the natural reactor in Gabon has moved less than six feet from where it was formed 1.8 billion years ago; the plutonium lies loose in the ground, of course, in a tropical-rainfall region. Plutonium sticks strongly to soil with which it comes in contact.

Transportation of Spent Fuel Rods

The burial of HLW will obviously involve the shipment of spent fuel rods from power plants to the burial site. Many people ask: Are such shipments safe?

The handling of spent fuel is based on the defense-in-depth concept just as reactor safety is. As stated earlier, when spent rods are discharged from the reactor, they are first stored in water-filled concrete pools at the reactor site for several years.

The rods lose about 95% of their radioactivity in the first few years.

When the YM site is ready, the fuel rods will be shipped there in carefully designed, fabricated, and tested shipping containers. These massive containers are normally 15 to 20 feet long with foot-thick walls; they weigh 25 to 40 tons for highway shipment and up to 125 tons for rail shipment. (It may prove practical to use the same cask for shipping as for burial.)

The containers or “casks” must be designed to meet NRC requirements and be licensed by that agency. They must be able to withstand all of the following events, one after another:

- the equivalent of being dropped several hundred feet onto a hard surface,
- being immersed in a 1,475° F fire for 30 minutes, and
- being submersed under water for eight hours.

Engineers at Sandia National Laboratories have tested casks of this type extensively. In one example, a locomotive speeding at 80 miles per hour smashed broadside into a cask parked on the railroad track. The locomotive was demolished, but the cask suffered only negligible damage. No material escaped from the cask. In another example, a cask was mounted on a railway car that crashed into a concrete wall at 80 miles per hour. The cask was then surrounded by a fire that was hot enough to melt all the lead in the cask. Again, the cask received only minor overall damage. Another cask was dropped 2,000 feet onto packed ground as hard as concrete. It was traveling 235 miles per hour when it hit the ground, and it buried itself four and one-half feet deep. The only damage was to the paint on the surface.

Additional steps are to be taken to ensure transportation safety. For example, routes proposed for highway shipment will be submitted to the NRC for approval. Escorts and local community emergency agencies will be required, and they must be trained in physical protection of the shipment; at least two armed escorts will be required in heavily populated areas. The escorts must call the communication center every two hours. For highway shipments, the driver must be given special training in security procedures.

The National Conference of State Legislatures issued a report about ten years ago on transporting spent fuel. It stated that over 2,500 shipments of radioactive materials had been made, with no deaths or injuries due to any radiation-related cause. Most of the shipments were by truck, some were by rail. Since 2004, over 3,000 shipments have been successfully transported in the U.S.

Thus, our safety record in shipping radioactive material is outstanding; it should continue this way with spent fuel.

Waste Treatment in Other Countries

There is a significant difference between how we plan to dispose of HLW and how other nations do it. Instead of burying whole spent fuel rods, some nations (including Belgium, England, France, India, Japan, and Russia) intend to chemically process (dissolve) the rods and remove the uranium and plutonium. These metals will be reused in the reactor, and only the fission products and remaining transuranics will be buried. This approach will allow them to utilize the energy in the uranium and plutonium from the spent fuel. It will also mean that there will be much smaller quantities of waste to bury; the volume of the fission fragments and transuranic elements (other than plutonium) is only a small fraction of that of the unprocessed spent fuel rods.

It was also American policy to process chemically the rods during the administrations of Presidents Eisenhower, Kennedy, Johnson, and Nixon. However, dissolving the rods under the process used then and today leads to the presence of pure plutonium. Plutonium is relatively easy to handle, and it can be the major ingredient in atomic bombs. Officials in the Ford and Carter administrations in the 1970s became concerned about separating the uranium and plutonium; they worried that the existence of pure plutonium at several locations worldwide would lead to the theft or diversion of the material by terrorist organizations and rogue nations. Consequently, the policy was established under President Carter that the United States would not dissolve the rods before burial; it was hoped that other nations would follow our lead. However, that did not occur, and President Reagan reversed the policy in the 1980s. By that time, however, American industry had lost interest in the process, and we have no commercial facilities of this type in the U.S. Therefore, as matters stand now, American practice will be to bury the whole rods.

In burying the HLW, we risk losing large quantities of uranium and plutonium — only about 1% of the energy available in the original ore would have been utilized. Many people strongly oppose burial for this reason — believing that it is too wasteful. Recovery of buried fuel would be difficult.

Yucca Mountain Delays

Before HLW can be buried at YM, the DOE must satisfy the NRC that any radiation leakage from the site will be less than levels established by the Environmental Protection Agency (EPA). The levels set up by EPA place limits, for example, on the amount of radiation dose that any individual could receive at the YM site boundary and on the amount of radioactive material that could escape into potential drinking water at distant sites. One EPA standard applies for the next 10,000 years: no individual (who spent 24 hours per day for 365 days at the site boundary) would be permitted to receive more radiation from the HLW than 5% of our annual background radiation. (This amount is equal to about one and a half chest X-rays. It is also *less than one-sixth* of the amount of excess radiation that workers in our U.S. Capitol building in Washington routinely receive every year from the granite in the building.) A second EPA standard applies for the remainder of a million years; during that period, no individual who spent 24 hours per day for 365 days at the site boundary could receive more radiation from the HLW than 120% of our annual background radiation. DOE has had difficulty in demonstrating that it can meet the EPA standards, and this has been a major cause of the delays in opening the site for HLW storage.

Many people in the scientific community feel that these EPA standards are unduly harsh, in part because of the low radiation allowances to hypothetical individuals thousands of years hence; in part because some Nevadans living near YM today receive more than three times the U.S. average annual background dose; and in part because the YM site is uninhabited, desolate wasteland covered by sagebrush and tumbleweed. In addition, the Department of Defense has exploded hundreds of atomic and hydrogen bombs underground just a few miles from YM; tons of plutonium and other radioactive materials remain as underground residue. It is estimated that any leakage of radioactive material into ground water, for example, would be *far greater* from the bomb-test site than from the highly-corrosion-resistant casks in the HLW storage site.

Interim HLW Storage

As stated earlier, spent fuel is stored initially in pools at power plant sites and subsequently in air-cooled dry casks. This is a satisfactory HLW storage method for several decades. However, some people are concerned that the presence of spent fuel in pools and casks at 50 or 60 sites around the country, although heavily guarded, is a target for terrorist activity. Consequently, it has been proposed (but no action has been taken) that DOE set up a centralized, above-ground storage site at YM and that the casks be shipped there for interim storage.

Another approach for interim storage has been developed by a group of utility companies that consists of transporting the spent fuel casks to Utah and storing them above ground on the Skull Valley Goshute Indian Reservation. This approach, termed Monitored Retrievable Storage, has been studied extensively, the Goshutes approve, all technical requirements have been met, and the NRC has given its approval. Such an approach appears suitable for storage for at least many decades. It is believed that the only remaining obstacle before the plan is activated is political — the State of Utah has recently taken steps to prevent construction of a necessary rail spur from nearby transcontinental railroad lines to the Reservation site.

Future Developments

YM has limited capacity and can handle only the HLW that will exist within several decades; thus, added burial sites will eventually be needed under current practices. Obviously, the federal government would like to avoid having to find and develop new sites.

There is an alternate approach to isolating HLW — specifically, destroying it. As discussed, the components of spent fuel having long half-lives are the uranium, plutonium, and the other transuranics. Uranium (and plutonium) fissions and thus is destroyed when it is recycled through the light water reactors used today. The transuranics (including plutonium) will fission and could be destroyed in "fast" reactors that are discussed in Ch. 9 below. Thus, if the uranium and transuranics were separated chemically and recycled through suitable reactors, all the long-half life materials would be destroyed. The remaining waste would be "30 year" half-life materials that would be harmless in 300 or so years.

DOE has been studying the technology for fissioning transuranics in fast reactors for several years. In addition, it has begun studies to develop a new method to separate the uranium from spent fuel rods but keep the plutonium mixed with the other transuranics. This new initiative is aimed at minimizing concerns about proliferation caused by the existence of pure plutonium. Under this new approach, the plutonium would always remain as part of a mixture with enough intensely-radioactive transuranics to make theft and diversion highly unlikely.

Thus, the concept envisioned to eliminate the need for long-term HLW storage is: a) to separate the uranium from the spent fuel and recycle it in today's reactors; b) to separate the plutonium and other transuranics as a group from the fuel and recycle them through fast reactors to fission and destroy them; and c) to bury the remaining fission products. Recycling the non-plutonium transuranics gives another benefit: since they fission, they release energy just as uranium and plutonium do. One centralized fast reactor could destroy the transuranics formed in several of today's reactors

Development of these technologies looks promising.

Summary

Bruce Babbitt, a geologist by training, a former governor of Arizona, and Secretary of Interior in the Clinton Administration, commented in 2001 that the disposal of HLW at YM is "almost entirely a political issue." He called the site "safe and solid." Underground burial represents a satisfactory solution for HLW disposal in this author's view also, and I anticipate that YM will be approved within a few years. I am also optimistic that new technology will eliminate the need for additional, YM-type storage sites.

Comparison with Other Energy Sources

The fuel requirements for nuclear plants are significantly smaller than for plants using other fuels or sources of energy. This is shown in the following table for an example city:

Yearly Fuel Requirements for a Power Plant Generating Enough Electricity for a City of 560,000 People.
(Credit: Department of Energy)

Fuel	Requirements
Uranium	33 tons
Coal	2,300,000 tons
Oil	10,000,000 barrels
Natural gas	64,000,000,000 cubic feet
Solar cells	39 square miles
Garbage	7,000,000 tons
Wood	3,000,000 cords

A wind plant would require an area of about 39 square miles if it ran all of the time, or about 155 square miles if it ran 25% of the time and stored energy when running.

The annual requirement of 33 tons of uranium fuel can be shipped in a few railroad boxcars. Shipping 2,300,000 tons of coal requires about 214 trains of coal, each train being about 105 coal cars in length. This is equivalent to a single train 250 miles long.

The quantity of waste discharged from a nuclear plant is also significantly smaller than from a coal plant. Dr. Hans Blix, former Director General of the International Atomic Energy Agency, compared the wastes from a coal plant having optimal pollution abatement equipment with the wastes from a nuclear plant. The plants were approximately the size of the plants in the table above, and Blix’s figures are given in the table below:

Yearly Wastes Discharged from Power Plants
Generating 1,000 Megawatts of Electricity.

Wastes	Coal Plant	Nuclear Plant
Sulfur Dioxide, SO_2	1,000 tons	0
Nitrogen Oxides, NO_X	5,000 tons	0
Particulates	1,400 tons	0
Carbon Dioxide, CO_2	7,000,000 tons	0
Ashes	Up to 1,000,000 tons	—
Spent Fuel	—	20-30 tons

The carbon dioxide emitted by the coal plant is an overwhelming quantity. We have no means to handle it except to discharge it into the atmosphere where it becomes an important factor in global warming.

The acid-forming SO_2 and NO_X are also discharged into the atmosphere, as are tiny particles of soot. Scientists blame this soot for 20,000 to 60,000 premature deaths per year in the U.S.

Some ashes are put to practical use, while others are stored in settling ponds (with or without liners at the bottom of the pond) or used for landfill. At one coal plant in Tennessee, the ash discharged in 2004 contained 150 pounds of mercury and 90 tons of arsenic compounds, chromium, lead, and nickel.

The volume of waste from the nuclear plant is also small. If the spent fuel is chemically reprocessed, the yearly volume of highly-radioactive waste will be about three cubic yards — about one-fifth the size of an automobile. The entire nuclear chain supporting the plant, from mining through operation, will generate an additional 800 cubic yards of lower-level waste per year — a volume smaller than 50 automobiles.

If the spent fuel is not reprocessed, the volume of highly-radioactive waste will increase to about 25 cubic yards — the size of about two automobiles. The spent-fuel waste, whether reprocessed or not, will be encased in shielding before underground burial; the volume of waste and shielding together will be 10 or 20 times the volume of the waste alone.

Dr. Blix stated his viewpoint about nuclear wastes as follows:

> "The issue of safe disposal of nuclear waste that remains radioactive for tens of thousands of years needs to be put into perspective. The argument has been made that it is irresponsible to leave any long-lived radioactive waste behind us. That argument, in my view, would apply with much greater strength to the toxic chemical residues — such as arsenic, mercury, lead, and cadmium — that result from the burning of fossil fuels. Their impact on health and safety is often more immediately drastic, and they do not have half-lives. *They remain toxic forever.*
>
> The reality is that we *must* leave some waste behind us, if we want to maintain or create high living standards. The questions rather are: How do we *minimize* these wastes, and how do we make sure that they do not cause harm? The main problem with the wastes of fossil fuels is that they are so voluminous that they cannot be taken care of. Their final disposal sites are the surface of the earth and the atmosphere we breathe! On the other hand, nuclear waste, because of its *limited* volume, can be put back in the crust of the Earth from where the uranium originally came. In my view, we should talk not only about alternative energies, but also about "alternative wastes." The limited volume of nuclear wastes, I submit, is one of the greatest assets of nuclear power."

Chapter 8

DIVERSION OF NUCLEAR MATERIALS

Public acceptance of nuclear power requires satisfactory answers to questions such as: Can terrorists steal uranium or plutonium from nuclear power plants to make bombs? Could they make a bomb if they had the material? Could hostile nations make weapons from their own spent nuclear fuel? These questions are reasonable because explosive devices can be made from small amounts of either U-235 or plutonium; amounts in the range of 20 to 50 pounds are adequate, depending on the choice and purity of the material.

Fuel Rod Theft

Let us start by addressing the question of whether terrorists could steal fuel rods and make bombs. We will consider the situation in the United States initially.

The first answer is that the uranium in fuel rods cannot be used to make a bomb. The U-235 content in new or fresh rods is raised or "enriched" from the natural 0.7% to about 4% or 5%. However, a mixture of U-235 and U-238 must consist of at least 20% U-235 to be explosive. Further, the U-235 content in spent fuel rods is less than in fresh ones; U-235 is consumed as the reactor is operated.

The second answer is that it would be very difficult — maybe impossible — for a terrorist group to make a bomb from the plutonium in fuel rods. There are many reasons. First, there is no plutonium in fresh rods; the terrorists would have to steal spent fuel to get plutonium. Second, spent fuel is intensely radioactive and is transported in massive casks, as described earlier. A terrorist group would have great difficulty stealing such fuel. It would have further difficulty avoiding the intensive police manhunt that would follow. It would no doubt be faced by a massive search operation employing the most sensitive detection equipment available.

Even if it succeeded in stealing spent fuel, the terrorist group would then have to separate the plutonium from the other materials in the rods; rather pure plutonium is required for a bomb. The group would have considerable difficulty doing so, partly because of the dangerous radiation levels involved. A person standing for a few minutes near a typical spent fuel assembly that had been out of the reactor for 10 years would be immediately incapacitated; the individual would die within a week. Heavy shielding and complex robotic equipment would be required to protect workers during the chemical-separations process.

Further, the terrorists would need scientific competence and thorough expertise in a wide range of technical specialties before they could make a bomb. These specialties would include implosion hydrodynamics, critical assemblies of nuclear components, chemistry, metallurgy, machining, electrical circuits, explosives, radiation protection, and others. At least several people who could work together as a team would be required; they would have to be carefully selected to ensure that all necessary skills were covered.

Costs would be high. These would include support for personnel over a period adequate for planning, preparation, and execution; surely, years would be required. A wide variety of specialized equipment and instrumentation would also be needed.

The group would encounter numerous hazards besides radiation; these would include the possibility of a premature nuclear explosion and handling conventional explosives.

There is adequate information in our libraries to tell a group *how* to make a bomb — to understand what must be done. However, practical problems usually arise when any complex device is made for the first time. Consequently, the group would not be assured of a successful explosion on a first attempt. Police authorities would no doubt stop a second effort.

Thus, for the previously mentioned reasons alone, I believe it is extremely unlikely that a terrorist group in the United States could make a damaging bomb from stolen fuel rods. Dr. Luis Alvarez, a scientist who worked on the first atomic bomb, said in 1987 that "making (a plutonium bomb) explode is the most difficult technical job I know."

However, there is an additional obstacle the group would face. Pu-239 is made in a reactor when U-238 nuclei capture neutrons. This isotope of plutonium is the ideal material for making plutonium bombs. If the Pu-239 remains in the reactor for a long period, undesirable impurities build up. For that reason, fuel rods remain in military plutonium-production reactors for only a few weeks or months. The rods are discharged before impurities can form.

Commercial nuclear power plants are operated differently. Because new fuel rods are very costly, they are left in the reactor for three or four years. During that time, many impurities build up. One of the most significant is Pu-238; this isotope emits large quantities of heat.

Plutonium bombs are made by surrounding plutonium with high explosives like dynamite. When the high explosive is detonated, the inward pressure causes the density of the plutonium to increase; this increase is enough to cause the plutonium to detonate. However, the heat generated by the Pu-238 is so intense that it would probably cause the high explosive to melt; this would happen long before the bomb could be used. The melted high explosive would not detonate, and so the plutonium would not either. It would be very difficult for a terrorist group to get around this heating problem. Competent scientists and engineers have given considerable thought to how melting could be prevented; none has found an easy answer. There is no simple solution.

In actuality, much of the Pu-238 is formed after the fuel rods are discharged from the reactor. The transuranic element, curium, is formed in the reactor as stated earlier; it then decays to Pu-238 with a 163 day half-life. Within a year after the rods are discharged, adequate Pu-238 is formed to cause melting. Spent fuel rods are stored in spent-fuel-storage pools for at least a year before leaving the reactor site. Further, it is almost impossible for a terrorist group to steal large quantities of spent fuel from a storage pool.

You may logically wonder if the Pu-238 can be removed from the other plutonium in spent fuel; the practical answer is "No." Elements such as uranium and plutonium can be separated by chemical processes. However, except in rare instances, isotopes cannot be separated chemically. It is much more difficult to separate isotopes than elements. Isotope separation is beyond the capability of any "ordinary" terrorist group.

Thus, terrorists almost certainly cannot use the plutonium in normal spent fuel from nuclear power plants to make a bomb.

Separation of Plutonium in Spent Fuel

As noted earlier, many countries chemically process their spent fuel and separate the plutonium. The plutonium is then used to make new fuel rods; it is substituted for part of the U-235 in the rods. The United States may do the same in the future. The question then arises: Would use of this process change the likelihood of terrorists making bombs from stolen fuel rods?

In one respect, the terrorist's job would be easier; fresh fuel rods containing plutonium would be a new target for theft. Fresh fuel rods would be much less radioactive than spent fuel; handling them would be simpler than handling spent fuel. One or two hundred shipments of fresh rods might be made yearly from fuel fabrication plants to power plants. However, our federal agencies would no doubt require stringent security measures to safeguard them. Thousands of plutonium shipments have been made in the United States in the last 50 years without apparent theft. I believe the terrorist would be no more successful than before.

Related to plutonium in fresh fuel rods is the fact that separated plutonium would exist at the reprocessing and fuel fabrication plants. Could a terrorist group make bombs from pure plutonium stolen from these sites? Again, I believe the practical answer is "No." There would be only two or three reprocessing centers and, at most, only a few fuel fabrication sites. With the stringent federal regulations we would no doubt have, the possibility of theft would be very small. Even if theft occurred, the terrorist would still face the other obstacles to developing a successful bomb.

Activities in Other Nations

Theft of spent fuel by terrorists may be more probable in nations other than the United States; some nations no doubt have less-stringent security measures than we do. Even so, the other obstacles to building a successful bomb would still exist.

Successful plutonium diversion would be more likely by a nation than by a small terrorist group. A nation having nuclear power plants would have access to its own spent fuel. It could bypass several of the technical obstacles discussed previously toward making a bomb. In particular, it could discharge fuel rods from its own reactors a few months after the fuel was loaded; then, there would be little Pu-238 or other impurities in the plutonium.

Consequently, there has been a concerted political effort by several leading nations (including the United States) to control the diversion of nuclear materials. This has led to actions such as the following:

- Most nations of the world have signed a Nuclear Non-Proliferation Treaty. Under the Treaty, each nation agrees to open its commercial nuclear power activities to inspection. The International Atomic Energy Agency, headquartered in Vienna, performs these inspections. It is hoped that all nations will follow the Treaty and use their commercial power plants for power production only.

- The United States has tried to limit the reprocessing of spent fuel, as discussed earlier.

- Most advanced nuclear countries have refused to sell nuclear plants to a few rogue nations such as Iraq and Libya. They have also refused to sell equipment useful for making bombs. The United States has been a leader in encouraging the advanced nations to withhold such sales.

These political efforts have been successful as a whole. Not all individual efforts have fully succeeded — for example, several nations, including India and Pakistan, have not signed the Non-Proliferation Treaty, and few nations followed our decision not to reprocess spent fuel. However, I do not know of any case (except possibly India) where a nuclear power program has significantly assisted in the development of bombs.

Further, no country is likely to make plutonium in a commercial power plant — there are simpler ways to obtain it. A power plant is large, complex, and expensive; a U.S. plant costs in the range of two billion dollars. In contrast, plutonium can be made in a simpler reactor that might cost only a fraction of that amount. Further, American-type power reactors require expensive, enriched fuel to operate; some simple reactors can use inexpensive, unenriched natural uranium. Thus, a nation wishing to make plutonium for terrorism purposes would normally choose to go the simple-reactor route. Still another strong reason for using a simple reactor is that the rogue nation would likely wish to build its bombs in secrecy. A simple reactor can probably be built secretly; the entire world will usually know if the country purchases and builds a commercial plant.

In fact, North Korea has followed this route in attempting to manufacture plutonium in the last few years. It has no nuclear power plants, but it has built simple reactors and a chemical-reprocessing facility. U.S. intelligence agencies learned of this effort; our government is currently negotiating with the country to persuade it to stop its plutonium program.

A dozen or so nations in the world are believed to have plutonium nuclear weapons. All of them built their weapons before they had power plants. The United States, for example, built atomic bombs in the 1940s; it did not have nuclear power until the 1960s. (India may have used heavy water, a component of some non-American-type power plants, to build a bomb.)

Related Background Material

There are other serious concerns about the use of nuclear bombs in the world today. The media frequently fail to state the source of the concerns clearly. Consequently, the public often incorrectly ties them to nuclear power. For that reason, it is worthwhile to explain the concerns briefly. Note specifically, however, that *none of them is related to the use of nuclear power in the United States.*

"Dirty" Bombs

Although terrorist groups would have difficulty making U-235 or plutonium bombs, they could more easily make and detonate so-called dirty bombs. The latter are generally defined as radioactive materials that are distributed by an explosion of dynamite or other material. There are many sources of radioactive material including hospitals and industrial sites. However, such bombs would likely have little connection with nuclear power and will not be discussed further here.

Additional Rogue Nation Activity

Rogue nations may be able to make U-235 bombs as well as plutonium bombs secretly. Natural uranium can be enriched to the 20% U-235 level or above by several processes. None are simple, but several nations, including the United States and the former Soviet Union, have uranium bombs in their stockpiles. Uranium bombs are much easier to design and fabricate than plutonium bombs. Dr. Alvarez, who was mentioned earlier, also said in 1987 that — if a supply of highly enriched U-235 were available — "even a high school kid could make a bomb in short order."

Iraq was endeavoring to make highly enriched uranium until it was stopped by the 1991 Persian Gulf War, and Iran and North Korea may be endeavoring to do so at the present time. Note that none of these countries has had nuclear power plants.

Surplus Uranium and Plutonium

With the end of the Cold War, the United States and Russia have agreed to reduce the amount of highly enriched uranium and plutonium that each has stockpiled; these materials were made in special military facilities for weapons purposes. There is fear that some of these materials, particularly those in Russia, could be stolen or diverted.

The United States is buying many tons of the Russian enriched uranium; this will be mixed with natural uranium to a level of 5% U-235 or less. The mixture will then be used in commercial power plants. However, this use is simply a way to consume potential bomb material; U.S. nuclear power plants will contribute to solving an international problem.

The United States and Russia have also agreed that each will remove about 37 tons of plutonium from their military stockpiles. There is disagreement between the two nations on what to do with the material. Our government has considered two methods to dispose of our plutonium: a) mixing it with intensely radioactive fission products and burying the mixture deep underground, and b) mixing it with uranium and using it in the fuel rods of commercial power plants in the manner discussed earlier. In item b, some of the plutonium would be consumed as it is fissioned in a reactor; the remainder would be buried in spent fuel rods. Note here, too, that the item b approach is simply a way to consume potential bomb material; in this way, U.S. nuclear plants would contribute to solving an international problem. Our plants are not dependent on the availability of such plutonium; in fact, our government would likely have to pay the plant owners for using the plutonium. The second method is our likely choice.

The U.S. government has endeavored to set an example and has encouraged the Russian government to dispose of its plutonium in a similar fashion. However, plutonium is about 10 times as expensive as gold and can be used advantageously in advanced reactors. The Russian position is that it intends to store the material and use it in such reactors at some later date. Thus, final use or disposal of their material is uncertain at present.

There are occasional articles in the newspapers about people being arrested in Poland and elsewhere for selling small quantities of uranium or plutonium on the black market. These materials apparently all come from Russia. However, they probably come from laboratories and institutes rather than from military stockpiles.

Surplus Weapons

Some of the U.S. and Russian surplus material exists in the form of finished, tested bombs — for example, artillery shells composed of nuclear explosives. Each country has around 10,000 bombs and there is fear that some could be stolen in Russia. This is particularly so because the Russian army has gone through a difficult period. Troops are reportedly underpaid and sometimes not paid at all; morale is supposedly poor. Such conditions could lead to theft and diversion.

Factors Beyond Our Control

It is sometimes stated that, if the United States abandoned nuclear power, the rest of the world would also; all of the world's nuclear problems would disappear. This is obviously wishful thinking. Most of those problems are related to military applications and are independent of nuclear power. In addition, abandoning nuclear power would intensify other problems such as those arising from burning fossil fuels.

Further, nuclear power use is very important to much of the world — many nations cannot or will not abandon it regardless of what we do. We can offer leadership on its safe use, and most nations will follow us — as they have done. We can also exert leadership in getting other nations to conduct their power programs openly — to allow international inspections. We led in establishing the International Atomic Energy Agency; most nations have given it authority to inspect their civilian programs. Thus, we can have a positive influence on nuclear power worldwide. However, we cannot lead other nations to take actions against their own best interests — as our efforts to halt the chemical processing of spent fuel demonstrated. Fortunately, few of the world's pressing problems arise from commercial nuclear power.

Summary

In summary, we need not fear the possibility of diversion of nuclear materials from the U.S. nuclear power program. Of course, we should continue to be vigilant with our safeguards. On the international level, the United States and other nations must continue political and diplomatic efforts to control the use of nuclear materials; however, this need is independent of the use of nuclear power in the United States. There are legitimate concerns about the diversion of explosive materials and devices — particularly from Russia's military program; however, *they are unrelated to commercial nuclear power.*

Chapter 9

ADVANCED REACTORS

Today's nuclear power plants can be compared with early airplanes and early TV sets. A leading airplane in the 1940s, the DC-3, carried about 25 passengers at speeds up to 200 miles per hour for 500 miles. The 747 today can carry 450 people at 550 miles per hour for nonstop distances of 5,000 miles. A typical TV set in the mid-1950s could pick up stations 75 miles away in black and white. Today's sets can bring in stations worldwide via satellite in color. Today's nuclear plants are also "early" models, and newer models will show improvements, although perhaps less dramatic than those for the other examples cited. The 103 plants currently operating in the U.S. are termed second-generation plants; they were preceded by a half dozen small, experimental units which have since been shut down.

We can expect changes of many kinds in the future, but we will focus our discussion on: a) evolutionary improvements in the water-cooled reactors currently in operation, b) fast reactors that were first constructed in the 1950s, and c) other advanced reactor initiatives currently in progress. Let us look at each.

Evolutionary Changes in Today's Reactors

American efforts have been underway for several years to design improved, third-generation plants. Participants in this program include the utility industry, which owns and operates the present plants; the manufacturers of the plants; and the Department of Energy. Foreign groups (industrial and governmental) have also been involved. Their efforts are aimed at designing plants that will be simpler to build, be easier to maintain, require fewer operators, be even safer, and generate electricity at lower costs than today's second-generation plants.

These third-generation units will also be standardized, as is the case in France. Instead of each utility buying a unique plant as was done earlier, there will be a choice of only a few designs from which to choose. This will likely also simplify operator training.

These evolutionary thrusts have already produced results. For example, the General Electric Company (GE) has worked with Toshiba and Hitachi Corporations in Japan to design an Advanced Boiling Water Reactor plant. Such plants have been constructed in Japan in less than 4.5 years and below budget. In contrast, U.S. plants built in the 1980s required as much as 11 years before they could be operated, and many had huge cost overruns. GE supplied the nuclear reactors, the fuel rods, the turbines, and the generators for the first new Japanese plants. Two such plants are also under construction in Taiwan. Westinghouse Corporation is working along a similar path with other Japanese companies on pressurized water plants. South Korean organizations are utilizing an advanced pressurized water reactor developed by the ABB-Combustion Engineering Corporation. French organizations have also been very aggressive in designing advanced plants and are currently constructing one in Finland.

The U.S. Nuclear Regulatory Commission (NRC) has completed detailed safety reviews of several of those American-related types of evolutionary designs and given Final Design Certification for each. It is believed that Commission approval has been quite important for other nations to accept these plants. U.S. safety standards are highly respected worldwide.

There has also been an important, parallel thrust in the licensing area; it is aimed at simplifying the U.S. licensing process. In the past, when a utility organization wished to construct and operate a nuclear plant, it was required to:

- obtain approval from the NRC to build the plant,
- purchase the components and construct the plant, and
- obtain approval from the Commission to operate the plant.

The last step was controversial. A utility must borrow money to build a plant. However, there was no assurance that the newly-constructed plant could be operated until the latter approval was granted; there was also no assurance that the lender would get his/her money back until actual operation was approved. In addition, groups opposed to the plant or to nuclear power in general could institute legal suits to delay the granting of permission. Such actions could be very costly to the utility; if a $2 billion plant sat idle and if the utility had to pay interest at the annual rate of 12%, the delay would cost $240 million per year. The add-on cost in four years would exceed a billion dollars. Unnecessary delays are believed to have added over a billion dollars to the cost of the Seabrook plant in New Hampshire.

Industry, the Nuclear Regulatory Commission, and Congress have taken steps to eliminate the controversial third step. The thrust of the effort is as follows:

- The utility will apply to the Commission to build a standardized, pre-approved plant design at a pre-approved site, and
- The Commission will grant approval prior to construction

of the plant for the utility to build and operate the plant. Approval will require that the plant be constructed as proposed, of course.

It is believed that this process will remove much of the risk that investors face in lending money for nuclear plants.

As discussed in Chapter 10 below, whether and when such evolutionary plants will be built in the U.S. will be largely a matter of economics. The latter topic is under intense study.

Fast Reactors

As discussed in Chapter 3, the neutrons released in the fission process in today's reactors are slowed down as they strike the hydrogen nuclei in the water coolant; the reactor is termed a "thermal" reactor. A significant benefit results if a coolant is selected which does not reduce the speed of the neutrons. Specifically, more neutrons are released in a fission event involving high speed, or "fast", neutrons than slow ones. Reactors utilizing such coolants are termed fast reactors. Coolants can also be selected that will simultaneously absorb (and waste) fewer neutrons than will water.

One such coolant is the metal, sodium (element 11). It melts at 208° F (vs. 32° F for water, of course); because the reactor is much hotter than that, the sodium is melted into a liquid. It can be pumped like water and is an excellent coolant. Other coolants such as liquid lead and helium can also be used.

Excess neutron production beyond that needed to keep the chain reaction going results from choosing sodium, and these excess neutrons can be useful. One application is to use them to destroy or "burn up" long-lived transuranic wastes as discussed under Future Developments in Chapter 7. When an individual transuranic nucleus captures an excess neutron, it fissions and splits into much-shorter-lived fission products.

Although transuranic elements will fission and release neutrons in a thermal reactor, the number released per event is low enough that transmutation works well only in fast reactors.

As the next section discusses, experimental fast reactors have existed since 1951. It would be rather straightforward to develop and build larger units. The development of advanced fuels to allow destruction of the transuranic wastes will require further research and development work.

Fast Breeder Reactors

As discussed earlier, part of the energy released in today's thermal reactors comes from fissioning U-235. In addition, some neutrons released in fissioning are captured by U-238 to make plutonium, and that plutonium is also fissioned. However, there is a net decrease in fissionable material as we operate the reactor; more U-235 is used than plutonium is made. We are using up our supply of U-235 that exists in natural uranium. Apparently there is not enough natural uranium in the world to meet international needs for more than a century or so at competitive uranium-ore prices.

However, as discussed above, fast reactors can produce more neutrons than required to keep the reactor operating. Instead of using the neutrons for waste destruction, we can use them to interact with U-238 in the reactor and produce more plutonium than the amount of U-235 destroyed. This is the so-called "breeder" reactor. The use of such reactors could extend our supply of nuclear fuel to meet the world's electricity needs for centuries. When sodium (or lead) is used as the coolant, the reactors are termed Liquid Metal Fast Breeder Reactors or LMFBRs.

It was expected in the 1940s that the first nuclear power reactors would be fast breeder reactors. In fact, an experimental sodium-cooled LMFBR power plant was built in Idaho by Argonne National Laboratory in 1951; it produced enough electricity to light four 200-watt light bulbs. However, the U.S. Navy also developed water-cooled reactors for its submarine fleet in the 1950s. The latter reactors were successful, and American commercial-nuclear-power-plant manufacturers chose to base today's designs on water cooling rather than sodium cooling.

Several experimental LMFBR power plants have been built and operated since the 1950s in England, France, India, Japan, Russia, and the United States. These plants have had safe and generally successful histories, with three exceptions: the English and the second Japanese units have had sodium-leakage problems outside the reactors, and a large French LMFBR had design problems inside the reactor. A major purpose of building experimental units of any machines (reactors, airplanes, automobiles) is to uncover unexpected problems. Those encountered here should not be surprising; all should be correctable with reasonable engineering effort.

Officials under President Carter first and then finally under President Clinton chose to stop breeder reactor development in the United States, apparently because of concern over possible diversion of plutonium. However, other nations such as France, India, and Japan are actively continuing with their development. Russia has LMFBR power plants; it intends to build more. It also expects to use the breeder plants to desalinate water — to purify ocean or other salty water and make it suitable for uses such as irrigation.

There seems little doubt that large breeders could be developed and constructed to extend our natural uranium supplies when needed.

Diversion Resistant System

The current type of sodium LMFBR has at least two objectionable features. For one, the plutonium made in the reactor must be recycled, and this requires that it be separated chemically from other constituents (except uranium) in the spent fuel. The method used since the 1940s for treating spent fuel utilizes the "PUREX" chemical process, which leads to the presence of pure plutonium. Many people are concerned that the existence of such plutonium at various times and places around the world could lead to theft and proliferation.

Another undesirable feature is that the PUREX process requires large, expensive facilities; this, in turn, would lead to centralized fuel reprocessing sites. The latter would require the shipment of spent fuel from the reactor sites to the reprocessing centers; the probable shipment of plutonium from there to other sites for new fuel fabrication; and the shipment of plutonium-containing fuel back to the reactor sites. In addition, the process does not address the need to bury nuclear wastes in a Yucca Mountain-type repository.

The Argonne National Laboratory has developed a new LMFBR system, termed the "Integral Fast Reactor" (IFR) that addresses these concerns. Here, the spent fuel is reprocessed by a method that keeps the uranium and transuranics (including plutonium) intermixed as an intensely radioactive mixture. This makes theft or diversion very difficult. The uranium-transuranic mix is fabricated into new fuel rods and reinserted into the reactor, where the transuranics are fissioned and destroyed. The fission products are separated, mixed with solid materials, and stored or shipped offsite for burial. The entire process takes place within one site — all of the equipment (including the reactor) and operations would be confined "inside a heavily-guarded fence". In concept, make-up uranium would enter the gate, and electricity and fission-product canisters would leave.

The IFR could also be designed as a fast-reactor burner to destroy transuranic wastes.

This system would satisfy many concerns: plutonium would never exist as a pure metal; it would never leave the site;

HLW would rarely need to be transported across country; HLW storage would become a several hundred year problem rather than one of thousands or a million years; and the use of the IFR as a breeder would extend our nuclear energy resources for many centuries.

The Laboratory prepared a small-scale test of the entire IFR system at a site in Idaho — the fuel fabrication equipment, a fast test reactor, the fuel reprocessing equipment, and the equipment to separate and encapsulate the fission products. The development work leading to the demonstration had cost hundreds of millions of dollars and required many years of effort. However, Congress, at the urging of the Clinton administration, chose to terminate the program, the stated reason being budgetary. This action was taken even though Japanese and private industry contributions would have reduced the remaining demonstration cost to a very minor amount. I believe this action was misguided and unfortunate. It is hoped that the system can be revived or an equivalent/better one be developed under the current DOE Generation IV Program discussed below.

New Initiatives

Three particular initiatives are underway in the U.S. at the present time and will be discussed here. In one, the U.S. and nine other countries including France, Japan, and the United Kingdom have agreed to cooperate in research for an advanced generation of systems known as Generation IV Nuclear Energy Systems. The aim is to develop a new generation of reactors that could be put into use by 2030. Improvements are targeted in several areas, with particular attention being given to: a) electricity generation, with the aim to be very cost competitive, b) hydrogen production and other non-electricity missions, and c) the destruction of transuranic wastes from spent fuels. The participants have selected six different reactor systems on which to concentrate their research efforts, and two will be discussed here.

High on the U.S. priority list, although not as an electricity generator, is the Very-High-Temperature Reactor System. The thermal reactor here is quite different from those discussed earlier in this book. Specifically, it uses the gas, helium, as the coolant rather than water, and the helium will leave the reactor at temperatures approaching 1000° C or 1800° F. Its primary mission would be to supply heat for a range of high temperature chemical processes such as the production of hydrogen and the gasification of coal. It could thus be a primary contributor to President Bush's initiative to develop a hydrogen economy and minimize our use of imported petroleum products. It could also be used secondarily to generate electricity, and its waste heat could be utilized for other purposes such as the desalinization of water.

Gas-cooled reactors are not new, with CO_2-cooled reactors having been used extensively in the United Kingdom and with small, helium-cooled reactors having been built in Germany, South Africa, the U.S. and elsewhere. This system will require significant advances in fuel performance and high temperature materials; nonetheless, design, construction, and operation of a demonstration plant by 2020 is predicted.

The second Generation IV system receiving high U.S. priority is the Sodium-Cooled Fast Reactor System discussed under Fast Reactors above.

A second major initiative is the Advanced Fuel Cycle Initiative (AFCI). Its purpose is to develop the system for destroying long-lived transuranic wastes discussed under Future Developments in Chapter 7 above. It thus involves: a) development of a new chemical reprocessing system for the spent fuel from today's thermal reactors, and b) development of the ability to couple that system to the sodium-cooled fast reactor system in the paragraph above.

Under a third new initiative in the early stage of development, the AFCI program is being expanded into the so-called Global Nuclear Energy Partnership (GNEP). Here, added emphasis will be placed on extending the benefits of the Generation IV and AFCI programs to worldwide users. Particular components of the initiative will include: a) the development of small-scale reactors for foreign nations, b) the establishment of a system whereby a few nations will supply fuel fabrication and reprocessing services to the large majority of other nations, and c) extensive construction of facilities during the next 15 years to demonstrate system operation and practicality. A major aim of the partnership will be to virtually eliminate the risk of nuclear proliferation. Details on this program can be found on the web at <GNEP.gov>.

Chapter 10

NUCLEAR POWER COSTS

Many factors influence the use of nuclear energy to generate electricity, the most prominent being its direct economic cost. In this chapter, we will look both at the cost of generating electricity in today's plants and at the cost predicted for new plants yet to be built.

Cost from Today's Plants

Today's nuclear plants were built typically 30 years ago, and their construction costs have already been paid. Therefore, the cost to generate electricity in them comes only from the cost of maintaining and operating the plant and making ongoing capital improvements; from the cost of buying new fuel and disposing of spent fuel; and from the cost of overhead items such as administration, taxes, money set aside for decommissioning, profits, and so on.

The cost of electricity from today's nuclear plants is the cheapest available from any energy source except possibly hydroelectric. Figure 14 from the Nuclear Energy Institute/Global Energy Decisions shows the operations, maintenance, and fuel costs of producing electricity in nuclear, coal, gas, and oil plants in the U.S. from 1995 to 2005; the costs are expressed in cents per kilowatt-hour. In 2005, the average nuclear cost was 1.72 cents per kilowatt-hour, coal 2.21 cents (28% higher), natural gas 7.51 cents (4.4 times as high), and oil 8.09 cents (4.7 times as high). Utilities find today's nuclear power plants to be very profitable investments.

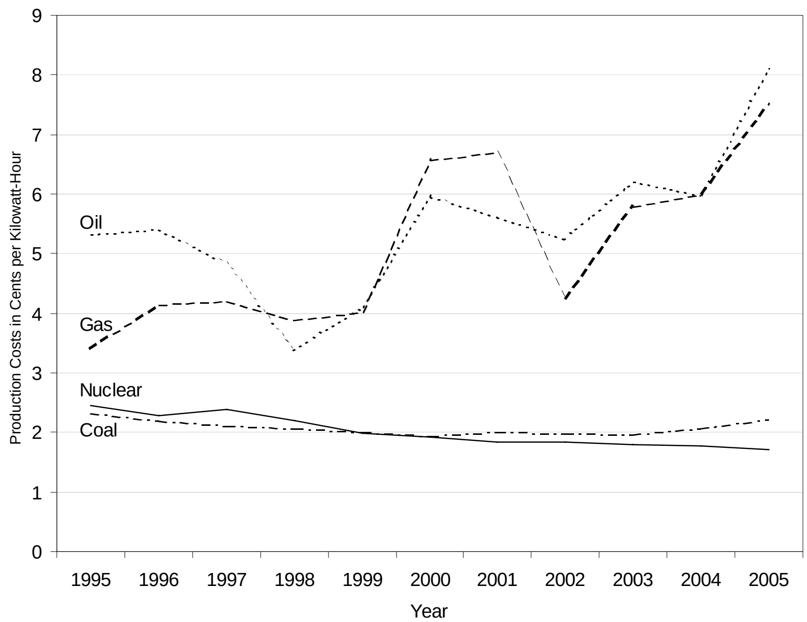

Figure 14: U.S. Electricity Production Costs

Nuclear plants have become very competitive economically over the last 30 years for two primary reasons. First, the plant operators have greatly improved plant performance. If a plant were designed and built to produce 1,000 megawatts of electricity, it could theoretically operate at that level for 24 hours per day 365 days per year. In 1980, the average American plant generated only 56% of its theoretical capability, whereas that figure jumped to 88% 20 years later. This huge improvement resulted primarily from: a) efforts such as careful planning, detailed scheduling, and practice runs to minimize the amount of time the plant had to be shut down for refueling and maintenance, and b) improved maintenance practices to reduce the amount of time the plant was shut down because of equipment failures.

A second major reason is that the owners have been able to modify the plants since they were constructed and to increase their generating capacity beyond the original design levels. In the U.S., the Nuclear Regulatory Commission has approved 110 upgrades totaling the equivalent of about five new plants since 1977.

Improved performance and management placed the equivalent of 24 new nuclear reactors on the electricity grid between 1990 and 2002 without new construction.

Nuclear costs are lower than the others primarily because of lower fuel costs. In 2004, the cost of the uranium fuel to release one million units of energy in a nuclear plant was about 50 cents; the cost of the fuel in a coal plant to release the same amount of energy was about $1.25; and the cost of gas was about $5.00.

Cost of Electricity from New Plants

The cost to build and operate nuclear power plants in the 1960s and 1970s was relatively low; nuclear power was considered cheap. New nuclear plants could be constructed at costs in the range of $250 for each unit of capacity to generate one kilowatt of electricity. (This is termed $250 per installed kilowatt, and a typical 500,000 kilowatt plant cost approximately $125 million.) The situation changed after the Three Mile Island accident in 1979. Long delays in construction were suddenly encountered, sometimes because of legal suits by environmental organizations and frequently because the Nuclear Regulatory Commission (NRC) required that changes be made after construction had begun. Interest costs were also very high then. At the Vogtle plant in Georgia, the construction cost, in the words of the Energy Information Agency, “skyrocketed from an estimated $287 per installed kilowatt to an actual cost of $3,857.” After construction was completed, the licensing system still required further hearings before the NRC would permit a plant to operate, and so new plants sat idle. Operating costs also rose to meet new Commission requirements.

Utility organizations were building large numbers of both nuclear and coal plants during that period, and an excess capacity developed when demand for electricity dropped because of a recession. Consequently, few plants of either kind were built in the 1980s and 1990s. In addition, it would have been considered financial suicide to build a nuclear plant.

Many changes have occurred since then. In particular, the federal regulations for constructing and operating new plants have been significantly streamlined to reduce the total time from start of construction to commercial operation. In August 2004, the University of Chicago issued a report sponsored by the Department of Energy on electricity costs from new nuclear plants. It stated that capital cost would be the single most important component in the cost of nuclear electricity in a new plant. It further stated that the time required to construct the plant would be almost as important as the actual construction cost itself. Although American plants required six to ten years for construction in the 1970s, new plants have been built in four years in Japan recently; they presumably could be built in the same time period in the U.S. now. However, a first plant might require a significantly longer time while the "bugs" were worked out of the system — with longer times adding to the cost.

The Chicago report also stated that the cost to build a newly-designed plant would be high because of the impact of first-of–a-kind engineering costs. These costs could amount to several hundred million dollars or raise the construction cost by as much as 35%. Construction cost would depend significantly on the plant designer who could choose to charge all of these costs on one plant or to spread them out over several. The report also considered many other factors such as the likely cost of fuel over the lifetime of the plant.

The report used several models to compare the predicted cost of electricity from new nuclear plants with those from coal and gas plants. In one model, the cost of nuclear electricity in 2003 prices ranged from about 5.0 to 8.0 cents per kilowatt-hour when capital costs were about $1,900 per installed kilowatt. These costs were not competitive; the cost of coal electricity was a little over 4.0 cents per kilowatt-hour with coal plant capital costs around $1,100 per installed kilowatt.

However, the report stated that: a) after first-of-a-kind engineering costs are recovered, b) after rapid construction times are demonstrated, and c) after the more-efficient licensing process is demonstrated, nuclear electricity will be very competitive with and possibly below the cost of fossil electricity.

Congressional concern about the nation's power supplies led to passage of the Energy Policy Act of 2005 that was intended to establish a comprehensive, long-range energy policy. It provides $14 billion of tax incentives over a 10-year period for programs in the areas of fossil fuel, renewable electricity, clean coal, conservation and energy, automobiles, and nuclear power. About 30% of the incentives are for encouraging or "jump starting" the construction of new nuclear plants. The incentives are aimed at helping to overcome first-of-a-kind engineering and construction costs and at providing insurance against breakdowns in the licensing system.

As a result of that Congressional action, several utility / designer / architect-engineer consortia are currently considering the feasibility of constructing new plants, and many cost studies are under way. The results of these studies should be available within two or three years. Those results will go far toward answering the question of whether nuclear power is economically competitive with coal and gas generated electricity.

Environmental concerns could also become a major factor (or the major factor) in electricity-cost competitiveness. For example, many proposals have been made that Congress impose a tax on carbon dioxide emissions, and some proposed taxes could more than double the cost of fossil electricity. The Chicago report states: "If environmental policies greatly restrict carbon emissions … nuclear power would then acquire an unquestioned cost advantage over its gas and coal competitors."

Decommissioning Costs

When nuclear plants are no longer usable, they must be disposed of or "decommissioned" so that they are not hazardous to public health. This is a component of nuclear-electricity cost that does not apply to fossil-fuel electricity.

The money for decommissioning is collected from customers as the plant is operated as part of the price of electricity. Utilities are presently collecting between one-tenth and two-tenths of a cent per kilowatt-hour for this purpose. The estimated cost of nuclear electricity from the new plants discussed above includes funds for decommissioning.

Summary

It appears very likely that new nuclear plants will produce electricity as cheaply as their competitors in the long term. They will unquestionably do so if adequate consideration is given to environmental factors. Given the new national energy policies, this author is hopeful (and reasonably optimistic) that new plants will be ordered within the next few years. Early Congressional action to impose a carbon-dioxide-emission tax needed to meet goals such as those of the Kyoto Treaty does not appear likely.

Other Countries

Decisions on what kind of power plants to build are easier to reach in many other countries — especially those having no coal or natural gas supplies. Nuclear electricity is highly competitive in parts of Europe; France exports approximately 15% of the nuclear electricity it generates for a profit. A Canadian utility profitably exports electricity to the United States. South Korean officials have described nuclear electricity as their cheapest form. Today there are 339 nuclear power plants in 30 countries outside the U.S. (and 103 in the U.S.). 30 are currently under construction in 11 countries, notably China (8), India (8), Russia (5) and South Korea (4). The latter country also plans to construct four additional plants which have received U.S. NRC design certification by 2015; their cost is expected to be US$1400 per installed kilowatt, falling to $1200/kilowatt in later units, with 48 month construction periods.

Chapter 11

THE PROMISES OF NUCLEAR POWER

The use of nuclear energy to generate electricity promises great benefits to you as an individual, to the nation, and to the world. These include the following.

1. *Clean Air:* Of all practical means for generating large amounts of electricity, nuclear power is the least harmful to the environment. Nuclear plants emit no CO_2 to cause the greenhouse effect as do coal and natural gas. They emit no sulfur compounds to cause acid rain as does coal nor nitrogen compounds as do both coal and natural gas. Nuclear power plants cause no silting of pristine river systems and no large loss of farms, homes, and wilderness to reservoirs such as do hydroelectric plants. A very strong argument can be made that nuclear power has no significantly harmful effect on the environment at all. Today, America's 103 nuclear plants spare the atmosphere about 700 million tons of CO_2, 3.3 million tons of sulfur dioxide, and 1.1 million tons of nitrogen oxides yearly.

   Recently, an important international environmentalist, James E. Lovelock, changed his stance and become strongly pronuclear. Lovelock is a British chemist whose work is believed to underpin much of modern environmentalism, including providing the foundation for Rachel Carson's work. He was honored in 1997 with the Blue Planet Prize, which is widely considered the environmental equivalent of the Nobel award. In September 2006, he was interviewed by the New York Times and responded as follows:

What's your perception of where we're headed with even conservative predictions for growth of both populations and energy use? "I think we're headed straight back to (a hot state of the Earth) that it's been many times in the past. It's about 14 degrees warmer than it is in these parts of the world now. … It means roughly that most life on the planet will have to move up to the Arctic basin, to a few islands that are still habitable and to oases on the continents."

Can you explain why you think nuclear power is so vital? "My justification of nuclear power is that we've reached a stage now where the dire things that threaten us are so great that even the results of an all-out nuclear war pale into insignificance as unimportant compared to what's going to happen."

You seem to say we have to get over the idea that renewable energy sources — wind, solar — in the short run, are a useful way out of this. "I feel they're largely gestures. If it makes people feel good to shove up a windmill or put a solar panel on their roof, great, do it. It'll help a little bit, but it's no answer at all to the problem."

Other environmentalists have also adopted new views. For example, Dr. Patrick Moore, a founding member of Greenpeace and President of Greenpeace Canada for nine years, wrote in April 2006: "In the early 1970s, I believed that nuclear energy was synonymous with nuclear holocaust. … Thirty years on, my views have changed, and the rest of the environmental movement needs to update its views, too, because nuclear energy may just be the energy source that can save our planet from another possible disaster:

catastrophic climate change. … Wind and solar power have their place, but because they are intermittent and unpredictable they simply can't replace big base load plants such as coal, nuclear and hydroelectric. Natural gas, a fossil fuel, is too expensive already, and its price is too volatile to risk building big base load plants. Given that hydroelectric resources are built pretty much to capacity, nuclear is, by elimination, the only viable substitute for coal. It's that simple."

Former Interior Secretary Babbitt has called climate change "the most important issue facing this planet." With respect to carbon dioxide, he termed the "emission-free nature of nuclear power an extraordinary asset. To me, it makes the case for reemergence of the nuclear power industry absolutely rock solid."

2. *Resource Conservation:* Coal, petroleum, and natural gas represent precious natural resources built up over millions of years. They have many uses, such as feedstocks for medicines, plastics, and other industrial products, and we should not squander them when substitutes are available. Uranium, in contrast, has no use except for power production, atomic weapons, and a few minor applications such as to serve as ballast in ships.

3. *Saving Lives:* As discussed previously, nuclear power has been demonstrated to be safer than power from coal. The evidence indicates more people lose their lives in the United States annually from coal electricity particle pollution than will lose their lives worldwide over the next 50 or 60 years from Chernobyl accident radiation.

4. *Preventing Wars:* Along with battery-driven or hydrogen-driven automobiles, nuclear power has the potential to prevent world wars over Middle East oil supplies. Middle East oil is crucial to the well being of many nations as long as they rely so heavily on gasoline-driven automobiles.

Development of practical, inexpensive storage batteries for electric cars, coupled with nuclear electricity to charge the batteries, could greatly reduce our need for gasoline.

Development of hydrogen-driven automobiles could accomplish the same objective. In this case, nuclear electricity could be used to separate the hydrogen from the oxygen in water. Hydrogen is not normally available as a separate material. The hydrogen would then be recombined with oxygen in a fuel cell to release energy and propel the car.

The financial cost of fighting wars is very high, and the payback from subsidizing the cost of battery or hydrogen-driven autos to reduce war-related costs could be quite large.

5. *Improving Our Economy:* The use of battery or hydrogen-driven autos would also drastically decrease the cost of importing oil. At the present time, we spend over $50 billion per year as a nation to import petroleum; some economists predict this will climb to $100 billion per year in a few years. Many economists believe these expenditures cause a serious drain on our economy — that they cost many jobs and lower our standard of living.

6. *Further Improvement of Our Air Quality:* Gasoline is a major contributor to smog formation and air pollution. Substitution of battery or hydrogen-driven autos for gasoline-driven vehicles would obviously have a great impact on air quality. For example, in the fuel cell discussed in item 4, the waste from the cell would be ordinary water — when the hydrogen and oxygen combined, water would be formed again. It is difficult to envision a more environmentally friendly system.

7. *An Almost-Unlimited Power Supply:* It is vital that our nation (and every nation) have an ensured, long-range supply of

electricity; there is enough uranium underground and in the oceans to meet our electricity needs for centuries using advanced reactors.

In the 1960s and 1970s before nuclear power costs climbed, people dreamed of many benefits of cheap electricity. One dream was that it might make possible the desalination of water at affordable prices — that low-cost water recovered from the oceans could be used to irrigate the world's deserts and grow food. This dream still exists — that we could *make the deserts bloom*.

Chapter 12

WHAT CAN WE DO?

This author believes that the expanded use of nuclear power around the world is inevitable as we face the challenge of climate change and as the need for electricity increases. All countries face the greenhouse gas/global warming problem. Many countries have neither coal nor natural gas, while others do not have rail systems to transport their coal to population centers where electricity is needed. In addition, uranium is easy to transport and stockpile, and many countries will rely on it for a secure energy supply. I also believe that there will be a resurgence in building nuclear plants in the United States. This will happen: a) as the nation recognizes the role nuclear energy must play in preventing climate change and/or b) when our electricity-generating companies conclude that nuclear is their best energy choice.

Companies will reach that conclusion when some combination of factors such as the following exists:

- When our national energy policy places increased emphasis on clean air.
- When the direct economic cost is clearly favorable for nuclear power.

- When the national energy policy gives greater recognition to saving lives.
- When the policy places greater emphasis on freeing the nation from the political turbulence associated with Middle East oil.
- When Congress and the President develop a long-range energy policy realistically shared by both political parties.
- When a satisfactory HLW storage system is established.
- When nuclear power "becomes popular again" — when there is recognition of the costs of *not* using nuclear power; when it is not fashionable for environmental groups to oppose nuclear energy; when political leaders or candidates cannot use an antinuclear platform to gain votes.

However, simply waiting for the inevitable to occur is not good enough. We can hasten the resurgence of nuclear power and bring about some of the immense benefits promised by it. Among the things we can do are the following.

First, if you agree that nuclear power does indeed offer great benefits, we all must be willing to speak out strongly in its favor.

We must challenge environmental and other groups that oppose nuclear power — to insist that they examine the facts and act accordingly. One effective way to do so is to stop supporting them financially if they resist.

We must speak out when the mass media — newspapers and TV in particular — make erroneous statements. We must oppose their use of dramatic headlines and stories that mislead and scare the public.

It is especially important to make our views known to our political leaders. They must be made to recognize that nuclear power gives us clean air today and saves lives today — and that we could be dumping far fewer pollutants into the air and saving thousands more lives. Letters to both the President and Vice President and to our Senators and Representatives are needed. Letters to state political leaders are also necessary. Public Service Commissions should be urged to compare not only economic but also environmental and health costs of different fuels.

In closing, we must be aggressive to gain the enormous benefits that nuclear power offers. Recent history has demonstrated that those benefits will not come easily.

DEFINITION OF TERMS AND ABBREVIATIONS

Acute Doses of Radiation: Doses received in a short time period such as minutes or hours.

CO_2: Carbon dioxide.

HLW: High-level waste, the material in used or spent fuel rods. See Chapter 7.

Isotope: Any of two or more atoms of an element which have the same number of protons but different numbers of neutrons in the nucleus. See Chapter 2.

Linear, No-Threshold Theory: The theory that radiation presents a health risk that is proportional to dose, no matter how small the dose. See Chapter 5.

Micron: One micron is equal to 1/70 the width of a human hair or 1/25,000 of an inch.

NRC: U.S. Nuclear Regulatory Commission.

One Year of Background Radiation: The amount of radiation the average American absorbs from natural sources each year. This radiation comes from four main sources as follows: (The amounts are given in standard terms called milliSieverts and millirems.)

Origin	milliSieverts	millirems
From the sun and outer space	0.27	27
From the earth, including uranium and thorium	0.28	28
From inside our bodies, including potassium	0.39	39
Radon (from our buildings and the ground)	2.0	200
Total	3.0	300

B. G. Bennett of the United Nations Scientific Committee on the Effects of Atomic Radiation gives the average radiation dose to the world's population from natural radiation sources as 2.4 milliSieverts per year.

Particulates: Particulates are composed of: a) solid particles emitted to the atmosphere such as dust or the soot from power plants or wood stoves, and b) other solid particles or liquid droplets formed in the atmosphere. The latter are called aerosols, and some are formed from the sulfur oxides and nitrogen oxides emitted when fossil fuels are burned. These fossil-fuel aerosols are usually smaller than one micron in diameter. Scientists believe the most harm comes from particles smaller than one micron.

Transuranics: Man-made elements that are heavier than uranium.

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