The Oil Drum: Europe
DISCUSSIONS ABOUT ENERGY AND OUR FUTURE

Will Nuclear Fusion Fill the Gap Left by Peak Oil?

Posted by Chris Vernon on January 11, 2007 - 10:45am in The Oil Drum: Europe
Topic: Alternative energy
Tags: electricity, fission, fusion, nuclear, uranium [list all tags]

[editor's note, by Chris Vernon] This is a guest post by TOD member Nick Rouse.

On the 12th. of December 2006 the UK Magnetics Society held its annual commemorative event with an afternoon seminar followed by the Ewing Lecture. This year the focus was on magnetic fusion energy.

Nuclear fusion has evoked opinions in the various energy blogs ranging from “sixty years of failure and a certain dead end”, to “the reason why we do not need to worry about peak oil”. This event was a good opportunity to gain a clearer view of what part, if any, fusion energy could play in filling the gap as oil and then gas production peak and decline.

After many years of half-hearted support there is now a surge of backing for fusion energy. Many will have heard about the agreement to built the International Tokamak Experimental Reactor ITER. Less well publicised have been the European Fast Track program and the bilateral agreement between the EU and Japan called ‘the Broader Approach’ which, amongst other things, will lead to DEMO, the first full electrical power generating reactor. From the UK side this new found enthusiasm has been in large part due to Sir David King, the Chief Scientific Advisor to the government, who may not fully accept the imminence of peak oil, but does see an energy crisis looming and has become convinced that the possibility of fusion energy is promising enough to warrant substantial investment.

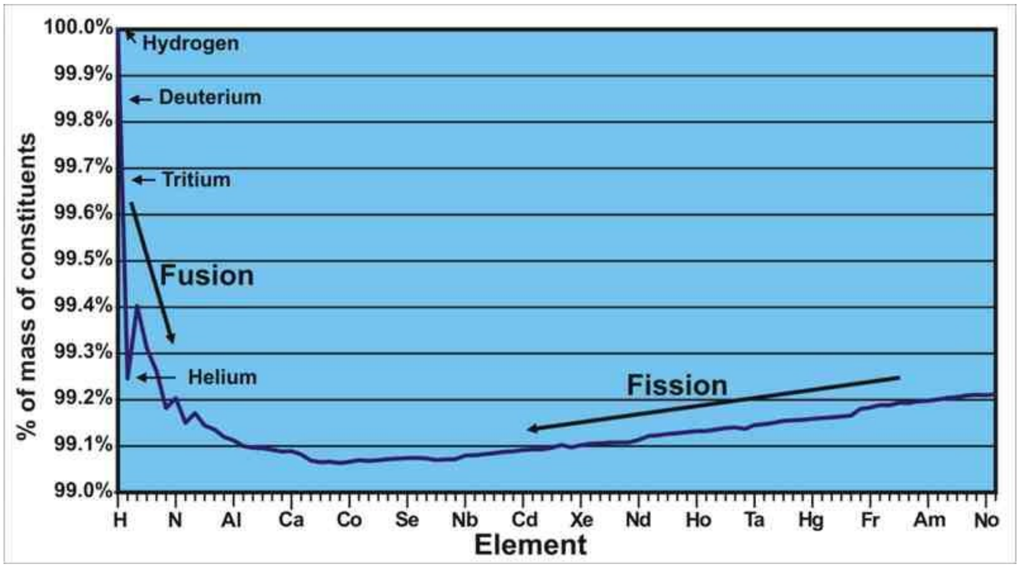
The four speakers in the seminar were senior members of the staff of the Culham Division of the United Kingdom Atomic Energy Authority (UKAEA). The lecture was given by Dr. Frank Briscoe, operations director at Culham. Culham has been the centre of fusion research in the UK since 1960 when the first large scale UK fusion experiment, ZETA was transferred there from Harwell. ZETA was still there, but no longer working, when I first visited Culham from Harwell as a student in 1964. I have retained a personal interest in fusion since then.

Of particular interest to this forum were the Ewing lecture itself, entitled ‘Magnetic Fusion Energy: Progress and the Remaining Challenges’ and the seminar presentation by Dr. Derek Stork entitled ‘Scientific and Engineering Challenges of a DEMO Fusion Reactor’. Since the various contributions overlapped somewhat and some of the material was of specialised interest to those involved in magnetics, I have combined those parts of the contributions that I hope are of interest to this forum.

Dr. Briscoe started his lecture with a brief summary of how nuclear fusion works.

Fusion Basics

Atomic energy, both fission and fusion, exploits the fact that atoms weigh less than the sum of their parts. This is because of the energy that binds them together and is released in forming the atom from its constituent protons, neutrons and electrons and would have to be expended to rip the atom apart back to these constituent parts. The energy released in binding relates directly to the drop in mass of the atom by Einstein's equation $E = mc^2$. This loss in mass is called the mass defect and varies between the elements. Energy can be released by either splitting very heavy atoms in two (fission) or joining light atoms together (fusion).



Mass defect: The mass of an atom of each element expressed as a percentage of the mass of the protons, neutrons and electrons that constitute the atom. The three isotopes of hydrogen plus the most common or stable isotope of the other elements are shown. Click to Enlarge

The problem with trying to fuse atoms together is that, although there is a very strong force of attraction between the protons and neutrons in the nucleus when they are very close due to the strong nuclear force, this force drops away very rapidly with distance so that at slightly greater distances the electrostatic repulsion between the positively charged protons becomes dominant. To fuse the nuclei of two atoms, they have to be forced together hard enough to overcome this repulsion until they are close enough together for the force to become attractive.

Many different fusion reactions and many ways of bringing the atoms together have been considered. Far and away the front runner, in terms of progress to achieve a large scale commercial electrical power plant, is the reaction between the hydrogen isotopes deuterium and tritium when heated to a temperature such that thermal collisions between the nuclei carry enough energy to overcome the electrostatic repulsion with magnetic forces being used to confine the reactants. The temperature required to cause the reaction is in the order of a hundred millions degrees. At such a temperature the reactants are completely dissociated into a cloud of nuclei and electrons called a plasma. The plasma is far too hot to confine with material walls but because the electrons and nuclei are charged and moving they can be deflected by magnetic forces and with a suitably shaped magnetic field, confined.

The fusion reaction is deuterium plus tritium gives helium plus a neutron:

$^{2}H + {}^{3}H \rightarrow {}^{4}He + n$

20% of the energy released by the reaction is carried off by the helium ion as kinetic energy (3.5Mev per ion). Since the helium is ionised it is charged and is confined by the magnetic field. In colliding with the rest of the plasma it gives up its kinetic energy, heating the plasma. If the condition called ignition can be reached this will be the only source of heat needed to maintain the plasma temperature once ignited.

The other 80% of the reaction energy will be carried off by the kinetic energy of the neutrons

(14.1MeV per neutron). Since the neutron is not charged it escapes the plasma. In a reactor designed to generate power, a 'blanket' surrounds the plasma and the collisions the neutrons make with the material of the blanket transfers the kinetic energy of the neutron to the blanket, heating it up. This heat, plus a little gained from absorbing the hard ultraviolet/soft gamma radiation emitted by the plasma, is transferred out of the chamber by a gas or liquid and used to heat steam, to drive a turbine, which turns an alternator to generate electricity.

Deuterium exists in enormous quantities in sea water where it forms 0.03% by weight of the hydrogen but tritium exists naturally in only tiny amounts generated by cosmic rays, and decays away with a half life of 12.3 years, so that there is only about 3.6kg of naturally generated tritium at any one time distributed all around the planet. All other tritium has to be made artificially. In a commercial reactor the blanket will also perform the function of creating tritium. It will contain lithium in some form and this will react with the neutrons bombarding it to form tritium using the reaction :-

$n + {}^{6}Li \rightarrow {}^{3}H + {}^{4}He$

This tritium will be collected to fuel the continuing fusion reaction. Lithium 6 is a stable isotope and forms 7.5% of natural lithium. Some blanket designs require enrichment of this isotope. The tritium breeding reaction is exothermic and increases the heat production by some 20%.

At first sight these reactions appears to combine to give an overall reaction of:-

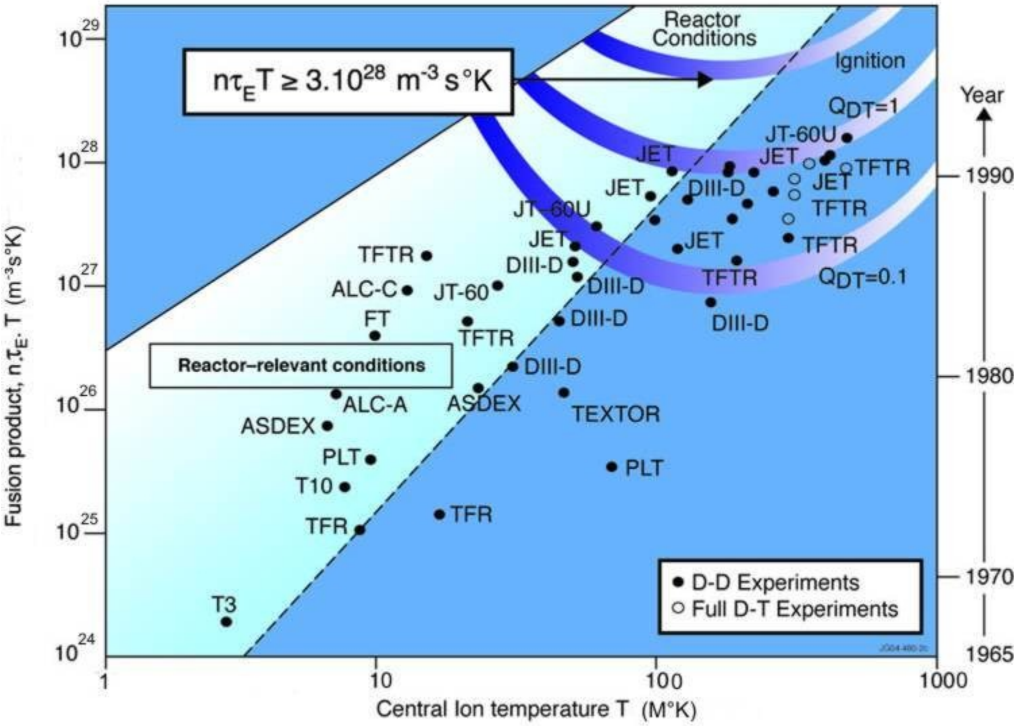
${}^{2}H + {}^{6}Li \rightarrow 2\,{}^{4}He$

However this neat cancellation requires that every neutron from the fusion reaction reacts with a lithium atom to form a tritium atom and that every tritium atom so generated is collected and fed back into the reactor and takes part in a neutron generating fusion reaction. In practice there are many loss mechanisms around the loop that mean that this path alone will not provide sufficient tritium to maintain operation. To augment the tritium production a neutron multiplier is added to the lithium. The main candidates for a neutron multiplier are beryllium and lead. Experiments have shown that tritium self-sufficiency is possible but difficult. To generate much in the way of a surplus is very difficult. Dr. Stork indicated that a tritium breeding ratio of about 1.1 was all that was expected of the designs being considered. This implies that for every 10kg of tritium fed in as fuel for the fusion reaction, 11kg of tritium will be recovered from the blanket. The magnitude of the excess tritium available is probably the limiting factor on how fast fusion energy can spread once a prototype commercial fusion reactor has been demonstrated, as discussed below.

Magnetic Confinement

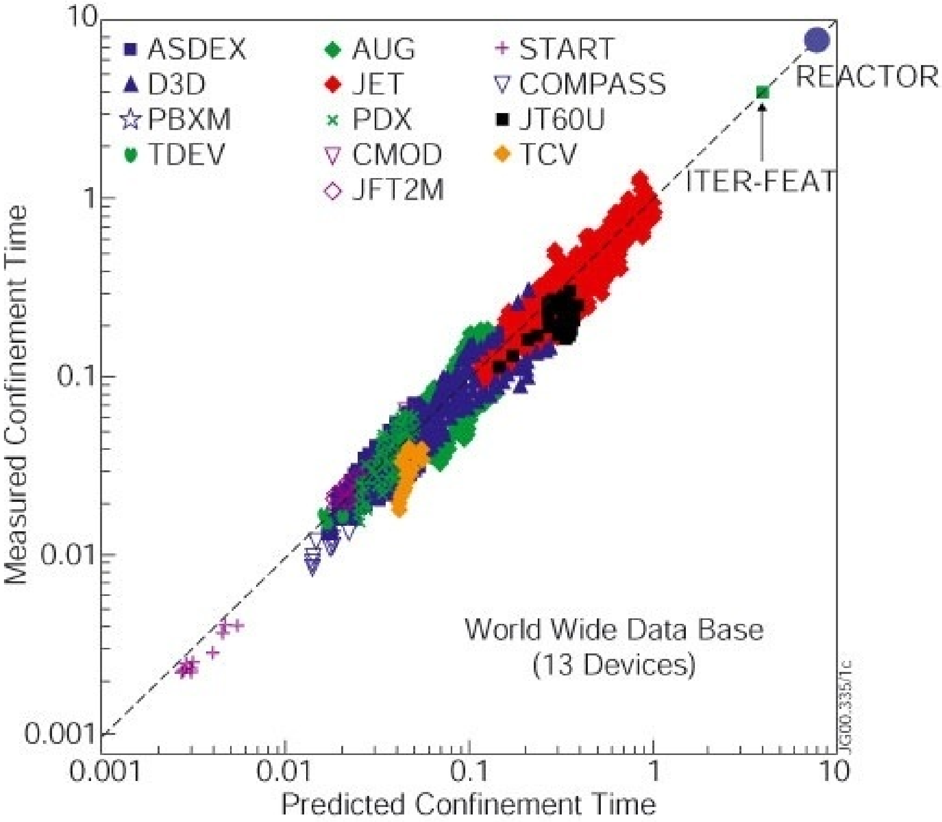
As part of his seminar presentation, Dr Tom Todd gave a fascinating review of the very varied magnetic confinement systems that have been, and are being, experimented with but again by far and away the front runner in the race to practical power systems are the toriodal systems first developed by the Russians called 'tokamaks', from a Russian acronym. The biggest and most successful tokamak so far is the European run JET system hosted in the UK at Culham. This produced a peak of 16MW of fusion power in 1997 but many other tokamaks have been built across the world.

Critics of fusion power have categorised these experiments as so many failures because none of them have produced more output fusion power than was put in. In truth none of them were built with the intention of achieving energy break-even. All were intended to understand and develop ways of controlling the seething monster that a dense plasma at a temperature of many millions of degrees is. For the most part these experiments have, after a fair bit of modification and adjustment, reached the sort of performance hoped for. Our ability to contain the plasma at high temperature, high density and for long enough to allow a sufficient degree of reaction to take place has increased four orders of magnitude over 40 years.



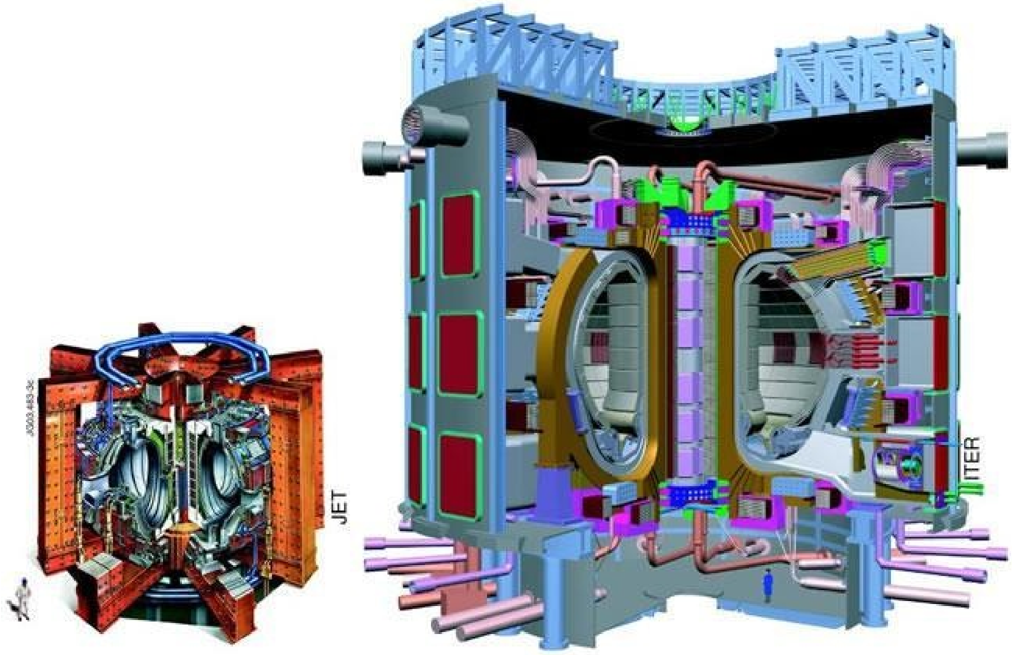
This shows the progress over the years at confining a hot plasma. The fusion product is the plasma density in particles/m^3 times the time in seconds that the plasma can be held in these conditions, times the ion temperature in degrees Kelvin. The requirement for this to be at least 3 x 10^{28} for ignition to occur in a deuterium/tritium plasma is one of the Lawson criteria formulated by JD Lawson 1955. The best results of JET and JT-60U are close to energy break-even, Q = 1. Click to Enlarge

There has also been great progress in predicting the performance of a plasma device as computer power has increased, so there are now fewer surprises in new experiments.



Predicted and measured confinement time for 13 different fusion devices under a great variety of conditions plus indications of where ITER and a commercial power reactor are expected to operate by scaling the results of existing machines. Click to enlarge

Although there is still more work to do on plasma control, we have now reached the stage where we can be reasonably confident that just scaling up the size of the reactor will produce substantially more power from fusion than is put in to create the reaction. Such a reactor has been designed in detail and the major parts have already been prototyped. On 21 November 2006, after years of delay, an agreement was signed to build ITER at Cadarache in France financed by China, the EU, India, Japan, Russia, South Korea, and the USA. Together these partners represent over half the population of the planet.



Jet and ITER: The two reactors are shown in cut away diagrams. Human figures give the scale. Click to enlarge.

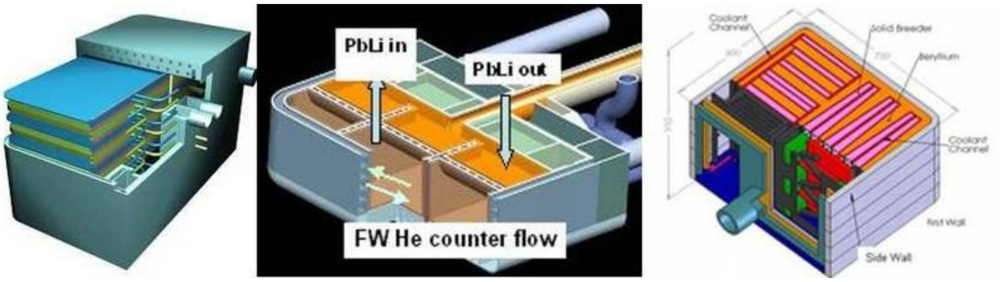
Power will be feed into the ITER plasma in three main ways: by transformer action causing up to 15 million amps to flow in the plasma; by neutral high energy beams of deuterium and tritium fired into the plasma; and by radio frequency energy fed in from antenna patches in the walls to excite resonances in the plasma, Transformer action is very efficient but necessarily pulsed. The other two forms of heating are less efficient but can be continuous. ITER is expected to generate 500MW of fusion energy output, with less than a tenth of that input power (Q>10) and hold that power for 400 seconds. Also it should generate 500MW output for an hour at an input of one fifth the input energy (Q>5). Although it is not stated as an aim, there is the hope that it might achieve what is called ignition where enough of the fusion energy remains in the plasma to keep the reaction going without the need of external input energy (Q = infinity). This will require higher plasma densities than needed with external energy input.

Although there seems to be reasonable confidence that ITER will come at least close to the target in plasma performance this is just the start of the challenge that needs to be met to build a commercial electrical power generating station.

If all goes well ITER will produce the first plasma before the end of 2016, but, in order to speed the development of commercial fusion power, a ‘Fast Track’ strategy is being adopted and in addition to the ITER agreement there has been a bilateral agreement between the EU and Japan called ‘the Broader Approach’. Studies of the DEMO reactor to follow ITER are part of this agreement.

Beyond ITER

A major hurdle to be jumped is the design the breeding blanket that lines the inside of the reaction chamber and the selection of suitable materials for it. This blanket is required for three purposes; to convert the energy given off by the fusion reaction to heat, to breed more tritium to fuel the reaction and to protect the superconducting coils and chamber wall from neutron irradiation There are a variety of different blanket designs that have been proposed and all of them have some problematical features to them. ITER will not have (certainly not in the early years) a full tritium breeding blanket. Most of the reaction chamber will be lined with a simple cooled neutron and heat absorbing blanket to stop the reactor overheating. There will however be space to fit in and remove small areas of tritium breeding blanket and it is proposed to try, in turn, a variety of different designs.



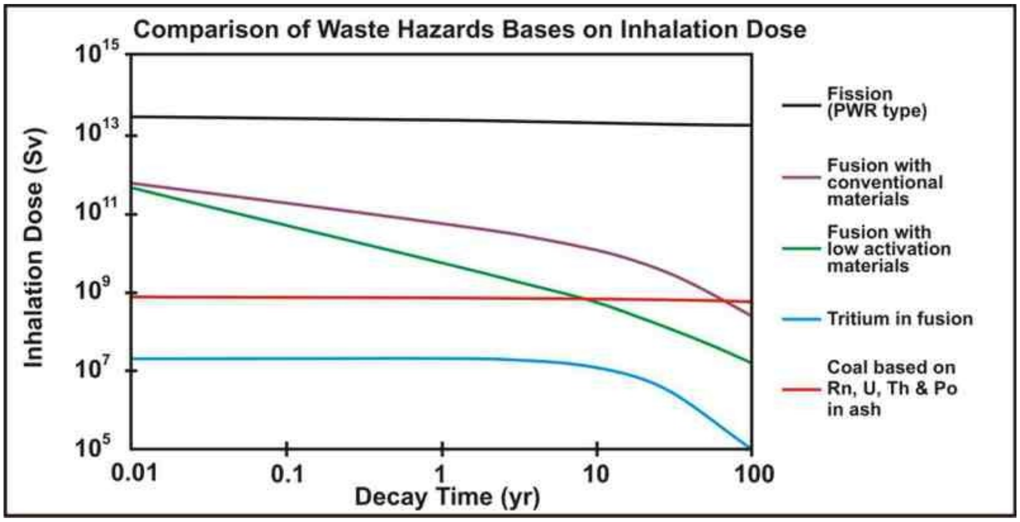
Montage of some of the proposed Test Blanket Modules. Click to enlarge.

DEMO will have a full breeding blanket to achieve tritium self-sufficiency. The materials used to make the breeding blanket and particularly the first wall facing the plasma need to survive an extremely severe combination of conditions and retain adequate strength and other mechanical properties. The heat flux on the first wall of the blanket will 0.1 to 0.3 MW/m² in ITER and rise to 0.5 MW/m² in DEMO. This DEMO figure is about twice that of a PWR type fission reactor and almost the same as a fast breeder fission reactor, The flux of energetic neutrons means that over about 5 years every atom in the first wall will have been knocked out of place an average of about 3 times for ITER and 50-80 times in DEMO and perhaps twice this in a full scale commercial reactor. Each displacement will shift the atom several tens of crystal lattice spaces from its original site. Atomic transmutations caused by the neutron flux will leave hydrogen and helium embedded in the wall. For DEMO this will result in 500-800 parts per million by atom count (appm) of helium and 2300 to 3600 appm of hydrogen. For ITER it will be acceptable for the blanket to be well cooled to keep it at a fairly low temperature but in a reactor trying to generate electricity by a conventional steam cycle, it is important for high thermal efficiency that steam and hence the blanket coolant are run at as high a temperature as possible. It is expected that the blanket structure will operate at 500°C to 800°C

This combination of requirements mean there is almost no chance of a breeder blanket that can survive the full life of the reactor. After a few years the material properties of the blanket structure will have degraded so much that it will have to be replaced. The inside of the chamber will be far too radioactive for a person to go in there, and so a remote handling arm will have reach in through one of the ports, bending around the central pillar where required, and remove the old blanket, section by section and replace it, section by section with a new blanket disconnecting and reconnecting the pipework (probably by cutting and re-welding) without spillage. The sections are likely to weigh several tonnes. The blanket sections will have to have a fairly tight fit to protect all the chamber wall and coils, but the extreme service conditions mean that they will be significantly distorted at the end of their service life. They must not jam in place or the long articulated arm will not be able to pull them out. There is reasonable confidence that a blanket of some sort came be built to operate for some length of time but the economics of a future power station will depend heavily on how hot the blanket can run and how long it can survive before replacement and how fast it can be replaced. The remote handling arm is a major engineering challenge.

The helium generated in the plasma by the fusion reaction and any other contaminants such as material coming off the structure under severe bombardment, need to be removed from the plasma continuously to allow the reaction to continue. To this end, at the bottom of the reaction chamber there is a divertor structure where the magnetic field is reduced so that a small fraction of the plasma separates and is allowed to cool as it circulates to the point where it recombines to form neutral atoms before colliding with the divertor plates. The gases can then be pumped out and the hydrogen isotopes separated for re-injection. Although the plasma has been cooled before hitting the divertor plates the heat flux on them is still enormous. In the DEMO reactor it will be about 15MW/m². This is about 15% of the energy generated by the fusion reaction and this energy will taken away by a coolant (probably helium) and will be used to generate electricity together with the heat from the blanket. 15MW/m² is about 20% of the power density at the surface of the sun. There is even less chance of the divertor plates lasting the lifetime of the reactor. In fact the lifetime may be as short as two years and these will also need to be replaced by remote handling in sections usually called cassettes.

As well as all the other requirements that must be met by the materials of the blanket and divertor, it is important that the amount of radioactivity induced in them by neutron bombardment is minimised. This precludes the use of some elements that might otherwise be useful for alloying. Theoretically there are no net radioactive materials produced by the main reactions of the reactor since the tritium is recycled. However there will be radioactive waste due to side effects such as neutron activation and tritium embedded in the structure. This will affect both the replaced parts during the reactors life time and the reactor itself when it is decommissioned. Predicting the level of radioactivity of the waste is difficult and impurity levels will have a strong influence. However the radioactivity has been estimated to be 2 orders of magnitude less than a fission reactor and to be short lived, so that after 100 years the level of radiotoxicity will be less than the waste from an equivalent-sized coal fired power station, Keeping the radiotoxicity low will require the tritium recovery and recycling to be achieved with extremely low leakage.



Decay with time of radiotoxicity. Click to enlarge.

The development and testing of materials to meet these very onerous requirements is crucial to the speed of deployment of fusion energy. Because ITER will not produce a plasma for almost 10 years at best and even then will not produce a neutron flux anywhere near as intense as in DEMO and that only intermittently, it has been decided to build a special facility to reproduce, over a small area, the conditions that DEMO and following reactors will have to face. This will be called the International Fusion Materials Irradiation Facility (IFMIF). This will be developed and tested in Japan as part of the Broader Approach agreement, although the final site for the installation has not yet been agreed. At IFMIF two 40MeV linear accelerators will provide 250mA of deuterons which will be targeted on flowing liquid lithium to produce neutrons with an energy spectrum up to 14Mev matching that expected in DEMO. The flux will be sufficient to produce 20 displacements per atom per year in the test samples. Further steps that will be taken to speed up development are that the JET reactor at Culham will have its present carbon chamber lining converted back to a metal wall to provide test data on this material for ITER and DEMO and the JT-60 tokamak will upgraded to have superconducting coils and to act as a satellite control for ITER. A smaller UK Tokamak MAST, which has a toroidal plasma aspect ratio squeezed so tight that it is like a spherical apple with the core cut out, will also provide input to the DEMO design.

Dr. Briscoe summarised the challenges ahead with the following table:

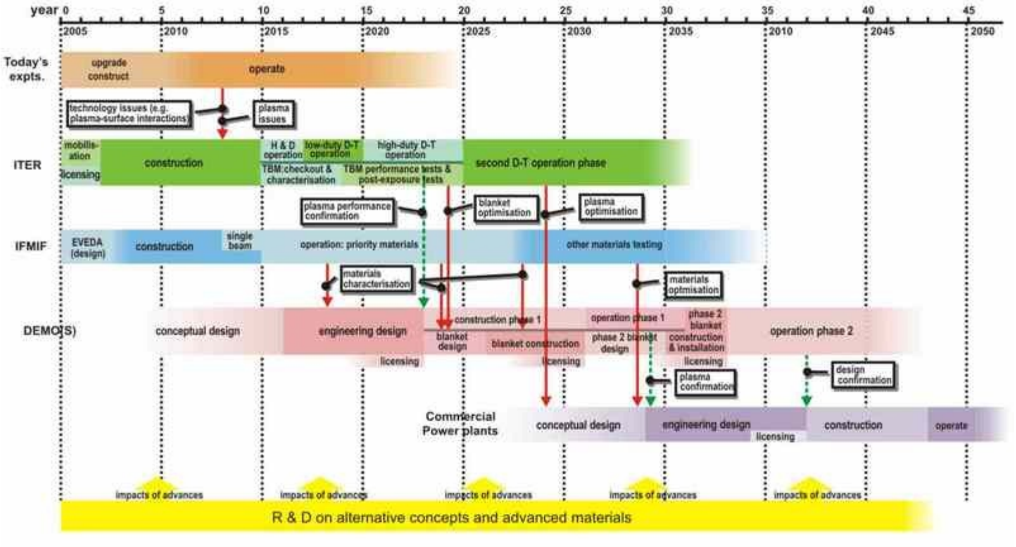
ITEM	Existing Devices	ITER	IFMIF	DEMO Phase 1	DEMO Phase 2	Power Plant
plasma disruption avoidance	2	3		C	R	R
steady-state operation	1	3		3	r	r
divertor performance	2	3		R	R	R
burning plasma at Q>10		3		R	R	R
power plant plasma performance	1	3		C	R	R
tritium self-sufficiency		1		3	R	R
materials characterisation			3	R	R	R
plasma-facing surface lifetime	1	2		2	3	R
facing wall/ blanket/ divertor materials lifetime		1	2	2	3	R
facing wall/ blanket components lifetime		1	1	1	3	R
neutral beam/radio frequency heating systems performance	1	3		R	R	R
electricity generation at high availability				1	3	R
superconducting machine	2	3		R	R	R
tritium issues	1	3		R	R	R
remote handling	2	3		R	R	R

KEY

1	Will help to resolve the issue
2	May resolve the issue
3	Should resolve the issue
C	Confirmation of resolution needed
r	Solution is desirable
R	Solution is a requirement

Timetable

A timetable has been proposed for the overlapping development of the various proposed devices. It assumes that the only obstacles to its implementation are technical ones and comes with many caveats, but it sees the first commercial power station operational in 2048. Even if this very compressed time table is met, it does not signify the widespread availability of fusion power. There is a limit to the rate at which the number fusion power stations can be multiplied set by the supplies of tritium.

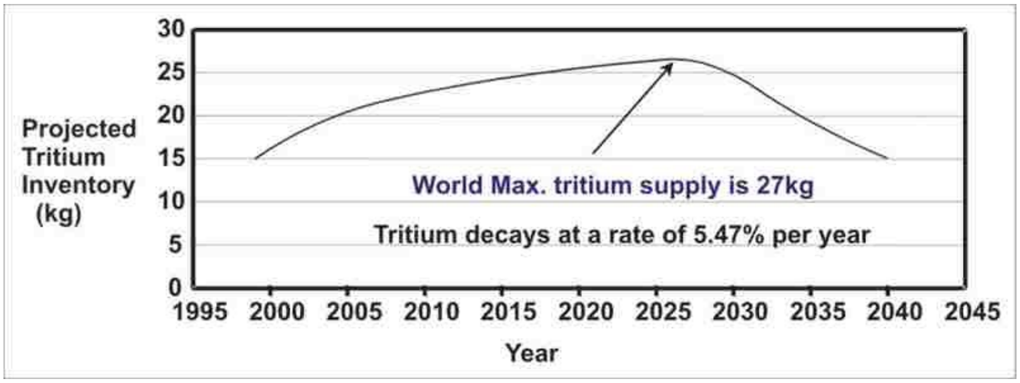


The Fast Track timetable. Click to enlarge.

Tritium Supplies

The large scale adoption of fusion energy will see tritium used on a scale vastly greater than has ever been seen before. Something like a 220kg per year of tritium will be consumed for every 1GW of continuous electrical generation, assuming that 4GW thermal will generate 2GW electrical of which 1GW will be used to provide all the inputs to the system leaving 1GW of output power. At present world-wide electrical consumption averages to a continuous 1700GW

Nearly all the worlds supply of non-military tritium comes from the heavy water used to moderate CANDU reactors and some of these will be closing down in the near future. The supply accumulated over 40 years of operation of CANDU reactors will peak in 2027 at 27kg.



The world's commercially available supply of tritium before any is removed by fusion programme. Click to enlarge.

Military reactors designed for tritium production produced only a few kilograms a year at a cost of about $200M/kg. Tritium increases the yield thermonuclear warheads (H bombs). It is thought that about 4g is used in each warhead, added in a container just before launch, so that decay of the tritium does not limit the shelf life of the weapon. There have been some hints that the latest warheads being designed will not use tritium. The US had a number of military reactors at its Savannah River site especially designed for tritium production but the last of these was closed down in 1988. It is believed that over 220kg of tritium was produced there over the years but that there was only about 73kg in 1995 which will have now decayed to about 37kg. It is unlikely the US military will release any of this for civil fusion power. One of the speakers said that he believed that at one time the Russians had mentioned the possibility of releasing some of their supply but had no further details. Other civil fission reactors could produce small amounts by placing lithium inside the reactor but some back of envelope calculations that I did for a comment to previous post show that it would take at least 60 tonnes of unenriched uranium to produce 1kg of tritium in a standard reactor and it may be much more. Specially designed accelerators are theoretically capable of producing tritium, and have been considered for military needs, but one to generate a few kilograms per year was estimated to cost $4.8 to 6.1 billion in 1991 prices and would produce vast quantities of radioactive waste.

Since ITER will produce only a tiny proportion of the tritium it uses (at least in the early years) because the experimental test blanket modules will only cover a small area of the chamber, ITER alone will severely deplete the worlds tritium stock. If DEMO is heavily overlapped in time with ITER the tritium supply will be very critical and it will be important to get the full blanket and tritium recovery system going as soon as possible if the programme is not to be delayed.

If fusion reactors are to proliferate, then probably near the start, and certainly after the first few, each new reactor will be relying on the small surplus tritium production from existing reactors to provide the start-up charge of tritium. This is likely to be some tens of kilograms. When I asked him, Dr Briscoe said that it will probably take two-and-a-half to three years from the start of one reactor for it to supply enough surplus tritium to start up another. The estimate he gave was that even if the only obstacles were technical ones it will be 2100 before fusion can supply more than 30% of Europe’s electricity.

The Energy Gap

All but the most dewy-eyed optimists foresee the production of conventional oil severely curtailed by then. If we are to get to 2100 without major economic collapse or using so much coal, tar and oil shale that the carbon dioxide will have risen to disastrous levels, we will have had to have adopted other energy sources on a major scale, as well as substantially cutting our energy consumption and finding some way of replacing liquid hydrocarbons for transport. Fusion will then be competing in a very different environment.

Cost estimates at this stage are obviously uncertain in the extreme but most estimates put the cost of generated electricity as comparable in today’s prices with today’s fossil fuel generated power. Most of the cost is in the capital cost of the plant amortised over the life of the plant. Running, periodic replacements and decommissioning costs coming next with fuel costs less than 1% of these and not likely to rise by depleting the richer ore, as would be the case with very widespread use of thermal fission plants. One estimate puts the capital cost at €14/W electrical for DEMO falling to €4/W for commercial plants in serial production. This link allows you to play with the assumptions and produce an electricity price.

These prices should be compared to today's fission and coal plants at €3 /W and €1.5 /W. respectively for the plant alone. However, the capital costs of coal plants do not include costs to mitigate environmental damage. Wind energy capital costs are now about €1.5/W but rarely have a load factor of more than 30%, whereas fusion plants after initial settling-in could have 85% load factor. Correspondingly more rated wind power plant would need to be installed to meet the same electrical demand. If wind power were to supply more than 30% of the total supply, extensive power storage would be needed and the transmission costs would be greater as many of the turbines would scattered across areas remote from demand.

The carbon dioxide emissions associated with fusion are again very difficult to estimate at this distance, but will also be dominated by that generated in building the reactor and its associated plant and the periodically replaceable parts. The carbon dioxide generated in fuel production and preparation will be constant and low in comparison. Fusion reactors are inherently proof against melt-down or nuclear explosion. There simply is not enough fuel in the reactor at any one time to cause one. Any failure of coolant, magnet supply or other major system will cause the reaction to die in milliseconds. There is not enough heat in the system even without coolant to breach the containment vessel. According to this report even in the worst credible accident with the release of all the tritium on site there would be no need to evacuate anybody beyond the site boundary. They are a very much less tempting a target for attack by violent political or religious groups than thermal fission reactors, still less than fast breeder reactors. If a large part of the energy gap world wide were to be made up by fission reactors using the present system of thermal reactors with once through use of enriched uranium we would rapidly be reduced to the use of ever lower grades of ore requiring more energy input. Some estimates put the point at which there is no energy gain to be 0.02% of uranium and that if nuclear energy were expanded from the present 16% to 50% of electrical generation we would be reduced to using such ores in 50 years. There has been much argument over such estimates but in the long term it is clear that if we are to rely on fission for a major part of our electricity let alone total energy we will need to move to fast breeder reactors or thorium reactors. The long development time of fusion energy may seem disheartening but that of fast breeders is not much better.

In 1946, the year I was born, the Nobel prize winner, Sir George Thomson, working at Imperial College London applied for a patent for using a gas discharge to generate controlled thermonuclear fusion. If the proposed timetable is kept to and if I live to be 102 I may just, in my dotage, see his dream brought to commercial reality. I do not know which of the two is more improbable.