Nuclear Power

The uranium-235 isotope reacts with a neutron to generate an unstable isotope, uranium-236. The heat that results from the fission of uranium-236 can be used to generate electricity. Nearly half of the electricity produced in Illinois is from nuclear power plants. In order to produce a fissionable nuclear fuel, uranium ore must be enriched

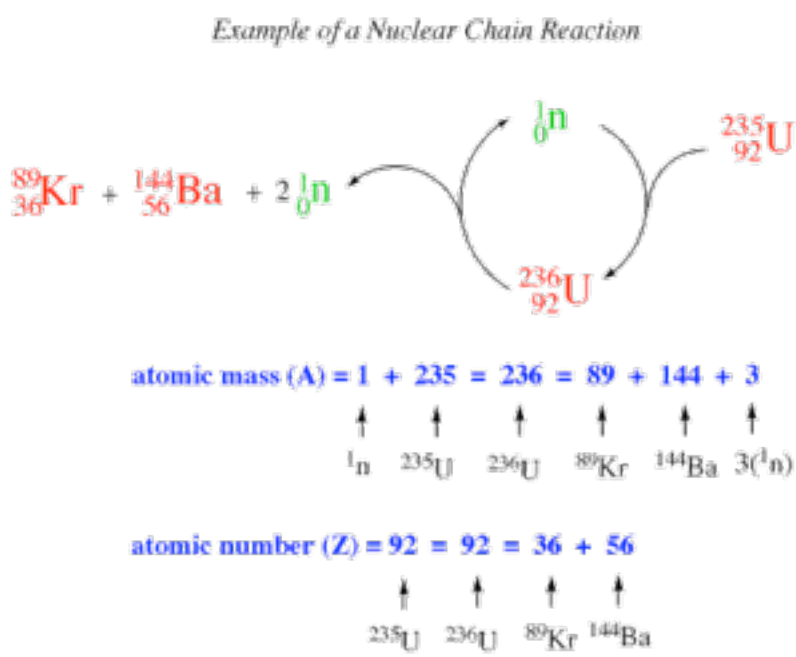
Outline

- Generating Heat
- Fuel for Fission
- Heat to Electricity
- Homework

Generating Heat

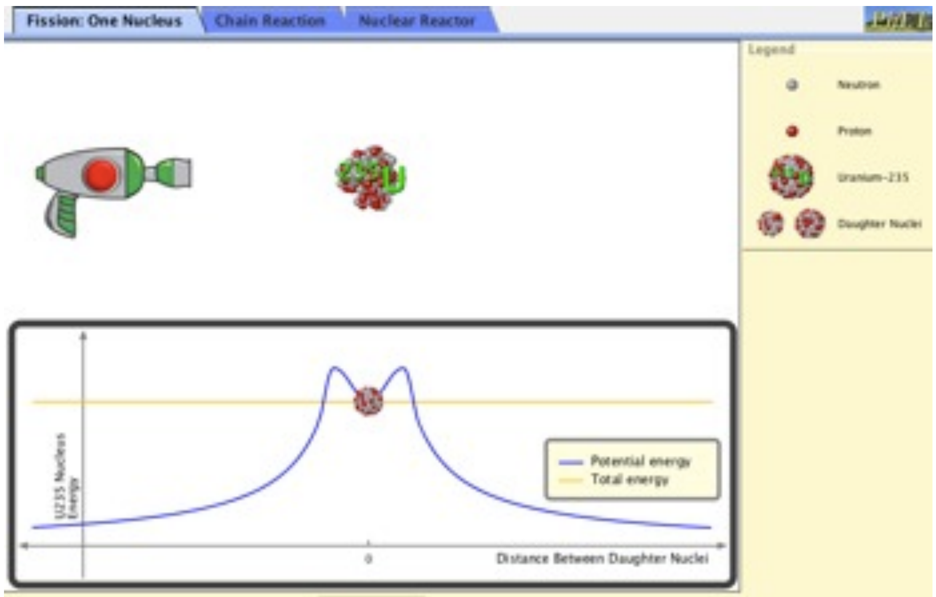
Fission

Fission produces energy and nuclear power plants use the fission reactions of U-236 to generate heat that then is converted to electricity. In a nuclear power plant, there is a chain reaction. Uranium-235 reacts with a neutron to generate uranium-236. This splits into fission products and also produces additional neutrons. The newly formed neutrons react with more uranium-235 to make uranium-236 that undergoes fission, etc. The result is a **chain reaction**.



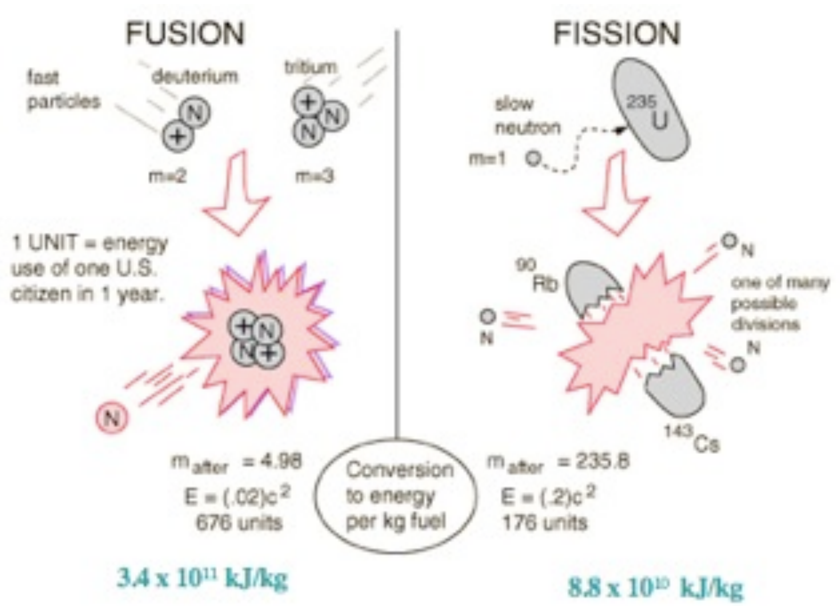
In the chain reaction above, krypton-89 and barium-144 are produced along with 3 neutrons. There are, however, many possible fission products. For any fission reaction, the sum of all neutrons and protons in the products is the same as the reactants and the total number of protons in the products is the same as the reactants. A small amount of mass is lost and this mass is converted into energy.

Click on the picture below to model nuclear fission. Fire a neutron at a U-235 nucleus to see what happens. The explore the chain reaction.



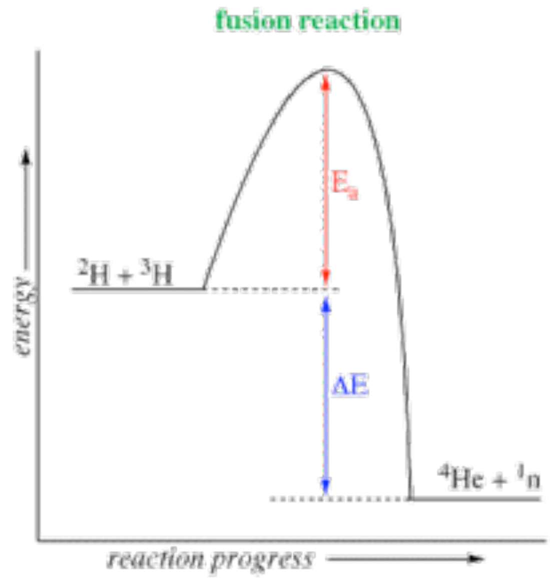
Fission vs. Fusion

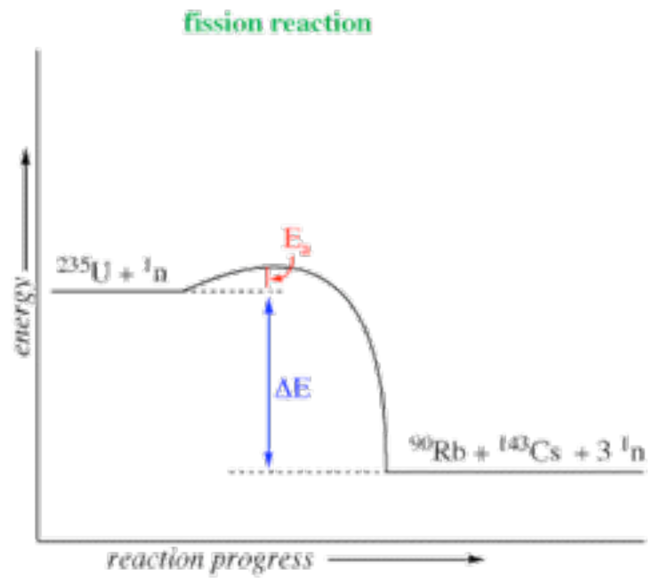
Fusion produces more energy per kilogram than fission but a fission reactor is much easier to build and requires much less energy input. The energy is released as heat. All commercial nuclear reactors in the US are fission reactors.



We can think about the two processes in reaction coordinate diagrams. As the fusion reaction begins (on the left), there are only hydrogen isotopes ^2H and ^3H at a particular energy. Energy must be expended (E_a

or activation energy) to heat the mixture to a very high temperatre and to pressurize it before the products can form. The products, a helium-4 nucleus and a neutron, have a much lower energy than the reactants. The energy difference is ΔE. At the end of the reaction (on the right), energy released as heat is equal to $\Delta E + E_a$.





In the fission reaction, much less energy must be added for the reaction to take place. The activation energy is very small. The energy difference between reactants and products is still very large but less than that of the fusion reaction.

Comparison to Other Fuels

You've already seen two chemical reactions that produce energy as heat. In the combustion of methane in natural gas, 890 kJ of energy is given off as heat for every mole of methane that burns. Methane includes 1 carbon atom (~12 g/mol) and 4 hydrogen atoms (~1g/mol) for a molecular weight of about 16 g/mol.

$$CH_4 + 2\,O_2 \longrightarrow CO_2 + 2\,H_2O \qquad \Delta E = -890 \text{ kJ/mol}$$

$$1 \text{ mole } CH_4 = \underset{C}{12 \text{ g}} + \underset{H}{4(1 \text{ g})} = 16 \text{ g}$$

$$\frac{-890 \text{ kJ}}{\text{mol}} \times \frac{1 \text{ mol}}{16 \text{ g}} \times \frac{1000 \text{ g}}{\text{kg}} = -5.6 \times 10^4 \text{ kJ/kg}$$

The combustion of hydrogen releases 286 kJ for every mole of H_2. A mole of molecular hydrogen weighs about 2 grams.

$$H_2 + 1/2\,O_2 \longrightarrow H_2O \qquad \Delta E = -286 \text{ kJ/mol}$$

1 mole $H_2 = 2(1\text{ g}) = 2\text{ g}$

$$\frac{-286\text{ kJ}}{\text{mol}} \times \frac{1\text{ mol}}{2\text{ g}} \times \frac{1000\text{ g}}{\text{kg}} = -1.4 \times 10^5 \text{ kJ/kg}$$

Nuclear reactions produce much more heat energy per kg than the chemical reactions. In the table below, the fuel for the nuclear reactions is the mass decrease. In the chemical reactions, the fuel results from the change in chemical bonds.

Reaction	Heat Energy (kJ/kg)
H-2 + H-3 $\longrightarrow$ He-4 + n	-340,000,000,000
U-235 + n $\longrightarrow$ Rb-90 + Cs-143 + 3 n	-88,000,000,000
$CH_4 + 2\,O_2 \longrightarrow CO_2 + 2\,H_2O$	-56,000
$H_2 + 1/2\,O_2 \longrightarrow H_2O$	-140,000

Fuel for Fission

Natural Abundance of U-235

Uranium has 3 common isotopes. These are listed in the table along with their natural abundances.

Isotope	Mass (amu)	Natural Abundance (%)
U-234	234.040946	0.0055
U-235	235.043923	0.7200
U-238	238.050783	99.2745

Of these three isotopes, only uranium-235 reacts with a neutron and undergoes nuclear fission in a conventional nuclear reactor. To have a sustained fission reaction there must be enough U-235 so that at least one of the neutrons it produces in fission will likely strike another U-235 nucleus. The needed concentration of U-235 must be about 3 % of the total uranium.

Uranium ore has an elemental composition of U_3O_8, 8 oxygen atoms for every 3 uranium atoms in the material. It is not a simple molecule though. The ore is relatively plentiful in the US, Canada, Australia, and South Africa. When purified from the other rock it has a yellow color and is called yellowcake. Because only 0.72 % of the uranium in yellowcake is U-235, it is not suitable as a nuclear fuel.

Separating Uranium Isotopes

Isotopes of an element are very similar. They have the nearly the same chemical and physical properties. The difference is a slight difference in mass. *Can this mass difference be exploited to separate isotopes?*

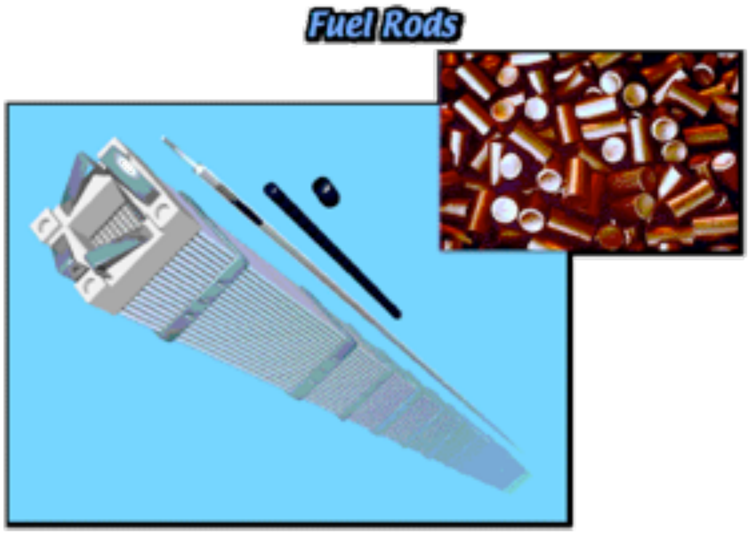
The first step is to chemically change the uranium ore into a gas-phase molecule. The uranium ore is transformed in a chemical process to UF_6. When heated, UF_6 is a gas.

The gas is pumped into a centrifuge. Spinning the gas at high speed causes some separation with the heavier $^{238}UF_6$ somewhat more concentrated at the bottom and the lighter $^{235}UF_6$ a little more enriched at that top. The UF_6 mixture from the top is taken to another centrifuge. The process is repeated hundreds of times. Below is a gas centrifuge apparatus for uranium isotope separation.

At the end of the process, the UF_6 contains 3 to 5% uranium-235. In another chemical process, the UF_6 is converted to a solid material with 2 oxygen atoms per uranium, UO_2

Fuel Rods

The solid UO_2 is packed inside zirconium metal pellets. The pellets are combined to make fuel rods.

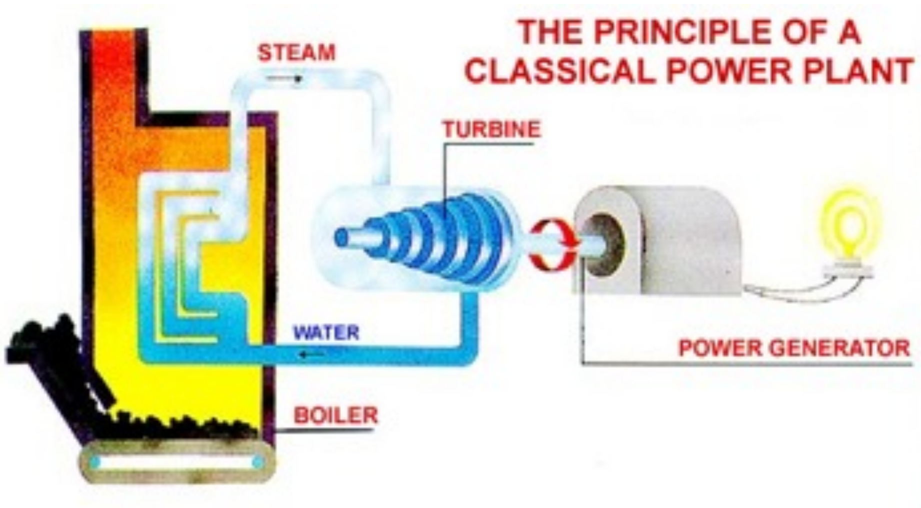


Below you can see some spent fuel rods in water.

Heat to Electricity

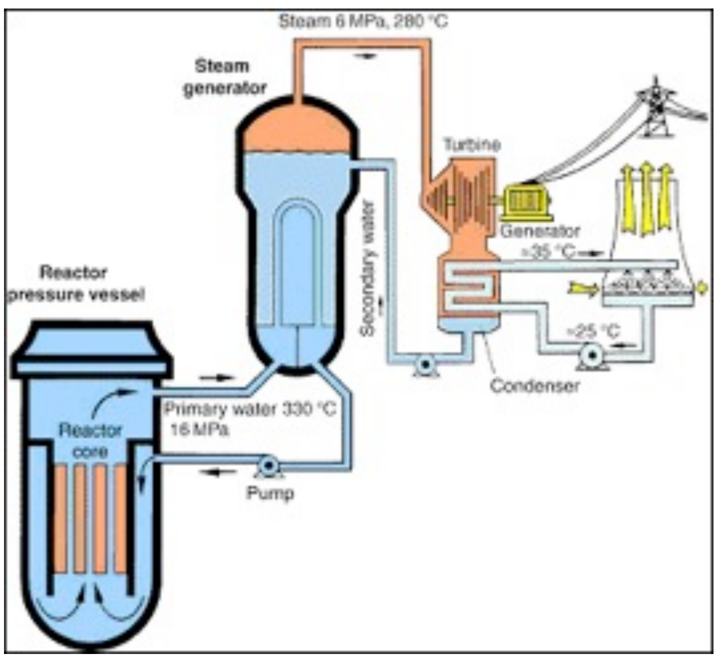
Standard Electric Power Plant

About half of the electricity produced in Illinois comes from burning coal in coal-fired power plants. The other half comes from nuclear power plants. Below is a diagram for a convention power plant. Some type of fuel (usually coal but also petroleum or natural gas) is use to heat water into steam. The pressure from the steam moves a turbine that is connected to a generator unit. The generator converts the motion of the turbine into electric energy that can be carried through power lines to the consumers. The steam is condensed and returns to the boiler.



Nuclear Electric Power Plant

Instead of burning a fossil fuel, water or other heat transfer fluid is heated by the energy given off by nuclear fission of uranium-236. The diagram below shows a pressurized water reactor. Note that the water that cools the reactor core is used to heat other water that actually drives the turbine. The water coolant is sealed so that radioactive material can't go outside the reactor core.



Because of radiation given off in the fission reactions, the reactor core is completely contained and separate from the electric generation part of the plant.

There are some parts of the plant that are unique to a nuclear power plant.

1. Fuel Rods

The fuel rods consist of zirconium-encased pellets of UO_2 with 3-5 % uranium-235 in uranium-238.

2. Moderator

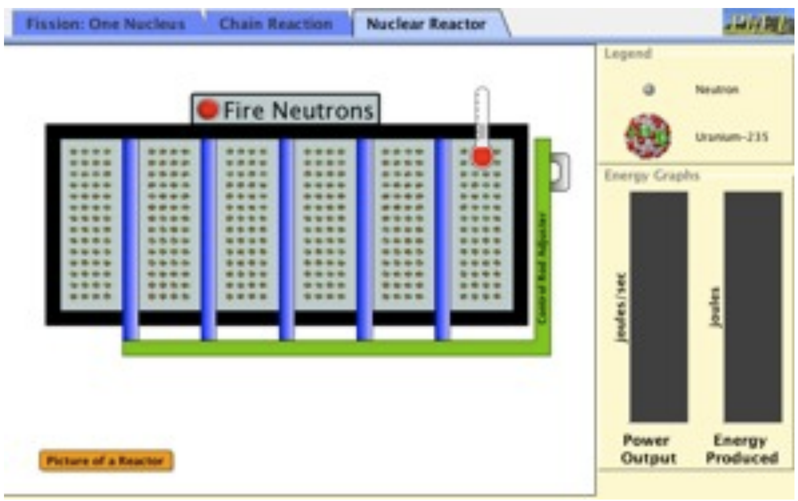
This is a substance that can slow the neutrons produced in fission so that these can be absorbed by the other nuclei and support the chain reaction. Water is the moderator in most reactors.

3. Control Rods

These are substances that absorb neutrons and can control (or stop) the fission reaction. Boron and cadmium are typical substances that absorb neutrons in these control rods. The rods can be moved into the reactor core as needed. Control rods can inserted or withdrawn. For a boron-containing control rod, the reaction with neutrons is:

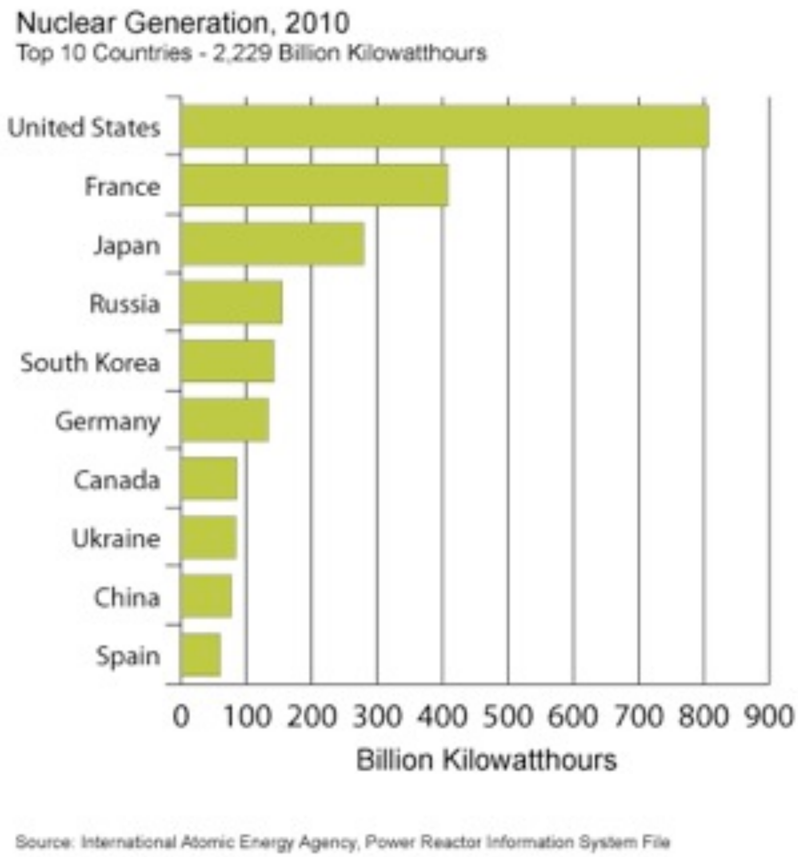
$$^{10}_{5}B + ^{1}_{0}n \rightarrow ^{7}_{3}Li + ^{4}_{2}He + 2.8\ MeV$$

Go back to the model fission reaction. Choose the nuclear reactor and observe the changes as you raise and lower the control rods.



US Use of Nuclear Power

There are currently 104 operable commercial nuclear reactors at 65 nuclear power plants in the United States. We have more nuclear power capacity than any other country and, on average, 20 % of the electricity in the country (nearly 50 % in Illinois) comes from nuclear power. Between 1985 and 1996, 34 new reactors were placed in service.



Clinton Power Plant

The Clinton Nuclear Power Plant is located near Clinton, Illinois is the closest one to the University of Illinois campus. It has a General Electric boiling water reactor on Clinton Lake. The power station began service on April 24, 1987.

REACTOR INFORMATION	
REACTORS OPERATIONAL	1 x 1043 MW
REACTORS PLANNED	1 at least 1,100 MW
REACTOR TYPE(S)	boiling water reactor
REACTOR SUPPLIER(S)	General Electric
POWER GENERATION INFORMATION	
ANNUAL GENERATION	9,250 GW-h