

The return of nuclear fusion?

It is still pie in the sky until they get a break through in the theoretical physics basis.

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The world's biggest nuclear fusion test reactor is about to begin construction in the hills of Provence. But with persistent doubts over fusion's capacity to generate energy efficiently and a raft of engineering conundrums, is this really money well spent?

They call themselves "fusion gypsies"—scientists who have travelled the world, moving from one nuclear reactor to the next, living the dream that some day, somewhere, they can re-create the reactions that take place in the heart of the stars to generate huge amounts of cheap, clean electricity for the world.

Their goal is nuclear power, but not as we know it. This is fusion and not fission. Fission involves mining, processing and irradiating vast amounts of uranium, and leaving behind an even larger legacy of radioactive waste with half-lives stretching into the next ice age. Whereas, say the fusion gypsies, a small vanload of fuel supplied to a fusion power station could supply the electricity needs of a city of 1m people for a year, and leave behind only paltry amounts of radioactive waste that will decay to nothing within a century.

Fission reactors split atoms to make power; fusion reactors force the elemental particles of the universe together till they fuse, releasing energy in the process. Fusion powers the sun, the gypsies say, and one day it could power the world's electricity grids too.

Fusion research got going in the 1950s. The first fusion gypsies are approaching retirement. But scientific progress has been slow and funding sporadic. They have yet to see a watt of power delivered to any grid anywhere. But earlier this year, after more than a decade in the doldrums, the gypsies had their biggest boost, when governments representing most of the world's population decided to invest \$10bn in trying to make the dream come true.

This summer, the fusion gypsies are reassembling in the wooded hills of Provence in southern France, where a new machine is to be built. Britons, Australians, Russians, Americans, Germans, Chinese, Japanese Czechs and many others are united now in a last stand to prove to the world they were right all along. John How, a bearded, sandalled Brit was the pioneer. He bought himself a farmhouse a couple of years ago in Provence in anticipation of just this moment. Now he can settle down at last, he told me, after a career stretching from Australia to Germany, France and Britain. "It's now or never for fusion power," he said.

The moment seems right. As oil prices soar, as concern grows about global warming, and as politicians balance the potential of conventional nuclear power and renewables, there is a growing need for a new source of electricity that combines the capacity of a nuclear power plant with the cleanness and safety of a wind farm. Fusion could, eventually, be the answer. Even fusion's most ardent supporters admit it will be several decades before the technology becomes commercial. But if the physics comes to fruition, it could be very big—just as the oil runs out and climate change accelerates.

In May, the governments of the EU, the US, China, India, Japan, Russia and Korea initialled a treaty to build the International Thermonuclear Experimental Reactor (ITER),

the world's largest fusion machine, in a forest at Cadarache in Provence. They will sign formally in November. Half of the money will come from the EU. ITER will take a decade to build and will then run for two further decades, performing tens of thousands of fusion experiments. At the end of that time, say its backers, the world will know once and for all if nuclear fusion has a viable future. Technically viable, that is. The economics will come later.

"This is the most significant science treaty ever signed, the world's biggest scientific collaboration," said Janez Potocnik, EU commissioner for science and research, at the initialing ceremony in Brussels. Britain's top fusion administrator, Chris Llewellyn Smith, smiled in the background. A tall, white-haired physicist and knight of the realm, he is director of the world's largest existing reactor, in the village of Culham in Oxfordshire. He says simply: "This project is of huge significance. It could lift billions out of poverty," by providing them with cheap electricity for the first time.

Not everyone is so sure. Greens dismiss the project as a "dangerous toy" and a waste of money that could be paying for thousands of wind farms. Even among physicists not everyone thinks that fusion has a future. Embarrassingly, shortly before the Brussels ceremony, America's leading research journal *Science* published the posthumous testament of one of fusion's pioneers, William Parkins, who concluded that "the history of this dream is as expensive as it is discouraging." The US alone, Parkins said, had spent \$20bn on the fusion quest over 50 years, without result. It was time to write off the venture. The journal's editor publicly backed the conclusion. As of May, the world is engaged in a game of double or quits to prove them wrong.

How might fusion work?

To see fusion in action, go to Culham in Oxfordshire. As well as being the largest, the fusion reactor known as JET (Joint European Torus) is, by common consent, the world's most successful. It is the prototype for the ITER machine, standing 20 metres high and surrounded by an acre of equipment on the site of the British Atomic Energy Authority.

It cost €1bn to build and so far, over its 23-year life, has cost another €1bn to run. It has at times soaked up half of Britain's entire government budget for energy research.

The reactor is constantly doing experiments into the more abstruse physics of how to make fusion happen, how to control it and how to do it better. Its greatest moment came in 1997 when, for a fraction of a second, the reactor produced 16.1 megawatts of electricity, which is still a world record. Headlines went round the world, though few mentioned that it took 25 megawatts to heat the reactor, and even more to run the other bits needed to keep it going, just for that fraction of a second.

The fact is that the Culham reactor, far from producing power, is by some way Britain's biggest single electricity user. During a typical experiment, of a kind undertaken several times a night and some 66,000 times in its history, the plant briefly consumes up to 2 per cent of all the electricity capacity available in the country. Its proximity to Didcot power station is probably no coincidence.

So what happens inside this extraordinary machine? Superficially it is a gas-burning boiler. But it is a boiler that requires only a tiny amount of nuclear fuel—about a gram at any one time—to generate vast amounts of energy. The fuel is made up of two isotopes of hydrogen, known as deuterium and tritium. The former is extracted from ordinary water. The latter, which is mildly radioactive, can be collected from the waste streams of some nuclear fission reactors, manufactured from lithium, a relatively common metal, or

generated inside the fusion reactor itself. The purpose of the reactor is to burn these two isotopes at super-high temperatures, generated by the world's hottest microwave oven. Heated enough, they form a plasma—a superheated gas—and fuse together. When that happens, they create another element, helium, plus large amounts of energy.

In practice, it's not that simple. Fine-tuning how it is done has become a life's work for some of the world's best minds. And even now, after 50 years of experiments, researchers have still never generated more energy than they need to fire up the microwave oven.

One problem is that, while deuterium and tritium fuse more easily than any other atoms, to make the reactions happen on earth still requires temperatures of 100m degrees Celsius. That is ten times hotter than the sun, which has huge gravitational fields allowing fusion to occur more easily. Another difficulty is that to maintain that temperature and sustain the fusion reactions, it is necessary to prevent the hot plasma from hitting the reactor wall, which will slow and cool everything down. This is done by making the reactor doughnut-shaped, so the plasma can flow endlessly round, and by installing the world's most powerful magnets to maintain a magnetic field 10,000 times stronger than the earth's.

This basic design, called a Tokamak, is a Russian invention—developed in the 1950s by Andrei Sakharov, the dissident and father of the Russian H-bomb. But his machines were small. As scientists have built larger ones, they have found that Sakharov's simple presumptions about how plasmas work break down. Instabilities break out in the plasma—like solar flares round the sun—that no computer can predict. Hence the large number of experiments, whose purpose, says Llewellyn Smith, is "to learn how to control the hot gas."

ITER is the next step up in size—twice as high and with ten times the volume of Culham. That means it should, at last, allow fusion researchers to generate more energy than they consume. Ten times more, according to How, who wrote the design specs. "It's like a teapot," he says, "the bigger it is, the better it retains heat." But the extra size may also create new problems in the operation of the plasma.

The instabilities in the plasma are not the only problem. In this world of extremes, some of the most pressing questions concern what the reactor should be made from. What kind of materials can best withstand the huge forces being placed on them inside the reactor: temperature gradients that some believe are greater than any in the universe; shock waves from hundreds of megawatts of energy travelling at a fifth of the speed of light; and magnetic fields 10,000 times greater than any experienced on earth?

"No one has ever subjected materials to these conditions," says Llewellyn Smith. Most believe that if the project fails it will be because of the engineering of materials rather than failures of basic physics.

These extreme conditions mean that JET can only create its super-high temperatures for 30-40 seconds before the whole apparatus has to be cooled down to prevent it shattering. ITER will have magnets cooled close to a temperature of absolute zero, because at those temperatures they become "super-conducting," and don't heat up so much. Researchers hope to be able to run it for half an hour or so at a time. But even that will not be anything like enough for commercial reactors.

That is why, in parallel with ITER, another international agreement will fund a \$1bn research centre in Japan, where new materials that can stand the extremes of a commercial reactor will be developed. Hopefully.

And if all goes, well, the technology could head in other interesting directions. A recent proposal would not connect fusion reactors to electricity grids, but rather use them to provide the large amounts of energy needed to manufacture hydrogen fuel for shipping round the world. This "fusion island" proposal could kickstart the much-discussed "hydrogen economy."

All this has been a long journey. ITER was first proposed as a successor to JET back in the mid-1980s, as part of efforts to thaw the cold war through science. Mikhail Gorbachev and Ronald Reagan agreed on a joint project to develop fusion power for the world. But through the 1990s, with oil prices low, Russia in economic free fall and interest in all things nuclear undermined by Chernobyl, governments backed off investment in fusion.

The US pulled out of the ITER project altogether in 1998, citing worrying scientific research that suggested turbulence inside the plasma would prevent fusion ever being generated for long periods. Since then, new research suggested the turbulence problems had been exaggerated, and the US rejoined the project in 2003. But William Parkins is not alone in claiming that nobody yet has answers to a series of technical conundrums: how to remove heat efficiently from the reactor vessel; and what, if any, materials would stop the vessel becoming either brittle or leaky. Nor is he alone in suggesting that there may be no answers. The physics may be good, he said, but the engineering will probably never work.

Publicly, the physicists say the science is all over bar the shouting. But one senior researcher at ITER may have given the game away when he told a room full of journalists in May: "We think it's going to work. We have to, or the politicians wouldn't give us the money."

What are we to make of this? One respected commentator has said that there may be a 20 per cent chance of the world getting 20 per cent of its electricity from fusion by 2100. Llewellyn Smith, while thinking the chances are rather better than that, says that even such long odds would represent a worthwhile gamble for the world, notwithstanding the opportunity costs. The director of the science office at the US department of energy, Raymond Orbach, says: "We think that fusion will, by the end of the century, be producing 40 per cent of the electricity produced in the world today," which would represent about 15 per cent of the total electricity demand in 2100.

But that is a long way off. There are several big steps along the way. If ITER, over the next 30 to 40 years, fails to demonstrate that fusion can generate an order of magnitude more power than it uses, then the whole programme, which by then will be almost a century old, will finally have to be abandoned. And the tens of billions of dollars spent on it blamed on overambitious physicists.

John How is familiar with the long history of delays to fusion research, and he smiles grimly at a ritual re-telling of the old industry joke: commercial fusion power is 40 years away, and always has been. "I've been in this for 40 years," he says. "The current timetable is very, very ambitious. I'd say commercially viable fusion energy is 100 years away still."

Maybe so. But the dream is alive again. And the fusion gypsies are back on the road and headed for the south of France.

Is it safe?

Unlike fission, fusion is intrinsically safe, say its promoters. There are no runaway reactions and only minimal radioactive waste. There are, it is true, health and safety issues for workers. At Culham, everybody is cleared out of the main building containing the reactor during actual operations, because radioactivity does invade the sealed area, though it decays quickly. At ITER, where the radioactivity will be higher, the plan is that only robots will go in. But if anything goes wrong in the reactor, the reactions simply stop within a few seconds.

After the machine is dismantled, some of its scrap metal will be radioactive. The design aim is to ensure this has decayed to safe levels within 100 years, so there are no long-term disposal issues; engineers seem confident this can be done. The main radioactive ingredient, tritium, is used only in small quantities and has a half-life of 12 years.

Is there a doomsday scenario? "If you flew a plane into the JET reactor, the worst that would happen is the release of about a gram of tritium," says Llewellyn Smith—though there is another 20 grams on site. In Provence they say that the worst possible accident might lead to the local village being evacuated for a few years.