craft fell out of orbit and burned up with the chipsats still in its hold.

"I was a little bummed out," says Zachary Manchester, an aerospace engineer who built the satellites as a doctoral student in aerospace engineering at Cornell. Fortunately, enough spare parts were lying around to make a second batch relatively quickly and easily.

The chipsats, called Sprites, carry little more than a pair of 60-milliamp solar cells, a radio and an antenna. The KickSat-2 payload includes some newer Sprites that can 'sail' by tilting towards or away from the Sun. A current is run through a coil, turning the chip into a compass needle that aligns with Earth's magnetic field, allowing the chipsat to control its orientation. The probes can be reprogrammed on the fly from the space station.

Sprite prototypes have already proved that they can survive the rigours of space. In 2011, three chipsats were attached to the outside of the space station. They were still working when scientists retrieved them in 2014.

That commercial electronics are good enough to survive space's vacuum and extreme temperatures is a "pretty big deal", says Mason Peck, an aerospace engineer who leads Cornell's chipsat team. But on a flight into deep space, chipsat electronics would face a high risk of damage from radiation. "There are some clear paths to radiation hardening, but it's expensive," says Peck. "And that's not the point. You don't want to make an exquisite satellite. You just launch a million; if only 1% survive then that's fine. You put statistics on your side."

There is plenty of science that Sprites can do closer to home. Peck says that the tiny satellites could be used to verify models of how small bits of debris behave in the upper atmosphere. Like feathers on Earth, the small, flat objects would be heavily affected by drag. "We're not very good at modelling that," says Peck. Another potential project would be to use Sprites to make a high-spatial-resolution map of Earth's magnetic field.

"That would be really useful," agrees Jeffrey Love, a geophysicist with the US Geological Survey in Denver, Colorado, who studies Earth's magnetism. "Ideally you'd want to be measuring it everywhere all the time. This could be a step in that direction."

For the long-term interstellar goal, chipsats will need much better laser-communication capacity. That should be possible, say Peck and Manchester, who are both on the Breakthrough Starshot advisory committee.

"We have gone a long way towards proving we can have a functional tiny craft," says Peck. ■

MATTHIEU COLIN/ITER

The gigantic ITER project is currently under construction in southern France.

NUCLEAR PHYSICS

US urged to stay in fusion project

Department of Energy says US should fund ITER until 2018.

BY DAVIDE CASTELVECCHI & JEFF TOLLEFSON

The troubled nuclear-fusion experiment ITER has received a cautious vote of confidence from the US Department of Energy (DOE). The multibillion-euro project has improved its performance and management, and the United States should continue to support it, at least until 2018, the DOE said in a report to Congress released on 26 May. But after that, the agency said, the country should re-evaluate its position.

ITER is a collaboration between the European Union, China, India, Japan, South Korea, Russia and the United States. Its goal is to show that fusing hydrogen nuclei to make helium — the same process that heats up the Sun and powers hydrogen bombs — is a technologically feasible way to produce electricity.

The reactor is under construction in St-Paul-lez-Durance in southern France, but the work is more than a decade behind schedule, and its costs have spiralled. The latest report comes against a backdrop of criticism directed at ITER's former management.

The DOE acknowledges ITER's scientific potential, and the substantial improvements since current director-general Bernard Bigot took over in March 2015. "ITER remains the best candidate today to demonstrate sustained burning plasma, which is a necessary precursor to demonstrating fusion energy power," US energy secretary Ernest Moniz writes in the report's introduction. But the agency says that the progress "must be balanced against several years of inadequate performance". Its recommendation to continue US funding for ITER is contingent on continued and sustained progress on the project, increased transparency and a suite of management reforms.

"I think it's an outstanding report that says all of the right things," says William Madia, a former director of Oak Ridge National Laboratory in Tennessee who led an independent review of ITER in 2013. That report excoriated the way in which ITER was run, and proposed reforms to save it from failure — recommendations that ITER's governing council embraced.

Madia says that the DOE is appropriately encouraged by recent management changes, and appropriately cautious about whether the project is actually back on track. "Bernard is doing a terrific job, but, my goodness, he's got a lot of work to do," he says. Bigot acknowledges this, and says that the DOE's conclusions are the most he could have hoped for at this point: "We know there is still a long way to go."

The DOE is a major funder of fusion research. But although the United States is bound by an international treaty to provide its share of ITER's costs — a relatively small 9% of the project's budget — it cannot meet its contributions if Congress does not approve them.

GROWING BUDGET

The report's recommendations have provoked scepticism on Capitol Hill. Senator Dianne Feinstein of California, the highest-ranking Democrat on the Senate panel that oversees DOE spending, says that the United States cannot afford to keep pace with ITER's growing budget. The DOE estimates that the country's annual contribution, currently US$115 million, will more than double by 2018.

Last year, the Senate proposed to end support for ITER, but backed down during final negotiations with the House of Representatives. This year, it is not clear that ITER will win a reprieve. On 12 May, the Senate approved an energy-funding bill for fiscal year 2017 that cut all spending on ITER. And on 26 May, the House rejected its own 2017 energy-spending bill, which included money for ITER.

Without the United States, ITER would probably survive, says Mark Koepke, a plasma physicist at West Virginia University in Morgantown who leads a government advisory panel on fusion research. But in April, Bigot told US lawmakers that the country's fusion expertise would be difficult to replace. Madia says that the effect of a US exit is impossible to predict: "It makes good cocktail conversation, but no one knows what would actually happen."

"ITER remains the best candidate today to demonstrate sustained burning plasma."

ITER's approach to fusion is to trap heavy isotopes of hydrogen in a doughnut-shaped vacuum vessel called a tokamak and heat them to 150 million °C. This should force their nuclei to fuse, releasing vast amounts of energy. Other tokamaks exist, but ITER would be the first to release substantially more energy than was put into the hydrogen plasma.

Begun in 2007, the project was originally due to be completed in 10 years for €5 billion (US$5.6 billion). Observers say that under previous director-general Osamu Motojima, who was in office from 2010 to 2015, the experiment was in denial about slipping deadlines and witnessed a drop in staff morale. After the independent review by Madia, the ITER Council accelerated the transition to a new director-general, nominating Bigot, a French nuclear physicist with extensive management experience, in late 2014.

By November 2015, Bigot's team had presented a revised timetable for the project, and estimated that it would cost an extra €4.6 billion to bring to completion. The team said that the earliest possible date for getting hydrogen plasma to run inside the machine was 2025, and that it would take several more years to inject the heavier hydrogen isotopes tritium and deuterium, and achieve fusion.

In April, an external review from the ITER Council Working Group confirmed that progress had been made on the recommendations of the Madia report, and that the new management had been realistic about the earliest possible date for plasma. But it pointed out that the estimates of costs and the completion date did not take into account possible contingencies.

The latest DOE report recommends funding the cost increases cited by Bigot, but remains sceptical about the schedule. It outlines two funding scenarios: one based on achieving first plasma in 2025, and a more realistic scenario that pushes the date back to 2028.

Bigot's team also proposed a more modest plan, which achieves first plasma on time but delays fusion. This should save money by postponing the parts of construction that are not needed for first plasma, but no one has yet calculated how much. ■

MATHEMATICS

Maths proof smashes size record

Supercomputer produces a 200-terabyte proof — but is it really mathematics?

BY EVELYN LAMB

Three computer scientists have announced the largest-ever mathematical proof: a file that comes in at a whopping 200 terabytes, equivalent to all the digitized text held by the US Library of Congress. The researchers have created[1] a 68-gigabyte compressed version of their solution — which would allow anyone with about 30,000 hours of spare processor time to download, reconstruct and verify it — but a human could never hope to read through it.

Computer-assisted proofs too large to be directly verifiable by humans have become common, as have computers that solve problems in combinatorics — the study of finite discrete structures — by checking through umpteen individual cases. Still, "200 terabytes is unbelievable", says Ronald Graham, a mathematician at the University of California, San Diego. The previous record-holder is thought to be a 13-gigabyte proof[2], published in 2014.

The puzzle that required the 200-terabyte proof, called the Boolean Pythagorean triples problem, has troubled mathematicians for decades. In the 1980s, Graham offered a prize of US$100 for anyone who could solve it. (He presented the cheque to one of the three computer scientists, Marijn Heule of the University of Texas at Austin, last month.) The problem asks whether it is possible to colour each positive integer either red or blue, so that no trio of integers a, b and c that satisfy Pythagoras' famous equation $a^2 + b^2 = c^2$ are all the same colour. For example, for the Pythagorean triple 3, 4 and 5, if 3 and 5 were blue, 4 would have to be red. ▶

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