WHAT IF ONE GAME CHANGING INVENTION PROMISED TO SOLVE OUR ENERGY NEEDS — AND OUR POLLUTION PROBLEMS — INDEFINITELY? WITH THE FATE OF THE PLANET AT STAKE, WOULD ACHIEVING THAT BREAKTHROUGH BE WORTH SHOOTING FOR, EVEN IF IT WERE MORE COMPLEX AND COSTLY THAN ANY SOLUTION TO DATE? AS **CHRIS WRIGHT** EXPLORES, SOME RESEARCHERS BELIEVE THAT TIME IS UPON US — AND THAT WHEN OUR CARBON CRAVINGS HAVE PASSED, THE WORD ON EVERYONE'S LIPS WILL BE FUSION

# FUSION TO THE RESCUE?

THE JOINT EUROPEAN TORUS (JET) TOKAMAK IS, FOR NOW AT LEAST, THE MOST SOPHISTICATED AND SUCCESSFUL FUSION REACTOR IN THE WORLD. TEACHING US MOST OF WHAT WE NEED TO KNOW ABOUT MAKING FUSION WORK. THIS CUTAWAY GRAPHIC OF THE JET VESSEL SHOWS THE PLASMA CIRCULATING INSIDE THE TORUS

PHOTO: EUROFUSION

# It is a Holy Grail of science. It promises non-polluting, safe energy from a fuel source that could last us millions of years. It could also solve the world's energy problems, end carbon-fuelled climate change, and bring about political stability and social equality. Yet, in a scientific sense, it has always seemed to be out of reach. It is nuclear fusion.

Fusion offers "this unbelievable promise of millions of years of carbon-free, safe, compact energy sources," says Professor Steven Cowley, Director of the Culham Centre for Fusion Energy and chief executive of the UK Atomic Energy Authority. And indeed, if Cowley sounds excited, he should. This is a man who has devoted his professional life to the subject of nuclear fusion, and will very likely continue to do so as long as he has the capacity to work.

He advocates that the potential benefit of this breakthrough energy source is both cleaner and safer than the nuclear energy we know now. "It doesn't produce any long-term radioactive isotopes, so you don't have to have geological disposal of your waste," he says. "It doesn't have any accident scenarios that would require evacuating people around power stations. It's an absolutely perfect way to make energy, except for one thing — it's bloody hard to do."

There has been a standing joke among energy experts that nuclear fusion was "always 30 years away." In the post-war environment of atomic energy exploration — chiefly for the military — nuclear fusion was understood chiefly as a theory. Yet even so, early pioneers such as Enrico Fermi for one, were talking about something like a fusion reactor back in 1945.

We are still, today, very likely 30 years away from a commercially viable, operating nuclear fusion reactor that provides us with electricity. But there is growing belief that it might really be possible soon, and that within our lifetimes we could finally see electricity produced in a way that neither throttles our planet, nor endangers it.

## OXFORDSHIRE CALLING

The world's leading centre for nuclear fusion can be found, not in some secret former Soviet facility, but around the corner from The Plough pub in the somnolent Oxfordshire village of Clifton Hampden.

It is sometimes a surprise to people who mock the viability of nuclear fusion, but a fusion reaction has already been completed successfully, in fact on several occasions. And the most successful, in terms of the energy that came out in

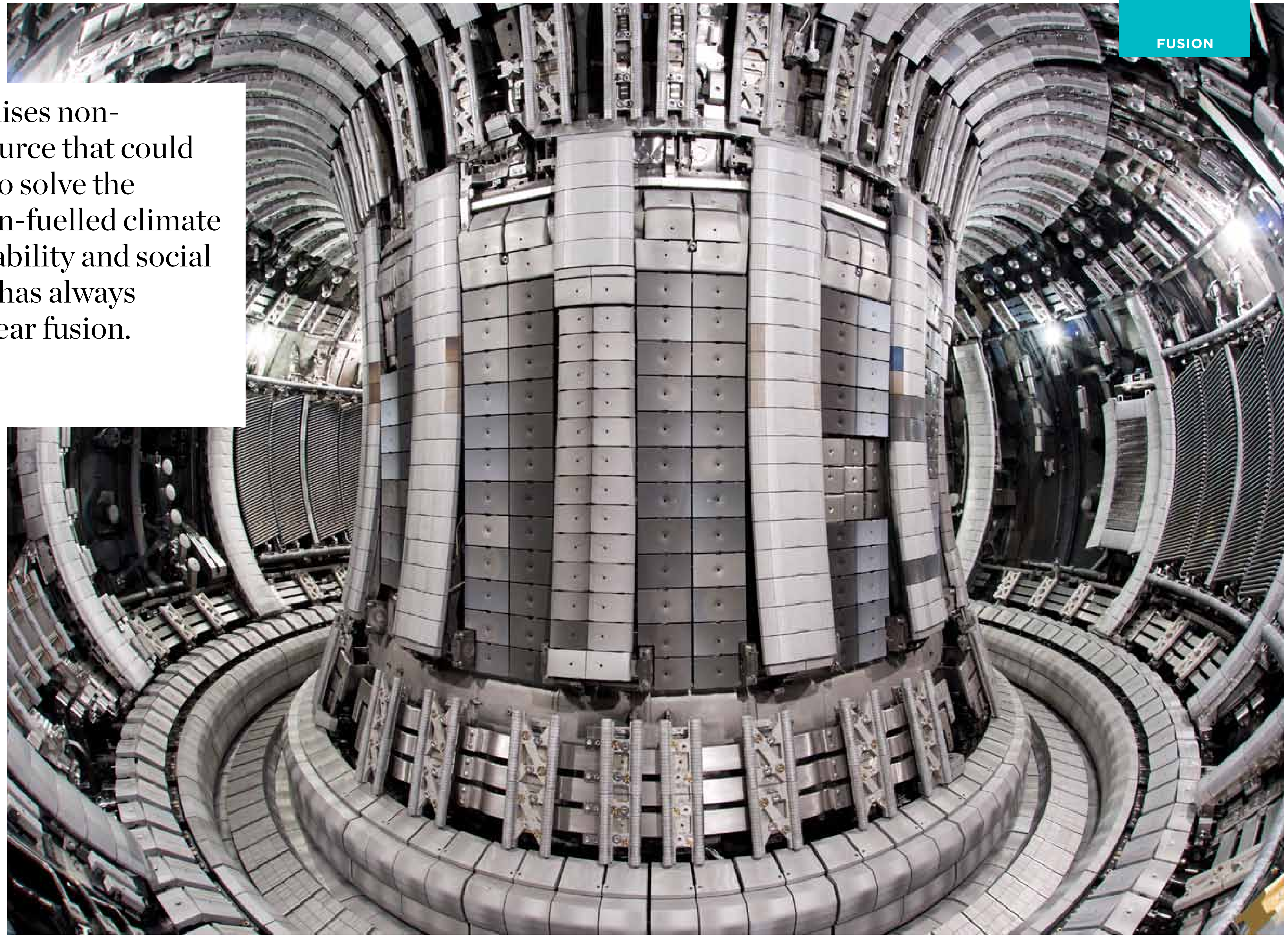


PHOTO: EUROFUSION

JET IS LOCATED AT THE CULHAM SCIENCE CENTRE NEAR OXFORD IN THE UNITED KINGDOM. MORE THAN 40 EUROPEAN FUSION LABORATORIES COLLECTIVELY CONTRIBUTE TO THE JET SCIENTIFIC PROGRAMME AND DEVELOP THE HARDWARE OF THE MACHINE FURTHER comparison to what was put *in*, was right here at the Culham Centre for Fusion Energy.

Furthermore, the record was set in 1997, which means that successful nuclear fusion actually has an almost 20-year history. And here, in this unassuming but historic location, sitting in front of a blackboard swamped with intimidating equations, Professor Cowley is trying to explain this extraordinary science to *DCM*.

So what is fusion? To understand it, one first has to understand what an atom is, and a little about how it works. We're all made of atoms; indeed, *everything* is made of atoms, those tiny units of matter that combine to make everything around us, from the ground that we stand on, to the air we breathe.

As we learned in school, every atom has a nucleus made up of things called protons and neutrons. And two major forces are at work in an atom: the strong force which at very close distances sticks neutrons and protons together; and the electrical force, where like charges repel, as with two identically-charged ends of a pair of magnets. Protons repel each other due to their electrical charge, but if the gap between them is small enough, they attract each other too because of the strength of the force.

Having first wrapped our heads around something unfathomably small, now think of something incomprehensibly big — a star. In the middle of a star, under immense gravitational pressure, atoms are squeezed together so hard that the electrical force is overcome and the strong force fuses things together. When that happens, they turn into something else, releasing energy as they do so.

The simplest of these elements is hydrogen. Fuse some hydrogen nuclei together and you get deuterium, and so on up through helium and lithium. Keep building and building, through carbon, nitrogen, oxygen, until you get everything that we are made of. The optimum nucleus in terms of its inherent stability, it turns out, is iron. Anything bigger than that becomes progressively more unstable, including the likes of uranium.

Nuclear power is all about taking advantage of these reactions to create energy. The nuclear power we're all familiar with today is made by nuclear fission, and that takes those unstable elements like uranium, or "accidents from an exploding star," as Cowley calls them, and splits their atoms, making power out of the energy that comes from doing so.

But we all know about the problems that can come with this brand of nuclear power. Fission creates radioactive waste, which can take thousands of years, tens of thousands sometimes, to become safe, in turn creating a huge headache for disposal and storage. It requires uranium fuel too, which suffers the same problem as fossil fuels, in that it will all run out in a few hundred years time.

And in the worst case, fission can cause dangerous chain reactions, as we have seen at the Three Mile Island, Chernobyl and Fukushima plants — endangering nearby populations and contaminating land and food. So what if we *didn't* split atoms, but tried to fuse them together instead, making our energy that way? Well, that's fusion — and it has a huge amount to recommend it.

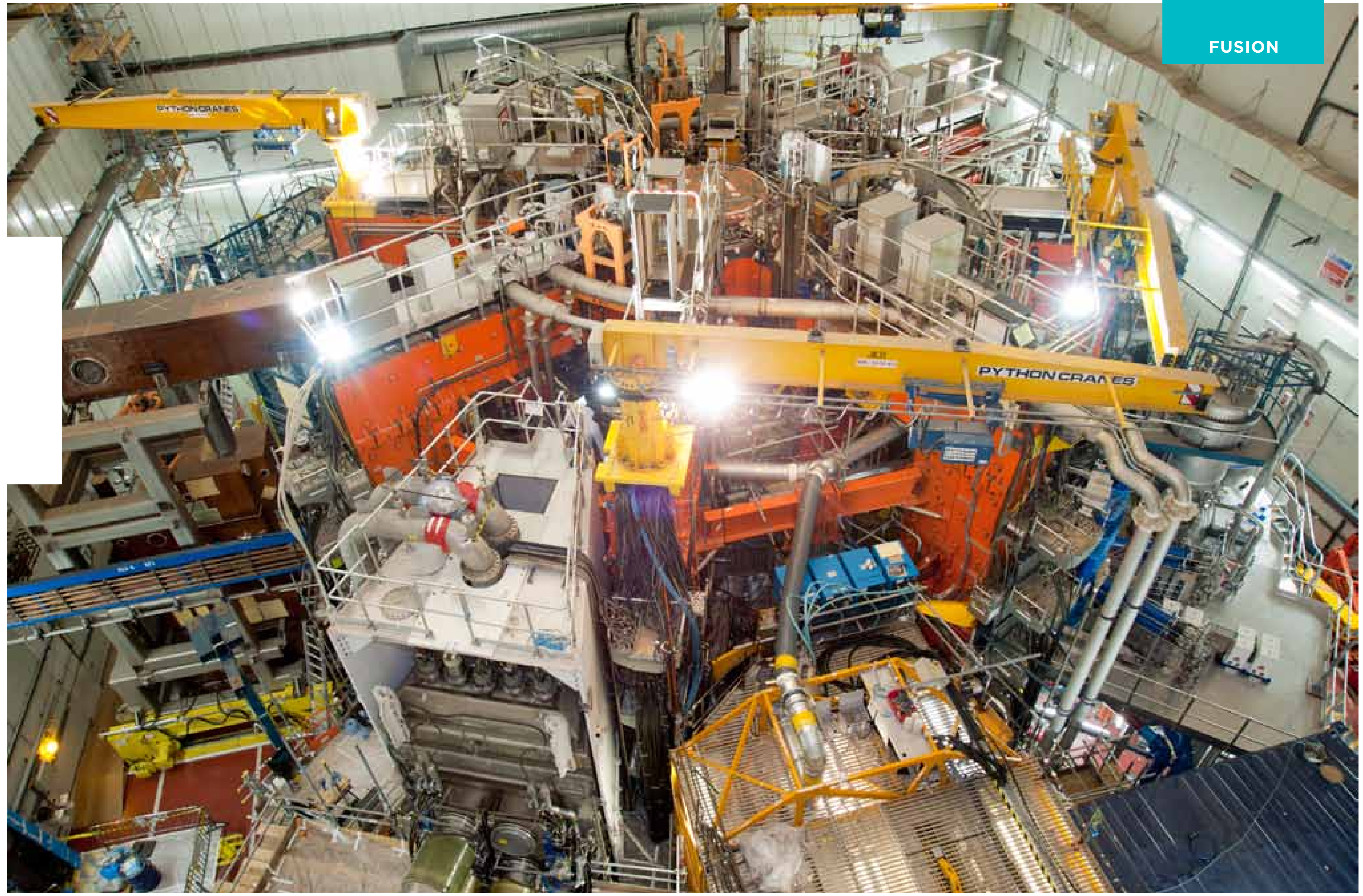
The easiest fusion to do — "by a factor of about 100," Cowley says — is between two forms of hydrogen: deuterium and tritium. That's a happy coincidence for us, for several reasons. For one, when you put these two things together and make them fuse, you get helium, plus an extra neutron. We'll be coming back to that extra neutron later. That's great, because helium is as inert as it gets. It's totally harmless, not radioactive — and as a bonus gives us a plentiful source for party balloons that make your voice go funny. And it *doesn't* give us dangerous waste.

Another plus is that one of these ingredients, deuterium, can actually be extracted from a plentiful source, namely seawater. "There is enough deuterium in seawater to power the planet, for the whole of our energy needs, for 60 billion years," says Cowley. "And there's going to be no more Earth after five billion years anyway, because the sun will have become a red giant and swallowed us," he adds.

**"THERE IS ENOUGH DEUTERIUM IN SEAWATER TO POWER THE PLANET, FOR THE WHOLE OF OUR ENERGY NEEDS, FOR 60 BILLION YEARS"**

The other ingredient, tritium, is more rare. In fact, it scarcely appears on Earth. But we can make it, by using lithium and adding one neutron. And if we remember that we were going to get an extra neutron from our reaction already, all you would need to do is have lithium in the walls of your reactor, and you would make the tritium you need automatically from the reaction you've set in motion.

We're familiar with lithium because our laptop batteries use it: we mine it from places like the high Andean deserts in Chile, and there's about a thousand years of it remaining. Better still though, just like deuterium, we can extract lithium from seawater.




PHOTOS: EUROFUSION (MAIN); GETTY IMAGES (LEFT)

**ABOVE:** FROM 2009 TO 2011, JET WAS SHUT DOWN FOR 18 MONTHS. THE AIM OF THE SHUTDOWN WAS TO BETTER UNDERSTAND HOW TO BUILD AND OPERATE JET'S SUCCESSOR, THE INTERNATIONAL THERMONUCLEAR EXPERIMENTAL REACTOR (ITER) **LEFT:** A SCIENTIST WORKING IN A FUSION REACTOR

And what about safety? A uranium plant requires a lot of fuel on site that can be burned up in a reaction. How about a fusion reactor? "The total weight of all the gas you have in the reactor at any moment is comparable to the weight of three postage stamps," says Tony Donné, programme manager of the EUROfusion consortium, which brings together the fusion work of 29 research laboratories across 27 countries, as well as almost 400 universities and smaller labs.

Donné says even fusion plant accidents need not be nearly as dire as for their fission contemporaries. "If something happened, like a hole in your reactor, firstly it's under pressure, so cold air would be sucked in and would extinguish the reaction immediately," he notes. "And second, when we stop the supply, there is never more than one second of fuel in the reactor to burn." Once that's burned, if no more fuel is introduced, the reaction goes out. The heat from an accident should not be enough to break through the walls. And, even if it did, it wouldn't have anything toxic to release.

It is true that those extra neutrons, when they hit the wall of the reactor, can cause it to become radioactive: but provided the right materials are used in those walls, the radioactivity should die away within a few years of storage — not thousands of years, like spent uranium fuel — after which it could be recycled.

Endless fuel? No pollution? Barely any radioactivity? No waste to dispose? If it's that good, why aren't we doing it already? Well, that brings us back to Cowley's earlier point. It's bloody hard to do.

## BACK TO THE LAB

*DCM* is wearing a hard hat in a room of quite extraordinary twisty novelty. It is a big room,

CONSTRUCTION WORKERS INSTALL EQUIPMENT INSIDE THE 10-METRE DIAMETER TARGET CHAMBER AT THE NATIONAL IGNITION FACILITY AT LAWRENCE LIVERMORE NATIONAL LABORATORY. THE CHAMBER WAS ASSEMBLED FROM THICK ALUMINUM PANELS WHICH WERE PRE-FORMED AND THEN WELDED IN PLACE. IT IS COVERED WITH CONCRETE THAT HAS BEEN INJECTED WITH BORON TO ABSORB NEUTRONS FROM THE FUSION REACTION

PHOTO: NATIONAL IGNITION FUSION

guarded by double doors that are thicker than a man is tall, and about the height of a four-storey apartment block. Within it, there is complicated angular machinery in every direction.

We can see vast orange transformers the height of

**TO MAKE FUSION HAPPEN, WE NEED TO MAKE THINGS COLLIDE WITH SUCH FORCE THAT THEY OVERCOME RESISTANCE AND FUSE WITH ONE ANOTHER**

construction cranes, sprawls of thick transmission cables, brown metal diagnostic devices taller than a house, overhead gantries and thick neutral beam tubes that recall an Apollo space launch.

And somewhere in the middle of this cluttered swarm of gadgetry, so swamped in its periphery that you cannot actually see it, is a thing called the Joint European Torus (JET) tokamak. This, when it's turned on, becomes the hottest place in our Solar System. JET at Culham is, for now at least, the most sophisticated and successful fusion reactor in the world. Streamlined and improved over a 30-year history, it has taught us most of what we need to know about making fusion work.

To make fusion happen, we need to make things collide with such force that they overcome resistance and fuse with one another. We need, in essence, to replicate what happens in the middle of the sun. We can't do this by firing things at each other — the scales are so very small — and we can't recreate the crushing gravity of the sun. Instead, we have to induce a situation where a lot of protons and neutrons are flying around and colliding with each other in a confined area. And the best way to induce this motion is by making things hot — very hot indeed.

"Temperature," says Cowley, "is a measure of how fast things are moving." (Spending time with scientists tends to confront you with a great deal that contradicts what you thought you already knew). "At about 200 million degrees you've got enough kinetic energy in these particles moving around, that when they run into each other dead on, they will get close enough to fuse."

Yes you read it right: that's 200 million degrees, more than 10 times the temperature at the centre of the sun. Naturally, you don't get that sort of heating from the Oxfordshire climate, or in fact from any conventional form of heating. In JET, the heat is created by a combination of radio frequencies (similar to the way we cook food in a microwave), a high-energy neutral beam, and an electrical current.

But how do we get the gasses to be where we want them to be? Well, as the gasses are heated, they become plasma, and plasma can be controlled and contained by a magnetic field. Cowley describes a process by which scientists can layer magnetic fields on top of one another — think of a ball of wool or elastic bands. This alone, he says, has taken more than 50 years for scientists to master. In these conditions, with the plasma held in place and subjected to intensely high temperatures, fusion begins to occur.

So fusion can be done: check. To date, the problem has been that it has required so much energy to make it happen, that it doesn't yet have a useful commercial purpose. In the landmark 1997 record, JET produced 16 megawatts (MW) of power — having used 25MW of power to bring it up to the required temperature. That is a yield — scientists use a measurement called Q — of 0.7. And that's not enough.

To be able to demonstrate something that would be useful as an energy source, keeping in mind all the inefficiencies involved in turning energy into electricity and then transmitting it where it needs to go, the yield



## IS THE ANSWER ON THE MOON?


In the 2009 film *Moon,* Sam Rockwell plays a man who is working alone mining helium-3 on the far side of the moon. The helium-3, we learn, is used to power fusion reactors on Earth.

Unusually for a movie, it turns out that the science behind this is not so far-fetched. Helium-3 would, in theory, be a wonderful thing to use for fusion, because unlike the deuterium-tritium process in the main story, it doesn't produce an extra neutron that causes problems with the reactor wall. Instead, an extra proton is formed, which can be easily contained and used to create energy. Helium-3 itself is not radioactive.

There are only two problems with helium-3 and fusion. First, it requires a much higher temperature than deuterium-tritium to create fusion with helium-3. This is also a problem with another mooted fusion idea, proton-boron, which is the preferred method of Tri Alpha Energy, an American company backed by Microsoft founder Paul Allen, the investment bank Goldman Sachs, and an eclectic mix of board members including Buzz Aldrin and former LA Law actor Harry Hamlin. The other problem with helium-3 is that it's all on the moon. Well, we could find much more of it in the solar system's gas giants, Jupiter and Saturn, but they're not exactly within reach.

For the moment, helium 3 — which we can make on Earth, albeit through a complex and costly process — is seen as a possible second-generation fuel for nuclear fusion reactors, with deuterium-tritium usually seen as the first generation. But it's not so far-fetched to see a future when we go back to the moon not for endeavour or science, but for mining.

figure needs to be more like 10. And JET will never manage it, because it's not big enough. But somewhere else soon will be.

## GLOBAL GAME CHANGER

In the beautiful south of France, not far from the 16th century stonework of the town of Aix-en-Provence, a remarkable project is slowly taking shape. This is the International Thermonuclear Experimental Reactor (ITER), and it's not an exaggeration to say that the long-term health and sustainability of the planet

**IF IT CAN PRODUCE SUCH AN ENORMOUS LEVEL OF ENERGY, THEN A CYNICAL WORLD WOULD HAVE TO CONCEDE THAT FUSION FINALLY HAS A FUTURE AS A WAY OF POWERING OUR PLANET**

could well be influenced by its success or failure.

For if JET has demonstrated that mere mortals can make star-bound miracles of fusion a reality, ITER is being built to demonstrate that it has technological and scientific feasibility as a source of energy. That means not just making fusion happen, but making it generate *ten times* as much energy as it consumes. The production specs require that from 50MW of input power, ITER should produce 500MW in return. If it can produce such an enormous level of energy, then a cynical world would have to concede that fusion finally has a future as a way of powering our planet.

In context, ITER is significant not only because of its scientific objectives. It is also a breakthrough in terms of the scale of global cooperation it involves. Its seven signatories are the European Union (now 28 member states), Japan, Russia, the United States, China, South Korea and India. These nations represent more than half the world's population. And they're not just backers or donors, but entrenched participants: each party is entrusted with delivering cutting-edge components that will be part of the final reactor.

In part due to the herding-cats nature of trying to marshal more than 30 countries to work together, progress has been immensely slow. When the ITER project was born, Russia was not the name on the founding document, but the Soviet Union. This was 1985, and the Berlin Wall had not yet fallen. Mikhail Gorbachev signed for the Russians, François Mitterand for the Europeans and Ronald Reagan for the Americans. Ever since conceptual design work got underway in 1988, delays have appeared for almost every conceivable reason, from politics and bureaucracy — to an incident when someone left a towel on a superconducting cable, which then ended up being compressed within a coil.

When *DCM* talks with Michel Claessens, head of communications at ITER, and asks him if things are back on track, he is honest. "It would be a little bit over-optimistic to say that right now," he notes. There has been, he says, a total of about three years of delay in construction, and in the supply of major components. But still, the endeavour of the thing, 35 countries, 39 technical buildings, and technology of an order that has never yet been attempted, surely deserves some latitude, and those on site say it is beginning to take shape.

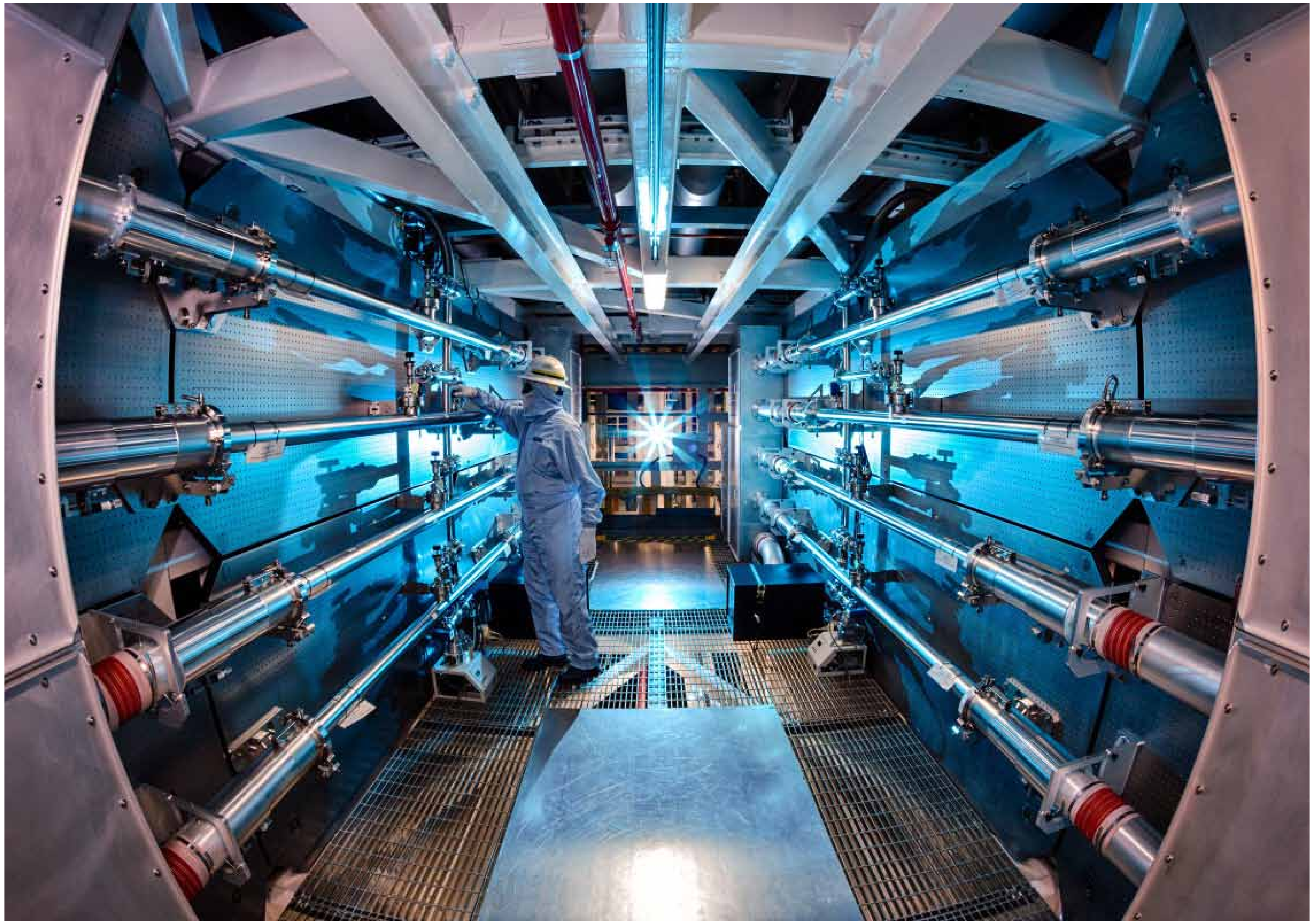
An 87-tonne high-voltage transformer manufactured by Hyundai Heavy Industry in Korea reached the ITER site in January 2015. Construction is underway on the complex's walls, and at press time, five large storage tanks were due to arrive from the US, in late March 2015. "If you were in my office right now, you would see construction is progressing," Claessens says. "Not as fast as we all would expect, but it's progressing."

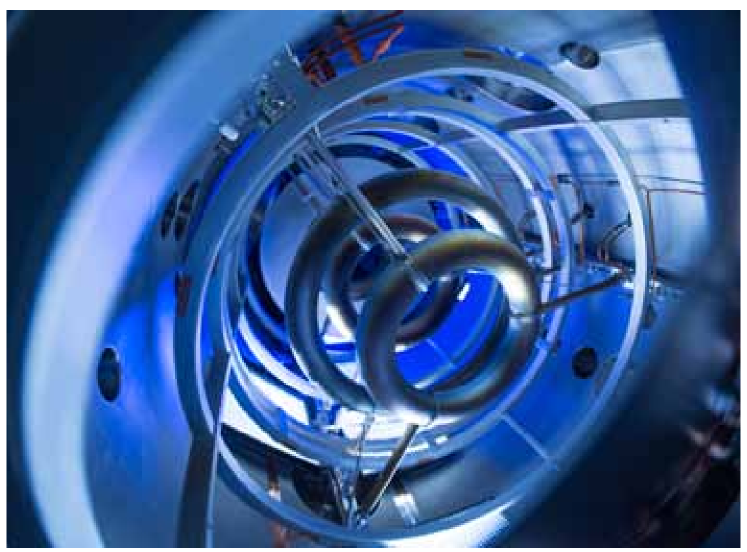
Realistically, the first attempts at reactions won't take place until 2022, even if there are no further delays. "It is challenging, because there is no other model we can refer to in managing such a big project with such huge international cooperation," he says. Yet if it works, the time it took to build the thing would quickly be forgotten. "What we say here, and what all my colleagues believe, is that we will make it, no doubt," says Claessens. "When exactly? That's an open question. But in terms of the result — we will make it."

What exactly would constitute "making it"? The ten-times yield will be considered a success, but in the process of doing that, something very interesting might happen. "Our calculations suggest that you will eventually get to a point where you don't have to put in any more energy at all," says Cowley. Really? That's because the helium that's expelled as part of the reaction would have its own kinetic energy, continuing the reaction without the need for the reactor to be externally heated.

"When you start a fire, you put a match to it: you're applying energy to get it going. But after a while, it has enough heat that you put another piece of wood on and it won't go out. ITER is like that," Cowley explains. "All you will need to do is put more deuterium and tritium in and it will keep going, self-sustained." This in turn would truly be an achievement. "It's going to be an amazing moment. From the point of view of a scientist, that's what you want to do — prove that you can make a self-sustained fusion burn."

What ITER won't do however, is produce electricity: it exists to show that the science can work. After ITER is up and running, it's likely the spirit of cooperation will splinter somewhat, as every country tries to put its expertise into practice. The EU, for example, has a clearly articulated roadmap for the next step after ITER, with the creation of a demonstration reactor, called DEMO, a functioning plant capable of making electricity from fusion. South Korea even has a law requiring it to build such a





**ABOVE:** NATIONAL IGNITION FACILITY SCIENTISTS FIRING UP 192 LASER BEAMS SIMULTANEOUSLY ONTO A SINGLE, TINY, TWO-MILLIMETRE TARGET, PRODUCING AN UNBELIEVABLE 500 TRILLION WATTS OF ENERGY — ABOUT 1,000 TIMES MORE POWER THAN THE ENTIRE UNITED STATES USES AT ANY GIVEN TIME
**LEFT:** THE MAGNETIC COILS INSIDE THE COMPACT FUSION (CF) EXPERIMENT ARE CRITICAL TO PLASMA CONTAINMENT
**RIGHT:** A CLOUD CHAMBER PHOTOGRAPH SHOWING PRODUCTION OF A PROTON AND A TRITIUM NUCLEUS

**PHOTOS:** LAWRENCE LIVERMORE NATIONAL LABORATORY (MAIN); LOCKHEED MARTIN SKUNKWORKS (LEFT); GETTY IMAGES reactor, and has cleared the land for it. China has deployed considerable resources towards the research of this and other similar energy theories. But in Europe at least, it's likely that we'll see electricity produced from nuclear fusion in the 2040s. That is, unless another method gets us there first.

## BRAZEN PREDICTIONS

Within certain aviation circles, the name Skunk Works can get the heart beating and make the hairs of the neck stand on end. Based in Palmdale, California, Skunk Works is the informal name given to Lockheed Martin's Advanced Development Programs division. Over the years it has been responsible for such iconic aircraft as the U-2, the SR-71 Blackbird and the F-22 Raptor. The former Apollo 8 astronaut Bill Anders, who as chief executive of General Dynamics once tried to buy Skunk Works, recalls: "I was lusting after them. If you owned Skunk Works, your you-know-what grew in that industry."

On October 15, 2014, Lockheed Martin came out with a quite unexpected press release. Its Skunk Works division, it said, was working on a new compact fusion reactor (CFR) that, "can be developed and deployed in as little as 10 years." To widespread astonishment from the scientific community, Lockheed Martin claimed that by miniaturising the process by 90 percent, it could produce working nuclear fusion reactors in a fraction of the time that the big state-sponsored labs of the world have discussed.

"The smaller size will allow us to design, build and test the CFR in less than a year," said Tom McGuire, compact fusion leader for the Skunk Works' Revolutionary Technology Programs team. Lockheed Martin declined an interview with *DCM*, but did provide a one-page factsheet with a diagram of a 10 metre by seven metre reactor capable of producing 100MW, or sufficient power to power 80,000 homes. "Compact fusion could be made small and light enough to fit on a large airplane," the sheet notes, "eliminating the need to refuel and giving unlimited range." This would entail burning less than 20 kilograms of fuel in an entire year of operation.

We asked Professor Cowley what he thought of the Lockheed announcement. His answer was a long time coming, and eventually accompanied by a smile. "Ballsy," he says. "Since they haven't actually got any results."

Cowley remains sceptical about the size theory —

> **"FROM THE POINT OF VIEW OF A SCIENTIST, THAT'S WHAT YOU WANT TO DO — PROVE THAT YOU CAN MAKE MAKE A SELF-SUSTAINED FUSION BURN"**

firstly due to the amount of shielding needed on either side of the reactor because of the neutrons coming out of the reaction. And secondly, because the exceptionally low temperatures necessary for the superconducting magnets Lockheed will use, would require insulation.

"Skunk Works are famous for a kind of style of doing things. 'Everybody said it was impossible and we did it anyway.' Great," he says. "I think the experiment will be interesting — it's along the lines of things we looked at in the 1960s and perhaps abandoned too quickly. But it's not a brand new idea where I sit down as a theoretical physicist and say, 'Wow, that will work.'"

Whether it works or not, it's nonetheless surely useful that the commercial world — and in particular the commercial world which services the military, often a source of technological innovation — is showing such an interest in fusion. After all, science like this costs a great deal of money, and governments won't fund it forever.

Certainly, the US is not short of enterprising people trying to

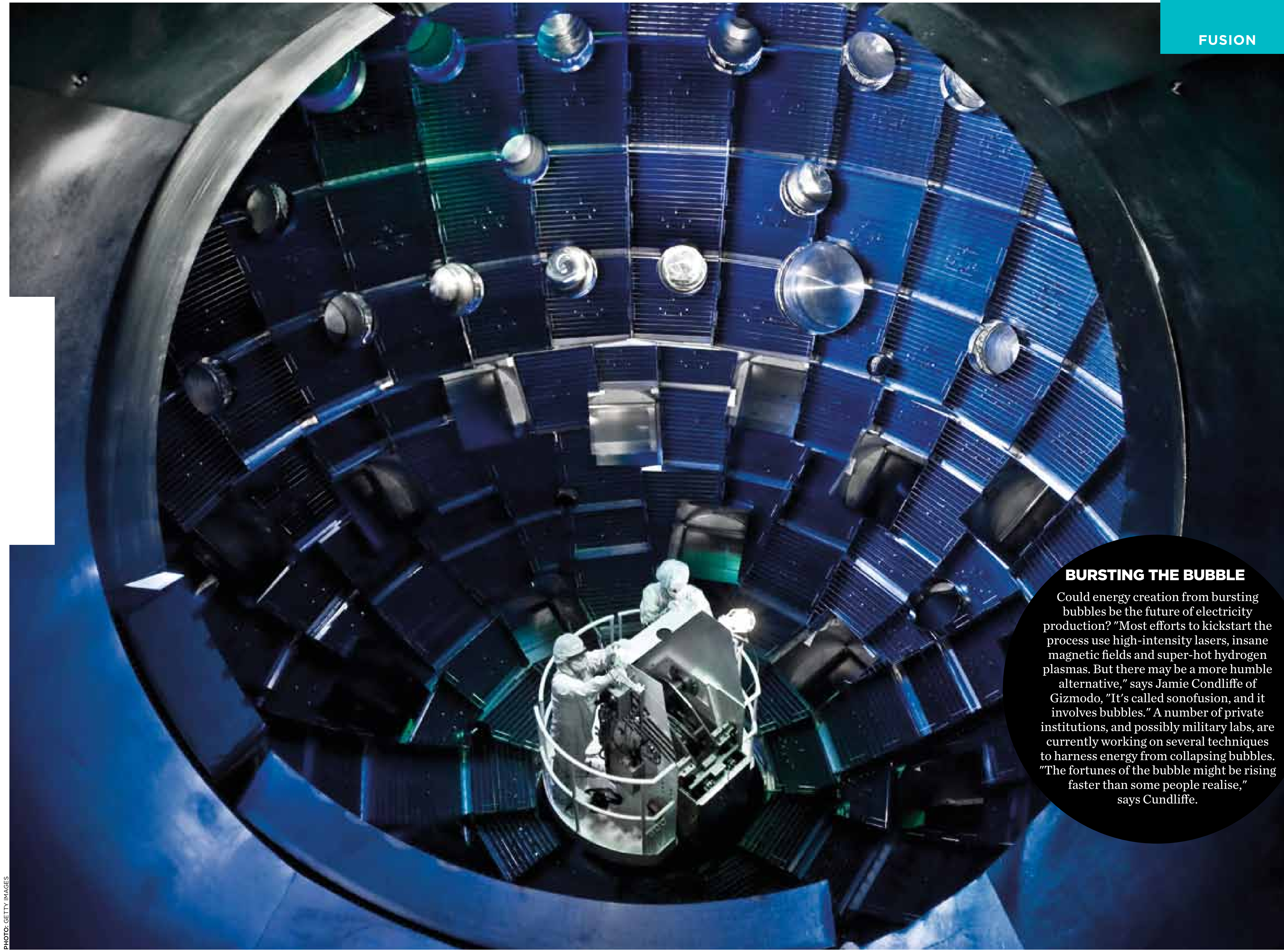


PHOTO: GETTY IMAGES

THE FUSION TARGET CHAMBER AT THE NATIONAL IGNITION FACILITY IN CALIFORNIA

### BURSTING THE BUBBLE

Could energy creation from bursting bubbles be the future of electricity production? "Most efforts to kickstart the process use high-intensity lasers, insane magnetic fields and super-hot hydrogen plasmas. But there may be a more humble alternative," says Jamie Condliffe of Gizmodo, "It's called sonofusion, and it involves bubbles." A number of private institutions, and possibly military labs, are currently working on several techniques to harness energy from collapsing bubbles. "The fortunes of the bubble might be rising faster than some people realise," says Cundliffe.

make fusion work. One of the leaders there is the National Ignition Facility (NIF) at the Lawrence Livermore National Laboratory in California. It announced in 2014 a milestone of releasing more fusion energy from a reaction than the energy that was used to confine the fuel. The NIF's model is different to JET. It involves firing a laser at a very small pellet of hydrogen fuel, contained within a gold enclosure.

The gold gives off X-rays, which squeeze the pellet down, creating what is in effect a small thermonuclear explosion. However, others point out that this positive outcome doesn't take into account the energy used in the laser, and say that in terms of true breakeven, the magnetic fusion model in use in Europe is closer to achieving it. "We are much closer,"

**"WHEN HUMANS WERE TRYING TO INVENT AN AEROPLANE, THEY HAD A NATURAL MODEL. WE DIDN'T HAVE THAT FOR A FUSION DEVICE"**

Donné affirms. He seems more impressed by what's happening in China. "With the Chinese it is very difficult to say," he notes. "But they are really moving rapidly forward."

## BRAND NEW SCIENCE

Fusion, if we can make it work commercially, will be an extraordinary scientific achievement for humanity. "There is no natural analogy for a fusion reactor except a star, and the star does it by immense gravitational field, the weight of the rest of the star pressing down on the middle of it," says Cowley. "We have to have a completely different technology than the way nature does it."

And this is unusual. "If you think of a lot of technologies, they imitate nature. A plane looks like a bird," Professor Cowley explains. "When humans were trying to invent an aeroplane, they had a natural model. We didn't have that for a fusion device."

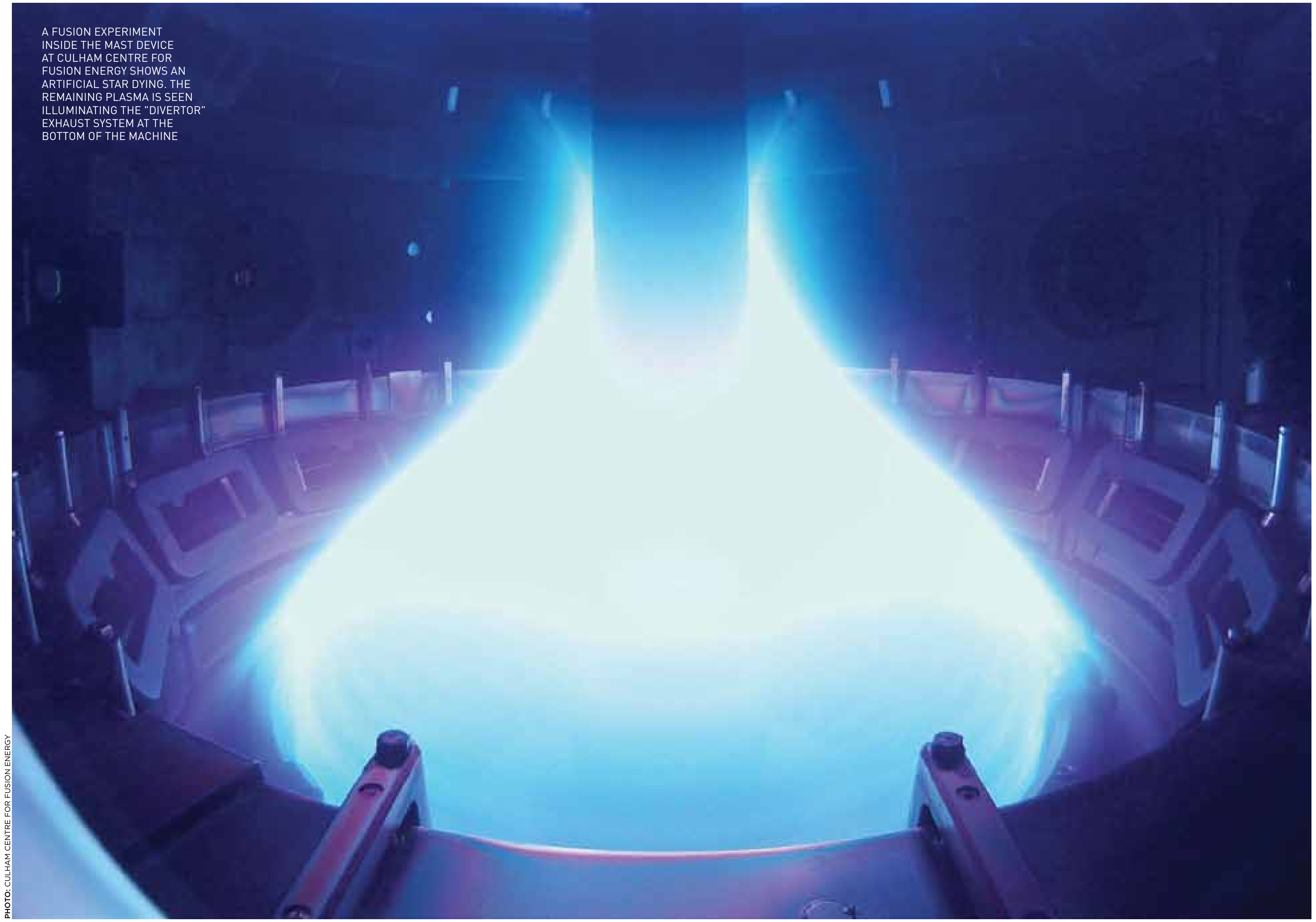
Will the sheer difficulty of achieving it be enough to persuade people to adopt it? The answer to that is going to come down to two things: money, and how scared we are about what we're currently doing to the planet.

There's no question that we need to do something. Even with fossil fuels sufficient to last us a few hundred more years, the impact on the planet of burning them all is likely to be catastrophic. A study from University College London, published in the journal *Nature* in January 2015, argues that trillions of dollars worth of natural resources, including over 90 percent of US and Australian coal, and almost all Canadian tar sands, cannot be extracted and burned if the global temperature rise is to be kept under the two degree celsius safety limit previously agreed by the world's nations.

It's possible we can bury carbon — this is what we mean by carbon capture and storage — but there are limits to that too. In an ideal world, we would stop burning fossil fuels in 20 years. And indeed, that's about the right timeframe for nuclear fusion to come on stream. But it's certainly not a given that we will all embrace this new power source.

"I worry about that phase of fusion development," says Cowley. "We'll build ITER, we will show fusion is scientifically possible, and people will just say, 'The cost of commercialising this is huge, fossil fuels are cheap, so why are we doing this?' Fossil fuels are going to be cheap for another century or two." As such it may take considerable commitment, and probably cost, to wean the world off carbon.

Cowley is also a fan of green and alternative energy. He is less bullish about wind power, which he says is only useful in some countries like the UK. But certainly, solar has strong prospects. "My view is, push on solar like crazy." He envisages a future where most energy is provided by solar, fusion, and high-breeder nuclear fission reactors.



A FUSION EXPERIMENT INSIDE THE MAST DEVICE AT CULHAM CENTRE FOR FUSION ENERGY SHOWS AN ARTIFICIAL STAR DYING. THE REMAINING PLASMA IS SEEN ILLUMINATING THE "DIVERTOR" EXHAUST SYSTEM AT THE BOTTOM OF THE MACHINE

PHOTO: CULHAM CENTRE FOR FUSION ENERGY

So far, nuclear fusion hasn't raised the ire of environmental groups. Indeed, *DCM* faced quite a challenge getting any of them to make a comment at all. If anything, there's an objection to spending more on nuclear fusion, because some doubt it can ever be commercially achieved. And there are certainly plenty of practical challenges still, chiefly around that pesky extra neutron coming from the fusion reaction.

Because it has an impact on the walls of the reactor, that inner wall will need to be replaced periodically. If that's any more frequently than every couple of years, then it will mean so many lengthy shutdowns, it won't be economic. In tandem with the development of ITER, there are plans to build another machine, probably in Japan, to work out the optimum material with which to coat the walls, in the hope that some form of steel will be found that only needs to be replaced every decade or so.

Scientists like Cowley would like us to focus on what *has* been done, not on what hasn't been done. They believe, unwaveringly, in the scientific models and extrapolations that tell them that ITER, if built properly, *will* work. It's tempting for us to dream of *Star Trek*-like warp drives that will spirit us to Mars in no time at all, and of planes that need never land. But in the meantime, we'd surely settle for a cleaner energy source — just in time to stop us obliterating the planet. ●

IN DETAIL

### ENRICO FERMI

The Nobel Institute isn't known for making rash statements without cause, so we can believe them when they write, "in 1938, Fermi was without doubt the greatest expert on neutrons." After the discovery of nuclear fusion in 1939, Enrico Fermi immediately saw the potential of going nuclear, as it were, with a chain reaction. His experiments led to the first controlled nuclear chain reaction, which took place in 1942 — on a squash court underneath Chicago Stadium

### ISOTOPES

If an atom is missing a neutron or is saddled with an extra neutron, its mass changes. This is an isotope, a variant of an element that varies in its properties, such as melting point or boiling point. Some isotopes are unstable, meaning they may decay into other elements or give off radiation. It's thanks to isotope decay, which can be precisely measured, that we are able to carbon date fossils

### TRITIUM

A radioactive isotope of hydrogen. Mix tritium with a chemical that emits light in the presence of radiation, and you get a useful source of illumination — hence why luminiscent watch dials, rifle sights and exit signs are often coated with tritium. If you look at the back label of most exit signs, you'll see a notice that says, "Caution — Radioactive Material"

### PLASMA

In physics, there are four fundamental states of matter. We're guessing you're familiar with the first three: solid, liquid, and gas. Plasma is the fourth, and differs from the other states, though it is also described as "ionized gas". A collection of charged particles that respond to electromagnetic fields, plasma is s the most abundant form of ordinary matter in the Universe