The quest for fusion power

Steven C. Cowley

Fusion power is one of a very few sustainable options to replace fossil fuels as the world's primary energy source. Although the conditions for fusion have been reached, much remains to be done to turn scientific success into commercial electrical power.

In 1920, Arthur Eddington, as president of the Mathematical and Physical Sciences Section of the British Association, delivered one of the greatest ever public lectures on science[1]. He conjectured that the Sun is powered by turning hydrogen into helium — and this is indeed what happens. We now call the process (nuclear) fusion. Eddington's deduction was remarkable given that little was understood about the atomic nucleus at the time. He went on to remark: "A star is drawing on some vast reservoir of energy by means unknown to us. 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 to release it and use it for his service. The store is well-nigh inexhaustible, if only it could be tapped." It is that dream of an almost perfect energy source that drives global efforts to develop fusion power today.

Unfortunately, fusion reactions do not happen at room temperature — the colliding nuclei must have sufficient energy to overcome the Coulomb repulsion and get close enough for the strong nuclear force to bind them together. There are many fusion reactions[2], but by far the easiest to initiate is the reaction between deuterium (heavy hydrogen, ^{2}H) and tritium (superheavy hydrogen, ^{3}H): $^2\text{H} + {}^3\text{H} \rightarrow {}^4\text{He}$ (3.5 MeV) + n (14.1 MeV). The values in brackets are the kinetic energies of the released He atom and neutron. Note that the helium nuclei receive one-fifth of the fusion energy. Almost all fusion research is directed at producing power from the deuterium–tritium (DT) reaction.

In addition to extremely high temperatures, one needs high pressures to make fusion efficient. In a DT plasma with a temperature of 10–20 keV ($116–232 \times 10^6$ K), random collisions produce a fusion power density of approximately $0.08p^2$ MW m^{-3} atm^{-2}, where p is the plasma pressure. For commercial fusion to be successful it is clear that power densities of many megawatts per cubic metre are required. Thus plasma pressures of at least ten atmospheres are required.

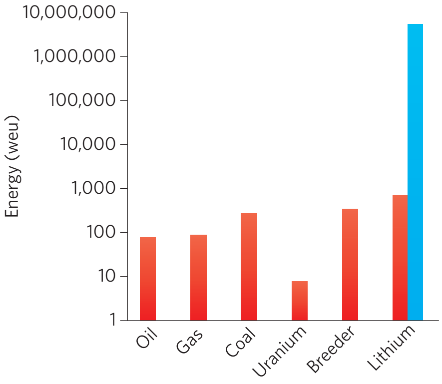

Figure 1 | Approximate amounts of remaining fuel resources. Values are given in world energy units (1 weu = 2.4 terawatt years). We cannot burn all of the remaining fossil fuel resources (oil, gas and coal) without catastrophic global warming. The world's known uranium reserves (at reasonable prices) used in existing nuclear fission technology would yield less than 10 weu. Advanced fission (breeder) technology would increase the energy available from the same uranium resource. For lithium (fusion fuel), the existing resource at current prices is shown in red and the resource of lithium from seawater is shown in blue. Clearly, only fusion is able to supply significant amounts of energy over millions of years. All sources are expected to have resources greater than the reserves shown here. Nonetheless, reserves are indicative of the available energy within a factor of two to three. Energy values calculated using data from: oil, ref. 20; gas, ref. 21; coal, ref. 22; uranium, ref. 23; lithium, ref. 3. The breeder energy is conservatively estimated as 50 times uranium energy.

One more issue is the availability of tritium, which is almost non-existent in nature because it has a half-life of 12.32 years. Fusion reactors will have to breed their own tritium via the reactions $\text{n} + {}^6\text{Li} \rightarrow {}^4\text{He}$ (2.1 MeV) + ^{3}H (2.7 MeV) and $\text{n} + {}^7\text{Li} \rightarrow {}^4\text{He} + {}^3\text{H} + \text{n} - 2.46$ MeV, where the second reaction has a small cross-section and consumes energy. The 'breeding blankets' in fusion reactor designs breed most of the tritium from ^{6}Li, which comprises ~7.5% of natural lithium.

Why bother?

The most obvious attraction of fusion is the abundance of fuel — deuterium and lithium-6. To set the scale, let us use the world's current electricity production in a year as a unit of energy — a world energy unit (weu) — where 1 weu = 7.5×10^{19} J = 2.4 terawatt years. A gigawatt fusion power station would consume about 120 kg of deuterium and four tonnes of lithium each year. Deuterium can be extracted from seawater at minimal cost. Each litre of seawater contains ~0.02 g of deuterium and there is therefore enough deuterium for fusion to supply more than 5×10^{10} weu. The current world lithium reserves are approximately 13.5 million tonnes[3] — enough for fusion to supply ~10^3 weu. However, lithium is present in seawater too with a concentration of 0.2 mg per litre. Hence, the 230 billion tonnes of lithium in the world's oceans is enough to supply ~25×10^6 weu if lithium extraction from seawater is made efficient enough. Clearly, DT fusion could supply the world with energy for millions of years (see Fig. 1 for a comparison with other terrestrial fuel sources) — a resource only rivalled by solar energy.

What would be the environmental impact of fusion? The net result of the tritium-production reactions and the DT fusion is a small amount of helium, a useful inert gas. However, the neutrons produced in the DT reaction will cause transmutation of the structural materials (steel, tungsten and so on) in fusion reactors[4,5]. These transmutations will produce some radioactive nuclei. However, the use of low activation materials — for example EUROFER, a reduced-activation steel[6] — ensures that the transmutations result in short-lived radionuclides[7]. Studies of fusion power plants show that the activation of their walls and structures decays to recyclable levels in 100–200 years[8].

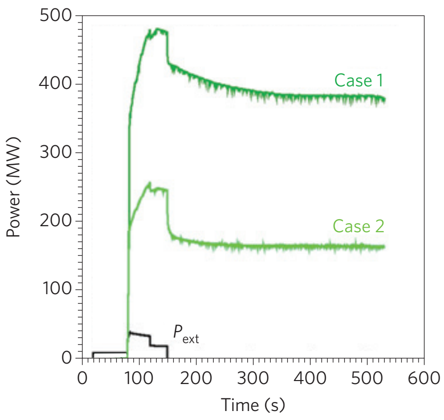

Figure 2 | Theoretical predictions of ITER performance in the baseline scenario. The generated fusion power is shown by dark green and light green lines for two possible scenarios and the external heating power, P_{ext}, is shown by the black line. The pressure at the top of the edge 'pedestal' is assumed to be 1.4 atm for case 1 and 0.94 atm for case 2. Current models cannot accurately predict this pressure but these two cases represent a range of expectations. At $t = 80$ s the external heating is turned on to 40 MW and the plasma starts to burn — the fusion power rising to nearly 500 MW in case 1. The plasma's self-heating by the alpha particles constitutes one-fifth of the fusion power. At $t = 150$ s the external heating is switched off and in both cases the plasma continues to burn. Case 1 shows a steady fusion power of 380 MW with no external heating — the fully self-sustained state is termed 'ignited'. Case 1 would approach ITER's baseline goal, which is to produce 500 MW of fusion power with less than 50 MW of external heating power. Figure courtesy of M. Romanelli.

Do fusion power plants pose any danger? The DT fusion reaction takes place at extreme temperatures and can be stopped in microseconds, so there are no runaway scenarios to consider. However, mechanical failure could release some activation. Analyses of worst-case accidents in fusion power plants conclude that it will be possible to design plants that would never require evacuation on technical grounds[8].

Clearly, fusion is potentially a very attractive power source — perhaps the most attractive. However, there are significant challenges remaining to be overcome. First, we must show that we can achieve a self-sustained fusion 'burn', and second, we must demonstrate that fusion power is economically viable.

Progress and status

To achieve the conditions for fusion, the DT plasma must be held at temperatures of the order of 20 keV (232×10^6 K). Fusion research has pursued two approaches for realizing confinement of an ultra-hot DT plasma: magnetic fusion, where the fuel is held in a strong magnetic field in a tokamak or a stellarator, inhibiting heat loss[9]; and inertial fusion, where a small capsule of compressed fuel reacts before the capsule is blown apart[10]. In both approaches, net energy production requires the fusion-produced helium nuclei (alpha particles) to supply most of the heating of the fuel — this is called a fusion burn. A controlled fusion burn has never been achieved on Earth — it is one of the great quests of modern science. But we are close. In magnetic fusion, the heat loss is dominated by turbulent transport of heat in the plasma — it is notoriously difficult, although now just possible, to make theoretical predictions of the plasma turbulence[11]. This turbulent heat loss is characterized by the confinement time, τ_E, which is defined such that the turbulent heat-loss power is equal to the stored plasma thermal energy divided by τ_E. Equating the turbulent heat-loss power to the alpha heating power yields the approximate criterion for fusion burn: $p\tau_E > 20$ atm s.

In 1997, the Joint European Torus (JET) at Culham Laboratory achieved the world record fusion performance — 16 MW of fusion power was produced when 24 MW of power was being injected into the fuel from external heating sources. The DT plasma was held in a magnetic field of 4 T at a temperature of 28 keV (325×10^6 K) — extraordinary conditions but not a fusion burn as the self-heating was only 16/5 MW = 3.2 MW.

JET is currently preparing to break fusion energy records again. Advances in computational modelling and the results from JET and many other experiments around the world established a predictive-physics model of the turbulent loss of heat from the magnetically confined plasma. The key conclusion from the model was that a machine twice the size of JET (and a magnetic field of ~5 T) would burn — and specifically, that it would produce at least ten times as much fusion power than the power needed to heat the DT plasma. Precisely such a machine, called ITER[12], a collaboration between the European Union, China, India, Japan, Korea, Russia and the US, is being built and is indeed predicted to burn[13]. Example predictions for ITER's performance are given in Fig. 2. Fusion burn in ITER is the critical step — the scientific demonstration that controlled fusion is possible via the magnetic-confinement route. Reaching a fusion burn and energy gain with the inertial-fusion approach is a similar challenge[10].

Beyond ITER lies the goal of developing the first electricity-producing fusion reactors. In Europe, the magnetic fusion programme is guided by a roadmap[14] that aims at achieving a demonstration electricity-producing reactor, called DEMO, in the 2040s. Pre-conceptual designs of DEMO point to needs for improvements (compared with ITER) in the exhaust-power handling and current sustainment. They also highlight the need to develop materials that are robust and qualified for use in the nuclear environment of a fusion reactor[15]. The step from ITER to a commercially viable power reactor clearly requires considerable innovation.

Innovation

To become a significant player on the commercial power market, fusion needs to achieve a high degree of efficiency and reliability at an appropriate scale. Efforts to drive innovation to reduce the cost and scale of future fusion reactors (and DEMO) are underway in numerous research institutes. We mention two promising strands. The spherical-tokamak programmes at Princeton, US (NSTX) and Culham, UK (MAST Upgrade, Fig. 3) are pursuing enhanced performance at reduced scale through turbulence

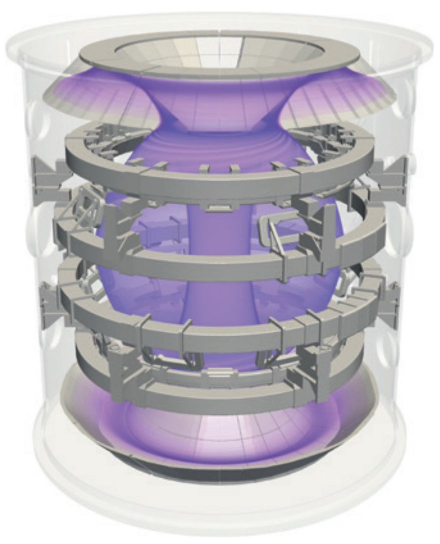

Figure 3 | Computer-generated image of the MAST Upgrade spherical tokamak device. The plasma, which appears as a cored purple apple in the image, will rotate at supersonic speeds to comb out turbulence. The flared purple plasma tails at the top and bottom are the exhaust, 'diverted' into the so-called Super-X divertor — a novel exhaust concept that may provide a solution to power-handling in reactors. MAST Upgrade will begin operation in 2017. Image courtesy of Rob Akers.

reduction and improved stability[16,17]. The Wendelstein 7-X (W7-X) stellarator in Greifswald, Germany has just begun operation[18]; the 3D magnetic field was optimized computationally to reduce the loss of heat due to collisional processes. The results are already interesting. All efforts would be helped by higher magnetic fields (see for example ref. 19) and several countries are running active programmes for the development of high-temperature high-field superconducting magnets, but these are not yet available at a useful scale.

Fusion is not ready for the market, but we are close enough to see the final challenging steps. We must make those steps. ❐

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Applied and fundamental aspects of fusion science

Alexander V. Melnikov

Fusion research is driven by the applied goal of energy production from fusion reactions. There is, however, a wealth of fundamental physics to be discovered and studied along the way. This Commentary discusses selected developments in diagnostics and present-day research topics in high-temperature plasma physics.

In the wake of the Second World War, several nations — notably the United Kingdom, the USSR and the United States — developed research programmes on controlled thermonuclear fusion with the aim of energy production. The main technical problems to overcome were confining the fusion plasma efficiently and achieving sufficient heating for fusion reactions to happen. Different lines of research were followed — initially largely independently by each nation, as fusion research was formally classified until 1956 in the USSR and 1958 in the UK and US — but by 1968, the tokamak (a Russian acronym for 'toroidal chamber with magnetic coils') had emerged as the most promising route to controlled fusion: the T-3A tokamak (Fig. 1) at the Kurchatov Institute of Atomic Energy in Moscow (then USSR) achieved a plasma temperature of 10 million degrees Celsius, a confinement time of 10 milliseconds and production of thermonuclear neutrons.

The original tokamak concept — a toroidal vessel holding a plasma that acts as the secondary winding of a transformer, created and sustained by the combination of the plasma current and an additional toroidal magnetic field so that the field lines of the total magnetic field describe helical paths within the torus — goes back to Igor Tamm and Andrei Sakharov, both involved in the Soviet Union's thermonuclear bomb programme. The strongest competitor to the tokamak is the stellarator, which produces the desired helical magnetic field by means of external windings, avoiding the intrinsic problem of tokamaks caused by the plasma current: magnetohydrodynamic instabilities. (For a review of tokamak and stellarator physics, see ref. 1.)

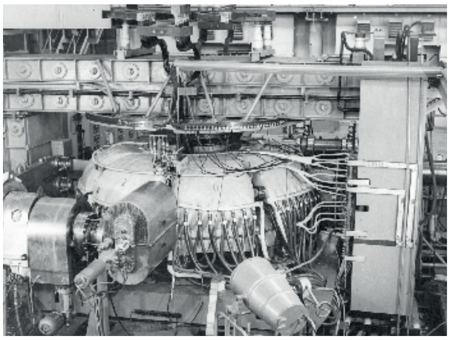

Figure 1 | The T-3A tokamak at the Kurchatov Institute of Atomic Energy. Photograph taken around 1967; reproduced with permission from the NRC 'Kurchatov Institute'.

After realization of the first tokamak in 1955, its design was improved step by step[2]. Important improvements developed in the Kurchatov Institute were, for example, the use of an iron core for the tokamak transformer, the use of control coils instead of a copper casing, the change from a circular to an elongated toroidal cross-section and the use of superconducting instead of copper coils.

After 1969, when a British scientific delegation had brought their state-of-the-art equipment from Culham to Moscow to double-check the temperatures generated in T-3A (ref. 3), tokamaks started to be built outside the Soviet Union. Mastering tokamak technology and pursuing magnetic confinement fusion quickly became major international research endeavours. The experience and knowledge accumulated over the past decades have culminated in the design of ITER, the largest ever tokamak, now being built in the south of France[4]. The evolution of tokamak design shows how an applied-physics goal sparked fundamental discoveries in