



ESA21

Environmental Science Activities for the 21st Century

Nuclear Energy: Nuclear Energy

Introduction Energy

As we discussed in the last activity, energy is released when isotopes decay. This energy can either be in the form of electromagnetic radiation or the kinetic energy of the nuclear fragments. The important question for us is, "How can this energy be converted into a useful form like electricity?" The most obvious thing to do is to allow either of these forms of energy to be absorbed by a substance in order to increase its internal energy and thus, increase its temperature. As the substance warms up above its surroundings, a temperature difference is created, and allows for any one of a number of heat engines to be placed between the two and convert some of the heat into useful energy.

Radioisotope thermoelectric generators create electricity from this heat difference by use of the Seebeck effect. Discovered in 1821 by Thomas Seebeck, a potential difference or voltage will be created across the juncture of two unlike metals whenever there is a temperature difference applied across the juncture. This potential difference will act as a current source if it is connected to a circuit. These types of generators are quite reliable, as there are no moving parts and the decay of the nuclear material is quite predictable. They have been used extensively in the NASA deep space probe programs, as solar energy is not usable for satellites that are going far away from the Sun. The picture above is the diagram of one of the RTG's that was placed in the Cassini spacecraft that was sent to Saturn.

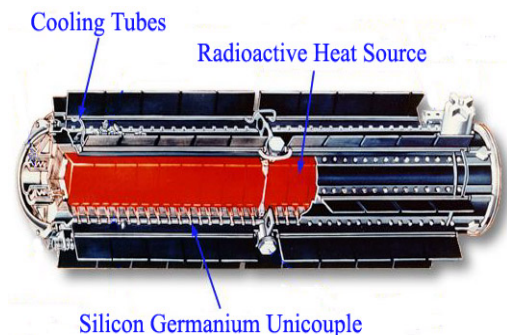


Figure 1: Diagram of the Cassini Spacecraft RTG

The efficiency of these radioisotope thermoelectric generators is not very good, being in the 6-8% range¹. A more efficient way to generate electricity would be to use the absorbed energy to boil water for use in a steam turbine. The steam turbine is the basis behind most of the electricity generated in the U.S., with most power plants of this type having efficiencies in the 30-40% range. Of course, to get efficiencies in this range, water temperatures above 600 °F must be reached.

Limitations on Nuclear Materials

In order to generate this level of thermal activity and to sustain it, power plants need a source that produces a tremendous amount of energy in a short period of time. For a nuclear power plant, this corresponds to having an amount of radioactive material that can fit in the plant that has a high activity. As we saw in last week's activity, a high activity requires either a large amount of a radioactive substance and/or an isotope with a short half-life. The physical limits on the amount of available isotopes and on the size of the power plant put constraints on the amount of material that can be used. Therefore, to get the required level of activity, a substance with a relatively short half-life is needed.

This presents a problem, as substances with short half-lives are rarely found in nature in large abundance. This should not be surprising. Given the fact that the Earth is approximately 5 billion years old, any short half-life material that was originally present would have completely decayed by now. New isotopes are being created all of the time, as we found out last week, and some of these might have a short half-life. However, by the time that the material is found, mined, refined, and put into a power plant, a significant fraction of the material will have decayed.

Thus, using natural decay of radioactive isotopes is not a very useful means for running a nuclear power plant. One could use bombardment of nuclei in order to break the isotopes apart and generate energy. As we pointed out last week, the easiest method for achieving this is to bombard the nuclei with neutrons, as their electrostatic neutrality means that there will be no force of repulsion from the protons in the nuclei. This does solve the problem of having enough nuclear material with a high enough activity to run the plant, as we can break apart even stable isotopes with this method. But it does create another problem. In order to bombard the material, we will have to input energy (separating neutrons from other material and accelerating a beam of them onto the nuclear material), which means that our overall efficiency will be less than what we desire.

Chain Reactions

We could get around this problem if we had a substance that produced free neutrons as a result of its being bombarded with neutrons. In other words, we need a substance that produces the catalyst (bombarding neutrons) from a reaction that was caused by the catalyst. It turns out that we are in luck, in this regard, as there is one naturally occurring isotope that is abundant enough to run a power plant. When uranium-235 (U-235) is bombarded with low energy neutrons, its nucleus will fragment into several parts, with neutrons being amongst them. A typical reaction for U-235 (one of many possibilities, all of which produce neutrons) is



The three neutrons that are released by this reaction are free to bombard three other uranium-235 nuclei, which would then decay into barium and krypton fragments with up to 9 more neutrons and about three times the amount of energy being released.

This **chain reaction** would look something like the picture to the right. There are two features about this chain reaction that require further discussion. The first of these is that it is only slowly moving neutrons that have a high probability of interacting with the uranium-235 nuclei and causing a reaction. Therefore, a **neutron moderator**, which slows the neutrons down, is needed in a nuclear power plant in order to keep the chain reaction occurring. The second feature has to do with the number of neutrons that will be present after several different decays. While there are many different possible decay reactions that could take place, the uranium-235 nucleus will average about 2.5 neutrons released in each one. This means that each reaction will produce more neutrons than what were there initially, thus causing more reactions to take place at the next stage. If this is allowed to go on for some time, there will be so many neutrons around ready to react that too many decays will start taking place, which will release too much energy and cause the material to melt down. For this reason, **control rods**, which are made from materials that readily absorb neutrons, need to be in the system in order to limit the number of reactions that can take place at any given time.

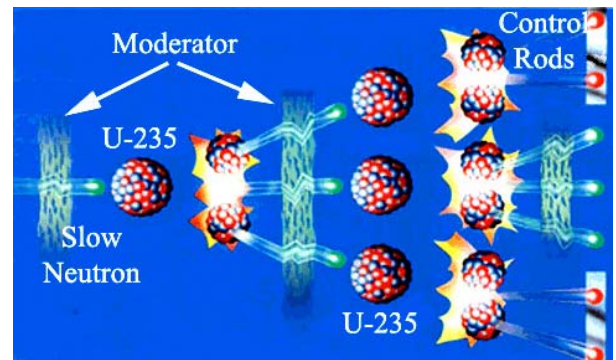


Figure 2: U-235 undergoing a chain reaction

Basic Reactor Design

Besides having neutron moderators and some method for controlling the number of neutrons in the reactor, a nuclear power plant also has to have some way of transferring the thermal energy of the nuclear material to water in order to create steam to power a turbine. This can be done in a number of ways, depending upon how safe you wish to make the reactor and how much energy you wish to create. In the U.S., we have two basic designs for reactors. A boiling water reactor (BWR) places the hot nuclear material directly in the water where steam is created. This expanding steam is used to turn a turbine, which is connected to a generator that creates electricity. After the steam has passed through the turbine, it is cooled by a heat exchanger until it condenses back to hot water, and is then pumped back

into the reactor chamber. A pressurized water reactor (PWR) looks similar to a BWR, except that the reactor is sitting in water that gets extremely hot, but is not allowed to turn to steam by the pressure applied to the chamber. This extremely hot water is used to heat another chamber of water where steam is generated. A diagram of a PWR is shown in Figure 3 below.

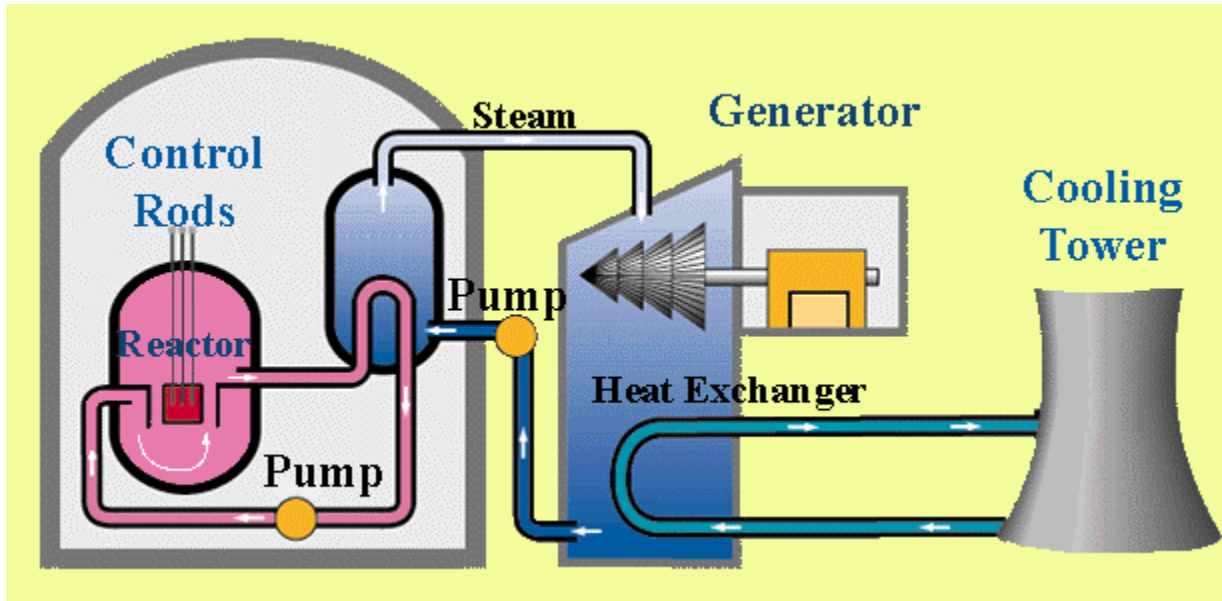



Figure 3: Schematic of a pressurized water reactor

While these are the two designs used in the U.S., they are far from being the only nuclear reactor designs. Other countries have experimented with different designs, with varying degrees of success. For instance, the former Soviet Union used an RBMK design that had carbon as its neutron moderator and water as a coolant that was passed through the reactor chamber in pipes, i.e. the fuel rods were not sitting in water. This reactor was the one that was involved in the famous accident at Chernobyl. To learn more about the different styles of reactors, check out the second link below.

Additional Reading

The following website leads to the U.S. Nuclear Regulatory Commission, which seeks to protect the public health and safety, as well as the environment, from the effects of nuclear reactors, materials, and waste products. This site provides information on reactors that are in operation in the U.S. and on the materials and waste that are involved in the process.

 <p>Nuclear Regulatory Commission</p>	<p>Summary: Links to information about U.S. reactors, nuclear materials, and nuclear waste Link: http://www.nrc.gov/</p>
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The next website is a privately owned website that is maintained by Joseph Gonyeau, a consulting nuclear engineer for the IAEA and the DOE. This site contains a wealth of information and links regarding the entire fuel cycle process. Of particular interest is the information on the various nuclear reactor designs found around the world.

<p>Virtual Nuclear Tourist</p>	<p>Topic: Nuclear Reactor Designs Summary: Private informational website about nuclear energy. Check under Plant Designs for information about different reactor types. Link: http://www.nucleartourist.com/</p>
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Internet Exercise

Reactor Simulation

The process of running a nuclear power plant is very complicated. It requires many people, and many thousands of hours of training. It would be impossible to replicate this experience without actually getting you a job at your local nuclear power plant. However, we can give you a feeling for some aspects of running a plant with a simple simulation of a nuclear power plant. The objective of the simulation is to run the power plant so that your power production remains high (above 10,000 kilowatts) throughout the life cycle of the fuel rods. If the power production gets too low, the local citizens will experience brownouts or blackouts, which is bad for business. If the power production gets too high, you risk having an accident, which is even worse for business. This simulation was written by Geoffrey Noles and has been checked out by nuclear engineers for realism.

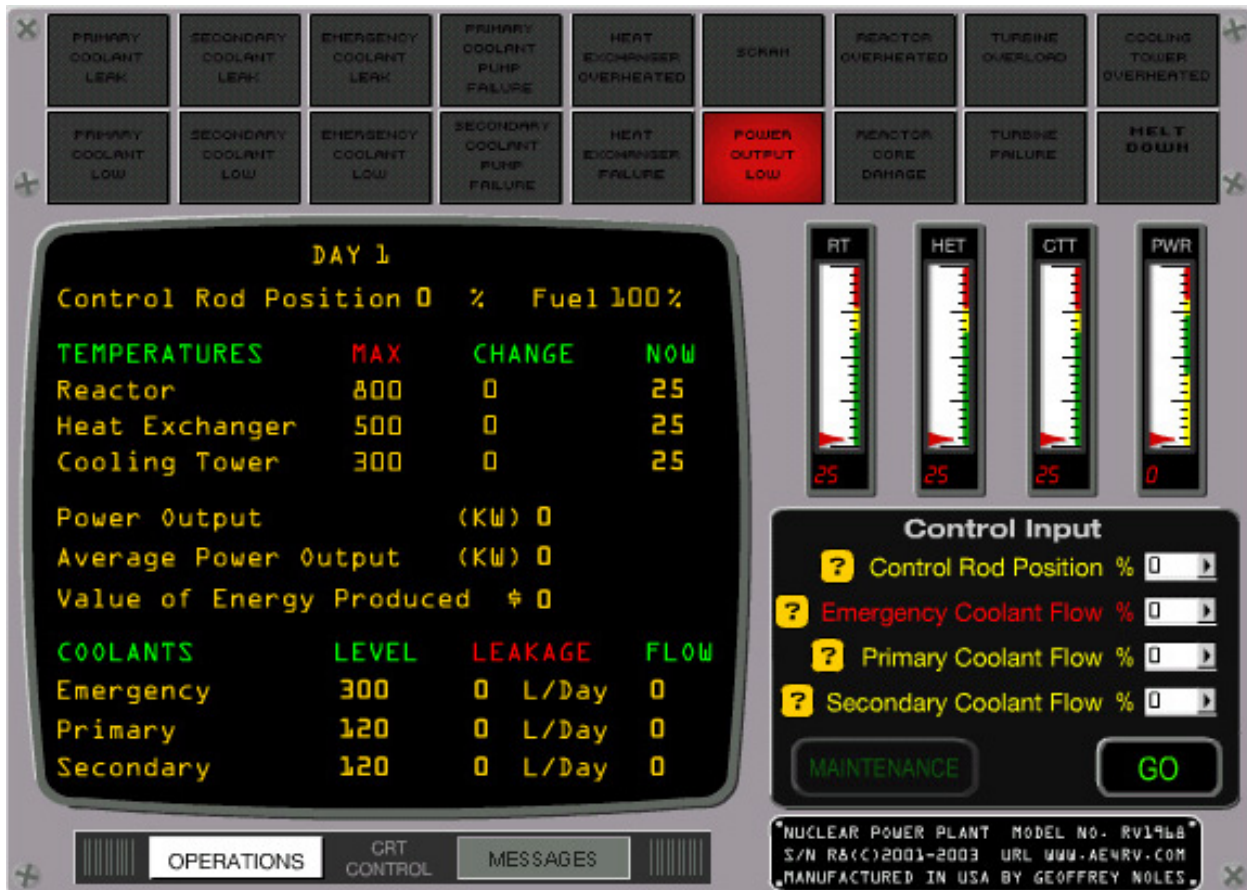


Figure 4: Image of the control panel from the simulation

A picture of the control panel from the simulation is shown in Figure 4. The simulation allows the user to control 4 major variables in a nuclear power plant: control rod positions, primary coolant flow, secondary coolant flow, and the emergency coolant flow. By increasing the control rods' positions, you will allow more neutrons to interact with the fuel, thereby increasing the number of decays in the chamber. This releases more energy and causes the fuel rods to get hotter. Thus, the control rod position acts similar to a temperature controller for the reactor chamber. However, it is not exactly the same thing. As the fuel rods become depleted, the rods will have to be pulled out further in order to maintain the same temperature. Also, if you push the control rods all the way in (position 0), it will take some time for the reactor to cool off back to room temperature.

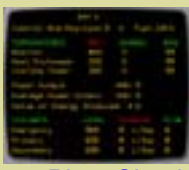
The temperature of the reactor chamber is also affected by the primary coolant flow. This switch is used to cool the reactor and to bring heat to the heat exchanger. This is a closed system, which means that

the amount of fluid in it is fixed unless a leak develops. The secondary coolant switch controls how much heat is taken from the heat exchanger in the form of steam and sent to the turbines for conversion to electricity. The higher the temperature in the secondary coolant system, the more steam is generated, and the more electricity is output. Just as with the primary coolant system, this system is closed, which means no coolant is lost outside of the occasional leak.

The last switch under your control is the emergency coolant flow. This coolant is only needed when a problem occurs at the plant and it needs to be shut down quickly (example: a leak develops in the secondary system and coolant levels become too low). If a problem should occur that requires maintenance, the temperature of the reactor chamber must be brought below 100 C before any work can be done. To get the plant to this situation quickly, you will need to shut the reactor down (put the control rods to position 0), and begin to pump emergency coolant into the reactor chamber. There is a limited supply of coolant that you can use, so keep an eye on how much coolant you have left before you put it in.

In the simulation, you will be able to change each of these variables once per day. After making your selections on these variables, you will click on Go, which will step all other variables forward one day in time. After you see the reaction that the system makes to your changes, you should decide whether to change the settings or to leave them as they are. If you are unsure of what a switch or light means, the simulation has mouseover help. Simply move your mouse over the dial or switch in question, and help will appear on the system display.

For this activity, we would like for you to operate the plant three different times, keeping track of your settings and output at 10 day intervals. You should keep track of the following variables: rod position, primary coolant flow, secondary coolant flow, reactor temperature, heat exchanger temperature, cooling tower temperature, power output, and average power output. At the end of each run, print off the last screen to verify what your final settings and output were. Fill in the tables on the activity sheet, answer the questions, and attach these three printouts.

 <p>Power Plant Simulator</p>	<p>Topic: Nuclear Power Plant Simulator Summary: Private informational website about nuclear energy. Check under Plant Designs for information about different reactor types. Required: Flash Plug-in Link: http://esa21.kennesaw.edu/activities/nukeenergy/nuke.htm</p>
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References

- 1 http://www.llnl.gov/seaborginstitute/training/radiation_misuse_2.pdf, June 9, 2003.

ESA21: Environmental Science Activities

Activity Sheet
Nuclear Power Plant

Name:
Lecture Professor:

Run 1

Day	Rod Position	Prim. Flow	Sec. Flow	Reactor Temp	H.E. Temp	C.T. Temp	Power Output	Avg. Power	Energy Value
10									
20									
30									
40									
50									
60									
70									
80									
90									
100									

Run 2

Day	Rod Position	Prim. Flow	Sec. Flow	Reactor Temp	H.E. Temp	C.T. Temp	Power Output	Avg. Power	Energy Value
10									
20									
30									
40									
50									
60									
70									
80									
90									
100									

Run 3

Day	Rod Position	Prim. Flow	Sec. Flow	Reactor Temp	H.E. Temp	C.T. Temp	Power Output	Avg. Power	Energy Value
10									
20									
30									
40									
50									
60									
70									
80									
90									
100									