Nuclear fusion: power for the next century

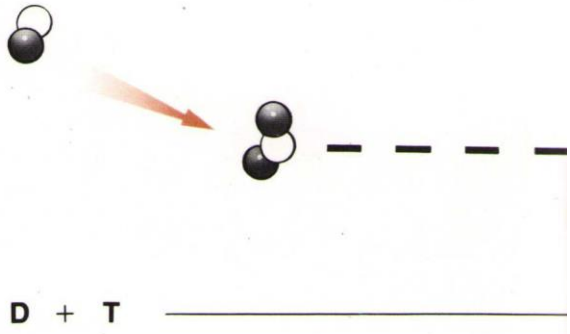
Nuclear fusion is one of the most promising future long-term energy options for the production of electricity.

Industrial societies have long sought new sources of energy but in recent years, the discovery and extraction rates for oil, gas and coal have not kept pace with the expanding world demand. The dilemma has highlighted the need for nuclear power to provide electricity, allowing coal to substitute for oil wherever possible. Oil would be concentrated on transportation and chemical uses for which it has no substitutes. Today about 12 per cent of Britain's electricity is generated in nuclear power stations.

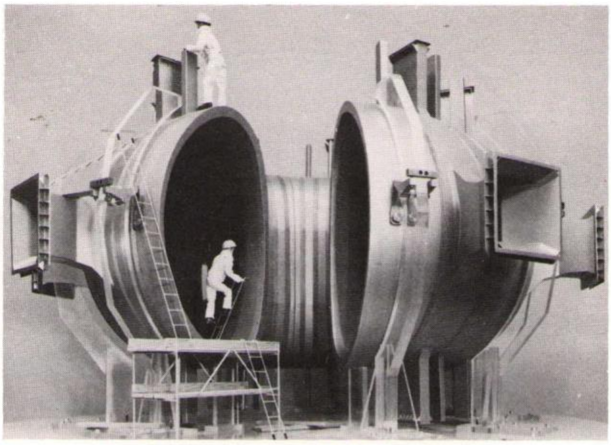
There are however two methods of releasing nuclear energy. Present nuclear power stations use the energy released by FISSION (or the splitting of heavy atoms such as uranium). The present generation of thermal reactors is essentially dependent on resources of uranium which are finite like fossil fuels. The next generation of fast reactors can produce energy from plutonium which arises as a by-product of the operation of thermal reactors. At the same time fast reactors can gradually convert the non-fissile form of uranium into additional plutonium, thus increasing by about 50 times the energy available from uranium.

The second method of releasing nuclear energy is by FUSION, the joining together of light atoms – particularly the atoms of hydrogen – the process by which the sun gets its energy. The fuels concerned, Deuterium and Lithium, are plentiful so that fusion offers the promise of a vast new energy resource.

The aim of fusion research is therefore to produce reactions similar to those in the sun under controlled



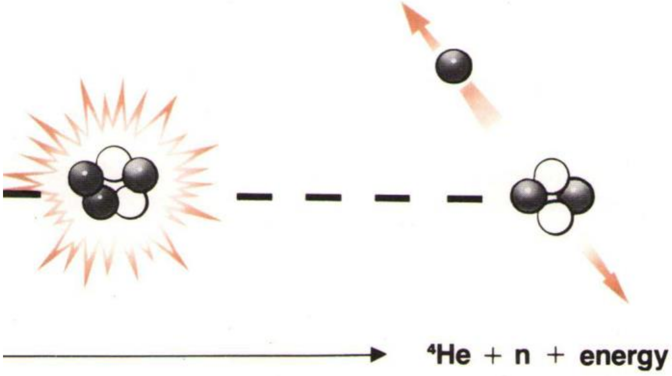
The Deuterium-Tritium Fusion Reaction.

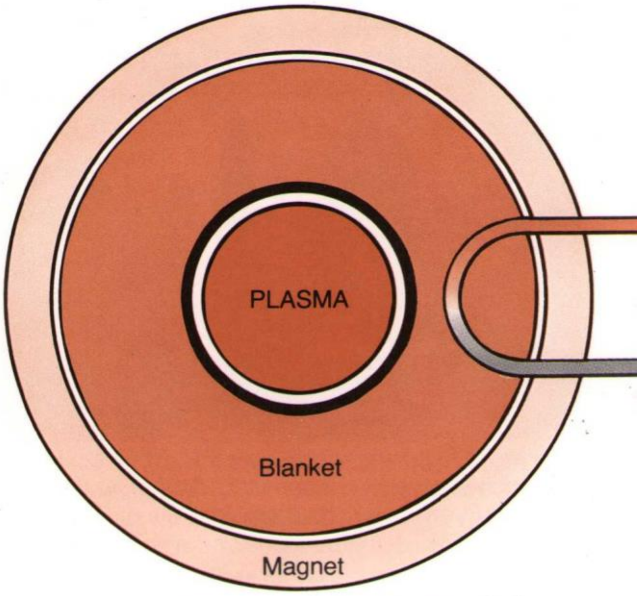


Scale model of the vacuum chamber of the JET fusion experiment.

conditions for electricity production. In the UK, research into nuclear fusion is conducted at the Atomic Energy Authority's Culham Laboratory in Oxfordshire as part of a co-ordinated European programme under the auspices of EURATOM – the European Atomic Energy Community. Since 1958, when security restrictions were removed from work on controlled nuclear fusion, there has been worldwide collaboration. The largest fusion programmes are in the Soviet Union and the USA, followed by Western Europe, Japan, and more recently, China.

In fusion reactions, light atoms (or to be precise the nuclei of atoms) are fused together to form heavier nuclei liberating enormous amounts of energy. There are many

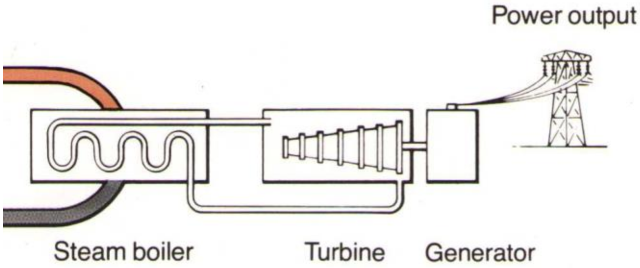




possible fusion reactions but the reaction most likely to give fusion power on earth is that between the heavy forms (isotopes) of hydrogen – deuterium and tritium – forming helium and a neutron.

Deuterium, a readily separated component of ordinary water, is exceedingly plentiful, but tritium does not occur naturally and must be manufactured. This can be achieved by surrounding the fusion region with a blanket containing lithium which can capture neutrons from the fusion reaction to breed tritium, as fast as it is consumed in the reactor. The capture of energetic neutrons heats the lithium blanket and it is this heat that is used in a conventional steam cycle to generate electricity.

Deuterium and lithium therefore are the basic fuels for a fusion reactor, the tritium produced being recycled leaving the inert gas helium as the only waste product. A major advantage of the deuterium-tritium fusion reaction is that neither the basic fuels nor the final reaction products are radioactive, but there are nevertheless some radiation effects. The intermediate fuel, tritium, is radioactive with a 12.3 year half-life – the time in which the radioactivity falls to half its original level – and a high engineering standard will be required to contain it. Also high energy neutrons released from fusion will make the reactor structure radioactive. However, the activity of the structural material in a fusion reactor will be considerably less than that of a fully-fuelled fission reactor of comparable output.



A fusion reactor.

Problems

Fusion reactions are much more difficult to achieve than chemical reactions, basically because the electric charges of the nuclei cause them to repel one another strongly, tending to prevent the close contact required for reactions to occur. To overcome this repulsive barrier, the nuclei must approach one another at high speed. One way of giving nuclei the required high speed for fusion reactions is to heat a mixture of deuterium and tritium gas to temperatures approaching 100 million degrees, several times hotter than the centre of the sun.

In a gas at normal temperatures, atoms are neutral having a positively charged core (nucleus) and an equal negative charge from the electrons orbiting the core. As the temperature rises the electrons effectively reach escape velocity and fly off, so that a neutral gas is transformed to a collection of charged particles, i.e. an ionised gas. An ionised gas is influenced by electric and magnetic fields and because its properties are different from an ordinary gas it is given the special name PLASMA. Plasma is the most common form of matter in the universe since the stars and the sun are all in the plasma state.

There are three basic steps to be taken to generate electricity from controlled nuclear fusion:

i To create and heat plasma to temperatures in excess of 100 million degrees Kelvin.

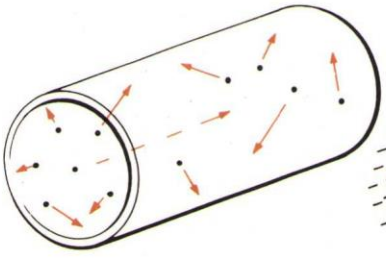
ii To hold enough plasma (i.e. less than one hundred thousandth of atmospheric pressure at room temperature) away from container walls for more than one second to allow abundant reactions to occur.

iii To design a practical fusion reactor to produce electricity economically.

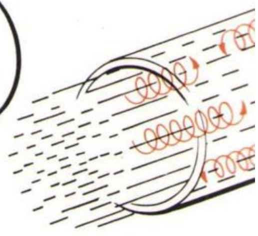
Many present-day experiments routinely create 10 million degree plasmas for up to one second (the average lifetime of individual particles being somewhat shorter). Four very much larger experimental devices are being built and when operating in the mid-1980s are expected to have plasmas at temperatures between 50 and 100 million degrees for several tens of seconds, long enough for abundant fusion reactions to occur. After these must come demonstration reactors leading to large commercial power reactors in the next century.

Plasma heating

Since plasma is a good conductor of electricity it can be heated by passing an electric current through it. This is the most common method used for plasma heating and in experiments currents of thousands and even millions of amperes are discharged through plasmas. Additional heating equipment is built onto the apparatus since the heating current becomes less efficient as the plasma temperature rises (as the plasma resistivity decreases). Methods employed include the use of microwaves and the injection of energetic neutral particles into an existing plasma. With the latter method a beam of hydrogen or deuterium ions accelerated from an ion source is neutralised before passing through the confining magnetic field into the plasma. There the neutral particles



Without magnetic field



Charges i
magnetic

are ionised, become trapped, and give their energy to the colder plasma particles. Plasma temperatures of 70 million degrees have been obtained using a combination of a large heating current and massive neutral injection heating.

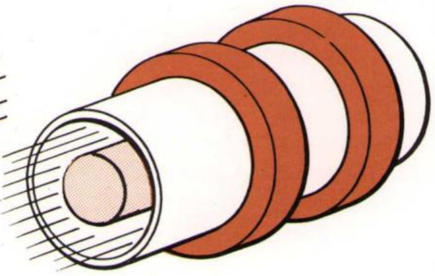
Plasma confinement

At the very high temperatures required for fusion it is necessary to consider how to confine the plasma, not because it might vaporise the equipment but because contact with the container cools the plasma and stops the reaction. This illustrates the inherent safety of a fusion reactor; the stored energy in the plasma is insufficient to do more than raise the temperature of the container by a few degrees.

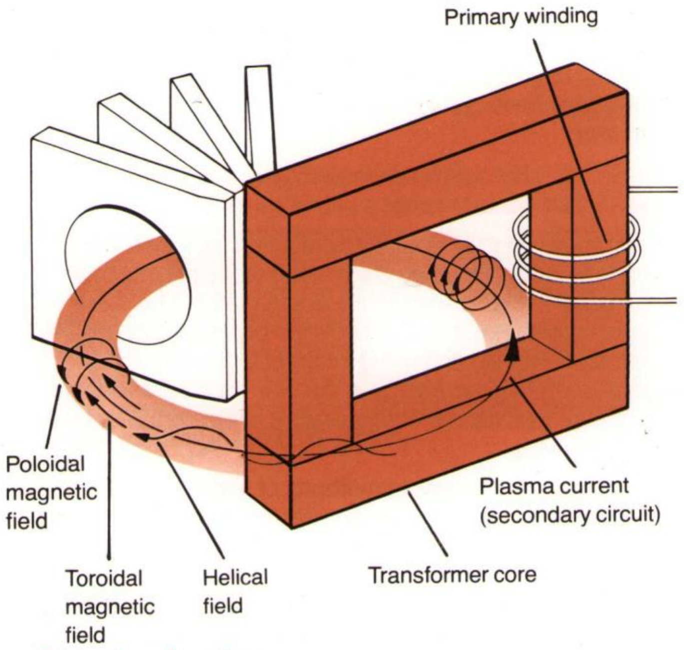
There are three possible methods of plasma confinement. Nature uses gravitational forces in the sun and the stars which are natural fusion sources obtaining their vast energy from nuclear fusion deep within their cores. But gravitational forces are only effective for enormous masses; for power generation on earth they are quite inadequate to confine a reactor plasma.

The second possible approach is to make the reaction so fast that the inertia of the fuel holds it together while the reactions take place. Inertial confinement is a possible approach to a practical fusion reactor; it is being studied in many laboratories around the world, especially in America, but like other methods it has yet to demonstrate a net gain of energy.

The most favoured method of confining high temperature plasma is to use magnetic fields. Just as gravity causes a



Plasma in a
magnetic field



Tokamak configuration.

satellite to orbit the earth instead of flying off into space, so a magnetic field forces a charged particle trying to cross it to follow a circle at right angles to the direction of the magnetic field.

A long straight magnetic field is the easiest to produce but since plasma would leak out of the ends most systems currently employed are ring-shaped and called toroidal systems. A toroidal system requires a complex magnetic field to confine plasma. This field is generally a combination of two fields, one around the major circumference (toroidal field) and the other around the minor circumference (poloidal field). The resultant helical magnetic field gives good overall confinement of hot plasma. The way in which the second field is produced categorises the different toroidal magnetic field systems of which the tokamak system is the most favoured and highly developed.

The tokamak plasma confinement system, first developed in the USSR in the late 1960s, consists of a toroidal vacuum chamber surrounded by a ring of magnetic field coils. Over these is a large transformer core which can produce a current through the plasma. This current not only gives the second (poloidal) field but also heats the plasma.

Progress

In recent years progress has been remarkably steady and it is predicted that the generation of large tokamaks now under construction will achieve the plasma conditions required in a fusion reactor.

The first generation in the late 1960s consisted of relatively small devices built to establish the basic confinement properties of the tokamak with relatively low temperature plasma and short confinement times. With larger apparatus, higher temperatures and longer confinement times were obtained. The introduction of powerful neutral injection systems gave much higher temperatures, including the record temperature of 70 million degrees, achieved in the US tokamak at Princeton in 1978. Much larger devices are now under construction – TFTR (USA), T15 (USSR), JT60 (Japan) and JET (Western Europe). JET (Joint European Torus), which will be approximately 12 metres high and 15 metres in diameter, is being built by the JET Joint Undertaking at Culham in Oxfordshire. These larger devices are expected to achieve higher temperatures, densities and much longer confinement times than hitherto and thus establish the plasma conditions required in a reactor.

A tokamak under construction.

Some of these machines when operating with a deuterium and tritium plasma will be generating several megawatts of thermal power in bursts of several seconds, although there will be no attempt to harness this energy. A further stage of tokamaks must then be built to establish the engineering aspects of an electricity-generating fusion device, before prototype reactors are built. An international working group under the auspices of the IAEA is studying what form the next step of fusion devices should take.

Fusion reactors studies

Fusion is the subject of long term research, but the rewards will be worth the effort. A 2000 MW(e) power station, as large as the largest coal fired station built today, would only need a few tonnes of fuel a year. One Culham design for a 2000 MW(e) station is based on a tokamak three times the size of JET with a deuterium-tritium plasma. The thermonuclear plasma is confined in a toroidal vacuum chamber. About 80% of the nuclear energy released appears as energetic neutrons, which will not be confined by the magnetic field but will be absorbed in a surrounding blanket or primary attenuator. The energy deposited in the blanket can be removed by heat exchangers followed by the production of electric power in the conventional manner. Another, but equally important, function of the blanket is to breed tritium for fuelling the reactor, hence the blanket must contain lithium. A major component of the reactor will be the strong magnetic field system needed to confine the plasma and the most economic way of generating these fields would be by using superconducting magnets. As these magnets will be operating at around the absolute zero of temperature they must be shielded from the heat generated in the blanket.

The scientific progress made in fusion in recent years has been encouraging and in experimental devices now under construction and expected to be in operation in the early 1980s, thermal fusion power of several megawatts is predicted. The engineering and technical feasibility of controlled nuclear fusion reactors has been under study for a number of years, and although there are some formidable engineering problems to overcome, there are outlined solutions envisaged for most of the individual problems. If the general progress and international co-operation continues, fusion power stations could become available in the next century at a time when fossil fuels will be in increasingly short supply.

Further information on atomic energy and its applications can be obtained from:

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