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THAMES TIDEWAY TUNNEL

HORIZONTAL TAKE-OFF FOR SATELLITES

PLASTIC TRUMPETS

SOLAR EXPLORER

ROYAL ACADEMY OF ENGINEERING

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Front cover

An artist's impression of the Solar Orbiter facing the Sun. See page 25 for the full article.

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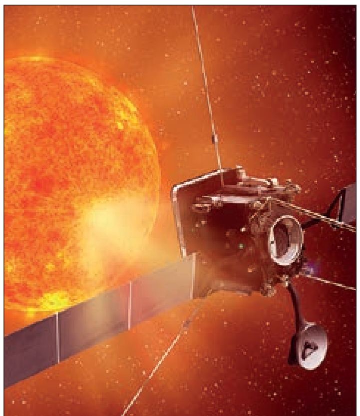

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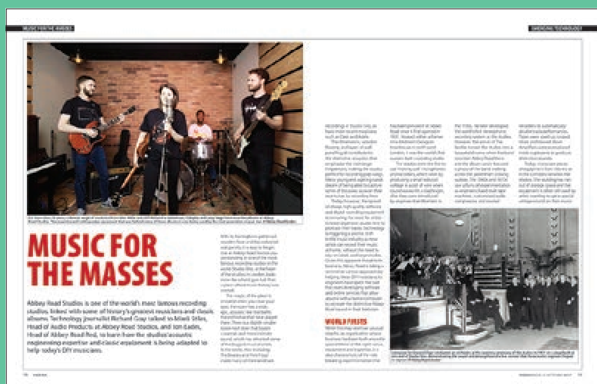
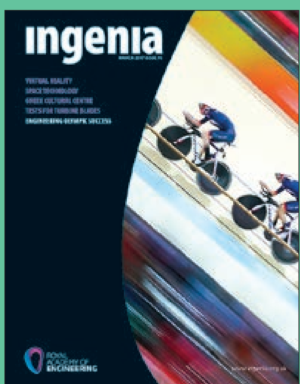




Ingenia publishes stimulating and informative articles about all aspects of engineering and technology, from robotics and data to the latest in renewable energy and medical technologies. It produces authoritative yet accessible content, aimed at engineering enthusiasts from 10 to 110, including students, engineering undergraduates, engineers at all levels, and academics.

To subscribe to receive a free copy each quarter, please visit **www.ingenia.org.uk**

EDITORIAL

WEDDED TO ENGINEERING

Scott Steedman CBE FREng

Few engineers can be satisfied with the public perception and understanding of the profession and the role it plays in solving society's challenges. So World Engineering Day for Sustainable Development (WED) deserves our support and attention. Proposed by the World Federation of Engineering Organisations and endorsed by UNESCO last November, the 4 March every year is set to become WED, with the very first WED having just passed. The plan is that industry and engineering organisations around the globe will run events to raise awareness of the importance of engineering and promote it as a career under the slogan, "If you want to change the world for the better, become an engineer."

WED comes at a time of growing interest in the UN's Sustainable Development Goals (SDGs) across governments, businesses and the public. The associated events will showcase the role that engineers and engineering must play if we are to make real progress in achieving those goals by 2030, the date agreed five years ago by all UN member states.

This year, many institutions held events to celebrate. In the UK, the Engineering and Physical Sciences Research Council hosted a workshop on lessons from the work over recent years on 'Global Grand Challenges'. The Academy also held a two-day conference at Prince Philip House on 3 and 4 March where industry, educators and policymakers debated the importance of taking a new approach to engineering education. The event also coincided with the launch of a new set of films as part of the Academy's successful *This is Engineering* campaign that showcase how engineers can make a difference in the world.

There is a growing sense that engineers need to do more and do it more quickly. After all, it is five years since the SDGs were agreed and only this year did we see the first World Engineering Day for Sustainable Development. There are many technical options for addressing the SDGs, the challenge is to deploy those engineering solutions at large scale around the world. That means tackling non-technical challenges that engineers face in solving these contemporary problems, not least the political hurdles. For example, in the UK the long running argument over whether to invest in the High Speed 2 (HS2) rail link, a decision that eventually required the intervention of the Prime Minister, illustrates just how sensitive the court of public opinion can be, even in connection with something as familiar as a railway project. The decades of political arguments over HS2 will seem simple alongside the decisions needed to address the SDGs.

To coincide with WED, the Academy published its first *Global Engineering Capability Review*. Commissioned from the Economist Intelligence Unit, the review provides a broad assessment of the engineering strength of 99 countries, using a new Engineering Index that measures the capability of nations to conduct engineering in a safe and innovative way. (The review also includes a detailed analysis of the strength of engineering in China, Colombia, Ethiopia, India, Jordan and Thailand.)

A key point that the review, and WED, try to make is that we need to think more broadly about what engineering really is. Are we constrained by a view of engineering that is too narrow, or too traditional?

The digital economy is frequently hailed as a development that will transform the breadth of engineering, linking everything to everything else, enabling the rise of what has been dubbed the Fourth Industrial Revolution. The impact of the digital economy in Africa is already enabling countries and industries to leapfrog traditional development pathways, connecting suppliers and markets, people and products in previously unimaginable ways. This bodes well for the rapid deployment of new technologies to tackle the SDGs.

The second game-changer that engineers need to be more engaged with is finance. The past year has seen an upsurge of interest in 'green finance' or more broadly, 'sustainable finance'. This is an important new lever for engineers to use in pursuit of innovation and change. Fund managers see sustainable investment becoming the norm, which in turn will drive new markets for sustainable engineering. Be it climate change, zero hunger, good health and wellbeing, clean water and sanitation or any of the SDGs, financial services hold the purse strings. WED must be about more than technology and education, it needs to embrace the worlds of finance and investment, not to mention politics.

Scott Steedman CBE FREng
Editor-in-Chief

IN BRIEF

SURFING IN BRISTOL

The Wave's 180 metre long surfing lake produces a range of wave heights from 50 centimetres to almost two metres © Global Shots

Opened in November 2019, a £25 million project in Bristol is providing surfers with up to a thousand waves an hour of varying sizes and shapes.

The Wave, an open-air surfing venue located three miles inland from the Severn Estuary, is a 200-metre-long cove-shaped lagoon that supplies whitewater waves for beginners and up to 1.8 metre high waves for elite surfers.

Wavegarden Cove uses a patented electro mechanical design consisting of 40 'paddles' set up along 80 metres of the lake. These slide backwards and forwards on a rack and pinion system coordinated by computer. The pulses of energy introduced at various points along a wave enable consistent power to be fed through to a wave until it dies out.

The advantage of this new modular system is that its working parts are out of the water, so if anything breaks or needs maintaining then this can be done while surfers are still using the facility.

It took Nick Hounsfield, a director of British Surfing and Surfing England, 10 years to find the financial backers and the right design to build the surfing set up.

Surfing will become part of the Olympics for the first time in 2020 and thousands of surfers visited the complex in its first three winter months of operation. The team is now developing a second 'Wave' in Lee Valley with several other potential sites across Europe and beyond.

Further inland surfing information can be read in *Ingenia* 69's article *How to create the perfect wave*.

A YEAR IN THE AIR


PHASE-35 undertook flight trials at the Royal Australian Air Force Woomera Test Range in South Australia © BAE Systems

In February 2020, a solar-powered aircraft conducted its maiden flight.

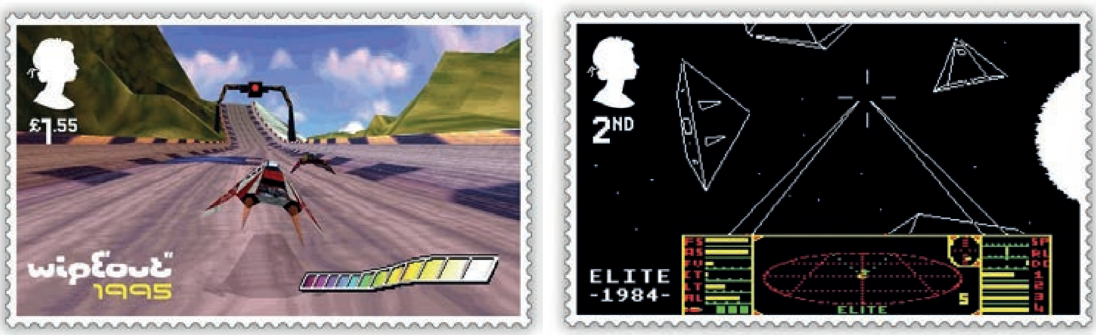
The PHASA-35 (persistent high-altitude solar aircraft with 35 metre wingspan) unmanned aerial vehicle (UAV) flies in the stratosphere, above the weather and conventional air traffic, which makes it a cheaper alternative to satellites. It can remain in the air for a year and can be used for different types of surveillance, such as fire detection or maritime supervision.

The high-altitude, long-endurance plane was developed by BAE Systems together with another UK company, Prismatic Ltd. The 150-kilogram UAV has a monocoque structure made of carbon-fibre-composite materials. The ultra-lightweight plane is powered by the Sun during the day via solar panels on its wing and by long-life lithium batteries at night. It can fly at a speed of between 50 to 78 knots at a height of more than 20,000 metres.

As well as its surveillance capabilities, the PHASA-35 could provide communications networks including 5G to remote areas, conduct polar summer operations and act as a supplement to, or replacement for, satellites. Whereas satellites have fixed orbits requiring long lead times for installation, this UAV is flexible and can be used for localised applications.

Further flights will be made during the year to test the UAV during taking off and climbing, when it is at its most vulnerable and susceptible to adverse weather conditions.

VIDEO GAME STAMPS



Stills from video games *Wipeout* (Psygnosis) and *Elite* (Acornsoft)

In January 2020, Royal Mail issued 12 stamps dedicated to UK-designed video games. Focusing on the early games launched in the 1980s and 1990s, the stamps show screenshots from the classics starting with *Elite* (1984) and ending with the *Tomb Raider* series, first seen in 1996.

Ian Bell and Dr David Braben OBE FREng were the game engineers and designers of *Elite*, the 3D space-trading and combat simulator, developed for BBC Micro and Acorn Electron computers. This groundbreaking game operated on just 22 kilobytes of memory; about the same needed to send an email today.

From these small beginnings came a raft of UK-generated video games – called 'computer games' at the time – some of which appear in the set. *Dizzy* was an adventure game that could be played with a keyboard or joystick, followed by the games *Populous* and *Lemmings*, which could be operated with a mouse. The racing games *Micro Machines* and *Wipeout*, the strategy game *Worms* and *Sensible Soccer* appear on their own stamps, with *Tomb Raider*'s Lara Croft featuring on a separate sheet of four.

The UK video game market has grown significantly since these innovative games were launched – it is now worth over £5 billion and growing. The game industry itself employs around 15,000 full-time staff in the UK, with a further 10,000 employed indirectly by the studios. The stamps celebrate the engineering, artistic and story-telling impact these games have had on generations of players.

FIGHT PLASTIC POLLUTION

The British International Education Association has launched its annual international STEM Youth Innovation Competition. Open to 9 to 21-year-olds, the 2020 challenge is to design a solution to 'save our shores from plastic pollution'. The entries need to be submitted by 31 March.

Competitors will need to research, design and write a report on an innovative and creative project that will help clean up plastic from remote mud banks and waterlines through innovative and creative solutions. Applicants can use the internet and other secondary sources to research their entries.

In April, the teams that have made it through this stage will be given a budget and asked to prepare proof of concept videos.

The winning teams from the 9 to 17 age group will be awarded cash prizes up to £5,000 to contribute to their school STEM labs. The winners from the 18 to 21 age group will take part in a 'University Challenge' and become youth STEM ambassadors.

For more information visit: **www.bieacompetition.org.uk**

SILENT NO MORE

Engineers have recreated the 'voice' of an ancient Egyptian priest who died 3,000 years ago.

Writing on the Egyptian high priest Nesyamun's coffin said that he wished to speak and sing his liturgies in the afterlife. Now, Professor David Howard FREng from the Department of Engineering at Royal Holloway, has helped to create a sound from the priest's larynx and vocal tract. The researchers 3D-printed a reproduction of Nesyamun's vocal tract and combined it with an artificial larynx sound used in speech synthesis systems.

The concept of re-generating a voice came from Professor Howard's work on creating authentic vocal sounds for those who have lost the normal speech function of their vocal tract or larynx. He was approached by Professor John Schofield at the Department of Archeology at the University of York to test the possibility of hearing the voices of historical figures.

The mummy of Nesyamun was lying in Leeds Museum and his soft tissue was thought intact enough to warrant further experimentation. His body was passed through a computed tomography (CT) scanner at Leeds General Infirmary and the 3D-printed vocal tract was generated. It is thought that Nesyamun may have died from an allergic reaction from an insect sting to the tongue.

Now, the archeologists and engineers involved want to develop a computer model that will allow the vocal tract to be moved around to form different vowel sounds and eventually words. This approach could then be applied to other well-preserved human remains and enable those long-dead to be heard once more. This has the potential to add an extra aural dimension when visiting museums in the future.

Listen to Nesyamun at **https://tinyurl.com/uuh4o8t**

Nesyamun's mummified remains being passed through a CT scanner
© Leeds General Infirmary

MOBILE LAB AND LIBRARY

A mobile gadget library for schools won the audience vote at Africa Prize Live 2020. Martin Bruce, the co-founder and business analyst for Lab and Library on Wheels, pitched the innovation with the other entrepreneurs shortlisted for the Africa Prize for Engineering Innovation prize and won the public vote at the first ever Africa Prize Live event.

Lab and Library on Wheels is a mobile, solar-hybrid cart with gadgets and e-learning resources for under-resourced schools. Geospatial engineer Josephine Godwyll came up with the idea while teaching at a rural school during an outreach programme. Her students did not have access to library books or laboratories and had to rely on theoretical lessons only.

Her unit contains laptops, tablets and practical teaching and learning materials, which are customised to suit the size of the school. Fixed libraries and laboratories cost up to $25,000 to build and cater for a limited number of students in Ghana. Many schools are unable to afford these and operate without a regular power supply.

Lab and Library on Wheels eliminates the need for fixed libraries and laboratories, as the $6,500 hand-cart with e-resources and kits can be pushed from one classroom to the next. Schools that are unable to pay upfront can arrange a payment plan. The team installs a solar panel on the roof of each school and energy from the panel is stored in a battery and used to charge all devices.

The winner of the Royal Academy of Engineering's 2020 Africa Prize will be announced at the final event in Accra in June. Innovations in the shortlist include facial recognition software to prevent financial fraud, a low-cost digital microscope to speed up cervical cancer diagnosis, bamboo bicycles made from recycled parts, and two innovations made from invasive water hyacinth plants: an animal feed and a cooking fuel.

Martin Bruce with the Lab and Library on Wheels

ENGINEERING PODCASTS

The DesignSpark team: (L–R) Harriet Braine, Professor Lucy Rogers and Bec Hill

A new series of the DesignSpark Podcast, featuring Professor Lucy Rogers, Visiting Professor of Engineering, Creativity and Communication at Brunel University, covers engineering topics including smart homes, space tourism and biometrics.

The former BBC Robot Wars judge is working with comedians, historians and engineers to create programmes about technology topics including augmented humans, big data and driverless cars.

The Engineering Edge series has Rogers on tour visiting locations such as the Surrey Space Centre to talk about satellites, the National Research Laboratory for Fusion Energy, and the UK Drone Racing Open event that selects pilots to compete for the world championships.

To date, the DesignSpark team has produced 20 programmes over the last two years. Listen to the podcasts on Spotify, Apple Podcasts or **www.rs-online.com/designspark/podcasts**

GLOBAL SHORTAGE OF ENGINEERING SKILLS SAYS REPORT

A report published on World Engineering Day for Sustainable Development has measured the abilities of 99 countries to conduct key engineering activities in a safe and innovative way.

The *Global Engineering Capability Review* focuses on six measures of engineering capability around the world: the strength and sophistication of the country's engineering industry, the availability and diversity of its engineering labour force, its knowledge base, built and digital infrastructure, and safety standards.

The report found that the lack of available data hampers action on safe and innovative engineering. Countries face challenges around quality of skills as well as quantity and the UK is lagging behind in supply of skilled engineers. The research suggests that, as the pace of technological change accelerates, no nation can afford to ease up on their efforts to conduct engineering in a safe and innovative way.

In the global engineering index of 99 countries, the UK features in the top 10 of just two categories — knowledge and safety standards. By contrast, Singapore is in the top 10 in five out of the six categories and comes first under labour force, digital infrastructure and safety standards. The US leads the knowledge rankings, in stark contrast with its safety ranking. The review aims to provide a baseline to help policymakers, educators and business executives understand their country's relative engineering strengths and to identify and address capability gaps that are barriers to safe and sustainable development.

The review showcases top-performing countries with case studies, including Iran, which tops the index for the highest percentage of graduates (of both sexes) from tertiary education in the fields of engineering, manufacturing and construction, at 30%, and Rwanda, which is ranked 12th for the percentage of medium and large companies in engineering fields as a percentage of all medium and large companies in the country.

This research was commissioned by the Royal Academy of Engineering and Lloyd's Register Foundation and written by the Economist Intelligence Unit. The interactive version of the report can be found at **www.raeng.org.uk/capability-review**

GET INVOLVED IN ENGINEERING

THIS IS ENGINEERING FILMS

The Royal Academy of Engineering launched a new season of *This is Engineering* films on World Engineering Day for Sustainable Development. The films show how engineers can 'be the difference'.

www.thisisengineering.org.uk

WES 100 VIOLETS EXHIBITION

21 March 2020
Brunel Museum, London

How do we predict the weather, recapture carbon from factories and power our homes? For one day only, seven teams of engineers from across the country will answer these questions and many more in family-friendly interactive engineering exhibits for the Women's Engineering Society 100 Violets Challenge.

www.wes.org.uk/100violets

PHOTO ELECTRONIC LIGHT ORCHESTRA SHOWCASE PERFORMANCE

20 May 2020
Arts and Innovation Centre, Pontio, Bangor University

This event will bring together eight participating schools, who have been developing unique musical instruments utilising coding skills and photonics to demonstrate their achievements over the course of the project.

MAKEFEST

30 and 31 May 2020, 11am to 4pm
Science and Industry Museum, Manchester

Makefest is taking over the Science and Industry Museum for another huge weekend of tinkering, testing, coding and creating. Get hands-on with dozens of DIY activities, brought to you by a whole host of engineers, hackers, coders, makers, artists and scientists.

GLASGOW SCIENCE FESTIVAL

4 to 14 June 2020
Glasgow

The festival will host a range of events across the city, including the Ingenious Circus, a project that explores the engineering that underpins circus performance.

www.glasgowsciencefestival.org.uk

FORMULA STUDENT 2020

22 to 26 July 2020
Silverstone

Each year, Formula Student sees over 100 university teams from around the world travel to Silverstone to compete in motorsport static and dynamic events.

www.imeche.org/events/formula-student

These events are not organised by the Royal Academy of Engineering. Please check with the organisers nearer the time.

HOW I GOT HERE

Q&A

BEN CROWTHER
MECHANICAL AND SYSTEMS ENGINEER WORKING IN AEROPONICS

Ben Crowther is the Chief Technical Officer and Co-Founder of LettUs Grow, a Bristol company that designs modular aeroponic farming systems

WHY DID YOU FIRST BECOME INTERESTED IN ENGINEERING?

I have always been interested in creating things. From a young age I dabbled in everything from building go-karts to dismantling old electronic systems. My grandad taught me to turn the fake rivet caps for the bolt heads on his model steam locomotive when I was really young, which is probably my earliest engineering memory.

HOW DID YOU GET TO WHERE YOU ARE NOW?

For a while, I followed what would be considered a traditional engineering route. I studied the sciences and maths at school, and then for a degree in engineering design at the University of Bristol. This helped develop my technical skills, but more importantly – for me now – it had a strong focus on engineering systems and working within interdisciplinary teams.

Afterwards, I moved into mechanical and systems engineering at a large local company where I learned to apply my technical skills to real-world systems.

In 2015, I used this experience and my technical skillset to start LettUs Grow with Jack Farmer and Charlie Guy, my co-founders who supported the biology and business fronts respectively.

WHAT HAVE BEEN YOUR BIGGEST ACHIEVEMENTS TO DATE?

I think my biggest achievement was taking the risk to leave a well-paid engineering job to start LettUs Grow. It certainly wasn't the obvious choice for many people, but I've been grateful for the support of friends and family, which made it a lot easier.

I don't often stop and look back at how far we have come with the business, but in retrospect I am incredibly proud of what we have built. We have created a novel technology from the ground up that shows real promise in making a positive impact in the world. We have developed a market-leading product in an industry that is growing incredibly quickly, and have created a brilliant company and culture.

WHAT GAVE YOU THE IDEA FOR LETTUS GROW?

I was reading around the subject of abundance and a more sustainable future when I was inspired by a section in a book by Peter Diamandis about the applications of vertical farming. I then met Jack at university and he was into aeroponics, considering different ways to curate a more sustainable food system more efficiently. We developed our aeroponic technology from there.


Ben Crowther with salads grown in the R&D facility at LettUs Grow

The world must increase food production by 70% to feed the 10 billion people that will be around by 2050. This needs to be achieved with 25% less farmland, degraded soils and in an ever more unstable climate. LettUs Grow aims to build the most efficient farms possible. Instead of growing plants in soil, we cover plant roots in a mist that is filled with nutrients, which reduces water and fertiliser usage by 95%. This increases the plants' growth and uses less water than traditional farming and no pesticides. The technique can be used across the world and in different environments, from cities to deserts.

WHAT'S DIFFERENT ABOUT WHAT LETTUS GROW DOES?

Traditionally, aeroponics has been understood as a very high-output, high-efficiency method of growing. However, there are various issues surrounding the initial complexity of setting it up such as clogging problems with nozzles, which are traditionally used to generate an aerosol. There are other factors that mean it's very difficult to grow the system to a sizeable scale. Our innovations are around removing these complexities. We've created an aeroponic system that is as simple as a hydroponic one but still has all of the advantages of aeroponics.

WHAT DOES A TYPICAL DAY AT WORK INVOLVE FOR YOU?

I don't ever have one day the same as the next. LettUs Grow's product and service offering is pretty broad so my role covers a mix of business, software, product development, research and development, and company strategy. One day I could be designing mechanical components and the next setting out the company's five-year product development roadmap.

WHAT WOULD BE YOUR ADVICE TO YOUNG PEOPLE LOOKING TO PURSUE A CAREER IN ENGINEERING?

Engineering is not all metal and hard hats! If you like making things and have a creative mindset, then it's a great career pathway. We've created undergraduate and graduate internships for people studying at the University of Bristol and University of West of England. We help them by sharing our experiences, where ideas have failed as well as where we've succeeded. They bring in specialist skills that help us grow in scale.

WHAT'S NEXT FOR YOU?

I'm really excited to be able to continue my role at LettUs Grow and build on the foundations we have laid down over the past couple of years. I'm looking forward to completing our new research centre and deploying more and more systems for customers that can make a significant positive impact in the world, as well as learning the skills I will need to do this successfully.

QUICK-FIRE FACTS

Age: **26**

Qualifications: **Mechanical engineering design with study in industry, MEng.**

Biggest engineering inspiration: **A local Bristol outfit called Open Bionics. I just love the way the company has been built and grown. It produces affordable, bespoke, lightweight, 3D-printed myoelectric prosthetic limbs.**

Most-used technology: **The Slack instant messaging platform.**

Three words that describe you: **Ambitious, passionate, persistent.**

OPINION

OUR 21ST CENTURY INFORMATION SUPERHIGHWAY

Vinton G. Cerf ForMemRS

Thirty-four years ago, then US Senator Al Gore characterised the nascent internet as an ‘information superhighway’. This metaphor understandably came to mind because his father, the senior Senator Al Gore, had introduced legislation in 1955 leading to the Federal Aid Highway Act. The resulting Interstate Highway system produced a housing and automobile manufacturing boom that altered the American landscape and economy. Former Vice President Al Gore correctly surmised that the internet could have a similar impact, albeit by the movement of information rather than wheeled vehicles.

From our 21st century perspective, the internet and its World Wide Web application, among other uses, combined with the computing and communication capability of smartphones and other programmable devices, have had and will continue to have a dramatic influence on the daily lives of billions of users. While about half the world’s population has direct access to the internet today, the rest will follow and are influenced by those who already have it.

The applications of information technology and computing are limited only by imagination and ability to program for the desired result. Perhaps more importantly, the capacity of the network to move digital information affects the feasibility of applications. When the internet was in early development, the backbone network had a capacity of 50,000 bits per second. Today one finds backbone speeds to the order of 400 billion bits per second and rising. The results of this progress includes massive amounts of streaming video, video conferencing on a global scale, digital voice communications, billions of web pages, social media and image sharing applications, electronic commerce, and on-demand transportation applications as well as a massive array of video/computer games.

All of these applications consume capacity in order to move digital information quickly and securely to virtually anywhere in the world. These ambitious applications rely on super-high-speed optical fibre networks on land and under the oceans. Submarine optical cables are being laid at increasing rates, connecting continents with bands of light.

The high speeds also achieve lower latencies (delay from transmission to reception) and that, in turn, enables real-time video conferencing and online group game playing. It also enables massive amounts of e-commerce and high frequency

Mobile communication has dramatically improved capacity over the past several decades from the first mobile phones in the early 1980s delivering tens of kilobits/second to today's smartphones running 4G and now 5G and Wi-Fi at tens to hundreds of megabits/second

stock trading. What all of these applications have in common is their dependence on the communication of digitised information. Physicists tell us that there is a fundamental relationship between information and the way the universe works. In some very basic way, the universe is computing itself. When weather clouds form, they are a visible manifestation of the universe's way of computing complex partial differential equations. It's instantaneous. Molecules of water 'know' how to form vapor because that's what their physical properties tell them. A flower develops in a particular way because its DNA 'tells' it how to do it. Moving information around the net allows us to 'tell' virtually anything that can understand the bits of information how to do anything we want it to do.

In a recent development, the University of Southampton, Professor Sir David Payne FREng FRS and his team are exploring the design of hollow optical fibre. Payne, the founder of the Zepler Institute for Photonics and the Optoelectronics Research Centre, realised that the speed of light is reduced in glass, the principal component of optical fibre. If the fibre could be made hollow, then light would propagate in air rather than glass. The speed of light in a vacuum is about 300,000 kilometres per second. In glass, it is more like 200,000. In air, it is only slightly slower than in vacuum. The result is to reduce propagation latency by about a third – it would take light in glass 1.5 seconds to go 300,000 kilometres while in air it would take only one second. This improves the performance of optical fibre networks in general without regard to electronics. The physics does the speed up. A major challenge, of course, is to perfect the ability to make many kilometres of the fibre for practical applications.

Higher speed fibre is not the only trajectory for communications technology. Wireless communication is also undergoing massive transformation in space and on the ground. Mobile communication has dramatically improved capacity over the past several decades from the first mobile phones in the early 1980s delivering tens of kilobits/second to today's smartphones running 4G and now 5G and Wi-Fi at tens to hundreds of megabits/second. Of course, access to this new capacity requires base stations to be positioned with increasing density and this is economical only for regions with a reasonably high population and subscriber presence. For rural areas, satellite is an attractive alternative but historically has suffered from high latency because of the distance between the subscriber and the satellite. Synchronous satellites are 36,000 kilometres away and at the speed of light it takes 120 milliseconds to reach the satellite and another 120 to come back to Earth. We are seeing major new efforts to place tens of thousands of communication satellites in low Earth orbit (700 to 1,500 kilometres high) providing very low latencies and much higher speeds thanks to the vastly shorter distances to and from the satellites. If these initiatives are successful, it will be impossible to avoid access to the internet and other communication networks. Even at the North and South Poles!

It should be abundantly clear by now that high speed transfer of information has become an integral part of our digital society. It is an infrastructure upon which we depend increasingly from moment to moment. Not surprisingly, this increases our need to make that infrastructure as reliable, safe and secure as possible. But that's another story.

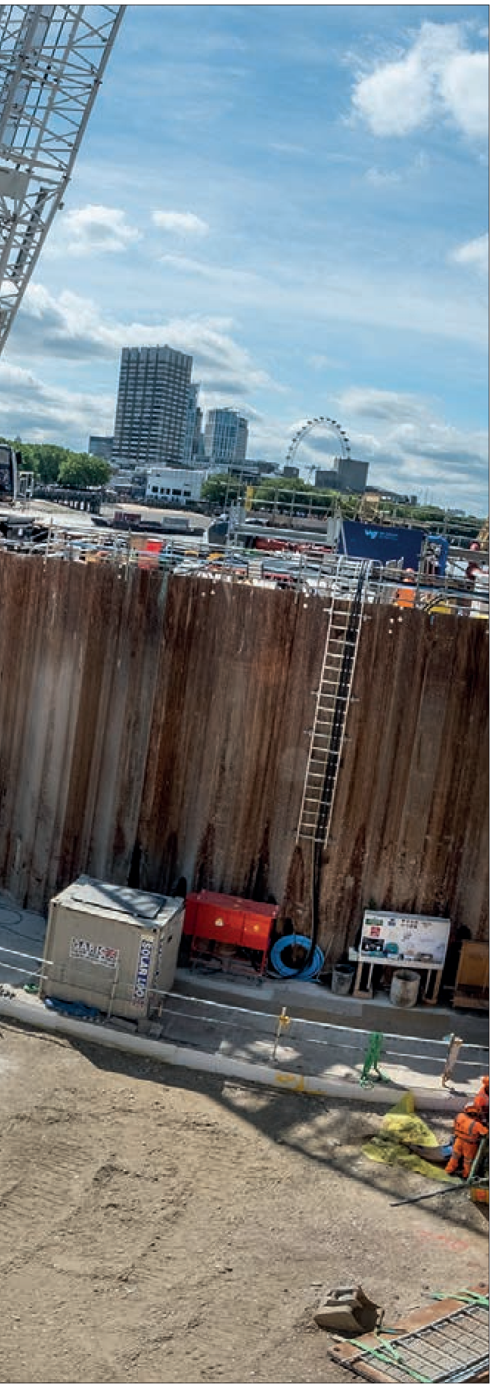
Vinton G. Cerf ForMemRS
Vice President and Chief Internet Evangelist
Google

BIOGRAPHY

Vinton G. Cerf ForMemRS also known as Vint Cerf, is an American internet pioneer and is considered to be one of the 'fathers of the Internet'. In 2013, he was part of the team awarded the Queen Elizabeth Prize for Engineering for their work on the internet. He was Founding President of the Internet Society and has been inducted into the National Inventors Hall of Fame.

CLEANING UP LONDON'S WASTE

A cofferdam was constructed on Blackfriars north foreshore so that a dry workspace could exist below the level of the River Thames. A drop shaft has been designed to intercept both the LL1 sewer located within the listed Bazalgette river wall and the existing Fleet sewer outfall, which is located under Arch 1 of the Blackfriars Bridge, to the new Tideway tunnel. The shaft is now excavated to a depth of 23 metres and when completed will be 53 metres deep (to invert level) with an internal diameter of 22 metres © Tideway



Tideway is an epic civil engineering project. At £3.8 billion, it is the UK's largest ever water infrastructure undertaking. It includes 25 kilometres of large-diameter tunnel deep below the River Thames, with 23 huge shafts and a workforce of 4,000. To Tideway's Chief Executive Officer, Andy Mitchell CBE FREng, it represents even more than that. At the halfway point of the project he spoke to Hugh Ferguson about his mission to reconnect Londoners with their great river.

The new Thames Tideway Tunnel will divert the millions of tonnes of raw sewage that flows into the Thames each year, and take it, by gravity, through a new tunnel to Beckton sewage works in east London. Construction started in 2016 with all work due to be completed in 2024.

Tideway will supplement rather than replace Sir Joseph Bazalgette's great network of sewers, completed in 1865 to combat the 'Great Stink' from the polluted Thames. Bazalgette estimated that the system, one of the greatest engineering achievements of the Victorian era, prevented around 12,000 deaths a year from cholera and other waterborne diseases.

Bazalgette's system comprised 2,100 kilometres of brick-lined sewers feeding into 131 kilometres of large interceptor sewers running west to east, parallel to the river. They stretched from Abbey Mills pumping station (and then to Beckton) on the north side of the river, and to Crossness pumping station in the south. He built the tunnels to last – 150 years later, they are still in remarkably good condition, and can continue to transport most of London's sewage for years to come.

Bazalgette also designed the tunnels so that, unlike some other cities' sewerage systems, they carry both sewage and storm water run-off, thus avoiding the need to dig up London's streets twice. He planned ahead, designing a system for a population of more than four million at a time when the actual population was only two million. Even so, rainfall is variable and Bazalgette realised that his system could not cope with the greatest storms, so he included a series of 57 combined sewer overflows (CSOs). During extreme events, these overflows allow rainwater and sewage to overflow into the Thames, rather than cause a back-up that would flood streets with sewage.

Three factors have combined and the system can no longer cope. Bazalgette's 'design population' of four million has increased to nine million and much of London's space has been transformed from open ground (which can absorb a great deal of rainwater) into buildings or 'hard standing',

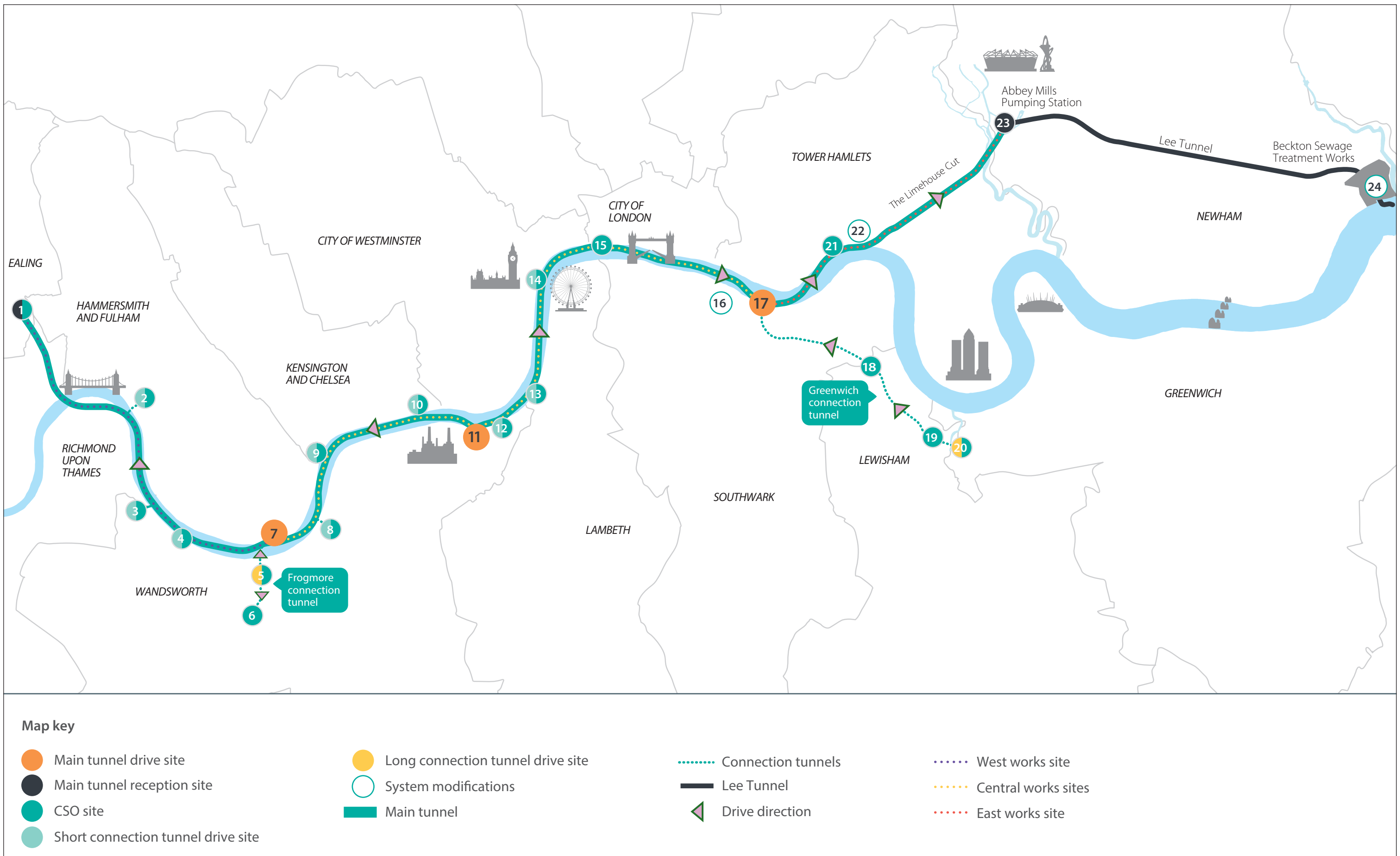
A combined sewer overflow releases rainwater and sewage during peak flows 60 times a year © Tideway

with water draining directly and immediately into the sewers. Thirdly, a consequence of climate change is more erratic and extreme weather, so that the water engineer's benchmark of a 'hundred-year storm' may now happen three times in five years.

The overflows, initially required about twice a year, are now used 60 times a year, and rising, tipping a staggering 40 million tonnes of sewage a year into the Thames. Worst of all, when heavy rain follows a long dry spell, when the system fills with sewage, the 'first flush' into the Thames is concentrated sewage.

WHAT TIDEWAY DOES

Tideway's job will be to capture all of this overflow and initially store it in its new network of shafts and tunnels, which together form a huge 1.6 million cubic-metre underground reservoir, releasing it only as fast as the pumps and sewage works at the eastern end can cope. The



The 25-kilometre-long Tideway Tunnel runs from Acton Storm Tanks in the west, beneath the Thames, to Abbey Mills Pumping Station, where it will connect to the already completed Lee Tunnel to Beckton. Tideway's 23 construction sites include Hammersmith Pumping Station (2), Blackfriars Bridge Foreshore (15) and King Edward Memorial Park Foreshore (21). Several additional connection tunnels bring sewage to the main tunnel. The largest tunnel runs five kilometres from Greenwich Pumping Station (20) to Chambers Wharf (17) © Tideway main feature of the network is a huge 7.2-metre internal diameter tunnel (large enough to fit three double-decker buses) running 25 kilometres from Acton in the west, beneath the Thames through central London, and then veering north to Abbey Mills in the east. Some £1.1 billion of preliminary works have already been completed by Thames Water – including the Lee Tunnel, the easternmost (and deepest) section of tunnel, from Abbey Mills to Beckton.

The tunnel is deep, principally to avoid London's myriad existing underground services: 30 metres in the west, with gravity flow to 66 metres at Abbey Mills (and deeper still at Beckton). Tideway has 23 sites for constructing its huge shafts that connect the overflows on either side of the river to the main tunnel. Some are also used for lowering and lifting the massive tunnel boring machines (TBMs).

Digging the Lee Tunnel required considerable technical innovation, in part as a testbed for the work on Tideway itself. These innovations included hydrofraises (large crane-mounted drilling machines with twin counter-rotating cutters mounted within a steel frame) for sinking panels under bentonite slurry to create the primary concrete linings of shafts and the use of slip forming to build the inner concrete linings of the shafts. Another innovation was the use of fibre optic monitoring to check structural

BLACKFRIARS BRIDGE WORK

Tideway's most visible construction site is at Blackfriars, in the City of London overlooked by people crossing Blackfriars Bridge. It is also prompted a major redesign, undertaken to avoid the risk of damaging the Victorian gas mains. In the summer, this will result in the largest ever structure to be floated on the Thames in Central London.

A combined sewer overflow from the River Fleet discharges under the north arch of Blackfriars Bridge. The plan was to build a twin-walled, sheet-piled cofferdam (a watertight enclosure that enables construction below the waterline). Within that, new concrete culverts would transfer the flow into a new shaft some 200 metres upstream and down the online shaft directly into the main Thames Tideway Tunnel.

Analysis showed that the cofferdam and particularly its heavy concrete tie-ins to the river wall, could cause movement to the wall and in turn movement to the Victorian gas mains. Damage to the gas mains could impact the gas supply to the City, while relocation of the gas main would delay the project and, worse, require closure of the Embankment – a major road artery – for several months.

Instead, the engineers came up with an ingenious solution. Reducing the twin-wall cofferdam to the upstream end, where the shaft is being sunk, would reduce wall movements enough to avoid damaging the gas main at its critical point further downstream. A large dry dock, drained of water, replaces the central section of the planned cofferdam. Inside the cofferdam, the section of concrete culvert connecting to the Fleet CSO is being prefabricated. Meanwhile, a prepared bed is being created beneath the bridge arch back to the cofferdam using crushed rock capped with a concrete mattress on which the culvert will sit.

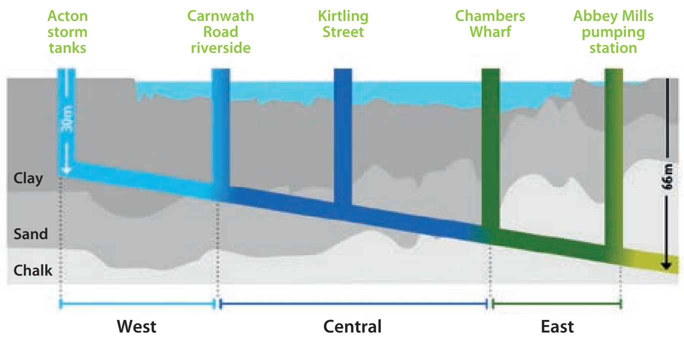
Around May, the dry dock will be flooded to float the culvert. The downstream end of the dock will open and the culvert winched some 100 metres before lowering into position on its bed. It may be only a short float-out, but its massive size – 100 metres long, roughly seven metres square in section and weighing 3,500 tonnes – breaks all records.

Then the culvert will be connected to the CSO (with a temporary gate to allow sewage outfall to release downstream until Tideway is complete), and the dry dock will be re-sealed, locking in the upstream end of the new culvert. With the dock re-drained, the section of concrete culvert linking to the shaft will be built, resting on piles sunk below the Thames.

Finally, the whole Blackfriars site will be backfilled and landscaped to create a new public open space adjoining the river. The new space is Tideway's largest and its proposed name is 'Bazalgette Embankment'.

Blackfriars north foreshore. A 100-metre, 3,500-tonne interconnecting culvert will be the largest structure to pass along the Thames later this year. It will be lifted into the central section above and then connected to the CSO drop shaft – below the crane on the left of the picture © Tideway

The route and tunnel



Construction has been divided into three sections – west, central and east – each with a separate consortium of contractors

behaviour of the shafts during construction. The Lee Tunnel also made widespread use of fibre-reinforced concrete in place of conventional reinforced concrete (see Lee Tunnel article in *Ingenia* 63).

Most of these innovations have been carried over to the Tideway project. Additional innovations include a lining erection machine for placing the secondary, inner lining on the east section. This will be similar to the back-end of a TBM, erecting precast segments to form the tube. This promises to be faster, more economical, better quality, safer, and more environmentally-friendly than the conventional method of casting the concrete inner lining in-situ. One of the hydrofraises has also been converted to electrical power, demonstrating the feasibility of converting much of the heavy plant on construction sites to electric power, with clear environmental advantages for the future. This electrification was made easier because some shafts already carried heavy duty electrical power for the TBMs.

The two TBMs on the east section are, as on the Lee Tunnel, slurry tunnelling machines. The other four, with different ground conditions, are earth pressure balance machines. Four TBMs are driving the main tunnel while the other two, smaller but still larger than any of the Crossrail tunnels, are digging connection tunnels. The longest of these tunnels, at five kilometres, due to start construction in June/July, will carry overflow from the Greenwich pumping station to the main tunnel at Chambers Wharf in Bermondsey.

Construction is currently at its peak with just over half of the main tunnel driven. Some shafts are completed; all have been started. Costs were revised upwards last year from the original target of £3.5 billion to £3.8 billion, due mainly to redesign of the works at King Edward Memorial Park in Tower Hamlets and Blackfriars – see *Blackfriars Bridge work*.

As at Blackfriars, work at King Edward involves creating a cofferdam in the river to enable a shaft to be sunk and connected to a local CSO. As fill was being placed inside the steel sheet-pile cofferdam, the piles started to deflect outwards at the top. Further ground investigation revealed an unexpected layer of soft, weak ground near the surface, resulting in the tops of the piles not being properly anchored. Concrete piles were added where necessary to stabilise the cofferdam, enabling backfilling to be completed, but two problems remained: the layer was predicted to settle over time by up to one metre, and the diaphragm walls for the permanent works could not be sunk through the weak ground. The solution was 'deep soil mixing'. Some 1,500 tubes were sunk up to 13 metres deep, inside which augurs were used to stir in a cementitious stabiliser.

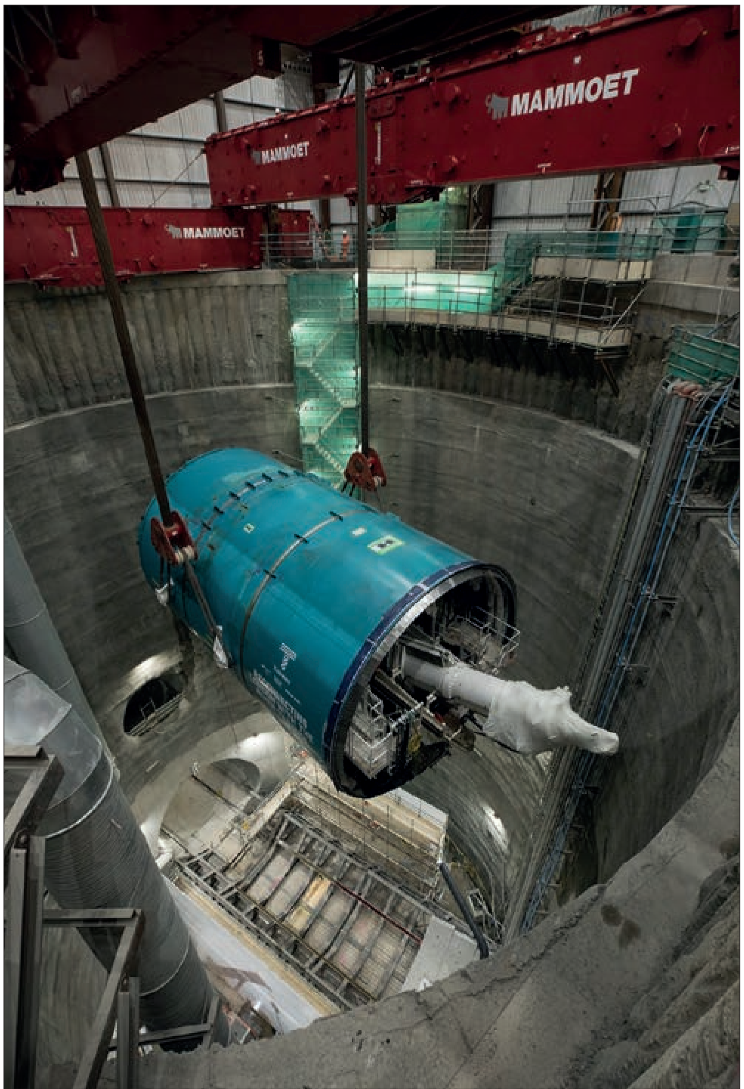
LESSONS LEARNED

Tideway itself has demonstrated how the river can be reinstated as a transport artery. Its barges bring most of the materials into the sites (using offsite construction where possible) and have carried away 95% of the nearly one million tonnes of tunnelling spoil. This represents 130,000 lorry journeys avoided, making the barges the largest users of the central London section of the Thames.

With most of the high-risk work now over, Andy Mitchell CBE FREng, Tideway's Chief Executive Officer, is confident that completion of tunnelling – by 2022 – should be free of unpleasant surprises, as will the subsequent commissioning phase. But his concern for the river will last long after Tideway is opened and he has moved on.

London's population is still increasing, more ground is being covered with hard surfaces, and climate changes will make heavy storms more frequent. Even on opening, Tideway will not be able to cope with the strongest storms: it has its own CSOs, which will be used about twice a year, though the sewage released will be much more diluted than now. Projections suggest that in as little as 60 years, unless something is done, Tideway's CSOs will be operating increasingly frequently, and London will need another Tideway tunnel.

So Londoners have 60 years to change their ways. The solution will require a combination of measures, which include sustainable drainage systems to contain the storm surges. These will include a series of relatively small-scale



The front end of 'Rachel', the tunnel boring machine (TBM) driving the western section of the main tunnel, being lowered down the shaft at Fulham. Tideway's six TBMs are each named after an inspirational woman from the local area, chosen by the public from a shortlist. The name 'Rachel' commemorates the pioneering engineer Rachel Parsons, daughter of Sir Charles Parsons, the inventor of the steam turbine. During the First World War she replaced her brother as a director of her father's company. She was founder President of the Women's Engineering Society (*Ingenia* June 2019) and in 1920 co-founded the engineering company Atalanta Ltd in Fulham Road, where all the employees were women

measures such as retention ponds, soil percolation and bio-filtration, all integrated into the urban drainage system.

This would be combined with the adoption of planning controls for new buildings. These may require, for example, dishwasher water to be recycled in the home to flush toilets, or rainwater capture systems in all homes to hold storm water and then release it gradually to the drains – much as the Thames Tideway Tunnel will do on a larger scale from 2024.

Andy Mitchell feels that such changes will require public support and personal choices. Londoners need to fall in love with their river again, and insist that it is properly respected – and never again treated as an open sewer.

FINANCING THE PROJECT

The method of financing Thames Tideway is novel, imaginative and appears to be working well. It could prove a model for attracting private finance into more large infrastructure projects in the future. A key to success was establishing a framework that would be attractive to the large pension funds that seek steady long-term (but not necessarily very high) returns, with very limited risk to their investment.

Four major shareholders own the Tideway company. They are investing money, largely from pension funds, into the project; around three million UK pension holders already have a stake in it. The company is committed to investing £3.5 billion – the target and regulatory baseline agreed at the start – with a completion date planned for the end of March 2024.

Three consortia of contractors are responsible for construction, under design-and-build contracts, with shared 'pain/gain'. If costs come in below target, Tideway and the contractors share the benefits, and they also share any cost overruns. If the cost rises above £3.5 billion, then Tideway shareholders have to find 60% of the additional cost. Costs have risen, to the current forecast of £3.8 billion (see main story), though with no change to the forecast completion date.

If the costs were to rise to 30% above target, to £4.55 billion or more, the company would have the right under the agreement to invite the government to finance any additional cost, diluting its own shareholding but getting the job finished.

The shareholders receive a return on their investment, calculated by using the agreed 2.5% per annum weighted average cost of capital, guaranteed until 2030. Beyond then the company will (at least in theory) continue indefinitely, with the shareholders' investment remaining and a continuing responsibility for maintaining the asset. It is Thames Water's ratepayers who fund the scheme, with a £20 to £25 addition to their water rates each per year.

BIOGRAPHY

Andy Mitchell CBE FREng was programme director of the Thameslink rail project and then of Crossrail before joining Tideway as CEO in 2014. His is also co-chair of the Construction Leadership Council.

Tideway's delivery partners:

Joint-venture contractors:
West section: BAM Nuttall/Morgan Sindall/Balfour Beatty Group
Central section: Ferrovial Agroman UK/Laing O'Rourke Construction
East Section: Costain/Vinci Construction Grands Projets/Bachy Soletanche
Programme manager: Jacobs
Systems integrator: Amey

Engineer and writer Hugh Ferguson also talked to Tideway project managers Darren Kehoe (Greenwich) and Peter Rouzel (Blackfriars), Morgan Sindall engineer Vasile Gornea (Hammersmith), and Bachy Soletanche marine manager Dominic Lovelock (King Edward's).

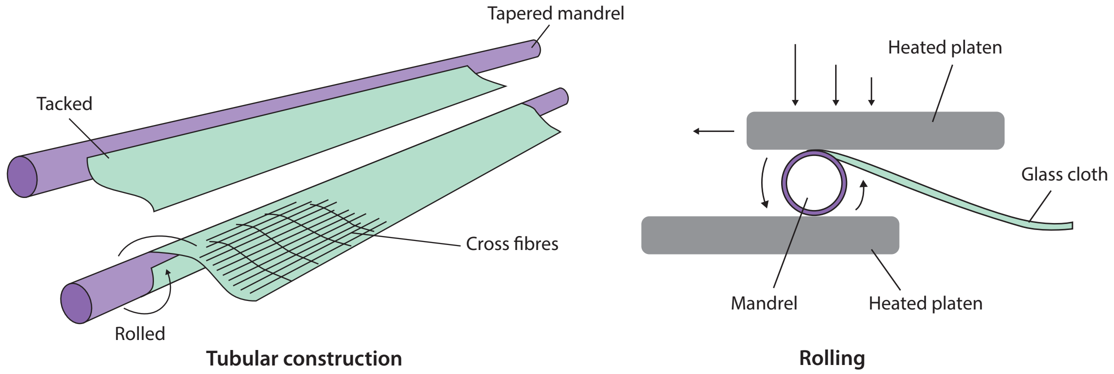
The pBone plastic trombone has proved popular with younger players and those who have difficulties with the weight and balance of a metal trombone. Hundreds of UK schools can now use a range of colourful wind instruments to attract pupils of all ages © Warwick Music Group

FROM BRASS TO RECYCLABLE PLASTIC – THE REINVENTION OF MUSICAL INSTRUMENTS

A quarter of a million brightly coloured trombones made of recyclable ABS plastic have been sold worldwide in the last few years. The pBone, weighing less than a kilogram and costing a tenth of its metal cousin, has driven a demand for a range of polymer-made instruments including a trumpet. Rachel Jones spoke to Warwick Music Group's CEO, Steven Greenall, and Innovation Director, Chris Fower, about the engineering hurdles that were overcome to enable this success.

The pBone journey began with an experiment developed by an engineering design student, Hugh Rashleigh, at Loughborough University. An amateur trumpeter, he was inspired by a peer-reviewed PhD paper from the 1980s suggesting that the surface quality in brass instruments could be as influential as the metal itself for sound quality. Rashleigh made a prototype trombone for his undergraduate project that, through an introduction to Steven Greenall – a venture capitalist and entrepreneur with a degree in electrical engineering – formed the basis of the pBone.

Greenall was a trombone player and owner of the music publisher Warwick Music Limited. He was interested in widening access to music education and saw a strong market proposition in Rashleigh's prototype. If a trombone of acrylonitrile butadiene styrene (ABS) plastic could retain a traditional instrument's features while lessening cost, maintenance and propensity for damage then it would have strong business potential.



To create the trombone slide a resin-impregnated glass cloth is wrapped over a cylindrical mandrel, rolled under high pressure and baked to melt the resin to a solid mass

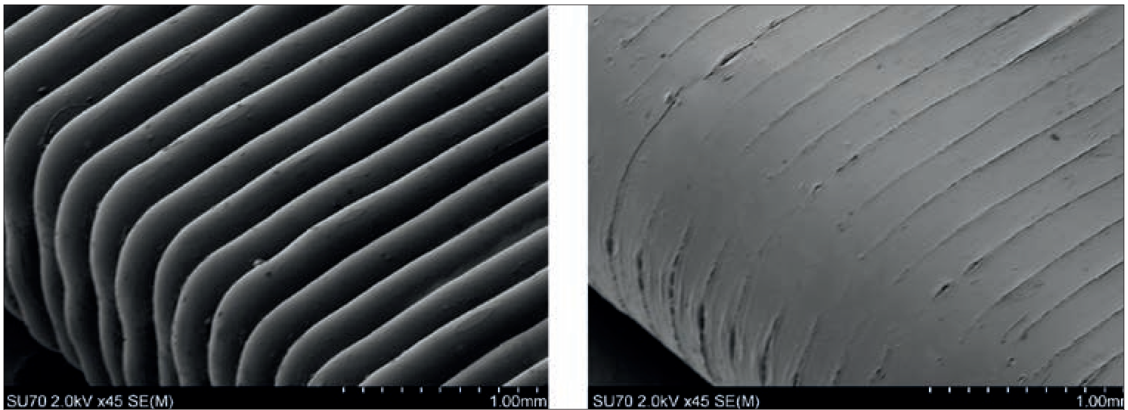
While the pBone was not intended for professional orchestras, it would have to be good enough to convince music teachers and get young people interested. Chris Fower, a professional trombonist and consultant involved in high-end trombone design, was brought in to help develop the project. Making a trombone from polymer would involve a matrix of design, engineering and manufacturing challenges.

LATERAL THINKING

Like trumpets, trombones produce sound by generating air vibrations in a tubular resonator. An extendable slide changes the tubing length and alters the harmonic series available. The slide itself comprises two parallel, stationary inner tubes and two movable outer tubes. "It's the trombone's weak spot, with two soft metals running over each other," Fower explains. "If you bash it, it's hard to repair – which can make the metal trombone a costly choice for children."

Rashleigh's solution for the slide drew on fibreglass manufacturing methods. A non-metallic material could potentially make the slide lighter, stronger and bash-resistant, but it would need engineering to remain stiff, light and parallel. "A metre-long piece of tubing with a wall thickness of 0.5 millimetres, that needs to be turned completely straight and completely rigid, is hard to engineer out of anything," says Fower. Experimenting with extruded plastics brought issues of longitudinal torsion and tolerancing into play.

To solve this, Rashleigh looked into the manufacture of fibreglass fishing rods. For these, a resin-impregnated glass cloth is wrapped tightly over a mandrel, rolled under high pressure and baked in order to melt the resin to a solid mass. Rashleigh



ABS 3D printed items have a higher surface roughness than traditionally formed parts. These images taken by a scanning electronic microscope show an untreated surface (left) and the surface after it has been vapour-polished (right) © Clayton Neff, Matthew Trapuzzano, Nathan B. Crane Department of Mechanical Engineering, University of South Florida

adapted this to create his own solution for the slide. "That bit of engineering was great lateral thinking," says Fower.

Seed funding of £90,000 from Advantage Creative Fund in 2008 enabled investment in newly-affordable computer-aided design and 3D printing. The trio began extensive testing, using players to trial prototypes containing ABS 3D-printed components. Focusing on separate parts of the instrument, they tested prototypes and tracked the benefits of each alteration. The sound quality was extremely uneven. "We had areas of low definition where it was insecure and muffled. The polymer helped produce quite a warm, dull, mellow sound, but clarity and precision were needed," says Fower. "It was necessary to find out and deliver the overtones that metal instruments could offer."

Altering the interior shape was vital in helping improve the sound quality, especially in areas of the prototype where the air changed direction, at the end of the slide and bell, or anywhere the pipe constricted or opened up. Experiments with 3D-printing demonstrated how the shape of components could improve acoustic qualities and help the plastic to resonate. Their work led to a first patent, filed in 2010, and used in all subsequent instruments. This was "essentially about varying wall thickness, using a polymeric material, to impact acoustic sound," says Greenall, who defended it in 2017 against a Chinese rival.

The notion that surface quality could be as influential as underlying material drove development. Most injected plastic parts have 'A' and 'B' surfaces, but something more than a 'B' surface was needed to replicate a brass instrument's polished interior tube. "Under a microscope, the ABS 3D printing looked like shredded wheat," recalls Fower. "It mimicked the shape but not the surface quality or material integrity. Blowing through, the air dissipated and it sounded pretty horrible." Overcoming this required a number of experiments in order to develop a solvent-based system to seal the surfaces and make them airtight.

From 2007 to 2010 the trio experimented with methods including sintering – the process of compacting and forming a solid material by heat or pressure without melting it to the point of liquefaction – and stereolithography, a form of 3D-printing. Another issue that was sorted out before production was bacterial growth. Brass trumpets contain raw nickel (a natural antimicrobial) but polymer-made instruments had antimicrobial additives incorporated.

By 2009, a manufacturing facility in China agreed to take on the instrument. The trio began moving to production, transferring printed shapes into engineering files, and creating tools. "We'd worked out where struts were going to go, shapes of turns, all of that," says Fower. The pBone's launch in late 2010 saw the first stock of 500 instruments sell out in 19 minutes. Since then, Warwick Music Group has sold more than 250,000 units worldwide, and in 2019 the pBone won the Queen's Award for Enterprise: Innovation.

DEVELOPING THE PTRUMPET

As Rashleigh stepped back from development, the team began work on the pTrumpet. Having solved acoustic issues in the pBone, they were ready to address the trumpet's greater challenges. One of the main obstacles lay around achieving acceptable tolerance (limits of variation) in piston valves. "The trumpet is half the length of a trombone, so the acoustic challenge was easier to deal with," notes Fower.

The modern trumpet valve, invented in the early 19th century, allows players to control the passage of breath, rerouting air through additional tubing, altering the pitch. As with the trombone, there have been a few innovations. The pair set themselves the target of replacing the metal valve system with one made entirely of plastic. "It was like making a combustion engine – in plastic."

Their original design scheme, making the system using only ABS injection moulding, proved unworkable. Injecting could lower costs and drive up repeatability, but for pistons, they couldn't inject to the tolerance required. Instead, CNC-machining (automated control of machining tools and 3D printers through a computer) allowed the pair to alter tolerances incrementally, and reduced cost. Pistons could be made from a single bar of polyoxymethylene – POM, a crystalline polymer.

After a trombone slide has had the interior tube smoothed out by a solvent-based solution it is given a blast of compressed air to check that it is airtight © Warwick Music Group

The varying temperature conditions on a production line presented a particular challenge. Small changes in temperature caused big problems. "If a valve block is cut at 20 degrees and a piston at 25 degrees, they won't fit together, or there'll be big holes." The solution was to move everything into a temperature-controlled environment to sit for 48 hours before being machined. Even then, machining plastic was not simple. "A compression wave follows the cut and pushes material out of the way," says Greenall. "It's difficult to get it thin."

Unlike handmade brass piston systems, the pTrumpet's would be mass-produced. 'Lapping' – the manual process for honing brass, improving an instrument's tonal quality – was especially hard to replicate. "In brass, you make inner and outer parts then hand-lap one of those two components until they fit," explains Fower. "The more expensive a brass trumpet, the more hand lapping." In polymer, success rested on good choices of material and precision in mass manufacture. This involved keeping close to suppliers to learn what was possible and make the process fully repeatable. "We pushed the weak spots around until we found a workable balance of tolerance and repeatability. The valve production is very repeatable now, and produces a surprisingly playable result."

With no competitors or research to inform the work, Fower and Greenall made "a few thousand trumpets that weren't good enough" before getting it right. Fower gives the example of air leakage from a prototype valve block. "Let's say it gave two litres a minute leakage at five bar [unit of pressure]. We'd design the rest of the instrument around that, but when we got into manufacturing and it leaked at 10 litres a minute, the adjustments went out of the window. We didn't know what real leakage was until we made it in a factory."

As with the pBone, tiny changes had large impacts. "Making thousands of exactly the same thing, such as pistons, meant we got better and better at making them." Mass manufacture offered enormous benefits, bringing the pTrumpet to children who could not otherwise afford to play, but "when you mass manufacture in plastics, it's hard to get a perfect prototype and build it. Instead, we had to learn how to build it – by building it".

Launched in September 2014, the pTrumpet weighed just 500 grams, and was an immediate hit. "It looks and sounds like brass at half the price," said *The Spectator*. With its universal valves (replaceable in any holes) and ability to operate without lubrication, it was a game-changer for music teachers teaching large groups.

A HYBRID TRUMPET

The pTrumpet's all-plastic system did not totally overcome the lack of compression. Escaping air makes tonal quality less focused, and can negatively affect intonation and timbre. Since the base sound quality of polymer-made instruments leans toward being warmer and less focused than brass, this leakage is particularly difficult to carry. Yet making plastic to the tolerance of 0.005 millimetres – possible with brass – was impractical commercially.

The limitations of a polymer-only solution drove Greenall and Fower to work on a hybrid: the hyTech. They aimed to retain the pTrumpet's lightweight robustness while improving playability and sound quality by adding metal where polymers "couldn't cut it at price point". Fower adds: "We'd become experts in the limits of where plastics technology could take us within reasonable budgets, so we began to think about different choices of material to create enhanced resonance."

Valves were again the main challenge. Using metal to achieve airtightness would

The pTrumpet hyTech's body is made from ABS plastic making it extremely light. The hybrid has metal for the valve block, valves, leadpipe and mouthpiece, which increases its durability and enhances resonance © Warwick Music Group

improve performance, but meant a higher price and more manufacturing complexity. The hyTech would feature a valve block made of CNC-cut yellow brass bonded into a polymer casement. The ABS plastic pistons were sleeved with stainless steel and ground to tolerance, then hand-lapped into the brass of the valve block. "The brass tubes needed to be CNC-machined to the correct dimensions within a very tight tolerance, held parallel with infilled ABS material shot around them in plastic injection mould," says Fower. "So we had to work out how to align three brass cylinders while surrounding them with strong polymer."

It was crucial to define clear parameters for tolerancing, and work closely with players and engineering manufacturing partners. Professional trumpeter Joshua MacCluer, former principal trumpet of the Hong Kong Philharmonic, helped to test prototypes. "We wanted a very tight fit on the valves to minimise air leakage and maximise sound quality, so we spent time with the factory quality staff, teaching them how to spot valves that needed reworking." Players need the ability to attain predictable resonance at a high level of action, explains Fower. "The amount of leakage in valves is really important. Metal-on-metal interaction in the system gives better compression, and that makes a player more secure in the 3D matrix of the harmonics." The hyTech would achieve valve tolerances of just .005 millimetres per side.

Fower and Greenall also developed a high-quality mouthpiece from brass with three-micron silver plating. The innovative element is in the way the receiver – the hole the mouthpiece goes into – is made. Normally in brass instruments, this tube is forced onto a mandrel two ways and manipulated, to get a double release. With the hyTech, the company CNC-mill the receiver from a solid bar of brass, and inject the internal shape. This means it has far more mass. Instead of using one or two thin bits of tube, a bar is used that allows for greater wall thickness and accuracy, as well as repeatability and consistency of finish.

Another bonus is that because the new receiver has more mass, it helps to centre the tone, while repeatability means the mouthpieces consistently fit with the right gap to make the notes stand up properly. Fower says: "It's simple engineering by modern standards, but we re-imagined how to make that part."

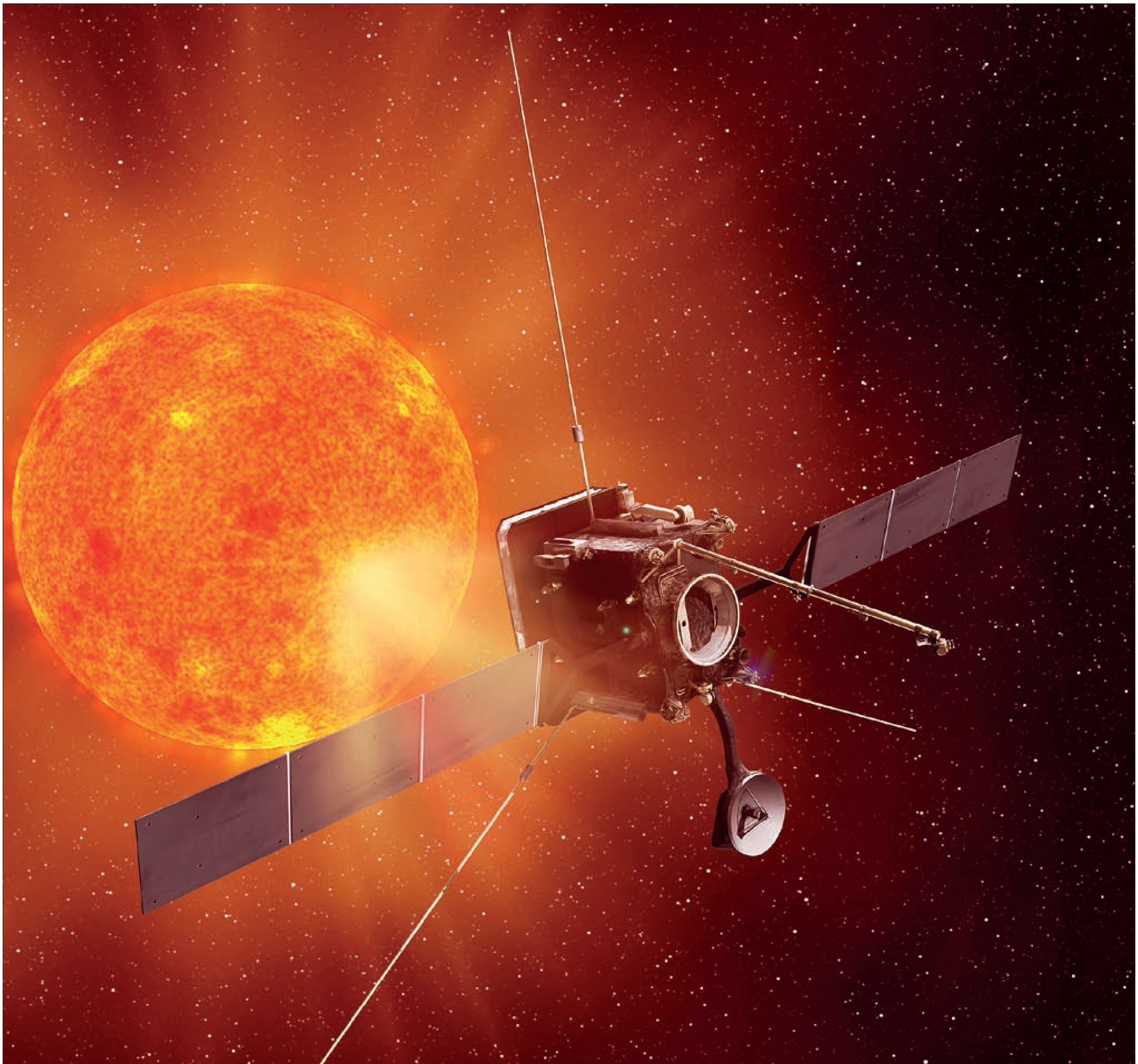
WHAT'S NEXT?

Since 2016, with the help of a second venture capital investor, Midven, Warwick Music Group has invested £1 million in R&D. It launched the hyTech in 2019 and now has eight instruments in its portfolio, including a pre-brass starter (pBuzz) that retails at just £15. Principal markets are currently the US, Europe and Japan and further instruments are being developed with another patent soon to be filed.

With few competitors, what has been the secret to its success? "We came in from the musical angle," says Fower. "An engineer can say 'I've created the perfect trumpet' but everything comes down to the sound. We had a deep understanding of why we were making this product, and we combined this with innovative thinking about materials and consultation with suppliers to transmit the 'why'. By bringing artists and engineers together, we made sure the conversation went straight and productively down the line."

Listen to the hyTech at: **https://pbone.co.uk/product/hytech/**

FLYING CLOSE TO THE SUN



An artist's impression of the Solar Orbiter facing the Sun © Airbus

A new European spacecraft, the Solar Orbiter, is set to improve our understanding of the Sun, including what gives rise to solar wind, a phenomenon that can affect technologies such as communications satellites and electric grids. The UK has invested €200 million in the €1.3 billion project and helped develop four of the instruments onboard. Tereza Pultarova spoke to Ian Walters, Solar Orbiter Project Manager at Airbus Defence and Space, about the space probe.

"The Solar Orbiter is one of the most complicated spacecraft we have ever built," said Ian Walters during a telephone call from Florida, where he and his team spent months ahead of the craft's successful NASA launch on 10 February 2020. "We have built many scientific satellites for the European Space Agency (ESA) in the past but most of them only had one instrument. Here we have 10 main instrument packages, each containing many sub-instruments; more than 30 instruments altogether, and many of them have conflicting requirements."

Airbus designed and built the 15-cubic metre probe for ESA at its UK facilities in Stevenage. The craft left the UK for Germany in September 2018 to undergo an extensive testing campaign at the IABG facility near Munich before it was shipped to the US in October 2019. Launched from NASA's Cape Canaveral base, the probe will swing twice past Venus and once past Earth, using their gravities so that it can approach the Sun in 2022 at the right angle to best view its poles.

The Solar Orbiter will travel around the star in an elliptical orbit. At its closest, it will observe the Sun from a distance of about 42 million kilometres, about a quarter of the distance between the Sun and Earth. With the exception of NASA's Parker Solar Probe, which carries a simpler set of instruments and doesn't have any telescopes to look directly at the Sun's surface, no satellite before has been so close.

This will enable the spacecraft's telescopes to see some of the never before imaged regions of the Sun, such as the north and south poles. Analysis of the star's polar regions will enable a better understanding of the Sun's magnetic field, which drives the powerful ejections of solar plasma that generate solar wind.

Geomagnetic storms caused by solar wind frequently disrupt the signals of navigation satellites, such as GPS, and could even knock out power grids on the ground and affect telecommunication networks. The Solar Orbiter will need to withstand these highly-charged electron and proton particles as well as temperatures up to 600°C and sunlight 13 times brighter than the levels experienced on Earth.

DEVELOPING A SUNSHIELD

Ensuring that the spacecraft and its instruments survive in this extreme environment for at least seven years was the

In October 2019, the Solar Orbiter had undergone a year's worth of tests near Munich. It is seen here being packaged up to be flown to NASA in Florida. The heat shield is shown on the left of the probe pointing upwards
© ESA – S Corvaja

main challenge faced by the engineers. The team could partly reuse some of the technologies developed for ESA's Bepi Colombo mission, which is currently on its way to Mercury, the planet closest to the Sun.

The Solar Orbiter, however, will get closer to the Sun than Mercury and therefore face even harsher conditions including extreme heat and cold. "However, the spacecraft will be hiding behind a sunshield," explained Walters. "That means that we don't need to design every item of the spacecraft to work at 600°C. The heat shield absorbs and re-emits the heat and behind that the spacecraft is relatively normal."

In the vacuum of space, heat can only be transferred by radiation, or by conduction between objects that are in contact with each other. The shield was therefore designed to restrict all conductive paths and radiate all the heat it absorbs to the sides rather than into the spacecraft.

The outer layer of the 3.1 by 2.4 metre-wide, 30 centimetre-thick shield consists of 40 thin layers of titanium foil, which can withstand temperatures of up to 600°C. Behind this sandwich structure is a gap that guides any heat that has made it through sideways and away from the satellite.

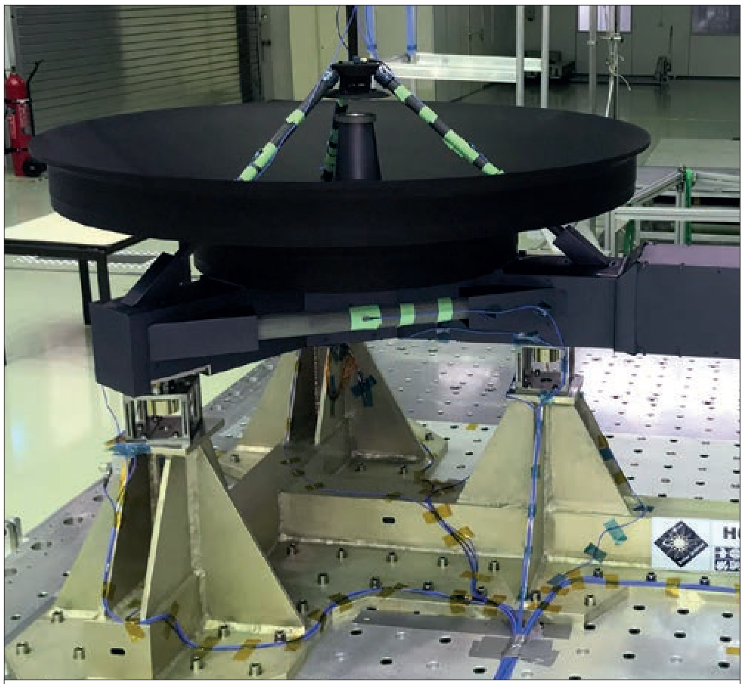
Behind the divide, attached by 10 star-shaped brackets, is the base of the shield, made of a five centimetre-thick aluminium honeycomb structure covered with 30 layers of insulation. This layer can withstand temperatures of up to 300°C with 10 1.5 millimetre-thin blades attaching the shield to the main spacecraft.

AS BLACK AS POSSIBLE

However, the key technology that enables such a close approach to the Sun is the coating on the outermost layer of the shield that directly faces the star. Called SolarBlack and developed by the Irish company ENBIO, the coating, according to Walters, is the blackest material ever flown in space and will remain as black as at the beginning of the mission, even after years in the extreme environment.

The blackness ensures that the shield radiates the heat it absorbs back into space in the most efficient way and will remain doing so after years of use. "People find it a little bit weird because black is hot on Earth," said Walters. "But if you put it in the heat, it absorbs heat fast, while also emitting it fast, so it actually gets a bit colder than if it were white." SolarBlack absorbs sunlight, converts it into infrared energy then radiates it back to space in the form of heat.

When choosing the right material for the task, it was important to ensure that it would not shed any material or release gases while in the extreme environment. In addition, the skin had to be electrically conductive in order not to create static charge, which could damage the spacecraft and disrupt measurements.



The high-gain antenna, coated in ENBIO's SolarBlack, during vibration testing at ESA's technical centre in the Netherlands © ESA/ATG medialab

The engineers considered carbon-fibre fabrics but they did not meet requirements. Instead, animal bones were used. These were burned, ground into a powder and then blasted onto the surface.

ENBIO developed the blasting process, called CoBlast, which uses two types of material simultaneously blasted onto the surface through a single nozzle. An abrasive element removes the natural protective barrier on the surface and exposes an active chemical bond to which the coating powders attach before an oxide layer forms on the surface. The abrasive element is completely inert and does not bond to the surface.

The engineers used the same material to coat the Solar Orbiter's high-gain antenna, a two metre diameter satellite dish that sticks up from behind the spacecraft into the bright sunlight and sends terabytes of scientific data to the Earth in a highly concentrated radio-frequency beam. The antenna generates a very fine beam, less than two degrees wide, to avoid any thermal distortion, which could disrupt the signal. The SolarBlack coating ensures that the antenna does not distort from the heat.

EXAMINING THE CORONAL ENVIRONMENT

The Solar Orbiter carries two types of instruments. The *in-situ* instruments measure properties of the environment in the vicinity of the spacecraft and are mounted on a 4.4 metre boom at the back of the spacecraft. There are also remote-sensing instruments, various types of imagers and telescopes to photograph the Sun at different wavelengths,

Solar Orbiter being encapsulated within the NASA rocket nose cone in February 2020 © ESA/ATG medialab

SORA

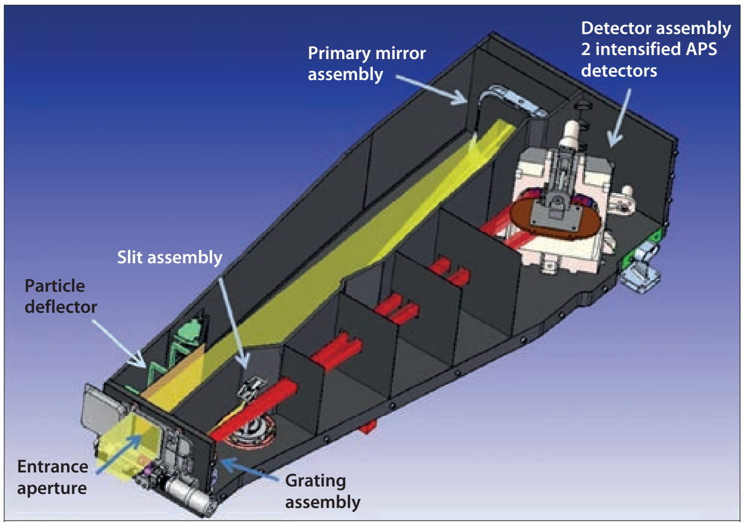
The Stood-Off Radiator Assembly, or SORA, is one of the technologies designed specifically for Solar Orbiter. It consists of a set of aluminium radiators attached to the sides of the spacecraft.

The radiators are connected to the instrument detectors with flexible cold straps, which are each 30 centimetres long and made of pyrolytic graphite, a highly conductive material consisting of layers of carbon.

These pyrolytic graphite layers are as thin as a sheet of paper and are banded together, 70 at a time, into a flexible scheme. The material is five times more thermally conductive than copper and extremely flexible. The flexibility is important because everything stretches under the heat load and also everything vibrates during the launch.

The flexibility ensures that the straps do not transmit any vibration to the sensitive instruments from the radiators, which have to be mounted away from the spacecraft on special thermally isolating mounts.

Through the cold straps, all the excess heat from inside the instrument is radiated into space. Thanks to this technology, the SPICE detectors, for example, reach the desired temperature of -20°C, at which they are most sensitive and effective.



SPICE instrument optical layout. The off-axis parabola mirror forms an image of the Sun onto the entrance slit assembly containing four interchangeable slits of differing widths. The slit selects a portion of the solar image and passes it to a concave toroidal variable line spaced grating that re-images the spectrally dispersed radiation onto two array detectors © STFC RAL Space

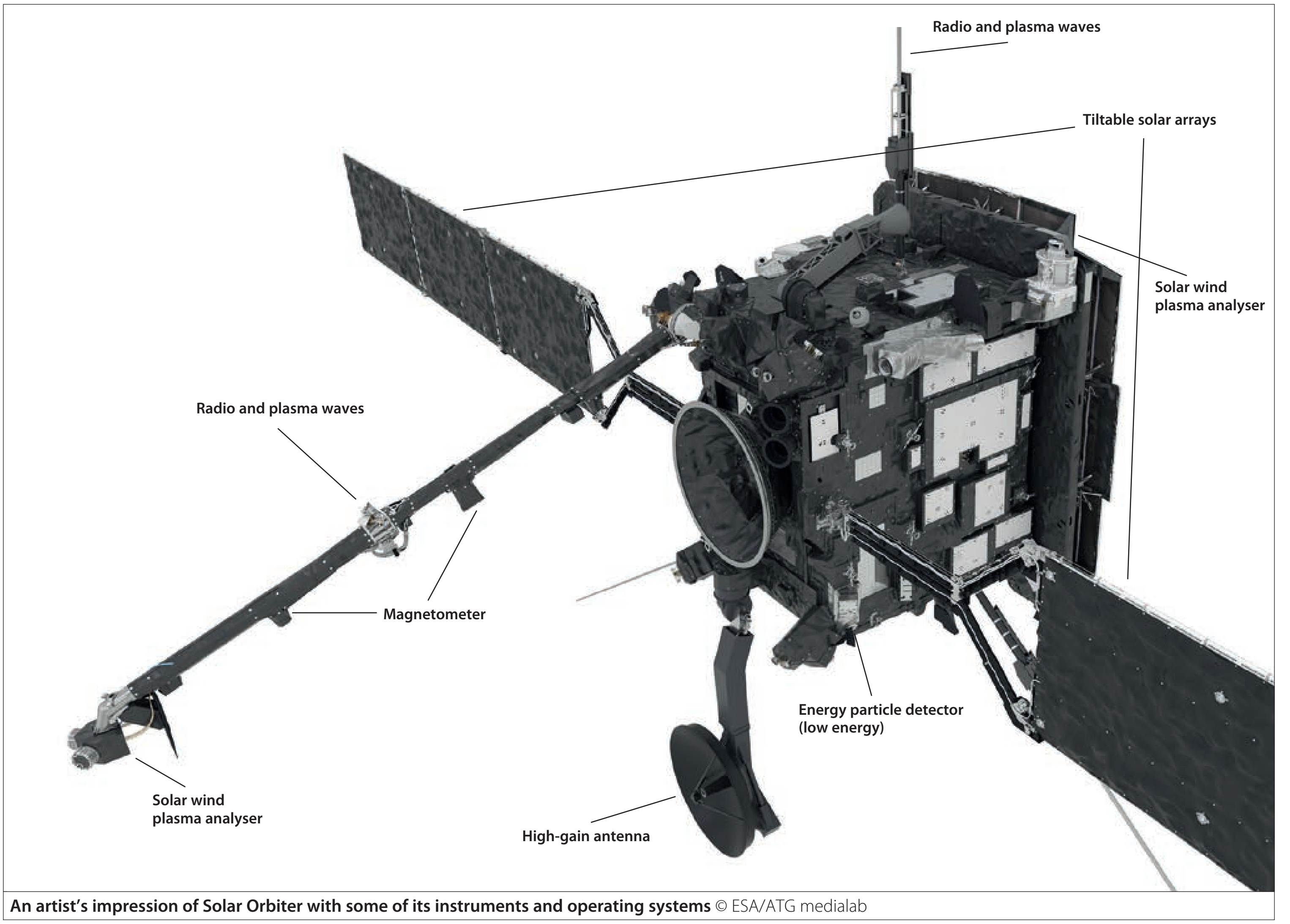
which need to look directly at the star. To enable that, the engineers cut tiny windows into Solar Orbiter's heatshield, which open at specific times for the observations. This approach prevents too much heat from leaking into the spacecraft through the instruments' feedthroughs.

SPICE (the initialisation of 'Spectral investigation of the coronal environment'), is one of these remote-sensing instruments. Built by an international consortium led by RAL Space, part of the UK Science and Technology Facilities Council, SPICE takes images of the Sun in the extreme ultraviolet part of the solar spectrum. It will study the temperature and velocities of the solar plasma, which gives rise to solar wind, according to Martin Caldwell, who served as the SPICE Systems Engineer at RAL Space.

The instrument is similar to other extreme ultraviolet spectrometers used previously on Sun-observing missions in the orbit around the Earth. SPICE though, had to fit into a much smaller envelope than had been used before, deal with the extreme amount of light and heat entering the instrument, and cool the spectrometer's detectors to -20°C to ensure accurate measurements.

"With the previous instruments, we only had to solve the optical design," said Caldwell. "But in this case, the optics wouldn't work without a very good thermal design. Also, although we might have a lot of light coming into the instrument, most of it is in the visible and infrared part of the spectrum, which not only has a heating effect, but is of no use to us."

As light enters the one-metre long instrument, it first encounters a particle deflector, a high-voltage plate that diverts the particles of the solar wind and prevents them from hitting a mirror at the end of the channel. The mirror is coated with thin boron carbide,



An artist's impression of Solar Orbiter with some of its instruments and operating systems © ESA/ATG medialab

which reflects only the extreme ultraviolet part of the spectrum into a detector compartment. The rest of the incoming energy passes through the mirror and is then sent back out into space. If the particles were not deflected and hit the mirror they would destroy the boron carbide filter within a few months.

BELOW ZERO REQUIRED

With the unwanted part of the solar spectrum out of the way, the engineers focused on optimising the measurements of the small amount of the extreme ultraviolet light. The instrument uses a two-stage detector, a UV image-intensifier plus a silicon micro electronic array, based on technology commonly used to produce integrated circuits, a complementary metal oxide semiconductor (CMOS). However, these circuits have a thermal background electric current that would interfere with the measurements. The intensity of this current drops with temperature and cooling down to -20°C is required to eliminate the problem.

"The front of the SPICE instrument behind the heatshield is about 120°C," said Caldwell. "At the end of the instrument, where the detector box is, it might be about 50°C. The detector box, which is about half the size of a shoe box, includes careful thermal-isolation, such as non-conductive materials to prevent the heat from seeping in. But that by itself wouldn't be enough."

The spacecraft engineers found a way to radiate all the excess heat out of the sides of the spacecraft that are permanently in the shadow of the shield and as cold as -200°C. The two silicon detectors, which are each only about 1.5 centimetres in size, are connected by what the engineers call a cold strap to a radiator on the shielded side – see *SORA*.

INTELLIGENT SOLAR ARRAYS

The Solar Orbiter's solar arrays presented another engineering challenge. The cells wouldn't survive the high temperatures close to the Sun and therefore have to be tilted flexibly as the spacecraft follows its elliptical orbit. The spacecraft's distance from the Sun can vary by 78 million kilometres, depending on where it is in the orbit. If the solar arrays were pointed towards the Sun perpendicularly, the temperature at the closest point would far exceed 300°C, the maximum at which the cells work efficiently. Over the planned 10-year mission span, the solar array will undergo about 20 hot-cold cycles, which, according to Walters, erodes them more than if they were constantly hot, as in the case of the Mercury probe Bepi Colombo.

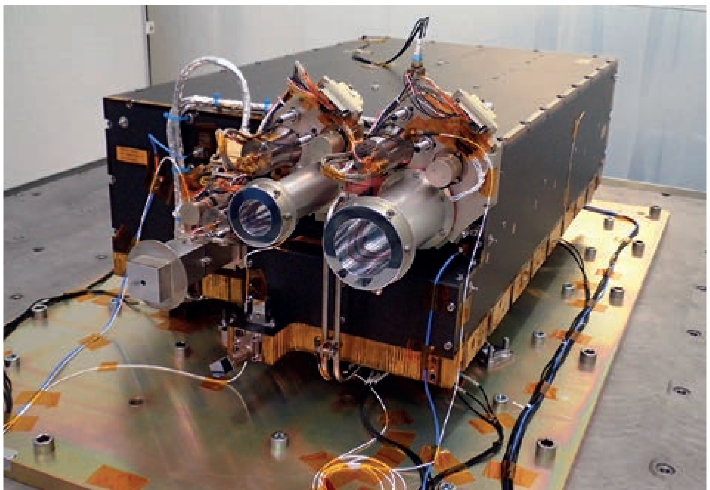
"When we are very close, at 42 million kilometres, the solar

INSTRUMENTS WITH UK INPUT

In addition to SPICE, Solar Orbiter carries three other instruments that have been built in cooperation with UK scientists and engineers. The extreme ultraviolet imager (EUI) is another remote-sensing instrument that takes images of the Sun in extreme ultraviolet. It consists of three telescopes; one dual-band full Sun-imager and two high resolution imagers, each operating on different wavelengths. The EUI will observe and analyse the global morphology and local dynamics of the solar atmosphere, in particular at the base of the corona.

The other two instruments measure the environment directly around the spacecraft. The magnetometer measures the magnetic field in the Sun's heliosphere. It is made up of two three-axis fluxgate sensors mounted on a boom in the spacecraft's shadow. Because of the magnetometer's sensitivity, the engineers had to ensure that the entire spacecraft is completely non-magnetic so as not to interfere with the measurements.

The other in situ instrument is the Solar Wind Plasma Analyser, created by a team led by UCL's Mullard Space Science Laboratory. This will provide measurements of the ion composition of the solar wind as it changes throughout the orbit, measuring its speed, density and composition. It will do this through three sensors and a data processing unit onboard. The electron analyser system will track solar wind electrons to determine the nature of the magnetic field. The proton-alpha system will define the state of the solar wind itself (such as whether it is fast or slow). Finally, the heavy ion sensor will provide the connection to spectroscopic remote-sensing measurements, thereby providing a means to identify the solar source regions of the ambient solar wind passing the spacecraft.



The fully integrated flight unit of the EUI instrument panel © Centre Spatial de Liège

array gets tilted 78 degrees away from the Sun, so that it's almost edge on," said Walters. "Otherwise it would get too hot and that would cause a lot of problems – the glues would stop being glues and the solar cells could detach, bend or distort. They would deteriorate rapidly; we would lose power and that would be mission-over."

The spacecraft runs advanced software to control the solar arrays. Fault Detection Isolation and Recovery detects faults and ensures that the temperature stays within the required limits. Since the spacecraft spends up to three months out of sight of the ground control stations, the software has to operate autonomously.

The Solar Orbiter will reach operational orbit in just under two years after launch, when it will be close enough to observe the solar surface features. The probe will train its telescopes on the surface of the Sun, revealing details on areas 70 kilometres wide. The instruments will sense the constant flux of charged particles, which engineers hope will help explain the mechanisms that are producing the magnetic fields. It could also determine what causes the huge solar explosions that have the potential to disrupt the space infrastructure orbiting the Earth. This tracking of 'solar weather' could be crucial both for future lunar explorers and those going to Mars.

BIOGRAPHIES

Ian Walters has been with Airbus since 1982. He is currently the Project Manager for Solar Orbiter. He has previously held positions of CTO / Chief Engineer for Galileo Industries, developing the complete Galileo navigation system for the EU, and Airbus VP for Navigation Systems, in Munich. He was also Engineering Manager for the Rosetta Platform and Project Manager for the James Webb Space Telescope Mid-Infrared Instrument (MIRI).

Dr Martin Caldwell is an instrument systems engineer at RAL Space, based at the Science and Technology Facilities Council's Rutherford Appleton Laboratory, part of UK Research and Innovation. He is project manager for the SPICE instrument on Solar Orbiter. His previous projects include optical instruments for the atmosphere-science mission EarthCARE, for the fundamental-physics mission LISA-Pathfinder and for the ground-based VISTA telescope at the European Southern Observatory.

Virgin Orbit uses a modified aircraft to launch satellites into low Earth orbit © Virgin Orbit

THE FINAL FRONTIER

Spaceports represent an ingenious solution to the logistical challenges of launching small satellites into orbit. Neil Cumins reports on two spaceports at opposite ends of the UK that are using different methods to launch low Earth orbit satellites into space.

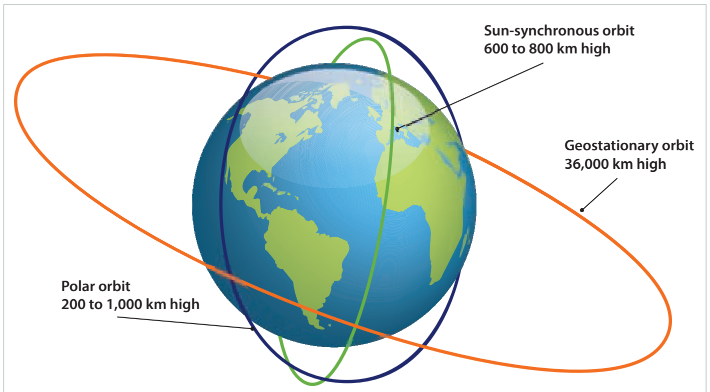
GEOSTATIONARY OR LOW EARTH ORBIT

Geostationary orbit satellites travel at the same angular velocity as Earth, remaining fixed over the same location. They can only cover latitudes between +70 degrees and –70 degrees from the equator, but a single satellite can reach a third of the planet. They travel from west to east, at a speed of around three kilometres a second. These satellites are ideally suited for weather forecasting and radio and TV broadcasting. Because one satellite can cover such a large area, ground-based infrastructure is simpler and does not need to track the satellite.

A low Earth orbit satellite has an altitude of 1,000 kilometres or less – it could be as low as 160 kilometres above Earth. These satellites take approximately 90 minutes to circle the Earth. A constellation of low Earth orbit satellites can provide 24/7 coverage around the world. Because they are orbiting in a less harsh environment, the satellites themselves can be less robust.

The uses for these small satellites range from remote sensing and planetary observation through to insurance and communications. For instance, mobile phone networks are investigating the potential for launching low Earth orbit satellites to support 5G networks, augmenting terrestrial base station antennas and small cell units broadcasting over millimetre wave frequencies. Low Earth orbit is much better for data-streaming activities such as 5G and other two-way voice and data services, since they can transfer data much quicker than geostationary satellites, thanks to their lower orbit. Because 5G will power everything from autonomous vehicles to remotely operated surgical equipment, potential outages are unthinkable; satellites could provide an always-on backup to our terrestrial infrastructure. In the coming years, companies like Amazon, SpaceX and OneWeb are planning to launch mega-constellations featuring thousands of data-distributing small satellites.

Low Earth orbit satellites can be in polar orbit– where the satellite passes above, or nearly above, both poles of the Earth on each orbit, from north to south. The alternative is a Sun-synchronous orbit, a nearly polar orbit that ensures the satellite remains in-sync with the Sun as the planet moves, so the Earth is always illuminated by the Sun at the same angle from the satellite. For launching into polar and sun-synchronous orbits, the higher the latitude the better.



The diagram shows the path and heights of different satellite orbits

There are currently over 2,200 satellites orbiting the Earth, performing a variety of civil, commercial and state-level functions

Next time you find yourself admiring the stars on a clear evening, take a moment to think about a manmade contribution to the skies above us. There are currently over 2,200 satellites orbiting the Earth, performing a variety of civil, commercial and state-level functions. However, rather than occupying a traditional geostationary orbit 36,000 kilometres above the equator, over two thirds of these satellites are in low Earth orbit, less than 2,000 kilometres above the Earth's surface.

Despite occupying a far lower altitude, low Earth orbit satellites have traditionally been launched into space using rockets, just like their geostationary cousins. These inefficient vertical-lift propulsion devices burn immense amounts of energy attempting to escape Earth's gravitational pull. For over 60 years, governments have been experimenting with alternatives to rocket-based satellite launches, and recent technological developments have heralded the arrival of the horizontal launch vehicle. So, how do horizontal launches work, and why are the spaceports they depart from being developed from Cornwall to the Shetland Islands?

THE NEXT GENERATION

Since 1957, when Sputnik I was successfully launched from the Baikonur Cosmodrome in what is now Kazakhstan, vertical take-off has been the only practical method of launch suitable for large satellites. However, recent advances in power and utility have resulted in smaller and lighter satellites. A small satellite is defined as one with a mass less than 500 kilograms, and almost three quarters of satellite launches planned for the next decade will be in this category. Some are the size of a shoebox, weighing as little as 25 kilograms, yet they're often able to complete tasks that would have been the domain of geostationary satellites just 20 years ago.

As satellites have become

The Shetland Space Centre plans to build and operate a satellite launch site and ground station on the UK's most northerly island, Unst © Shetland Space Centre

smaller and lighter, the necessity for vertical launches has diminished, and horizontal launches have risen to prominence. While fuel volumes vary according to factors such as the weight of the payload, a vast amount of energy is expended accelerating vertically from standstill to 26,700 kilometres per hour (the minimum speed required for a satellite to enter a circular orbit 800 kilometres above Earth's surface), while travelling through the five layers of our atmosphere. It's long been accepted that high-altitude launches from the troposphere (11 kilometres up, or around 37,000 feet) require far less fuel to send a satellite into orbit. Indeed, air launch technology has already underpinned a number of pioneering inner-space projects, from the US Air Force's X-15 to Orbital's Pegasus rocket.

These horizontal take-offs can be carried out by existing high-altitude vehicles, such as a plane or a balloon. These have already done the hard work of escaping the densest part of Earth's atmosphere and its strongest gravitational pull. An upper atmosphere launch location means that microsatellites can be launched into low Earth orbit comparatively affordably, potentially opening the market to smaller companies with limited funding. The launch vehicle itself can be safely returned to Earth and reused, with no parts shed (or at risk of falling back to Earth). This distinguishes them from vertical take-off rockets, whose immense fuel canisters are discarded as they struggle to escape the planet's gravitational pull. There's also an added irony that this propellant and its storage canisters contribute most of the rocket's weight on the launch pad. This further increases the four forces of flight acting on the launch vehicle (weight, lift, thrust and drag), all of which are negative factors in terms of everything from aerodynamics to fuel consumption.

A high-altitude launch also permits the use of efficient fuels that are banned from surface launches because of their relative toxicity. Stratospheric air launches aren't impacted by the tropospheric weather that could otherwise cause delays, and there are no issues with noise when a rocket is launched from 10,600 metres in the air.

Across the UK, companies and entrepreneurs have been developing innovative ways of launching small satellites without having to build launch pads and achieve escape velocity, taking advantage of these benefits.

BEST OF BRITISH

The UK has long punched above its weight in terms of satellite manufacturing. Today, one in eight satellites in the skies was manufactured in the UK. The space division of Airbus has facilities in Stevenage, while American-based Spire Global manufactures all its satellites at Glasgow's fittingly-named Skypark. Remarkably, Glasgow builds more small satellites than any other city in Europe, with the space industry contributing almost £15 billion to the UK economy each year. Indeed, the UK Space Agency has set itself a target of boosting this to over £40 billion by 2030, which would comprise a 10th of the global space economy.

Yet while the UK leads the world in satellite manufacturing and data processing, it has never had a launch site capable of sending these delicate scientific objects into space.

Virgin Orbit's Cosmic Girl takes off from Spaceport Cornwall © Spaceport Cornwall

Vertical launch sites need to be located in vast, remote (and ideally equatorial) regions, and every launch was state-funded until the 1980s. The private sector has grown in stature since then, but the continuing reliance on vertical launches has seen Glasgow satellites being shipped thousands of miles at great expense to launch sites in locations such as India.

SPACEPORT CORNWALL

The UK is at the forefront of the world's burgeoning horizontal launch sector. Spaceport Cornwall has become the UK's first horizontal launch site, using modified passenger aircraft as the satellite launch vehicle. Its status was secured by factors including immediate access to the North Atlantic with no national borders to traverse, relatively uncongested airspace, and a suitably lengthy runway already in situ. Combining civilian flights with satellite launches is a world first for any airport, but one aeroplane is very similar to another, with comparable take-off and landing procedures. Cornwall has the geographical advantage of being on a peninsular in the Atlantic ocean, and rockets can be deployed at 10,600 metres at around 480 to 800 kilometres off the coast west or north of Ireland depending on the required trajectory. However, an airliner could also take off from Cornwall and travel to any desired location before discharging its payload into a designated orbit.

Spaceport Cornwall uses the existing 2.7 kilometre runway at Cornwall Airport Newquay to send a modified carrier aircraft from partner organisation Virgin Orbit up to a standard cruising altitude of 10,600 metres, with a payload stowed underneath the aircraft's body. The pilot pulls the aircraft up to a relatively sharp pitch angle to facilitate the release of a 16-metre two-stage rocket that houses the satellites. This is dropped from under the aircraft wing – one of five air launch configurations known as 'captive on bottom'. Alternatives include towed or internally-carried upper-stage air launch systems.

Virgin's LauncherOne rocket is capable of carrying a gross payload of 500 kilograms. As this is dropped from the aircraft's wing, the main stage engine ignites, before detaching once its fuel is spent. The second stage then ignites to complete its satellite payload's journey into a low Earth polar or Sun-synchronous orbit. Once the payload has been successfully deployed, the carrier aircraft returns to the runway ready for its next mission. This enables rapid creation or replenishment of satellite constellations, and it is possible to schedule flights at just 24 hours' notice.

While horizontal launches are

Launch engineers monitor data screens on Cosmic Girl's flight deck © Virgin Orbit

not new, the dwindling size of satellites has meant that their delivery vehicles have also been able to shrink in size, cost and environmental footprint. Far less fuel is expended getting an aeroplane to 11,000 metres than a vertical launch rocket, and Virgin Orbit's Cosmic Girl launch aircraft is a reconditioned passenger airliner (see 'Who's that girl' box). The approximate cost of launching each satellite is around £10 million – a tiny amount compared to the cost of a vertical launch. With Cornwall acting as Virgin Orbit's European operations hub, launches could be scheduled mere days in advance without disrupting existing air traffic.

NORTHERN EXPOSURE

Over 900 miles north of Spaceport Cornwall, on the island of Unst, another domestic spaceport is taking shape using more traditional aviation technology. Located at the very edge of the Shetland Isles, two kilometres from Britain's most northerly house, the embryonic Shetland Space Centre offers a unique set of advantages as the location for low Earth orbit satellite launches from balloons. Direct flightpaths into polar and Sun-synchronous orbits do not pass over population centres or oil installations, and there is no interference from commercial airline traffic or military flights. In locations affected by one or more of these factors, dogleg launch trajectories are generally required – necessitating larger rockets and smaller payloads.

High latitude means that at the North Pole, satellites can be seen an unrivalled 16 times a day. Because Unst boasts the UK's highest latitude, Shetland Space Centre's comparable figure of 9.4 viewings per day is the best in the UK, making it an optimal location for downloading data from space. Unst has logistics infrastructure and supply chains already in place for the dwindling North Sea oil and gas industries, and after four decades of reliance

A trial balloon launch using a smaller balloon demonstrated the viability of the concept © Shetland Space Centre

on the oil and gas sector for jobs, Shetland boasts an established local workforce of talented engineers with transferable skills.

Companies like Lockheed Martin and ArianeGroup have already entered into partnerships with Shetland Space Centre (SCC). SSC is currently submitting a planning application to develop a 190-acre site across Lamba Ness and a former RAF airbase, incorporating everything from satellite assembly buildings to rocket fuelling facilities. In the meantime, SSC has hosted a test balloon launch by Bristol-based B2Space last summer. This successful trial demonstrated the viability of the Rockoon rocket launch technology, adapting a 1950s US Navy concept of conducting launches from a high-altitude balloon. Similar tests have already been conducted in the US's Mojave Desert, and it is anticipated that 25 kilogram satellites the size of a toaster could be affordably launched from 100-metre-tall gas-filled balloons, slowly ascending to the stratosphere before discharging their payload into orbit.

A VIRTUOUS CIRCLE

There is also a fringe benefit to the use of small satellites, which are intended to last a couple of years before falling out of orbit and burning up without leaving any space debris behind. Their shorter lifespans (compared to the 15 to 20 years of geostationary satellites) will necessitate a consistent turnover of new satellites being launched from facilities like Spaceport Cornwall and Shetland Space Centre. This cycle of regular replacement will provide long-term revenue streams for UK spaceports, supporting jobs and helping to maintain the UK's position as a world leader in satellite design, manufacturing and launch.

WHO'S THAT GIRL?

Virgin's involvement in horizontal launches might seem curious, but as with many of its business ventures, the company identified an underserved customer community – something of a rarity in the aerospace community. A department within Virgin Galactic (the division focused on human spaceflight and space tourism) was spun off in 2017 to form Virgin Orbit, focusing exclusively on satellite launch services.

Virgin Orbit chose a Boeing 747–400 as its carrier aircraft because of its large carrying capacity, global supply chain and some unusual technical criteria. This aircraft was always designed to carry weight where the rocket is located – known variously as the fifth engine pod or fifth engine carry position. A programme of internal modifications was then undertaken, from stripping out extra weight on the passenger deck (such as seats, overhead bins and the galley) through to reinforcing the left wing where the rocket hangs. This simple yet ingenious conversion has already convinced the RAF to sign up to fly payloads on Cosmic Girl and its LauncherOne rocket, while other clients include OneWeb, ImageSat and Spaceflight.

The LauncherOne rocket is carried under the aircraft wing © Virgin Orbit

Professor Sir Jim McDonald FREng FRSE has spent his career working in power engineering. In 2019, he was elected President of the Royal Academy of Engineering

LIFE IN ELECTRIFYING TIMES

Professor Sir Jim McDonald FREng FRSE has seen profound changes in his career in power engineering. First working as a transmission and distribution engineer, he moved into the academic world at a time when the electricity industry was going through a revolution in business and technology. On the way, he became immersed in policy issues, leading to a conviction that engineering is essential to delivering sustainable energy. In 2019, he was elected President of the Royal Academy of Engineering.

Sir Jim McDonald gets really enthusiastic if you ask about his family. "After the Academy, and Strathclyde, the other thing that I like to talk about my family. All my three children are engineers, including my twin daughters." One daughter works on smart grid technologies for UK Power networks, another daughter worked for National Grid before becoming a consultant at Deloittes working in infrastructure and energy. His son is just finishing a master's degree in electrical and mechanical engineering and when he graduates will join Scottish Power to work in renewable power. "I am very proud of my family," says Sir Jim. He jokes that, not to be outdone, when mixing in engineering circles his wife, a podiatrist, "calls herself a biomedical engineer" © Martin Gammon

Eminent engineers often mention Meccano and construction toys when asked what sparked their passion for their subject. Sir Jim McDonald adds visits to the rope-making facilities in the docks in Govan and Clydebank where his father worked. "These were very significant manufacturing processes," he explains. With this experience, and two brothers who were craftsmen, McDonald had a better idea than many of the possibilities of a technical career. "There were a lot of good craftsman skills running down the family," he says. "I was just surrounded by it. Anything that needed fixing could be fixed by the family." He still uses his father's tools.

Unfortunately, the family's fixing skills did not encompass electronics. "From about the age of 12, I had a dreadful habit of pulling radios apart," he explains. "I do remember managing to destroy one hire-purchase TV set. I was made to feel very guilty about that." Far from being a deterrent, if anything the experience spurred him on. "Once I had decided that I couldn't figure out how it worked, I started having conversations with my physics and maths teachers at school." Those chats set Sir Jim on the road to a career in electrical and electronic engineering.

Sir Jim had a practical reason for tackling electronics. Like many young people, he was interested in music, not just as a listener, but as a member of a band. Money earned stacking shelves and doing a paper round went into buying a second-hand electronic amplifier. Not content with how loudly the band could play, Sir Jim tweaked the amplifier's electronics to turn up the volume. "I was quite proud of myself," he boasts. "That got me even more interested in electrical and electronic engineering."

That early interest led to a career as an engineer in electricity distribution, power system economics, and the rise of Scotland's wind power industry, not to mention heading up the University of Strathclyde, the university that started his career in engineering.

Graduating in electronic and electrical engineering, Sir Jim's results were good enough to elicit an invitation to study for a PhD. The pull was not powerful enough to compete with another strong influence. Newly married, his wife was a podiatrist, "she was working and earning and was keen that I joined her on that journey." Sir Jim joined the electricity supply industry where he worked as a transmission and distribution engineer.

ELECTRICAL ENGINEER

His encounters with real world engineering began towards the end of his degree course, as a part of the Scottish Electrical Training Scheme (SETS). Sir Jim describes SETS, effectively a graduate apprenticeship, as "a terrific way for me to get into the world of work. While I was a keen engineer, I had no real experience of professional engineering." Sir Jim first worked in the state-owned electricity industry for the South of Scotland Electricity Board, now Scottish Power, and then the North of Scotland Hydro-Electric

Board, now SSE. In the private sector, he spent time with Parsons Peebles, Hayden Young – now part of Balfour Beatty, and Ferranti.

Working in the industry did not kill Sir Jim's interest in research. "Because I had been offered a PhD it was always in my mind that research studies could be interesting." He decided to continue his education with a master's degree in electrical power engineering. South of Scotland Electricity Board didn't just sponsor that course, it continued its support when Sir Jim decided to start a PhD in power system economics. "The PhD was for me to understand engineering policy and economics. I was broadening myself to be able to pursue maybe a senior industrial career."

As it turned out, the PhD, in spot pricing of electricity, began his move back into academic life. During that PhD, Sir Jim decided to gatecrash a leading research centre for power system economics at Massachusetts Institute of Technology. "I had done the usual Scottish thing," says Sir Jim, "I turned up unannounced, during a holiday to Boston. I said 'I am Jim McDonald, I'm working on power system economics, I really think I could be useful to your research programme.' After the laughter had died down, they invited me back for a short sabbatical and I completed my PhD."

This Scottish invasion of an American university was not part of a grand plan to return to full-time academic life. However, it wasn't long before Sir Jim was lured back in. At the time universities wanted to recruit people with business experience. "The New Blood Lectureship programme was launched in the UK." This was, he enthuses, a terrific scheme. "It was structured to get young men and women, who had maybe five to 10 years' of experience in industry, to go back into academia." So he returned Strathclyde in 1984 with the notion, he says, of staying for three years. "That was 35 years ago," he laughs. "I went in, and I truly enjoyed the engagement with students. I loved their energy. I loved their excitement."

For his part, Sir Jim offered students something a bit different. "I was giving them industrial insights." That was particularly useful in the latter years of a degree course, "when they are full of theory". They have spent plenty of time in lectures and laboratories. "Then we start talking about 'here are the sort of problems that you need to solve'."

Sir Jim immersed himself in research into electrical power systems and set about establishing facilities for that research. He embarked on this process around the same time that the government was privatising the generation, distribution and supply of electricity in the UK, with inevitable consequences for R&D in the sector. "Moving into private ownership meant that the drivers for innovation and technological impact were shifting."

"Purely by good fortune," Sir Jim explains, "we found ourselves in a very strong position to create what we called the Centre for Electrical Power Engineering." With credible industry experience as a transmission and distribution engineer and because he had started his research group just before privatisation, the academics were in a good position to take their research out of the laboratory and into industry. "We could," as he puts it in current parlance, "do translational research that was further up that Technology Readiness Level that was relevant to industry. It has been effectively a 25-year journey where we have built strength upon strength. We have kept at the core of that great PhD work and we now have the largest electrical power engineering group in Europe at Strathclyde."

When Sir Jim was forging his business links, in the 1990s, it was less common for academics, even in engineering, to work closely with industry. Sir Jim was always keen to make an impact. "The thing that always attracted me was the conduct of good curiosity-based research, but user-driven, user-inspired. That worked for me as a young academic with a growing group." He could pair his industrial experience with his growing research capabilities.

Sir Jim cemented his industry links by working with Rolls-Royce. "I became the Rolls-Royce Professor of Electrical Systems in 1993," he explains. "It was natural, the Centre for Electrical Power Engineering allowed me to cut my teeth on academic industrial collaborative research. We actually won the Queen's Anniversary Prize in 1996 for the work that we did on electrical power engineering."

Rolls-Royce then made a "big decision", as Sir Jim puts it, by setting up its first University Technology Centre (*Ingenia* 47, June 2011) in Electrical Power Systems in 1997 at Strathclyde. Sir Jim sees interesting engineering opportunities in bringing electrical engineering from the power sector into aerospace. "When we look at them structurally, aircraft start to look like flying electrical systems. Which means that we can start to translate what we know works in distributed generation systems, and we can take those architectures into both aerospace and marine applications."

He illustrates the value of maintaining close links between academics and industry with an example. In 1987, a call came from the chair of the Eastern Electricity Board. It had just come through the trauma of widespread power cuts caused

Past President Dame Ann Dowling OM DBE FREng hands over the Presidential medal to Sir Jim, with CEO Dr Hayaatun Sillem CBE

by the massive storms that had brought much of the UK to a halt. "They said 'Our control room engineers in Ipswich were overwhelmed by telemetry that had come in'." Far from being helpful, this data flood had made it more difficult for the engineers to restore the system. "They asked 'Do you guys do anything in data management or AI?' Well at that time we didn't." That soon changed. Sir Jim's group quickly drew up some PhD projects. "Within three or four years we had implemented, as we called them in those days, expert system decision support tools for the control room."

Sir Jim sees this as a nice vignette of the technology readiness level journey. "We heard loud and clear an industry demand statement, and we were able to respond with PhDs, and then to turn the research into a product."

SPINOUTS AND ENTERPRISE

This leads into a discussion into the role of spinout companies in commercialising university research. Sir Jim has been involved in several power and energy spinouts. For example, Bellrock Technology grew out of university work on AI. The company, still based in Glasgow, sells AI tools and techniques to the power industry. Another spinout company, Smarter Grid Solutions, supplies software that helps power companies to manage electricity generation from distributed sources of renewable energy, an increasingly important area of research at Strathclyde.

Sir Jim then mentions another business based on power engineering that also draws on optoelectronics, another of Strathclyde's strengths. Synaptec, founded in 2014, uses fibre Bragg grating sensors on a single optical fibre to measure current, voltage, vibration, and temperature in power networks. The sensors can monitor the health of power networks that have to accommodate an array of renewable energy sources.

These spinouts are good examples of how Strathclyde's academic research has facilitated the growth of 'clusters' of companies in power technology and photonics. The clusters have also attracted research organisations that can help to accelerate the conversion of academic research into commercial applications. For example, Sir Jim was involved in bringing the Offshore Renewable Energy Catapult to Glasgow eight years ago and is its senior independent director. "I think that Catapult can claim to have had a significant contribution to reducing the cost of offshore wind energy by two thirds." The university also hosts another Catapult, the Advanced Forming Research Centre, Scotland's only High Value Manufacturing Catapult centre. Glasgow is also a home to the Medicines Manufacturing Innovation Centre. In photonics, Sir Jim mentions the Fraunhofer Centre for Applied Photonics, the UK's only Fraunhofer, he adds. "One of the things that attracted them to us was our deep strategic commitment to the translation of our research into industrially applicable outcomes."

Sir Jim was also behind moves to provide another essential ingredient in the development of technology clusters and startup businesses: finance. Four years ago, he was behind the creation of Strathclyde's Enterprise and Investment Committee. He can even point to local connections who championed the idea of the Academy's own Enterprise Hub, now in its seventh successful year. "Hub founder Ian Shott was the founding chairman of our industrial and biotech innovation centre at Strathclyde."

Is there something about Glasgow that attracts these activities? "I am conscious that I shouldn't be talking too much about my own place, but you can't help it. I have to be careful not to put a kilt on this too often," he jokes. But there is no denying that the place has its attractions. He cites a recent example when, in 2017, the Scottish Government announced that Strathclyde would be the anchor university for the National Manufacturing Institute for Scotland (NMIS). With an investment of £65 million, NMIS will be heavily involved in skills and training and in research.

It could also play a role in Scotland's response to the concept of Industry 4.0.

Sir Jim see this as a "classic example" of the challenges and opportunities facing engineering and manufacturing. The concept, also dubbed the fourth industrial revolution, will change the shape of manufacturing. As Sir Jim describes it, Industry 4.0 is about data science, sensing, AI, robotics, and automation. "It is a fantastic opportunity for the UK to recognise the challenge for society, to engage with this, but to highlight the opportunity and, very importantly, to capture the economic value in the UK."

Sir Jim McDonald at Buckingham Palace receiving the Queen's Anniversary Prize for Higher and Further Education from His Royal Highness The Prince of Wales. He received the award on behalf of the University of Strathclyde, which was selected as a winner for its excellence in energy innovation

EVIDENCE-BASED POLICY

This takes the conversation into the broader area of policy and his new role at the Academy. His position at Strathclyde and in Scotland has given him plenty of experience to draw on. With Scotland's First Minister, he has co-chaired the Scottish government's energy advisory board since its inception. He describes this as "an excellent way for him to see how independent analysis generates data and how the evidence can be compelling."

On the research side, Sir Jim also chairs Scotland's Energy Technology Partnership, an alliance of 13 Scottish Higher Education Institutions. Supported and co-funded by the Scottish Funding Council, the partnership supports industry in and beyond the Glasgow energy cluster with energy R&D. Yet another role for Sir Jim is as chair of the Scottish Research Partnership in Engineering.

Sir Jim sees these activities as important in maintaining links with the research community. "It would be unfair to claim that I am leading research," he adds. "But I'm still well engaged with the research community." Research contacts are an invaluable source of the evidence that should guide informed policy decisions. Sir Jim has been around long enough to know that you cannot force politicians to follow evidence. However, as he puts it, "if you can get a strong evidence base, and you can gather support from business, industry, and civil servants who have been persuaded of the argument, my experience has been that it can be remarkably powerful."

For Sir Jim, the Academy's new National Engineering Policy Centre is "a fantastic asset. We are working in partnership with 39 other professional engineering institutions," he explains. He describes the Centre's recent report, *Engineering priorities for our future economy and society*, as "a solid piece of work that should set the tone for the new government".

NET ZERO

Another current study is on the systems approach to decarbonising the UK's energy system. This touches on one of today's most important policy issues where convincing evidence is essential: climate change and the ambition to achieve 'Net Zero' – eliminating the UK's emissions of CO_2 into the atmosphere. Sir Jim has previously worked with Chris Stark, chief executive of the Committee on Climate Change (CCC), the body that advises the government on emissions targets and preparing for climate change. "He and I worked very closely to generate the Scottish government's energy systems strategy. I think you will see echoes of that commitment in the CCC's recommendations for climate change Net Zero. That has had a remarkably quick impact on the UK government's commitment to addressing these climate change problems."

Some of the biggest impacts of moves to Net Zero will be in the electrical power industry. Across Europe there will be hundreds of billions-worth of investment in grid infrastructure, in energy sources, but it cannot be just more of the same, Sir Jim insists. "It has to be smart grid. It has to be low-carbon power sources. It has to be electrification of transport." Strathclyde has been preparing for this. "The whole notion of energy systems is where we have moved our research over the past 10 years."

Sir Jim plans to put sustainability, and the target for the UK to achieve Net Zero emissions of carbon dioxide, at the heart

Sir Jim in his role of Chair of the Academy's Research Committee at the annual Research Forum, which showcases world-class engineering research funded by Academy programmes

of his work at the Academy. "What I'm hoping to do with my colleagues in the Academy, and with the Fellowship and our partners, is to put global sustainability at the heart of what we are doing. Very importantly for me, engineering is a big part of how we might deliver that. The policy frameworks have to be in the right shape, investment opportunity has to be there because we need to build industries and economic opportunity, but the real thing that is going to make a difference is engineering that future."

While saving the planet is clearly essential, Sir Jim sees other benefits in striving for Net Zero. "There is a real opportunity for the UK to come up with its solutions to meet the Net Zero carbon targets and at the same time build market opportunity." By leading the way in developing and implementing new technologies, the UK can become a showcase for the rest of the world. "It will also attract people from around the world to come here to be both educated and inspired by the fact that the UK is implementing low-carbon solutions. Of course, this is something we will demonstrate this year when the UK hosts COP26 in Glasgow. The eyes of the world will be on us in November at this meeting and expectations are growing for agreements to be settled and acceleration from words to action as a matter of urgency."

It will require a massive effort to achieve these changes. "What we're finding now is that the multiple challenges of decarbonising energy, achieving energy efficiency, changing the face of transport, are going to need multiple engineering skills. The Academy can help move us from what is a problem space to a solution space, using the full spectrum of our engineering expertise across the Fellowship."

On the broader front, Sir Jim expects the Academy to play a significant role in the government's ambition to increase the UK's investment in R&D to 2.4% of GDP. "If we achieve that, it will be another £15 billion per annum going into R&D, two thirds of which is expected to come from private sector sources." Sir Jim believes it will be critically dependent upon collaboration between industry and academia. But industry and business need to see benefit there. "That is where the Academy has an important role to play, to connect the academic and industrial communities, to help to deliver what is a major policy target." Fortunately, Sir Jim has personal experience on all three fronts, academia, industry and policy.

BIOGRAPHY

Michael Kenward OBE has been a freelance writer since 1990 and is a member of the *Ingenia* Editorial Board. He is Editor-at-Large of *Science|Business*.

CAREER TIMELINE AND DISTINCTIONS

Transmission and Distribution Engineer, **1978**. Joined University of Strathclyde, **1984**. Professor of Electrical Power Systems, **1993**. Fellow of the Royal Academy of Engineering, **2003**. Principal and Vice-Chancellor of the University of Strathclyde, **2009**. Awarded knighthood, **2012**. Elected President of the Royal Academy of Engineering, **2019**.

WIRELESS FOETAL MONITOR

The Monica Novii wireless patch® system is a wearable device for women in labour that accurately and continuously monitors the baby's heartbeat.

The monitoring of foetal heart rate and contraction during pregnancy and labour has been clinical practice over the last 40 years – helping evaluate the wellbeing of the unborn baby and mother. Two belts wrapped around the mother's abdomen have been used to hold separate transducers connected to a bedside monitor called a cardiotocograph (CTG). Now, a team of engineers and healthcare experts have invented a wireless waterproof patch system that reliably and accurately measures a baby's heartbeat without belts.

The Monica wireless patch is a single-use, peel-and-stick disposable item that attaches to the woman's abdomen using adhesives. The patch incorporates electrocardiogram (ECG) electrode areas that pick up ECG and electromyogram (EMG) signals from the skin surface and passes them to the Monica Pod. The reusable pod magnetically connects to the patch to gather both the foetal and maternal ECG and EMG signals. This small electronic pod then filters, digitises and processes these signals to extract, in real time, the foetal and maternal heart rate, plus uterine activity (contractions) data. The pod wirelessly transmits this data to a bedside interface monitor directly connected to an installed base CTG machine, enhancing the efficiency of valuable hospital resources.

Before achieving European CE approval and US Food and Drug Administration approval in 2011, the device had to demonstrate over 90% success rate. It did this and succeeded in achieving just 0.4% foetal/maternal heart rate confusion compared with 10% of its nearest competitor. Previously, the need to frequently move the transducer belts to capture the heartbeats had taken a medic's time away from focusing on the mother-to-be. The innovative patch means that there is no need to reposition the device.

The small Monica pod attached to the mother's abdomen wirelessly transmits foetal heart rate, maternal heart rate and contractions to a bedside monitor © GE Healthcare

Research on this innovation started in the 1990s within the Department of Electrical and Electronic Engineering at the University of Nottingham. Electronics engineer Professor Barrie Hayes-Gill and biomedical engineer Professor John Crowe recognised the signature differences between the foetal and maternal ECG as a way of separating the two intertwined signals. However, because the foetal ECG was so small, the electronic noise on the mother's abdomen interfered significantly with the signal. The team worked to reduce the noise and eventually increased the visibility of the many foetal ECG complexes. They then created a three-channel abdominal system, which ensures that if the foetus moves out of range of one channel, it falls into the range of another. These features were subsequently combined into four international patents.

In 2005, Professor Hayes-Gill formed Monica Healthcare, a university spin-out, with electronic engineering colleagues, Dr Carl Barratt and Dr Jean Francois Pieri, along with mechanical engineer, Dr Terence Martin. With £500,000 of venture capital funding, Monica Healthcare worked to file a further eight patents and published work indicating significant improvements over the belt-based systems. In 2017, the company was sold to GE Healthcare – its North American distribution partner – which has led to the product, now called the Monica wireless patch®, being available to millions worldwide.

The patch allows mothers to move around freely while being monitored, which can help to shorten labour, reduce interventions and help the birthing experience. The device overcomes heart-rate confusion between mother and unborn child and is unaffected by high body mass index, unlike the traditional belt ultrasound method.

The Monica device has won many obstetric and engineering awards. The latest engineering award came in November 2019, when the Royal Academy of Engineering awarded the team with the Colin Campbell Mitchell Award.

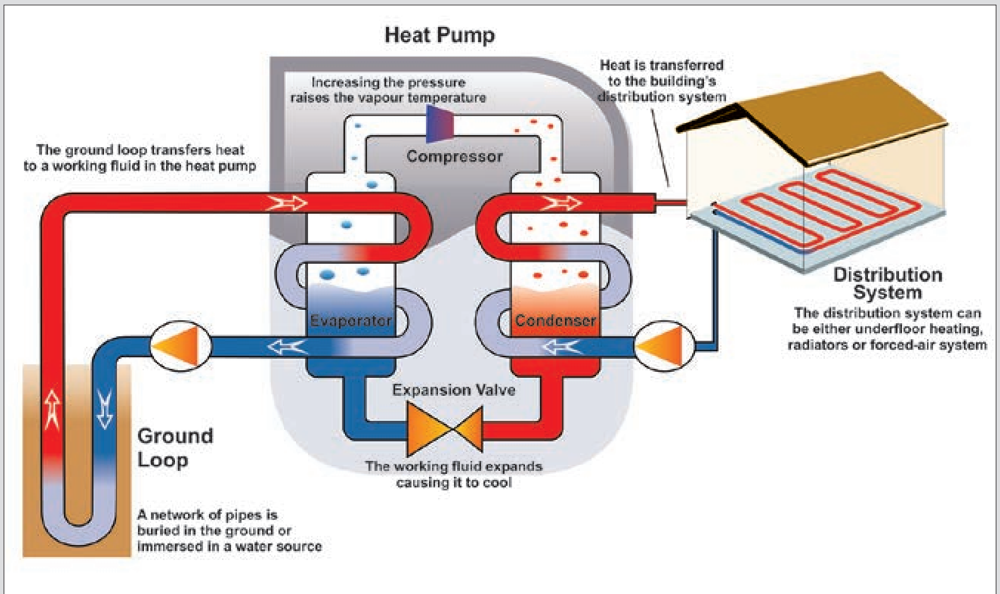
HOW DOES THAT WORK?

GROUND SOURCE HEAT PUMPS

These geothermal systems harness natural heat from underground to provide heating for buildings.

Ground source heat pumps (GSHPs) have been used for many years in North America, Sweden and Germany. Now they are being increasingly deployed in homes and commercial buildings in the UK, with the government providing financial incentives to owners who install them.

GSHPs are made up of three elements: a ground-heat exchange loop, a heat pump and a distribution system above ground. High-density polyethylene pipes are laid out underground, usually in coils to maximise the length available; for every 10 metres of pipe, one kilowatt of energy can be absorbed from the ground. The pipe is usually laid in horizontal trenches next to the building. If there is not sufficient room in the garden, a borehole can be drilled down to a depth of 15 metres to 150 metres. Another option is to lay the pipes in a pond or lake.



Source: Geothermal Heat Pump Association of New Zealand

A mixture of water and antifreeze is then pumped around the loop absorbing the trapped underground heat (around 10°C). The water mixture is then compressed and passes through a heat exchanger, which extracts the heat and transfers it to the heat pump.

The heat pump consists of an evaporator, compressor condenser and expansion valve, and uses the principles of the Carnot cycle to increase pressure and raise vapour temperature (up to 50°C). The evaporator converts the working liquid to a vapour; the compressor significantly raises its temperature and pressure; the condenser transfers the heat to the building's distribution system; and then the expansion valve cools things down so that it becomes, once more, a cold mix of liquid and vapour.

The maximum efficiencies derived from this system are through underfloor heating or large, low temperature radiators. If the heat pump needs to reach a higher temperature, the efficiency is reduced.

GSHPs generate less carbon dioxide than conventional heating systems although they still require electricity to drive the compressor unit and the circulation pumps. If this electricity is derived from renewables it becomes zero-carbon to run. For every unit of electricity used to work the pump, between three to four units of heat are made.

GSHPs can also be used on large-scale projects. The UK's largest GSHP system was recently completed in Enfield, London. A total of 400 flats across eight tower blocks were linked up to eight boreholes. Each flat has its own heat pump and it is expected that the residents will see their energy bills reduced by 30% to 50%. The initiative won the 2019 District Heating Project of the Year.

There is also a market for air source heat pumps in the UK. These operate in a similar way to GSHPs but use air to transfer heat from outside a property to the inside. The upfront costs are lower as they don't require any digging, just a unit set up alongside. However, air source heat pumps are less efficient than GSHPs because they are subject to fluctuating air temperatures and must work harder (use more electricity) to produce heat when the outside air temperature is lower.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