WISHING ON A BOTTLED STAR

It's perpetually just over the horizon, but if fusion power ever actually arrives, can it solve our energy problems once and for all? Tom Hawking investigates.

Since the industrial revolution, we've met our ever-increasing energy needs by slowly working our way through four billion years' worth of hydrocarbons—essentially, the liquified remains of our ancestors.

Unfortunately, as well as being hugely destructive to our atmosphere—along with all the planet's ecosystems—burning fossil fuels is inherently inefficient. Combustion produces energy from the breaking of chemical bonds between atoms and/or molecules, and there's just not that much energy stored in those bonds.

The discovery of the atomic nucleus in 1911, and its internal structure over the next 20 years, pointed the way to a much greater source of energy: the force that holds together the protons and neutrons that make up an atom's nucleus. These particles are far more tightly bound than atoms or molecules, and separating them promised to let loose a whole lot more energy than simple combustion.

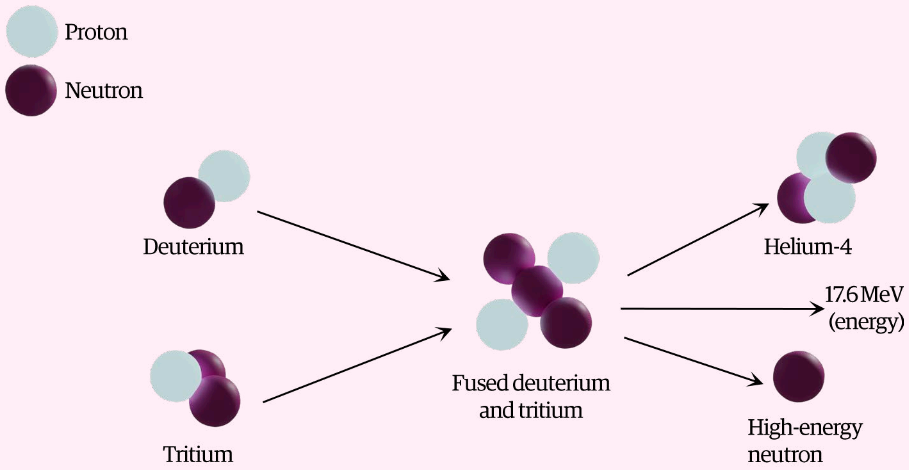
Of course, the past century or so has demonstrated the various stercobilin-scented linings on the silver cloud of atomic-era optimism. Nuclear fission—the process of splitting heavier atoms into lighter ones—generally requires uranium for fuel and generates radioactive byproducts (some that take an extremely long time to decay into other elements). And when it goes wrong, hoo boy can it go *spectacularly* wrong.

However, there's another form of nuclear power, one that seems to have been just out of reach for as long as anyone can remember: nuclear fusion. It promises the apparently impossible dream: limitless clean energy, with no toxic by-products and no CO_2. But will it ever actually arrive?

What is fusion?

So, to get this out of the way: nuclear fusion has nothing to do with nuclear *fission*, the process that provides all the nuclear power we currently use here on Earth. In fact, they're basically opposite processes.

As its name suggests, fission splits heavy atoms into lighter ones, releasing energy in the process. Fusion, by contrast, generates energy by fusing light atoms into heavier ones.



Graphic: Renew

The deuterium-tritium fusion reaction. An electronvolt (eV) is a unit of energy that is defined as the kinetic energy gained by a single electron passing through a potential difference of one volt. A mega-electronvolt (MeV) is a million eV. A single eV is equivalent to about 1.6 x 10^{-19} joules, so 17.6 MeV is about 2.81 x 10^{-12} joules. That mightn't sound like much, but remember this is *per atom* of helium-4 produced.

How does fusion work?

To understand how *both* these processes can liberate energy, we need to take a brief detour into the inner workings of the atomic nucleus. Apart from the simplest hydrogen nucleus, which contains a single proton, all nuclei are made up of two particles, referred to collectively as "nucleons": protons, which carry a positive electric charge, and neutrons, which have no electric charge.

But wait: if atomic nuclei comprise only protons and neutrons, and electromagnetism dictates that like charges repel, do protons not repel one another? Indeed they do. However, there's another force at play here: the strong nuclear force, which is significantly more powerful than electromagnetism, and which is thus able to overwhelm the repulsive electrostatic forces between protons.

However, there's a caveat: the strong nuclear force has a very limited range, and its effect falls off rapidly. At a distance of 1 fm (10^{-15} m, which is around the radius of a proton or neutron), its attractive power is 137 times greater than electrostatic repulsion. By 2.5 fm, though, it becomes insignificant in comparison to electromagnetism.

This rapid change in the balance between electromagnetism and the strong nuclear force has profound implications for what's called the binding energy of nuclei. This term refers to the amount of energy that needs to be applied to separate a nucleus into its component parts.

Toward the start of the periodic table, where nuclei are relatively small, the force pulling nucleons together is stronger than that forcing them apart. It's therefore more energetically favourable for nucleons to be together than apart, and the process of pulling them together is *exothermic*: it releases energy. This process is what we call fusion.

After a certain point,[1] though, nuclei become so large that the ability of the strong nuclear force to hold them together starts to decline. Once this is the case, it's fission that becomes exothermic—the amount of energy required to hold such heavy nuclei together is such that energy is released when the nucleons are pulled apart.

How do fusion reactors work?

If you want to see a fusion reactor at work, look up into the sky, because there's an awfully big one up there: the Sun.[2] Like every other main sequence star in the universe, the Sun fuses hydrogen (the lightest element) into helium (the second lightest).

Here on Earth, almost all fusion reactors work with the same elements: they also fuse hydrogen into helium albeit via significantly

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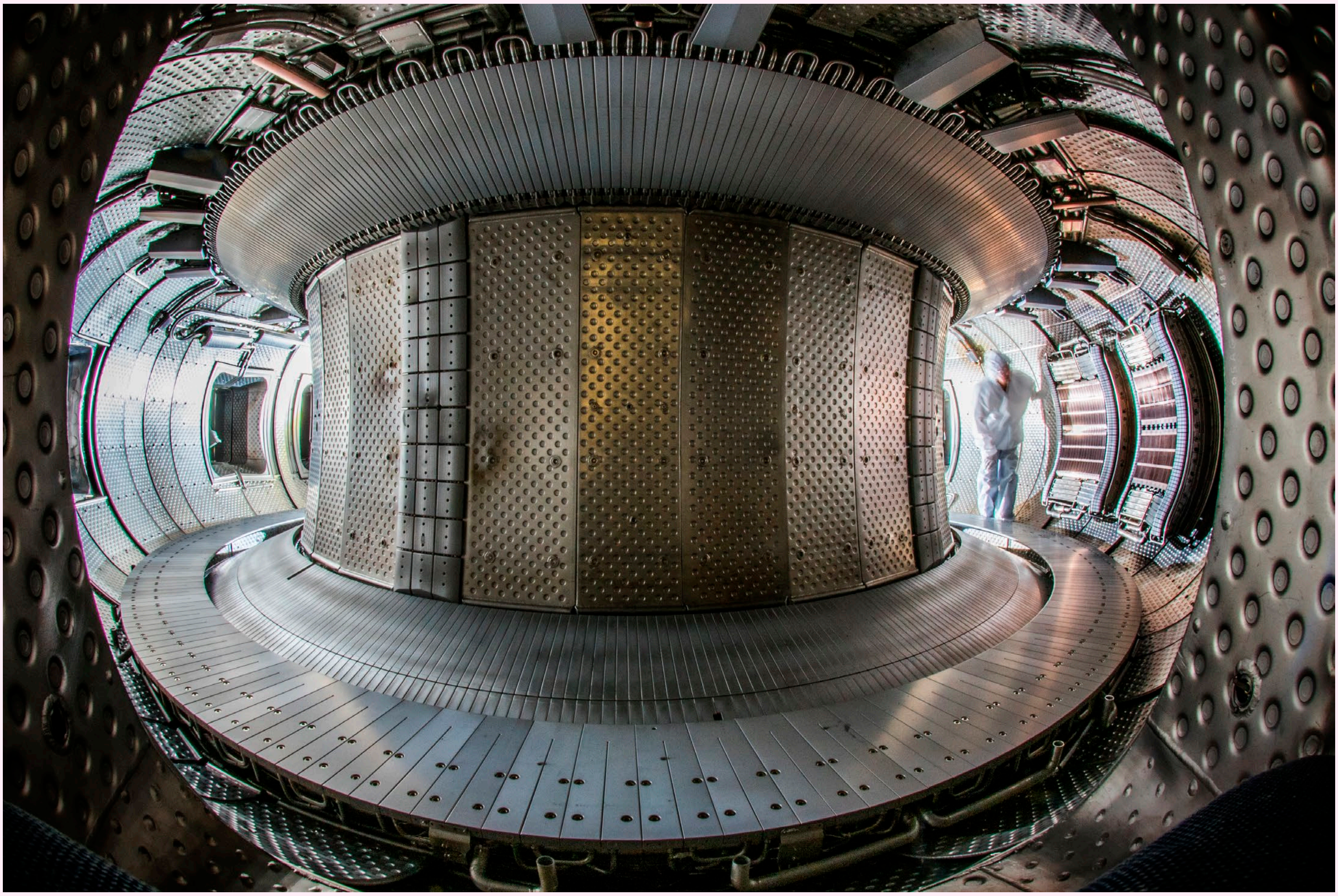
[1] This point occurs around element 26, which is iron.

[2] This sentence is rhetorical—you shouldn't need us to tell you this, but don't actually look straight at the Sun.



The impressively sci-fi interior of a tokamak reactor, with the toroidal shape clearly visible. This one is the WEST experiment, located at the Cadarache centre in the French department of Bouches-du-Rhône, which is also the site where ITER is being constructed.

Image: Christopher Roux/EUROfusion/Wikimedia Commons

different processes.[3] Either way, though, the key point is that the mass of one helium nucleus is about 0.7% less than that of four hydrogen nuclei. That mightn't sound like much, but think about Einstein's famous equation relating energy and mass: energy equals mass times the speed of light *squared*. The speed of light is a very large number. The speed of light squared is an unimaginably large number. And so it turns out that a mass difference of 0.7% translates to a lot of energy.

However, it's only when nuclei are brought close enough together for the strong nuclear force to take over that fusion is possible. Because the strong force's range is so small, getting nuclei close enough for this to happen is no trivial task, especially because just as individual protons repel one another via electromagnetism, so too do individual nuclei—being composed entirely of protons and neutrons means they all carry a net positive charge.[4]

In a star, the conditions for fusion are created by gravity, which compresses immense amounts of hydrogen into a relatively small—and thus highly dense—area. The resultant pressure also generates heat, enough to create an ionised plasma, in which bare hydrogen nuclei are careening around at extremely high speeds. Gravity also keeps the hydrogen confined, and the result is an ongoing fusion reaction that will last for billions of years.

Here on Earth, given that actually creating a miniature star is impossible, we need to find different ways of creating conditions in which fusion will occur—and, crucially, of doing so in a way that the resultant fusion reaction produces more energy than that used to generate the conditions for it to happen in the first place. The latter, in particular, is the fundamental challenge of Earth-based fusion.

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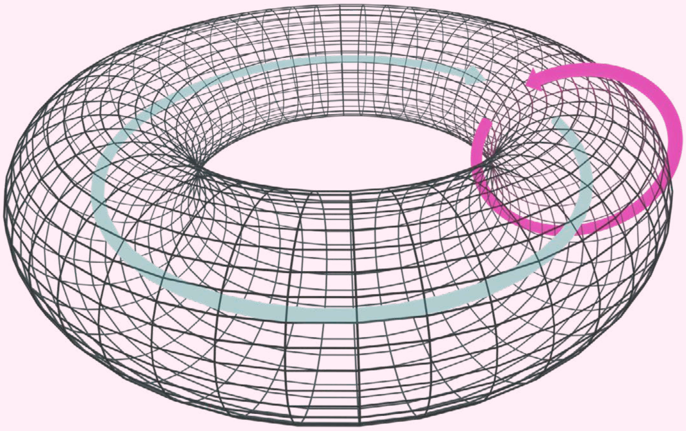
[3] The exact nature of these differences, along with questions like "How do four protons become two protons and two neutrons, anyway?" are beyond the remit of this piece. However, readers interested in the ins and outs of stellar fusion—which is fascinating!—are encouraged to google "proton-proton chain reaction" for details.

[4] The electrons that usually counterbalance the nucleus's positive charge are stripped away when atoms are accelerated to the velocities required for fusion. This process is called ionisation, and as we'll see, proves crucial for some terrestrial fusion reactors.



The two axes of a torus: toroidal (blue) and poloidal (magenta).

Graphic: *Renew*

Professor Matthew Hole, the head of ANU's Plasma Theory Modelling Group, explains that there are three key requirements for achieving fusion: "You need high density, high temperature and high confinement." High temperature (which is, after all, essentially just a measure of kinetic energy) ensures that the nuclei are moving fast enough to get close enough to fuse. High density means that there are enough nuclei in a given space to make such encounters at least vaguely probable. Confinement maintains these conditions long enough for as many events to take place as possible.

In summary, then, improving the chances of fusion reactions taking place means increasing density, temperature and confinement. "You need the triple product," says Professor Hole. "You can push any one of these parameters, but unless you push all three simultaneously, [the result] might be impressive, but it's not a demonstrated advance towards fusion power."

Fuelling the reaction

As we discussed above, pretty much every terrestrial fusion project uses the same fuel for their fusion reactions as stars do: hydrogen. However, there's a key difference. While the Sun starts with the most abundant form of hydrogen, which has a single proton as its nucleus, fusion reactors on Earth use the two heavier isotopes of hydrogen: deuterium (one proton, one neutron) and tritium (one proton, two neutrons).

Professor Hole explains that there are several reasons for this. "The DT [i.e. deuterium-tritium] reaction is the one you want to harness for power," he says. "The main reason is that the reaction cross section[5] is much higher [than deuterium-deuterium, proton-proton, or other reactions]."

So we have fuel: deuterium and tritium. The next step is to satsify the requirements of density, temperature, and confinement. There are two main approaches to this challenge: magnetic confinement and inertial confinement. These—along with other, more exotic processes—are discussed in the next section.

Magnetic confinement

The possibility of Earth-based fusion was first explored as early as the 1940s. It became apparent very early on that any sort of physical confinement of a plasma at the temperatures required for fusion was out of the question: we're talking around 100m K, six times hotter than the core of the Sun.

However, the fact that an ionised plasma is electrically conductive raised the possibility of controlling it via electric and magnetic fields. The idea of using the latter to confine the plasma was first explored in the 1950s, and remains the most promising approach today. ITER, the transnational project that involves financial and material contributions from the EU, China, India, Japan, Korea, Russia and the USA, is building a prototype reactor based on magnetic confinement in southern France. This is the world's largest fusion project, and aims to explore the viability of magnetic confinement as a technology, as well as providing valuable data on how the reactor concept could be improved.

But if magnetic confinement has been around since the 1950s, why are we still trying to make it work 70 years later? As Professor Hole—who is also the head of the Australian ITER Forum—explains, "[Early scientists] didn't think that confinement would be such a problem. [But] you're trying to put a large amount of stored energy into a confined space, and nature doesn't like that. Nature wants to relax, and it will find any way it can [to do so]. So you have to constrain it in some way, to avoid ways that the plasma can lose energy—and there are lots of ways[6] a fusion plasma can lose energy."

Nevertheless, the use of magnetic fields remains arguably the single most promising approach to plasma confinement. There are various reactor designs that take this approach, all of which date (in principle, at least) back to the 1950s. Foremost are the tokamak (like ITER) and the stellarator, both of which are based on the idea of confining the plasma around the interior of a donut-shaped chamber. (Or, to give it its proper name, a torus.)

This seems simple in principle, but the naïve approach of simply placing magnets around the torus turns out to be flawed: the field is stronger on the interior of the torus than on the exterior, resulting ultimately in a significant loss of plasma confinement. This means that the plasma needs to be constrained poloidally—i.e. around the circular axis of the torus—as well as toroidally. (See diagram above.)

The key to doing so turns out to be "twisting" the field around the torus's toroidal

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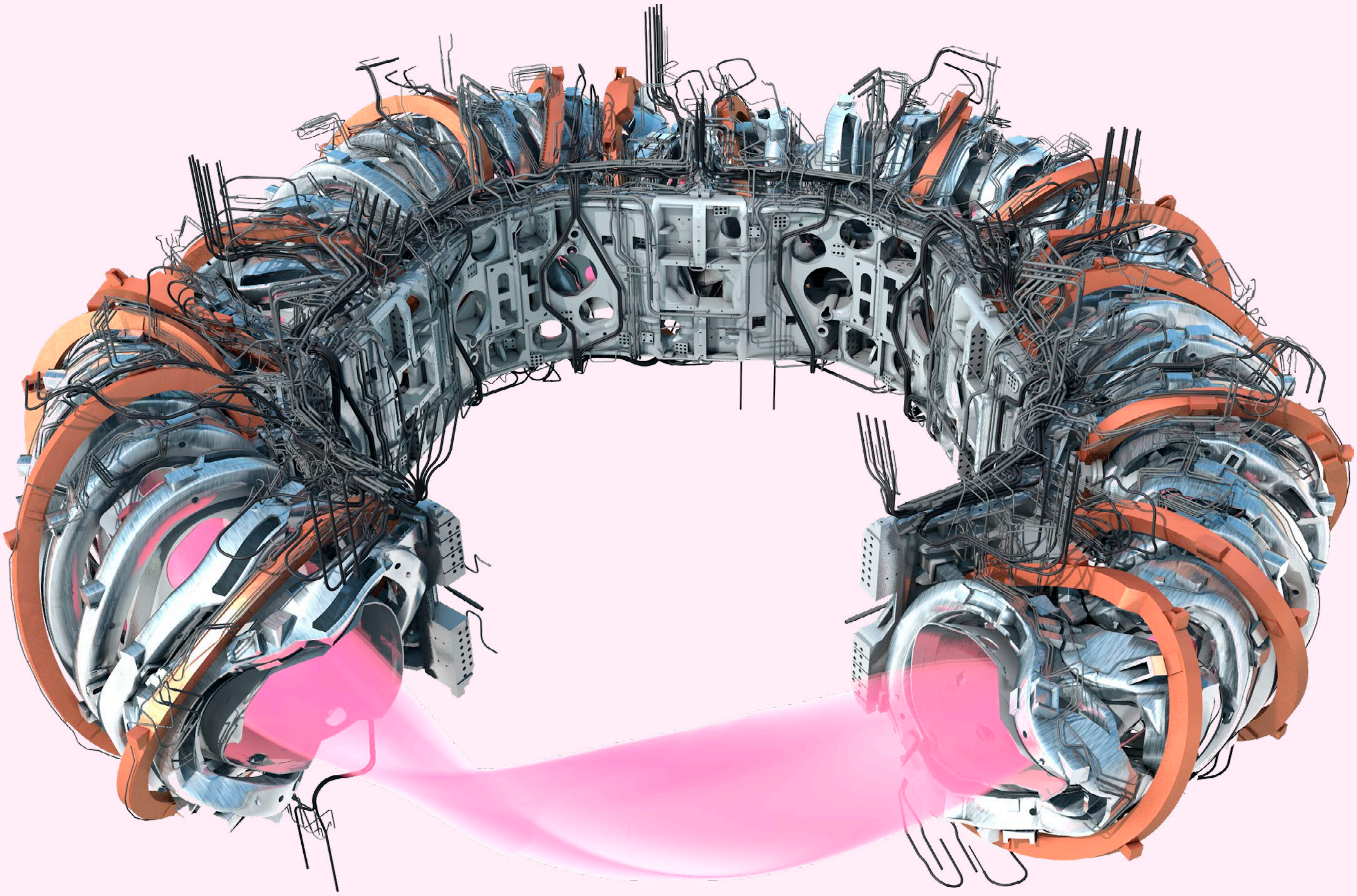
[5] Broadly, a term that refers to the probability of an event taking place. In this context, a higher cross section means a higher number of fusion events at a given velocity.

[6] He's not exaggerating—readers wondering just how many ways plasma can lose energy are advised to have a look at en.wikipedia.org/wiki/Plasma_stability#List_of_plasma_instabilities



So, when we said below that stellarators were complicated to build… this is what we meant. This image is a schematic of the Wendelstein 7-X, the world's largest stellarator, which resides at the Max Planck Institute for Plasma Physics in the German city of Greifswald. The main image shows the plasma (the notably twisted pink stream at the forefront of the picture) along with the superconducting coils (silver), the planar magnet coils (orange) and supporting structure, current leads and cooling pipes.

Image: Max Planck Institute for Plasma Physics

axis. The tokamak and the stellarator differ in their approaches to generating this twist: the former does so with a combination of external magnetic coils and a current within the plasma, while the latter does so entirely with external coils. The trade-off is that stellarators normally use asymmetric coils, which mean they are much more complicated to build. Tokamaks use relatively simple magnets, but their large current can make them susceptible to current-driven disruptions.

-A star neutron

Readers may have noticed the excess neutron produced in the deuterium-tritium reaction. This neutron might seem undesirable, since energetic neutrons have an unfortunate habit of doing unpleasant things to living tissue, even more so than gamma rays of comparable energies.

However, the neutron can be put to good use: it can be slowed by a thermal blanket and heat exchanger, which produces steam to drive a turbine. Some of these neutrons are also harnessed to generate more tritium to fuel the reaction. While deuterium is relatively stable, tritium is not—its half-life is only 12 years, so it needs to be produced constantly. Modern tokamak designs include a blanket of lithium in the wall of the reactor chamber. When the extra neutron collides with a lithium atom in this blanket, it will split that atom into a helium nucleus and a tritium nucleus. Further neutrons may also be released, depending on the exact reaction that occurs—there are several possibilities, depending on the isotope of lithium involved. To generate sufficient tritium for replenishing fuel, a neutron multiplier is proposed.

Inertial confinement

An alternative approach to confining a plasma with magnetic fields is confining the fuel—which, again, comprises deuterium and tritium—within a small volume, and then compressing that volume to generate the required density, temperature and confinement to initiate fusion. This mechanism is similar to that used in the secondary stage of thermonuclear bombs, which use the thermal x-rays generated by an initial fission reaction to send a small quantity of plutonium into a supercritical state. This in turn compresses a canister of fusion material, causing an immense release of energy.

The similarity is no accident—the idea of inertial confinement fusion as an energy source grew out of something called Project PACER, a US government program that investigated the hair-raising idea of using nuclear bombs to generate power.[7] That idea, thankfully, was abandoned, but compressing small quantities of fuel to ignite a fusion reaction continued as an area of research—most prominently at the US-based National Ignition Facility, which commenced operations in 2009.

This facility emerged from—and continues to be funded by—the US's nuclear weapon stewardship program, which exists to maintain the country's ageing weapons stockpile and measure its continued effectiveness without actually carrying

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[7] No, we are not making this up. The 1970s were wiiiiiiild, man.

out nuclear tests. The idea of using the experiments to generate energy wasn't exactly at the forefront of anyone's minds when the program was conceived, but the NIF was recently in the news when one of its experiments returned 70% of the energy put into instigating the fusion reaction—the closest yet any experiment has gotten to breaking even on energy in vs energy out.

Modern approaches to inertial confinement fusion place the fuel into a canister called a "hohlraum" (a German word that translates literally as "hollow room"), which is heated by lasers until it produces x-rays. These heat the fuel within until it gets hot enough to instigate fusion. The fuel can also be compressed directly by shining lasers onto a spherical container, but it is extremely difficult to keep the compression symmetrical—which is important, because asymmetries can significantly undermine the efficiency of the reaction.

Exotic fusion

While magnetic and inertial confinement reactors using deuterium and tritium are definitely the most promising approaches to achieving viable fusion power, they're certainly not the only ones. Here are some more exotic alternatives.

-"Cold"/muon-catalysed fusion

Readers of a certain age will remember the notorious 1989 experiment that claimed to have achieved room-temperature fusion with a small tabletop device. The "miraculous" result made headlines worldwide, generating a wave of optimism about cheap, boundless energy—a wave that crested and receded rapidly once it became clear that no-one could replicate the duo's results.

This isn't to say that "cold fusion"—i.e. fusion at a temperature far lower than those required in stars and conventional fusion reactors—is impossible. It can and has been achieved with a form of hydrogen called "muonic hydrogen", in a process called muon-catalysed fusion. The muon is an elementary particle that is identical to the electron in all respects except two—it's some 207 times heavier than its lighter cousin, and it's also highly unstable, with a mean lifetime of 2.2μs.

Replacing a hydrogen atom's single electron with a muon leaves you with a neutral atom that's similar to a plain old hydrogen atom, with the difference that it's smaller. Because it's so massive, relatively, the muon is a lot closer to the nucleus. This makes the atoms far easier to pack closer together without ionising them, and therefore doesn't require the high temperatures required to fuse "normal" hydrogen.

However, while muon-catalysed fusion is both an impressive technical achievement and one that's fascinating academically, it shows little promise as a commercial source of fusion power, for the simple reason that it requires a lot more energy to create muons than you get back from fusing muonic hydrogen.

This means that unless someone works out how to generate muons in a far less energy-intensive manner, this form of fusion will remain an intellectual curiosity.

-Hydrogen-boron fusion

There have been some gushing headlines of late about a novel approach to fusion that uses boron—the fifth element on the period table—as one of its ingredients.

The process, pioneered by Australian company HB11, uses pulses of high-energy laser light to accelerate hydrogen atoms toward a boron fuel pellet.

The company recently published a study in the journal *Applied Sciences* outlining its process and claiming eye-catching results, with an accompanying press release trumpeting the news that "HB11 Energy's ... hydrogen-boron energy technology is now four orders of magnitude away from achieving net energy gain when catalyzed by a laser... This is many orders of magnitude higher than those reported by any other fusion company, most of which have not generated any reaction despite billions of dollars invested in the field."

So is *this* the future? Professor Hole counsels against getting overly excited: "I think [hydrogen-boron fusion] is very difficult because the cross section is tiny. So the only way that approach is going to work [is] to artificially multiply that cross section by [those] four orders of magnitude to make it comparable to DT [fusion]."

How far away are we?

It's become something of a running joke that fusion is 20 years away—and always will be. But seriously: how far away are we? This question feels more pressing with every passing year, given the imminence of climate change and our apparently unbreakable addiction to fossil fuels.

Sadly, Professor Hole isn't promising miracles. "It's still a long time scale," he says. "Even ITER's DT experiments are not until 2032 or thereabouts."

So will we have a fusion power plant within 30 years? "Maybe," he says, "but it would be a very inefficient device. What we hope will happen over time is that we understand how to operate in this regime and the costs will come down. I mean, there's no guarantee that a tokamak is the optimal magnetic confinement configuration. It probably isn't! But it's the one that has been closest to demonstrating net power gain."

He continues, "But look, the first of a kind of any kind of experiment or technology is likely to be ludicrously expensive. The first car engine was totally inefficient, and cars were luxury items [that] nobody could afford. So the question is, 'Are there configurations that will be more cost competitive?'. The answer is probably 'yes'. But there's no guarantee."

Given all this, it's pretty clear that while our technological ingenuity may well deliver us a source of clean, cheap energy, it won't do so in time to avert the need to move away from fossil fuels. If fusion is going to save us, we need to save ourselves first.

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RESOURCES:

ITER: iter.org

Australian ITER Forum: fusion.ainse.edu.au

IAEA page on fusion power: bit.ly/3MAfDta