The fusion era: How today's technology delivers tomorrow's power

Fusion power is one of the most appealing options for the future of energy supply at a time when our natural resources are dwindling. Melanie Windridge looks at what's in store for the technology behind this potential source of sustainable power.

What if someone told you that they were from a future where there was an energy source that produced no greenhouse gases, that had an unlimited fuel source and that had an output 10 million times that of coal? What if they told you that the abundance of fuel was equivalent to living in a world where the land was made entirely of coal and the oceans of oil? And it's a clean, green, safe, renewable and abundant source of power. Would you want to make this part of your future? This energy source is already here and it's fusion.

Fusion is the opposite of fission. Both are nuclear reactions, but where energy is released in fission reactions by splitting large nuclei apart to make smaller ones, in fusion the energy comes from the binding of small nuclei to make larger ones. In both of these reactions the mass of the products of the reaction is less than the mass of the original particles, and it is this missing mass, Δm, that is released as energy according to Einstein's famous mass–energy relation, $E=\Delta mc^2$.

Also known as the binding energy, or the total internal energy of the nucleus, this is the energy needed to tear a nucleus apart. The binding energy of a nucleus divided by its mass number (its atomic mass) is the average binding energy per nucleon, and the binding energy curve produced by plotting this against the mass number gives an indication of the stability of the nuclides (figure 1). In such a graph, the initial rise of the binding energy curve and then subsequent drop at high mass number tells us that the region of greatest stability is around mass numbers 50–80. This is why energy is released by the nuclear fission of a massive nucleus into smaller fragments, or by the fusion of two small nuclei into a larger, single nucleus. The steepness of the curve at the fusion end gives an indication of how much more energy can be produced by fusion reactions than by fission.

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For fusion to occur, the fusing particles must be within range of each other's attractive nuclear forces. However, the fusing particles are positively charged ions, so the probability of a reaction taking place at low energy is small because of the mutual coulomb repulsion experienced between particles of like charge. Given sufficient energy, the particles can overcome this coulomb barrier, and this process of raising the temperature of the material to engender fusion is known as thermonuclear fusion.

Fusion occurs continually in the Sun and the stars, at temperatures of 10–15 million degrees Celsius. At such high temperatures the particles are in a state known as plasma, where electrons are separated from the nuclei of the atoms, which become charged ions. In this state the thermal velocities of some of the nuclei are sufficient to overcome the coulomb repulsion and fusion may take place. The most readily attainable fusion process on Earth is that involving the isotopes of hydrogen, deuterium (D) and tritium (T). This occurs at temperatures of around 100 million degrees Celsius. The reaction can be represented as ${}^2_1D + {}^3_1T \rightarrow {}^4_2He\,[3.5\,MeV] + n\,[14.1\,MeV]$.

The products of this reaction are helium (He, an alpha-particle) and a neutron, which carries away 80% of the energy released. Other fusion reactions are also possible, but the D–T reaction is preferred because it has a higher reaction cross-section at lower energies. Additionally, due to quantum mechanical tunnelling, fusion occurs at a lower energy than that required to overcome the coulomb barrier, so less heating is needed. A further advantage of the D–T fusion reaction over other forms of power generation is that the fuels are widely available and distributed evenly around the world. Deuterium is abundant and can be extracted from water, and tritium, although not occurring naturally, can be produced by the interaction of fast neutrons with lithium in a blanket around the reactor.

Obtaining fusion power

In such massive objects as the Sun and stars, the huge gravitational fields keep the particles confined long enough to fuse. The challenge for scientists on Earth is to maintain the nuclei at the optimum temperature for fusion reactions, at a sufficient density and for long enough in the reacting region for the reactions to take place. Magnetic forces or inertia are used to this end, and researchers actively study both inertial confinement fusion and magnetic confinement fusion.

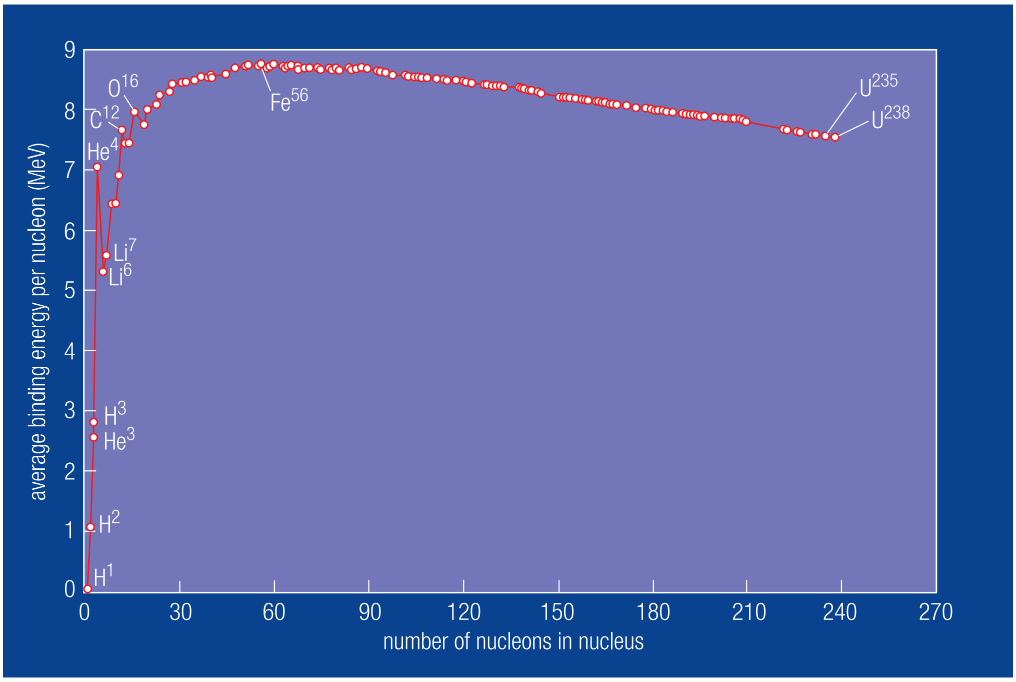

Figure 1: The graph shows the initial rise and subsequent fall of the binding energy curve. The region of greatest stability occurs between mass numbers 50–80.

Of course, confining the plasma at temperatures of around 100 million degrees Celsius is a major problem because it cannot be contained within material walls. One way to get round this is to use a device known as a tokamak. This consists, in essence, of a toroidal (doughnut-shaped) vacuum vessel around which are wound poloidally (the short way round) a set of coils that produce a toroidal (the long way round) magnetic field B (figure 2). Magnetic fields control the plasma and keep it away from the walls. Plasmas are charged, so imposing a magnetic field causes the charged particles to orbit around the magnetic field lines (figure 3). The particles are therefore trapped, following the toroidal field lines round and round the torus. Unfortunately, the particles can drift across the field lines as a result of effects arising from the variation of the magnetic field and the presence of electric fields owing to charge separation, which ultimately results in the plasma escaping. A toroidally flowing plasma current is imposed to avoid this. This current is generated by induction using an iron transformer core – the plasma acts as the secondary winding in the transformer circuit. This toroidally flowing plasma current then produces a poloidal magnetic field. Combined with the toroidal field, this produces a helical magnetic configuration. The charged particles follow these magnetic field lines and are thereby confined within the tokamak.

Achieving high energy gain

Driving of the toroidal plasma current in a tokamak is very important for continuous operation. This is impossible if the current is produced wholly inductively by transformer action, because the current in the primary winding must always be changing, so the device would have to operate in pulses. It would then have to cool down between pulses, producing higher stresses in the machine from thermal cycling. Non-inductive current drive is therefore required. The most commonly used methods include neutral beam current drive, electron cyclotron current drive and lower hybrid current drive. However, none of these methods has a high efficiency, so providing 100% of the plasma current by these alone would be prohibitively expensive.

Fortunately there is a naturally arising current in the plasma produced by radial diffusion in the presence of a pressure gradient. This is known as the bootstrap current. With this providing 50–90% of the plasma current, a viable steady-state reactor concept can be envisaged. The plasma then has to be heated so that there is sufficient energy for the fusion reactions to take place. The plasma current performs a second function here by heating the plasma. This occurs through the resistance to the current caused by electron–ion collisions and is known as ohmic heating. However, this is limited because it becomes less effective as the plasma heats up due to the inverse proportionality of the plasma resistivity to temperature.

Other heating methods must therefore be employed, and these are often the same techniques as used for current drive. They include neutral beam heating, radio frequency heating and electron cyclotron resonance heating. The helium nuclei produced in the fusion reaction also heat the plasma through collisions. Tokamaks strive to achieve a high energy gain, where the plasma temperature can be sustained predominantly by this alpha-particle heating.

The Joint European Torus (JET) in Oxfordshire is currently the largest tokamak in the world. The diameter of the vessel is 8 m, with the entire machine standing at around 15 m tall. JET will be superseded by ITER (about twice as big as JET in all dimensions, and therefore a plasma volume of eight times JET's), and is designed to be the last step before a demonstration fusion power plant. ITER's objective is to demonstrate the scientific and technological feasibility of fusion energy, so it will be used to study the physics of burning plasmas and to test the necessary technologies. JET plays an important role in the fusion research programme, performing vital experiments that contribute

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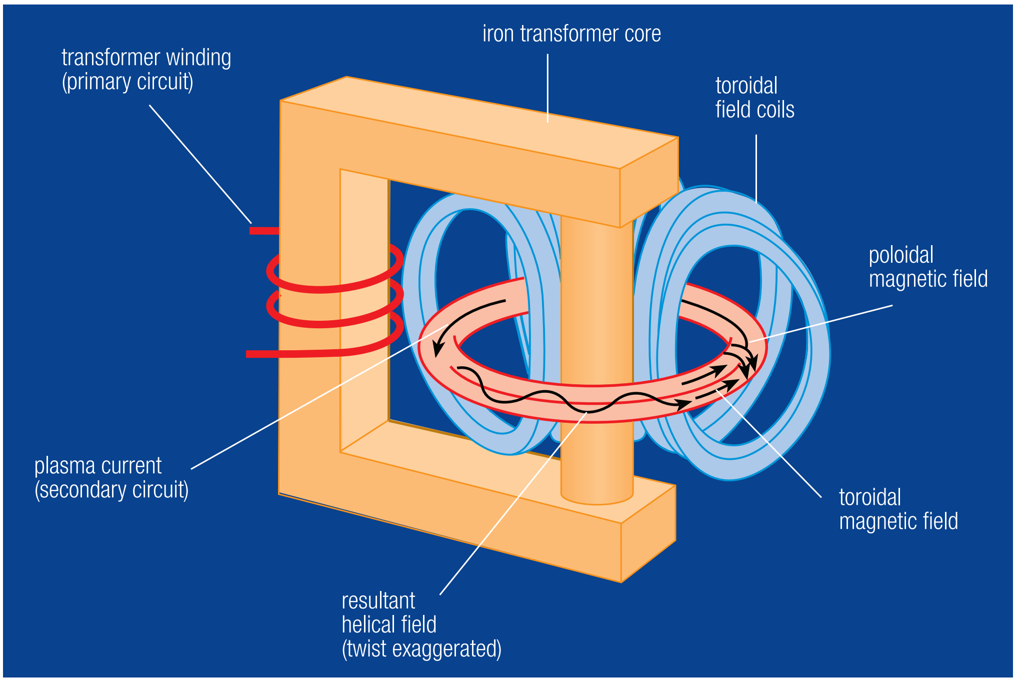

Figure 2: An example of a tokamak, showing its toroidal vacuum vessel. A doughnut-shaped set of field coils create a toroidal magnetic field. The resultant helical field has been exaggerated in the diagram to show its twisting motion.

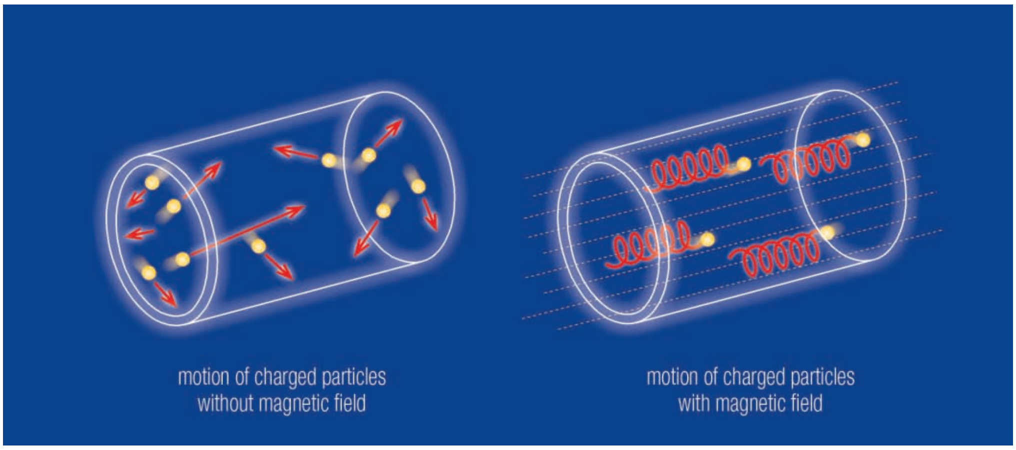

Figure 3: The diagram shows how the magnetic fields confine the plasma current, keeping it away from the walls. Introducing a magnetic field causes the charged plasma particles to orbit around the magnetic field lines, therefore trapping them. The particles are forced to follow the toroidal field lines round and round the torus.

to ITER. It is the only existing device to use tritium as well as deuterium, and it has also demonstrated robotic technology to prove that remote maintenance of the tokamak is possible. JET has produced almost 20 MW of fusion power, while ITER is expected to produce about 500 MW.

Harnessing fusion power

The major challenges now lie in the handling of the power produced and how to design robust machines that can withstand the huge amounts of heat and energetic neutrons that will be hitting the walls. The choice of materials for the surfaces that are in closest contact with the plasma is crucial. Removing impurities from the plasma will also be a central issue in ITER because the huge heat loads and the long operation will lead to the release of material from the walls. The alpha particles produced, once they have given up their energy to the plasma, will also become a source of pollution, diluting the fuel, so they must be removed. Polluting impurities that remain in the plasma also cool it, so that more heating is required to maintain fusion. ITER will also be testing and developing tritium breeder blanket modules, so that tritium can be produced from lithium in a blanket surrounding the plasma.

ITER is due to begin operation in 2016 and is expected to produce about 10 times as much energy as is put in. While ITER is operating there will be another facility, the International Fusion Materials Irradiation Facility, which will be testing materials at high neutron flux to see how they will stand up to the neutron bombardment expected over the lifetime of a power plant. A demonstration power plant is expected to be operational by around 2035 and commercial power plants by the middle of the century.

Over the duration of our careers, new fusion scientists will come to see the culmination of decades of work in making fusion power a reality. Its importance cannot be refuted. With the world population growing, the world's energy demands increasing, hydrocarbon depletion and global warming becoming more and more prominent issues, and renewable resources feared insufficient to fill the gap, fusion offers an economically and environmentally viable alternative. Overcoming the challenges will be a lengthy and intense learning process, but it will be one that will make a clean, green, safe, renewable and abundant source of power part of our future.

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