What goes up...

How is NASA is planning to decommission the International Space Station? And what will replace it, asks **Jon Cartwright**

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THE International Space Station (ISS), as well as being the most expensive object ever made, can also lay claim to being one of the most cooperative endeavours in scientific history. Since the beginning of the century, it has been continuously inhabited by a total of 280 crew members – and counting – from 23 countries. While leaders on the ground have been squabbling or even threatening war, astronauts and cosmonauts have been circling Earth unconstrained by geopolitical borders, floating in serene microgravity.

But nothing lasts forever. Sometime around 2030, the ISS project will come to an end. From its orbit about 400 kilometres above Earth, the space station will fall through the atmosphere, burning up and splintering into a thousand pieces before crashing into the Pacific Ocean. It is unlikely that any of it will ever be seen again.

Artificial satellites reenter the atmosphere all the time – almost every day, in fact. But the $150 billion ISS is no ordinary satellite. More than 100 metres long, and with the mass of a fully loaded jumbo jet, it is by far the largest and most complicated one ever built.

Managing the end of the ISS's life is far from straightforward. How can such a cumbersome object, all 420,000 kilograms of it, be brought down and destroyed safely? Should it be destroyed at all? And will we ever see its ilk again?

The history of the station dates back to the cultural chauvinism of the 1980s, when NASA – calling it "Freedom" – intended it to challenge the Soviet space station Mir. By the early 1990s, however, warmer post-Soviet-era relations between the West and Russia laid the groundwork for a more collaborative project, involving not just NASA and Russia's space agency Roscosmos, but also the European Space Agency (ESA), the Canadian Space Agency and the Japan Aerospace Exploration Agency. Amazingly, this spirit of cooperation has lasted despite political tensions – recent years included, when Russian contracts have been cancelled on almost every other joint aerospace project due to the invasion of Ukraine.

Theoretically, the ISS could keep going, receiving more astronauts and continuing to be a site for more of its famous low-gravity experiments (see "Out of this world", page 38). Alternatively, it could be boosted into a higher orbit, to live on indefinitely without the need for more propellant. Two years ago, Greg Autry, a senior space strategy adviser to former US president Donald Trump, argued that this would preserve it as a space museum – "an attraction for space tourists or even students on space field trips".

Neither of these options would be a good idea, according to a white paper published by NASA earlier this year. By 2030, most of the

components will have already exceeded their original structural lifetimes with ever-increasing risks of failure. At higher altitudes, there is also a greater risk of collision with space junk. A big impact could blow the ISS to smithereens, unleashing so much debris that it would render any low Earth orbit uninhabitable for centuries.

The only way is down

Other space enthusiasts have suggested the ISS could be dismantled, with the pieces either returned to Earth or repurposed for the next habitable space station. Alas, this too is pie in the sky. Building the space station took dozens of rocket launches, mostly with the now-defunct space shuttle, and more than 160 space walks. Today, it consists of 16 pressurised modules – including living quarters, laboratories, storage bays and airlocks – as well as solar panels, radiators, return vehicles and much more besides. Think of a Lego model the size of an American football field, and you aren't far off. Dismantling this humongous structure could be just as costly as reassembly, and no states today have $150 billion burning a hole in their pockets.

So, down it must go. There are, however, good deorbits and bad deorbits. The end of Skylab, NASA's first crewed space station, was a bad one. In 1979, after its altitude had been waning for months, the 75-tonne structure was sent into a dive to finally disintegrate in Earth's atmosphere, but with little control over precisely where. Debris fell over the Indian Ocean, as hoped, but also over populated areas of Western Australia. No one was hurt, although the small own of Esperance in that region did charge NASA a small fee for littering.

A much better deorbit was that of the 130-tonne space station Mir, which Roscosmos neatly disposed of in the Pacific in 2001. It splashed down in a tract of water officially known as the South Pacific Ocean(ic) Uninhabited Area – aka the "spacecraft cemetery", which has been the final resting place for upwards of 250 satellites over the years. Roughly midway between New Zealand and South America, it is so remote that the closest people to it are often, in fact, on the ISS as it passes overhead every hour and a half or so.

Still, hitting this bullseye isn't easy. In a low Earth orbit, a satellite is travelling at 7.8 km per second relative to the ground below, or about eight times the speed of a rifle bullet. By the moment of impact, its debris may have slowed to as little as 270 metres per second, but a lot of ground – or sea – can be covered in the interim. That is especially true ›

in the case of a Skylab-type reentry, where drag from the rarefied upper atmosphere causes a satellite to spiral inwards gradually, with a shallow angle of descent, an unpredictable impact zone and a long debris trail. To shorten the debris trail and have control over the satellite's impact zone, you really want the descent to be as steep and swift as possible.

That means deliberately throwing its orbit out of kilter – in effect suddenly shifting its centre away from Earth so that at some point the satellite no longer tries to go around the planet, but through it. For Mir, a docked Russian cargo vehicle called Progress successfully performed this manoeuvre with three big burns of its engines. But the ISS has more than treble Mir's inertia. "You need the right amount of oomph in a short amount of time," says Jonathan McDowell, an astronomer at the Harvard-Smithsonian Center for Astrophysics in Massachusetts who monitors satellite launches and reentries. "And the amount of oomph you need for a 400-tonne space station is pretty high." For a deorbit, the ISS could dock with three Progress vehicles, but to save enough propellant, flight controllers would need to rely on atmospheric drag for the first third of the descent, before firing up the engines.

This is where it gets tricky. The atmosphere isn't entirely predictable: the weather on Earth, as well as "space weather" – chiefly the stream of particles from solar activity – can alter the degree of resistance, potentially causing a spacecraft to tumble out of control and break up prematurely. Engines can stabilise it, but this steals propulsion from the deorbit manoeuvre.

By this point, the ISS would have descended below a point of no return, unable to reboost back to its original orbit and try again. Should anything go wrong – a system failure, say, or an impact with space debris – it might go off course, and there would be nothing anyone could do about it.

Perhaps riskiest of all would be relying on Russian-made vehicles. In 2021, a year before the invasion of Ukraine, Russian officials considered withdrawing from the ISS programme early. Then, last year, they changed their mind. Possibly uncertain of its biggest partner's commitment, NASA tendered out an $843 million contract for the supply of a dedicated deorbit vehicle – a contract that was won in June this year by US private firm SpaceX. No details about the vehicle have currently been released, but McDowell believes it is likely to be a modified version of one of its Dragon modules, which have already visited the ISS more than 40 times.

Of course, nothing is foolproof. "The nightmare scenario is that the burn fails halfway through," says McDowell. "[That means] you're going to reenter in the next two or three days, but you don't know where... You'd expect maybe 40 to 100 tonnes of debris would survive to the surface, with a risk to life and property."

Up in flames

NASA and its partners prepare for all sorts of contingencies, making this scenario highly unlikely. A much more delicate issue is how anyone is going to manage this as a PR exercise. Just when relations between the old cold war adversaries are deteriorating, "you've got the biggest ever Russia-Western project burning up in flames over the Pacific", says McDowell. "That's quite a metaphor." (NASA didn't make anyone available for interview for this article.)

The ISS has come to symbolise how

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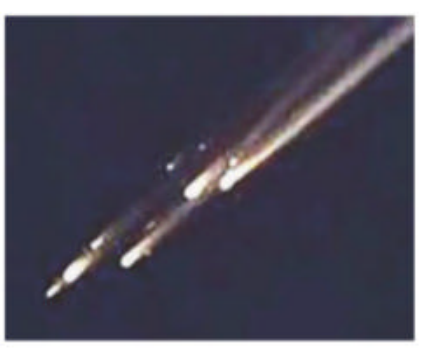

NASA

After its deorbit, chunks of the Skylab station were found on land (left). The Mir station (below) burned up and splashed down into the Pacific Ocean

Out of this world

Since the inception of the International Space Station (see main story), visitors have performed more than 3000 experiments in the satellite's microgravity and heightened radiation. Here are four of them.

Artificial retinas

For millions of people with degenerative conditions affecting the retina – the layer of light-sensitive cells at the back of the eye – there is no cure, only ways to slow progression. US-based company LambdaVision has created an implant to mimic the function of the retina, however, by depositing layers of a light-activated protein. On Earth, solutions tended to clump, but much better results came early this decade in the microgravity on the ISS.

Invisible flames

Aboard the ISS, flames look rather different to those on Earth. With little gravity, oxygen can only diffuse into the flames, so they spread gradually and persist for much longer – even after they appear to die out. In experiments beginning in 2009, ISS researchers discovered that these invisible flames continue to burn, but at relatively cool temperatures of 200°C to 500°C. The hope is that on Earth, this can be recreated and used to burn diesel more efficiently.

The ageing process

Astronauts in microgravity lose muscle mass and bone density and their immune systems deteriorate, almost like an accelerated ageing process. ISS experiments use this environment to study ageing in rodents. These include hardware to measure bone density, map the function of the immune system, explore the blood-brain barrier and chart liver metabolism. The data could one day feed into treatments for conditions like osteoporosis, muscular dystrophy and cancer.

Biomining

On Earth, microbes can be used to extract rare earth metals that are vital to modern technologies, but scientists assumed gravity was integral to the process. In 2020, however, data from ISS experiments found at least one microbe, Sphingomonas desiccabilis, can leach rare earth elements just as well in microgravity. Biomining could be a way to harvest materials for human settlements on future lunar or Martian bases.

NASA JOHNSON

Growing plants on the International Space station

humans can transcend politics on Earth. It remains the only place in the universe where a US service member can have a commanding officer from the Russian military. For astronauts and cosmonauts aboard the ISS, this has been an eye-opener. "When you're looking down from above, I'm sorry, but there are no borders," says Frank De Winne, a former ESA astronaut and current head of the European Astronaut Centre. "They are imaginary lines that we as human beings have drawn on a map, and we fight over them."

Assuming we can agree on how to bring the ISS down, will anything like it be possible again? Certainly, the prospects of a future US-Russia collaboration look grim, says Cathleen Lewis, a curator at the Smithsonian National Air and Space Museum in Washington DC. She is even doubtful that Russia will be able to gain a similar status with China, which finished its own space station, the 100-tonne Tiangong, in 2022. Like their ISS counterparts, most of the Tiangong crews have been performing experiments, although China is also considering visits for tourists.

"The Russians have sacrificed their space legacy on a fantasy [by invading Ukraine]," says Lewis. "It's especially sad for those people involved in the programme." As for the war itself, she and her former Russian colleagues avoid the topic. "We mostly just share puppy and grandchildren pictures," she says.

> "The biggest ever Russian-Western project burning up in flames over the Pacific – that's quite a metaphor"

Times are changing in other ways, too. With the rise of national space programmes in China, India and Japan, NASA isn't the unrivalled global leader it once was. Indeed, the next front-runner might not be a national agency at all, but a private company like SpaceX. For instance, US-based firm Axiom Space is hoping to attach its own modules to the ISS and detach them before the deorbit, so that they can become a freely orbiting "hotel", with architect-designed interiors – though many are doubtful of its business case.

When the ISS goes down, it may have the air of a royal funeral, with all of the collective mourning and the anxiety of what the future will bring. And, as at a royal funeral, there will also be those who question whether the deceased was worthy of the fanfare. "Thirty years into the space station programme, it's still very controversial," says McDowell. "A lot of the promises about scientific developments never really panned out... It's had a rocky road, and they forged ahead. But it never really captured the public imagination the way that the moon landings did, or even the space shuttle for that matter."

Whatever the legacy, it is too late now to change it. The final ISS crew will probably depart in the next couple of years, during the first phase of natural orbital decay. Around 2030 – the precise date isn't yet known – SpaceX's vehicle will dock and provide the singular thrust that both disrupts the station's orbit and sounds its death knell.

Within hours, the altitude will have dropped to 120 km. Here, the fast-thickening atmosphere will create a headwind strong enough to rip off the station's solar panels. Another 20 km down, the core modules will rupture, tearing through the heavens at temperatures high enough to melt titanium. To anyone on the right side of Earth, the spectacle will look like a cluster of missiles shooting across the sky, diminishing in number as, one by one, they disintegrate.

Finally, whatever doesn't burn up entirely will (hopefully) pierce the surface of the remote Pacific in a hail of scalding debris, then sink. As an official Russian press release put it when Mir deorbited, the ISS – and everything it stands for – will then "cease to exist".

Tim Braithwaite, the Canadian Space Agency's main liaison at NASA's Johnson Space Center in Houston, Texas, expects some tears to be shed. He began working on the ISS in 1990, developing a 17-metre-long robotic arm for it. While, like everything else, this is destined to be either vaporised or lost on the seabed, he insists its "DNA" will be preserved.

"By the 2030s, people will be thinking of moon bases," he says. "They will be standing on our shoulders, just as we stood on the shoulders of the folk behind the space shuttle and Skylab – and Mir." ▮

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