Case Study: Indian Point: Should a Nuclear Power Installation Operate Near One of America's Major Cities?
Two nuclear reactors at Indian Point, New York, are required to relicense in the next few years. Even though they have operated for decades with no major problems, there is a highly contentious debate about whether to relicense the plants for further operation. The plants are near a great many people, and there seems to be some definition needed for what "major" means in terms of a nuclear accident. It seems that nuclear power, while having a pretty good track record and being one of the most highly regulated industries, is one of the best examples of the NIMBY Principle: Not In My Back Yard.

Chapter 17

NUCLEAR ENERGY AND THE ENVIRONMENT

17.1 CURRENT ROLE OF NUCLEAR POWER PLANTS IN WORLD ENERGY PRODUCTION

Nuclear power produces about 17% of total electricity in the world and 4.8% of total energy from 436 operating plants.

17.2 WHAT IS NUCLEAR ENERGY?

There are two kinds of nuclear processes: **nuclear fission** and **nuclear fusion**. Fission is the splitting and fusion is the fusing of the nuclei of atoms. Both reactions release an enormous amount of energy, but fusion reactors have not yet been made energy efficient.

A Closer Look 17.1: Radioactive Decay
The fundamental difference between one element and another is the number of protons in the nucleus. For example, a carbon atom, and only a carbon atom, has 6 protons. The elements usually have an equal number of neutrons, but some variation occurs. These variants are called **isotopes**. Most carbon atoms have 6 neutrons, given an atomic weight of 12. This is one kind of carbon isotope, and this is written as ^{12}C, where the superscript 12 refers to the atomic weight. There are two other carbon isotopes. They are ^{13}C and ^{14}C with 7 and 8 neutrons, respectively. Some isotopes are stable, others are not. ^{14}C is unstable, whereas ^{12}C and ^{13}C are stable. When an isotope is unstable it will decay; when it decays it releases radiation. Unstable isotopes are **radioactive** and are referred to as **radioisotopes**, meaning that they release radiation when their atoms decay. The decay occurs exponentially at a constant rate that is specific to the isotope. Decay rates are measured in units of **half-lives**. The half-life of ^{14}C is about 5600 years. Some radioactive isotopes are **fissionable**, meaning that they can be coaxed into decomposing spontaneously when hit by the alpha particles emitted by an adjacent, decaying atom. Thus, a **chain reaction** is possible when you pack enough radioisotopes together. When a chain reaction occurs, there is an enormous release of energy. When the chain reaction is uncontrolled, it is an exploding bomb. There are 3 kinds of radiation: **alpha**, **beta**, and **gamma**. Each has different biological effects that depend on where they are in the body and what their penetrating ability is.

● Conventional Nuclear Reactors
The first human-controlled nuclear fission (discounting failed attempts in Nazi Germany) occurred in 1942 at the University of Chicago. Nuclear power generation occurs in fission reactors using ^{235}U as a fuel (pronounced "U-235"). Uranium in ore is about 99% ^{238}U and about 0.7% ^{235}U; at that concentration no fission occurs. In processing facilities the ^{235}U is concentrated in uranium fuel pellets to a final concentration of about 3%, which makes fission possible when the fuel rods are packed together in a reactor core. Fission produces neutrons, which strike other atoms and produce a chain reaction that must be controlled by raising and lowering **control rods** to block the neutrons.

There is an enormous amout of heat generated, which is carried away from the core by a circulating fluid (**primary coolant**). If water is used, it may be turned to steam by the heat and used to turn a turbine, but often a heat exchanger is used to transfer heat from a coolant such as liquid sodium to water to turn it to steam.

This steam must be condensed back into water, and this is accomplished with cooling water drawn from a nearby source. The cooling water leaves the reactor as hot water, and this is evaporated or discharged directly back into the source.

As the fuel in the rods of a typical **burner reactor** (as opposed to a **breeder reactor**, see below) decay, the concentration of ^{235}U declines, and the concentrations of other dangerous radioisotopes rises. The waste products include radioisotopes of plutonium, iodine and strontium.

17.3 NUCLEAR ENERGY AND THE ENVIRONMENT
The full nuclear fuel cycle encompasses mining, refining, fuel assembly, operation, and waste. There are risks and challenges associated with each step.

● Problems with the Nuclear Fuel Cycle
The mining operation produces radioactive tailings and exposes workers to rather high doses of radiation; waste is also produced by enrichment and assembly fabrication. Site selection of power plants is extremely important, as in the chapter introduction regarding Indian Point, NY. Nuclear power plants are vulnerable to catastrophic accidents.

There are numerous problems associated with the handling and disposal of nuclear waste; there still is no permanent and operational repository for nuclear waste in the U.S. The U.S. does not reprocess nuclear fuel, but is on the verge of doing so.

Nuclear plants have a limited life, and there is a high cost associated with decommissioning the plant and protecting the site that continues long after the plant is closed.

A Closer Look 17.2: Radiation Units and Doses

Measures of radioactive decay, which is a very "physics-y" way of measuring radiation, is based upon the *number of radioactive particles that decay per unit time*. In the SI system, this is reported in **becquerel** (Bq), which is one radioactive decay per second. An older unit, the **curie** (Ci) is equivalent to 3.7×10^{10} disintegrations per second.

Measures of actual absorbed dose of radiation is often more important in environmental health, and is based on the *amount of energy absorbed by a mass*. It's International System equivalent is the **gray** (Gy), which is a dose that causes 1.0 Joule of energy to be deposited in one kilogram of mass. An older unit, the **rad** (rd; "radiation absorbed dose") is a dose that causes 0.01 Joule of energy to be deposited in one kilogram of mass. (Therefore, 1 Gy == 100 rad.)

Different forms of radiation affect tissues differently, and an attempt to quantify the **biological effects of radiation** involves multiplying the gray (Joules/kilogram) by constants that depend on factors such as the type of tissue and the form of radiation, collectively know as the **relative biological effectiveness**. It's International System equivalent is the **sievert** (Sv), which is also measured in Joules/kilogram. An older unit is the **rem** (rd; "Röntgen equivalent man"). (1 Sv = 100 rem.)

Because of extraordinary confusion in the units of radiation, the National Institute of Standards and Technology's *Guide for the Use of the International System of Units* (SI) "strongly discourages the continued use of the curie, roentgen, rad, and rem". (http://www.nist.gov/physlab/pubs/sp811/index.cfm)

For understanding, ask students to calculate the amount of energy their own body absorbs if they get a typical American dose of 3 mSv/year.

17.4 NUCLEAR RADIATION IN THE ENVIRONMENT, AND ITS EFFECTS ON HUMAN HEALTH

● Ecosystem Effects of Radioisotopes

A release of radioisotopes into the environment exposes organisms to radiation externally and internally. Exposure to radiation from external sources is usually episodic, but internal exposure to radiation can be chronic. Internal exposure occurs when radioactive particles are inhaled and lodge in the lung, or when radioisotopes are consumed. Radioisotopes can enter the food chain. Some of these are natural, mainly from rocks and soil and cosmic sources, but between 50% and 75% of a typical American's exposure is due to human activities.

● Radiation Doses and Health

The LD_{50} in humans is about 5,000 mSv. Exposure to 1,000-2,000 can cause significant health problems, including sterility, abortion, and vomiting. At 500 mSv, physiological changes can be detected.

There is much uncertainty in the assessment of health hazard or low doses of radiation. The maximum allowable dose of radiation per year for workers in the nuclear industry is 50 mSv, which is about 30 times the average natural background. Studies have shown that there is a delay of 10-25 years between the time of exposure on the onset of disease, including cancer.

17.5 NUCLEAR POWER PLANT ACCIDENTS

The NRC estimates that the probability of a meltdown is 0.01%, but if/when we have 1,500 nuclear reactors (4x present world total), the probability of a meltdown somewhere is estimated at once every 7 years.

● Three Mile Island, Pennsylvania, US

On March 28, 1979, the worst accident in US nuclear history occurred at Three Mile Island near Harrisburg, Pa. A mechanical failure compounded by human error caused a loss in the water needed to cool the reactor and led to a partial meltdown of its core , and an unexpected bubble of hydrogen gas collected inside the reactor building that threatened to blow up the building. The operators had to vent the hydrogen and a great deal of radioisotopes to the atmosphere. Three Mile Island never became a major public health threat, but for a few apprehensive days the utility and the Nuclear Regulatory Commission were unsure how to contain the accident. Public acceptance of nuclear power plummeted. In the early 1980s investing in nuclear power made little economic sense. The accident at Three Mile Island and movies like *The China Syndrome* made many Americans apprehensive about nuclear energy. Then the April 1986 explosion at the Chernobyl nuclear plant in what is now Ukraine spread radioactivity across Europe and fear of nuclear power increased. Three Mile Island is clearly seen on Google Earth.

● Chernobyl, Ukraine

Unit number 4 of the Chernobyl NPP exploded in the spring of 1986. The reactor core burned for days until the fire was eventually smothered by helicopters. The nearby city of Prypyat was evacuated within days of the disaster. Small towns in the surrounding countryside were also evacuated. A large area around the reactor will remain uninhabitable for decades. The accident, which happened as the result of a safety experiment, resulted in a large loss of life. Childhood leukemia is high and the mortality rate in the overall population of Ukraine has risen significantly since the accident. The reactor today is still hot, and the building is enclosed in an unstable structure known in Ukraine as the ‘object shelter’ and known here as the “sarcophagus”. There are dozens of waste dumps all around the countryside where highly radioactive equipment was hastily buried, and not inventoried. Radioisotopes are leaking into the groundwater and have been detected as far as the Black Sea. Chernobyl is on a major flyway for migrating birds that stop and feed, and then carry radiation off site. The area is also subject to serious flooding from the Dnieper and Prypiat Rivers. One could say that the accident here is still in progress. The accident site is blurry on Google Earth (at the time of this writing), but the abandoned city of Prypiat is an eerie site.

17.6 RADIOACTIVE WASTE MANAGEMENT

Radioactive wastes are by-products of the use of nuclear fuel for electricity generation. There are four types of radioactive waste: **mine tailings**, **low-level**, **transuranic**, and **high-level**. In the Western United States, 20 million metric tons of radioactive mine tailings will produce radiation for 100,000 yrs.

● Low-Level Radioactive Waste

Low-level radioactive wastes are defined as being sufficiently low in radioactivity to be buried in shallow pits, one of which is located in Barnwell, SC. Low level radioactive waste includes contaminated clothing, gloves, medical equipment, laboratory waste, solutions from processing, etc. The Nuclear Regulatory Commission divides them into three classes (A, B, and C) based on degree of potential hazard.

● Transuranic Waste

Transuranic waste is composed of human-made radioactive elements heavier than uranium. Most transuranic waste produces low levels of radiation, but isolation is necessary because of the very long half-life of these products. Plutonium, for example, must be isolated from the environment for about 250,000 years. This waste type includes trash and contaminated equipment, and is generated mainly at nuclear weapons facilities. There is a pilot project at Carlsbad, NM to bury transuranic waste 2000 ft deep in salt caverns.

● High-Level Radioactive Waste

High level radioactive waste consists of commercial and military nuclear fuel, including uranium and plutonium. The waste is highly radioactive and toxic. Presently many 1000s of tons waste is piling up at more than 100 sites in 40 states until a final repository is developed. This repository is scheduled to open in Yucca Mountain, NV.

● What Should the United States Do with Its Nuclear Wastes?

There are at least 3 significant problems with high-level waste disposal. One is transportation. When a repository finally opens there will be large scale movements of high level waste across the Nation's highway system and rails. A second problem is that the repository must remain geologically stable and hydrologically isolated for several hundred thousand years. The third problem is ensuring that future populations will understand that the repository is not to be disturbed. How can we communicate this message to people 1000's of years into the future?

The repository at Yucca Mountain is years behind schedule, over budget, and is opposed by the Sate of Nevada. In July 2004, a Federal Appeals Court threw the future of the

Critical Thinking Issue: Should the United States Increase or Decrease the Number of Nuclear Power Plants?
The federal government of the United States seen to support the development of nuclear energy, as evidenced by positions of both the Bush and the Obama administrations. There may, however, be a trend in local government to block them being placed in their areas. This leads to serious confusion of policy. The Shoreham plant on New York's Long Island was ordered in the mid-'60s and cost over $5 billion to complete. Its construction was delayed by activists concerned about safety issues. One question was how to evacuate the population of Long Island in the event of an accident. Shoreham was finally completed and won its operating license, but with the company on the verge of bankruptcy, the plant was never operated. Gov. Mario Cuomo, an opponent of a Shoreham startup, negotiated a deal that allowed the power company to pass the cost of Shoreham along to the utility's consumers in exchange for closing the plant. Today, a perfectly good facility, capable of serving hundreds of thousands of homes, sits rusting. Who was at fault, and how can policy be changed to make everybody happy?

Yucca Mountain repository in doubt by ruling that the federal government must devise a new plant to protect the public against radiation releases beyond the next 10,000 years. However, DOE remains confident that it can come up with an acceptable plan.

17.7 THE FUTURE OF NUCLEAR ENERGY

Advocates argue that nuclear energy does not contribute to global warming by release of GHGs, it does not cause acid rain pollution or nitrogen deposition and, if breeder reactors are used, the amount of fuel will be increased. **Breeder reactors** are designed to produce more fissile material than it consumes. The reactor core, at its center, has concentrations of ~20% fissile ^{239}Pu and 80% non-fissile ^{238}U. Surrounding fuel rods are 100% ^{238}U which is transmuted to ^{239}Pu. After a year of operation, the center rods will have 15% ^{239}Pu and 85% ^{238}U, with the surrounding material having 95% ^{238}U and 5% ^{239}Pu . This results in a net slight net production of ^{239}Pu. Plutonium has a 24,360 year half, is extremely toxic, and can be made into a bomb. In 1977 President Carter called for an indefinite suspension of the construction of our first and only breeder reactor on the Clinch River, TN because of concerns about proliferation, and the Senate finally killed the CRBR project in 1983. Breeders are important energy sources in some nations, e.g. France.

Standardization and smaller size of reactors could also make them much safer in the future.

Critics argue that there are safety concerns and economic and political issues, nuclear is not likely to have any impact on global warming any time soon, and some nations may use nuclear power as a path to developing weapons. Current reactors are also very inefficient and would require major redesigns.

Plant safety is no longer the most important issue facing the nuclear industry, nuclear waste is. If nuclear energy were phased out, or frozen, would it make a difference? It does supply 20% of electrical energy in the U.S., and it is greenhouse neutral. In the face of rolling brown outs and spiraling energy costs in California and blackouts in the North East, Americans seem to be warming to nuclear energy.

● Possible New Kinds of Nuclear Power Plants

New designs of non-breeder fission reactors such as the **Boiling Water Reactor**, the **High Temperature Gas Reactor**, and the **Pebble Reactor** are designed to be safer and more efficient, but they are still in planning stages. There are various Internet sites dedicated to these if students wish to research them more.

Fusion reactors essentially smash small particles together in a similar fashion as the sun, producing an enormous amount of energy. However, this requires high temperatures and a confined plasma which is technologically difficult to get to run efficiently.

Web Resources

http://www.nrc.gov/ The NRC home page with links to maps of nuclear power plants, educational material, and statistics.

http://www.nei.org/ The home page of the Nuclear Energy Institute, with links to statistics and educational material.

http://www.uic.com.au/nip22.htm An excellent account of the Chernobyl accident.

http://www.uic.com.au/nip.htm A comprehensive collection of facts from the Uranium Information Centre in Melbourne. Excellent.