CLEAN ENERGY AND THE FAST TRACK TO FUSION POWER

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INTRODUCTION

I gave the opening talk at EPAC 1994 (on the LHC), while the opening talk this week was given by Robert Aymar, who was working in fusion in 1994. The science and aims of particle physics and fusion are very different, but there is a large overlap in the technologies that are involved. The fusion laboratory that I now direct was set up by John Adams, after he built the PS and before he returned to CERN to build the SPS, while the Joint European Torus (JET, which we at Culham now operate on behalf of Euratom) was built by Hans Otto Wuster, who was John Adams' deputy at the SPS.

THE LOOMING ENERGY CRISIS

The Underlying Problems

The potential energy crisis is the result of three factors:

1) World energy use is expected to double by 2045 [1], largely as a consequence of the very welcome economic growth in China and India, where energy use per capita is currently very low by European standards.
2) Currently 80% of primary energy supply is derived from burning fossil fuels (oil, coal and natural gas) [1], which
   - is producing very serious pollution, and
   - generates the CO_2 that is driving climate change.

   [Burning wood, waste etc. provides another 11%.]
   The consequences of climate change are potentially so serious that many people think that it is irresponsible to continue burning fossil fuels. Even if we could find ways to capture and store CO_2 at a reasonable cost, fossil fuels will eventually run out.
3) The only alternative energy source that is able today to satisfy a large fraction of global need is nuclear fission, which is of course very unpopular in many countries. However, nuclear is only useful for producing electricity, which currently accounts for around one-third of primary energy use. Nuclear won't power cars, although cars may eventually be powered by electricity or hydrogen generated (indirectly) by nuclear fission, or fusion [2].

Climate Change

Levels of CO_2 have risen from around 280ppm to 375ppm in the last 100 years, and are headed for 800-1000 ppm by the end of the century if we do not change our ways (information on climate change may be found at or via [3]). Climate modellers can now reproduce the changes observed in global temperatures over the last 150 years in some detail, so their predictions that increasing CO_2 will lead to substantial rises of temperature in the future must be heeded. The many potential effects of climate change include rising sea levels which, if CO_2 production is not seriously abated, will submerge land currently occupied by hundreds of millions of people by the end of the century. Some effects are already visible. For example, nine of the hottest summers on record in Europe have occurred in the last 14 years; the rate of retreat of glaciers has accelerated threefold in the last 40 years; the Thames Barrier – built to protect London from tidal surges that had occurred roughly every three years (with the potential to cause up to £30 bn damage) – was closed 3 times in 1983-87, 8 times in 1988-92, 19 times in 1993-97, and 37 times in 1998-2002.

A frequently quoted goal, which would ameliorate but not eliminate these affects, is to limit atmospheric CO_2 to twice pre-industrial levels by 2050. This would require that, of the total world power market of 30TW predicted in 2050, 20TW is CO_2–free - substantially more than today's total world-market (13TW). In the words of the US Department of Energy [4]: 'The Technology to Generate this amount of emission-free power does not exist'.

Remaining Fossil Fuels

There is a Saudi saying that: 'My father rode a camel. I drive a car. My son flies a plane. His son will ride a camel.' Is this true? Many people have tried to estimate the total amount of oil in the world, including oil yet to be discovered [5]. The US Geological Survey's estimate [6], which is the most optimistic (it includes 40% for improvements in extraction, which would be surprising given the maturity of the oil industry), corresponds to 60 years remaining supply of conventional oil at current levels of use. If the present increase in the use of oil continues, this would be reduced to 40 years. Of course it won't happen like that: much sooner, prices will go up as oil becomes scarcer, and consumption will go down.

Production of conventional oil is expected to peak when approximately half the world's accessible oil endowment has been used up. Discovery of new oil fields has been falling for years – easily discovered fields have been found, while production from old fields is dropping as pressures fall. Many analysts [7,8,9] expect the peak to occur in the next 5-10 years (the USGS estimate implies a later date, depending on assumed growth). Production is then expected to fall ~ 3% pa (leading, it is predicted [9], to 'prices going up, inflation, recession, and international tension'). Others believe that this is crying wolf [10]. They point to purportedly wrong predictions of the world's oil endowment in the past (but see below), and recall that the world contains lots of unconventional oil (shales, tar sands, etc.) - this is true, but there are big challenges involved in turning it into petroleum, which will be very expensive.

Part of the disagreement is (implicitly) over whether 20 - 40 years is a long time (compare the International Energy Agency's sanguine words in Chapter 2 of [1] with fig 7.1, which alarms me). It seems to me that even the USGS estimate does not allow much time to make a transition to new energy sources with new infrastructures and end-use technologies.

It is estimated [1] that natural gas will last 200 years, and coal 200+ years, but again this at current levels of use (and with no allowance for gas and coal being used to replace the role of oil).

I believe that we must act now to avert the coupled challenges of climate change and the impending exhaustion of fossil fuels. Those who claim that there is little to worry about often point to the Club of Rome's wrong predictions of impending catastrophic exhaustion of resources [11] (based on the assumption of 7% growth, which would rapidly use up any resource). In fact, the Club of Rome's estimate of the world's oil endowment was in line with today's (apart from that of the USGS).

The Club of Rome also predicted that failure to feed rising populations would lead to major famines. This did not occur thanks to the 'Green revolution'. We now need to seek the revolutions needed to secure ample supplies of clean energy. To quote the DOE once again: 'Major scientific breakthroughs will be required to provide reliable, economical solutions'.

WHAT NEEDS TO BE DONE?

First, wider recognition of the scale of the problem is needed, and that it can only be solved by new and/or improved technologies (although fiscal measures designed to change the behaviour of consumers, and stimulate R&D by industry, will also be essential). Second, increased investment in R&D on energy is crucial. In fact, despite growing concerns about pollution, climate change and security of energy supply, publicly funded R&D has gone down 50% globally since 1980 in real terms, while private funding has also decreased world-wide (e.g. by 67% in the USA in the period 1985-98) [5]. The size of the world's total energy market, which is $3 trillion pa, provides a reference scale. A 10% increase in average energy prices would cost $300 bn, pa, while the market for a technology that captures just 1% of the market is $30 bn pa.

The solution will be a cocktail, and we must explore all sensible avenues. What should we include?

Energy efficiency– yes, with high priority (although it will only ameliorate but not solve the problem).

CO_2 capture and sequestration – yes (although there are big challenges and uncertainties, and – if it is possible – it will add to costs).

Development of renewables – yes (although, with the exception of solar which is currently very expensive, and mostly in the wrong places, renewables do not have the potential to meet a large fraction of global demand).

Energy storage – yes (it is essential if intermittent energy sources are to become more than marginal players, but note that energy storage/retrieval inevitably produces significant losses).

Alternative power sources for (or systems of) transport – yes, including the development of hydrogen as a carrier (NB not a source) of energy (although there are huge challenges to be met), and bioethanols.

Nuclear – yes: see below.

Fusion – yes: see the next section.

There have been remarkable improvements in the reliability, safety and cost of nuclear power, which currently produces 16% of the world's electricity, and today is the only CO_2-free source capable in principle of meeting a large fraction of the world's needs. Further improvements are possible, and the Generation IV Nuclear Consortium [12] (which involves Governments and industry in 10 countries, and Euratom) is developing future 'highly economical, enhanced safety, minimum waste, proliferation resistant' reactors.

The major non-political constraints on the growth of nuclear power are a) the lack of storage space for waste, and b) the impending/eventual exhaustion of relatively cheap uranium. These constraints can be combated by the use of (possibly accelerator driven) nuclear waste incinerators, reprocessing, and (possibly accelerator driven) breeder reactors (which however require large Pu, or - using the Th cycle - fissile ^{233}U, inventories). If nuclear power grows at 3% pa, the Generation IV Consortium believes that it will be necessary to move to breeders within 30 years.

Spallation neutrons have been proposed to

1) drive a Th/U cycle 'energy amplifier'. This seems attractive to me, but the nuclear community, which is relatively unconcerned about criticality, asks – why pay the over-cost of an accelerator when a critical thermal reactor will do the job? Focus is therefore currently on using spallation neutrons to
2) burn minor actinides (possibly producing energy as a by-product to help cover the cost).

Accelerator driven nuclear incineration was the subject of the previous talk, so I shall not go into details except to say that a) although the concept looks simple in principle, the very high levels of incineration that are quoted require extremely efficient chemical partition, and b) the complete reprocessing + partitioning + incineration cycles that have been considered are very complex in practice.

FUSION

Basics

Apart from fossil fuels, solar, and nuclear fission, fusion is the only known energy source that is capable in principle of producing a large fraction of the world's electricity. With so few options, I believe that we must develop fusion as fast as possible – although success is not certain.

The Joint European Torus (JET) at Culham in the UK has produced 16MW and shown that fusion can be made to work on earth. The big question is when/whether we can develop the technology to build robust, reliable and hence economic fusion power stations.

The prime candidate reaction for producing fusion power on earth is

deuterium + tritium → helium + neutron + 17.6 MeV

in a D-T plasma heated to over 100M°C (150M°C, ten times the temperature of the centre of the sun, is routinely achieved in JET). The challenges are to make an effective 'magnetic bottle', that prevents the plasma being cooled (and polluted) by touching the walls, and a robust container.

A chemical reaction typically produces (fractions of) an electron volt, while D-T fusion produces 17.6 MeV. Correspondingly, while a 1GW fossil fuel power station burns 10,000 tons/day (= 10 train loads of coal), a 1GW fusion power station would burn 1 kg of D+T per day. The natural deuterium/hydrogen ratio is 1/6700 and deuterium is easily extracted from water. Tritium can be bred in a fusion reaction in the process neutron + lithium (which is very abundant) → tritium + helium. Used as fusion fuel, the lithium in one laptop battery together with the deuterium in 45 litres of water would (allowing for inefficiencies) produce 200,000kW hours (the same as 40 tons of coal), which is equal to the UK's current per capita electricity production for 30 years.

Fusion Power Stations

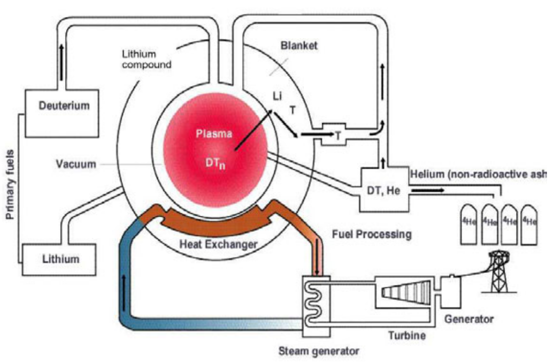

Fig. 1 A Fusion power plant would be like a conventional one, but with different fuel and furnace.

Figure 1 shows the conceptual layout (not to scale!) of a fusion power station (models of power stations and a discussion of the safety and economics of fusion can be found in [13]). At the centre is a D-T plasma with a volume ~ 1000m^3 (actually in the form of a torus, not a sphere). The mass of the plasma is only ~ 1/10 of a gram, but, being at over 100M°C, it is at around atmospheric pressure. The neutrons generated by D-T fusion escape the magnetic fields that confine the plasma, and penetrate the surrounding blanket. The one metre thick blanket will be heated by the neutrons to ~ 800°C. The heat will be extracted through a cooling circuit (containing water or helium), which in turn will heat water that will drive steam turbines. The neutrons will encounter lithium in the walls and breed tritium, as explained above. There are various competing reaction channels but some of them produce additional neutrons (a process that could be enhanced, e.g. by adding beryllium) that can also produce tritium. The result is that (on paper at least – this will be tested at ITER) it is possible to breed more than 1.1 tritons per neutron.

Advantages and Disadvantages

The advantages of fusion [13] are

- essentially unlimited fuel;
- no CO_2 or air pollution;
- major accidents impossible (there is far too little D+T and it is too much dilute to allow a runaway reaction; the D+T would stop burning if anything at all went wrong; even if the cooling circuit failed completely, radioactive decays in the blanket would only raise the temperature to ~ 1200°C and meltdown would be impossible; even if all the tritium were released [and no one has conceived a way this could happen] no evacuation would be necessary);
- no radioactive 'ash' or long lived radioactive waste (activation in the blanket is discussed below);
- 'internal' costs (i.e. costs of generation) that look reasonable, while the 'external' cost (impact on health, climate) would be essentially zero: assuming 70% availability, the estimated generation cost (construction, which dominates and depends on what materials are used + operation + maintenance + decommissioning) for the 10th reactor to be built is US(6-12)C/kw hour. This number, which is less than the cost for most renewables, should not be taken too seriously: the point is that it is not \$s/kw hour, and encourages us to continue.
- it meets a need (see above).

The disadvantages are that

- the structures surrounding the plasma will become radioactive: however, the half lives are ~ 10 years, and after 100 years ~ 50% (depending on what materials are used) would be completely inactive, while the rest could be recycled (perhaps ~ 35% easily; ~ 15% robotically) to make a new fusion power station [13];
- the development of fusion power is incomplete.

State of the Art

Figure 2 shows JET, which is currently the world's largest tokamak (= toroidal device that confines a plasma using the magnetic configuration described below): a semi-popular description of JET and its contributions up to 1999 may be found in [14]. JET is operated by UKAEA as a facility for European scientists. The person at the bottom shows the size, which is about half (in linear dimensions) that of the proposed International Tokamak Experimental Reactor (ITER), which will be approximately the size of the 'furnace' in a fusion power station.

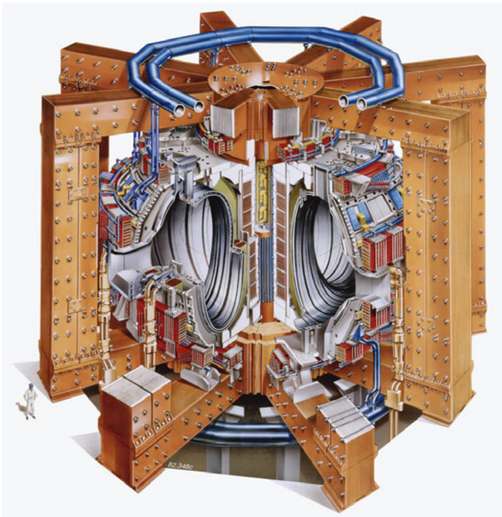

Fig. 2 The Joint European Torus (JET).

The toroidal chamber, which is surrounded by a solenoid that generates a toroidal field of up to 4T, is first evacuated. A puff of ~ 1/100 grams of gas (D or D+T) is then injected. Next, a current is discharged through a coil wrapped round the common centre coil of the eight large iron rectangles that surround the torus. By transformer action, this drives a toroidal current (of up to 7 MA) through the gas, which acts as the secondary of the transformer, thereby ionising and heating it. The poloidal magnetic field generated by the current combines with the toroidal field to produce a helical field that spirals very slowly round the torus and confines the plasma.

The resistivity of the plasma drops like $(T_e)^{-1.5}$ as the electron temperature T_e rises, and consequently the current can 'only' heat the plasma to ~ 3.5keV. Auxiliary heating is therefore needed to bring the plasma to above 10keV as required for fusion. It is provided by (a) injecting neutral beams (JET has two clusters of eight accelerators that provide ~ 20 MW of heating power by injecting neutrals of ~ 100 keV; energies of ~ 1 MeV will be used at ITER), and (b) injecting microwaves (of 10s of MHz to 10s GHz, coupled to ion and electron cyclotron motion and collective modes at intermediate frequencies). These heating systems also serve to help keep the current flowing (by directing the neutral beams or phasing the microwaves), and hence sustain the poloidal field, which is essential for confinement.

In addition to the heating systems, JET and other experimental tokamaks are surrounded by diagnostic systems (not shown in figure 2) that measure and study temperature and density profiles of the electrons and ions, magnetic fields, neutron production, energy and particle loss paths, impurities, turbulence, instabilities, heating processes, etc.

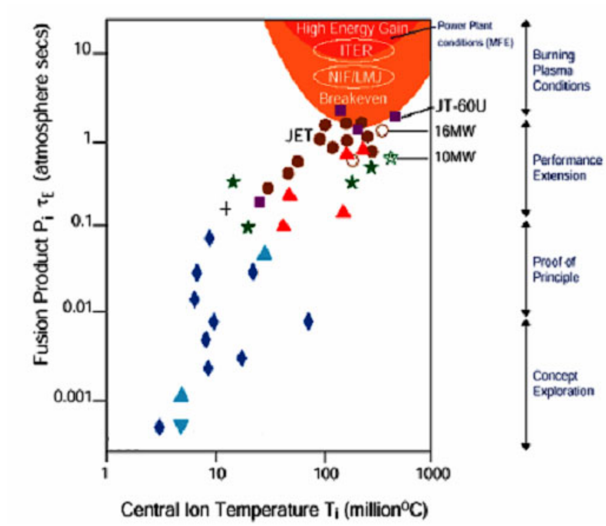

Fig. 3 Fusion Performance (when JET was designed in the early 1970s, only the data at the bottom left existed).

Figure 3 summarises progress in fusion research. Viable power production requires a temperature above 100M°C, and a 'fusion product' = pressure (in atmospheres) x energy confinement time (in seconds) > 10, where energy confinement time = (total plasma energy)/(heating power). When JET was being designed in the early 1970s, existing tokamaks (which had volumes around $1m^3$) generated temperatures that were a factor ~ 15 too small, and a fusion product that was four orders of magnitude away from the target region. The priority was therefore to build bigger tokamaks, with higher toroidal fields, larger currents, and more heating power, and to discover how performance improved with these parameters. The plot shows that the desired temperatures have been achieved, while empirical scaling laws that interpolate between the performance of different tokamaks give us considerable confidence that the fusion product at ITER will fall in the predicted region.

The Next Steps

The major next steps are

1) Construction of ITER.
2) Intensified R&D on structural and plasma facing materials, and the construction of the International Fusion Materials Irradiation (IFMIF).

There is still much to be done in improving understanding and control of plasmas (curbing instabilities at the edge of the plasma, producing steady state operation, etc.) before a power station can be built. Nevertheless there is now sufficient confidence that the requirements can be met and that ITER will meet its goals, that most fusion scientists and many governments (including the Euratom Member States and Japan) advocate moving ahead in parallel with ITER and IFMIF on the so called Fast Track to Fusion Power.

ITER [15] will look much like JET, but will be twice the size. Unlike JET, ITER will have a super-conducting toroidal magnet, so that long pulse (or even continuous) operation will be possible, and incorporate blanket modules that will test tritium breeding and other functions needed in an actual fusion power station. The design goal is produce at least 500MW of fusion power, corresponding to Q = (power out)/(power in) of at least 10 (JET has achieved Q = 0.65). The aim is to demonstrate integrated physics performance and engineering on the scale of a power station.

ITER will cost €4.5 bn and will be built by a consortium of Euratom (the EU + Switzerland), Japan, Russia, the USA, China and South Korea. The project is ready to begin once a choice has been made between the candidate sites in Europe (at Cadarache in France) and Japan (at Rokkasho, in Northern Honshu).

Assuming that ITER meets its goals, it is essential to resolve the outstanding materials issues [16] in parallel in order to make it possible to move on directly to construct a prototype fusion power station (known as DEMO – for Demonstrator – in the fusion community). Structural materials are required that can withstand $2MW/m^2$ of 14 MeV neutrons, which will cause ~ 20 displacements/atom/year [dpa] (normally – but not always – followed by relaxation to the original equilibrium position). Such conditions have not been met previously (14 MeV neutrons produce much bigger cascades of secondaries than those generated in Fast Breeder Reactors, and breed helium and hydrogen in the container). The plasma-facing materials will be subject to an additional $500kW/m^2$ in the form of plasma particles and electro-magnetic radiation, while the so-called 'divertor' (which exhausts helium and impurities) will be subjected to up to $20MW/m^2$.

Various candidate materials have been identified and studied theoretically. While increased modelling, and certain proxy experiments, can play a very important role, it will be necessary to test the materials with a neutron spectrum and fluence close to that of an actual power station before a real power station can be licensed and built. This can only be done by IFMIF.

IFMIF [17], which was described in the first talk this morning, will consist of two CW, 125 mA, 40 MeV (5 MW) deuteron accelerators. The beams will hit a liquid lithium target, where stripping reactions (such as $^7Li(d,2n)^7Be$, $^6Li(d,n)^7Be$, $^6Li(n,T)^4He$) will produce neutrons with a spectrum and fluence close to that generated in a fusion reactor. The neutrons will produce > 20 dpa/year in samples in the 0.5 litre high-flux target zone (1-20 dpa/year in the 6 litre medium-flux zone, and < 1 dpa/year in the 8 litre low-flux zone). Two accelerators are required to (a) generate sufficient fluence, and (b) meet the goal of 70% overall availability (allowing for one month/year + 8 hours/week for maintenance, plus periodic failures of other components, the accelerators are required to be 88% reliable during scheduled operation, with periods when a single accelerator is operating counting as half up/half down). Construction of the €750 M IFMIF (accelerator + target) will clearly be very challenging.

CONCLUSIONS

If ITER and IFMIF are both started now, and progress is maintained at other facilities (especially JET) during their construction, DEMO could be putting power into the grid within 30 years. More detailed work on the design of DEMO also needs to begin now, leading to a construction timetable set by the Just-in-Time availability of ITER and IFMIF results that are needed to finalise the design of certain DEMO components.

Bringing DEMO into operation within 30 years will be very challenging. It will require an increase in fusion funding (from the present world total of ~ $1.2 bn pa, which should be compared with the $3 trillion pa world energy market), and that there are no major surprises. When asked when fusion power would be available, the great Russian scientist Lev Artsimovich replied: 'Fusion will be ready when society needs it'. The need is now very apparent. Let us hope that fusion power will be ready as soon as possible.

ACKNOWLEDGEMENT

This work was funded by the UK Engineering and Physical Sciences Research Council and EURATOM.

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