Nuclear Fission and Fusion

Spontaneous and Induced Nuclear Fission

Nuclear fission is the process in which a very heavy nucleus splits into two lighter nuclei.

Some heavy nuclei undergo nuclear fission spontaneously, and some heavy nuclei can be induced to undergo fission by the capture of a neutron. In either case the nucleus splits into two nuclei and several neutrons, with accompanying emission of gamma rays.

When a nucleus is too big (i.e. heavy) it can tend to elongate (stretch out) meaning that the repulsive coulomb force on each end of the nucleus is still strong but the attractive nuclear force is not. The two ends of the nucleus therefore break away from each other, releasing neutrons and gamma rays in the process.

Since neutrons have no charge they can approach and enter a nucleus, becoming part of the nucleus. A nucleus that would not spontaneously split can *capture* sufficient neutrons until it is too heavy and therefore will undergo fission.

The total mass of the reactants in a fission reaction is greater than that of the products, releasing energy given by $E = \Delta m\, c^2$, where Δm is the mass of the reactants minus the mass of the products. This energy is released in some combination of the kinetic energy of the product particles and the energy of the gamma ray photons.

This conversion of mass to energy releases *much* greater amounts of energy than chemical reactions. For example burning one molecule of octane gives out 9.2×10^{-18} J while the fission of one uranium atom gives out approximately 3×10^{-11} J which is about 10^6 times more.

Chain Reaction

On average more than one neutron is emitted in nuclear fission. This leads to the possibility that these neutrons will induce further fissions, resulting in a *chain reaction*.

The neutrons emitted as a result of nuclear fission have high speeds (since a large amount of energy is released during the reaction) corresponding to energies of 1 to 2 MeV. The energies needed for neutron capture are however much lower than this, for example ^{235}U and ^{233}U undergo fission with slow neutrons of energy of about 10 eV or less. Hence to induce fission in these nuclei the neutrons must be slowed down, which is achieved by collisions with the particles in a *moderator* material.

One commonly used moderator is heavy water, which contains deuterium (hydrogen-2), and another is carbon-12 (not as effective but cheaper).

The most effective moderator will have:

- *particles of low mass (similar mass to neutrons)*
  Conservation of momentum during a two-particle collision means that the smaller particle will always come away with more kinetic energy. If large particles were used for a moderator, it would take many more collisions for the neutron to pass its energy to the moderator.
- *low absorption of neutrons*
  If the neutrons are absorbed by moderator nuclei then they will not be able to continue the chain reaction with the fission material.

Note that many of the neutrons emitted during fission are absorbed by surrounding nuclei, or escape and cause no further fissions.

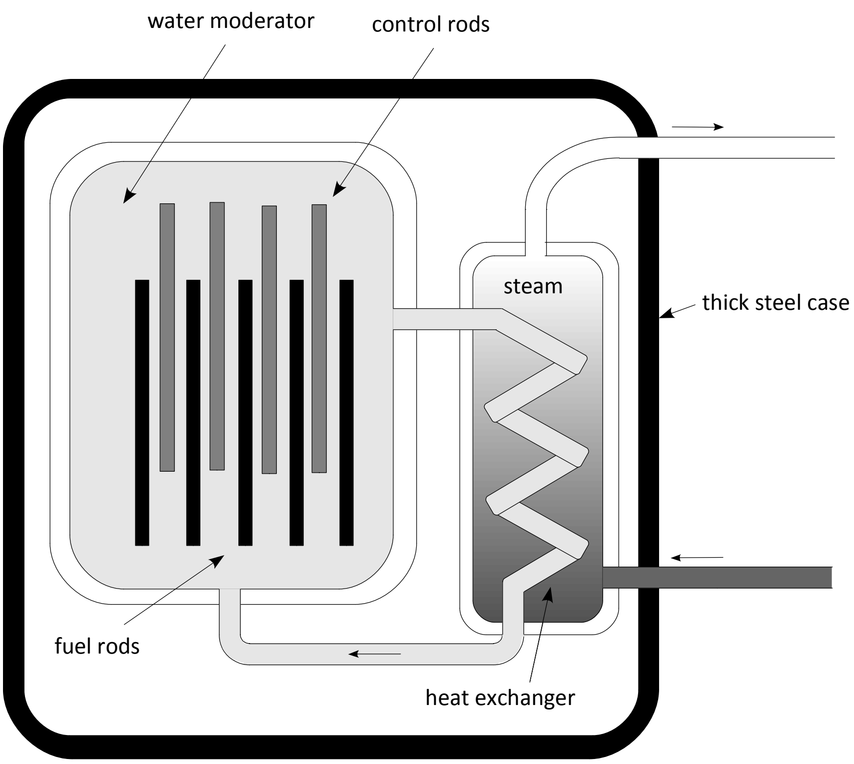
Uranium-235 is a naturally occurring *fissile* (capable of sustaining a chain reaction of nuclear fission) material, however only a small amount of natural uranium is ^{235}U. It is therefore necessary to increase the fraction of ^{235}U in uranium order to achieve a sustainable chain reaction. The process by which this is done is called 'enrichment'. Uranium cannot be used for a continuous chain reaction unless it is enriched since natural uranium has so little ^{235}U that too many neutrons will absorbed into other uranium nuclei or lose their energy before reaching a uranium-235 nucleus.

Some other comments about nuclear fission:

- A small fraction of the neutrons produced in nuclear fission are emitted after a delay of 10 seconds or more, because they are released during the decay of the nuclei fragments.
- There is no unique fission for any given nucleus. The *many possible reactions* result in the production of a range of fission products.
- The nuclei produced by fission reactions are likely to have an excess of neutrons, and hence are likely to be radioactive. The excess of neutrons is due to the original nuclei having high neutron to proton ratios. The smaller nuclei need much fewer neutrons in order to be stable, and therefore the products of fission are likely to undergo *beta minus decay*, converting neutrons to protons.
- Fission products (radioactive waste) are hazardous and difficult to process, since they start off with too many neutrons (as discussed above) and therefore are radioactive. Similarly the products of decayed products are often radioactive, and so on.

Fission Nuclear Power

Power can be produced by use of nuclear fission in a *nuclear reactor.* A diagram of a water-moderated reactor is shown below followed by a list of its main components.



- *core* – the nuclear reactions take place here, contains fuel rods, control rods and moderator
- *fuel rods* – long thin tubes containing enriched uranium-235
- *moderator* – pressurised water, encloses fuel rods and slows down neutrons
- *control rods* – thin rods containing boron or cadmium, good absorbers of neutrons, can be lowered into the reactor to slow the reactions (this regulation is only possible because of the delay between neutron emissions)
- *heat exchanger* – the water moderator is heated up by the reactions in the core (meaning it acts as a coolant) and this heat energy is passed to a secondary coolant (also water) to produce steam to drive turbines which generate electricity
- *safety rods* (not shown on diagram) – a separate set of control rods that can be quickly dropped into the core during an emergency to shut down the reaction
- *shielding* – a thick steel case surrounded by very thick concrete (the steel stops particle radiation from eroding the concrete)

The fission nuclear reactor is essentially operated by the raising and lowering of the control rods. To start the chain reaction, the control rods are partly withdrawn. This means that less neutrons are absorbed and more fissions take place. Once the reaction reaches the desired level of power, the control rods can be lowered.
At normal operation the control rods are at such a point relative to the fuel rods and the moderator that on average each fission leads to one more fission. The reactions are of course producing more than one energetic neutron, but most are absorbed by the control rods.

To stop or slow the reactor, the control rods can be lowered deeper into the reactor. When enough neutrons are being absorbed the chain reaction will slow and eventually stop.

Most of the neutrons emitted during nuclear fission appear almost immediately. If all neutrons were of this type, the reaction would be very hard to control since everything would happen very quickly. Fortunately a small fraction are of a delayed type, emitted after a time interval (since they arise from the decay of the products rather than the fission reaction itself). The time interval between fissions caused by these neutrons (10 or more seconds) is long enough to allow control rod movement to regulate the reactor behaviour.

Comparison of Nuclear Fission Power Stations to Fossil Fuel Power Stations

Advantages of Nuclear Fission	**Disadvantages of Nuclear Fission**
No greenhouse gas emissions	Dangerous radioactive waste with long half-lives
Efficient (small amount of fuel can produce a large amount of energy)	Expensive safety measures must be adopted
Small volume of waste product	Disasters can be catastrophic
Reliable	

Nuclear Fusion

Nuclear *fusion* is the process in which two nuclei combine into a single nucleus.

For fusion to occur, high kinetic energies are needed to overcome the repulsive electrostatic force between the nuclei, and to allow the nuclei to approach within the very short range of the nuclear-attractive forces.

As for fission, the total mass of the reactants in a fusion reaction is greater than that of the products, releasing energy given by $E = \Delta m\, c^2$, where Δm is the mass of the reactants minus the mass of the products. Typically, nuclear fusion can produce 10^7 times the energy of a chemical reaction.

The sun (and other stars) mainly produce their energy by fusion. The high temperatures within the stars provide the high kinetic energy required for hydrogen nuclei to overcome the coulomb repulsion and undergo fusion.

Nuclear Fusion as a Source of Power

Advantages

- The fuel (deuterium) is found in large quantities in the ocean.
- Not much radioactive waste produced (and the most common product, helium, is chemically inert).
- Reduced risk of meltdown or radioactive leakage. The fuel contained in the reaction chamber is only enough to sustain the reaction for about a minute, whereas a fission reactor contains about a year's supply of fuel. Fusion is not a chain reaction and therefore requires very extreme and precisely controlled conditions of temperature, pressure and magnetic field parameters to run. If the reactor were damaged, these would be disrupted and the reaction would rapidly extinguish.

Disadvantages

- To sustain a fusion reaction, extremely high temperatures must be reached. At the moment, we cannot maintain such temperatures for enough time to produce a continuous fusion reaction.