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Fusion ☆

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ABSTRACT

Fusion works. It powers the Sun and the other stars, and the Joint European Torus (JET) at Culham in the UK has produced 16 MW of fusion power. Fusion has many potential advantages, including essentially limitless fuel, no carbon dioxide or other emissions, and intrinsic safety. Recent progress has been good and the outlook is promising. Several steps are needed before a prototype (demonstration) power station ('DEMO') can be brought into operation. These steps are: (1) build a power-station-size experimental device (an international tokamak experimental reactor (ITER)) and a materials test facility (i.e. an international fusion materials irradiation facility (IFMIF)), which will take 10 years; (2) run these facilities and incorporate the results into the design of DEMO—up to a further 10 years; and (3) build DEMO—up to another 10 years. DEMO could therefore be in operation within 30 years. Fusion power could follow on a significant scale, 10 or more 1.5 GW power stations, before the middle of this century. In the second part of the century, fusion could power large centres of population and perhaps be used to produce hydrogen fuel. Meeting growing energy demand (primarily driven by needs in developing countries) while reducing carbon emissions is a large and growing challenge. A portfolio approach is needed—there is no magic bullet. Given fusion's potential, it is essential that it is developed as rapidly as is reasonably possible (even if success is not 100% certain) as one of very few options available for large-scale production of base-load power.

1. Current status of fusion research and development

1.1. Fusion challenges

The most effective fusion reaction for power production uses two isotopes of hydrogen, deuterium and tritium, which can fuse to produce helium and a neutron, which carry large amounts of energy (for non-technical introductions to the state of fusion development see McCracken and Stott, 2005; Llewellyn Smith and Ward, 2005; Culham Science Centre website (vwww.fusion.org.uk); and for a professional introduction, see International Fusion Research Council, 2005).

There are three challenges:

1. Heat a large volume of deuterium and tritium gas to over 100 million °C, while holding it in a 'magnetic bottle' (known as a tokamak) to prevent it being cooled by touching the walls. This temperature—10 times hotter than the core of the Sun—is needed in order to allow the particles to fuse rather than just bounce off each other's electrical charge. It is routinely achieved in the Joint European Torus (JET) at Culham (and in other devices), but the volume of hot gas in JET (which is currently the world's largest fusion device) is around 100 m^3, and JET is not designed to operate for more than about a minute. A fusion power station will have to contain a few thousand cubic metres and operate round the clock. The next step is to construct a power-station-scale experimental device known as an international tokamak experimental reactor (ITER) in which 'steady-state' operation should be possible.
2. Show that the candidate materials for the walls can survive for years in the harsh conditions of a reactor, which combine bombardment by energetic neutrons (carrying several megaWatts per square metre), very high thermal loads, and intense interactions with deuterium and tritium. This will require tests in an accelerator-driven facility known as the international fusion materials irradiation facility (IFMIF).
3. Ensure reliability of what will be very complex systems.

1.2. Fusion power stations

A number of studies have considered possible designs of fusion power stations (the most recent, Maisonnier et al. (2005) refers to earlier studies). Fig. 1 shows the common conceptual layout (not to scale). At the centre is a chamber (which will actually be

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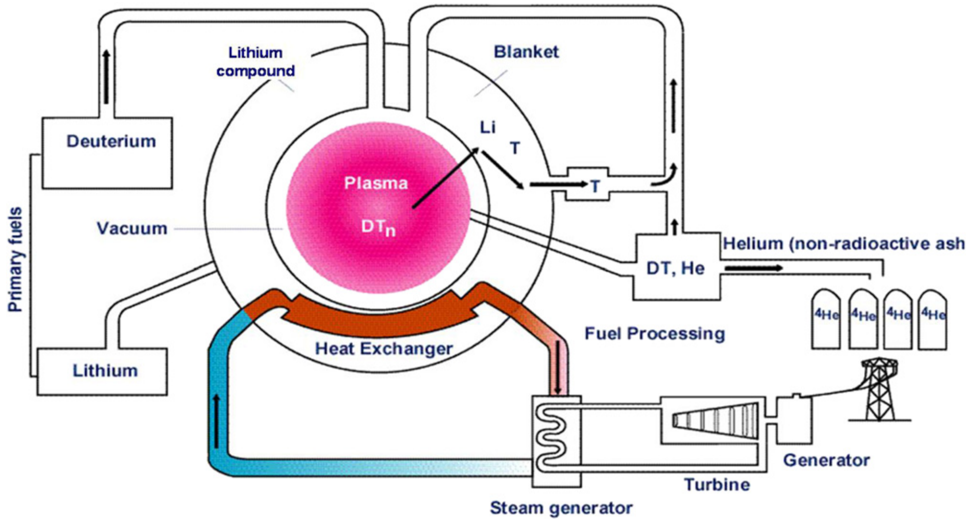

Fig. 1. A fusion power station is conceptually similar to an existing thermal power station but with a different furnace and different fuel. The figure is not to scale. In reality, the fusion core would be a very much smaller part of the whole power station, and the 'blanket' would be about 1 m thick, while the plasma (which would be contained in a toroidal chamber) would occupy 1000–3000 m^3.

toroidal) with a volume of 1000–3000 m^3 containing a hot deuterium–tritium gas or 'plasma'. Deuterium and tritium are fed into the core and heated to over 100 million °C. The helium nuclei that are produced by fusion (being electrically charged) remain in the magnetic 'bottle', where their energy serves to keep the plasma hot. The neutrons, which are electrically neutral, escape into, and heat up, the surrounding structure, known as the 'blanket' (which will be about 1 m thick). This heat is then used to drive turbines and generate electricity.

A recent European study considered four model designs, ranging from:

- a 'near-term' (water-cooled steel) model with 'plasma performance' (essentially, the pressure that can be maintained in a stable manner at a given temperature) not much beyond that foreseen in ITER;
- to an advanced model (lithium–lead-cooled silicon carbide composite, allowing a higher blanket temperature and hence higher efficiency in generating electricity) with much more advanced plasma performance.

Assuming 75% availability, it was estimated that a first-generation, 'near-term' model would generate electricity for €0.09/kWh (the cost is dominated by construction costs, which were checked by comparison with cost estimates for ITER components that have been validated by industry). For the first-generation of the most advanced model, the estimated cost was €0.05/kWh. These costs are based on existing technologies and could be reduced significantly by new developments, e.g. of high-field high-temperature superconductors. Uncertain though they may be, these estimates suggest that fusion could compete with other low-carbon technologies and encourage the continued pursuit of fusion power.

1.3. *Potential attractions*

The attractions of fusion are:

- *Essentially unlimited fuel.* The raw fuels are water, from which deuterium can be cheaply extracted, and lithium. Lithium implanted in the blanket, in some form, will react with the neutrons produced by the fusion process to produce tritium, as indicated symbolically in Fig. 1. Allowing for inefficiencies, the lithium in one laptop battery plus half a bath of water would produce 200,000 kWh of electricity (the current total UK electricity production per capita for 30 years). There is probably enough lithium to power the world for millions of years.
- *No production of CO_2 (or other greenhouse gases) or air pollution.*
- *Major accidents are impossible.* Fusion must be continuously fuelled, so it is easily stopped. Furthermore, the large volume of hot gas at the heart of a fusion reactor will only be at around atmospheric pressure, and will not have enough stored energy to drive dangerous accidents. Tritium is radioactive, but very little will be used (fractions of a gram in the active part of the system, with more in secure storage). It will be easy to design a reactor so that, even in the worst imaginable accidents or incidents (such as earthquakes or aircraft crashes), only a small percentage of the tritium inventory could be released and evacuation of the neighbouring population would not be necessary.
- *No long-lived radioactive waste.* The blanket will become activated when struck by neutrons, but the radioactivity will decay with half-lives in the order of 10 years, and all the components could be recycled within 100 years.

1.4. *Progress to date, potential problems and potential improvements*

The physics of the fusion process has been known for over 65 years. It was initially thought that mastering fusion would be relatively straightforward, but it took many years to develop the physics of hot plasmas. It was only in 1969, when experiments in a tokamak with a plasma volume of 1 m^3 measured a temperature of 3 million °C, that the tokamak emerged as the leading candidate for fusion configuration. Bold pioneers soon proposed taking the enormous step to 100 m^3 (JET) and that this should be followed by a 1000 m^3 device (which eventually became ITER). JET came into operation in 1983 (3 years having been lost choosing between candidate sites). ITER has recently been approved and should come into operation in around 2016 (more than 10 years having been lost since 1983, including two in choosing the site because there was no sense of urgency).

There were many positive developments in the 1980s and 1990s in plasma physics (see www.fusion.org.uk) and identifying suitable materials for use in fusion reactors (see Zinkle, 2005), including:

- The discovery (following a prediction made at Culham) of a self-generated ('bootstrap') electrical current in the hot plasma, with the consequences that: (a) much less external power than previously thought will be needed to keep the electric current in the plasma (which generates part of the essential magnetic field) flowing; and (b) achieving steady-state operation will be less of a challenge.
- The serendipitous discovery (in a fusion experiment at Garching in Germany) of a 'high confinement' plasma mode that allows higher pressure, and hence higher fusion power, with a given magnetic field.;
- The discovery in tests at fission reactors that special (body-centred cubic) steels can probably survive in fusion reactor conditions (it had previously been thought that exotic materials would be necessary).

Of course, there are potential problems, for example:

- There could be new instabilities in the 'burning' plasmas that will be generated (for the first time) by ITER, although this is generally regarded as unlikely.
- Perhaps, despite the bootstrap current, steady-state operation will prove elusive. If so, it will be necessary to consider building pulsed machines, which will suffer from greater stresses, or using an alternative magnetic configuration ('stellarator').
- Production of helium by neutron-induced reactions inside structural components could compromise their durability, and finding materials that can withstand the full heat load on a component called the 'divertor' (through which the gases are exhausted) could be a severe problem, although the load could be reduced by making compromises in the design.

But there are also potential improvements, such as:

- better control and mitigation of potential plasma instabilities (on which there is continuous incremental progress), which would allow higher pressures and hence a higher fusion reaction rate;
- the wider use of advanced materials (e.g. silicon carbide composites as assumed in the advanced model cited above), which would allow higher blanket temperatures and hence greater efficiency in generating electricity.

2. Future developments

2.1. Next steps: from ITER and IFMIF to DEMO to commercial fusion power

Construction of ITER (by a consortium of the EU, Japan, Russia, USA, China, South Korea and India) at Cadarache near Aix-en-Provence in France is about to begin (see the ITER website (www.ITER.org)). The EU and Japan have recently agreed on a €150 million final R&D and design phase of the materials test facility (i.e. IFMIF). If followed immediately by a decision to build, IFMIF could be in operation soon after ITER. Meanwhile, there is much to be done, at JET and in other devices, preparing for ITER, tackling potential problems, such as those listed above, and exploring potential improvements that could speed up the exploitation of ITER and IFMIF.

Design of DEMO should proceed in parallel with construction and use of ITER and IFMIF. It will probably take something like 8 years to assimilate results from ITER and IFMIF into the design of DEMO and accumulate enough experience to justify starting the construction of DEMO, which could also take some 10 years. The result would be that DEMO could be in operation in under 30 years (Cook et al., 2005). This is not a prediction; it is a statement of what looks technically reasonable. Whether it actually happens will depend on there being no major adverse surprises and adequate funding (see below).

Commercial fusion power on a significant scale could follow by the middle of this century. There seem to be no resource limitations on the growth of fusion power, which will depend on whether it is economically viable in the circumstances that then prevail.

The increase in scale from JET to ITER to DEMO/commercial fusion power is illustrated in Fig. 2.

2.2. The potential role of fusion in the second part of the century

The economics of fusion favours large fusion power plants. The possible costs quoted above were for plants with 1.5 GW electrical output, which was taken to be the maximum readily acceptable by the grid—although somewhat larger (fission power) plants are being built. The cost per kWh would be some 25% less for a 3 GW plant. The consequences are that:

- Fusion power will be most appropriate near major centres of population, which currently house ~50% of the world's population (a percentage that is growing). In this sense, fusion will be complementary to most renewables and dispersed micro-sources of power.

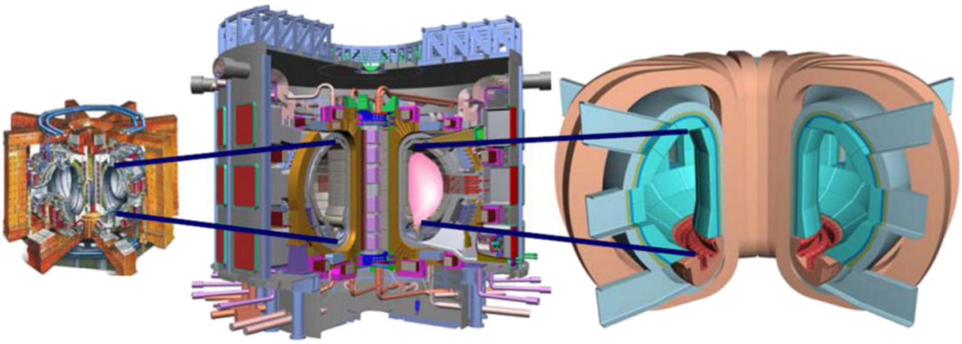

Fig. 2. JET (on the left), ITER (centre) and the core of one possible model for DEMO, i.e. a commercial fusion power station. The figure of a person at the bottom right of the ITER shows the absolute scale. The success of the tokamak was established in a device with a volume of 1 m^3. JET (100 m^3) came into operation in 1983 (3 years having been lost in selecting a site). ITER (800 m^3) should start to operate in 2016 (a further period of at least 10 years having been lost through lack of political will to proceed and in site selection). DEMO (shown here as about 2500 m^3) could in principle be operating, putting power into the grid, before 2035. The scale of the devices and their cost make it prudent to proceed step-by-step, and explain the time scale for developing fusion.

- Fusion is capital-intensive and the operating costs will be low. Off-peak fusion power is therefore potentially an excellent source of hydrogen, either through electrolysis or through high-temperature thermochemical or catalytic decomposition of water.

There seem to be no technical or resource barriers to the rate at which fusion power could be deployed once it has passed the threshold of viability. In 1998, the Netherlands Energy Foundation (ECN) looked in detail (using MARKAL, which seeks an overall cost minimum for power production, distribution and use) at the potential role of fusion in Europe up to 2100 (a world study is currently being carried out in the framework of the European Fusion Development Agreement). While some of the assumptions no longer look reasonable (e.g. the assumed cost of oil), others are still valid (e.g. the expected cost of fusion-generated electricity). All such modelling is, of course, subject to large uncertainties, especially in relation to the assumed discount rate and environmental targets, and should be seen as an exploration of what might happen, not a prediction of what will happen.

Subject to these caveats, the outcome of the ECN modelling was that:

- With no constraints on carbon emissions, coal will dominate EU electricity production in 2100.
- Fusion plays an important role if atmospheric CO_2 is limited to 600 ppm or less, or carbon is priced at €30/tonne or more. This conclusion is relatively insensitive to other assumptions because meeting expected demand with carbon constrained is very difficult, e.g. changing the assumptions to allow more fission reduces the use of gas, not the role of fusion (unless unlimited fission is allowed at the current uranium price, which seems very unlikely).

3. Conclusions

Meeting growing energy demand (driven primarily by need in developing countries) while reducing carbon emissions is a large and increasing challenge. A portfolio approach is needed—there is no magic bullet. More R&D is needed across the board. The authors find it almost incredible that, worldwide, public spending on energy R&D is half what it was in 1980 in real terms,[1] and represents less than 0.3% of the world energy market.

Given that there are few alternatives for the large-scale environmentally responsible production of base-load power, the portfolio should include fusion. Fusion is progressing well, on a timetable that has been set by assuming a step-by-step progression through devices of increasing size to prototype power stations that could be followed by commercial fusion power around the middle of this century. Models suggest that fusion could play a major role in the second half of the century, although this will depend on the cost of fusion power relative to the cost of alternatives and environmental constraints.

Worldwide, current funding of fusion development is around $1.2 billion a year (a very small sum compared with the total energy market of $4.5 trillion a year). This will increase somewhat during ITER construction. The introduction of fusion power could be brought forward with an increase in the budget. In a 'crash' programme, alternative solutions to the outstanding technological problems could be developed in parallel. This would reduce the risk of delays and should bring forward the date at which fusion matures.

The budget of the UK's national fusion programme (which is carried out as part of an integrated European programme) is about half of the French and Italian budgets, and one-sixth of the German budget. The UK's programme is nevertheless outstanding, but it is vulnerable as JET will close in a few years and the mega ampere spherical tokamak (MAST) pioneered at Culham, which is making important and unique contributions, needs upgrading. Increased funding is needed for the UK to maintain its world-class role in fusion research (at JET and then ITER, as well as at MAST) and maintain its important influence as the leading advocate of a fusion programme that is focused on the rapid development of fusion power as an energy source (rather than on fusion/plasma science).

The magnitude of the energy challenge and the potential of fusion argue for developing fusion power as rapidly as reasonably possible. Clive Cookson, Science Editor of the *Financial Times*, recently wrote that: 'even if ITER runs well over budget … This would be a small price to pay even for a 20% chance of giving the world another energy option.' We agree, although we think that 20% is extremely pessimistic.

Acknowledgement

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[1] In contrast to 1980, the public is now paying significant sums (through the cost of Renewable Obligation Certificates, feed-in tariffs, etc.) to underwrite the roll-out of renewables (and some of this funds R&D by the industries involved). Europe-wide, market incentives for renewables (ultimately paid for by the public) amount to some €6 billion a year—three times the public funding of energy R&D. We are not opposed to this support for the deployment of renewables, which should, however, be taken into account when judging the relative levels of public support for different parts of the energy portfolio.