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FUSION - ENERGY SOURCE OF THE FUTURE ?

How far advanced are the Europeans with their JET-experiments ?

JET - the Joint European Torus - having successfully completed its first phase of operation, is now well established as the most powerful nuclear fusion experiment in the world.

As the largest project within the Communities' fusion programme, JET's principal aim is to establish the scientific feasibility of fusion as a new source of energy. Fusion is potentially a vast new source of energy since the basic fuels, deuterium and lithium, are very plentiful and geographically widespread. The fuel requirements for a large nuclear fusion power station (e.g. 1000 MW(e)) would be about half a tonne per year. This would be made up of about 150 kg of deuterium which could be extracted from 5000 cubic metres of water and 400 kg of lithium, a light metal found in sufficient quantities in the earth's crust. Such a power station would be an inherently safe system and, although involving radioactive materials, would have some environmental advantages over other energy-producing systems. However, there are many formidable scientific and technological problems to overcome before a commercial fusion power station could be built and JET is a crucial step in the fusion research and development programme of the European Communities.

Fusion reactions are believed to be the source of energy in the sun and stars. In these reactions the nuclei of light atoms are fused together to form heavier ones; in the process a small part of their mass is converted into a large amount of energy. In the sun these reactions take place at relatively low temperatures - about 15 million degrees Celsius - and the atoms are held together (confined) by the sun's gravity. But to duplicate the

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fusion process on earth without the help of the sun's large gravity field requires temperatures well above those in the core of the sun - temperatures of 100-200 million degrees Celsius. The essential aim of the JET Project is to study ways of heating and confining matter at temperatures up to 100 million degrees Celsius. At these temperatures the nuclei (ions) and electrons of atoms are separated from one another and the gaseous fuel is in the so-called "plasma" state. A plasma thus consists of a mixture of positively charged ions and negatively charged electrons.

In a neon advertising sign the glowing gas is a low temperature plasma whilst the sun and the Northern lights (aurora borealis) are good examples of naturally-occurring plasmas.

There are many possible fusion reactions among the light nuclei but the most accessible reaction, because it requires the lowest temperature, is that combining the two isotopes of hydrogen-deuterium (D) and tritium (T) to form helium (He^4) and a very energetic neutron (n). Like in the blanket of fission reactors, neutrons will be slowed down in a moderator (surrounding blanket) of a lithium compound, causing the blanket to heat up to a few hundred degrees Celsius. This heat will be extracted to produce electricity in the conventional way. A secondary, but equally important, function of the lithium blanket is to produce tritium. As the neutrons are slowed down in the blanket, they are captured by the lithium atoms to produce tritium and helium. This is essential since tritium does not occur naturally, except in very small quantities. A very distant prospect is for fusion reactors using the reaction involving deuterium alone which would give a virtually inexhaustible source of energy but this reaction takes place at much higher temperatures (greater than 1000 million degrees) and is consequently much more difficult to achieve. The JET apparatus has therefore been designed to be operated with deuterium/tritium plasmas in the final phase of its programme, with earlier phases concentrating on the non-radioactive hydrogen and deuterium plasmas.

Over the past 25 years, world fusion research has concentrated mainly on systems in which high temperature plasma is confined by magnetic fields to prevent contact with the wall materials of the containment vessel. In recent years the emphasis has been on toroidal (ring-shaped) systems, in particular the so-called tokamak magnetic field configuration pioneered in the Soviet Union. (Tokamak is an acronym for Toroidal Magnetic Chamber). Detailed studies in a series of relatively small tokamaks in national laboratories in Europe and elsewhere produced a consistent pattern of encouraging results. Plasmas with increasingly higher temperatures confined for progressively longer times were obtained. The knowledge thus gained clearly indicated that to create the plasma conditions required in a fission reactor would require a large apparatus. A large-sized device is required as the losses from the plasma are a surface effect whilst the energy production is a volume effect. Since a large tokamak would be an expensive installation it was decided to share this facility within the European Community.

The design team, set up in 1973, completed their plans by 1975. After two years' debate, the Council of Ministers decided that the device would be built on a site adjacent to the Culham Laboratory, the UK's nuclear fusion research laboratory, and that the UKAEA would act as Host Organisation to the Project. The Members of the JET Joint Undertaking, established on 1 June 1978, are the European Community, with its Fusion Programme, as well as its associated partners in the framework of the fusion programme including Sweden and Switzerland, Greece, Ireland and Luxembourg, which have no national research laboratories having Contracts of Association with the Euratom - Treaty based Fusion Programme.

The expenditure of the Joint Undertaking is borne by the European Community (80 %), the UKAEA (10 %) and the remaining 10 % is shared between all Members having Contracts of Association within the Programme in proportion to the Communities financial participation in the total costs of the Association.

The Project Team is formed of temporary delegated agents from the associated institutions and staff made available by the UKAEA. Each member having a Contract of Association with the European Community undertakes to re-employ staff whom it placed at the disposal of the Project as soon as the Project has been completed.

The construction of the JET laboratories, the JET tokamak iself, its associated power supplies and supporting equipment started in the spring of 1979. Contracts were placed with European industry for the manufacture of the numerous components of the machine and the team of engineers, scientists and administrators for the Construction Phase were recruited. By June 1983, the main construction work was complete and JET operated for the first time. This phase of the programme was successfully completed on schedule and broadly to the estimated budget, allowing some increase in the rate of inflation.

In the heart of the JET apparatus is an all-metal toroidal vacuum vessel of major radius 3m and with a D-shaped cross section 4.2m by 2.5m. During operation a very small quantity - about 1/10 g - of hydrogen gas (later deuterium and tritium gas) is introduced into this highly evacuated torus. By passing a large current through this gas, it is turned into plasma and heated. JET is designed for a maximum plasma current of 4.8 million amperes in the latter stages of operation. The plasma current is produced by transformer action using the massive 2700 tonnes eight-limbed magnetic circuit linking the torus. A set of coils around the centre core of the magnetic cirucuit forms the primary winding of the transformer whilst the plasma ring is the single-turn secondary winding.

The main magnetic field - a so-called toroidal field - for confining the plasma is produced by 32 water-cooled copper coils spaced evenly around the vacuum vessel giving a maximum field at the centre of the plasma of 3.5 T. These coils are housed in a massive mechanical shell designed to withstand the strong electromagnetic force generated when the coils are energised . The second component of the confining magnetic field - orthogonal to the toroidal field - is generated by the plasma current itself. Finally there is a third set of coils arranged as six horizontal loops around the outside of the mechanical shell which are used for shaping and controlling the position of the plasma centrally in the vacuum vessel.

The peak electrical power required for JET during operational pulses could exceed 900 MW. Since this exceeds the power which can be drawn directly from the national electricity grid, much of the pulsed power is produced by two flywheel generators each capable of delivering 400 MW of peak power. Each rotor, weighing 775 tonnes, is accelerated by a motor up to a speed of 225 revolutions per minute. When power is needed for a JET plasma pulse, ~~the~~ rotor windings are energised, the rotational energy of the flywheel is turned into electrical energy causing the rotor to slow down to about half speed.

A wide range of diagnostic measuring equipment is employed on JET to determine the plasma characteristics throughout the pulse. Techniques used on smaller machines have had to be redesigned to be compatible with neutron flux produced during the final phases of JET operation. In many cases, the main detection systems are located outside the 2.8 m concrete protective shield surrounding JET so that they can be easily operated and maintained.

The design and construction of the various diagnostic systems is mainly carried out by the Associated Laboratories in the Member countries. Some diagnostic systems and all the interfaces are designed and procured by JET staff.

Amongst the numerous diagnostic systems are magnetic pick-up coils on the vacuum vessel walls used to measure the plasma current and the plasma shape and position. The central electron temperature and density is measured with a laser light-scattering system whilst radiation from the plasma is used to give spatially-and temporally-resolved electron temperatures. Ion temperature measurements are made with a neutral particle analyser,and using the deuterium plasma these are confirmed with measurements of neutron yields from the deuterium/deuterium fusion reactions. Spectrometers are used to study levels of impurities in the plasma; additional data on temperatures and impurities are obtained from measurements of X-rays coming from the plasma. Further diagnostic equipment will be added to JET during Phase II operation .

JET, in its first year of operation, has fulfilled its design expectations. The first plasma pulse obtained in June 1983 had a modest current of about 16 thousand amperes for about 1/10 second. This relatively low plasma current was due primarily to the cooling influence on the plasma of impurities coming from the surface of the chamber . However, after baking the walls of the vessel these impurities were significantly reduced, allowing the plasma temperature and thus the plasma current to rise. By the end of the first phase of operation in September 1984 plasmas with currents up to 3.7 million amperes were routinely produced for periods greater than 10 seconds - a performance which will remain unsurpassed by other fusion experiments for many years. The peak temperatures thus obtained were about 40 million degrees Celsius with a plasma density of about one third of the required reactor value. The magnetic fields isolating the plasma from the walls essentially provide the plasma thermal insulation whose effectiveness can be evaluated by a measurement of the energy confinement time. The energy confinement time is the time in which the total energy would be lost from the plasma and in a reactor this must be about 1 to 3 seconds. In JET the best energy confinement time to date is 0.6 seconds,which exceeds the performance of any other fusion experiment by about a factor of two. To put this figure into perspective, it should be noted that a few years ago the best energy confinement times were typically ten times smaller than the JET values reached . It can therefore be seen that the three principal plasma parameters "temperature, density and energy confinement time achieved in JET during its first phase of operation" are each within a factor of 2-3 of the required values for a reactor. The next phases of the JET programme aim at progressively increasing these values.

To date, plasmas have been produced with modest heating provided by the plasma current alone. This method is known to be ineffective at high temperatures because the plasma resistance falls to very low levels. Two additional heating systems are therefore to be progressively installed on JET for Phase II operation. These are Neutral Injection heating and Radio Frequency heating. In the former, intense beams of energetic neutral atoms are injected across the magnetic field into the plasma. There the atoms give up their energy to the plasma,increasing its temperature. This technique has been successfully employed on smaller tokamaks but not at the powers or energies required on JET. The development of the JET injectors has been carried out by a joint team from JET and the two associated laboratories of Culham Laboratory (UK) and Fontenay-aux-Roses (F). The first neutral injection unit giving 5 MW of power to the plasma will be installed on JET early in 1985 with the second unit following about one year later.

In the Radio Frequency heating system, high power electromagnetic waves are radiated from antennae on the walls of the vacuum vesel into the plasma and by a resonance process impart energy to the plasma particles. Several stages of radio frequency heating will be added to JET during Phase II operation to give a total of 15 MW of power to the plasma.

During Phase II operation it is hoped to increase not only the temperature with the additional heating systems but also the plasma density and energy confinement time.

Observations indicate that the critical density limit can be increased if the level of impurities can be reduced. Consideration is therefore being given to lining the vacuum wall with a material of low atomic number such as carbon or beryllium. This would reduce the high atomic number impurities coming from the vacuum wall which would have the effect of increasing the plasma density. The energy confinement time is observed to increase with density ;thus reducing impurity levels should allow plasma of higher densities and longer energy confinement time to be achieved.

With the 25 MW of additional heating operating it is hoped that at full power (by about 1989) average plasma temperatures of 50 million degrees Celsius - with peak temperature typically twice this value - will be obtained in deuterium or hydrogen plasma and plasma densities of nearly fusion reactor values.

If the results of these experiments justify it, then the decision to introduce the tritium, the radioactive form of hydrogen, into JET to attempt an ignition demonstration can be made. A high yield of neutrons would be produced,causing the apparatus to become radioactive,and thus all further maintenance and modification must be carried out by remote-handling techniques. However the abundant fusion reactions expected in the deuterium-tritium plasma will not only yield neutrons (which in a reactor will be moderated in a surrounding lithium blanket for electricity generation) but also helium (alpha particles) which will be trapped in the magnetic field and consequently provide further heating to the plasma.

The extra power deposited in the plasma by the alpha particles from the thermonuclear reactions would then cause the central plasma temperature to rise to the required 200 million degrees. In the extremely optimistic prediction, ignition could occur;so with the external heating systems turned off the temperature of the plasma would continue to rise until the end of the pulse determined by the electrical parameters of JET. At the other exteme, the pessimistic result would be that the plasma parameters achieved would not even justify the use of tritium in JET. Whatever the outcome, JET will provide definitive information on the possibilities of fusion power generation.

In the Community fusion programme it is envisaged that there will be a minimum of two stages between JET and a commercial fusion reactor. These are NET (Next European Torus) and DEMO (Demonstration Reactor). NET, for which the study group has already been set up in IPP Garching (D), will aim at establishing the technological feasibility of fusion power and will address itself to the problems of tritium breeding, radiation damage of the vacuum wall, plasma control for long periods, refuelling and exhaust of the plasma and similar problem areas. DEMO, which realistically would not operate until well into the next century would then need to optimise scientific, technological and engineering parameters to prove the economic viability of fusion as a major new energy source.

JET is therefore an important step on the long and difficult road towards commercial fusion power; experiments in the next few years will decide whether or not plasma conditions with temperatures hotter than the centre of the sun can be achieved on earth.

If readers want to increase their basic knowledge about Plasma Physics and Fusion Technology, they are invited to order the booklet "The European Programme of controlled Fusion", catalogue number : CD6NE-001,supplied by the Office for Official Publications of the European Communities, L-2985 Luxembourg.