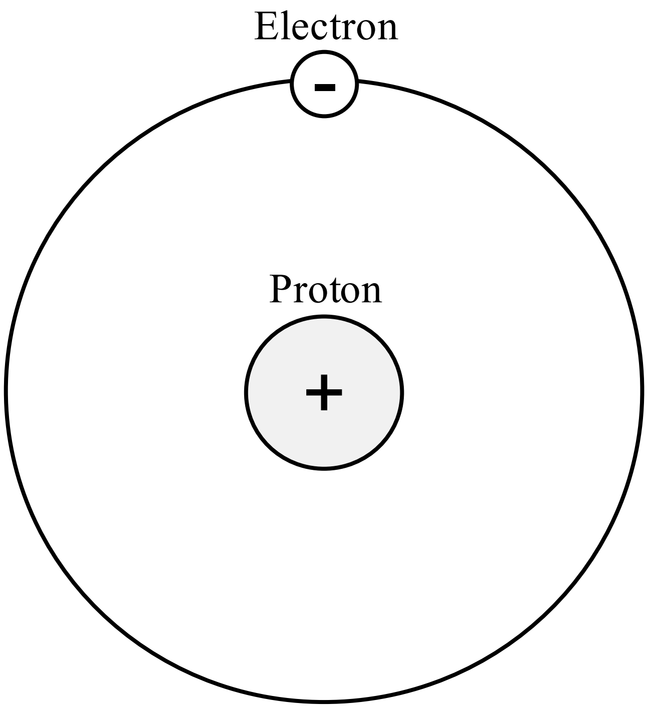
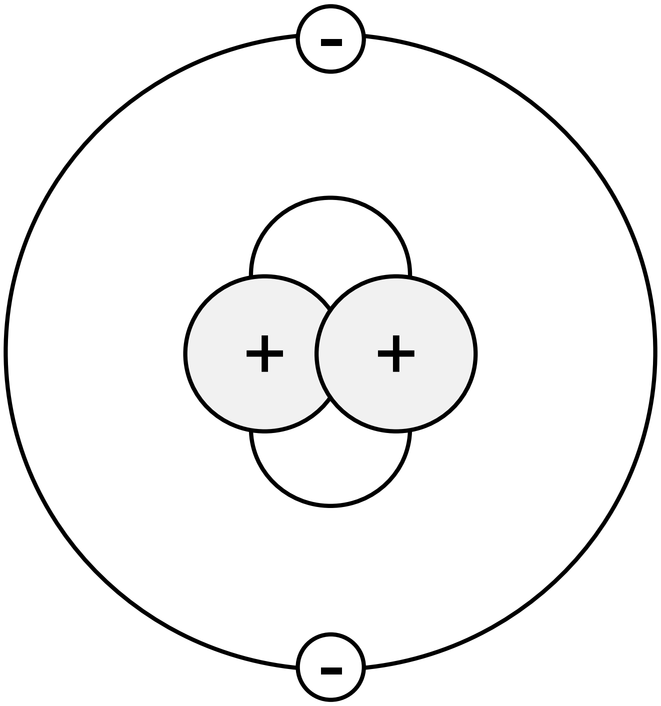
The Fission Process and Heat Production

A nuclear power plant converts the energy contained within the nuclei of atoms into electrical energy. This section discusses the release of nuclear energy by the fission of uranium atoms and the methods used to control the rate at which energy is released and power is produced.



$^{1}_{1}\mathrm{H}$ Hydrogen

Atoms are composed of positively charged protons in the nucleus and negatively charged electrons orbiting the nucleus. The simplest atom is hydrogen, composed of one proton and one electron. Its atomic number, which is equal to the number of protons, is 1.



$^{4}_{2}\mathrm{He}$

Helium

More complex atoms have more protons and electrons, but each unique combination of protons and electrons represents a different chemical element. Helium, for example, with two protons, two neutrons, and two electrons, has an atomic number of 2.

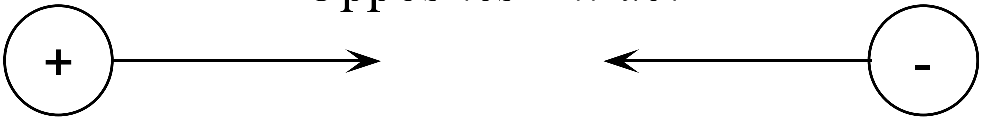
Periodic Table of the Elements

1 H																	2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba		72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra		104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 110	111 111	112 112		114 114		116 116		118 118
			57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
			89 Ac	90 Th	91 Pa	**92** **U**	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

Each element has a chemical symbol. Elements are listed by increasing atomic number and grouped by similar chemical characteristics in the Periodic Table of the Elements.

Like Charges Repel

Opposites Attract

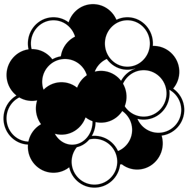


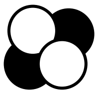
Electrostatic Force

Since all protons are positively charged, and since like charges repel, electrostatic force tends to push protons away from each other.

Neutrons

Provide
Nuclear
Attractive
Force





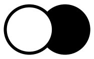
Minimum
Electrostatic
Repulsion

Hold Larger Atoms Together

Neutrons, with no electrical charge, provide the attractive nuclear force to offset the electrostatic repulsive forces and hold atoms together. All atoms found in nature, except the basic hydrogen atom, have one or more neutrons in their nuclei.

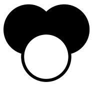
Hydrogen Isotopes

Deuterium



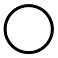
$^{2}_{1}\mathrm{H}$

Tritium



$^{3}_{1}\mathrm{H}$

Hydrogen

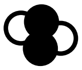


$^{1}_{1}\mathrm{H}$

A chemical element can have several different combinations of protons and neutrons in its nuclei. Hydrogen, above, has three naturally occurring combinations (known as “isotopes”):

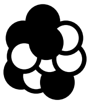
1) Basic hydrogen (one proton, one electron, and no neutrons),
2) Deuterium (one proton, one electron, and one neutron), and
3) Tritium (one proton, one electron, and two neutrons).

$_{1}\mathrm{H}$

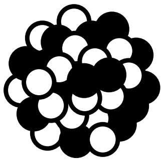


$_{2}\mathrm{He}$

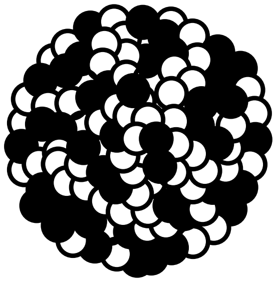
$_{3}\mathrm{Li}$



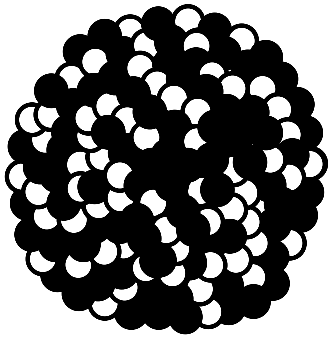
$_{8}\mathrm{O}$



$_{27}\mathrm{Co}$



$_{79}\mathrm{Au}$



$_{92}\mathrm{U}$

The number of protons an element has (atomic number) determines its chemical characteristics. Atomic numbers are always related to the same element (hydrogen-1, cobalt-27, uranium-92).

When used in technical literature, the atomic number is usually written to the lower left of the chemical symbol (as shown above). Often, the atomic number for an element will be omitted from technical writing since this number will never change for the element under discussion.

Naturally Occurring Carbon

$^{12}_{6}C$

6 Protons
6 Neutrons

$^{13}_{6}C$

6 Protons
7 Neutrons

$^{14}_{6}C$

6 Protons
8 Neutrons

Since chemical elements can have different numbers of neutrons, the use of isotopic numbers (or mass numbers) is necessary to distinguish one isotope from another. Naturally occurring isotopes of the element carbon are shown above. The isotopic number (shown to the upper left hand of the chemical symbol) is the sum of the number of protons and the number of neutrons in the nucleus of an atom.

Naturally Occurring Copper

$${}^{63}_{29}\mathrm{Cu}$$

29 Protons
34 Neutrons

$${}^{65}_{29}\mathrm{Cu}$$

29 Protons
36 Neutrons

The commonly found isotopes of copper are shown above. Although the placement of the isotopic number in the upper left is technically correct, many variations are encountered. For example:

$${}^{63}_{29}Cu \quad {}^{63}Cu \quad Cu^{63} \quad Cu - 63 \quad Copper - 63$$

All of these variations refer to the same isotope of copper.

Naturally Occurring Uranium

$^{234}_{92}\mathrm{U}$	$^{235}_{92}\mathrm{U}$	$^{238}_{92}\mathrm{U}$
92 Protons	92 Protons	92 Protons
142 Neutrons	143 Neutrons	146 Neutrons

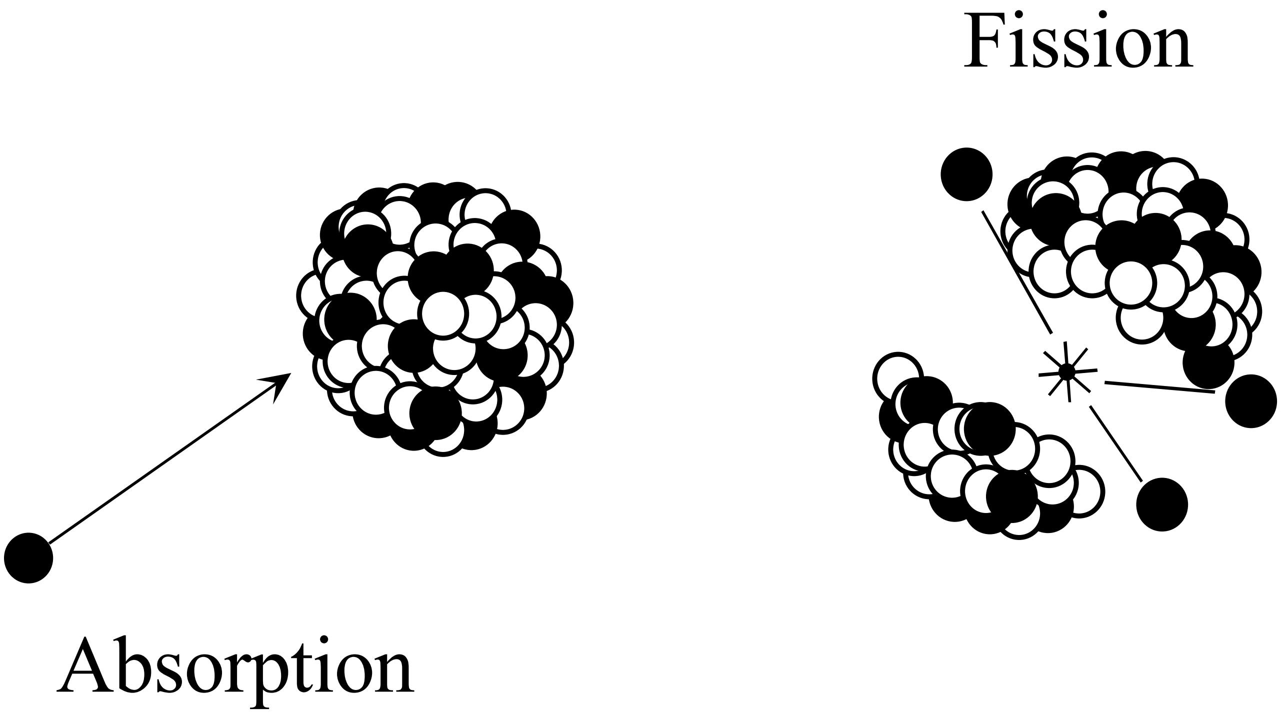
Power reactors in the United States use uranium as fuel. The naturally occurring isotopes of uranium are shown above. About 99.3% of all uranium atoms are the isotope U-238, and the remaining 0.7% are U-235. Trace amounts (far less than 1%) of U-234 can be found. Another isotope, U-233, does not exist naturally, but it can be manufactured and used to fuel some types of reactors.

ENRICHMENT
(% U-235)

Uranium Ore (0.7%)

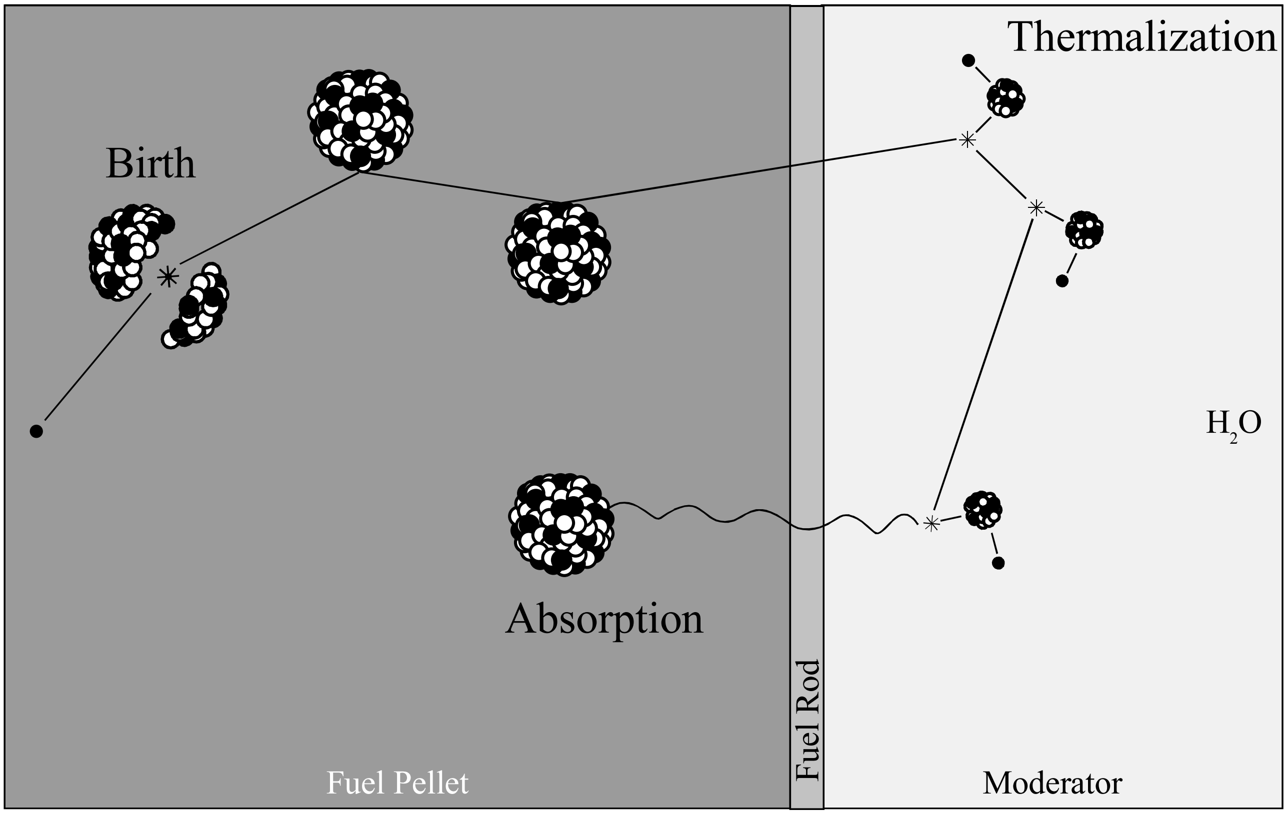
Fuel Pellet (3.5%)

Uranium-235 (enriched from 0.7% abundance to 3.5% to 5%) is the fuel for most power reactors in the United States.



Uranium-235 is useful as a reactor fuel because:

1) It will readily absorb a neutron to become the highly unstable isotope U-236.
2) U-236 has a high probability of fission (about 80% of all U-236 atoms will fission).
3) The fission of U-236 releases energy (in the form of heat) which is used to produce high pressure steam and ultimately electricity.
4) The fission of U-236 releases two or three additional neutrons which can be used to cause other fissions and establish a "chain reaction."



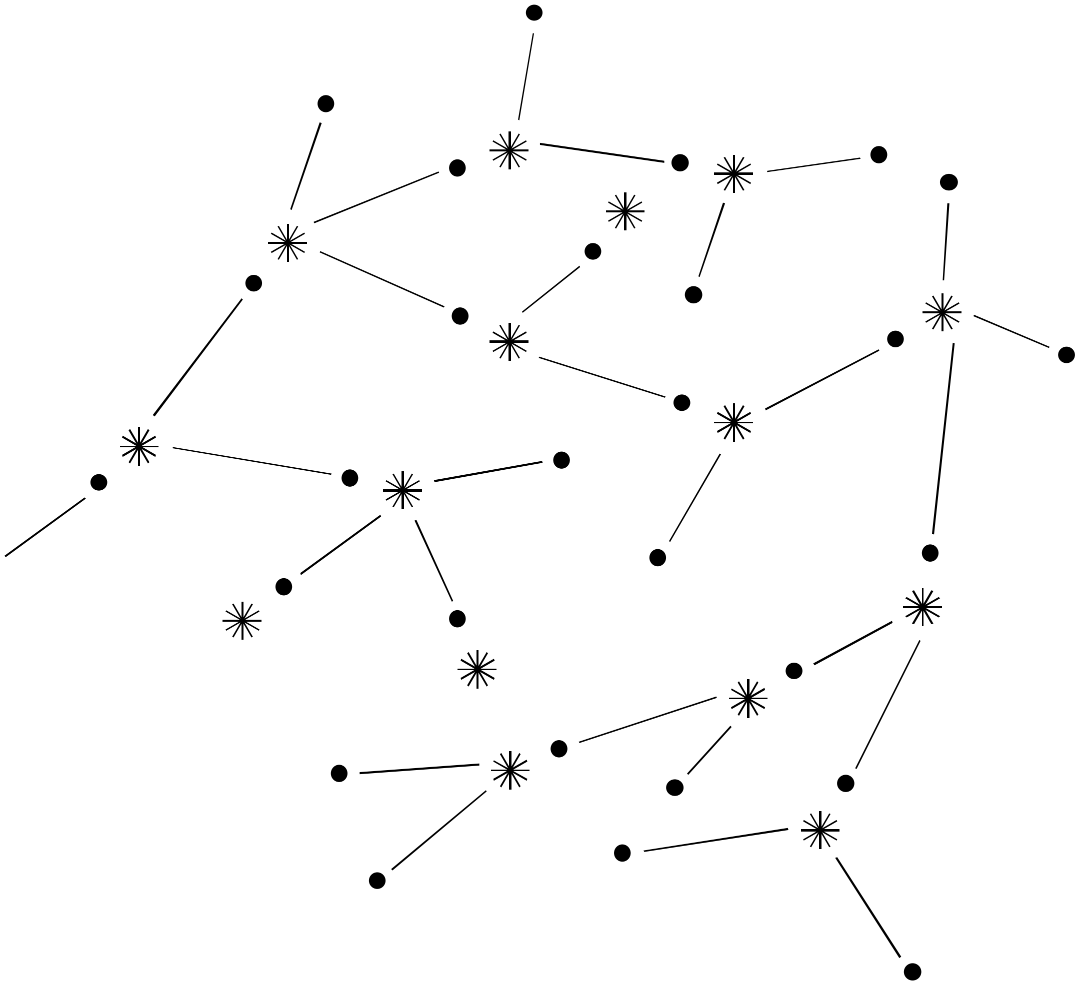
Neutron Life Cycle

U-235 does have a high probability of absorbing a neutron. However, the probability increases even more if the neutron is moving slower. Therefore, in the reactor, it is desired to slow the neutrons down and then let the U-235 absorb them. This slowing down process is accomplished by the same water that is used to remove the heat from the fuel. Therefore, the water circulating through the reactor (called the reactor coolant system) has two important functions. First, the water carries the heat from the reactor core to produce the steam used in the turbine. This prevents the fuel from becoming too hot, which could lead to fuel damage. Second, the water is used to control the fission process by slowing the neutrons down and by acting as a reflector to bounce back any high energy neutrons that try to escape. This conserves the neutrons so that even more fissions may occur. The “slowing down” process is called “thermalization” or “moderation.”

Fissions Y Heat

Controlling Fission Rate Y Controlling Heat Production Rate

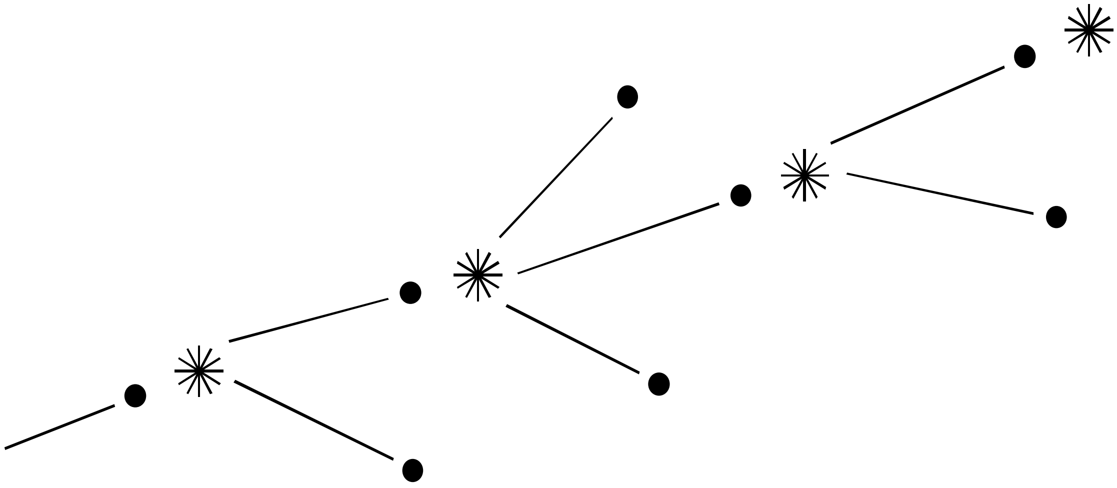
Every fission releases a tiny amount of heat. Trillions of fissions per second are necessary to produce the high temperature, high pressure steam for the production of electricity. The rate at which the uranium atoms are fissioned determines the rate at which heat (and power) are produced.



Fission Chain Reaction

Since neutrons are necessary to cause the fission event, and since each fission releases neutrons, there is the potential to set up a self-sustaining chain reaction. For this to occur, there must be sufficient material capable of fissioning, and the material must be arranged such that the neutrons will reach other fuel atoms before escaping.

Criticality



Steady Rate of Power Generation

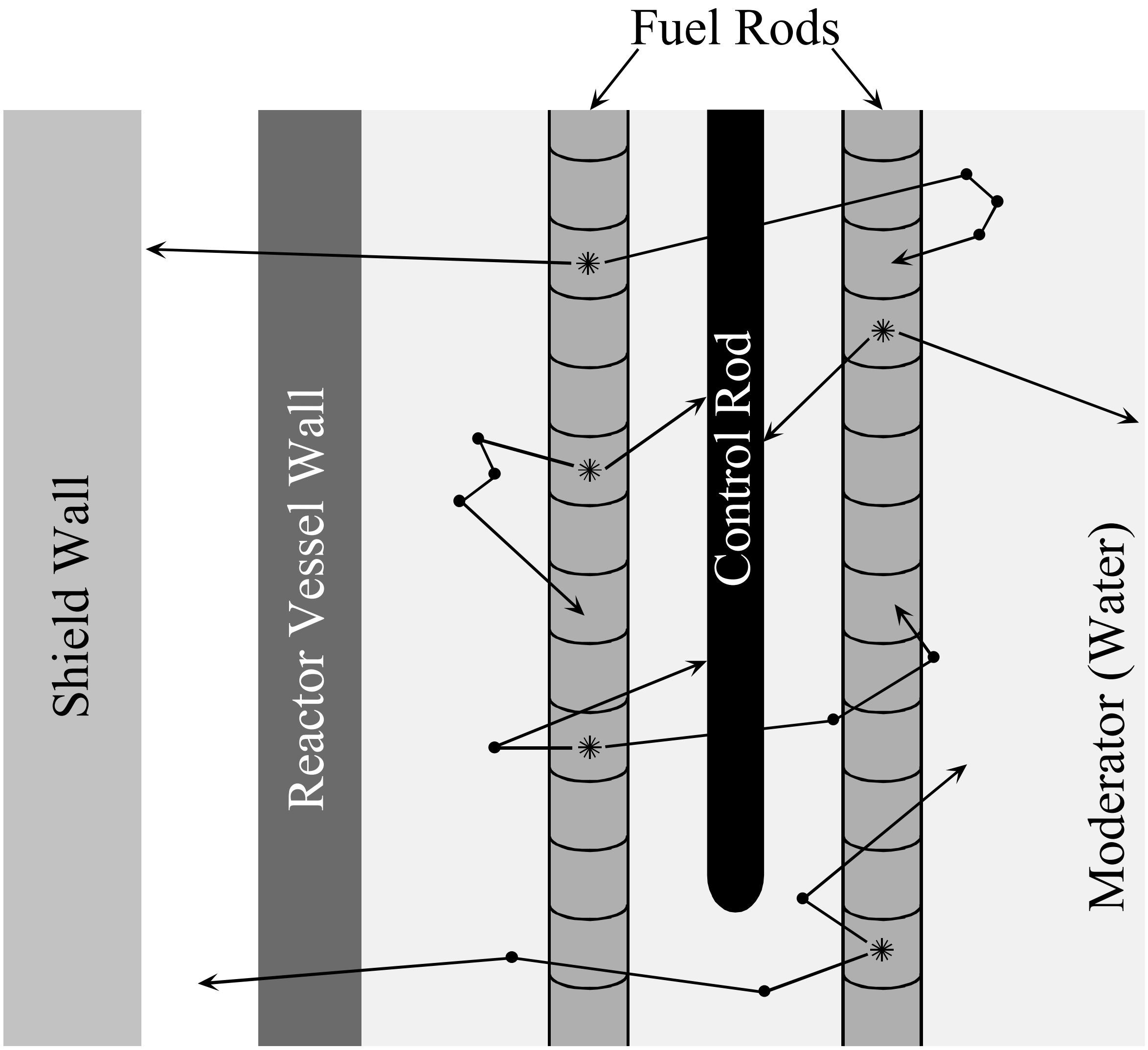
If the conditions in the core allow, the chain reaction will reach a state of being self-sustaining. At this point, for every fission event that occurs, a second event occurs. This point of equilibrium is known as "criticality." This just means that the number of neutrons produced by the fission events is equal to the number of neutrons that cause fission plus the number of neutrons that do not cause fission. Therefore, the reactor has reached a state of equilibrium. That is, the amount of power, and therefore heat, being produced is constant with time.

NEUTRONS THAT DO NOT CAUSE FISSIONS:

Leak out of the core, or

Are absorbed by neutron poisons

Because all neutrons that are produced by the fission process do not end up causing subsequent fissions, enough neutrons must be produced to overcome the losses and to maintain the “critical” balance needed for a constant power level. The neutrons that are lost to the fission process either “leak out” of the fuel area (escape) or are absorbed by materials that do not fission. The materials that absorbed neutrons and do not fission are called “neutron poisons.”



Some of the neutrons released by fission will “leak” out of the reactor core area to be absorbed by the dense concrete shielding around the reactor vessel. All the neutrons that remain in the core area will be absorbed by the materials from which the various core components are constructed (U-235, U-238, steel, control rods, etc.).

Neutron Poisons:

Control Rods
Soluble Boron
Fission Products
Uranium-238
Structural Components

Any material that absorbs neutrons and does not fission is a "poison" to the fission process. The reactor vessel, structural components, and the reactor coolant all absorb neutrons. Several fission products (the elements that are formed from the splitting of the large U-235 nucleus) absorb neutrons (for example, xenon-135 and samarium-149). Uranium-238 will sometimes fission after absorbing a fast neutron. When it does not, it acts as a neutron poison. These neutron poisons are uncontrollable by the operator.

Reactor operators can manipulate the total amount of poisons in the reactor by adjusting the position of the control rods. Also, in a pressurized water reactor, the operator can adjust the amount of boron that is dissolved in the reactor coolant. The control rods and the soluble boron are called controllable neutron poisons.

Control Rods

IN Y Fewer Neutrons Y Power Down

OUT Y More Neutrons Y Power Up

Control rods are concentrated neutron absorbers (poisons) which can be moved into or out of the core to change the rate of fissioning in the reactor. Rod insertion adds neutron poisons to the core area, which makes fewer neutrons available to cause fission. This causes the fission rate to decrease, which results in a reduction in heat production and power.

Pulling the control rods out of the core removes poisons from the core area allowing more neutrons to cause fissions and increasing reactor power and heat production.

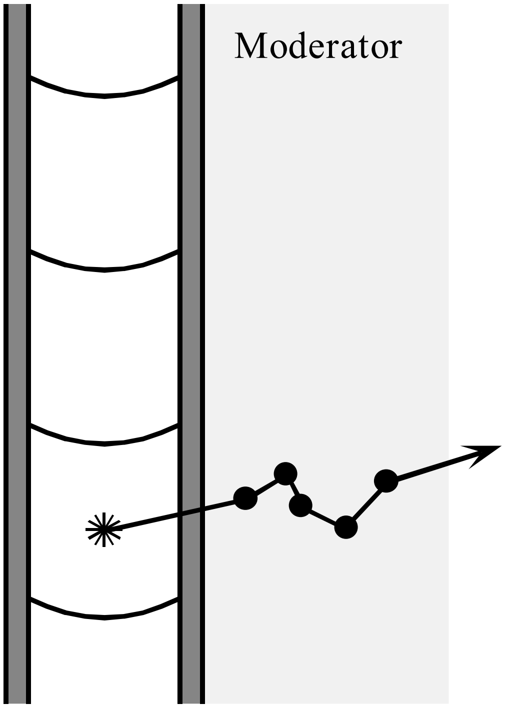
Temperature/Density Relationship of Water

Moderator Temperature 8Y

Moderator Density 9Y

Neutron Leakage 8Y

Power Output 9



The use of water as a neutron moderator helps produce a steady rate of reactor power by slowing the neutrons down that will be absorbed by the U-235 and by reflecting many of the neutrons that try to leak out of the reactor back into the core. The water can also remove neutrons from the fission chain.

First, water has a limited capacity to absorb neutrons, thus acting as a neutron poison. But an even greater effect is the changing of the moderator temperature. If the reactor coolant temperature increases, the water becomes less dense. This means that the water becomes less effective at slowing the neutrons down and more will leak out of the core. Conversely, if the coolant temperature decreases, the water becomes a better moderator, and the number of neutrons available for fission will increase. If the only action to occur was a change in the temperature of the moderator, power would also change. This moderator temperature effect is a major factor in the control of the fission process and heat production of the reactor.

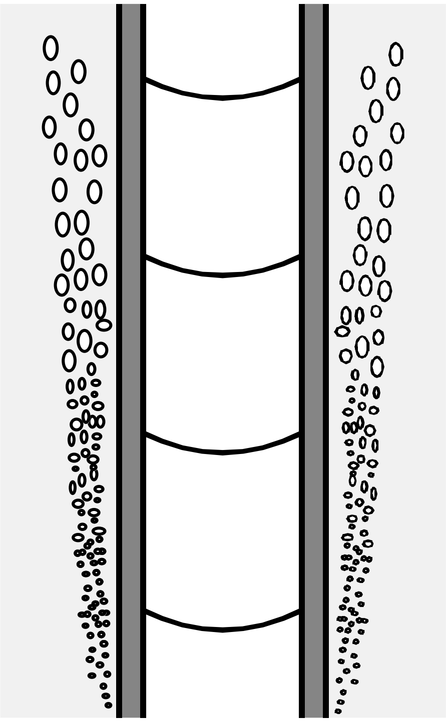
Voids (Steam Bubbles)

Moderator Void Content 8Y

Moderator Density 9Y

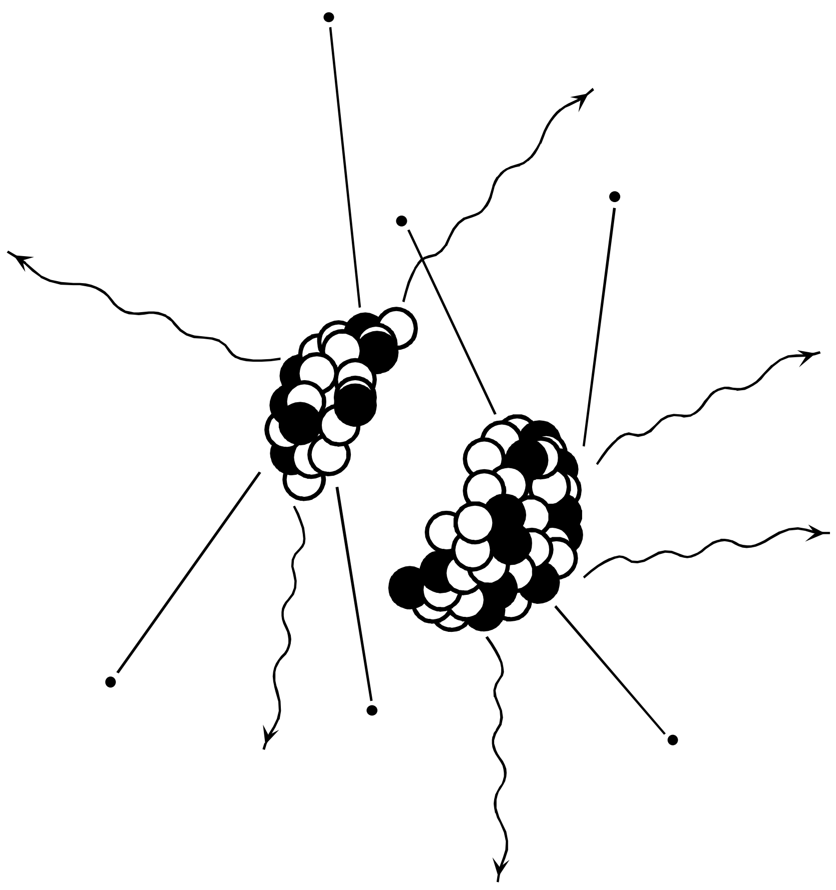
Neutron Leakage 8Y

Power Output 9



Since the moderator density plays such an important part in the control of the fission rate and the power production in the reactor, the formation of steam bubbles, or "voids," must also be considered. A steam bubble is an area of very low density water.

In a boiling water reactor, the conversion of water into steam produces a dramatic change in the density of the water from the bottom to the top of the core. Water at the bottom of the core is far more dense than the water-steam mixture at the top. Therefore, neutron moderation is much better towards the bottom of the core. In a pressurized water reactor, the high pressure of the reactor coolant will prevent all but just a very minimum amount of steam bubbles from being formed. Therefore, the effects of voids on the power production in a pressurized water reactor are very minimal.



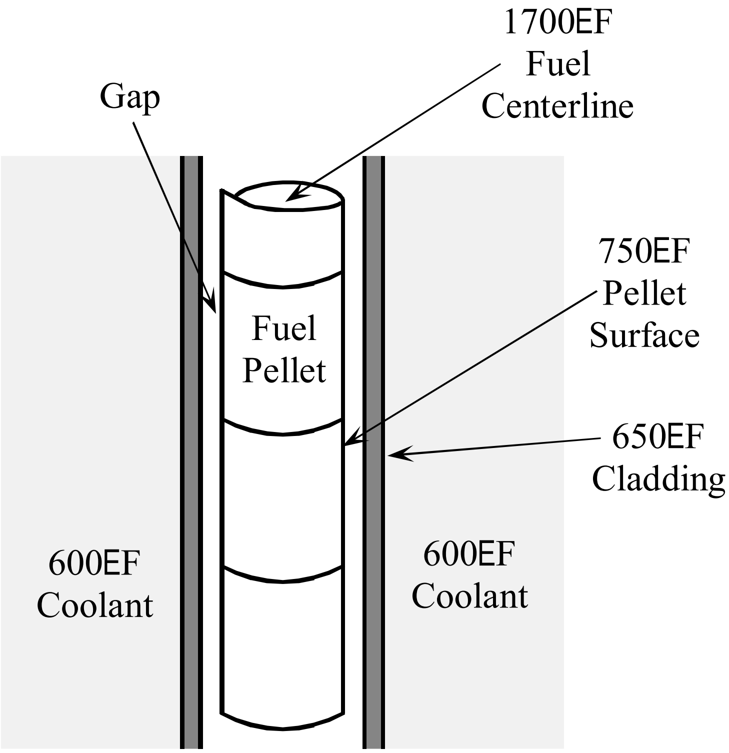
Fission Product Decay

Radiation

Decay Heat

Because of the unique properties of the nuclear fuel, there are some byproducts of the heat producing process. “Fission products” are the smaller atoms produced when the larger uranium atoms are split during the fission process. Some of these fission products are neutron poisons, and therefore, must be compensated for by removing some of the controllable poisons (such as the control rods for boiling water reactors or control rods or boron for pressurized water reactors) as they are produced. The fission products are usually very highly radioactive. They emit a large amount of radiation, and therefore, must be contained within the plant. A system of “barriers” has been developed to prevent these atoms from escaping into the environment. These barriers are the fuel pellet and cladding, the reactor coolant system pressure boundary, and the containment.

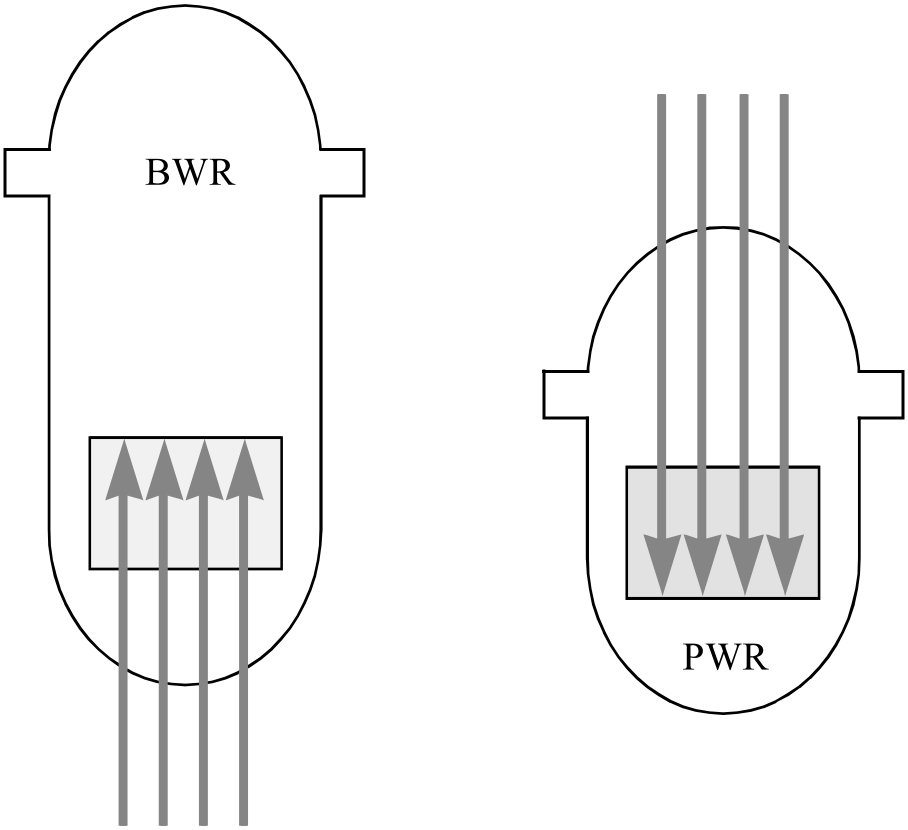
Another problem with the fission products is the generation of decay heat. When an atom decays, it gives off energy or particles to become more stable. The energy or particles then interact with the surroundings to generate heat. This heat will be collected inside the fuel pellet area. If this heat (decay heat) is not removed, it could possibly cause damage to the fuel pellets or other parts of the “barrier” system. Therefore, we have systems designed to remove this heat after the plant is shut down (residual heat removal system, for example). Radiation, decay heat, and fission product barriers will all be discussed in subsequent sections of this manual.



Fuel Rod and Coolant Temperatures

When a reactor is operating at full power, the approximate temperatures of the fuel centerline, pellet surface, cladding surface, and coolant are shown above. The average fuel pellet temperature under normal operating conditions is about 1400EF. The melting temperature of the ceramic fuel is approximately 5200EF. The fuel cladding can be damaged by temperatures in excess of 1800EF. Significant fuel damage can be expected at sustained temperatures above 2200EF. The plant systems, both normal operating and emergency, must be designed to maintain the fuel temperature low enough to prevent fuel damage. For example, if conditions approach an operating limit, the reactor protection system will rapidly insert the control rods to shut down the fission chain, which removes a major heat production source. This rapid insertion of rods into the core is called a reactor trip or scram.

Reactor Scram (Trip)



Rapid Insertion of Control Rods
to Shutdown the Fission Chain Reaction

A reactor “scram” (or “trip”) is the rapid (two to four seconds) insertion of the control rods into the core to stop the fission chain reaction. Even though all of the fissioning in the core is not stopped, the chain reaction is broken down, which causes a significant decrease in reactor power in just a few seconds. When the reactor is shut down (all rods inserted), the amount of heat being generated due to the fissions which are not stopped and the decay heat is much less than that which can be removed by the plant systems. Therefore, the fuel can be protected from an over-temperature condition.

In a boiling water reactor, the control rods are inserted from the bottom of the reactor vessel into the core. In a pressurized water reactor, the control rods are inserted (dropped) from the top of the reactor vessel into the core.