UK FUSION IN THE ERA OF FUSION BURN

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The Presidential Address by Arthur Stanley Eddington to the 1920 meeting of the British Association in Cardiff is perhaps one of the greatest examples of scientific deduction on record. Using simple arguments based on a wide range of observations, Eddington pieced together much of the modern theory of the sun and stars. Despite the fact that little was known about the nuclei of atoms at the time, he posited that the sun was being powered by converting hydrogen to helium – and indeed it is. Using $E = mc^2$ and the recently measured masses of hydrogen and helium, he calculated the sun had enough energy to shine for 15 billion years. He had deduced the existence of what we now call nuclear fusion.

Eddington went on to state (in delightfully dated language) that *"This reservoir can scarcely be other than the sub-atomic energy which, it is known, exists abundantly in all matter; we sometimes dream that man will one day learn how to release it and use it for his service."* The quest for fusion energy – Eddington's dream – has not been easy but the era of fusion burning experiments has arrived. What then needs to be done to make fusion a commercial power source? How should the UK position itself if it is to participate in a future fusion economy?

Perhaps the first question should be: why bother to develop fusion? The answer is simple. There are only three energy sources with sufficient resource to replace fossil fuels as a base load for the long term – solar, nuclear fission with uranium or thorium breeders… and nuclear fusion. Each technology requires significant research and development before it is ready to be deployed at large scale. Arguably, fusion has the greatest promise and the toughest challenges. It has practically unlimited fuel (millions of years of lithium and deuterium); low waste; no CO_2 production; attractive safety features and insignificant land use. These features are sufficient reason to develop fusion urgently even if success is not 100% certain.

To initiate fusion, an ionized gas (plasma) of deuterium (heavy hydrogen) and tritium (super heavy hydrogen) must be heated to above 100 million degrees C. This is ten times hotter than the centre of the sun. Remarkably, these conditions have been achieved. In 1997, the Joint European Torus (JET) at Culham Science Centre in Oxfordshire produced 16 megawatts of fusion power. Strong magnetic fields held the plasma together while the deuterium and tritium fused to form helium and release an energetic neutron. Admittedly, 25 megawatts of input power was needed to sustain the reaction. In 1997 a larger, more powerful device was already on the drawing board. Seven international partners, representing more than half the world's population, are now building this device, called ITER, at Cadarache in Southern France. The baseline performance is to produce 500 megawatts of fusion power with less than 50 megawatts of input power – a ten-fold amplification, at least. The ITER plasma will then be largely self-heated by the energetic helium produced in fusion reactions. Although the target is to sustain this power level for only 400 seconds at a time, recent experiments on JET and other machines suggest that it should be possible to sustain this almost indefinitely. During the run up to ITER the focus of worldwide fusion research is still in the UK. JET is continuing to find new regimes and to define improved ITER operating scenarios. In 2013 or 2014 JET will resume tritium operation and is predicted to beat all previous fusion power records. It is therefore expected that the UK will continue to operate JET for EURATOM until at least 2014-15. If successful, ITER will generate industrial levels of fusion power and demonstrate the scientific feasibility of high gain fusion devices. This is a critical step on the road to fusion power. UK

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expertise gleaned from years of running JET will be decisive to that success.

As any nuclear engineer knows, however, there is much more to commercial power generation than a demonstration of scientific feasibility. Critical components of the future fusion reactor – in particular the systems that convert neutron power to electrical power – have yet to be tested at any scale. In a reactor, a blanket of lithium surrounds the fusing plasma. The blanket is a complex system to absorb the neutrons, extract heat and 'breed' tritium from lithium. Tritium is extracted from the blanket and used to fuel the plasma. For economic viability, the blanket must operate robustly at high temperature in a harsh neutron environment for many years. (This need will hold whether we commercialise magnetic fusion, currently the most practical approach, or discover scalable techniques for other fusion schemes such as laser driven fusion.) Blankets will contain much of the intellectual property associated with the commercial development of fusion. The UK fusion programme is therefore beginning a strategic shift of effort into the technologies of the blanket and the wall.

First, we must develop the blanket and wall materials: structural materials, breeder materials and high heat flux materials are needed. These materials must not only retain structural integrity in very challenging conditions, they must also be made of elements that do not become long-lived radioactive waste under neutron bombardment. Progress is being made and several promising candidate materials have been proposed. For example theoretical calculations and ion beam tests by UKAEA Culham and UK Universities suggest that special steels are suitable structural materials. The International Fusion Materials Irradiation Facility (IFMIF) is being developed by the international community to test small samples of the promising materials. They will be irradiated in a beam of neutrons for several years to evaluate the changes in structural properties.

But materials development is not enough: an integrated wall and blanket system is needed. Promising blanket designs are being developed but much needs to be done to ensure a commercially viable system. If ITER proves as successful as expected, then this is probably the critical path for fusion. The central issue is how to test blanket and wall designs. In the later stages of ITER, operation test blanket modules will be placed in the walls. However, a continuous fusion neutron flux of 1-2 megawatts per square metre for several years is required for a definitive test. Even the ITER tests will not deliver this flux. In the Culham 'fast-track to fusion' study, the first generation of reactors ('DEMOs') will be built thirty years from now. Leaving blanket testing to this stage is probably too late from a licensing point of view. It certainly carries a high level of risk and would surely slow progress.

A compact, affordable fusion device that can deliver reactor-level neutron flux over many square metres is needed to lessen the risk and significantly accelerate the development of blanket and wall structures. Fortunately the 'spherical tokamak' – a compact plasma configuration – is just such a device. In the last decade, Culham has pioneered spherical tokamaks. MAST (the MegaAmp Spherical Tokamak) at Culham has achieved near-fusion plasma conditions at very modest scale and cost. Both Culham and Oak Ridge Laboratory in the US have developed conceptual designs of component test facilities based on spherical tokamaks. Whole components of the blanket and wall could be tested at full power for many years in these facilities. Both designs are compact and require only a modest investment in comparison to ITER. An upgrade to MAST is needed to demonstrate that the plasma performance of the component test facility can be achieved – this upgrade is a central part of Culham's ten-year plan. If the upgrade is successful then a component test facility could be built in parallel to ITER. A vigorous programme of wall and blanket development coupled with ITER's programme could pave the way for the first demonstration reactors (DEMOs) in the 2030s. The component test facility is also key to positioning the UK in the critical technologies of a future fusion economy.

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Reducing the time scale to commercial fusion by a full decade has enormous consequences for a world that is hungry for energy. Predictions of the timescale of fusion's entry into the energy market are necessarily imprecise while blanket development is untested. It is time to recognise this reality and begin development of a component test facility. The UK is leading efforts to persuade the international fusion community of this view. Eddington's dream may need such a pragmatic vision.