ingenia

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GREENER CONCRETE

MAKING THINGS IN SPACE

INNOVATIONS TO STEM BLOOD LOSS

DECARBONISING INDUSTRIAL HEAT

Royal Academy of Engineering

Royal Academy of Engineering

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Front cover
Artist's impression of thermal energy storage depicted by a flamed butterfly captured in a net representing various forms of storage © Benjamin Leon

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WELCOME

Engineers come up with solutions. They can address complex challenges in areas such as decarbonisation, manufacturing and healthcare – as demonstrated in this issue.

On page 15, authors and military personnel Colonel Nigel Tai and Rob Staruch call on engineers to tackle the challenge of stopping the bleeding caused by non-compressible haemorrhages, potentially saving thousands of lives in the process. Meanwhile, the opinion on page 8 explains why the views of both patients and healthcare professionals are key to developing medical devices.

With a focus on sustainability, on page 10, Leonie Mercedes looks into current approaches to decarbonise concrete, to cut down on its significant CO_2 emissions. And a few pages later, we look at some of the technologies that researchers are investigating to store the heat used at high temperatures in industry.

Engineers are also looking at challenges in pioneering ways, such as manufacturing in space – from 3D printing parts to developing cancer drugs – and using AI to predict the weather, the latter of which is discussed by Met Office CEO Penny Endersby CBE FREng in the profile. And in this issue, our How does it work? article explains how some very specific engineering helps divers to breathe underwater.

What challenges would you like engineers to look at? Have your say by contacting us at **ingenia@raeng.org.uk** or **@RAEngNews** on X using **#IngeniaMag**.

Faith Wainwright

Faith Wainwright MBE FREng
Editor-in-Chief

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CONTENTS

UP FRONT

FEATURES

IN BRIEF

MACHINE LEARNING INNOVATORS WIN 2025 QEPRIZE

Three of the winners of the 2025 Queen Elizabeth Prize for Engineering (L–R): Professor Yoshua Bengio, Professor Yann LeCun, and Dr Bill Dally

In February, the 2025 Queen Elizabeth Prize for Engineering (QEPrize) was awarded to the seven engineers who made modern machine learning possible. The contributions of Professor Yoshua Bengio, Professor Geoffrey Hinton, Professor John Hopfield, Dr Yann LeCun, Jensen Huang, Dr Bill Dally, and Dr Fei-Fei Li have been vital in driving progress in artificial intelligence (AI).

The collective effort of these engineers has been pivotal in advancing the three core pillars of modern machine learning: advanced algorithms, high-performance hardware, and high-quality datasets. These interrelated breakthroughs underpin the widespread adoption and application of AI systems that are revolutionising industries, transforming daily life, and reshaping how we live and work – all made possible by the pioneering vision of this year's laureates.

Modern machine learning, which enables systems to learn from data, recognise patterns, and make predictions without explicit programming, has revolutionised AI by allowing models to self-improve with new data. Professor Yoshua Bengio, Professor Geoffrey Hinton, Professor John Hopfield, and Dr Yann LeCun have been instrumental in championing artificial neural networks, which are now the dominant model for machine learning. Their groundbreaking research laid the conceptual foundations for this approach, enabling machines to process and learn from vast amounts of data in ways previously unimaginable.

Jensen Huang and Dr Bill Dally led developments for the hardware that underpins the operation of modern machine learning algorithms. Their graphics processing units (GPUs), and later more advanced chip architectures, have been central to scaling machine learning algorithms, making them powerful enough to support today's AI applications.

Dr Fei-Fei Li recognised the critical need for high-quality datasets to

The winning trophy design (left), by Prerak Bothra from India (centre). (Right) Ramya Krishnamoorthy (right) receives the Highly Commended prize from Create the Trophy competition judge, Dr Zoe Laughlin (left), who is Co-Founder and Director of the Institute of Making at UCL © QEPrize_JAlden benchmark progress as well as train and evaluate machine learning models effectively. By creating ImageNet, a large-scale image database, she enabled access to millions of labelled images that have become indispensable and instrumental in training and evaluating computer vision algorithms.

The contributions of these seven engineers have laid the foundation for machine learning technologies powering some of the most exciting innovations of our time. From revolutionising healthcare diagnostics to enabling self-driving cars and personalised recommendations, their work highlights the transformative potential of AI in shaping a better future.

The winners of the QEPrize will share a £500,000 prize for their achievements, and will also receive a unique trophy designed by the 2025 Create the Trophy competition winner, Prerak Bothra, from India. The competition asks young people aged 14 to 24 to apply their creative talents to the latest in 3D-design technology to design a trophy for the winners. On his trophy, Prerak said, "My design was inspired by the core values of the QEPrize – innovation, global impact, and excellence. I aimed to create a trophy that embodies these values and reflects the essence of engineering."

The judges also awarded a highly commended prize to Ramya Krishnamoorthy. Ramya's design was built around triangles, with three pillars representing commitment, creativity and a growth mindset.

REPORT URGES GOVERNMENT TO PROMOTE, PRIORITISE AND INVEST IN SUSTAINABLE AI

© Markus Spiske/Unsplash

In February, the National Engineering Policy Centre (NEPC), called on the government to ensure that tech companies accurately report how much energy and water their data centres are using. The report, *Engineering Responsible AI: foundations for environmentally sustainable AI*, noted that data centres can and should be designed to use less water and critical raw materials, but that the government must set the conditions for this as the *AI Opportunities Action Plan* is rolled out.

The report recommends an extension of mandatory reporting on AI's energy and water use, carbon emissions and e-waste recycling of data centres, as well as key actions to minimise risks to the environment, people, and the economy by managing the resource demands of AI systems.

Dame Dawn Childs DBE FREng, CEO of Pure Data Centres Group said: "Engineering has a vital role in making AI more efficient and, in turn, more environmentally sustainable. Some of this will come from improvements to AI models and hardware, making them less energy intensive. But we must also ensure that the data centres housing AI's computing power and storage are as sustainable as possible. That means prioritising renewable energy, minimising water use, and reducing carbon emissions – both directly and indirectly."

The report was developed by the Royal Academy of Engineering in partnership with the Institution of Engineering and Technology and BCS, the Chartered Institute of IT, under the NEPC.

COULD SELF-HEALING ROADS SOLVE THE UK'S POTHOLE PROBLEM?

Dr Jose Norambuena-Contreras, a senior lecturer in the Department of Civil Engineering at Swansea University, with a sample of self-healing asphalt © Swansea University/King's College London

Scientists have created a self-healing asphalt, designed to heal cracks before they appear. It contains engineered plant spores that burst to release a recycled oil that fills the cracks.

Potholes are a hazard for cars and cyclists and a huge issue in the UK. In December, the government announced a £1.6 billion package to repair roads and fill potholes. The exact mechanism responsible for cracking in roads is unknown, but occurs when bitumen, the sticky black component that holds asphalt together, hardens through oxidation.

A team from King's College London and Swansea University, in collaboration with scientists in Chile, used machine learning to probe the behaviour of organic molecules in complex fluids such as bitumen. They developed a new model to accelerate atomic-level simulations of bitumen, advancing research into bitumen oxidation and crack formation.

Thanks to these insights, the team found a way to repair cracks in asphalt as they form. To make the asphalt 'self-healing', they chemically treated plant spores, filling them with recycled sunflower oil. When the asphalt begins to crack, the oil is released from the spores, which reverses the cracking process. Their lab experiments showed that the self-healing asphalt completely healed a microscale crack on its surface in under an hour.

Dr Francisco Martin-Martinez, an expert in Computational Chemistry at King's College London, said: "In our research, we want to mimic the healing properties observed in nature. For example, when a tree or animal is cut, their wounds naturally heal over time, using their own biology. Creating asphalt that can heal itself will increase the durability of roads and reduce the need for people to fill in potholes."

GET INVOLVED IN ENGINEERING

© Neil Mewes/Unsplash

NATIONAL RAILWAY MUSEUM'S 50TH BIRTHDAY

York
Throughout 2025
This year, the National Railway Museum celebrates its 50th birthday with a range of activities happening throughout the year. Its new Railway Firsts exhibition spotlights the pivotal innovations and unexpected 'firsts' that shaped the railways. You can also have an immersive VR experience on the Flying Scotsman and see the engine for real at the museum in April. Visit the website to find out about all the exciting events happening in 2025.
railwaymuseum.org.uk

EDINBURGH SCIENCE FESTIVAL

Various locations
5 to 20 April
Celebrating the wonders of science, technology, engineering, and mathematics (STEM), the Edinburgh Science Festival programme includes explosive shows and hands-on activities for families and engaging talks and immersive experiences for adults. Visit the DiscoveryLab and find out what scientists do; listen to NASA astronaut and oceanographer Dr Kathy Sullivan as she talks about her career; or code your own Mars mission at the National Museum of Scotland. To find out about all these events and many more, visit
edinburghscience.co.uk/festival/whats-on

DISCOURSE: THE FUTURE OF ENGINEERING BIOLOGY

Ri, London, in person and online
25 April 2025
The field of engineering biology uses the whole span of biological sciences alongside technology and engineering to benefit multiple sectors and our society more broadly. Join Dame Angela MacLean, the government's Chief Scientific Adviser, as she discusses this transformative field. To book tickets, visit
rigb.org/whats-on/discourse-future-engineering-biology

CURIOUS INVESTIGATORS

The Beacon, Wisbey Park, Bradford
13 April 2025
As part of Bradford City of Culture 2025, children aged between 3 and 7 can join Scribble and Clipboard, recyclers who have found a mysterious egg in the rubbish and need the audience's help to stop it from smashing. Creators One Tenth Human make shows with artists, scientists and kids in collaboration with engineering experts from Lancaster University. To book tickets, visit
bradford2025.co.uk/event/curious-investigators

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CONCORDE ANNIVERSARY EVENTS

Aerospace Bristol
12 April
Mark the anniversary of British Concorde's first flight in April 1969 with two events at Bristol Aerospace. The first is a special Q&A with Concorde captains and crew: Captain Les Brodie, who piloted Alpha Foxtrot's final flight on 26 November 2003; Captain Colin Morris, the longest-serving Concorde Captain, and Neil Smith, a cabin crew member aboard Alpha Foxtrot's last journey. The second event will see the three panel members take attendees on a two-and-a-half-hour tour after hours. To find out more about both events and book tickets, visit
aerospacebristol.org/whats-on

HOW I GOT HERE

Q&A

SARAH BARRINGTON
PHD STUDENT


Sarah visiting the White House in January 2024

After studying engineering in the UK and embarking on a career in data science, Sarah Barrington is now a PhD student at the University of California, Berkeley. She studies AI harms and deepfake detection.

WHY DID YOU BECOME INTERESTED IN SCIENCE AND ENGINEERING?

I have always been fascinated in how things work and explaining the world around me. Even as a child, I spent a lot of time breaking things, trying to put things together. I was fortunate to have very supportive parents. My dad is an engineer, so supported me with tinkering with things and helping me build my own internal model of how the physical world works. I really enjoyed the sciences right up to university level, and decided I wanted to continue with what I was building then, which was an engineering skillset.

HOW DID YOU GET TO WHERE YOU ARE NOW?

At university, I was fortunate to be involved in Cambridge University Eco Racing, a racing team where you design, build and race a solar-powered car. I learned a lot about working as part of a high-performance engineering team. I also enjoyed having the opportunity to try a range of different jobs each summer, everything from sustainability consulting to finance internships. My favourite was when I got to work for McLaren as an intern in their Applied division.

That internship turned into a real job, which I did for a few years, and I saw how these cutting-edge predictive modelling techniques that were being used in our work could be applied to even broader problems. Ultimately, this inspired me to try the world of entrepreneurship.

I worked with one of my best friends (who later became my co-founder) to build a digital marketing team and then also did some work in the blockchain space. Eventually, the blockchain side joined with a management consultancy in London and I became part of the data science team there. Ultimately, I kept finding that the parts of my job that I really enjoyed were the research-focused parts, and realised that it was time to return to academia. I knew I had to get closer to Silicon Valley and so I applied to Berkeley. I was fortunate to be awarded a Fulbright Scholarship to help me get over there and study my master's, which turned into a PhD.

WHAT HAS BEEN YOUR BIGGEST ACHIEVEMENT TO DATE?

I think probably the biggest one would be getting into my PhD programme to work with my adviser, Professor Hany Farid, because it really was a culmination of everything that's come before, but also a huge amount of hard work, and it just felt really right. Hearing that I'd got the internship at McLaren and receiving my offer from Cambridge were also highlights. Having said that, I don't think I would have been able to achieve half as much in my career had it not been for my very patient and supportive family, friends, colleagues, and mentors.

Sarah working in the simulator at McLaren's Applied division during her internship

QUICK-FIRE FACTS

Age: **31**

Qualifications: **BA, MA, MEng – general engineering at the University of Cambridge, MIMS – University of California, Berkeley**

Biggest engineering inspiration: **My father. He worked as an engineer in the automotive industry for 30 years and is a huge part of why I chose engineering too**

Most-used technology: **probably my phone!**

Three words that describe you: **curious, determined, driven**

WHAT IS YOUR FAVOURITE THING ABOUT BEING AN ENGINEER?

I suppose I'm not a classical engineer any more – I'm more of a computer scientist. But the fundamental skillset is the same. I sit down with a challenge or a problem that often seems completely impossible to solve. I try and work back from that end goal to understand the steps to getting an answer that's robust, trustworthy and makes sense. So, then I design experiments or tools or write code that can help get me to that answer.

I think my favourite thing about being the kind of engineer I am is the satisfaction you get when you've reached that end point – and you don't always reach the end point. You have to go back to square one many, many times. But when you eventually see a project from zero to something that's working and something that answers the question you wanted to understand, it's the most satisfying thing in the world.

WHAT DOES A TYPICAL DAY INVOLVE FOR YOU?

My days are very varied because as an academic, there are different types of responsibility you'll have throughout the academic year. At the moment, I'll wake up, probably go to campus to have a meeting with my adviser. We'll talk about the very niche research we've been working on in our field of deepfake detection and AI forensics. Then I'll go to class for a few hours. I'll grade some papers, because I'm working as a teaching assistant. Then I might write some code where I'm building on the comments that happened in my adviser meeting.

Then I might go and give a guest lecture somewhere talking about our work and how it's applicable to the real world. Sometimes we also advise private sector companies or even the government to tell them about the risks and dangers of AI misuse and how our work can support their work in policymaking or in private sector innovation and development. Every day looks different. But that's what I love about it.

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

At school, just try and do work experience: try and shadow someone, or email local companies that you might be interested in visiting and seeing what they're about. Even if you only spend a day somewhere, that experience is really, really valuable and will set you apart when you apply to university.

At university, it's similar – get these internships and experiences under your belt while you're in the safety net of studying, because the stakes are pretty low. Try different internships and summer jobs, extracurriculars as well. Get a flavour for the kinds of problems that you want to work on.

And then beyond that for career engineers I would say staying up to date with the latest developments in tech and in engineering is really crucial to career development. Certainly, in the world of AI and computer science, there's a new development that fundamentally changes your job every week. So being able to stay on top of that and still lead a cohesive career while adapting to these new developments is really, really important.

WHAT'S NEXT FOR YOU?

I spend a lot of time thinking about this. At the moment I have probably two years left of my PhD, but my entire career has been about developing methods that can go and make the world better in some way. My next step will inevitably involve taking the research from my PhD in this space – of AI harms and deepfake detection – into the world and trying to do some good with it. That might be through policymaking, or through staying in academia and trying to get on the route to professor so I can carry on research in this field and educate other students as well. But I think there is a transition that can happen from research to impact that I'm really, really interested in. After building that foundation on the research side for a couple more years, I think I'll be going out into the world and trying to implement some of it.

OPINION

WHY CLINICIAN–PATIENT RELATIONS SHOULD MATTER TO ENGINEERS

Technology developed to specifically help people manage certain health conditions can help them live more independent lives. However, sometimes the development, deployment and use of such technologies can unintentionally introduce negative impacts. Dr Robert Farnan, Professor Steven Johnson and Professor Jonathan Ensor from the University of York explain why the relationship between clinicians and patients should play a crucial role in the development of healthcare technology.

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There is growing emphasis on medical devices that help people to control and manage long-term diseases, such as continuous glucose monitoring (CGM) devices for diabetes. For some, these technologies are empowering, while for others the technology can be difficult to use and understand, undermining health outcomes and relationships with healthcare professionals. Developers and commissioners of medical devices should design and deploy medical devices that benefit all patients.

The government's *Equity in medical devices independent review* highlights how healthcare technologies can have negative impacts. For example, the report describes how unintentional racial bias in the performance and clinical impact of pulse oximeters, which measure oxygen levels in blood, has resulted from development and calibration based on testing on light-skinned test subjects.

In the UK, it's well documented that people particularly from Black and South Asian communities are disproportionately more likely to be affected by health inequities than other communities. Diabetes UK's 2022 workshop on addressing health inequalities in diabetes care has further helped to identify that some social categories drive health inequities. It has published recommendations for researchers and funders about how to address this key aspect of inequity.

In the University of York's Equitable Technology Lab (ETL), we are interested in equity of medical devices. We have been working with patients to explore attitudes and views of CGM devices. Although at an early stage, our work with Type 1 diabetes (T1D) patients in Sheffield and Scarborough has already highlighted that age and gender-related factors affect how patients use and feel about

CGM devices. For example, young women express apprehension over the wearability of their devices in public while elderly patients have reported difficulties navigating and managing data and digital interfaces.

Cognitive and physical factors, such as neurodiversity and hearing issues, can also make devices difficult to use and can contribute to experiences of inequity. This work, together with current literature, suggests that inclusive participation that recognises intersecting social categories such as gender and race can actively address such unintended consequences and inequities in healthcare technologies. Inclusive participation will ensure that otherwise marginalised groups are adequately and meaningfully involved in developing healthcare technologies that cater for their needs.

However, this is not the whole picture. To fully address inequity in medical devices, we need a more nuanced appreciation of how technologies shape and are shaped by the context in which they are deployed and used. For example, at ETL our work has started to show that the way CGM technologies are used can mould the relationship between clinician and patient. This arises from how the data, information, and decision support systems associated with CGM devices are largely geared towards the needs of clinicians rather than patients. In some cases, this can lead to a problematic distinction between the 'expert' (clinician) and 'nonexpert' (patient), which can undermine relationships with healthcare professionals.

The inequities and unintended outcomes that patients often experience when using medical devices are frequently informed by a disconnect between the needs of clinicians and those of patients. A key driver here is that a scientific understanding of health and disease frames the data gathering and interpretation by medical technologies. However, this tends to overlook the contextual differences that are important in how patients experience and respond to their condition and to healthcare interventions. Put simply, patients do not think about their disease in the same way that clinicians do – or indeed the way other patients do.

This problem is increasing in scale and complexity. Within UK healthcare, the notion of patient self-management supported by technological innovation is becoming increasingly dominant as a viable, cost-effective solution for reducing the NHS's operational burden. This has driven new relations between patients and health professionals, which today includes clinicians, consultants, nurses, and local patient advocates. These relationships are increasingly mediated by medical devices and digital systems.

Inevitably, technologies (such as CGM) inform how patients are understood by clinicians and healthcare practitioners. And these technologies also change how healthcare professionals interact with patients and the terms on which they seek to regulate their behaviour. Our findings are revealing how technologies are unintentionally altering these relations, removing the opportunity to appreciate the patient's own views on their condition or particular circumstances.

There are unintended consequences of all this. One – a key finding – is that many patients work collectively to amplify their voice in relation to medical devices. For example, many of our research participants have turned to advocacy groups, such as Diabetes UK, for solidarity and support in navigating the unexpected outcomes associated with managing their condition. This has included peer-to-peer advice on how to understand and use the data produced when operating their medical devices.

Our initial research with local Diabetes UK groups has indicated that these groups help patients share their knowledge and expertise of self-management with others across different contexts. This has allowed patients to better manage their devices, providing them with both technical guidance on operation and maintenance, as well as emotional support for the psychological impacts. Indeed, interviews with patients highlight that the emotional aspects of medical devices have significant implications for how well they are taken up and used. However, in the clinician–patient relationship, patients may not share factors such as aesthetic appeal, data overload and responsiveness to lifestyle, because of the lack of importance that clinicians assigned to them.

Our work suggests that the disconnect between the needs of clinicians and patients at the heart of these data-driven relationships should be highly visible in healthcare interventions. This requires rethinking how medical devices can preserve clinical expertise, without diminishing patients' voices. Recognising this presents a design challenge for technology developers and engineers. It requires understanding clinician–patient relations alongside a wider consideration of how patients interact with, and make sense of, medical devices. Designing equitable medical devices will, then, require inclusive participation, but this must be part of a broader understanding of engineering focused on how social and technical arrangements combine to deliver equitable outcomes for patients.

BIOGRAPHY

Robert Farnan is a researcher at the Stockholm Environment Institute, University of York, and has spent over a decade researching the interplay of knowledge production, equitable development, and democratic politics. In ETL, his work draws upon critical social science to develop a socio-technical approach to the design and deployment of medical technologies.

Steven Johnson is a Professor in the School of Physics, Engineering and Technology at the University of York where he also co-leads ETL. His research aims to rethink how equity is embedded into technology innovation, with a particular focus on the innovation of novel sensor technologies for use in medical diagnostics and environmental monitoring.

Jonathan Ensor is a Professor at the Stockholm Environment Institute, University of York, and co-leads ETL. He is a social scientist with research interests in processes that can lead to increasingly equitable human development. He has a background as an engineer and has worked in human rights and international development practice.

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CONCRETE FOUNDATIONS FOR NET ZERO

Did you know?

- The Romans made self-healing concrete using volcanic ash, lime and seawater
- Over its lifetime, concrete naturally absorbs carbon dioxide
- The most common type of cement, Portland cement, is very polluting because it has to be heated in a kiln to over 1,400ºC

If concrete were a country, it would be the third largest emitter of CO_2 after the US and China. The race is on to slash its emissions. Swapping out its most polluting ingredients, locking in carbon, and upcycling our industrial and construction waste could hold the key, says Leonie Mercedes.

It's hard to imagine a world without concrete. The most used resource on Earth after drinking water, we make 14 billion cubic metres of it every year, about the same volume as 6,000 Great Pyramids of Giza. Concrete makes up our buildings, roads, bridges, and tunnels. It also has a near-unbeatable track record as a building material. The Pantheon in Rome is made from a form of concrete, and has stood for almost 2,000 years.

But it's a massive polluter. Cement, concrete's key ingredient, makes up just 5 to 10% of the material's mass, but is responsible for most of its emissions. In fact, cement accounts for about 8% of all global CO_2 emissions.

We're already taking steps to reduce concrete's carbon footprint, such as by making production more efficient and replacing some cement with other materials. However, these alone cannot do enough to reach our net zero goals. We're going to need a cement that is near-zero carbon, as well as approaches that capture carbon and lock it away. That's not where the challenge ends – widescale adoption of these new technologies will depend on the right incentives.

PORTLAND CEMENT: THE KEY INGREDIENT

Concrete is a mixture of aggregates (such as sand and gravel), cement, and water. Where aggregates make up the bulk of concrete, cement is the 'glue' in the mix. Cement and water form strong crystals that bind the aggregates together.

Portland cement is by far the most common kind of cement, and we've been making it in much the same way since the 19th century. The most polluting part of the process is transforming raw materials into lumps of clinker: the stuff that makes cement, cement. In this process, limestone and other materials are heated to about 1,450ºC in a rotating kiln. This heat drives carbon dioxide off the limestone to form the clinker. The clinker is cooled, pulverised and mixed with gypsum, a mineral also used in plaster, to make the Portland cement.

Portland cement is relatively cheap, uses abundant raw materials, and slots neatly into our construction industry. Finding a replacement for it will not be quick or straightforward. "It's very difficult to move away from

Portland cement, because we want our infrastructure to last for decades or centuries," says Rupert Myers, a senior lecturer in sustainable engineering at Imperial College London. While it's difficult to say whether we could move away from it completely, he adds, it is definitely possible to reduce its carbon footprint.

It has been common practice in the UK to replace some of the cement with what are known as supplementary cementitious materials (SCMs). SCMs both reduce the amount of clinker needed and strengthen the resultant concrete. Examples include industrial by-products such as blast furnace slag (from ironmaking) and fly ash (from burning coal). These approaches reduce embodied carbon, that is, the emissions released throughout its lifecycle.

However, SCMs can't bring emissions down enough to reach our net zero goals. Also, as they're by-products of other fossil fuel-intensive industrial processes, we'll need to find alternative solutions for reducing embodied carbon in the long run.

The nearly 2,000-year-old Pantheon in Rome is made from concrete. The cement they used was typically based on crushed volcanic ash, lime and seawater. Roman concrete is self-healing and has inspired many replacements for Portland cement
© Unsplash/Gabriella Clare Marino

ALTERNATIVE BINDERS

Alkali-activated binders cut the heat – and thus a lot of the carbon – from the cement-making process. These binders are also made from blast furnace slag (from ironmaking) and fly ash (from burning coal), or natural materials such as volcanic ash, which are combined with an alkaline medium. This chemical reaction creates a hard, cement-like binder.

One company creating cement in this way is UK startup company Material Evolution. "We don't believe that heat's the way to change materials," says its Founder and Chief Executive, Elizabeth Gilligan. Instead of a kiln, the company uses an alkali fusion reactor at ambient temperature, where feedstock materials become cement under high mechanical forces rather than heat.

The company, which has raised £15 million, claims that its kiln-free process produces up to 85% less carbon emissions than Portland cement. Last October its Wrexham plant produced its first batch of cement. Gilligan told *The Times* that, as the company scales up, it could be the same price as Portland cement in the next five years.

Sweden-based Cemvision uses industrial byproducts and waste – which may have been sitting dormant for decades – from steel and other heavy industries to produce the two cement binders in its Re-ment product. It claims that its binders and production process generate little to no CO_2 emissions.

By treating and purifying these feedstocks, Cemvision can also recover metals such as iron, nickel and chromium, which the steel industry "wants back" as additives for alloys, explains Cemvision's Chief Technology Officer Claes Kollberg.

The company aspires to this kind of circularity, as should all of society, Kollberg says. "We have to go to circular flows instead of linear flows," he explains. In 2024, Cemvision struck up a partnership with green energy supplier Vattenfall. According to a press release, the new cement could be used in power distribution and foundations for wind power turbines.

Material Evolution's low-carbon cement uses an alkali fusion process. This involves reacting an alkaline solution with slag from blast furnaces (or materials with similar properties). The mixture hardens into a powder, just like Portland cement
© Material Evolution

Inside A1 – Material Evolution's first-of-a-kind Wrexham facility © Material Evolution

LOCKING CARBON UP FOR GOOD

Where these carbon reducing technologies can cut emissions in the short term, in the long term, we need strategies for eliminating carbon. "Reducing carbon emissions can only get us so far," says Mike Cook, adjunct professor at Imperial College London. "We need to get better at carbon capture too – ideally by sequestering the CO_2 that is being emitted into new materials that have a use and a value. This gives an incentive to capture carbon by making it profitable."

Carbon capture technologies involve trapping carbon emissions at source, such as in industrial flues. The carbon can either be used elsewhere or permanently stored. This is the difference between carbon capture and storage (CCS), which has a cost, and carbon capture and utilisation (CCU), which produces useful products.

Carbon capture works by permanently locking carbon dioxide into rocks in a process known as CO_2 mineralisation. "CO_2 mineralisation is a really promising method to reduce the carbon footprint of cementitious materials," Myers says. Cement paste or concrete exposed to the air will naturally recarbonate, he explains. In CO_2 mineralisation, exposing the concrete to a high concentration of CO_2 accelerates this process, Myers adds. The material is then ready to build with and acts as a carbon store.

Cook chairs one such company making products with captured carbon: Seratech. This Imperial College London spinout captures CO_2 from the atmosphere and reacts the gas with the naturally abundant mineral olivine. The end product is a cement that the company says can replace Portland cement in concrete products such as bricks, blocks and planks. Seratech claims there's a CO_2 reduction of more than 95% compared with Portland cement, and that it is 20% cheaper.

In September 2024, Seratech partnered with a company called Xytel to design a pilot plant for making the material. The modular plant, which is set to run for about a year after opening in July, will test the feasibility of Seratech's technology and provide a stepping stone for bringing it from the lab bench to industrial scale.

We know carbonating concrete does change its properties, including making it more acidic, though those changes are well understood. That said, any new materials must be tested for their performance before they can replace conventional concrete. "It's not like we could just pick a very exotic concrete with low CO_2 emissions and substitute

RECYCLING CEMENT

Up to 500 million tonnes of construction waste is generated every year in the EU, and at least a third of that is concrete. Why start from scratch when tonnes of cement exist in the piles of rubble of demolished buildings?

Cambridge Electric Cement is putting recycled cement to use by 'piggybacking' on a process for recycling steel in an electric arc furnace. During this process, lime – a product of heating limestone in a kiln – is normally added to react with impurities in the molten steel to form a slag that floats up to the surface.

The engineers behind Cambridge Electric Cement discovered that recovered cement paste can replace the lime, 'reactivating' the cement without affecting the steelmaking process. The recycled cement forms a slag. Once the slag is cooled and pulverised, it forms a powder that, the company says, is "virtually identical" to regular clinker from a rotary kiln. The product aims to be a direct replacement for Portland cement.

Material Evolution's plant in Wrexham, North Wales © Material Evolution

that for conventional concrete," Myers says. "It doesn't work like that because the chemistry's so different."

With the image of crumbling schools still fresh in the memory following the reinforced autoclaved aerated concrete (RAAC) debacle, proving the safety of these low- to no-carbon concrete alternatives will be paramount in scaling their adoption. New products undergo compressive (squeezing) and tensile (stretching) tests to comply with the UK's concrete and cement standards, explains Gilligan.

A new version of one of these standards, BSI Flex 350, provides a framework for identifying and using lower-carbon concrete to make it easier for engineers, designers and contractors to adopt these alternatives as they enter the market. The standard is based on the performance of these new binders, rather than prescribing a specific mix of ingredients.

"It's a crucial step," says Gilligan. "This is the standard that will allow new technologies to be adopted and scale in the cement industry."

GETTING THE RIGHT MIX

No single technology can fully replace the huge amount of concrete currently made with Portland cement. They simply cannot be scaled quickly enough to match the volume of material we'd require. But a combination of technologies could help us close the gap. "Technologies we'd need would be many and various," says Cook. "To really achieve full net-zero concrete we will need to develop alternative cements that don't require the burning of chalk [a form of limestone]."

On top of that, no new technology will be adopted at the scale we need, unless it provides a solution that is least as profitable as what we've already got.

In a report comparing the maturity of different lower carbon concrete technologies, the Institution of Structural Engineers noted that while most technologies that can reduce carbon are more expensive than conventional concrete, they can become cheaper with economies of scale. Government and industry regulation aimed at reducing embodied carbon will also make these technologies more attractive. "The government needs to mandate carbon reductions in the production of our essential construction materials – not wait until it's too late," says Cook.

In the EU at least, a piece of legislation called the Emissions Trading System will gradually implement a CO_2 tax on the cement industry from 2026 to 2034. This means that in a few years' time, it's going to be much more expensive to make Portland cement, Kollberg says. These are the kinds of incentives that will bring the focus to lower-carbon cements.

If this is the way the wind is blowing, businesses must take note. "You cannot be successful in the future if you are not transforming your business in the direction towards sustainable production," says Kollberg.

It's also important to remember that a net zero world depends on net zero construction. We discuss alternative sources of energy, and that's very important, Cook says. "But what's seldom recognised is the CO_2 that's emitted when making the materials needed to make the massive concrete nuclear power stations, and the heavy foundations and superstructures for new wind turbines. Creating a decarbonised energy supply currently contributes massively to carbon emissions due to construction of new energy infrastructure. We need to change this as fast as possible."

There's no shortage of ingenious approaches to decarbonising construction. What we are short on, however, is time. The next few years will be crucial. Although with the UK government committing to taking time-bound steps to decarbonising the steel and cement sectors with the Green Public Procurement Pledge, it looks like we're taking a step in the right direction.

BOOSTING CARBON LOCK-UP

There's no shortage of concrete. What if we could boost its capacity for carbonisation, letting us lock away even more carbon? A team of researchers along with Myers is looking into a method that lets you do just that, by running fine organic fibres through the dense material. "The idea is to have very, very small radius fibres, but enough of them so you could completely carbonate parts of a dense concrete element," he says. "We're working out how much spacing you require between [the fibres] to make… completely carbonated concrete samples or significantly carbonated concrete samples."

Leonie Mercedes thanks Elizabeth Gilligan, Co-Founder and CEO of Material Evolution; Claes Kollberg, Co-Founder and CTO of Cemvision; Mike Cook FREng, adjunct professor at Imperial College London and Chair of Seratech; and Rupert Myers, Senior Lecturer in Sustainable Materials Engineering at Imperial College London for their contributions to this article.

STOPPING THE BLEED

Haemorrhage is second only to traumatic brain injury as a cause of death in injured patients in the UK. Tourniquets are well known for treating blood loss from limbs, but there is no proven equivalent for patients with a non-compressible haemorrhage. Surgeons, emergency department physicians and other trauma specialists grappling with this problem are now looking to engineers for new solutions.

Did you know?

- First responders normally apply pressure to serious bleeding with a tourniquet on limb injuries or by packing gauze and pressing on injuries elsewhere
- This doesn't work for all injuries, so engineers are developing ways to stem bleeding that include applying pressure directly to the wound from the inside
- These aim to keep patients alive until a surgical team can repair the damage to blood vessels or organs in hospital

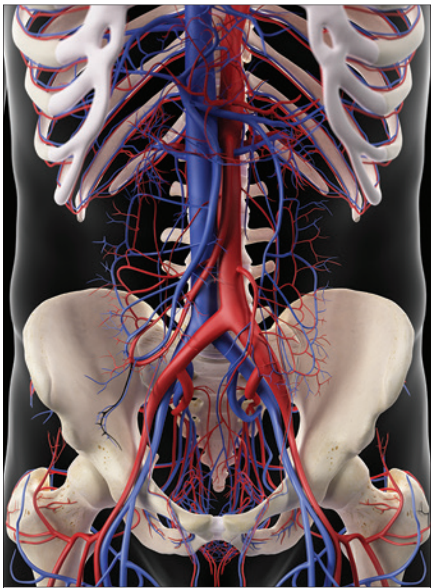
US Army medics in training to apply tourniquets, which prevent haemorrhage by stopping blood flow to limbs © Alamy

Our story starts in a quiet commuter-belt town, just outside the M25. At first, Caleb* didn't realise he'd been stabbed during a fight that almost ended his life. He didn't see the knife, thinking he had merely been punched. Caleb only realised the extent of his injury when his friends pointed out the blood on his T-shirt. The knife had pierced his lower abdomen, cutting the iliac artery, a major artery deep in the pelvis.

Thirty minutes after the 999 call, the air ambulance arrived. Another half an hour later they arrived at the major trauma centre. By this time, they had used up the stock of blood carried on the helicopter. On arrival in hospital, Caleb went straight into surgery. Saving Caleb's life took three anaesthetists and four surgeons, and then 22 days of intensive care and two further operations. He was discharged from hospital five weeks to the day from the attack.

Caleb can't remember much about his assault. 40% of his blood volume – some two litres – bled into his abdominal cavity and the tissues around his iliac artery. The prolonged period of low blood pressure, known as haemorrhagic shock, caused permanent changes to Caleb's cognition. He never resumed his degree studies. If the initial haemorrhage-control surgery had been delayed, even by a few minutes, he wouldn't have survived. The continued blood loss would have induced cardiac arrest, from which the chances of recovery are close to zero.

The situation would have been much simpler if the knife had wounded a limb. The first responders could have limited the bleeding with a tourniquet, a relatively simple device that applies pressure to stop blood flow. Unfortunately, in Caleb's case, the haemorrhage was 'non-compressible': applying external pressure would not stop the bleeding.



The aorta carries blood from the heart to major blood vessels, such as the iliac and femoral arteries to the lower limbs, and the arteries supplying vital internal organs such as the liver, spleen and kidneys. When cut or torn, vessels in this dense network are very difficult or impossible to compress compared to those in the limbs © Shutterstock

BRIDGING THE GAP TO HOSPITAL

"Non-compressible haemorrhage patients who make it alive to hospital will almost always survive, with the sophisticated surgery and resuscitation strategies available to us," says Professor Nigel Tai, a British Army trauma surgeon who also looks after patients in London. Typically, the greatest risk to life is on the street or on the way to hospital. In conflicts, this is on the battlefield, before evacuation. "We call these deaths 'preventable'," says Tai. If medics can keep patients alive until they reach a hospital then surgical teams can stop the bleeding, repair damaged blood vessels and pack injured organs.

In recent years, surgeons have relied on blood transfusions and drugs that support clotting before getting to the operating theatre – but these techniques can't stem catastrophic bleeding. New devices are needed to plug holes and seal off bleeding tissues that would normally only be accessible via a surgeon's incision. A complicating factor is the sheer number of different types of non-compressible haemorrhage (NCH) – among them, bleeding from stab wounds such as Caleb's, to severe bleeding after childbirth.

Because such different anatomies are involved, no single device will work for all injuries. "This has led to an innovation gap," says Tai, "and a need for new thinking." Until recently, researchers focused on a conceptually easier approach, developing new ways of replacing lost blood, instead of stemming blood loss in the first place. Tai firmly believes we need engineers' skills to solve the issue.

TIME IS LIFE

If you've ever seen *127 Hours*, *Saving Private Ryan*, or *Band of Brothers*, the tourniquet takes a starring role. Tourniquets wrapped tightly around the limb can apply enough pressure to stop blood flowing into the vessel. These simple medical devices are very successful in managing bleeding from the limbs.

However, tourniquets are "useless" in managing non-compressible bleeding, explains Surgeon Commander Pippa Bennett, a Royal Navy trauma surgeon at the Oxford Trauma Service. Take the junctions between the torso and legs, arm, and neck. It's clearly inadvisable to apply a tourniquet at the neck, and there's not enough purchase at the groin or shoulder – it's difficult to apply enough local pressure when a bleed is deep within a body or behind a bone.

The only current solution is ligation with a suture, tying a thread or wire around the vessel to close it off. "Where time is life, the time to an operating theatre could be the difference between life and death. We need something in between," says Bennett.

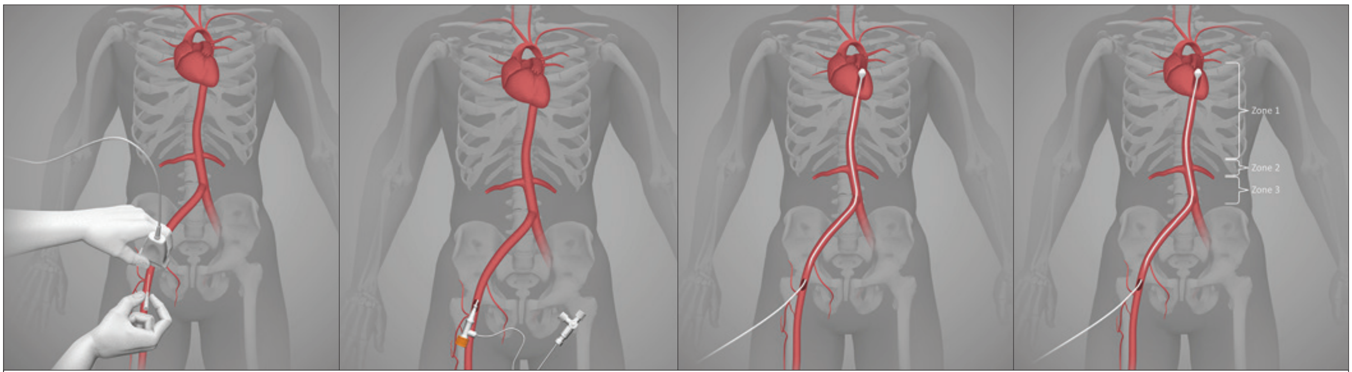
There is a critical technology void between tourniquets and surgery, where engineering approaches could address the problems. These approaches must consider the armpits, groin, abdomen, pelvis, and long bones such as the arms and legs. New devices may need to be based around a thorough understanding of how a complex, flowing fluid such as blood, containing multiple different cell types and component fluids, behaves in injured, leaking blood vessels. Equally, the material properties of injured tissues, and the interface between them and any new device must also be accounted for. The problems may appear complex, but solutions could involve simple adaptions or exploitations.

Cases like Caleb's demonstrate one of the key challenges with managing NCH: detection. In many cases, the clinician cannot diagnose it in time to save the patient. Early detection is critical. It is easy in patients with large visible wounds and significant bleeding. Injuries to the solid organs in the

A NEEDLE IN A HAYSTACK

Non-compressible haemorrhage within the human torso can have many sources that may be difficult to identify, such as:

- organs (for example the lungs, liver and spleen) causing bleeding into a body cavity
- blood vessels, including arteries such as the aorta, and large veins. These can be in body cavities or at junctions, such as the neck, groin or shoulder
- pelvic bones
  - direct bleeding from hundreds of small blood vessels, which tear as the bone breaks
  - indirect trauma to large nearby pelvic vessels torn by the fractured ends of bone.



REBOA is inserted through the femoral artery, threaded to the aorta and inflated © Image permission kindly granted by the authors of the paper 'REBOARREST, resuscitative endovascular balloon occlusion of the aorta in non-traumatic out-of-hospital cardiac arrest: a study protocol for a randomised, parallel group, clinical multicentre trial', Brede et al, *Trials*, 2021

abdomen or pelvis or long bones can cause significant blood loss that can take time to identify.

This isn't easy to detect outside of hospitals, where CT scanners can take cross-sections of the body and pinpoint injury. Thanks to improved clinical training, clinicians now have better 'spider senses', attuned to significant internal bleeding. But this can go only so far. Handheld ultrasound, where available, may detect blood in the chest or around the intestines but can't detect blood in the tissues at the back of the abdomen that anchor the major abdominal blood vessels.

BALLOONS, FOAMS AND AI-GUIDED ULTRASOUND

Since the 2010s, the medical toolkit has expanded beyond manual pressure and tourniquets to several early-stage devices.

Air ambulances in the UK and Norway have trialled the snappily named resuscitative endovascular balloon occlusion of the aorta. REBOA, for short, is designed to treat haemorrhages to the abdomen or pelvis. The 'balloon' itself is small, with a working volume of about eight millilitres when inflated. It is attached to a long tube or catheter. Getting the balloon in place involves inserting the tube and empty balloon into the femoral artery in the upper thigh and threading it about 45 centimetres to the aorta. Once in place, inflating the balloon drastically reduces blood flow beneath it, meaning that less blood leaks out from the injured tissues.

REBOA requires a skilled clinician, and often access to imaging tools. The evidence around benefit is mixed. In 2023, a UK clinical trial found that patients receiving REBOA in the emergency department were slightly more likely to die than patients who didn't receive it. This was surprising as other (albeit unrandomised) studies done in the US have shown that REBOA helps survival. Some have concluded that the poor results in the UK trial were likely down to the delay in getting patients into theatre and other nontechnical factors.

Researchers at MIT are working on a handheld ultrasound device that uses AI and robotics to get the tube to the femoral artery more easily. One researcher behind the device likens it to "an intelligent stud-finder married to a precision nail gun". A startup company, AutonomUS Medical Technologies, is working on getting the device regulatory clearance.

Another consideration is REBOA's potential side effects. The aorta carries blood to the kidneys, intestine and lower limbs. Blocking it can have fatal consequences. To address this, clinicians are also testing a twist on REBOA, P-REBOA, where the balloon is only partially inflated. This trade-off allows some blood flow to sustain organs, but it raises the risk of haemorrhage compared to the fully inflated balloon.

ResQFoam is another strategy designed to stop bleeding into the abdominal cavity. It's delivered as two liquids squirted simultaneously into the cavity, where they mix and expand as a foam, filling the space surrounding

ACT Medical's device to treat stab wounds, before and after activation

the organs. The foam stops bleeding by exerting pressure on the bleeding structures and tissues inside, until it solidifies and is later removed during surgery.

So far, ResQFoam has only been tested on animals, but clinical trials are on the horizon in trauma centres in the US. These will test how safe and effective the foam is in treating patients who have lost more than 30% of their blood volume, or about 1.5 litres.

After two of his friends were stabbed in London, Joseph Bentley wanted to find a way to help first responders treat knife wounds. A final-year product design student at Loughborough University at the time, Bentley developed a Dyson Award-winning prototype and received an Enterprise Fellowship from the Royal

Academy of Engineering to support its development. Today, he leads ACT Medical, a startup company that has commercialised the device.

Stab wounds tend to be deep and narrow penetrating injuries. Medics ordinarily pack these with gauze and blood clotting agents to staunch blood flow. However, once in hospital, the gauze is hard to remove without tearing out blood clots, causing bleeding.

ACT Medical's device, the balloon occlusive barrier (BOB), works in a similar way to the REBOA and ResQFoam, although its mechanism is very different. While BOB's composition is a trade secret, Bentley explains that it is effectively an engineered sponge that uses manually stored energy to expand once activated, acting like a spring to deliver pressure to the inside of the wound.

When inserted into the wound, the sponge expands, applying enough internal pressure to stop bleeding. According to ACT Medical's tests, it takes three minutes to control the bleeding. The device stays there, buying the patient time, until theatre, when it is deflated and removed. Unlike the gauze, the blood clot stays intact. "I often say it's like the balloon on the inside of a papier mâché," says Bentley.

Last summer, the team successfully conducted preclinical trials. The team hopes to have regulatory approval for the device in just over a year for wounds to limbs and junctional regions such as the groin or shoulder.

EVERY WOUND IS DIFFERENT

Human anatomy is complex. NCH can result from injury to the torso – anywhere in the abdomen, chest or pelvis – and where it joins the arms, legs and neck. The bleeding might come from a large vessel, such as the aorta that joins the heart, or from several smaller vessels in an organ, such as the liver. Unlike compressible haemorrhage, it may be difficult to locate NCH.

This is especially true in blunt-force trauma, where there may be no open wound. Such injuries in the torso can be particularly lethal. The median time to death in soldiers injured in the torso is about 30 minutes.

Trauma is not the only cause of NCH. Severe bleeding as a complication of childbirth causes a quarter of maternal deaths. It can also be psychologically traumatic – another reason to develop new solutions to NCH. External aortic compression devices, which press on the aorta to stop blood flow, can help medical staff treat haemorrhage.

The story doesn't end there. As Bentley puts it, "no two wounds are the same." None of these solutions is a silver bullet. Each type of NCH may need a different solution, tailored to a specific body part. Medics treating someone with multiple types of NCH may need a toolkit of different devices and solutions to buy them enough time and get them to the operating theatre. It's not just the wound that affects the solution. Some environments, such as a poorly lit roadside or a battlefield with uneven terrain, are more challenging than others. This could make a real difference in conflicts such as Ukraine or Gaza, where bleeding from wounds from gunshots, shrapnel and explosions is the main cause of death.

ENGINEERS, TAKE NOTE

The fact that these approaches to trauma relief have been developed in the past 15 years is a testament to the ingenuity of trauma specialists, engineers and designers. "This type of problem-solving invention shows the significant impact engineers can have on serious global issues and is why I created the James Dyson Award," said Sir James Dyson FREng FRS, on presenting his international award to Bentley in 2021. The innovation demonstrates the value in bringing fresh perspectives to generating new approaches to this condition.

All of this underlines the need for engineers' unique skills. "What surgeons may see as a problem of anatomy, engineers may see as an opportunity to rework solutions from nonclinical areas such as hydraulics, civil engineering and materials science," explains Tai. "These are the new perspectives this space is crying out for."

Caleb's story is not unique. It is one of many young people in the UK and globally who are the victims of non-compressible bleeding. Caleb was one of the lucky ones, his injury happened in a country with a well-developed prehospital care system and trained medics. Many aren't so lucky; their country lacks the infrastructure or the capacity to quickly move patients to hospital. By developing new approaches that can buy time, we can improve their chance of surviving to hospital.

**Names and narrative details have been changed.*

BIOGRAPHY

Colonel Nigel Tai is a British Army Trauma and Vascular Surgeon who is a consultant at the Royal London Hospital Major Trauma Centre. He leads the UK Defence Medical Services (DMS) Non-Compressible Haemorrhage working group. Col Tai is the DMS Professor of Military Surgery and an honorary Professor of Trauma Surgery & Innovation at Queen Mary University of London.

Rob Staruch is a military specialist trainee in burns, plastic and reconstructive surgery based in Oxford. After attending Harvard University as a Fulbright Scholar, he gained a PhD from the University of Oxford in 2023 on the effects of primary shock waves from explosive blast on skeletal muscle. His interests lie in engaging engineers in critical defence healthcare problems.

Surgeon Commander Pippa Bennett is a consultant orthopaedic trauma surgeon in the Royal Navy working at the John Radcliffe major trauma centre in Oxford. She has a specialist interest in fractures involving the pelvis and acetabulum.

TAKING THE HEAT OUT OF CLIMATE CHANGE

So far, only a quarter of the energy produced to generate heat currently comes from non-carbon emitting sources © Shutterstock

When we think of storing energy, we usually think of batteries. But with a huge slice of global carbon emissions resulting from producing heat, engineers are developing ways to store this critical resource with the hopes of driving us closer to net zero, writes Stuart Nathan.

The 'invention' of fire is often seen as the first step along the path to modern civilisation. Whenever people needed heat, they burned something, whether it was to cook food; for warmth; or to make pots and pans, tools and weapons. Controlling fire and heat took us from the Stone Age through the Bronze and Iron Ages.

As we have come to realise the effects on the climate of burning fuels, particularly fossil fuels, we've been searching for alternative ways of generating heat that do not release carbon dioxide. But combustion to produce heat is so entrenched in civilisation's infrastructure that heat generation is seen as the hardest use of energy to decarbonise.

In 2022, the International Energy Agency (IEA), which tracks and forecasts

Did you know?

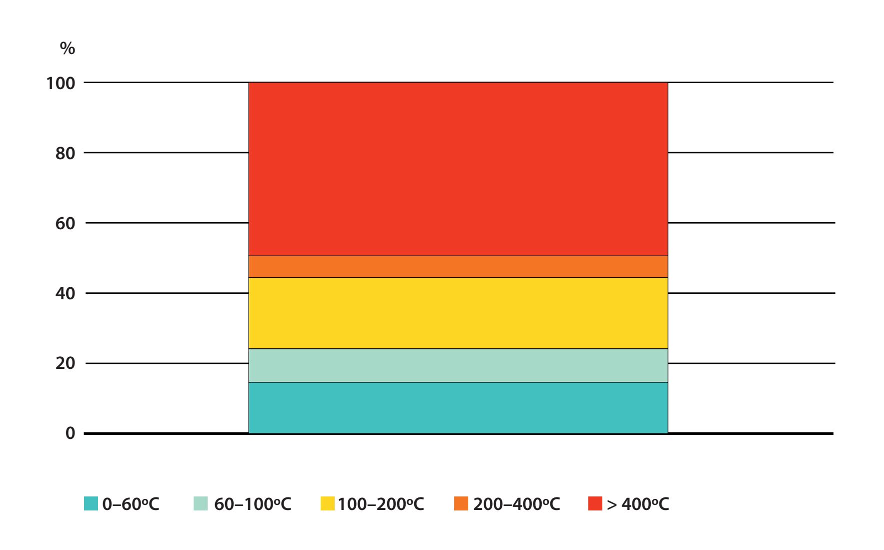
- Half of the world's energy consumption is for heating things, whether the spaces we live in or transforming materials into everyday products
- Solar furnaces reflect sunlight using arrays of mirrors to reach temperatures of thousands of degrees, which is hot enough to make advanced ceramics
- Phase change materials are one way to store heat. Instead of changing temperature, they release or absorb energy as latent heat during their phase change

the world's energy needs, estimated that heat accounted for almost half of all energy consumed. This amounted to 38% of the world's 36.8 gigatonnes of energy-related CO_2 emissions that year. Of that 38% (nearly 14 gigatonnes), the IEA estimated that industry emitted 9 gigatonnes. To reach net zero targets by 2050, this needs to fall to 7 gigatonnes by 2030. So far, only a quarter of the energy produced to generate heat currently comes from non-carbon emitting sources.

An important factor in this is the range of temperatures needed from heat. Keeping homes and other spaces comfortable for human habitation, using space heating, needs fairly low temperatures. Proven technologies such as air- and ground-source heat pumps can deliver this. It takes much higher temperatures to transform raw materials into the products that make up modern society.

However, according to the IEA, industry needs more than half of its heat at temperatures over 300°C. Producing ammonia, an essential component of synthetic fertiliser, requires temperatures of 300°C. Many raw materials, such as the lime used for steelmaking, must first be purified by heating them to up to 1,000°C without oxygen. Sand is melted at over 1,300°C to eventually become glass, while the furnaces and kilns that make steel and cement burn at up to 2,000°C.

Standard heat pumps cannot provide heat at these temperatures, but renewable sources can. For example, arrays of mirrors can concentrate solar energy, and electricity from wind turbines or photovoltaic solar cells can generate heat. These sources are intermittent, and can't supply the round-the-clock needs of industry. Therefore, attention has turned to ways of storing heat in a way that can be drawn upon at any time.



Industrial heat demand by temperature range, 2018 © IEA

CANNED HEAT

This thermal energy storage (TES) is analogous to the development of batteries to store electricity, according to Professor Yulong Ding FREng, founder of the Birmingham Centre for Energy Storage at the University of Birmingham. But there has been much more research and development on batteries.

Professor Ding explains that there are three main methods of storing heat. The first, sensible heat, involves simply heating up a material, then keeping it insulated. The second approach, with phase change materials (PCMs), most often involves melting a solid material, which absorbs heat as it transforms into a liquid, and then recovering the heat as this liquid solidifies. The third approach is thermochemical storage. An example is heating a material to drive off water, before adding water again to release and recover that energy.

Of these three approaches to TES, sensible heat has received the most development. "It already has a long history in industry," Professor Ding says. "Steelmaking has used a system called hot stove for more than 200 years." Here, hot exhaust gases from the furnace heat up a ceramic material that preheats the air being blown into the furnace. Preheating the air reduces the furnace's fuel consumption and improves its efficiency

Using sensible heat for other industrial applications follows similar low-tech lines, for example, with air or an inert gas heated by low-carbon electricity or concentrated solar heat

Reaching temperatures of over 3,000°C, the solar furnace at the Sun Institute of Uzbekistan is one way of reaching the high temperatures needed to transform materials. An array of giant mirrors (just seen) reflect sunlight towards the concentrator's 10,700 mirrors, which focus reflected sunlight to a blisteringly hot point. Opened in 1981 during the Soviet era, it was used to make advanced ceramics © Shutterstock

circulating around a solid material in an insulated tank. To recover the heat, fans blow air or an inert gas over the hot material. The cache can store heat for hours or days and can provide heat at temperatures over 1,000°C. For lower temperatures, water reservoirs or underground caches of meltable salts can store the heat.

University of Edinburgh spinout Exergy3 is commercialising ultra-high-temperature sensible TES technology, invented by technical lead Adam Robinson. Its storage medium is ceramic bricks, which are enclosed in an insulation material. This is in turn surrounded by a heat exchanger to recover radiated heat. The core is at a temperature of over 1,200°C, and the whole system is housed in a module the size of a standard shipping container.

Exergy3's technology is being trialled in a £3.6 million UK Department of Energy and Net Zero-funded project to produce zero-carbon whisky at Annandale Distillery in the Scottish Borders. In June 2024, the company installed a 36 megawatt-hour TES unit to power a 4-megawatt boiler to run the distillery's stills. The system charges using excess renewable electricity from the National Grid, at a rate that allows it to quickly store energy from wind turbines that would otherwise have to be switched off.

Also using this approach is German startup Kraftblock, which has its sights set on industries such as steel, glass, food, and paper. The company fills shipping containers with spheres of its heat media, developed by founder Martin Schichtel while researching nanoparticle composites and smart coatings at Saarland University. The exact recipe is undisclosed,

HOT STUFF: HOW THERMAL ENERGY IS STORED

Phase change materials: with PCMs, heat breaks the bonds (or disrupts intermolecular forces) between the atoms or molecules of a material, but does not change its temperature. Instead, the heat goes into turning the solid into a liquid, or otherwise changing the material's phase. This can be from a solid phase to a solid phase, or a liquid phase to a liquid phase. The energy is recovered when the material returns to its original phase.

Thermochemical storage: is based on reversible reactions or chemical processes that consume or generate heat depending on the direction of the process. For example, one option is to remove water from compounds that exist as hydrated salts to change their form. Heat drives water from their crystalline structure: add water and it releases heat.

A notable example used in school chemistry is blue copper sulfate crystals. These turn grey when heated, becoming the grey anhydrous form. Add water and the blue colour returns, with emitted heat. This chemical method has received the least research attention and is much further from practical applications.

but Kraftblock says 85% is based on upcycled materials, including steel slag.

Kraftblock's first collaborations are underway. One replaces a 25-megawatt gas-fired boiler for heating oil at a PepsiCo crisp factory in the Netherlands. Its storage temperature is 800°C. Another will store heat from a local steel company at temperatures up to 1,300°C.

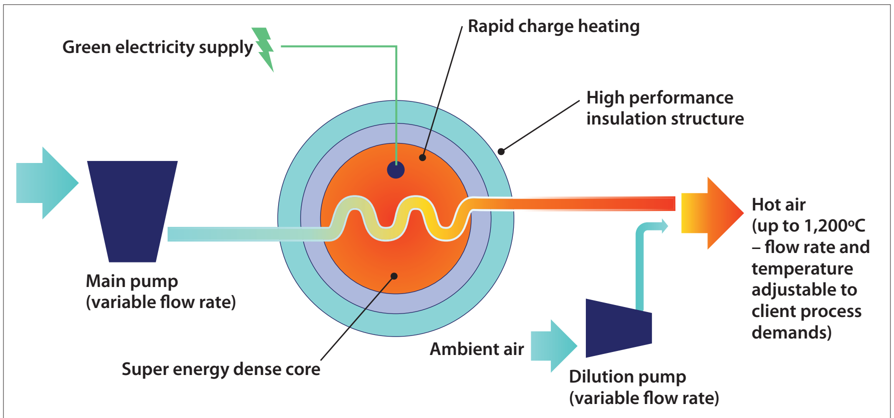
In France, meanwhile, Eco-Tech Ceram has installed two TES units at a brick and tile manufacturer, Wienerberger, near Paris, storing energy recovered from ovens so that it can be reused in dryers. The system uses ceramics heated to 600°C as a storage medium. Previously, the company lost half the heat from its ovens in chimney-stack emissions.

NOT JUST A PHASE

Professor Ding's current research focuses on PCMs. These have two advantages over sensible heat materials. First, they can store heat per unit volume or mass, several times more efficiently than typical sensible heat storage materials, for a given temperature range – meaning less storage material is needed. Second, because their temperature doesn't change, thermal management is easier.

The disadvantage is that the heat has to be transferred from a solidifying liquid, which poses an engineering challenge. Chemical plants and power stations normally use systems called heat exchangers to transfer heat from one material to another. (A radiator is a simple example of a heat exchanger.) But these only work with flowing liquids or gases.

To cope with this, the PCM is incorporated into bricks of a solid composite (also known as a skeleton material). "We use a porous material as a matrix to contain the PCM, which is generally an inorganic salt," explains Professor Ding. Typically, the chosen salt is a magnesium nitrate, but his group has also used magnesium carbonate, sulfate and chloride salts.



Edinburgh firm Exergy3 has developed a high-temperature sensible heat storage system. Inside what looks like a standard shipping container, green electricity supplies a rapid charge heating system, which keeps ceramic bricks at 1,200°C in a cubic chamber. The chamber is surrounded by concentric layers of heat exchangers and insulation. Air pumped through the core is heated up to 1,200°C and used to drive industrial processes

Each of these store heat across different temperature ranges: nitrates will cover temperatures of between about 100°C to 550°C, carbonates between about 400°C to 800°C; and sulfates up to 900°C. Other materials can be mixed with the PCM, such as graphite flakes, to enhance heat transfer into the PCM.

Much of Professor Ding's team's research goes into ensuring that the components of the composite are compatible with each other; salts can be corrosive and could potentially degrade the skeleton material. Because the heat transfer enhancing material heats up, the composites are a hybrid between a PCM and a sensible heat material, known as a composite phase change material (CPCM). Capillary action, the same mechanism that pulls water into a sponge, draws the liquefied PCM into the pores of the matrix. "This avoids leakage of PCM and problems of change of shape as the material heats up; if the material were to soften and slump, it would not be effective. The PCM remains as a stable block. It also accommodates a small volume increase that accompanies the phase change," Professor Ding explains.

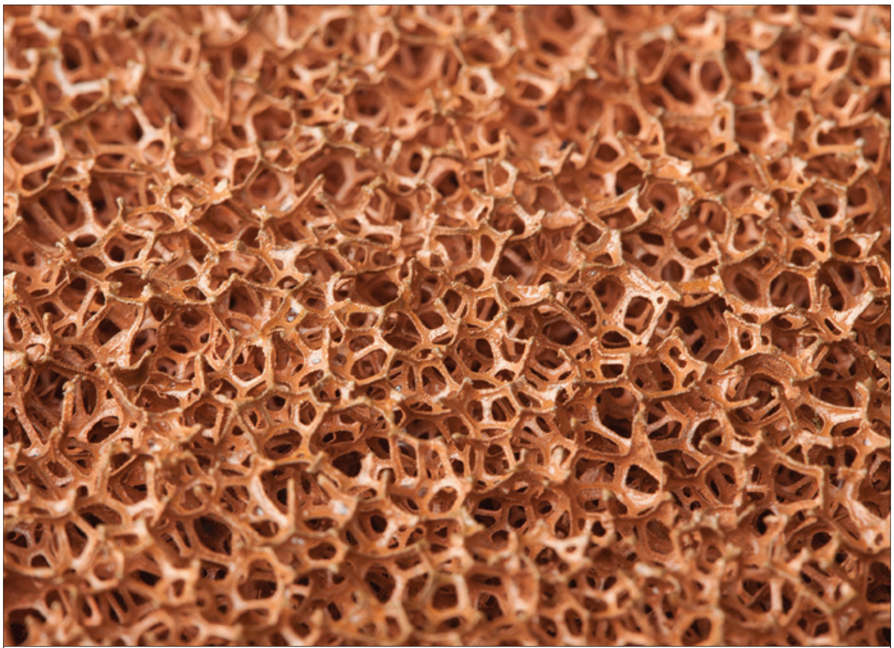
Thanks to the composites, the actual heat storage installations are very similar to those for sensible heat storage. Arrays of blocks, easy to handle and stack, are arranged so that hot gases can circulate around them. This charges the system up by melting the PCM, before cold gases are warmed up by the material resolidifying.

Following a successful 24-kilowatt (100 kilowatt-hour) lab-scale test in Leeds and a 200-kilowatt (2 megawatt-hours) pilot plant in Changsu, China, a first industrial-scale unit was installed in northwest China in 2016. Built by Chinese firm Jinhe Energy, this 6-megawatt (36 megawatt-hours) unit stores excess energy from wind turbines and uses it for space heating. In its first three years of operation, it stored almost 30,000 kilowatt-hours of energy, which would otherwise have been wasted. It reduced CO_2 emissions by some 10,000 tonnes.

In a collaboration with another Chinese company, CRRC Shijiazhuang, Professor Ding's team has developed CPCM technology to chill shipping containers. Aimed at replacing diesel-powered refrigeration units, the containers are 'passively' cooled, working more like a cold box containing an ice pack than a fridge. It takes about two hours to chill down the PCM with electrical refrigeration – potentially green energy – and the containers can maintain an internal temperature of between 0°C and 14°C for over a week.

Last year, Professor Ding's group licensed its CPCM Intellectual Property to Vital Energi, a Blackburn-based energy specialist, which plans to commercially develop it for space and water heating. Vital's development director, Chris Taylor, told *Ingenia* that its clients, including hospitals and universities, had previously depended on gas-fired heating systems.

"Lots of companies were setting net zero goals and pretty much everything involving gas was going,"



To store energy using phase change material, engineers incorporate them into porous matrix materials, such as metal foams © Shutterstock

he says. "About five years ago, we started to look ahead and realised that electrification of heat was probably the way it was going to go." However, he added, electrified heating systems cannot be operated the same way as gas-fired, in part because the price of electricity is much more volatile than that of gas. This means that energy storage is an essential part of any system, with two options. "One is to store electricity and then convert it to heat. The other is to store the heat, and we realised that was cheaper."

Elsewhere, a European project called SEHRENE – Store Energy and Heat foR climatE Neutral Europe – is exploring another approach to storing waste industrial heat and renewable electricity with PCMs. Funded by the EU, the project includes two UK partners participating via the Horizon scheme: the University of Leicester's Materials Innovation Centre (MIC) and Manchester-based digital technologies firm Technovative Solutions (TVS).

SEHRENE, a three-year project coordinated by the French Alternative Energies and Atomic Energy Commission (CEA), is a multinational initiative that is developing an electrothermal energy storage (ETES) technology. Like Ding's, it is based on a composite PCM, but also adds in a high-temperature heat pump as the source of the energy to melt the PCM. The team reckons the PCM's metallic foam matrix, selected to ensure good heat transfer, increases energy density so that it is 30% better than the current state of the art. The goal is to store energy eight to 12 times longer than lithium-ion batteries, at a storage cost that beats pumped hydroelectric energy, currently the cheapest commercial energy storage method. By the end of the project, which has a budget of over €3 million, the consortium aims to build a proof-of-concept prototype system at CEA in Grenoble.

MIC will test the compatibility of the PCM and the metallic foam. "Our role is to understand how construction and phase change materials interact, as relying solely on one without considering the other is not effective," explains MIC Director Dr Shiladitya Paul. "You can have a great phase change material but if it is not compatible with any material of construction that's used, then you have a problem. Likewise, excellent construction materials are rendered ineffective if they are not compatible with available phase change materials." The centre is studying how corrosion, ageing, stress, and thermal cycles affect the materials.

In its work on this, TVS is developing digital models of the component systems to assess their environmental impacts and compare these to the impact of lead-acid and lithium-ion batteries.

THE NEXT STEP

The IEA's analysis suggests that renewable sources will meet just 70% of the projected global increase in total heat demand between 2023 and 2028, with the use of fossil fuels increasing to fill the gap. Electricity from renewable sources isn't likely to keep up with the rising demand for heat. Any attempts to reach net zero clearly need new approaches to delivering the heat that underpins much of manufacturing. TES can be a part of the answer, but only if we begin to match the research effort into this aspect of energy technology as has gone into developing new types of batteries for storing electricity.

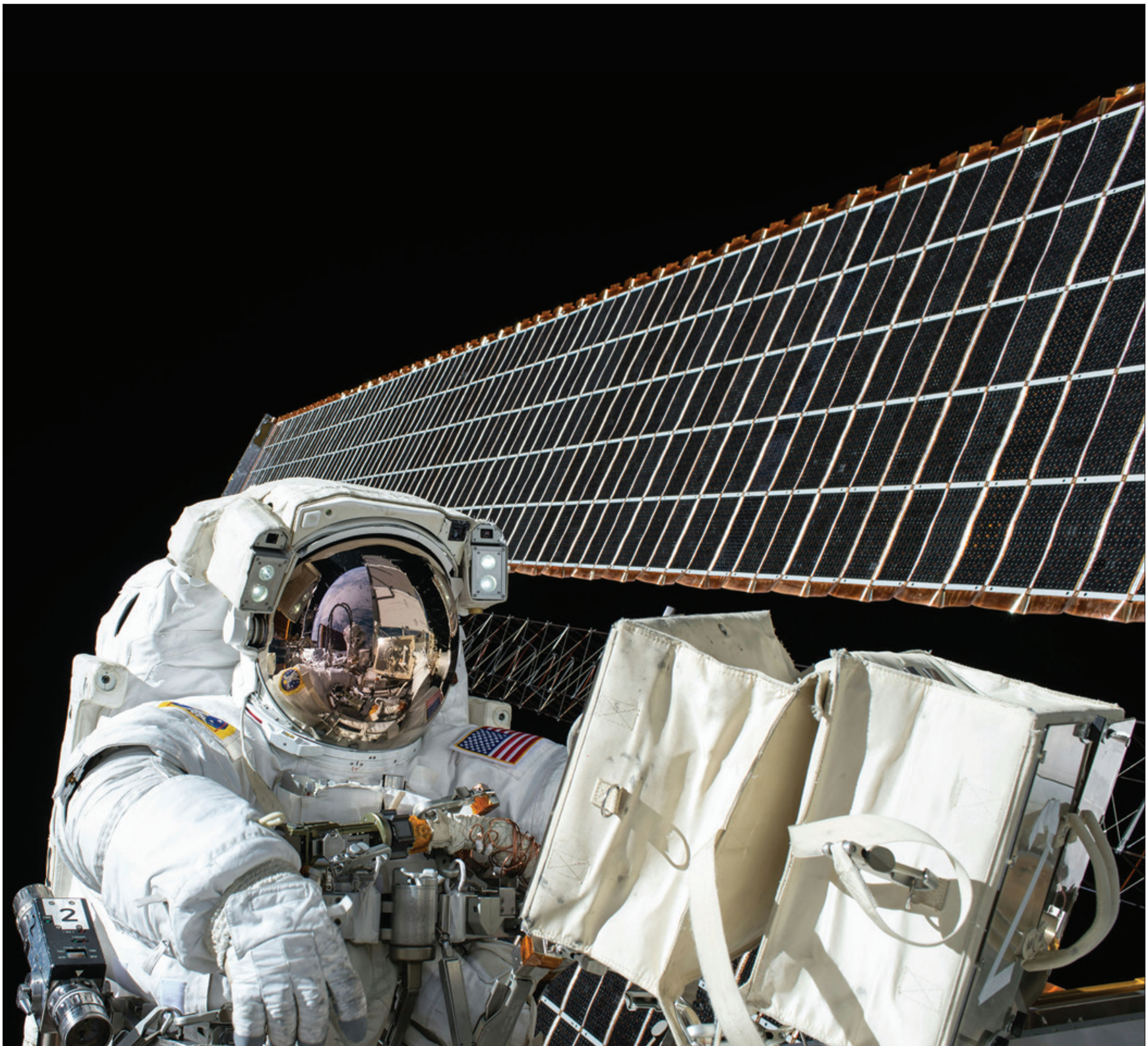
BIOGRAPHIES

Professor Yulong Ding FREng holds founding Chamberlain Chair of Chemical Engineering at the University of Birmingham. He is an inventor of liquid air energy storage technology and led its initial stage of technology developments. He developed composite phase change materials for thermal energy storage, leading to large scale commercial deployments, at about 1,000 megawatts (or 8 gigawatt-hours). His work on passively cooled container technology has led to large scale commercial demonstration for cold chain applications.

Chris Taylor is technical development director at Vital Energi, and was previously technical director at Zeus Renewables after spells as a development engineer with Dalkia Energy and Parsons Brinckerhoff.

Stuart Nathan would like to thank Doug King FREng for his help when putting together this article.

THE FUTURE OF IN-SPACE MANUFACTURING



Without gravity's constraints, structures such as large antenna or radar built off-Earth could be lighter, larger, and use materials more efficiently, delivering better performance and greater capability © NASA

Did you know?

- Engineers are exploring manufacturing in orbit, from 3D printing to cancer drugs
- Microgravity in orbit can drastically change manufacturing processes
- In-orbit manufacturing could lead to lighter structures in space, as they do not need to withstand launch forces

Imagine a future where spacecraft repair themselves, satellites grow their own antennas, and new missions launch without adding to the growing clutter of orbital debris. Dr Gilles Bailet, a researcher in space technologies at the University of Glasgow, explains in-space manufacturing – and what it's like doing high-stakes experiments during parabolic flight.

With rocket launches becoming cheaper, it's tempting to think we can just send more hardware into orbit – but the real solution lies in creating smarter, larger, and more sustainable space ecosystems through in-space manufacturing.

Everything humanity has built so far has been constrained by Earth's gravity. It might seem natural to build within these limits, but when we manufacture in orbit, the rules – and possibilities – completely change. In my work, I focus on 3D printing in space, which offers a radically different approach to designing and building systems for space missions.

UNCONSTRAINED BY GRAVITY

Traditionally, spacecraft must be designed to fit within the limited mass and volume of a rocket's payload fairing, the protective cone that protects it against the pressure and heat of launching through the atmosphere. At the same time, it must also withstand the intense accelerations and vibrations of a launch.

In-orbit manufacturing will allow us to bypass these constraints entirely. Instead of optimising for launch, we can optimise systems for their mission, which may last decades. Without gravity's constraints, structures such as large antenna or radar built off-Earth could be lighter, larger, and use materials more efficiently, delivering better performance.

Preparing for parabolic flight: (left to right) Professor Colin McInnes FREng, Dr Gilles Bailet, and Satyam Bhatti, from the University of Glasgow's James Watt School of Engineering

Combining in-space manufacturing with recycling has transformative potential. Imagine if spacecraft were refurbished every decade: it could extend their lifespans to a century, reducing the need for new launches.

This vision aligns with a more sustainable future for space exploration, where waste is repurposed, and innovation continues without adding to orbital debris. By enabling a circular economy in orbit, we can redefine the future of space engineering, ensuring resource efficiency and environmental responsibility.

One of the biggest challenges we faced in our own programme of research was overcoming the limitations of existing 3D printing methods. Many types of 3D printer, including those using polymer filaments or resin, are prone to defects, failures, and inefficiency. For example, resin-based printing often traps gases that create internal defects, while filament-based systems are prone to tangling or breakage. Powder-based 3D printers, on the other hand, require complex containment systems to manage material flow, which are difficult to implement in microgravity.

To address these challenges, we have developed and patented a granular 3D printing material for microgravity. This method avoids the complexities of traditional systems by eliminating the need for spools, curing processes, and consumables. Instead, we use a purely mechanical system with anti-clogging mechanisms

Gilles awaiting take-off on board the Air Zero G plane

to transport feedstock efficiently. A second breakthrough was creating a technology that allows us to reload the 3D printer while it's operating, eliminating interruptions and minimising failure risks.

HEIGHTENED SENSES

Testing these technologies in microgravity was a critical step in validating their potential. Parabolic flight, a type of aircraft flight that simulates the weightlessness astronauts experience in space, provided the perfect environment to do so.

I've done quite a bit of skydiving, so I thought parabolic flight would feel familiar. I couldn't have been more wrong. Microgravity sharpens your senses, making everything feel more vivid. Astronauts training with us described how the heightened blood flow to the brain enhances perception, and I could feel it myself. Having worked on this experiment for years, I was hyper-focused during the first of the three parabolic flights we joined. The stakes were high, and every detail mattered. When our initial tests matched our best-case simulations, it was a massive relief.

Floating freely in microgravity, I felt a surreal connection to the physics that inspired my career. It was a reminder of why I pursued space engineering in the first place. As the tests progressed, I began to relax, appreciating the unique sensations of weightlessness and the opportunity to witness years of hard work come to life in real time.

Building on the success of these foundational technologies, the next step is to 3D print active systems – structures embedded with electronics. This step is critical for creating spacecraft that can evolve and adapt over time. We'll begin by testing these techniques in ultra-vacuum environments on Earth before advancing to in-flight demonstrations.

A further cornerstone of our progress is the UK Space Agency's Enabling Technology Programme, led by our group in partnership with the UK Manufacturing Technology Centre, which is vital for both the technological and business sustainability of our work. This initiative not only supports the development of new materials and methods, but also ensures that safety, environmental responsibility, and economic feasibility are at the forefront.

"Having worked on this experiment for years, I was hyper-focused during the first flights. The stakes were high, and every detail mattered," says Gilles.

By rigorously testing materials in space-like conditions, we're minimising risks associated with defects that could lead to structural failures or space debris. This programme is paving the way for creating technologies that are not only innovative but also responsible.

Our vision is bold yet achievable: a future where in-space manufacturing transforms how we build, repair, and sustain our presence beyond Earth. This vision doesn't just advance space exploration – it reshapes it entirely, creating opportunities for deeper interplanetary missions and fostering a sustainable presence in orbit.

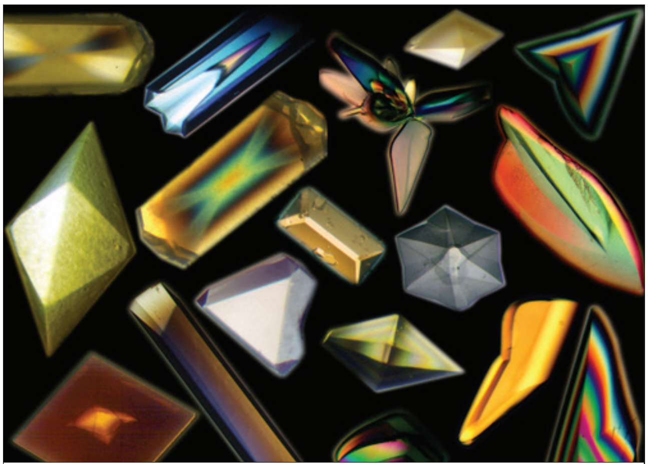
MAKING PARABOLIC SPACE EXPERIMENTS POSSIBLE

Dr Gilles Bailet's in-space manufacturing programme has been supported by a Royal Academy of Engineering Chair in Emerging Technologies held by Professor Colin McInnes FREng, along with funding from a Royal Academy of Engineering Proof of Concept Award. The programme is investigating space technologies at extreme length scales – so a femto-satellite, with a mass lower than 100 grams, developed by Dr James Beeley was also flown as part of the experiment package. Extra funding to support the parabolic flight from the University of Glasgow's Glasgow Knowledge Exchange Fund and the EPSRC Impact Acceleration Account has been led by Dr Gilles Bailet. The microgravity demonstration was part of the 85th European Space Agency Parabolic Flight Campaign. Conducted in collaboration with Novespace, this saw Dr Gilles Bailet, Professor Colin McInnes, and Satyam Bhatti fly on three parabolic flights to operate the experiment in microgravity. Dr James Beeley provided ground-based support at Glasgow.

BIOGRAPHY

Dr Gilles Bailet is a lecturer in space technology at the University of Glasgow, specialising in in-space manufacturing, CubeSats, and solar system exploration. With a PhD from Centrale Paris, he has led multiple ESA, UKSA, and industry-funded projects; secured patents; funded a space centre in Paris; and pioneered microgravity experiments. His work bridges novel space technologies, innovation, and education, shaping the future of space exploration. He is currently seeking sponsorship to send Scotland's first hardware to the Moon — an art display serving as a scientific instrument.

MAKING CANCER IMMUNOTHERAPY DRUGS IN SPACE



Protein crystals grown on the US Space Shuttle or Russian Space Station, Mir. Photographed under polarised light, the crystals include plant proteins, animal proteins such as antibodies, and viral proteins. They range in size from a few hundred microns long to more than a millimetre © NASA Marshall Space Flight Center/Dr Alex McPherson, University of California, Irvine

Another venture exploring manufacturing in space is BioOrbit, a startup investigating how microgravity could change the way cancer antibody treatments are delivered to patients.

Antibody treatments are a type of cancer immunotherapy, which means they help the patient's immune system to fight cancer. In this case, antibodies, large protein molecules, attach to cancer cells so the immune system can attack them.

These treatments are usually administered via intravenous (IV) drip into the vein, so people have to go in to hospital to receive treatment. If the treatments could instead be delivered subcutaneously – into the fatty tissue under the skin – it would allow people to self-inject their treatments, similar to an insulin pen for diabetes. This way, patients could potentially stay at home, in a more comfortable and familiar environment.

However, it's not possible to deliver the same volumes of drug that can be delivered by IV drip by subcutaneous injection (for one thing, it would be painful). So, to deliver the same dose, a higher concentration of the antibody protein is needed. The problem is, at high concentrations the antibodies are too viscous to inject – imagine pushing honey though a needle. One way to reach high enough concentrations at low viscosity is to form solid crystals out of the protein, in a process called protein crystallisation.

But there's a catch: on Earth, protein crystallisation is known to be extremely challenging. It is governed by tiny forces, and under Earth's gravity, these can cause the crystals to vary in size, making for lower quality crystals. Under microgravity in space, these forces drop, resulting in more uniformly sized crystals that are higher quality.

Astronauts have been aboard the International Space Station since the 1980s, to analyse proteins that cause disease and help them to develop new drugs. However, BioOrbit's work isn't just exploratory. The company aims to set up a pharmaceutical factory. As Dr Katie King, CEO, puts it, "we need to start thinking about [manufacturing in] space as almost like manufacturing something in a different country. It's just a different environment and location."

Initially at a small scale, BioOrbit will first develop the hardware to crystallise the drug protein on board spacecraft. There are sizeable engineering challenges to solve, including how to mix chemical solutions in space and harvest the crystals. "And this all has to be automated as there are no humans there," Katie adds. To cap it all off, yet another problem to solve is discovering how to harvest the crystals and transport them safely back to Earth.

BioOrbit's first in-orbit demonstration will be in 2025, where its setup will be tested on the International Space Station. With a better idea of how the system functions in space, the team will then apply those learnings to develop the next-generation system, which will launch in 2026. All of this has been made possible by commercial space launch providers such as SpaceX, which has changed the game in terms of cost of launch.

When Katie finished her PhD in nanomedicine, she wanted a job in the space sector, specifically using the benefits of microgravity to enhance medical research. At the time, no jobs of this kind existed. So, she and a team she met at the International Space University founded BioOrbit to create their own jobs. "The impact that space could have on driving innovation to benefit humanity is huge," says Katie. "The health and space sector is growing, and the next generation of forward-thinking engineers and scientists are needed."

This could create entirely new careers, such as microgravity biologist or microgravity pharma production scientist. Companies such as BioOrbit are creating a new industry, shaping the future applications of space tech.

Words by Fern Ellis

The BioOrbit team © BioOrbit

HOW TO WEATHER THE RISE OF AI

Penny Endersby CBE FREng's journey to running the UK's leading engineering and research centre for weather forecasting and climate change took in fuel cells, materials research for armoured vehicles, and cyber defence before she got her dream job. As CEO of the Met Office, she is now at the forefront of bringing AI to weather forecasting and the UK's understanding of climate change. She talks to Michael Kenward OBE about how she overcame her aversion to management.

Modern meteorology depends on an array of scientific disciplines, underpinned by physics and overlaid by a blend of information technologies. Penny Endersby has experience in both those key domains, but her journey to becoming the CEO of the Met Office was anything but straightforward. After a brief spell in fuel cell research, she moved to research in materials engineering for armoured vehicles before switching to information technologies. At the Met Office, she now leads an organisation of about 2,300 people and a revenue approaching £300 million, leading research into weather and climate change.

Like many school students, Endersby had little exposure to engineering as a career option. At least her girls school was, unlike many, "very, very good at getting girls to do science," she says. "But they had no idea about engineering whatsoever."

Yet, Endersby wasn't completely ignorant of the engineer's life. Her father worked for British Gas. She remembers him bringing home instruments that he would take out for nighttime noise surveys. He would start setting things up at home, showing her how to turn the sounds in the room into visual representations on paper. "I remember one of us sneezed and the needle went whoosh." Endersby isn't sure if her father really needed test his equipment or if he wanted to entertain and educate his daughters (Endersby's younger sister grew up to be a chemical engineer), but the experience stuck.

Another nudge towards engineering came in sixth form when Endersby undertook an extended period of work experience at the GEC Hirst Research Centre, which was sponsored by WISE (the Women and Science in Engineering campaign), and saw early work on photo-optical communications. In the mid-1980s, fibre optics weren't widely used. She recalls peering down a microscope at optical waveguides, checking to see if they were usable. She was excited by "that sense of seeing something that no one else knew yet".

Intent on keeping her options open, she chose to study for a natural sciences degree at the University of Cambridge. Endersby considered doing a PhD there but instead opted to work on solid oxide fuel cells at British Gas, the company that had sponsored her degree. After a short spell, she moved to the Ministry of Defence (MoD) and its Fort Halstead research site in London, before it moved to Porton Down and became the Defence Science and Technology Laboratory (Dstl).

"I have not regretted [not doing a PhD], although I sometimes feel a little sheepish, surrounded by deep experts," Endersby says. But she thinks that her research career more than made up for the missing academic qualification. "I've spent all my life as a working research scientist in industry and in the Ministry of Defence." It is just that much of her work was secret and didn't make it into a list of published papers.

TIME FOR CHANGE

The MoD had brought her back to ceramics and their use in armour, in this case investigating how to make armoured vehicles much lighter, such as removing the large slabs of metal as armour to prevent projectiles from smashing into a vehicle. The idea was to see if electrical energy could repel incoming projectiles instead. It turned out that the science behind the concept of 'electrical armour', as it came to be called, wasn't too bad, but it proved difficult to put it into a vehicle that could operate safely with personnel on board in conflict zones.

Endersby's research career had to change to match the MoD's priorities, a message she likes to get across when she talks to young engineers. You have to adapt your career to meet the needs of the client. And this next career change was more in response to circumstances than research demands. She was happily progressing along the scientific path at Porton Down, where she then worked. As part of a small team of researchers she says that she was "really quite allergic to any kind of management. I not only did not want to do management, but I also actively thought was it a bit of a waste of time that got in my way."

Endersby changed her mind when the MoD wanted someone to lead a new electrical team. She decided to apply for the job. "I didn't want someone who didn't know about my science telling me what to do." She laughs that this was

As a choir member at Exeter Cathedral and other churches, Penny Endersby became canon scientist at the cathedral. In this new role, "invented by the dean," she says the role will be to bring her "wisdom and understanding of scientific matters to a faith context, and to help the church in its own sustainability journey". She also hopes to "help the congregation to understand in a conflicted information environment where they might look for information that's reliable and trustworthy"

"a really rubbish reason", but it resulted in what she describes as a life-changing conversion. She'd wanted to do science since about the age of 16, and yet here she was setting off on a new path that would mean less time spent at the research frontiers.

Despite her previous distaste for management, Endersby took to it. "To my utter confoundment and surprise, I found that I was actually really rather good at leadership and I enjoyed it. I could achieve more with a team of 10 than I could on my own. And I enjoyed developing people. I enjoyed the ability to deliver more impactful things."

Endersby first led groups working on shock and acoustics as well as materials, her original beat. In 2009, she went on to head all physics work at Porton Down, with teams of 300 or 400 people. A brief detour deeper into management proved to be an important lesson. It turned out that even as a part of the MoD's management team, she missed the connection with research. Endersby was temporarily in charge of 'safety and estates', with little connection to science. Previously she may not have been doing research herself, but it was around her all the time. "I hadn't realised how much energy I took from seeing and understanding and sharing and finding ways to make better scientific advancements, even if I was not a researcher."

Endersby wanted to be back rubbing shoulders with researchers. She could have returned to physics, but by then the MoD had another research challenge. Would she like to be director of the Information Management department? Cybersecurity was making its presence felt at Dstl. She admits that this was "one of those imposter syndrome moments. One minute you're leading a physics department, you've been steeped in physics for 20 years, and the next minute you're leading a bunch of coders, and you can't code your way out of a paper bag." Nevertheless, she took the plunge. In 2015 she was put in charge of Dstl's Cyber and Information Systems Division, working on a very different security challenge.

EMERGING TECHNOLOGIES

Endersby's move into the cyber world in 2012 had amusing consequences. "I could not say we were creating an offensive cyber capability, because it was not declared. So I was recruiting people into something [where] I couldn't tell them the exciting stuff they were going to do."

Around the time that Endersby's career "went cyber", a colleague at Dstl spotted a call from the Royal Academy of Engineering for its Visiting Professors (VP) scheme. VPs are working engineers who spend time at a university so that students could have face-to-face encounters with real-world engineering (An introduction to the 'real world', *Ingenia* 67). 'Why not apply for that?' was their suggestion to Endersby.

Endersby liked the idea. She sees the scheme as "a laudable attempt to bridge the gap between the theory of engineering and the practice of it". Despite Endersby being relatively new to the cyber world, the selection decided that it would be a good idea to match her with one of the UK's prestigious computer science schools. "I was thinking 'goodness me, I knew nothing about this', and I'm suddenly a professor of computer science at the University of Southampton. I'd have been much more comfortable being professor of physics, or even in materials for engineering, than I would have been as a professor of computer science."

In the event, after saying that she wouldn't be up to lecturing on computer science, Endersby could certainly fulfil the VP's role of giving students some real-world contact. She could also make connections between her engineering work on the emerging challenges of AI in intelligence and the theory of cyber assurance, both areas of growing academic interest. It also gave the academics an opportunity to connect with someone who could talk about defence work, an area where, as Endersby puts it, "you don't necessarily put out what you can't do".

THE WEATHER WILDCARD

In her career progression, Endersby narrowly missed out on becoming the head of Dstl. "Maybe next time," was the message. But she still had ambitions albeit with a clear idea of what she wanted. "I'd like to be promoted. I don't want to work in London. I like working for the government. I like doing

QUICK Q&A

What inspired you to become an engineer?

To some extent I was influenced by my father who was an acoustic engineer for British Gas. But I also made a gradual transition from physics, as I realised I get most satisfaction from seeing new scientific advances realised as working products.

Who influenced your engineering career?

I've been blessed by some wonderful managers and mentors. Dame Wendy Hall at the University of Southampton and Dame Frances Saunders as Chief Executive of Dstl were particularly inspiring and generous with their advice to me.

What's the best part of your job now?

The extraordinary variety. I'm writing this on the air bridge back from the Falkland Islands, where the Met Office maintains a 24/7 team in support of all the activity on the islands, especially defence. The harsh conditions mean that weather is a factor for almost any activity.

Which engineering achievement couldn't you do without?

I have terrible eyesight: short sight, astigmatism and now age-related reading issues. I am thankful to engineers for the ability to make contact lenses and fancy varifocals.

Most impressive example of engineering to look at?

I was lucky to visit the two aircraft carriers when they were in build in the Rosyth shipyards (we were supporting their cybersecurity at the time). I loved the carriers, but I think my favourite engineering item was the gargantuan crane that lifted the sections into place to be welded together.

The Met Office allowed Penny Endersby to indulge her interest in the natural world. With her husband, she took the opportunity of lockdown to undertake the Dartmoor 365 challenge and find something interesting in every square of the National Park. "So I really do know the park very, very well." She is now a part of a group that acts as a go between with the MoD, her old employer, "and the many, many stakeholders who think the moor is theirs and want to use it for ecological purposes or public access, or farming their sheep on it, or protecting its historic monuments."

something that's valuable and purposeful in life." Out of the blue she saw an advert for the top job at the Met Office. "It just ticked every box. I could see it was my dream job."

As she saw it, while she might not put it like that, her credentials also made her a dream candidate. "They wanted somebody who could be a credible scientist and represent their science outwards and run an organisation of more than 2,000 people with a big turnover." She had been through the Civil Service training system, rising through the ranks from being a junior manager, through middle and senior management to an executive role. She could also throw in the visiting professorship and time as a trustee of the Wiltshire Wildlife Trust as evidence of her long-standing interest in nature.

Yet another section on Endersby's CV was as one of the first engineers chartered to the Institute of Physics. She went on to chair the institute's charter engineering committee. "I've always ridden the boundary between physics and engineering" – natural territory for meteorology. Nevertheless, Endersby admits, "I think I was a bit of a wild card for them."

When Endersby arrived at the Met Office a key item on her agenda was commissioning a new supercomputer system. It takes powerful computers to run the models of the atmosphere that underpin weather forecasts and predictions of climate change. Endersby believes that in future the Met Office may not run its own computer system and will join the general migration to 'the cloud'. Then there was the growing importance of IT, especially AI, in the organisation's work.

With so much riding on computer expertise, the Met Office is naturally asking what AI might do for its work. "We are applying AI and machine learning in many ways in the Met Office" (See 'Weathering the climate storm'). As she sees it, the jury is out on AI's ability to replace physical modelling: there can be no AI models without the data that goes into the weather models. "It's all built on AI being trained off the physical models." Maybe one day AI can learn directly from observations rather than physical models. But not yet.

"I am really quite open minded about how far this will be another useful tool we add to our suite – I'm sure it will be at least that – versus the big disruptor that means that what we do will be completely transformed and we might not need the physical models. In the remaining time of my career, I think I'm going to be riding two horses."

WEATHERING THE CLIMATE STORM

Penny Endersby's remit as CEO at the Met Office is to oversee its work on both weather forecasting and climate change. They may not be the same, but they come together in their science. "We predict them through the same techniques," she explains.

The Met Office uses the same 'unified model' for all of its forecasting. Run the model one way and it provides weather forecasts; in a different mode it predicts climate change. "If we change something in the unified model that improves the weather forecast, it's a pretty good bet that it will predict the climate better as well. If so, you've got the physics right."

The Met Office, through the Hadley Centre, provides one of the key models that goes into the Intergovernmental Panel on Climate Change's (IPCC) climate projections. It also provides climate projections for the UK. "They're worth a Google," she says. And they're free. "It's interesting to look in your own area." The projections provide information down to a two-kilometre grid for different climate scenarios over different timeframes. "That enables anyone building infrastructure or whatever to look at what they need to be resilient against."

Weather models run on powerful computers, which consume a lot of energy. AI has a different challenge. "In terms of energy, running an AI model is trivial, training it is hideous. But you only do that once." You do have to update your training, but eventually AI may well help out on the energy front.

AI can be useful in smaller ways, even if it isn't being used for climate projections. The Met Office takes in 200 billion observations a day, she explains, so picking out poor quality observations is a really simple one for AI. Another role is looking at how ice sheets are thinning. "You can use AI with more traditional image processing techniques with our weather machine learning". Another task still worth solving is how ocean chemistry is changing.

Then there are the Met Office's all too familiar weather warnings. "Could we use AI to give us first-guess weather warnings from what the model is producing, rather than that those are done by a human being at the moment?" So far, she says, it's still a human doing it. The forecasters use expert judgment, look at what the model says and "literally draw a polygon on the map by hand".

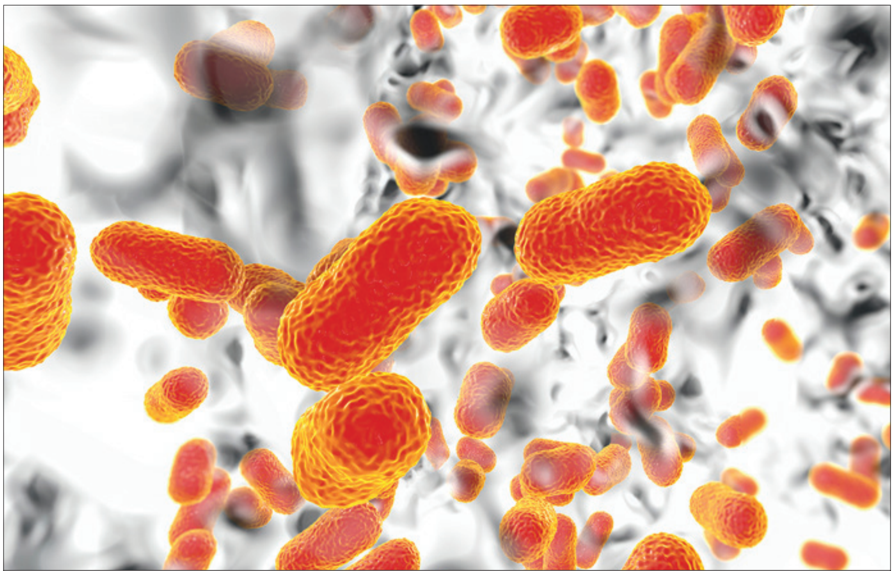
Even when AI gets to a position where it can begin to match human forecasters, it would take some time to get the regulatory approval needed for civil aviation, for example. She explained the position at a recent event on AI and weather forecasting at the Academy to mark last year's MacRobert Award winner ('AI shakes up the world of weather forecasting', *Ingenia* 101). When meteorologist and BBC weather presenter Tomasz Schafernaker asked her how humans and AI might work together in the future, she told him: "I don't think you need to worry about your job."

CAREER TIMELINE AND DISTINCTIONS

Studied natural sciences at the University of Cambridge, **1988–1991**. Various roles including at Royal Armaments Research and Development Establishment at Fort Halstead; manager of the physical sciences department; Head of Cyber and Information Systems; and acting Chief Technical Officer, Dstl, **1993–2018**. Member, Board of Trustees, Institute of Physics, **2000–2004**. Visiting Professor in Electronics and Computer Science, University of Southampton, **2013 to present day**. Honorary Treasurer and Member, Board of Trustees, Wiltshire Wildlife Trust, **2016–2018**. Chief Executive, Met Office, **2018 to present day**. Fellow, Royal Academy of Engineering, **2021**. Canon Scientist, Exeter Cathedral, **2023 to present day**. President, European Centre for Medium-Range Weather Forecasts, **2023 to present day**. Awarded a CBE for services to meteorology, defence science and technology, **2024**.

THE MEDICAL TEST BATTLING ANTIBIOTIC RESISTANCE

Every year, more than a million people die as a direct result of 'superbugs' that have become resistant to antibiotics. Now, a test that can identify common bacterial infections in minutes and pick out the right drug to prescribe will help us use these lifesaving drugs more wisely.



'Superbugs' that have developed resistance to antibiotics are one of the greatest global health threats of our time © Shutterstock

Antibiotic resistance is one of the biggest global health threats we face. As the problem grows, we're running the risk of bacterial infections becoming fiendishly difficult to treat. If we can't effectively treat bacterial infections, routine medical treatments such as surgeries and chemotherapy become far riskier.

Overprescription is a major contributor to antibiotic resistance. This can happen when GPs can't diagnose the exact bacteria causing common infections. Confirmation usually involves sending a sample to be analysed in a microbiology lab, which can take several days. Patients can't always wait this long for treatment.

So, to avoid severe complications such as sepsis, doctors must sometimes prescribe antibiotics before they know if they'll be effective. The problem is, whenever antibiotics are used, bacteria can become resistant to them.

Now, a Swedish spinout company, Sysmex Astrego, has developed a test that can determine whether (and which) antibiotics should be prescribed to treat a urinary tract infection in a matter of minutes. It shrinks the suite of tests that normally require a microbiology lab into a compact machine designed for GP's offices and A&E departments. The test won the Longitude Prize on antimicrobial resistance in 2024 run by Challenge Works.

The test requires just 400 microlitres of urine, which is injected into a cartridge the size of a smartphone. Air pressure is used to manoeuvre the sample through tiny channels and into traps that capture the bacteria, holding them in view of a microscope at a high magnification while feeding them with antibiotics. Every minute, it takes about 60 images of the channels to see whether bacteria are present. If they are, it calculates how quickly the bacteria grow with different antibiotics, or with no antibiotics.

"You can clearly see if an antibiotic starts slowing down the growth rate," says Mikael Olsson, the company's CEO. For some antibiotics, he adds,

EYES ON THE INNOVATORS

Ingenia **is keeping a close eye on the engineering breakthroughs making a difference around the world.**

Imperial College London spinout **MintNeuro** and its partners have secured £17 million from the Advanced Research and Invention Agency to translate its brain implants.

Research from the **University of Sheffield** shows integrating solar panels in a farming-friendly way will meet the UK's solar energy targets.

For Sysmex Astrego's test, a urine sample of less than half a millilitre is loaded into a smartphone-sized cartridge. The cartridge is then inserted into an analyser, which exposes bacteria to different antibiotics and provides results in minutes
© Sysmex Astrego

you see the bugs "pop like balloons" in the fluidic traps.

ANTIBIOTIC TESTING ON A CHIP

The test's beginnings go back to 2015, when Swedish biophysicist Professor Johan Elf was developing ways to study chemical reactions inside individual bacteria at Uppsala University. This involved channelling liquids containing bacteria down tiny tubes and looking at them under a microscope.

These tiny tubes are called microfluidic and nanofluidic traps. They're sometimes called lab-on-a-chip technologies, as their precisely patterned channels are embedded in small silicone and glass chips. At their largest, the channels are hundreds of micrometres wide. Nanofluidics, on the other hand, contain channels narrower than one micrometre wide – about a hundredth of the width of a human hair. At this scale, the properties of fluids change. "You get very good control over what goes where and when," says Elf. "You can spatially and temporally time when different chemistries occur."

With this precise control over different fluids, Elf and his team could pump in different antibiotics and bacteria to see if the microbes responded to the drugs or not. "The first time I saw that the bacteria died in front of our eyes in just a couple of minutes. That was really a critical moment to see this will actually work," says Elf. "It's unusual you get that clear-cut results in the lab."

Once he realised its potential usefulness, Elf patented the technology and spun out a company, with plans to make the incredibly complex and expensive system cheaper and more user-friendly.

SQUEEZING A LAB SETUP INTO THE SIZE OF A PRINTER

Turning what was at the time a biophysics lab setup, custom-built for studying cells, into something more or less the size of a desktop printer, was a major challenge. It took two years to develop a prototype. Then, it had to be robust and easy to manufacture, with software and data analysis challenges to address along the way.

The second big challenge came when the device's first clinical tests came along. Urine samples vary enormously between patients. They may or may not contain bacteria. Those bacteria may or may not die when they're exposed to antibiotics. Other factors change how the machine reads any one sample such as the cocktail of various human cells it contains.

The fluidic technology helped. Big cells tend to stay away from surfaces, whereas small cells move closer to surfaces, explains Elf. In practice, this means the test can filter out most of the types of cell that you don't want to analyse. Urine samples, for instance, contain red blood cells, white blood cells, and a variety of other cells other than bacteria.

Olsson explains the team found a way to compensate for the different parameters, by collecting clinical samples showing the full range of how bacteria might respond to antibiotics, from the vulnerable to the very resistant 'superbugs'.

BRINGING BACK DISCARDED ANTIBIOTICS

While antimicrobial resistance is still growing, access to precise and rapid diagnostics will allow us to use the antibiotics we have available.

"We can bring back antibiotics that have been discarded because of the high resistance [to them]," says Elf. Even if 20% of the population are resistant, he adds, we can still use them for the other 80% of people.

With proper diagnostics, we can also opt for more narrow-spectrum antibiotics, rather than settling for broad spectrum antibiotics that drive resistance.

Following the 10-year journey that led them to winning the Longitude Prize, Olsson explains the company is now ramping up production to meet demand in Europe and hopes to expand to the US and Asia.

The next stop after that could be applying the diagnostic tool to new infections. Among the candidates are sepsis, lower respiratory tract infections, and tuberculosis. Elf has already begun work on tuberculosis at Uppsala University, which currently takes four weeks to diagnose. He hopes to push this down to 12 hours, although acknowledges that it will take time until there is a product for tuberculosis. "There are lots of different challenges in terms of the microfluidics because they grow in a different way," he explains.

"The beauty of this platform is that it's quite applicable to lots of different infections," says Olsson. "It's a smorgastable of selecting the next one."

A team from the **University of Cambridge** has developed 'smart pyjamas' to monitor sleep disorders at home.

Run by **Zenobe**, Europe's largest battery storage site has begun operating in Scotland and will store power from offshore wind farms.

Microsoft says its new Majorana 1 chip will bring about quantum computers able to solve meaningful problems in "years, not decades".

HOW DOES THAT WORK?

BREATHING UNDERWATER

A specially engineered two-stage regulator system attached to a gas cylinder allows scuba divers to safely breathe underwater while moving about freely so they can explore the underwater world.

Covering 71% of the Earth's surface, the ocean is a largely unexplored world. Recreational scuba diving, where divers swim with their own independent air supply, allows humans to experience this environment firsthand. People are drawn to scuba diving for many reasons, but since humans cannot breathe underwater, divers rely on dependable engineered equipment to safely breathe air beneath the surface.

Divers carry air on their backs in cylinders, but if the cylinders were simply filled with air at atmospheric pressure, they wouldn't be able to stay underwater for long. As a diver descends, water pressure rapidly increases – as does the density of air that the diver is breathing in. At a depth of just 10 metres, the surrounding pressure has already doubled, meaning a person would need twice as much air to fill their lungs with the same breath.

To solve this, standard scuba cylinders store air compressed up to 300 times atmospheric pressure. A typical 12-litre cylinder, holds about 3,600 litres of air – enough to fill 10 refrigerators and provide divers with enough air to stay underwater for much longer. Made from aluminium or steel alloys, the cylinders are designed to be portable and withstand extreme pressures while remaining corrosion-resistant for their continuous use underwater.

The high-pressure air cannot be breathed directly, so a scuba regulator – the equipment that connects the cylinder to the diver's mouth – reduces the pressure sequentially in two stages.

"Taking air from 300 bar to a breathable less than 25 millibar is a significant engineering feat," says Gavin Anthony, a scientific adviser to the British Sub-Aqua Club.

The first stage of the regulator is attached to the cylinder, and it reduces the air pressure from the cylinder to an intermediate level using a diaphragm or piston mechanism. As a diver descends, the increasing water pressure pushes against the diaphragm or piston, which moves to keep the intermediate pressure at about 10 bar above the surrounding water pressure of the diver. The force needed to maintain this pressure difference comes from a compressed spring inside the first stage. Air then flows through a hose to the second stage within the mouthpiece.

"From that 10 bar, just a small inhalation from the diver takes the pressure down to just a few millibars," Gavin says. Inside the mouthpiece, a flexible diaphragm moves as the diver inhales, opening a downstream valve that releases air only when needed, allowing it to expand and match the surrounding pressure for breathing. This on-demand system, rather than a continuous flow, makes air consumption more efficient. "When someone is resting, they take in only a small amount of gas from the regulator, but equally, if they are exercising vigorously and require more air, the regulator gives them the amount they need," he adds.

To ensure scuba regulators are easy to breathe from, they must meet strict safety standards and undergo testing using a breathing simulator. Gavin explains that: "in the UK and Europe, the EN 250 rating marked on your regulator indicates it has been tested to meet those safety standards". The equipment that divers use to breathe underwater has been refined over decades of research, and the engineering behind it means that divers are able to breathe easily so they can fully immerse themselves in the sights and wonders that the ocean has to offer.

Words by Jasmine Wragg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