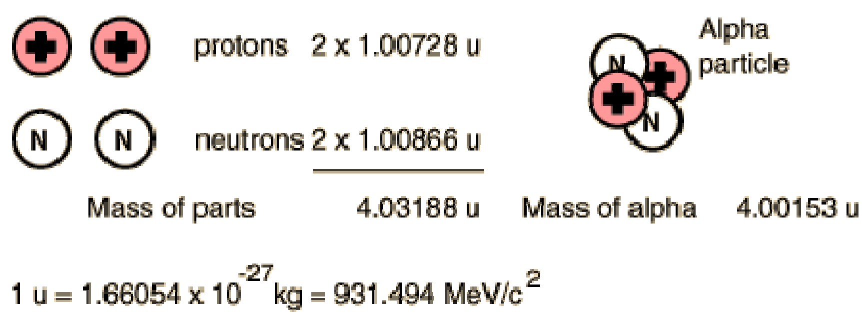
Nuclear Energy

Nuclear energy can also be separated into 2 separate forms: nuclear fission and nuclear fusion. Nuclear fusion is the splitting of large atomic nuclei into smaller elements releasing energy, and nuclear fusion is the joining of two small atomic nuclei into a larger element and in the process releasing energy. The mass of a nucleus is always less than the sum of the individual masses of the protons and neutrons which constitute it. The difference is a measure of the nuclear binding energy which holds the nucleus together (Figure 1). As figures 1 and 2 below show, the energy yield from nuclear fusion is much greater than nuclear fission.

Figure 1

$$\text{Nuclear binding energy} = \Delta mc^2$$

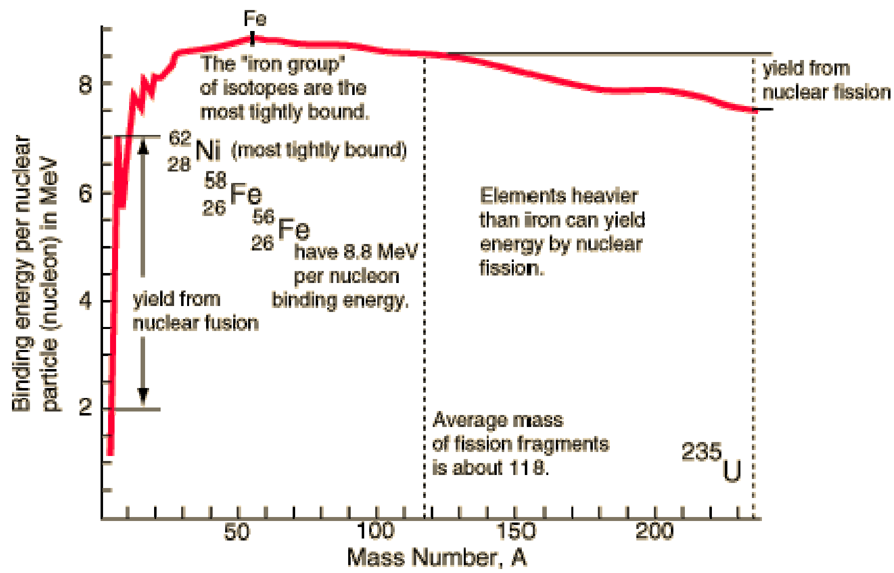
For the alpha particle $\Delta m = 0.0304$ u which gives a binding energy of 28.3 MeV.



(Figure from: http://hyperphysics.phy-astr.gsu.edu/hbase/nucene/nucbin.html)

Fission and fusion can yield energy

Figure 2



(Figure from: http://hyperphysics.phy-astr.gsu.edu/hbase/nucene/nucbin.html)

Nuclear fission

When a neutron is fired at a uranium-235 nucleus, the nucleus captures the neutron. It then splits into two lighter elements and throws off two or three new neutrons (the number of ejected neutrons depends on how the U-235 atom happens to split). The two new atoms then emit gamma radiation as they settle into their new states. (John R. Huizenga, "Nuclear fission", in AccessScience@McGraw-Hill, http://proxy.library.upenn.edu:3725) There are three things about this induced fission process that make it especially interesting:

1) The probability of a U-235 atom capturing a neutron as it passes by is fairly high. In a reactor working properly (known as the **critical state**), one neutron ejected from each fission causes another fission to occur. (Huizenga)
2) The process of capturing the neutron and splitting happens very quickly, on the order of picoseconds ($1x10^{-12}$ seconds). (Huizenga)
3) An incredible amount of energy is released, in the form of heat and gamma radiation, when a single atom splits. The two atoms that result from the fission later release beta radiation and gamma radiation of their own as well. The energy released by a single fission comes from the fact that the fission

products and the neutrons, together, weigh less than the original U-235 atom. The difference in weight is converted directly to energy at a rate governed by the equation $\mathbf{E = mc^2}$. Something on the order of 200 MeV (million electron volts) is released by the decay of one U-235 atom.[1]That may not seem like much, but there are a lot of uranium atoms in a pound of uranium. A pound of highly enriched uranium used to power a nuclear submarine is on the order of a million gallons of gasoline. (Huizenga)

There are some drawbacks of nuclear fission reactors, namely:

1) Mining and purifying uranium has, historically, been a process that leaves very toxic byproducts.
2) Improperly functioning nuclear power plants can create big problems. The Chernobyl disaster is a good recent example that dramatically shows the worst-case scenario. Chernobyl scattered tons of radioactive dust into the atmosphere.
3) Spent fuel from nuclear power plants is toxic for centuries, and, as yet, there is no safe, permanent storage facility for it. Yucca mountain in Nevada is the future permenant depository when it becomes operational.
4) Transporting nuclear fuel to and from nuclear plants poses some risk, although to date, the safety record in the United States has been good.

Nuclear Fusion

The sun releases energy through nuclear fusion reactions. The immense temperature and pressure in the Sun forces hydrogen atoms fuse into deuterium, then the deuterium atom fuses together with another hydrogen atom to form a tritium atom, and then the tritium atom fuses with another hydrogen atom to from a helium atom. The resulting helium atom's mass is less than four hydrogen atoms. The missing mass is transformed into energy by Einstein's $E=mc^2$ equation (Figures 1 and 2). The reaction between the nuclei

[1] 1 eV is equal to 1.602×10^{-12} ergs, 1×10^{7} ergs is equal to 1 joule, 1 joule equals 1 watt-second, and 1 BTU equals 1,055 joules).

of the two heavy forms (isotopes) of hydrogen - deuterium (D) and tritium releases 17.6 MeV (2.8 x 10^{12} joule).

There are currently two types of fusion reactions that are considered the most promising for nuclear fusion reactors: the deuterium tritium reactor, and the helium-3 deuterium reactor.

Deuterium tritium reaction

The fusion of deuterium and tritium reaction yields 17.6 MeV of energy but requires a temperature of approximately 40 million Kelvin to overcome the coulomb barrier and ignite it. (Post et al., 2005)

Even though a lot of energy is required to overcome the Coulomb barrier and initiate hydrogen fusion, the energy yields are enough to encourage continued research. Hydrogen fusion on the earth could make use of the reactions:

$$\left.\begin{aligned} {}^{2}_{1}\mathrm{H} + {}^{2}_{1}\mathrm{H} &\rightarrow {}^{3}_{2}\mathrm{He} + {}^{1}_{0}\mathrm{n} + 3.27\ \mathbf{MeV} \\ {}^{2}_{1}\mathrm{H} + {}^{2}_{1}\mathrm{H} &\rightarrow {}^{3}_{1}\mathrm{H} + {}^{1}_{1}\mathrm{H} + 4.03\ \mathbf{MeV} \end{aligned}\right\} \text{deuterium-deuterium fusion}$$

$${}^{2}_{1}\mathrm{H} + {}^{3}_{1}\mathrm{H} \rightarrow {}^{4}_{2}\mathrm{He} + {}^{1}_{0}\mathrm{n} + 17.59\ \mathbf{MeV} \quad \text{deuterium-tritium fusion}$$

(Post et al., 2005)

These reactions are more promising than the proton-proton fusion of the stars for potential energy sources. Of these the deuterium-tritium fusion appears to be the most promising and has been the subject of most experiments. In a deuterium-deuterium reactor, another reaction could also occur, creating a deuterium cycle:

$${}^{2}_{1}\mathrm{H} + {}^{3}_{2}\mathrm{He} \rightarrow \mathrm{He}^{4}_{2} + \mathrm{H}^{1}_{1} + 18.3\ \mathbf{MeV}$$

(Post et al., 2005)

This reaction also releases a neutron. This neutron is difficult to contain due to its non-polar nature. As a result the walls of the reactor suffer significant damage over a short time from a constant barrage of neutrons. Current research is continuing in an effort to contain the neutrons without sustaining reactor damage. (Post et al., 2005)

Helium-3 deuterium reaction

The Major advantages of ^{3}He- deuterium reactions are: 1. a significant reduction of radiation damage in the form of neutrons to the reactor wall, 2. reduction of avoidance of radioactivity, 3. higher energy conversion without waste heat (Kolinsky, 2001). However, there are still some problems. The reactors need to operate at higher temperatures than deuterium- tritium reactions, and there is a very limited source of helium-3 on the surface of the Earth. Helium-3 is a natural part of the solar wind. Our atmosphere does not allow helium-3 to reach the surface, but the Moon has no atmosphere and is constantly bombarded by helium-3. (Kolinsky, 2001).

The deuterium and helium-3 atoms come together to give off a proton and helium-4. The products weigh less than the initial components; the missing mass is converted to energy. 1 kg of helium-3 burned with 0.67 kg of deuterium gives us about 19 megawatt-years of energy output. The fusion reaction time for the D-^{3}He reaction becomes significant at a temperature of about 10 KeV, and peaks about about 200 KeV. A 100 KeV reactor appears to be optimum. (University of Wisconsin, Fusion Technology institute, http://fti.neep.wisc.edu/presentations/lae_dhe3_icenes07.pdf) A reactor built to use the D-^{3}He reaction would be inherently safe. The worst-case failure scenario would not result in any civilian fatalities or significant exposures to radiation. (Kolinsky, 2001).

Inertial Electrostatic Confinement (IEC) and toroidal magnetic field for confining a plasma (Tokamak)

There are currently 2 methods in which helium-3 has been shown to fuse in a reactor. One is a high pressure (gravity, and inertial confinement) and high temperature (electrostatic confinement and magnetic confinement) reactor. At the Fusion Technology institute at the University of Wisconsin-Madison they have developed an Inertial electrostatic containment device that is the first known fusion of helium-3 with deuterium on a steady state basis. (Radel, Kulcinsky, Donavan, Detection of HEU Using a Pulsed D-D Fusion Source, March 2007)

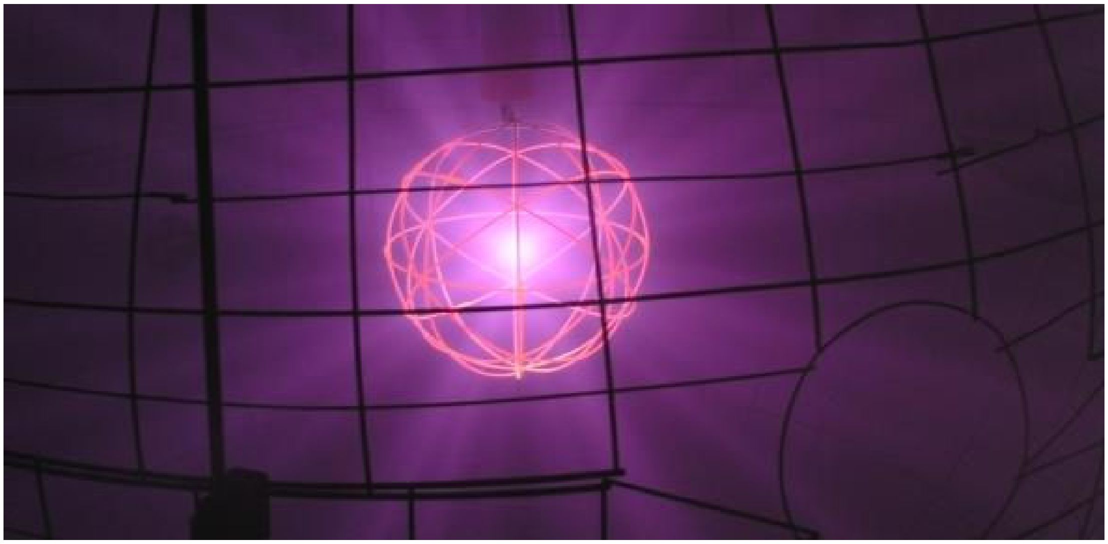
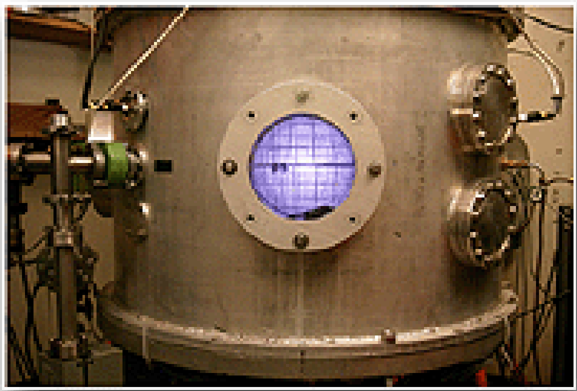
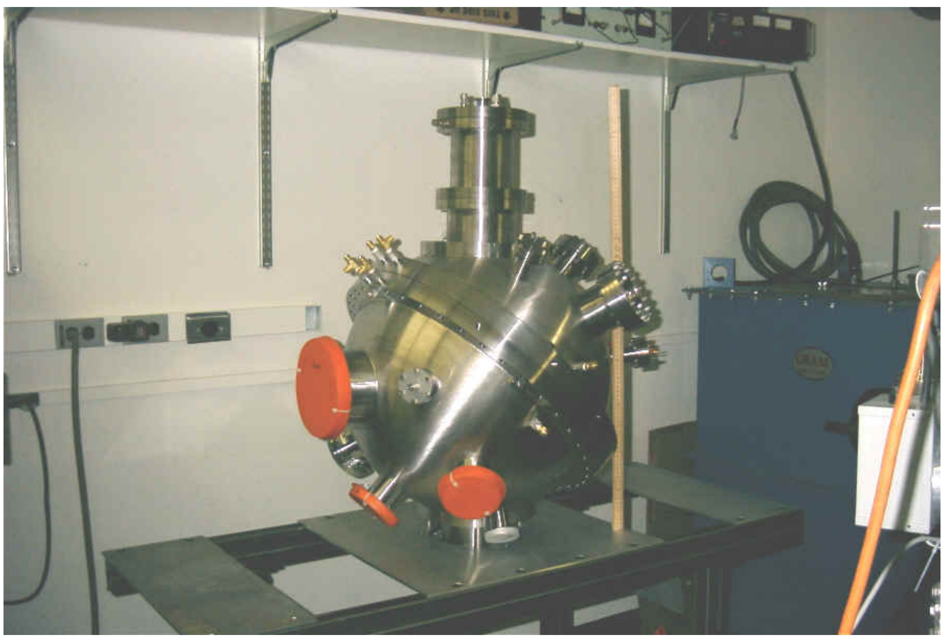


Photo of IEC in action (http://iec.neep.wisc.edu)

The gridded IEC approach possesses the advantage that ions can be continuously accelerated to high fusion relevant energy with relative ease (tens of KeV). The steady state burning of advanced fusion fuels such as deuterium- ^{3}He and ^{3}He-^{3}He is a key feature of IEC devices. The IEC device does not require any magnetic coils for plasma confinement, allowing it to be lightweight and portable. Since the reaction does not utilize deuterium- tritium the problem of neutron activation of the reactor is of far less significance. The device is small. It is an approximately one meter in diameter aluminum vacuum cylinder that is 65 cm high. (Radel, Kulcinsky, Donavan, Detection of HEU Using a Pulsed D-D Fusion Source, March 2007)



(photo from: http://fti.neep.wisc.edu/ncoe?rm=iec)

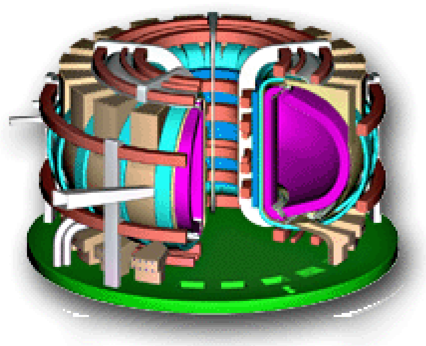


(photo from: http://iec.neep.wisc.edu/photopages/GeneralOpPics.htm)

The device produced a steady stream of protons, neutrons, helium-4, tritium, gamma and x rays. (Radel, Kulcinsky, Donavan, Detection of HEU Using a Pulsed D-D Fusion Source, March 2007)

Fusion fuel cycles, except He-3-He-3, are not completely aneutronic due to their side reactions. Neutron wall loadings can be kept low (by orders of magnitude) compared to

D-T fuelled plants with the same output power, eliminating the need for a breeding blanket [2]and the replacement of the first wall and shielding components during the entire plant lifetime. The availability of He-3 and the attainment of the higher plasma parameters required for burning are challenging problems for the D-He-3 fuel cycle. High beta and/or high field innovative confinement concepts, such as the field-reversed configuration and, to a lesser extent, the TOKAMAKks are suitable devices for advanced fuel cycles. In the early 1990s, the ARIES-III D-He-3 TOKAMAK was developed within the framework of the ARIES study. (The ARIES program is a national, multi-institutional research activity. (Guebal et al, *2007)*.



(ARIES III TOKAMAK from: http://fti.neep.wisc.edu/ncoe?rm=dhe3)

Its mission is to perform advanced integrated design studies of the long-term fusion energy embodiments to identify key research and development directions and to provide visions for the fusion program. It is funded by the Office of Fusion Energy Sciences, U.S. Department of Energy.) The UW D-He-3 Apollo series, along with ARIES-III, demonstrated attractive safety characteristics, including low activity and decay heat levels, low-level waste, and low releasable radioactive inventory from credible accidents. Another advantage for the D-He-3 system is the possibility of obtaining electrical power by direct energy conversion of the protons and radiation produced by fusion reactions.

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[2] Protect the magnets and the vacuum vessel from neutron and gamma radiation, produce the tritium necessary for continued fusion reactions, convert neutron energy into heat and evacuate it to generate a cycle capable of supplying electricity.

The nuclear fusion reaction can only be self-sustaining if the rate of loss of energy from the reacting fuel is not greater than the rate of energy generation by fusion reactions. The simplest consequence of this fact is that there will exist critical or ideal ignition temperatures below which a reaction could not sustain itself, even under idealized conditions. In a fusion reactor, ideal or minimum critical temperatures are determined by the unavoidable escape of radiation from the plasma. A minimum value for the radiation emitted from any plasma is that emitted by a pure hydrogenic plasma in the form of x-rays or bremsstrahlung. (Charged particles moving through matter will lose energy by emitting a photon, or interacting with the matter causing it to lose energy.) Thus plasmas composed only of isotopes of hydrogen and their one-for-one accompanying electrons might be expected to possess the lowest ideal ignition temperatures. In fact, it can be shown by comparison of the nuclear energy release rates with the radiation losses that the critical temperature for the D-T reaction is about 4×10^7 K. For the D-D reaction it is about 10 times higher. Since both radiation rate and nuclear power vary with the square of the particle density, these critical temperatures are independent of density over the density ranges of interest. The concept of the critical temperature is a highly idealized one, since in any real cases additional losses must be expected to occur which will modify the situation, increasing the required temperature. (Richard F. Post, Allen H. Boozer, Eric Storm, Bogdan Maglich, James S. Cohen, "Nuclear fusion", in AccessScience@McGraw-Hill, http://proxy.library.upenn.edu:3725, DOI 10.1036/1097-8542.458800)

The absence of neutrons and radioactivity removes the need for shielding. This is particularly significant for aero-space applications, since the weight of shielding in a (Post et al., 2005)

An aneutronic reactor [3] also offers the advantages of non-radioactive fuel and non-radioactive waste. Since all nuclear energy released in aneutronic reactions is carried by

[3] **Aneutronic fusion** is any form of fusion power where no more than 1% of the total energy released is carried by neutrons.

charged particles, if these particles could be directed into a beam a flow of electric charge would result, and nuclear energy could be converted directly into electrical energy, with no waste heat. (B. Maglich and J. Norwood (eds.), Proceedings of the 1st International Symposium on Feasibility of Aneutronic Power, *Nucl. Instrum. Meth.*, A271:1–240, 1988)

An aneutronic reactor could be small, producing 1–100 MW of electric power, and mass production might be possible. Aneutronic reactors cannot breed plutonium for nuclear weapons. (B. Maglich and J. Norwood (eds.), Proceedings of the 1st International Symposium on Feasibility of Aneutronic Power, *Nucl. Instrum. Meth.*, A271:1–240, 1988)

The only practical source for helium-3 and a viable commercial aneutronic reactor is the Moon.