Paragraph No.

Controlled Fusion on Earth - The Joint European Torus (JET)
(Freely adapted from Fusion basics http://www.jet.efda.org/.)

Nuclear reactions are capable of releasing huge quantities of energy. Such reactions can be achieved either by the nuclear fission (splitting) of elements of high atomic number or by the nuclear fusion (joining) of elements with low atomic number. In astrophysics, fusion reactions power the stars and produce all but the lightest elements. 1

In the core of the Sun, at temperatures of 10-15 million kelvin, Hydrogen is converted to Helium by fusion - providing enough energy to keep the Sun burning - and to sustain life on Earth. 2

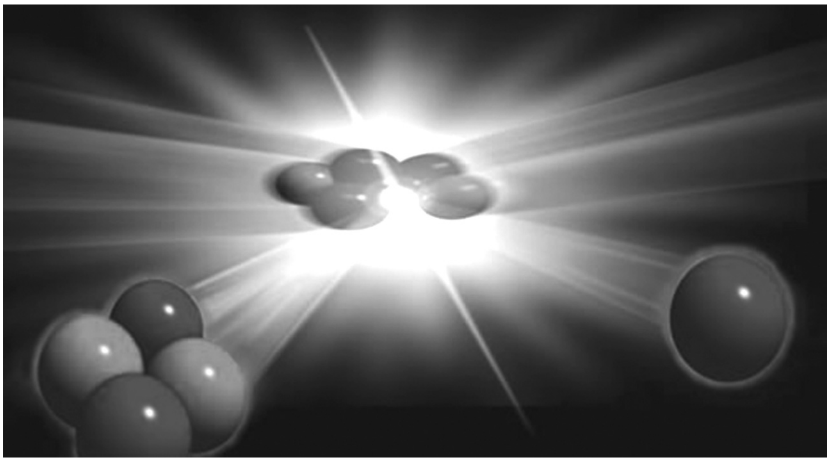

Diagram 1

A vigorous world-wide research programme is underway, aimed at harnessing fusion energy to produce electricity on Earth. If successful, this will offer a viable alternative energy supply within the next 30-40 years - with significant environmental, supply and safety advantages over present energy sources. 3

To harness fusion on Earth different, more efficient, fusion reactions than those at work in the Sun are chosen - those between the two heavy isotopes of Hydrogen: Deuterium (D) and Tritium (T). Protium, the common form of Hydrogen has one proton and no neutrons, Deuterium has one neutron, and Tritium has two. If forced together, the Deuterium and Tritium nuclei fuse and then break apart to form a helium nucleus (two protons and two neutrons) and an (uncharged) neutron. The excess energy from the fusion reaction (released because the products of the reaction are bound together in a more stable way than the reactants) is mostly given to the free neutron as kinetic energy. In fact, of the 17·6 MeV produced in each reaction, the neutron receives around 80% as kinetic energy and the helium nucleus around 20% as KE. 4

Fusion occurs at a sufficient rate only at very high energies (temperatures) - on Earth, temperatures greater than 100 million kelvin are required. At these extreme temperatures, the Deuterium-Tritium (D-T) gas mixture becomes a **plasma** (a hot, electrically charged gas). In a plasma, the atoms become separated - electrons have been stripped from the atomic nuclei (called the "ions"). For the positively charged ions to fuse, their temperature (or energy) must be sufficient to overcome their natural charge repulsion. 5

For a sustained fusion reaction to occur in a plasma, three conditions based on plasma temperature, density and confinement time need to be achieved simultaneously. The product of these is called the triple product. For D-T fusion to occur, this product has to exceed a certain quantity - derived from the so-called **Lawson Criterion** after British scientist John Lawson who formulated it in 1955. This criterion ensures **Breakeven** - the point where the fusion power out exceeds the power required to heat and sustain the plasma. 6

Plasma Temperature

Fusion reactions occur at a sufficient rate only at very high temperatures - when the positively charged plasma ions can overcome their natural repulsive forces. Typically, in the European fusion project (JET), over 100 million kelvin is needed for the Deuterium-Tritium reaction to occur. 7

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Density

The number of fusion reactions per unit volume is roughly proportional to the square of the density of fuel ions. Therefore the density of fuel ions must be sufficiently large for fusion reactions to take place at the required rate. The fusion power generated is reduced if the fuel is diluted by impurity atoms or by the accumulation of Helium ions from the fusion reaction itself. As fuel ions are 'burnt' in the fusion process they must be replaced by new fuel and the Helium products (the "ash") must be removed. 8

Confinement Time

The Energy Confinement Time is a measure of how long the energy in the plasma is retained. It is officially defined as the thermal energy contained in the plasma divided by the power input required to maintain these conditions. At JET we use magnetic fields to isolate the very hot plasmas from the relatively cold vessel walls in order to retain the energy for as long as possible. A significant fraction of losses in a magnetically-confined plasma is due to radiation. The confinement time increases dramatically with plasma size (large volumes retain heat much better than small volumes) - the ultimate example being the Sun whose energy confinement time is massive. 9

For sustained fusion to occur on Earth, the following plasma conditions need to be maintained (simultaneously). 10

* Plasma temperature: (T) 100-200 million kelvin
* Energy Confinement Time: (t) 4-6 seconds
* Central Density in Plasma: (n) 1-2 × 10^{20} particles m^{-3} (approx. 1/1000 gram m^{-3}, i.e. one millionth of the density of air).

Note that at higher plasma densities the required confinement time will be shorter but it is very challenging to achieve higher plasma densities in realistic magnetic fields. 11

Magnetic plasma confinement - the Tokamak

Since a plasma comprises charged particles: ions (positive) and electrons (negative), powerful magnetic fields can be used to isolate the plasma from the walls of the containment vessel - thus enabling the plasma to be heated to temperatures in excess of 100 million kelvin. This isolation of the plasma reduces the conductive heat loss through the vessel and also minimises the release of impurities from the vessel walls into the plasma that would contaminate and further cool the plasma by radiation. 12

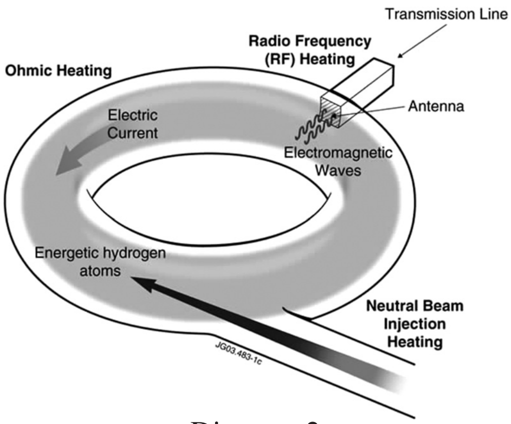

Diagram 2

In a magnetic field the charged plasma particles are forced to spiral around the magnetic field lines. The most promising magnetic confinement systems are toroidal (ring-shaped) and, of these, the most advanced is the Tokamak. Currently, JET is the largest Tokamak in the world. 13

The Tokamak

In a Tokamak the plasma is heated in a ring-shaped vessel (or torus) and kept away from the vessel walls by applied magnetic fields. 14

The toroidal field is a magnetic field within the torus (diagram 2). This is maintained by magnetic field coils surrounding the vacuum vessel. The toroidal field provides the primary mechanism of confinement of the plasma particles. 15

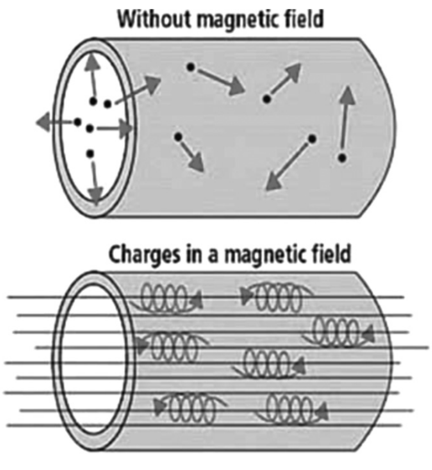

Diagram 3

Very high temperatures are achieved by inducing a large current (up to 5 million amperes in JET) within the plasma. 16

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Fusion as a future energy source

Global demand for energy continues to grow year by year as the world population expands and society becomes more and more dependent on energy supplies. The need to find new sources of energy becomes increasingly important as environmental concerns mount over the emission of CO_2 from burning fossil fuels. 17

Advantages of fusion

Abundant fuels

Deuterium is abundant as it can be extracted from all forms of water. If all the world's electricity were to be provided by fusion power stations, present deuterium supplies from water would last for millions of years. 18

Tritium does not occur naturally but can be bred from Lithium within the machine. Therefore, once the reaction is established, even though it occurs between Deuterium and Tritium, the external fuels required are Deuterium and Lithium. 19

Lithium is the lightest metallic element and is plentiful in the earth's crust. If all the world's electricity were to be provided by fusion, known Lithium reserves would last for at least one thousand years. 20

The energy gained from a fusion reaction is enormous. To illustrate, 10 grams of Deuterium (which can be extracted from 500 litres of water) and 15g of Tritium (produced from 30g of Lithium) reacting in a fusion powerplant would produce enough energy for the lifetime electricity needs of an average person in an industrialised country. 21

Inherent safety

The fusion process in a future power station will be inherently safe. As the amount of Deuterium and Tritium in the plasma at any one time is very small (just a few grammes) and the conditions required for fusion to occur (e.g. plasma temperature and confinement) are difficult to attain, any deviation away from these conditions will result in a rapid cooling of the plasma and its termination. There are no circumstances in which the plasma fusion reaction can 'run away' or proceed into an uncontrollable or critical condition. 22

Environmental advantages

Like conventional nuclear (fission) power, fusion power stations will produce **no** 'greenhouse' gases - and will not contribute to global warming. 23

As fusion is a nuclear process the fusion powerplant structure will become radioactive - by the action of the energetic fusion neutrons on material surfaces. However, this activation decays rapidly and the time span before it can be re-used and handled can be minimised (to around 50 years) by careful selection of low-activation materials. In addition, unlike fission, there is no radioactive 'waste' product from the fusion reaction itself. The fusion byproduct is Helium - an inert and harmless gas. 24