Technologies

Nuclear Fusion

Nuclear fusion is now evidently feasible.Technical questions remain; but private money is becoming involved

What it is

The difficult we do immediately, the impossible takes slightly longer.

Nuclear fusion reactors use the energy produced from the fusion of two smaller atoms,[1] typically isotopes of hydrogen, such as deuterium (D) and tritium (T),[2] to form a larger atom, usually helium.

Individual atoms are repelled from one another by the electrostatic force produced by their circling electrons. When subjected to very high temperatures (>100 000 000°C) they are stripped of their electrons to reveal their core.[3] Given the separated electrostatic charges of these atoms and electrons, this heated cloud of superheated atoms and electrons – 'plasma' – can be controlled by magnetic and electric fields. The strong nuclear force can then pull atoms' cores together to fuse, producing a larger atom and thereby releasing energy. It is keeping the hot and volatile plasma stable for long enough for this to occur that is the major challenge for fusion.

To capture the energy generated by nuclear fusion there are several proposed methods,[4] but one of the simplest is to heat a fluid and drive a turbine, much as with fission reactors.

Approaches

There are two main methods of producing plasmas hot enough to enable fusion:

- **Magnetic confinement** uses electric currents to generate enough heat to fuse the fuel and magnetic currents supplied by super-conducting electromagnets to control the plasma.[5]
- **Inertial confinement** uses pulses from high-powered lasers to heat solid fuel pellets. The ignition produces a shockwave that compresses the fuel to the immense densities needed for fusion, and the plasma retains its shape just for a split second by inertia alone, before spreading out and dissipating its energy. This method has demonstrated 'net energy output'.[6]

Several fusion reactor designs using these methods have been proposed. The most successful to date are **Tokamaks** [7] and **Laser** [8] reactors which use magnetic- and inertial-confinement respectively. Other reactors under active development include: **Stellerators**,[9] **Magnetised target reactors**,[10] **Field-reversed configuration beam reactors**,[11] and **Shock-wave reactors.**[12]

Implications and issues

Although some important advances have been made recently, nuclear fusion reactors are still in the early stages of development: even optimists doubt that they will contribute significantly to the world's energy mix before mid-century, long after the climate crisis needs to have been averted.[13] However, the promise of essentially unlimited energy with negligible pollution and no risk of reactor melt-down[14] means that it continues to attract investment,[15] both public (~$30bn)[16] and private (~$4.8bn).[17] Other, more immediate, considerations include:

1. **Plasma confinement.** Advances in computing and superconducting magnets have enabled significant improvements, but fusion plasmas are still not wholly predictable.[18]
2. **Neutron degradation.** The release of neutrons from the plasma can degrade the reactor vessel, making it difficult to maintain the fusion reaction, thereby increasing downtime.[19]
3. **Fuel shortages.** There are both limited stocks (~25kg) and sources of tritium, and present research plans may exhaust them before 2050.[20] Helium-3 could be used instead, but the only place it is found in abundance is on the Moon. Another potential fuel is Boron-11. However, this requires temperatures 10 times higher than for deuterium-tritium fusion, around 1bn Celsius.
4. **Downtime.** Both plasma instability and neutron degradation limit the time for which a fusion reactor can run, so that producing a baseload of electricity is challenging.[21]
5. **Cost.** Given that the price of renewables is comparatively low, and expected to get lower,[22] in many circumstances it may not make economic sense to choose fusion energy, even if available. This is especially pertinent if there are significant advances in battery storage.

Fusion has been demonstrated to be possible. But the road to commercialisation is a long one. Nonetheless, the potential promise is too great to pass over.■

[1] When two atoms of an element lighter than iron (^{56}Fe) fuse, they release energy. Such 'fusion energy' is responsible for the reactions occurring in the core of our Sun.

[2] Hydrogen commonly exists in nature as the isotype ^{1}H with a single proton and a single electron, typically bound in molecules such as water. However, other isotypes exist, such as deuterium (^{2}H), which has a single neutron in addition to the proton and electron, which brings its atomic mass to 2; and the usually short-lived, radioactive tritium (^{3}H).

[3] The basic structure of an atom is taken to be a core comprised of positively charged protons and neutral neutrons, which both have a certain mass, surrounded by a cloud of negatively charged electrons, which lack any significant mass.

[4] The fusion start-up company Helios aims to simplify the energy capture stage of fusion by directly capturing the energy as a plasma undergoing fusion expands, pushing its magnetic confinement field back. This change in field induces a current, which is then directly captured as electricity. This removes the need for any complex heat transfer apparatus. See: https://www.helionenergy.com/our-technology/.

[5] These super-conducting magnets are using liquid helium cooled to within a few degrees of absolute zero. Recent advances in their efficiency have improved prospects for spherical tokamaks. See: https://www.cfs.energy/.

[6] The method of inertial confinement has demonstrated "net energy gain", or positive energy output: essentially that fusion reactions on Earth can produce more energy than is put in. At the end of 2022 an output of 130% was recorded at California's experimental National Ignition Facility, meaning that 130% of the energy put into the reactor was then produced by the fusion reactions within. It is estimated that a net gain of 300% is required for a reactor to be a feasible energy source. See: https://www.nature.com/articles/d41586-022-04440-7 & https://www.ft.com/content/4b6f0fab-66ef-4e33-adec-cfc345589dc7

[7] Essentially a large, hollow, donut-shaped reactor which contains the plasma in a ring, the most famous of which is the International Thermonuclear Experimental Reactor (ITER) based in southern France. There are variations on the tokamak design, such as the Spherical Tokamak being developed by Commonwealth Fusion Systems. A more spherical reactor, it avoids some of the issues from the original tokamak design. See: https://www.energy.gov/science/doe-explainstokamaks, https://www.iter.org/proj/inafewlines, & https://www.cfs.energy/.

[8] The National Ignition Facility (NIF) in California is the main example of this. Pea-sized plastic capsules of D–T fuel are imploded by nanosecond pulses of laser light to ignite fusion. The NIF has achieved the highest Q-value of any current fusion reactor so far –1.3 – meaning that the fusion reaction it contained was capable of producing 130% of the energy input. See, https://www.nature.com/articles/d41586-021-02338-4 & https://lasers.llnl.gov/news/high-energy-shot-puts-nif-back-on-track-toward-ignition

[9] The stellarator is a twisted-ring magnetic confinement reactor. This avoids some of the instability issues associated with tokamaks but which was deemed impossible until recent advances in computing allowed for the calculation of the precise shape of the magnetic fields within. At present there is only one demonstration reactor, Wendelstein 7-X, in Germany, which cost approximately €1 billion. See: https://www.ipp.mpg.de/w7x & https://www.science.org/content/article/twisty-device-explores-alternative-path-fusion.

[10] Magnetised target fusion strikes a compromise between magnetic confinement and inertial confinement methods. It involves compressing the plasma more slowly, for example by using pistons, but also using magnetic confinement to prevent heat from dissipating as the plasma is compressed. General Fusion's design is planned to be built in Culham, UK, and will use a centrifuge to spin a chamber filled with molten lead and lithium. When spun, the liquid metal will open a cavity where the plasma will exist. A piston system will push more molten metal into the chamber, further compressing the plasma. Fusion will begin, the pressure will be released, and the process repeated in 1-second pulses. One important aspect of the reactor is its ability to produce, or "breed", tritium within the liquid-metal compression system itself, rather than when neutrons escape the reactor and hit a lithium blanket lining the reactor; as in ITER and other tokamak designs. See: https://generalfusion.com/fusion-technology/

[11] Field-reversed configuration fusion involves confining the plasma with a cylindrical magnetic field produced by a solenoid. As a result the fusion plasma essentially spins on itself. This achieves greater stability than in other magnetic approaches and requires weaker magnets, thereby avoiding the difficulties of super-conducting electromagnets. Another advantage of this reactor is that the fuel it is designed for, boron-11, is far more abundant than Helium-3 or tritium, and does not produce excess neutrons, which might damage the reactor. The difficulty with this design, being pursued by TAE Technologies, is that p–11B fusion (proton-boron-11 fusion) requires temperatures 10 times greater than those required for deuterium-tritium fusion, approximately 10 billion degrees Celsius. See: https://tae.com/news/

[12] Electromagnetic shock wave fusion uses an electromagnetic pulse to propel a physical projectile into the target hydrogen isotopes. This approach is being pursued by the start-up company, First Light Fusion. They have kept the exact process secret but have acknowledged that to achieve fusion it requires the material to be fired at 50km/s. This is double the current speed achieved. See, https://firstlightfusion.com/technology/our-approach.

[13] See: https://www.iea.org/reports/net-zero-by-2050 & https://www.iter.org/fr/newsline/255/1491

[14] Fusion reactions quench rapidly upon destabilisation. Indeed, the main problem is keeping them going to generate energy, rather than preventing runaway reactions.

[15] A 2021 article captures this wave of optimism and details some of the most advanced projects, although the exact numbers are now out of date. More recent numbers are provided by the Fusion Industry Association. See:

https://www.nature.com/immersive/d41586-021-03401-w/index.html & https://www.fusionindustryassociation.org/about-fusion-industry.

[16] The International Thermonuclear Experimental Reactor (ITER) currently has a price tag of around $22bn, although this is disputed. And the Wendelstein 7-X reactor, a predominantly German-led stellarator project, cost more than €1 billion (US$1.15 billion) to build, staff, and operate up to its first plasma testing in 2015. The US National Ignition Facility (NIF) was initially designed to provide research for thermonuclear weapons, but has also served as a proof of principle and research plant for fusion. So far it has cost $3.5 billion. See: https://www.nature.com/articles/d41586-021-02338-4, https://www.science.org/content/article/twisty-device-explores-alternative-path-fusion, & https://physicstoday.scitation.org/do/10.1063/pt.6.2.20180416a/full/

[17] See: https://www.fusionindustryassociation.org/about-fusion-industry

[18] See: https://news.mit.edu/2021/MIT-CFS-major-advance-toward-fusion-energy-0908 & https://www.science.org/content/article/twisty-device-explores-alternative-path-fusion

[19] This is a significant takeaway from the successful demonstration of fusion energy output at the NIF in late 2022, where 130% of the energy put in was produced but the reactor vessel was damaged, requiring significant repairs. See: https://thebulletin.org/2017/04/fusion-reactors-not-what-theyre-cracked-up-to-be/

[20] The current production of tritium is dependent on the CANDU fission reactors in Canada & South Korea. These use 'heavy water' – deuterium (^2H) – to cool their cores and 'moderate' the nuclear chain reactions within, absorbing excess neutrons. This produces tritium (^3H) as a by-product. Over the coming 30 years, many of these CANDU reactors are expected to retire, presenting a problem for supply, just when it is most required. Another source of tritium could be the fusion reactors themselves, and research into tritium 'breeding' is taking place at ITER using lithium 'blankets' to absorb excess neutrons. But it remains to be seen if it can be wholly sustainable and produce more tritium than its' own requirements. See: https://www.science.org/content/article/fusion-power-may-run-fuel-even-gets-started.

[21] The longest fusion reaction to date took place in the Joint European Torus (JET) near Oxford, UK, in 2021. It lasted for 5 seconds, producing 59 megajoules of energy. JET is a much smaller tokamak reactor than ITER, but of a similar design, so this bodes well for ITER's future. See: https://www.nature.com/articles/d41586-022-00391-1

[22] See: https://www.irena.org/publications/2022/Jul/Renewable-Power-Generation-Costs-in-2021, https://www.iea.org/reports/projected-costs-of-generating-electricity-2020, & https://www.iea.org/reports/renewable-energy-market-update-may-2022