A giant leap for fusion

Can fusion offer the world a secure energy supply? Vital decisions are about to be made which could shape the 21st century.

by NOLAN FELL

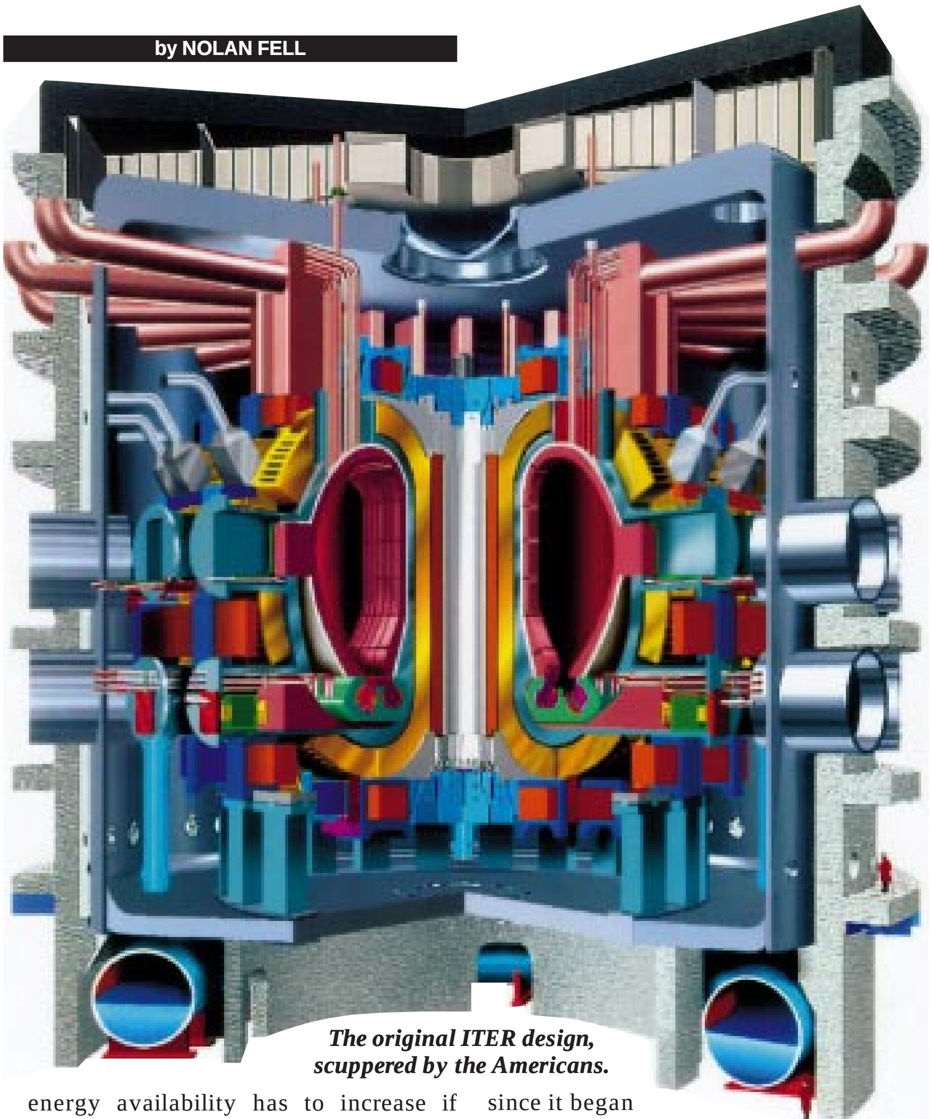
At the start of the 20th century homes were lit by gas or by candles, wood or coal provided heat for cooking and comfort, and the horse and the bicycle were the dominant modes of transport. Today electricity provides a clean and convenient energy supply in our homes and oil is the basis for transport. Changes in energy provision were fundamental to all the last century's technological advances, from the car to the computer. Energy provision is central to the quality of life of the six billion people who now live on this planet.

At the start of the 21st century, two of those six billion people live without electricity. Energy poverty equates with financial poverty and developing energy supplies to the world's poorest is vital if their lives are to improve. But fossil fuels, which drove the industrial revolution in Europe and the US and allowed millions in the temperate world to escape poverty, have a down side. The carbon released to the atmosphere during combustion is the main cause of global warming, a phenomenon which becomes ever more apparent with each passing hurricane, flood or drought. Within the last six months tens of thousands have died in Venezuela and India from natural disasters which may be an expression of global warming. Experts generally believe that climatic extremes are more likely in a greenhouse world.

The last two centuries were dominated by fossil fuels; firstly coal, then oil and gas. If the world is to avoid the most damaging impacts of global warming, such as major melting of the polar ice caps and rapid shifts in climatic regions, an alternative to fossil fuel has to emerge. Ending dependence on oil for transport and coal and gas for electricity is one of society's most fundamental challenges.

Nuclear fission, a 20th century technology, does not produce greenhouse gases and its proponents continually argue that the problems such as waste, military applications and safety, are greatly exaggerated. Technological problems may be solvable, political ones are far more difficult. Democracy may be the 'least worst' political system, but the short term vision of democratic politicians means difficult or unpopular decisions are avoided and planning beyond the next election is rare.

A new technology, without the problems fission produces, is needed. Renewables such as wind or solar power offer clean energy but their low power density makes it difficult to envisage anything other than a small fraction of energy demand ever being met through these means. And global energy availability has to increase if poverty is to decrease.



The original ITER design, scuppered by the Americans.

Only one technology could provide the energy the world needs without the risks of global warming or the political difficulties of fission. Fusion offers the possibility of high power density, no high level radioactive waste and no greenhouse gases. It is the process that powers the sun, ultimately providing all the energy to support life on earth. Since the birth of the atomic age it has been a holy grail. It may now be within our grasp.

THE NEXT LEAP FORWARD

In the next few months the European Union and Japan must decide whether to back the next stage in fusion research. The Joint European Torus (JET), the largest fusion reactor yet built, was completed in 1983 and fusion scientists have made great progress since it began operating. To make the next step, a bigger reactor is necessary: one that can emit more energy than it consumes and can produce a self-sustaining reaction. If these objectives were achieved, the experimental basis of fusion power would be established. Fusion would no longer be a holy grail, it would be a reality.

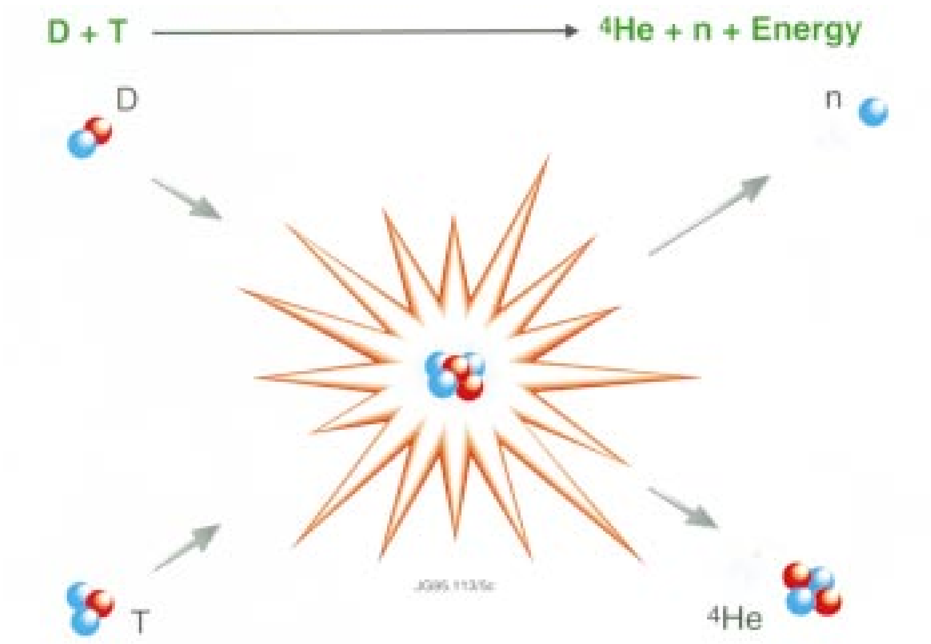
Fusion scientists call it 'the next step'. Their work has reached the stage where they have to make this next step, or the efforts so far committed will amount to nothing. In 1998 an international working group of fusion scientists completed the design. They called it the International Thermonuclear Experimental Reactor (ITER) and it was designed to meet the criteria which would prove that fusion can produce useful energy. But at $6 billion, it frightened politicians. It frightened US politicians so much they pulled out of the project, despite the fact that it was Reagan and Gorbachev who first backed work on the reactor's development.

As a result of the US exit, the costs had to be reduced. Japan, Russia and Europe remain committed, but the reactor's budget is limited to $3 billion. Fusion scientists went back to their labs and developed the ITER - Fusion Energy Advanced Tokomak (ITER- FEAT), the outline design of which has just received approval from the ITER Technical Advisory Committee (TAC). The costs of the new design are down to 56% of the original ITER, and the TAC is confident that engineering advances can reduce the cost further, so that the target of 50% of ITER's original cost will be met.The new design will still achieve the targets of a self-sustaining reaction and a net energy gain, but the ambition is reined in. It will probably not reach the kind of energy gains that would be necessary in a power plant, but it will establish the experimental basis to show that this is possible.

The confidence of fusion scientists that the ITER-FEAT would achieve these targets is based on their understanding of the physics which underpins the fusion process. The fusion reaction involves light atoms, the hydrogen isotopes deuterium and tritium, fusing to form a helium nucleus, otherwise known as an alpha particle, and releasing neutrons. The reaction results in a slight loss of mass and therefore a release of energy which is transferred to the alpha particle and neutrons (see diagram above). In the sun immense temperatures and pressures overcome the repulsive forces which the particles experience in close proximity to each other. On Earth it is not possible to reproduce these conditions and tokomak, or doughnut shaped reactors such as JET and ITER, can only produce a plasma – the fourth form of matter, in which atoms are stripped of their electrons – with a pressure of 2-3 atmospheres. So fusion has to be achieved by heating the plasma to 100 million degrees. Hotter than the sun and too hot for any material to remain solid. The plasma has to be held in empty space.

The plasma is held in empty space by powerful electromagnetic forces created by currents running through the plasma and through the structure of the reactor. Superconducting materials will be used in ITER-FEAT to create the forces and the development of suitable compounds, in particular niobium tin (Nb_3Sn), has been one of the major advances during the years of work on the ITER design. The development of niobium tin will continue and the potential of another compound, niobium titanium (NbTi) will also be explored. The need for superconducting materials adds a level of complexity to the engineering challenges that would be considerable even without them.

Pressure; density; the controlled removal of helium atoms (effectively the ash of the process); the removal of excess heat; ensuring the alpha particles produced as a result of the fusion reaction remain at the right concentration to maintain the reaction – too many and the reaction will overheat, not enough and it will die; the maintenance of the plasma in empty space; and the absorption of neutrons in the wall surrounding the reactor and the conversion of the neutrons' kinetic energy into useful energy are just some of the challenges that need to be addressed.



The D-T fusion reaction.

The TAC is confident all the challenges can be met and the ITER-FEAT reactor is necessary to achieve this. To maintain the plasma in optimum conditions requires balancing a whole series of criteria. Push the envelope with any one of the limiting criteria and the plasma could collapse. Too much pressure leads to instabilities in the plasma, it develops a condition known as the neoclassical tearing mode (NTM). This instability can lead to the plasma hitting the wall of the reactor, damaging the wall material. One challenge is to produce more robust materials which can cope better when this happens. Instabilities like NTMs can happen if kinks or errors form in the confining electromagnetic field. The errors need to be of a certain size, referred to as the seed island size. If any part of the superconducting coils warm to a temperature where the material becomes resistive, the field will collapse and the plasma escapes. Maintaining a plasma in steady state is like holding a jelly in empty space without touching it.

"The plasma performance depends on how much pressure you can put in, as the fusion power is proportional to the pressure squared," says Martin O'Brien, a programme manager at Culham, the UK's centre for fusion research. "You want to operate at as high a density as possible. But at high densities the performance can degrade. Experimentally it is hard to go higher than an empirically observed density, the Greenwald Limit. There are a variety of boundaries due to instabilities, and all factors must be optimised."

Pressure is not uniform across a plasma; it tends to reach a maximum at its centre. The shape of the plasma is also very important as its affects how much pressure can be contained. The more like a D rather than an O the plasma cross-section, the greater the pressure. The profile of pressure across the plasma is also important, as is the pressure at the edge, known as the pedestal size. Maximising the pedestal is a key research objective of ITER-FEAT.

INTERNATIONAL APPROVAL

The TAC last met in Naka, Japan, on 20-22 December 1999 to approve the outline design report. The committee issued a series of key recommendations, many of which focused on the research objectives of the ITER-FEAT machine.

The report on the meeting outlines the objectives:

"The TAC considers that the profile sensitivity of all the scenarios including the pedestal size should be studied to understand the variations in operating domains and the influence on achieving the objectives. Due consideration of the plasma performance degradation near the operating boundaries and the compatibility with successful divertor operation should be analysed."

The divertor is an area within the reactor which removes exhaust heat and alpha particles from the plasma. The plasma touches the wall at this point and therefore a lot of research into the divertor plate's material needs to be done. In fusion reactions one fifth of the energy transfers to alpha particles. This energy can be used to maintain the reaction, but once the particles have lost their excess energy, they must be removed or they inhibit the fusion reactions. The other four fifths of the energy is released in neutrons which escape the plasma and enter the reactor wall. The divertor controls the quantity of alpha particles in the plasma.

It is therefore a vital part of maintaining a stable plasma, one of the main aims of the ITER project.

The energy from the plasma which is converted to useful heat energy is that released in the neutrons. The neutrons are absorbed by the surrounding wall. The material challenges for constructing this wall are considerable. In particular the first two centimetres of the structure have to withstand high neutron fluxes, immense heat and the impact of high energy particles. Work is currently focussing on stainless steel coated with beryllium, graphite or tungsten, but in an operating reactor the stainless steel would need to be replaced with another material, possibly silicon carbide, as steel becomes irradiated when exposed to neutrons. Beyond the first 2 cm is a 40 cm thick wall of steel cooled with water. This is where the neutron energy would be converted to heat to generate electricity.

Other important areas of research include fuelling the plasma and developing a complex neural network diagnostic system to control the plasma. Plasmas are generally fuelled by inserting the deuterium and tritium gases from the side of the reactor. Work has been done on firing pellets of frozen deuterium into the centre of the plasma. The research suggests that this fuelling technique may result in a better pressure profile, or pedestal size, across the plasma. Research into neural network control systems has been done on the small Compass and Start experimental reactors at Culham in the UK. With the plasma being such an ephemeral and intrinsically unstable structure, a rapidly evolving and responsive control system clearly offers the possibility of maintaining the plasma closer to optimum conditions.

It is possible that at some stage during ITER-FEAT's 20 year operation, research will be carried out on lithium blanket modules incorporated into the reactor wall. Lithium bombarded with neutrons produces tritium. In a power plant the blanket would act as a tritium 'breeder'. There is unlikely to be a shortage of tritium during the ITER-FEAT phase as it is available from fission reactors such as AECL's CANDU design. This may not have been so in the original ITER design and it is an important factor in the cost reduction. If fusion becomes a commercial power source lithium blankets will be needed to produce tritium.

The fundamental objective of the ITER-FEAT project is to show that getting useful energy from fusion is possible. It needs to achieve a better value of Q, the ratio between the energy released as a result of the fusion reactions taking place and the energy put in to the system to maintain the reactions. Any Q value above 1 implies that more energy has been released than consumed. More specifically the performance objectives are:

- To achieve extended burn in inductive operation with Q > 10, not precluding ignition, with an inductive burn duration between 300 and 500 seconds, a 14 MeV average neutron wall load > 0.5 MW / m2 and a fluence > 0.3 MWa / m^2.
- To aim at demonstrating steady-state operation using non-inductive current drive with Q> 5.

NEED FOR NON-INDUCTIVE BURN

Inductive burn operates when a current produced by a transformer runs through the plasma. By definition this makes it a pulsed machine, although pulses can be more than 1000 seconds long. It is possible, by heating the plasma with fast particle beams or radio frequency waves, to drive a current through a plasma without a transformer and this is referred to as non-inductive current drive. Stellerators, fusion reactors of a different design to tokomaks, with far more complex electromagnetic fields and plasma shape, operate without a current in the plasma and avoid this problem. However research on this design is not as advanced and scientists have not achieved Q ratios anything like as good as those achieved at JET and other tokomaks. The ITER-FEAT design has placed more emphasis on achieving a steady-state burn using non-inductive currents than the original ITER design.

At JET the highest Q that has been achieved is 0.65. Scientists are confident that the increased size of the ITER-FEAT reactor will produce a Q value well above 1.

The main reason for their confidence is that data from different reactors of different sizes around the world suggest that there is a direct relationship between the size and the Q ratio. The logic is therefore that to get Q greater than 1, all you need is a large enough reactor.

"By doing fusion in different sized devices you can establish a scaling law which integrates all the various factors," says Martin O'Brien. "There is a central database which has the confinement times and variations in other criteria of all the experiments that have taken place in all the world's reactors. Scalings capture the dependence on quantities such as the plasma current, magnetic field, power necessary to heat the plasma, plasma density, plasma size, aspect ratio and the vertical elongation of the cross-section."

The aspect ratio is between the large radius of the doughnut shaped plasma ring and the small radius within the ring. Extrapolating this scaling law to a reactor of ITER-FEAT's size produces a result for Q between 6 and 15. In a reactor designed to produce electricity the Q value would be between 30 and 50.

According to Jerome Pamela, formerly head of the French fusion programme at Cadarache and now leading the experiments at JET, organised within the European Fusion Development Agreement which co-ordinates most fusion research across the continent, it is not the value of Q which is the most important issue.

"Q does not give you an appreciation of the physics," he says. "The fraction of plasma heating by alpha particles is more important. For a power producing reactor you need to achieve 90-95% alpha particle heating – its proportion can be estimated using the calculation Q / Q+5. With Q=10 that implies 67% alpha particle heating. If we can control a plasma with 67% alpha particle heating we would be very close to achieving 90% heating."

ENSURING SAFETY

Despite the fact that fusion produces no high level radioactive waste, the machine does become irradiated and maintenance will have to be carried out remotely. In safety terms the most important issue is the management of tritium and ensuring that it cannot be released to the environment. Neill Taylor is an engineer who has worked on fusion safety issues for many years.

"Tritium is the one thing which you could postulate in an accident could be released," he said. "The aim is therefore to confine it. The first confinement is the vacuum vessel of the reactor itself and the second is the cryostat, which encloses the cooling circuits and other support infrastructure. The cryostat maintains a rough vacuum to keep the magnets cool. Beyond that the building acts as a third defence.

"The other main issue is the activation of steel due to neutron bombardment. It is not that hazardous, but you can't handle it directly. Component removal has to be carried out remotely. The safety issue is mainly occupational. We've done intensive analysis on the risk of tritium escape. These have shown that the maximum conceivable release is well below the public evacuation level."

Beyond the relatively trivial public and occupational safety issues, research is focusing on the safety of the reactor itself. With such a high energy plasma and the complexities of superconducting materials, it is possible to make a mistake and cause quite severe damage. Work needs to be done on ensuring that should a problem occur such as the plasma hitting the reactor wall, part of the superconducting coil becoming resistive, known as quenching, or instability in the electromagnetic field, the energy in the magnetic coils can discharge almost instantly. Switches that can dump the charge through resistors are incorporated into the design. A problem such as a quench can be detected almost immediately through changes in the coil current and helium flow. These are used as indicators to operate the switches.

POLITICAL DECISIONS

Assuming the EU and Japan both agree to back the ITER-FEAT project, a vital issue yet to be resolved is the location of the reactor. Canada, which in fusion terms is part of the European research team, has been active in trying to persuade the Europeans to back building the reactor at either its Bruce or Darlington sites. Canada offers a number of distinct advantages, in particular the supply of tritium from its CANDU reactors. Canada can also offer cheap electricity and the project is backed by industry, including Ontario Hydro, and by the local population. Another advantage to siting the reactor in Canada is the proximity to the US. Despite the US's political decision to withdraw from ITER, most people in the fusion community hope it will return. It is clear that the US Department of Energy wants to be involved and the reasons for the US withdrawal are more to do with internal conflict between President Clinton and the Republican controlled Congress than scientific value. A political change in the US could see its return to the fold. Other possible sites include Japan and Italy. Both countries have actively backed fusion for many years.

The debate over the reactor's location, its cost and the need for the work to be done reflect the political nature of fusion research. Since the 1950s it has been a political as well as scientific project. During the cold war fusion research was one of the few contacts between East and West. Its international nature has posed scientists and engineers with cultural difficulties and a new mode for international research has developed partly through the fusion experience.

ITER-FEAT represents a new form of international research, under which fusion research carried out by all the parties will be integrated into an overall strategy. Europe's involvement is managed under the European Fusion Development Agreement, which will also co-ordinate research at other reactors. For example the UK Atomic Energy Authority now has an operating contract with the EC to maintain the JET facilities, but the experiments carried out will be decided at a European level with an enabling agreement from Euratom. Advances in information technology mean it is now possible to participate in experiments at JET remotely from anywhere in the world. Jerome Pamela is responsible for managing the JET implementing agreement.

"There is a much more co-operative spirit across Europe now," he says. "We feel the new structure is an important development for fusion, it is more like the structure for particle physics research at CERN.

"The objective at JET now is to consolidate the design and physics basis of the ITER project. The specific aims are to improve the understanding of basic physics. More specifically to improve our understanding of H-mode – high energy – plasmas and to work on various scenarios which need more sophisticated control of the plasma, through current control and pellet injection.

"We have reached the stage where we have gained a basic understanding of plasma behaviour and are concentrating now on plasma control, current, pressure etc. The current JET programme, which runs to the end of 2002, will focus on these areas. There are also discussions about changing the divertor and increasing heating power. This could improve the plasma performance by a factor of two to three and would allow us to make progress in understanding deuterium tritium plasmas. JET is the only fusion reactor that can use tritium, the others all operate with deuterium fusing with itself."

The ITER project is a major undertaking and the financial resources required are bound to make any politician think very carefully. Unlike other areas of scientific research the fusion project could be killed almost with a single shot, but if Europe or Japan fails to back the project forty years of research could be lost and the benefits in terms of materials development, international co-operation and ultimately a non-polluting and unlimited energy source will not be realised.

"ITER will be one of the most significant international research projects in the world," said Klaus Pinkau, former head of the Institute of Plasma Physics at the Max Plank Institute in Garsching, Germany. "It will require international cultural contacts with a degree of intensity so far not experienced. I believe many politicians want this learning process to take place."

Although many politicians are thinking only of the next election, some will want to leave their mark on history. What could be a more profound and significant legacy than that of backing a project which may be the best chance society has of eventually releasing itself from dependence on fossil fuels, providing the energy needed to address global poverty and preventing the dislocations that major climate change will inevitably bring. ■

The Joint European Torus is at Culham, UK, but is operated as part of an EU-wide project.