10 Nuclear Power Reactors

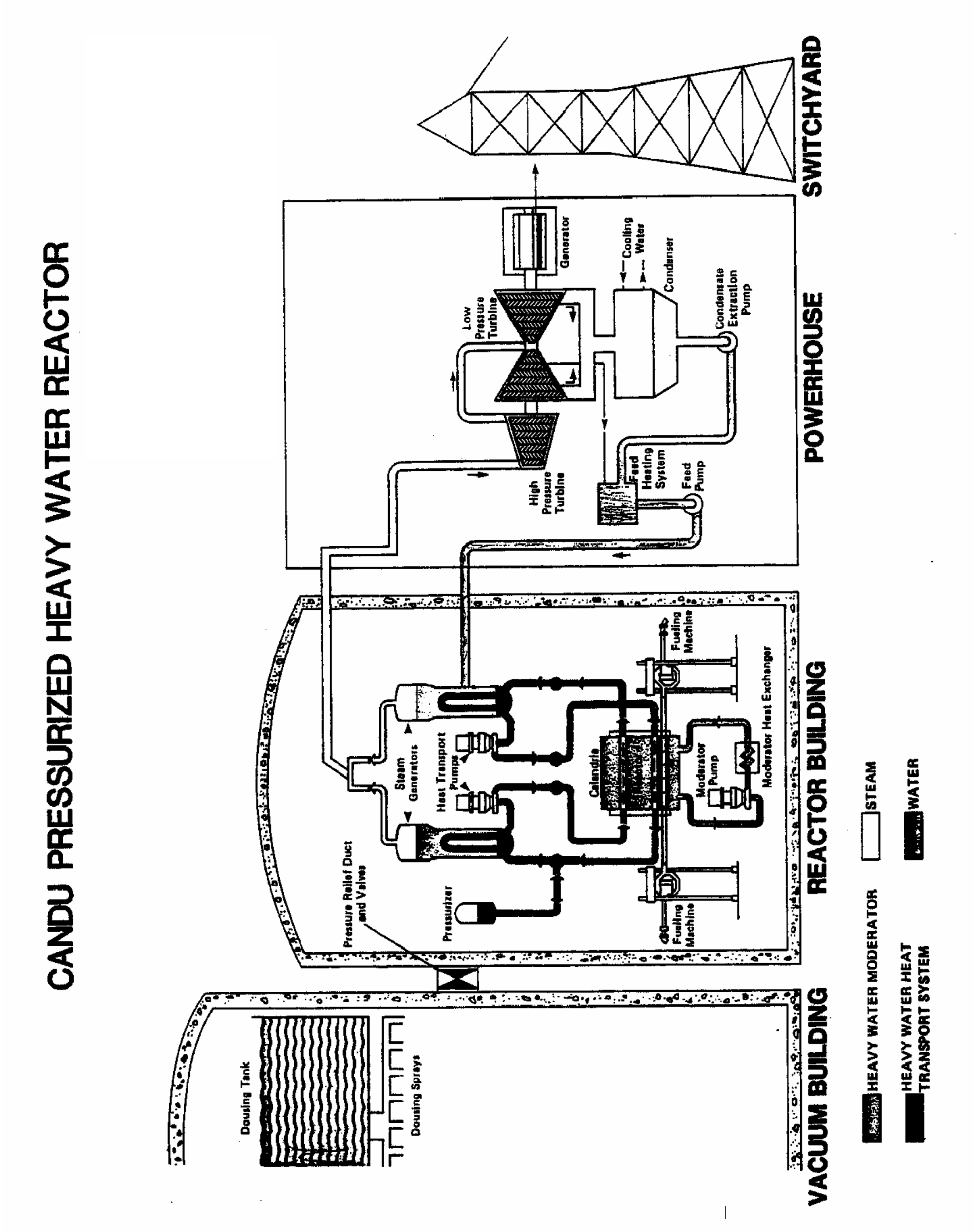

Figure 10.1

10.1 What is a Nuclear Power Station?

The purpose of a power station is to generate electricity safely reliably and economically.

Figure 10.1 is the schematic of a single nuclear generating unit. Often several units share equipment. Each nuclear power station in Ontario includes four CANDU reactors. Quebec and New Brunswick have built single unit stations. The next sections of the course are mostly about the systems and equipment shown inside the reactor building of Figure 10.1

An obvious difference between a nuclear power station and a fossil fuelled plant is the heat source. In the CANDU reactor, heavy water coolant is pumped over hot uranium dioxide fuel and becomes hot. It then flows into a boiler where it gives this heat to ordinary water, converting it to steam. In a conventional plant, heat to make steam comes from burning coal or oil. In each case the steam drives a turbine that turns a generator.

The name CANDU comes from CANada Deuterium Uranium.

Heavy water is deuterium oxide, D_2O. Deuterium is a heavy form of hydrogen, which is found naturally at a concentration of about one deuterium atom for every 7000 hydrogen atoms.

The part of the nuclear reactor that produces heat is called the reactor core. It includes the fuel, the coolant and the moderator. The nuclear fuel can get hot only when the moderator surrounds it. A distinctive feature of CANDU reactors is the heavy water moderator.

10.2 Hazards

The fuel generates heat and intense radiation when it is in the reactor. It is safe to handle before it is used, but it contains deadly quantities of radioactive matter after it has been in the core for a short time. These radioactive materials continue to produce radiation for a long time.

The thermal power output from the core of a CANDU at full power ranges between 1700 and 3000 MW_{th}. If systems that remove the heat fail, the heat will damage the fuel and reactor components. This could allow lethal radioactive material to escape from the reactor core. Damage results when thermal expansion and high pressure cause stress and distortion of reactor parts. Also, materials may become weak or melt at high temperature.

Considering this obvious hazard, why do we have nuclear reactors? The next section of this module gives some reasons. The rest of the course shows how safe, reliable and economical nuclear power production is possible.

10.3 Summary Of The Key Ideas

- The purpose of a power station is to generate electricity safely, economically and reliably.
- The core of a CANDU reactor contains natural uranium dioxide fuel, heavy water coolant and heavy water moderator.
- The fuel in a reactor generates heat to make steam, but produces radiation and radioactive materials in the process.
- Heavy water has unique nuclear properties that allow CANDU reactors to use natural (unenriched) uranium in the fuel.
- 1 MW (megawatt) = 1000 kW (kilowatts). Power units measure the role energy is produced or delivered. Electric energy is sold in watt or kilowatt hours (kWh). For example, a rate of energy production (power) of) MW delivers 1 kWh of energy every 3.6 seconds. You will also see the symbols MWth (megawatts thermal) to indicate heat energy production wad MW_e (megawatts electrical) for electrical generation.

10.4 Production Methods Compared

10.4.1 Alternatives

We have become used to reliable and relatively inexpensive electric power. As a result, we do not always use electric energy appropriately or efficiently. Effective conservation can reduce the demand for electric power. This can delay or even eliminate the need for some new power stations.

Small power sources (for example, windmills in remote locations and dams on smaller rivers) also can fill certain niches. Most utilities forecast the need for additional large power stations. Until someone finds a better technology, the choice is between nuclear power and fossil fuelled plants.

10.4.2 Economics

The inventors of nuclear power expected it to be a much cheaper energy source than energy from fossil fuels (coal, gas or oil). The economic advantage of electricity from nuclear power compared to fossil fuel comes from the cost of the uranium fuel. For comparison, in

1990, nuclear fuel costs in Ontario were about 10% of the fuel cost for an equivalent sized fossil plant. A large coal fired plant uses about 20,000 tonnes of coal a day. The equivalent nuclear plant uses about 20 fuel bundles, each with less than 20 kg of uranium.

People who predicted cheap nuclear power overlooked costs that offset fuel savings. Nuclear plants are expensive to finance, build and maintain. Capital cost is at least three times that of an equivalent fossil plant Also, nuclear plants take 3 or 4 years longer to construct, commission and bring into service.

Predicting the cost of both conventional and nuclear power production is difficult. Financing for construction must be in place years before revenue from power sales begin. The cost of nuclear power, with its high front-end cost, depends strongly on interest rates. Fuel cost is a much more important part of the price of electricity from fossil fuels.

From initial construction to in-service presently takes 8-10 years for a nuclear plant. The designer is expecting that a modular construction technique will allow the newest design of small reactor to be built in half that time.

Cost estimates for each kind of power generation depends on how prices change during the life of the plant. Fossil generated power becomes expensive if fuel costs increase sharply after the plant is built Cost increases after the plant starts operating do not affect the cost of nuclear power as much. Borrowing money to build a nuclear plant is a good strategy when costs are expected to increase, especially if interest rates are low. When fuel costs are stable or expected to fall or the cost of borrowing money is high, coal may be a better choice.

Cost comparisons affect how we run our power plants. Electricity demand varies, so plants do not all run continuously at full power. In a fossil fuelled plant, power reductions save money on fuel. Most of the costs of nuclear power continue, whether or not the plant is producing energy. As a result, the economic way to run a nuclear plant is to keep it operating at full power.

We call continuous operation at full power base load operation. When demand changes, the fossil fuelled plants adjust their output. We call this load following or demand power operation. Some nuclear units also adjust their output to the load. Large power maneuvers are not possible because of operating problems caused by nuclear processes in the fuel. This will be discussed more in future sections of this course.

Frequent power changes increase the risk of damaging the nuclear fuel because of thermal stress.

When a nuclear unit is down for repairs, expensive electricity from a fossil fuelled plant replaces the lost production. Meanwhile, nuclear costs remain high during the shut down. Equipment failures, unplanned maintenance and operating errors cause expensive outages in nuclear plants. It is important to the utilities to prevent unplanned outages and when they do occur to limit the duration.

Experience with CANDU reactors shows nuclear power is much less expensive than fossil fuel power when nuclear plants are kept running 80% or more of the time. New CANDUs routinely do this well or better.

Good performance over the life of a reactor will result in a significant cost advantage of nuclear over fossil fuel. Poor operation can make nuclear power very expensive.

A capacity factor of 60% is sometimes given as a crude estimate of the break-even point between nuclear and fossil fuelled plants.

The advantage of uranium over fossil fuel will likely increase as world oil and gas supplies dwindle and concerns about greenhouse gases grow. The supply of uranium is finite too. Canada is fortunate to have supplies for itself and for a large export market for at least 50 to 60 years. It is possible, but not now economic, to use thorium as the nuclear fuel in a CANDU reactor. When uranium is used up, thorium could extend fuel supplies for 100 years or more.

10.4.3 Environmental Effects

The effects of nuclear and fossil fuelled power plants on the environment are very different. Radiation is an inevitable disadvantage of nuclear power production. Both heat and radiation are produced when the process of nuclear fission converts uranium, which is slightly radioactive, into highly radioactive fission products. Fission products in the fuel emit radiation long after the fission process has stopped. Activation produces some radioactive substances in materials exposed to radiation from the core.

These factors affect the construction of nuclear plants and how work is performed in them. Radioactive releases to the public, however, are extremely small. Releases are carefully monitored. The legal limits on release of radioactive materials are lower than the radiation level from sources in the natural environment. Typical releases during operation are a fraction of allowable releases. We know there are small emissions, but sampling near CANDU plants does not show radiation levels higher than normal background.

What alarms people is the chance of an accidental release of large amounts of radioactivity. This course describes equipment that helps prevent such accidents. The following principle of safe operation is oversimplified, but is essentially correct.

If the fuel is kept wet it will not fail and release radioactive material.

The following sections will point out features of the reactor design intended to make sure the fuel stays wet. We examine reactor safety, which depends on people as well as equipment, in other courses.

Activation is the name given to any interaction of radiation with matter that converts over time matter into a radioactive substance.

Conventional plants also produce wastes. A large coal fired unit without scrubbers generates over 15,000 tonnes of carbon dioxide ($C0_2$), 200 tonnes of acid gas (sulphur dioxide and oxides of nitrogen), several tonnes of fly ash and 500 tonnes of ash each day. These wastes are much less harmful than nuclear radiation, but they are not completely harmless. The above includes, for example, more than a tonne of poisons such as arsenic and mercury.

Scrubbers reduce releases from modern conventional plants, but the release of some acid gases and toxic materials is inevitable. Scrubbers cannot remove carbon dioxide. CO_2, while not directly harmful to health, adds to global warming.

With or without scrubbers, a conventional plant produces a large quantity of solid waste that requires disposal. A large nuclear unit, in contrast, uses fewer than 20 nuclear fuel bundles a day. That is less than a half tonne of waste. At present, water pools at the plant site hold highly radioactive used fuel. Concrete silos can safely store older fuel.

Long-term storage of nuclear waste is another problem. Radioactivity from nuclear decay decreases over time. The radioactivity of different materials decreases at different rates. In 100 years or so, the radioactivity of the used fuel comes from a few very long-lived radioactive substances, mainly plutonium and the remaining, unused uranium.

Because of these long-lived isotopes, the used fuel must be isolated from the environment for a very long time. Designing a secure storage method has been difficult. The political problem of setting up a disposal site also will be difficult.

In summary, used nuclear fuel contains extremely dangerous radioactive materials. This material is kept localized, with a very small chance of release. Waste from fossil fuelled plants is less harmful, but is not kept isolated from the environment. For example, the smokestack spreads substances that may harm health or the environment over a large area.

All power plants discard heat into the surroundings. Nuclear plants are not as efficient as modern conventional plants and produce more waste heat. In Canada, plants are sited on large bodies of cold water. The effect of this heat on the surroundings is not believed to be particularly harmful.

10.5 Summary of Key Ideas

- Nuclear power is less expensive than fossil fuel power if the nuclear plant is operated reliably at high power for long periods. The cost advantage comes from the low fuelling cost.
- Nuclear power production is less flexible than power production from a conventional plant. There are two reasons. Costs in a nuclear plant continue even when it is not producing power. Technical reasons limit the depth and frequency of power maneuvers.
- The consequences of radiation release from a nuclear plant are very serious. Extreme care is taken to run the plants safely. The hazard from a fossil fuelled plant is much less, but some harm to the environment is inevitable.
- Conventional plants produce huge volumes of relatively harmless waste. Nuclear plants produce very small quantities of highly hazardous waste, and this material remains hazardous for a very long time.
- Both conventional and nuclear plants produce large quantities of waste heat, but this waste heat is not believed to cause serious problems.

10.6 The Energy Flow Path

The introduction stated that an obvious difference between fossil fuelled and nuclear power plants is the source of heat. You will see another difference if you compare the size of the steam equipment.

A good conventional plant produces hot, high pressure (dry) steam. A CANDU reactor delivers steam at lower temperature and pressure (that is, saturated almost wet, steam). This requires larger volumes of steam flow to transfer the same amount of energy. As a result, the steam piping and the steam turbine are physically larger than similar equipment in an equivalent fossil fuelled plant

To increase steam temperature and pressure in the CANDU, the design would have to use thicker material. The tubing that carries the coolant past the fuel interferes with the fission process by absorbing neutrons that cause fission. It cannot be thicker. Also, the fuel would need to be redesigned to operate at a higher temperature.

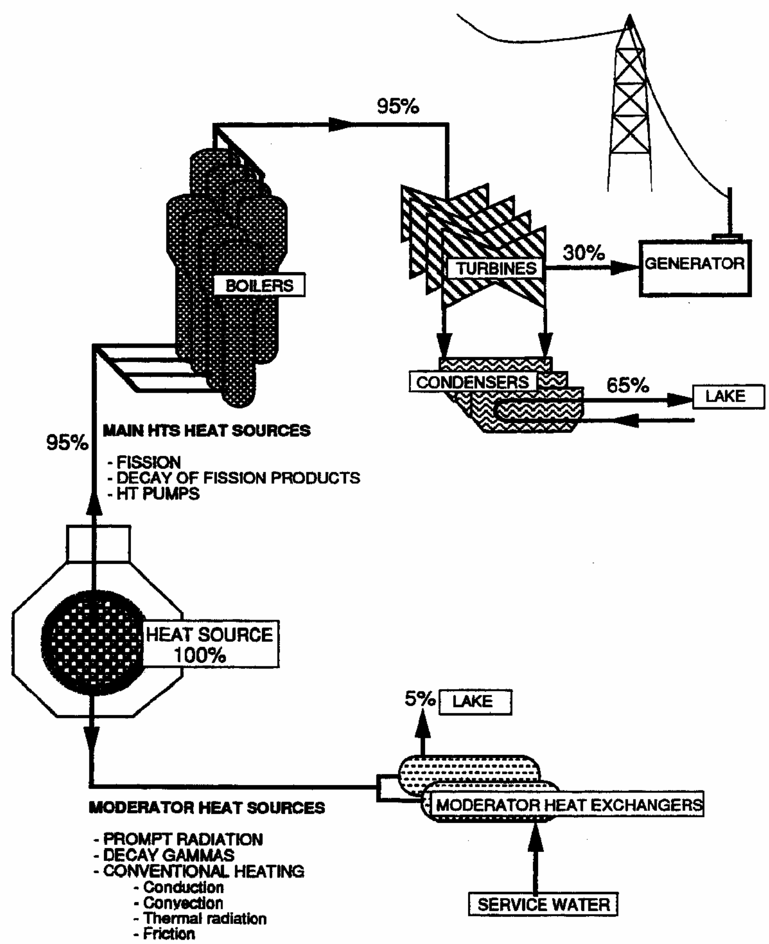

Figure 10.2
Major Energy Flow in a CANDU Power Station

Using saturated steam affects the thermal efficiency of the nuclear plant.

Equipment that turns heat energy into mechanical energy is never very efficient. In round numbers, a conventional plant throws away about 60% of the heat energy generated by burning oil or coal. A nuclear plant wastes as much as 70%. (Your automobile engine is even less efficient!)

You can see the source of this inefficiency for a steam turbine. The turbine, to operate, must have high pressure at one end and low pressure at the other. The condenser condenses the exhaust steam with cold water to maintain the pressure difference. Heat removed by the water is wasted.

The efficiency of the energy transfer depends almost completely on the temperature difference between the hot steam and the cold condensing water. With cooler steam, a higher percentage of the heat is wasted.

We now describe the energy flow path more carefully, using typical numerical values. This is useful background for understanding the purpose and operation of systems described later.

The CANDU operating license limits the total heat output from the fuel at full power. The smallest units have a license limit of almost 1700 MWth. The limit for the largest units is over 2800 MWth. The megawatt is a measurement of power, the rate of producing and transferring energy. A unit producing 2800 MWth must get rid of 2800 megajoules of energy each second. To see where this energy goes, refer to Figure 10.2 as you read the following.

The steam condensers reject about 65% of the total heat energy produced. This waste heat passes to the lake.

The turbine converts about 30% of the total heat energy produced into mechanical energy. The generator converts the mechanical energy to electric energy. The electrical grid distributes most of this energy to customers. The station uses some of this electricity to operate equipment.

About 5% of the total energy produced shows up as heat in the moderator system. This percentage includes a small amount of heat that escapes into the shielding around the core. Heat exchangers cool the equipment and transfer the heat to the lake.

In principle, the steam could be exhausted to the atmosphere. This would be even less efficient.

The various energies have names. The next few paragraphs define these and illustrate them with design numbers.

The reactor thermal power is the net heat transferred from the fuel to the coolant. A large unit might deliver 2700 MWth to the boilers. Steam pressure developed in the boilers turns the turbine that drives the electric generator.

The gross electrical power is the electric power produced by the generator. Usually about 30% of the reactor thermal power is converted to electricity; this is the thermal efficiency of the energy conversion process.

The unit thermal efficiency is defined as the ratio of the unit gross electrical power to the reactor thermal power.

The electric power used by equipment in the plant is called the station service power. Station service power takes 5% or so of the generator output. The rest of the electric power is delivered to the grid. It is called the unit net electrical power. In our example the power produced by a large unit operating at its maximum design capacity is as follows:

reactor thermal power	2700 MWth
gross electrical power	837 MWe
station service power	47 MWe
net electrical power	790 MWe
unit thermal efficiency	837/2700= 31%

At 80% of full power, the net electrical production would be 632 MWe.

This number leaves out the heat lost to the moderator. For this example, moderator heat is about 120 MWth, so total heat from the fuel is about 2820 MWth

Some station documents quote overall net efficiency. This number compares net electrical power to total power from the fuel. In the example it is 790/2820= 28%.

10.7 Summary Of Key Ideas

- There is a license limit on the total thermal power from the fuel.
- The reactor thermal power, which makes steam, is less than the total heat from the fuel. The moderator system removes about 5% of the heat.
- The turbine/generator set converts about 30% of the reactor thermal power to electricity. This is the gross electrical power.
- The ratio of gross electrical power to reactor thermal power is the unit thermal efficiency.
- The station equipment uses about 5% of the gross electrical power (the station service power). The net electrical power that remains is sold to customers to generate revenue.

10.8 Assignment

1. The reactor core includes fuel, coolant and moderator. What are these for and what are they made of in a CANDU reactor?

2. Give the most important advantage and the most important disadvantage (in your opinion) of nuclear power production compared to conventional power production. Briefly explain your selection.

3. Briefly outline how you think improved energy conservation would affect: (There is no right answer to this question).

    a) The economics of power production from nuclear and from fossil fuels;

    b) The environment

4. What is meant by:

    a) Net Electrical Power?

    b) Reactor Thermal Power?

    c) Thermal Efficiency?