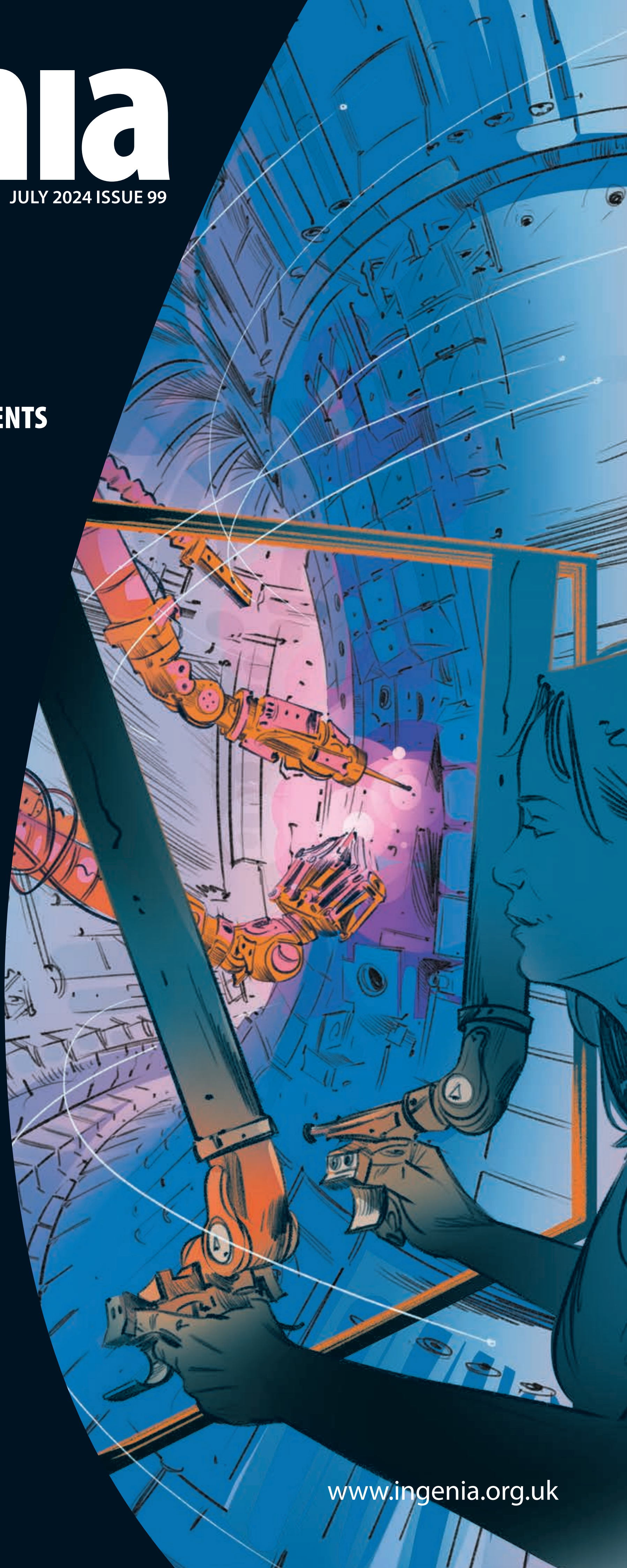
ingenia

JULY 2024 ISSUE 99

CELEBRATING INNOVATION
MORE PRECISE EYE SURGERY
THE FIGHT AGAINST MICROPLASTICS
ROBOTS IN HAZARDOUS ENVIRONMENTS



Royal Academy of Engineering

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Royal Academy of Engineering

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Front cover
Artist's impression of a generic remote handling robot
© Illustration by Benjamin Leon

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WELCOME

Robotics are increasingly becoming a part of our everyday lives, and in this issue we look at how they are being employed to reach the places that humans cannot.

On page 10, engineer Christos Bergeles is working with ophthalmic surgeons to develop a new robotically controlled instrument to precisely deliver treatment to the back of the eye. Later in the issue, you can learn how robots are going into some of the world's most hazardous environments, in particular nuclear facilities, and how engineers design them to withstand these extreme settings.

Engineers make the world safer and healthier. Professor David Butler FREng discusses how engineers are playing a key role in cleaning up wastewater through improvements to infrastructure. On page 24, engineers are coming up with solutions to reduce the harmful microplastics that find their way into our oceans, vegetables and even in human tissue.

Our profile subject, Professor Cath Noakes OBE FREng, provided critical expert advice to government on air flow around buildings at the height of the COVID-19 pandemic, and our Innovation Watch tells the story of Lewis Hornby's jelly sweet that is helping thousands of people avoid complications relating to dehydration.

Ingenia continues to bring you the stories of how engineers are driving change in the world. And our next issue, out in September, is a milestone for us – celebrating 25 years and our 100th issue. It will an extra special issue, so please do keep a look out for it.

In the meantime, please do let us know what you think of this issue at **ingenia@raeng.org.uk** or via Twitter using **#IngeniaMag**

Faith Wainwright

Faith Wainwright MBE FREng
Editor-in-Chief

@RAEngNews #IngeniaMag

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UP FRONT

FEATURES

Corrections: In issue 97, on page 2, the caption labelled the 'Everyday Engineering' competition winners incorrectly. It should have been Monica Wai (*left*) and Kira Goode (*right*).

In issue 98, Alice Delahunty FREng's opinion on page 8 was first published on openaccessgovernment.org in January 2024.

IN BRIEF

FINALISTS ANNOUNCED FOR 2024 MACROBERT AWARD

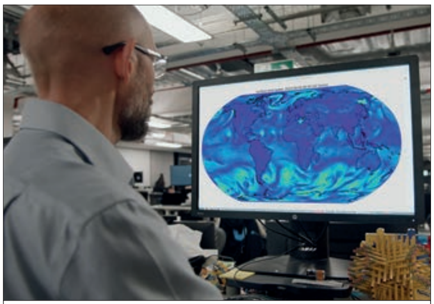
Groundbreaking AI-powered weather forecasting, innovative heat batteries using phase-changing materials and the rapid manufacturing scale-up of a Covid vaccine have been announced as finalists for the 2024 MacRobert Award, the UK's leading prize for engineering innovation.

The three innovations – developed by Google DeepMind, Sunamp and the University of Oxford Vaccine Consortium with AstraZeneca – come from some of the UK's fastest growing and successful sectors, each of which is crucial to the UK economy. They are recognised not just for technical innovation but also for the commercial and societal impact they have demonstrated.

GraphCast, developed by Google DeepMind, represents a revolution in weather forecasting, using machine learning instead of traditional numerical weather prediction methodologies. The AI-powered tool uses cutting-edge machine learning algorithms and vast data sets to give highly accurate and timely weather predictions up to 10 days in advance. The model currently takes just 45 seconds to generate a forecast that would take more traditional forecasting methods over an hour on a supercomputer; a developmental leap that has advanced weather forecasting significantly. By significantly improving the reliability of weather predictions, GraphCast could help mitigate the impacts of severe weather events, optimise resource allocation, and support critical decision-making across various industries.

Sunamp has pioneered the development of innovative heat batteries using phase-change materials to revolutionise thermal energy storage. These advanced batteries store and release large amounts of thermal energy through the melting and solidifying of the specially developed phase-change materials, providing a highly efficient and sustainable solution for heating and cooling applications. Current products provide heat storage for domestic hot water that are more space efficient and energy efficient than traditional hot water cylinders. By integrating this cutting-edge technology into homes, businesses, and industrial processes, Sunamp is making significant strides forward in the quest for sustainable energy solutions by helping to reduce carbon emissions, enhance energy efficiency and alleviate fuel poverty.

The University of Oxford and AstraZeneca led a consortium of manufacturers, suppliers and other partners in the development of an innovative manufacturing process that was rolled out globally to supply over three billion doses of the ChAdOx1 Covid vaccine, saving over six million lives. The innovative approach combined cutting-edge cell culture technologies with streamlined workflows and robust quality control processes, enabling swift and efficient production of billions of vaccine doses at multiple sites in record time. This effort not only played a crucial role in managing the pandemic but also set new benchmarks in pharmaceutical manufacturing, process development and technology transfer, and made possible a more efficient and versatile route to disease control now and in the future. Using the pioneering new process, one of the collaborators, the Serum Institute of India, has since successfully scaled up manufacturing of an Ebola vaccine in response to an outbreak, delivering doses in just 81 days.



GraphCast harnesses the power of graph neural networks to model complex weather patterns and offers unprecedented precision in forecasts and an enhanced ability to predict extreme weather conditions © Google DeepMind

The Covid vaccine consortium played a key role in managing the pandemic and set new benchmarks in pharmaceutical manufacturing, process development and technology transfer © John Cairns

Sunamp's heat batteries offer superior energy density, rapid response times, and long-lasting performance compared to traditional storage methods © Sunamp

The winning team will receive a gold medal and a £50,000 prize, as well as a luxury weekend at Douneside House in the heart of the MacRobert estate in Aberdeenshire.

This year's winner will join an esteemed group of past recipients who have delivered outstanding innovation, commercial success, and tangible societal benefits. Since the presentation of the first award in 1969, the MacRobert Award has recognised transformative contributions, from the world's first bionic hand, developed by Touch Bionics, to innovations from Jaguar Land Rover and Inmarsat that continue to have a global impact.

Read more about some of the previous MacRobert Award winners on page 14.

AFRICA PRIZE AWARDS TENTH INNOVATOR

On 13 June, Kenyan innovator Esther Kimani became the 10th person – and third woman – to receive the Africa Prize for Engineering Innovation.

Her early crop pest and disease detection device was selected as the winning innovation for its ability to swiftly detect and identify agricultural pests and diseases, reducing crop losses for smallholder farmers by up to 30% while increasing yields by as much as 40%.

Five million smallholder farmers in Kenya lose on average 33% of their crops to pests and diseases. Kimani's innovation not only provides real-time alerts within five seconds of an infestation, offering tailored intervention suggestions, but also alerts government agricultural officers to the presence of diseases or pests, contributing to broader agricultural management efforts.

The solar-powered tool uses computer vision algorithms and advanced machine learning to detect and identify crop pests, pathogens or diseases, as well as the nature of the infection or infestation. The device then notifies the farmer via SMS. This affordable alternative to traditional detection methods leases for just $3 per month, significantly cheaper than hiring drones or agricultural inspectors.

Africa Prize 2024 winner Esther Kimani

Esther said: "My parents would lose up to 40% of their crops each farming season, which affected our standard of living. We are empowering smallholder farmers, many of whom are women, to increase their income. We aim to scale to one million farmers in the next five years."

Esther received £50,000 to further develop her device, while three runners up were each awarded £15,000. A separate 'One to Watch' award was also awarded to Dr Abubakari Zarouk Imoro on the night for their innovation's impact on local communities. Voted for by live and online audiences, Dr Imoro receives £5,000, conferred in 2024 in honour of Martin Bruce, a late Ghanaian alumnus of the Africa Prize.

INGENIOUS PROJECTS FOR THE NEXT GENERATION OF ENGINEERS

Students take part in a Formula 1 day at school, organised by the Lightyear Foundation

In May, the Royal Academy of Engineering announced 17 new *Ingenious* public engagement awards for projects across the UK designed by engineers to engage the public with engineering and inspire the next generation.

This year's projects focus on topics from sustainable agriculture and future sources of water to Formula 1 and the history of women's involvement in engineering. Future Farming will work with engineers at Edinburgh Science to design, develop and deliver interactive activities for students, young people and their families, which will explore engineering solutions to sustainable agriculture. Formula 1 Engineering Lab for Children with SEND (special educational needs and disabilities) is a project led by Lightyear Foundation that will design and deliver an accessible and inclusive Formula 1 Engineering Lab in SEND schools, introducing the world of race car engineering to a new generation of potential drivers and engineers.

Many projects are aiming to introduce young people to engineering careers, including Emergency! Engineers Wanted!, which will inspire primary school pupils across Cardiff and the South Wales valleys to explore engineering careers by participating in an engineering lab.

The newly funded projects will engage communities throughout the UK to help reach underrepresented audiences and change perceptions of engineering. The programme provides engineers with training and encouragement to share their stories and engineering expertise with the public.

To find out about other projects funded by the scheme, please visit the Royal Academy of Engineering website.

BOOST TO INVESTMENT IN OFFSHORE WIND

Two recent announcements have signalled significant investment in the UK's offshore wind sector.

In April, Scotland's Flotation Energy and Norway's Vårgrønn revealed a joint venture to build the world's biggest floating offshore wind farm off the coast of Scotland. The Green Volt wind farm will have 35 turbines, which will generate 560 MW of renewable energy. The power aims to replace the current natural gas and diesel energy used to power drilling operations at North Sea oil and gas platforms. The wind farm will also generate six times as much energy as the current largest wind farm, just off the coast of Norway, some of which will be transferred back to the grid to power homes in Scotland. It will bring in about £3 billion in investment and should reduce carbon emissions by about 1 million tonnes per year.

In May, UK Research and Innovation announced that it would provide £85.6 million of capital funding for the Offshore Renewable Energy (ORE) Catapult to expand and upgrade its testing facilities to develop the next generation of wind turbines in the UK.

The new facilities will enable faster product development of turbines through test, validation and certification and are expected to prevent 2.5 million tonnes of CO_2 emissions. They aim support the growth of UK supply chains and provide critical research infrastructure to support inward investment into the UK wind industry. They will also create 30 new jobs in Blyth and support five PhDs a year.

© Image by Thomas G. from Pixabay

GET INVOLVED IN ENGINEERING

NOMINATE AN INSPIRATIONAL ENGINEER

The Royal Academy of Engineering is asking engineers a question: who inspired you to be who you are today? For National Engineering Day on 13 November 2024, it is seeking role models to inspire the next generation to take up careers in engineering – and it needs your help. In a bid to recruit a new, more diverse generation of engineers, it is asking for nominations of engineering role models.

If you know an inspirational engineering role model, please nominate them via the form at **raeng.org.uk/national-engineering-day** by 16 August 2024. On National Engineering Day the Academy will be unveiling statues of your chosen role models, brought to life in creations fit to move and inspire the next generation.

© Image by torstensimon from Pixabay

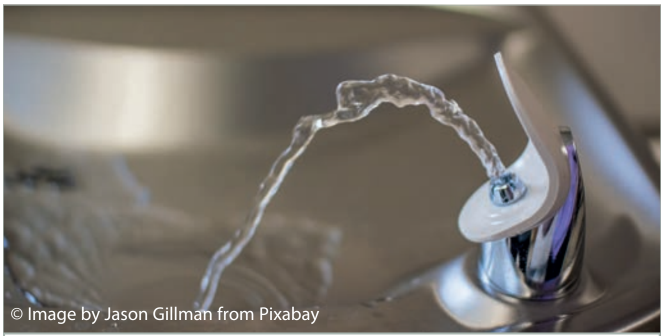
INJECTING HOPE: THE RACE FOR A COVID-19 VACCINE

Science and Industry Museum, Manchester
From 19 July
Uncover inspiring stories of scientists and innovators collaborating around the globe in this new free exhibition, which features a variety of artworks and personal objects that illustrate the worldwide effort to develop vaccines in response to the COVID-19 pandemic. Book tickets at **scienceandindustrymuseum.org.uk**

HOLIDAY WORKSHOPS AT THE RI

Royal Institution, London
29 July to 2 August
Student can take part in a range of hands-on workshops at the Ri, led by experts from across industry and academia. Choose from a week-long introduction to robotics for 15 to 18-year-olds or a day session on making music for 12 to 14-year-olds, or one of many more.

Visit **www.rigb.org/season/holiday-workshops** to find out more.



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CREATE THE FUTURE

Podcast
What happens after we flush? Sanitary engineers might just be the unsung heroes of civilisation, ensuring the safe disposal of wastewater and assuring a supply of safe drinking water. Host Guru Madhavan discusses sanitation systems with Pam Elardo, former Deputy Commissioner for New York's Bureau of Wastewater Treatment, and Andrew Russell, science historian and Provost at SUNY Polytechnic Institute. Download from **qeprize.org**

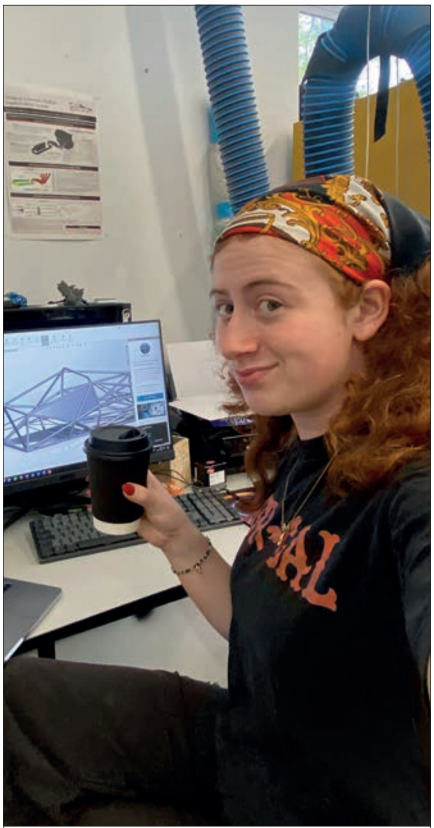
TECHNO SPARKS SUMMER CAMP

W5, Belfast
22 July to 16 August
W5's summer camp allows 11 to 14-year-olds to explore the world of coding, film magic, robot mastery, and more. It has five electrifying themes each week, jam-packed with activities to supercharge digital skills, forge new friendships, and unleash creativity. Each day costs £35. To find out more, visit **w5online.co.uk**

HOW I GOT HERE

Q&A

CARA FOX
MECHANICAL ENGINEER



"Some much needed caffeine to work on our 2024 Livery." – Cara © Cara Fox

As team principal of Queen Mary University of London's Formula Student team, Cara Fox has laid the foundations for an exciting career in motorsport.

WHY DID YOU BECOME INTERESTED IN SCIENCE AND ENGINEERING?

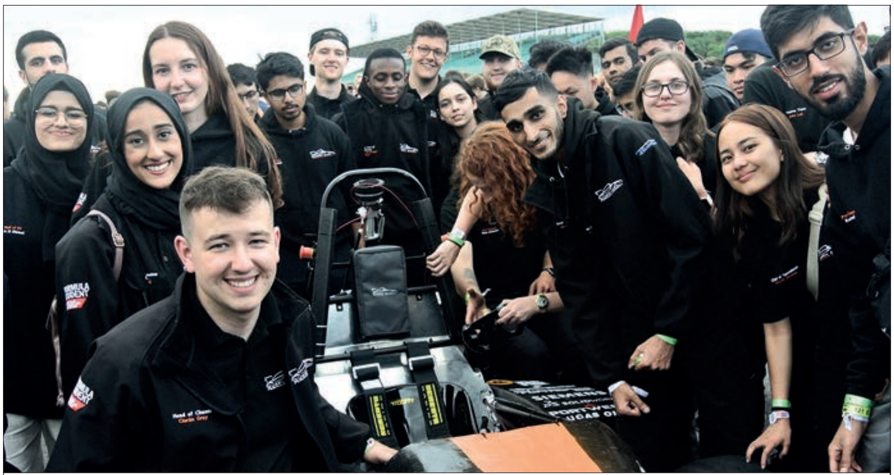
My mum and dad are a huge reason for my interest in science. They noticed I would come home from school and talk about the science experiments I had done, so they started getting me activities like a chemistry set and a model engine to encourage that interest. I used to attend the Royal Society Summer Exhibition every summer, which I would really recommend to parents who aren't super into science. My dad would just follow me around the stalls all day and hold the goodies I collected, which to his credit he never complained about. But the core of my passion for engineering comes from my problem-solving mentality. I can do maths and physics but I'm not particularly academic, engineering is really about the challenge of creating solutions for me. I enjoy using knowledge I've gained to innovate and build for the future.

HOW DID YOU GET TO WHERE YOU ARE NOW?

I'm currently in my master's year in mechanical engineering at Queen Mary University of London. I've completed A levels in maths, physics, further maths, and philosophy; a year's internship at Element Six; a summer internship with Ansys; and three years of my degree. I have just finished my last exam for this year and will be graduating in July 2024. My journey has focused on gaining my degree to work in the engineering field of my choice, motorsport. While studying, I have completed as much extracurricular work as possible, including running my university's Formula Student (QMFS) team for the last two years. These achievements have culminated in a dream role starting in September at Mercedes AMG High Performance Powertrains. As the daughter of two civil servants, Formula One was so unattainable I still can't quite wrap my head around that sentence. I'm extremely grateful to both for helping me believe in myself.

WHAT HAS BEEN YOUR BIGGEST ACHIEVEMENT TO DATE?

Despite all I mentioned about my engineering journey, my biggest achievement is almost completely unrelated. Since I was five, I've been involved in competitive Irish Dancing,



The 2023 Queen Mary Formula Student team with Aisling, the FSUK23 car
© Queen Mary Formula Student team

a sport that has significant history in my family. My gran and grandad, from Belfast and Dublin respectively, are founding members of my dance organisation. My aunt and mother are both dancing teachers, my mother is my own dancing teacher. My dad even attended a few lessons as a child. I was brought up in the dance world and developed a particularly competitive nature. In 2017, I won the An Chomhdháil World Championship title, which I have also won four times since, most recently as the Senior Ladies World Champion in 2023. Although Irish Dance and engineering couldn't be more different by definition, my experience as a competitive dancer made me passionate, confident, and altogether determined when I set my mind to a goal. It has taught me that there is no such thing as an impossible goal, just one you may have to sacrifice for.

WHAT IS YOUR FAVOURITE THING ABOUT BEING AN ENGINEER?

The community. I think when most people imagine engineering, they imagine someone sat in front of a computer for hours on end with an energy drink. And while this was the case for a few too many of my university submissions, the experience of working in engineering is much different. You experience it on a small scale at Formula Student, where you and your fellow students are working towards this huge and often daunting goal. But the payoff is enormous, the feelings of submitting a good document, finally sorting a design issue, or when we all get new uniform, those are some incredible moments of human connection. The power of engineering is strongest with a cohesive team and a lot of my work at QMFS has been building unity to foster this special sort of success.

WHAT DOES A TYPICAL DAY INVOLVE FOR YOU?

I will admit, I'm not a super early riser, so usually my day will start between 8 and 9am, checking messages. Once I get to the workshop, I catch up with anyone already there and see what they're planning to do for the day. We will have decided on the week's activity at our Monday meeting but it's nice to keep an eye on progress so we can catch any issues early in the week. I like to use the start of my day to complete urgent admin tasks, which might include organising finances or events, double-checking documentation and I even like to get involved in creating social media content. I'll check emails in this time and do a mental check that I've not got any outstanding tasks for the team's stakeholders including the school, the students' union, the Institution of Mechanical Engineers, our sponsors, and of course our lovely team members. It's never a dull day at QMFS and I rarely get through the day having completed my to-do list, in fact it usually gets longer. As the day goes on, I like to get more and more involved in the engineering of our vehicles. As a final year student, I try to transfer as much of my gained knowledge and experience to newer team members by working with them on their problems. I like to finish up my day by doing something practical and recently I've been working on creating the seat for the 2024 vehicle. In the evenings I tutor in maths and physics as a part-time job, attend dance classes and do a little bit more admin.

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

Find the thing you're passionate about. Engineering is so broad, which can be daunting when you're just getting started but it gets easier as you rule out things you don't want to do. I would also recommend that if you're at university, joining an engineering society should be top of your list! When I started at university, I was adamant I wouldn't be joining an engineering society, I reasoned that I'd already be hanging out with engineers all day. But honestly? I wished I had joined much earlier.

WHAT'S NEXT FOR YOU?

From September I'll be working at Mercedes AMG High Performance Powertrains. I'm on a one-year contract rotating around their Formula One powertrains and battery technology departments. I'm looking forward to moving out of London and slowing down a bit, although I don't doubt I'll find some other hobby to keep me occupied soon enough. I'm also hoping to progress towards chartership and sharpen my engineering skills in this high demand, high reward environment.

QUICK-FIRE FACTS

Age: **22**

Qualifications: **Undergraduate in mechanical engineering**

Biggest engineering inspiration: **Someone who really inspires me in engineering, especially for sustainability and social justice is Alexis Williams, you can find her on most socials**

Most-used technology: **My headphones, I can't go five minutes without listening to something!**

Three words that describe you: **Passionate, confident, determined**

OPINION

OUR WASTEWATER INFRASTRUCTURE MUST IMPROVE TO PROTECT PUBLIC HEALTH

As news of contaminated waterways increasingly hits the headlines as more people take to the UK's open water for recreation, the National Engineering Policy Centre has published the first report looking at how to mitigate health risks posed to the public from human faecal pathogens. Professor David Butler FREng, chair of the report's working group, sets out the role that engineering interventions can play in a much-needed upgrade of our wastewater infrastructure, alongside collaborative action with other stakeholders to bolster a robust and efficient wastewater system.

Our sewage system has long helped keep us safe from major diseases. It has been remarkably successful in interrupting the transmission of major epidemics and protecting the environment by treating wastewater before it is returned to our rivers and seas. But with ageing wastewater infrastructure, growing urbanisation, and the increased intensity and frequency of rainfall expected due to climate change, the strain on this system is mounting. At the same time, the popularity of activities such as swimming and boating in our rivers, lakes, and coastal areas has increased. These recreational activities can be great for mental and physical health and wellbeing, but also increase exposure of the public to sewage pollution.

Recent reports of people falling ill after spending time in our waters serve as a stark reminder of the public health risks associated with sewage pollution. Now more than ever we have greater public awareness of water pollution and greater availability of water quality data. All of which contributes to changing public expectations of water quality.

Heightened awareness of pollution incidents in rivers and beaches, *Encouraging sustainable drainage solutions and promoting better management of surface water are key steps to reducing overflows and contamination*

particularly from storm overflows, has resulted in calls for action. But storm overflows aren't the only source of sewage pollution. Sewage passed through treatment works will have a substantially reduced concentration of faecal organisms, but this treated sewage can still contain harmful organisms, and is discharged into our waterways all year round. While we may not always find causal links to specific disease outbreaks, the public's increased interaction with natural water sources highlights the urgent need to ensure they are clean and safe.

In creating our latest National Engineering Policy Centre report, *Testing the waters: Priorities for mitigating health risks from wastewater pollution*, we consulted more than 100 engineers, wastewater experts, the water industry, campaign organisations, and policymakers.

This is the first thorough assessment of interventions to reduce public health risks associated with the use of sewage contaminated public waters. We quickly learned that addressing these challenges requires a comprehensive approach that combines immediate actions to reduce public health risks with long-term transformational strategies to upgrade our sewage infrastructure for future generations.

We have identified three priorities. Firstly, water companies must prioritise maintenance and rehabilitation of our existing infrastructure to resolve some of the causes of overflows. Secondly, we need a much better understanding of the impact of faecal pollution on microbiological water quality and the associated public health risks, and ways to monitor it in real time. And thirdly, this evidence must inform bathing water regulations.

Alongside these in the immediate term, investment in monitoring the flow through our wastewater system and modelling at a local level will deepen our understanding of infrastructure health and enable proactive management of the system. Encouraging sustainable drainage solutions and promoting better management of surface water are key steps to reducing overflows and contamination. We need more innovation and technology pilots in the water sector to develop treatments that effectively remove organisms, microplastics and metals that harm public health and ecology.

Of course, engineering solutions alone cannot reduce risk to public health. Communicating risk effectively to the public through educational campaigns and community involvement will be essential for raising awareness and promoting responsible behaviour. Improved signage and information available at recreational sites will mean people can make informed decisions about whether they choose to swim or kayak that day. A comprehensive review of bathing water standards is also essential to ensure our assessments of water quality keep pace with our ever-evolving public health needs.

Looking further ahead, there is real opportunity for transformative change. We need an ambitious vision for a future sewage system. One that preserves our environment, promotes societal wellbeing, and places public health at its heart. This vision must be supported by measurable targets to ensure accountability, track progress, and enable engineering and innovation to identify the 'win-win' solutions.

To deliver on this vision, we need a collaborative and collective effort by governments, the engineering industry, regulators, water companies, and the public. By embracing evidence-led, risk-based approaches and engaging stakeholders, we can set foundations that are essential to inform regulations, standards, and policies.

It is a sad fact, but as more people make use of the UK's wonderful rivers, lakes, and coastal waters, our ageing sewage system is increasingly unable to protect their health. Despite treatment, harmful organisms still contaminate our waters, but our report highlights what can be done. We're not suggesting these solutions are deployed at all sites across the UK, instead a risk-based approach is required. This means local decisions about how to best protect the waters people want to use – and putting public health back at the centre of our sewage system.

BIOGRAPHY

Professor David Butler FREng is Co-Director of the Centre for Water Systems and Professor of Water Engineering at the University of Exeter where he is an internationally leading researcher, teacher, manager, and consultant in the water sector. He is a chartered civil engineer and a Fellow of the Royal Academy of Engineering, the Institution of Civil Engineers, the Chartered Institution of Water and Environmental Management, and the International Water Association.

To read *Testing the waters: reducing health risks from water pollution* and its recommendations in full, please visit **nepc.raeng.org.uk/testing-the-waters**

© Shutterstock

ROBOTICS AT THE MICROSCALE

Engineers are working with ophthalmic surgeons to create a robotically controlled needle with a flexible tip that has the precision required to inject therapeutic materials into the tissue lining the back of the eye. Geoff Watts spoke to engineer Professor Christos Bergeles, who is developing a better way of delivering a new treatment for a common cause of blindness.

Did you know?

- Age-related macular degeneration (AMD) is the leading cause of blindness worldwide and is expected to affect 288 million people by 2040
- A 2018 trial placed patches of stem cells on the retinas of patients with AMD, with the patients able to read again after a few months
- Advances in microrobotics have led to development of a robotically assisted instrument that can place the stem cells with more precision

Robotics are increasingly being used in healthcare settings and the benefits of robotic assistance in performing surgery are easy to understand. Robots can offer enhanced dexterity, better control of instruments (by, for example, the avoidance of tremor), greater precision, and, through the use of a camera inside the patient's body, a clearer view of the operating site. However, although explored in many branches of surgery, the use of surgical robots is not widespread – and some 70% of the million and a half robotically assisted procedures worldwide are performed in the US. Even in prostate surgery and orthopaedic joint replacement, in which they are most commonly used, they still account only for a minority of operations.

Robots are particularly valuable in procedures that are intricate and small scale, which is one of the main reasons that they are used in prostate surgery. The use of robots to operate at the truly microscopic level is still in its infancy. Unsurprisingly, ophthalmology is at the forefront of this endeavour, as few of the body's most critical anatomical structures are as complex and delicate as the retina.

With the aid of an operating microscope, eye surgeons have extensive experience in performing intricate procedures – and not only on the visible outer parts of the eye, but also its deeper structures including the retina. However, as in other branches of medicine their ambitions keep on advancing. Among recent advances is an intention to treat potentially blinding diseases such as AMD using stem cells. These cells have the potential to give rise to a population of any of the many cell types that exist in the body, including those found in the retina and directly responsible for vision. Recent experimental surgery has already demonstrated the feasibility of using stem cells in the eye.

A first clinical trial of the procedure involved placing 'patches' of stem cells (see 'AMD and stem cells') towards the back of the patient's eye, and just below the diseased area of the retina. The trial has seen positive results – but enhancing the surgical precision should boost efficiency and improve outcomes. Ideally, surgeons should be able to inject stem cells precisely where they are needed within the various layers of the retina, some of which are as thin as 10 to 20 µm: less than the width of a human hair.

Today's microscopy already allows surgeons clear sight of the back of the

AMD AND STEM CELLS

AMD is the most common cause of vision loss in older people. The condition results from the degeneration of the retinal pigment epithelium, one of the constituent layers of the retina, which is the light-sensing tissue that lines the interior of the eye. The macula area of the retina is responsible for the sharp and detailed images at the centre of our visual field, and tissue degeneration here leads to the severe blurring that characterises AMD. Reading, driving and recognising faces or details of any kind become progressively more difficult.

AMD is categorised as 'wet' – resulting from the growth of abnormal blood vessels at the back of the eye – or 'dry' – caused by a build-up of fatty deposits within the retina. Drug injections or other treatments designed to inhibit the growth of the blood vessels can often prevent wet AMD from worsening. Dry AMD can be alleviated with a vision aid.

One of the main non-drug treatments for wet AMD relies on administering a light-activated chemical agent and then shining a beam of light on to the troublesome blood vessels. Once activated, the chemical destroys the sensitised vessels. An alternative is to destroy the abnormal vessels using a laser beam. However, neither method is suitable for every patient nor guaranteed to work. Hence the interest in stem cells, which could, in theory, prove valuable in treating a lengthy list of medical conditions, including both types of AMD.

In 2018, vitreoretinal surgeon Professor Lyndon da Cruz of Moorfields Eye Hospital and Professor Peter Coffey of the UCL Institute of Ophthalmology reported their success at introducing retinal pigment epithelium (RPE) stem cells into the retinas of AMD patients. In the laboratory, they first grew single layers of stem cell derived RPE cells on synthetic membranes. When the cells were ready to use, they cut out small 6x3mm 'patches' of membrane that they could pick up and handle using a specially designed surgical tool. They were able to use this tool to slide the patch between the layers of the retina in the region affected by the AMD. The new RPE cells integrated with the patients' own cells and began functioning. Within months, both patients were able to start reading again.

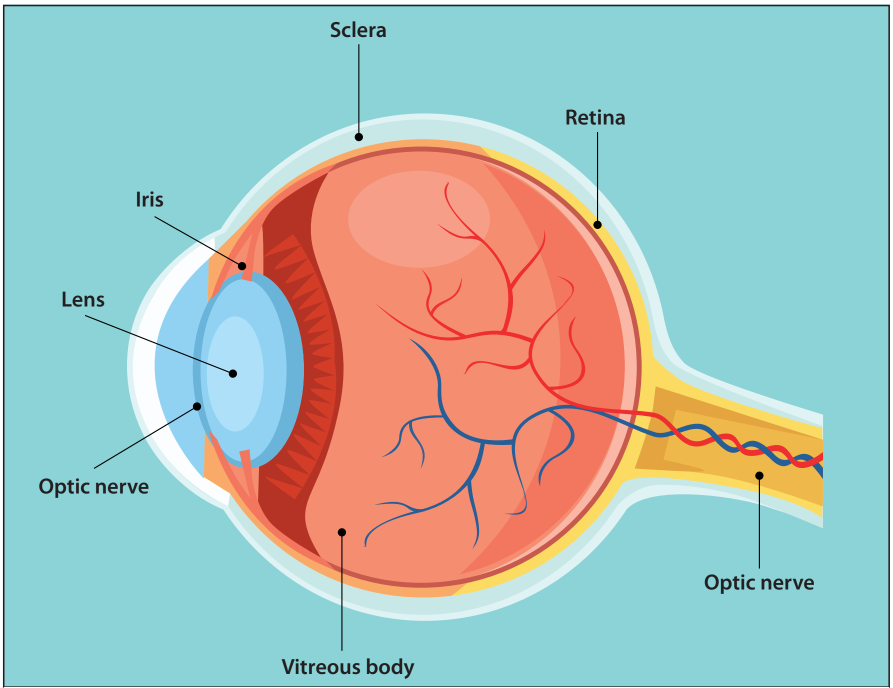
eye. But for future possible operations, even the best view of the area to be treated is not, by itself, enough. The operating procedures involved demand a steadiness and delicacy that even the most skilful hands would find hard to achieve. The biology of creating and using stem cells has run ahead of the technology required to make the best use of them. Hence the need for the assistance of a robot.

ENHANCED PRECISION

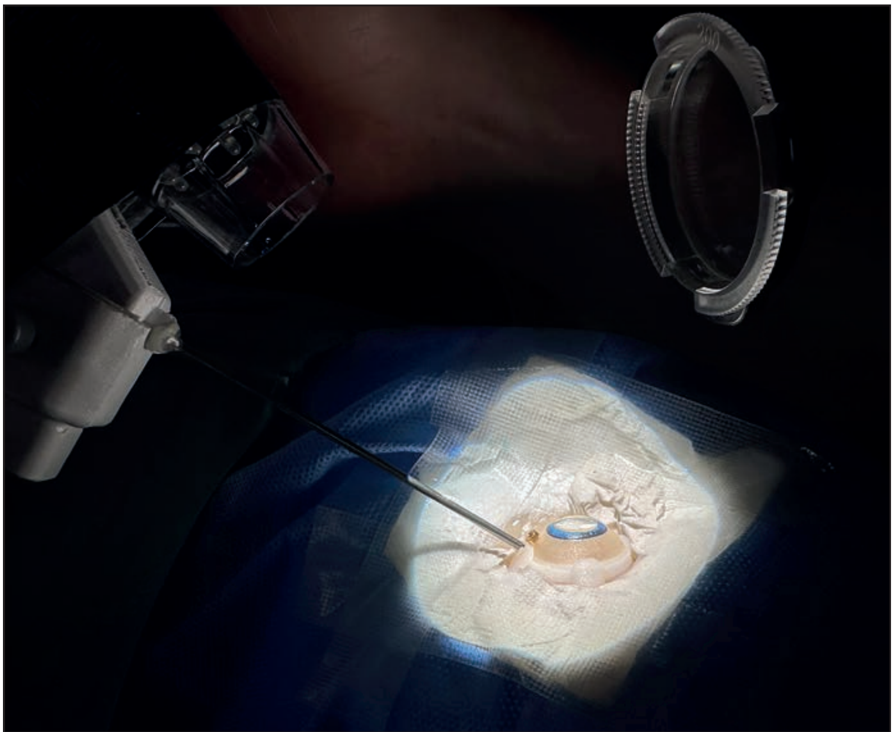
Robots already feature in some surgical operations, but most of these procedures rely on the use of rigid instruments. Engineer Christos Bergeles is Professor of Surgical Robotics at King's College London where his work is partly funded by the National Institute for Health Research. In collaboration with ophthalmic surgeon Professor Lyndon da Cruz, he is aiming to add greater precision and flexibility to robotic microsurgery. As Bergeles points out, when aiming to work within the layers of a tissue as thin as those of the retina, instruments must take a tangential approach to their target: one in which the tips of the instruments can move towards the tissue surface at a slight angle. This allows the instruments not only to penetrate the retina but slip between its layers. So how to achieve such an approach when the target tissue is the inner lining of a sphere, and the surgeon is using instruments that have entered the eye by being pushed through its outer wall? Bergeles's answer might be summarised as relying on a needle comprising 'tubes-within-tubes'. Using this approach he has been able to achieve the snake-like flexibility required to create a needled instrument with a tip that can be pointed in any direction.

The needle used by his robot comprises several fine, concentric metal tubes with a shape memory of a simple curve. To penetrate the tough outer layer of the eye – its white or sclera – the surgeon first uses a conventional circular cutting tool to make a small hole. They then move the robot, which has a short, narrow and rigid tube on the end of its arm, to the newly created opening. Once its tip has entered the jelly-like fluid, or vitreous, that fills the interior of the eyeball, a short length of the first of the nested tubes emerges and forms itself into a curve. From this tube emerges the next of the group and from it, in turn, the narrowest of the tubes. Each of these assumes its own, 'memorised' curve, with the outer end of the narrowest serving as the tip of the needle.

At this stage the tip's orientation will depend on the curvature of the three tubes. The robot's operators can



The figure illustrates key components of the eye anatomy. The retina is the element that is responsible for capturing light, and creating the electrical signals that are sent to the brain. The retina is a layered structure, and different diseases affected its different layers © Shutterstock



Close up of the experimental setup illustrated in the next figure. A phantom eye with dimensions and appearance similar to a human eye is used for evaluation. The surgical tool is approaching the eye to be inserted through a trocar (orange insert)

Left: The developed robotic system, showcased within the mock operating room of the Department of Surgical and Interventional Engineering at King's College London. Right: Illustration of potential system draping, so that it can enter the sterile zone of an operating room © Left image courtesy of China Global TV Network

then lengthen or shorten each tube and rotate each one independently of the others. This alters the position and movement of the tubes: in effect steering them and allowing the operator to move the needle tip as needed before sliding it into the retina at a chosen point. The outer diameter of the widest tube is some 800 µm; the narrowest, forming the needle's tip, is just 160 µm.

As Bergeles explains, while it might be tempting to consider simply injecting the required stem cells at one particular location in the hope that they will then diffuse through the retinal tissue to where they are needed, this doesn't work. Instead, the surgeon will have to slowly introduce the stem cells successively in tiny, microlitre volumes of fluid, each containing perhaps a few thousand cells. Each injection may take up to a couple of minutes before the needle is withdrawn from the retina and reinserted in one of several nearby locations covering a chosen region. For an unaided human operator, this task would require extraordinary powers of concentration, dexterity, and physical control; it will still need considerable skill, even with the aid of a robot that can compensate for factors such as hand tremor.

HOW TO CONTROL THE ROBOT

Surgeons will use a console of some kind to advance and retract the needle, and to steer it in three dimensions. The distances moved by the surgeon's hands will be scaled down to allow for the tiny movements needed to correctly align the needle inside the eye, slide it into the tissue, and introduce the cells. Bergeles is aiming for a resolution of just a few microns.

To give the surgeon a clear view of the back of the eye, a light source illuminates its interior, having been introduced through another small slit in the sclera. The operating site will then be visualised in the normal way through the patient's dilated pupil. Bergeles hopes that this will eventually be supplemented by optical coherence tomography, a non-invasive technique that offers a real-time, cross-sectional view of the retina. This could reassure surgeons that the infused stems cells are being deposited in the correction location.

The electric motors and the associated gearing that move and rotate each of the instrument's concentric tubes are housed in a container mounted on a firm robotic arm with three directional mobility. This moves the robot towards the patient's head and aligns it with whichever eye is to be treated. The robot then carefully moves forward to bring the short rigid tube projecting from its front surface into contact with the small hole already made in the outer wall of the patient's eyeball, through which the needle enters.

Although Bergeles has focused his attention on AMD, an instrument offering such precision and flexibility could be widely applied to treat other eye diseases. As well as using different stem cells to treat other retinal conditions, it could be used to deploy other therapeutic agents that need precise placement, such as gene therapy for example. So far, Bergeles has tested the technique on cadaver pig eyes and on the plastic model eyes that ophthalmic surgeons use in training. Bergeles and da Cruz hope to start preliminary human trials in a few years. In the meantime, their group is investigating various commercialisation opportunities.

The benefits of a robotic approach will not only make existing eye operations safer and more effective but, as in the work of Bergeles and de Cruz, offer the possibility of new procedures that would otherwise be virtually impossible.

BIOGRAPHY

Christos Bergeles is Professor of Surgical Robotics at King's College London where he leads the Robotics and Vision in Medicine Laboratory based at St Thomas's Hospital. He has previously worked in the Hamlyn Centre for Robotic Surgery at Imperial College London, and the Department of Medical Physics and Biomedical Engineering at University College London.

THE IDEAS BEHIND GROUNDBREAKING INNOVATION

This year, the MacRobert Award – the UK's longest-running prize for engineering innovation – celebrates its 55th anniversary. Having been commissioned to create a set of images to mark the award's 50th anniversary in 2019, photographer Ted Humble-Smith has once again created photographs that capture the thought processes behind some of the winning innovations.

From the CT scanner to the Raspberry Pi microcomputer, MacRobert Award winning innovations have changed the world. The first award in 1969 was made jointly for two iconic innovations: to Rolls-Royce for the Pegasus engine that powers the Harrier Jump Jet and to Freeman, Fox and Partners for the aerodynamic deck design of the Severn Bridge. Subsequent winners have included the engineers behind advances ranging from catalytic converters and the roof of the Millennium Dome to intelligent prosthetic limbs.

When the award celebrated its 50th anniversary, Ted Humble-Smith talked to the engineers who developed the concepts behind 10 former winners and has repeated the process to depict eight more winning innovations for its 55th year.

He says that the joy of these projects is getting behind the finished product and finding out the journey that led to success. "The sheer determination of people never ceases to amaze me. The lengths they go to in order to bring their idea to life, the wonderful imagination and creativity that is involved with bringing something new into the world is so uplifting to engage with.

"All the MacRobert Award winning innovations are incredibly complicated, so when working on a project like this, you have to go through a sort of distillation process to get across something that people can understand. For me it was incredibly exciting to start with an innovation, then go back and do the research, taking the opportunity to meet the engineers who worked on these projects and then planning how to capture that story in a single image."

The stories that come out during Ted's discussions with the engineers behind the winning innovations form the backbone of his creative vision – this can be a single word or a distillation of a 30-year journey. "All of the winners are very kind and generous with their time, and very patiently explain using accessible language," he adds.

Each one of the innovations he focuses on has had an impact, otherwise it would not have won a MacRobert Award. "Being able to tell that story in a new light is exciting and challenging."

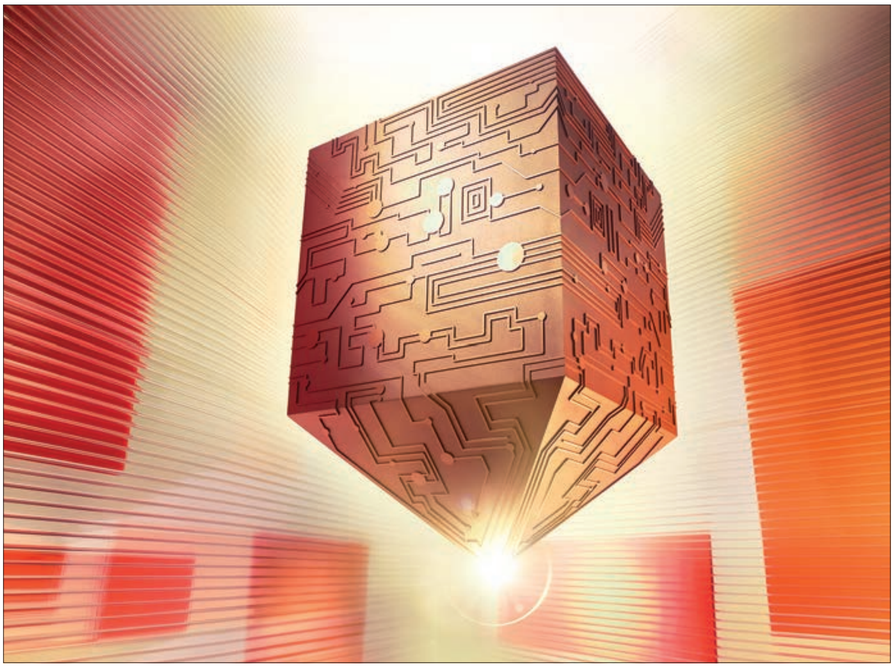
Founded by the MacRobert Trust, the annual award is run by the Royal Academy of Engineering, supported by the Worshipful Company of Engineers.

Over the next few pages, you can read about the concepts behind the innovations and see the images that Ted created after speaking with the engineers. Use the QR codes to read longer, in-depth articles and find out more about the winners on the *Ingenia* website.

OPENING THE DOOR TO EYE HEALTH – OPTOS

The Dunfermline-based company won the MacRobert Award in 2006 for the world's first laser retinal scanner. The Optos retinal scanner captures 30 million readings in 0.2 seconds, giving an unparalleled image of the retina. Not only does this give a remarkable insight into the health of the retina, it can also provide early-warning indications for several other conditions. The original Optos scanner was invented by Dr Douglas Anderson OBE FREng FRSE after his five-year-old son went blind in one eye when a regular eye checkup failed to detect a detached retina.

For the image, Ted imagined trying to photograph a whole room through a keyhole without touching it. This effect was achieved by placing a crystal ball on a wooden block to create the keyhole shape. "I see the similarity between looking into a crystal ball to supposedly predict the future and how looking into a retina can diagnose many health conditions."



MODELLING COMPLEX BEHAVIOURS – PROCESS SYSTEMS ENTERPRISE LTD

PSE received the MacRobert Award in 2007 for its gPROMS (general-purpose PROcess Modelling System) software. The software was developed to model a wide range of complex process plants, from oil and gas to chemicals, pharmaceuticals and food, and to optimise all aspects of their design and operation. For engineers, the scope and capability of such modelling tools provided a step forward in the ability to innovate and to manage the risks associated with process plant design. These tools can build and solve extremely complex mathematical models, which means they are able to capture process behaviour in a truly predictive way.

Ted has reimagined the system as an all-seeing digital entity – a digital twin of the real-life process.

FROM OCEAN WAVES TO EXCAVATORS – ARTEMIS INTELLIGENT POWER

2015 MacRobert Award winner Artemis Intelligent Power developed an energy-saving digital displacement hydraulic transmission for wind turbines and trucks. The innovation grew out of 1970s research on harnessing the power of the oceans in Scotland. Many of the Artemis group's ideas dated back to the work of the late Professor Stephen Salter MBE FRSE, the 'father of wave power', whose research group took a collective approach to problem-solving, developing ideas that could take on a life of their own.

Ted has imagined these ideas as jellyfish-shaped clouds, made from PVC tubing twisted into brain-like shapes, rising from the water. "I felt that the development of ideas didn't belong to anybody and could swim away and have their own life – much like a jellyfish."

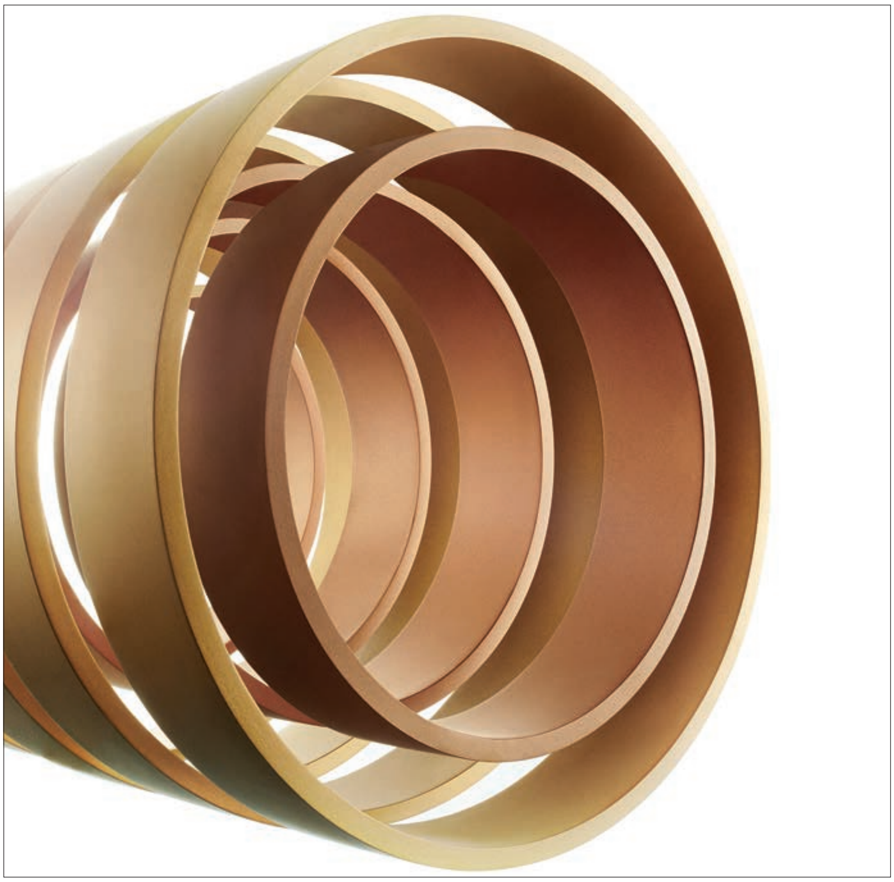
A SUPER CONDUCTOR – OXFORD INSTRUMENTS

The MacRobert Award winner in 1986, Oxford Instruments developed the superconducting magnet technology that made possible magnetic resonance imaging (MRI), used in hospitals around the world. The huge wire coil that forms the magnet must be supercooled using liquid helium and the enormous magnetic power stabilised and contained.

Ted has represented the powerful magnetic forces in balance using metal bands with light and shade. "I found this interesting because, for the technology to work, other people had to invent different things."

The set was made from acrylic bands painted with metallic colours, which were then all suspended together in the studio.

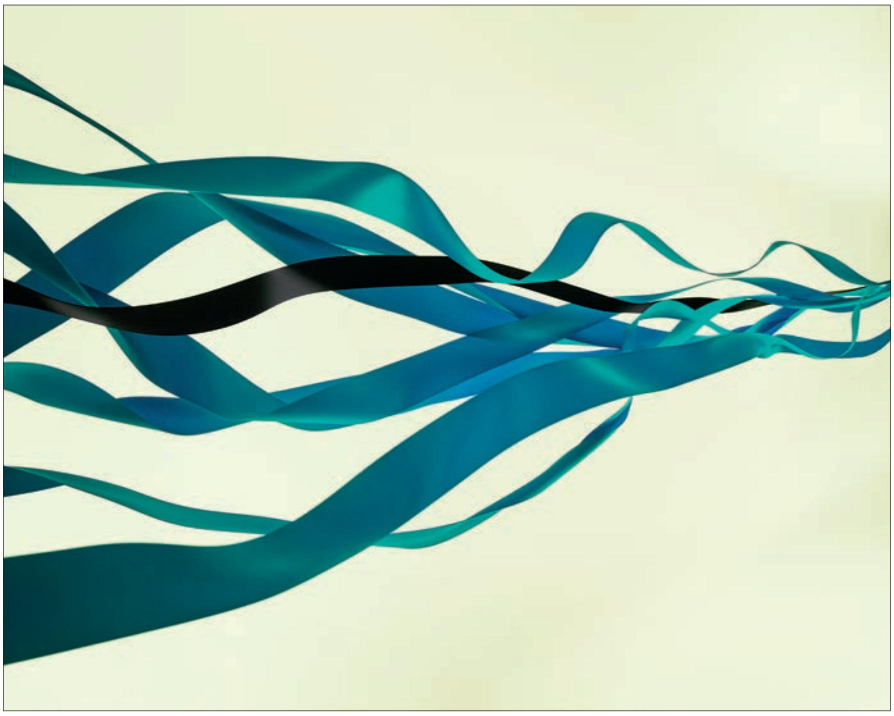
"The image is all about forces within forces; the control of one magnetic force with another. The eye is drawn into the tunnel as that is where you actually go when being scanned."



A NEW DAWN FOR KIDNEY DIALYSIS – QUANTA DIALYSIS TECHNOLOGIES

Quanta, which won the MacRobert Award in 2022, developed SC+, a portable, easy-to-use, high-performance dialysis machine allowing more flexible and accessible care for patients with renal failure in their treatment in hospital or at home. The technology in the machine was inspired by the system used in dispensers to reconstitute orange juice from concentrate.

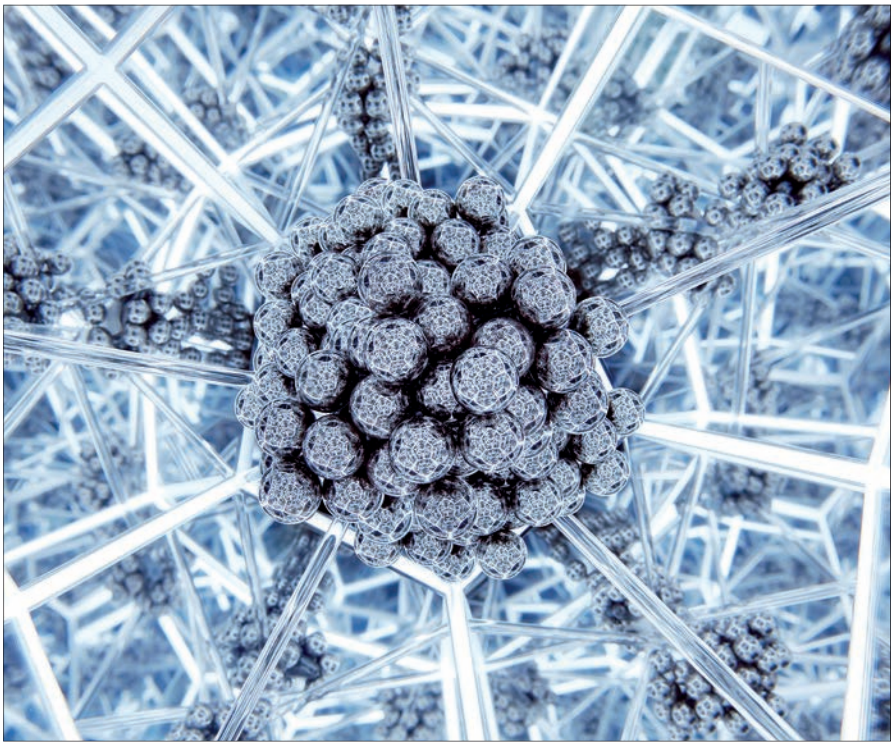
Ted used a slice of orange, photographed up close, to represent a new dawn for managing our bodies' requirements – clean blood using the power of orange juice tech.



THE INFORMATION WE BREATH OUT – OWLSTONE MEDICAL

Owlstone Medical's Breath Biopsy® breathalyser won the MacRobert Award in 2018. It was suspected for years that breath expelled from our lungs carries clues to our health, but capturing those clues requires meticulous processes. You need to make sure the air that goes into the lungs is completely clean and then you need to capture the breath on its exit. The sample carries chemical markers that can help with early diagnosis of disease present in the body. The company's breathalyser captures that breath on patented cartridges, which can then be analysed to determine its volatile organic compound profile – the ultimate non-invasive test.

Ted imagined the clues carried on the breath samples as ribbons of information.



CHIPS WITH INFINITE POSSIBILITY – RASPBERRY PI

The credit-card-sized Raspberry Pi, which won the MacRobert Award in 2017, is the world's smallest and most affordable desktop computer, originally developed to interest more students in programming. Since 2012, more than 60 million Raspberry Pis have been sold and they are increasingly used in industry as control systems, everywhere from the International Space Station to the bottom of the ocean.

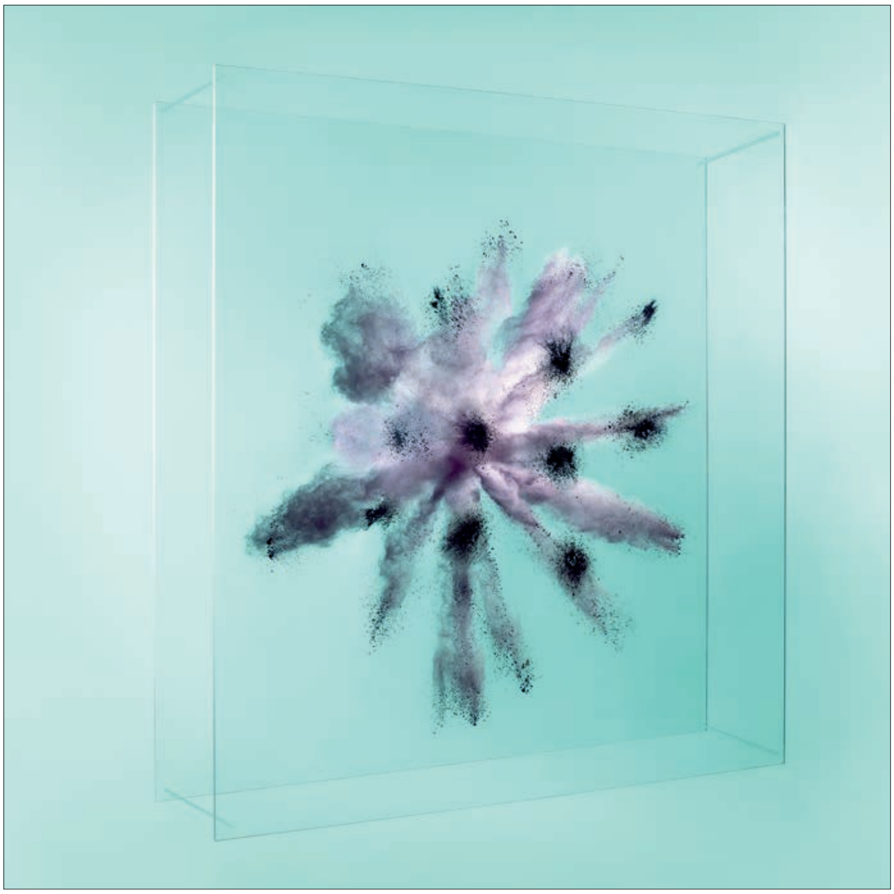
Ted visualised the Raspberry Pi unleashing a journey of discovery with infinite possibilities. To do this, he employed a five-sided shape with ball bearings inside, which were reflected in the mirrors placed on the inside of the shape, giving a sense of infinite ideas. "To me, it felt high tech and almost sci-fi like. A Raspberry Pi machine has the potential to release an explosion of learning, feeding the imagination, and unleash endless journeys to discovery with infinite possibilities."

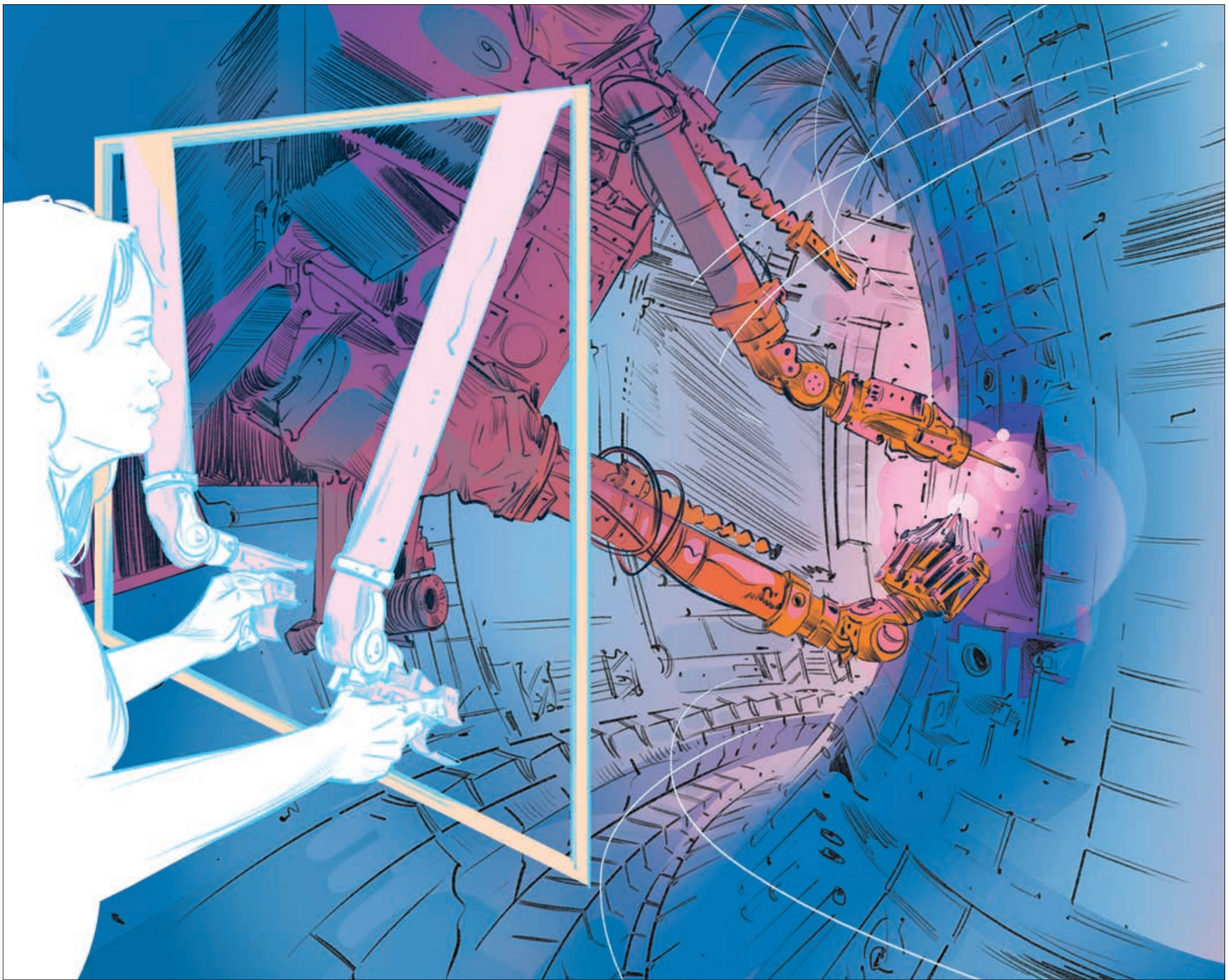
MAKING WINDSCREENS SHATTERPROOF – PILKINGTON BROTHERS LTD

In 1978, Pilkington Brothers won the MacRobert Award with the Triplex Ten-Twenty 'superlaminated' windscreen, one of the biggest advances in windscreen safety in the 1970s. Most vehicle windscreens at the time were made of either toughened or laminated glass. Triplex Ten-Twenty combined the best of both kinds, producing a windscreen that would crack but remain in place in the event of an accident, reducing the risk of injuries from broken glass.

Ted imagined the bonded sheets of toughened glass withstanding an explosion between them and containing the shattered glass instead of fragmenting.

To create this effect, Ted used a powder cannon sandwiched between two acrylic sheets, so the resulting explosion was unable to escape its structure.





Artist's impression of a generic remote handling robot © Illustration by Benjamin Leon for *Ingenia*

THE ROBOTS WORKING IN RADIOACTIVE PLACES

Did you know?

- Radioactive dust, mud, soil, debris, and even gases can contaminate robots sent into nuclear facilities
- When Boston Dynamics' quadruped robot, Spot, was sent into Chornobyl's New Safe Confinement, engineers protected it from contamination by putting rubber socks on its feet
- Radiation can harm electronics. Engineers must sometimes wire out sensitive components so robots can still operate in high-radiation environments

From highly radioactive environments to the ocean floor and out in space, some places are just too hazardous for humans. Beverley D'Silva explores the 'hot' robotics under development to take our places in nuclear environments, from safely storing waste to maintaining and decommissioning fusion facilities.

In December 2022, US diver Josh Everett became the first person to enter Sellafield's Pile Storage Pond since 1958. This 100-metre-long pond was built in the 1940s to store highly radioactive spent nuclear fuel at the Cumbrian decommissioning, waste treatment and storage site. Josh and his fellow specialists worked in shifts of up to three and a half hours at a time to clear sludge comprising decaying nuclear fuel, algae and other debris. For now, some such tasks are destined for humans encased in radiation-proof protective gear and working with extreme caution. But robots are getting closer and closer to being able go in our stead.

"Robots are great for three things: the dirty, the dull and the dangerous," says Nick Sykes, Director of RACE, a division of the UK Atomic Energy Authority (UKAEA). Based in Culham, Oxfordshire, RACE (which stands for Remote Applications for Challenging Environments) is a research centre dedicated to 'hot' robotics designed for extreme industrial environments, including in nuclear decommissioning and fusion research. RACE's work grew out of the need to maintain the Joint European Torus (JET), the world's largest and record-holding facility for fusion research. As JET is now being decommissioned, one of RACE's priorities is repurposing its remote handling robotics for this next chapter.

"This is a really exciting time to be in hot robotics because we're on the verge of a new technology shift," says Sykes. "[Robots are] becoming more and more capable of working in hazardous environments."

Two places where hot robotics have already seen a lot of action are Chornobyl (the Ukrainian spelling of Chernobyl), and Fukushima Daiichi, sites of major nuclear accidents in 1986 and 2011. "[They] are very dangerous, so it's vital to keep humans out of harm's way," says Sykes. "Remediating these sites will also take a lot of repetitive activity. The best way we can do both is to use robots." But aside from the somewhat extraordinary environments of Chornobyl and Fukushima, hot robotics are also prime candidates for more typical decommissioning activities, such as at Sellafield in the UK.

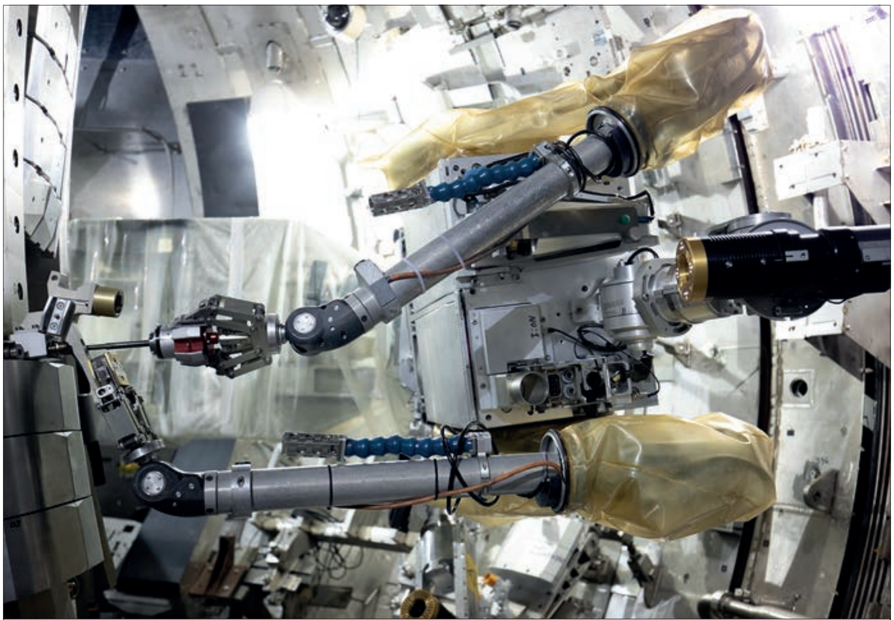
WHAT'S SO 'HOT' ABOUT HOT ROBOTICS?

'Hot robotics' are robots designed to operate in a 'hot' environment: that is, any place that's too harmful for humans to be. Aside from radioactive nuclear environments, other hazardous places include far out at sea, for example, offshore wind farms, deep under the sea, or in space.

SQUARING UP TO THE UK'S NUCLEAR LEGACY

"You could say we are among the major players [in robotics R&D] because we've got some of the biggest – if not *the* biggest –challenges in the western world," says Dave Megson-Smith, academic lead at the University of Bristol's Hot Robotics facility, which develops mobile robots for hot environments (see box 'The many abbreviations of the UK's hot robotics scene'). He explains that decommissioning Sellafield will be "vastly costly … and will be for the next 100 years. And most of that work will be done by robots."

The to-do list for decommissioning is long and varied, with different specialisms needed for different tasks. Some robots inspect sites, some collect the dangerous radioactive material, some transport it, some sort it, and others safely package it for storage at a licensed site. To help us address this



The Joint European Torus fusion facility in Oxfordshire has recently upgraded its remote handling robots to help it with decommissioning. MASCOT, pictured, has haptic feedback that allows the operator to feel every action from carrying a new component to tightening a bolt © UK Atomic Energy Authority

huge challenge, we need every robotics tool at our disposal – from navigation systems, to approaches to robotic mobility and manipulation.

Often, the first step is a survey by ground or air (by drone) to map radiation hotspots and assess the scale of the challenge at a nuclear site. Dull routine tasks such as inspection are ideal for robots, but both Sykes and Megson-Smith agree that contamination control is one of the biggest problems for robots sent to nuclear facilities.

Tracked robots can pick up contaminated dust, mud, soil, or bits of debris that stick to their treads, risking contaminating clean areas. And while wheeled robots have less surface area to become contaminated, they cannot climb stairs. Legged robots, on the other hand, can reach most of the places humans can. Megson-Smith was technical lead on the decommissioning team that sent Spot – the dog-like quadruped robot developed by US firm Boston Dynamics – into the Fukushima Daiishi nuclear plant in 2022 to survey the site and plan for its future. He's also been on teams that have deployed the robot at Chornobyl. "The reason we took Spot into Chornobyl is because he's a walking robot and the walking robot only has four points of contact, so the only places that can get contaminated are the bottoms of his feet," says Megson-Smith. The solution? Rubber socks. "Take those off, throw them away and you have a decontaminated robot."

Spot can even be fitted with a manipulator so it can open doors. "We've had teams in Sellafield who have taken to using Spot really flexibly, making their work faster, safer and cheaper for them to do," Sykes says. He gives the example of an alarm sounding at a facility. These alarm systems are designed to alert humans to low levels of radiation – say, before a leak becomes a serious threat to personnel. A mobile robot equipped with a manipulator can enter a room and check the systems in case the alarm has been set off by a procedural mistake or sensor failure. In the event of a leak, no humans are put at risk.

After inspection, more complex tasks follow. At legacy nuclear fission plants, reactors must be 'defuelled', emptied of spent radioactive fuel. Here, decommissioning teams use purpose-built machines incorporating radiation shielding and systems that automatically locate fuel rods.

Waste is normally transferred to a deep storage pond, such as those at Sellafield, as it cools and the water shields its radioactivity. One of the most complex decommissioning tasks at Sellafield is clearing these pools of debris and sludge. Remotely operated submersibles have made some headway here, although some tasks are still best suited to more dexterous humans.

Other robots have other specialties. For example, robotic arms mounted on

THE MANY ABBREVIATIONS OF THE UK'S HOT ROBOTICS SCENE

To appreciate the UK's standing in hot robotics involves some tongue-twisting acronyms and organisations.

RAICo is the Robotics and Artificial Intelligence Collaboration between UKAEA, the Nuclear Decommissioning Authority, Sellafield Ltd, and the University of Manchester.

NNUF-HR (the National Nuclear User Facility for Hot Robotics): UK academics, startups and industry can hire facilities and an array of robots at four NNUF-HR sites for their nuclear research:

- RACE (Remote Applications for Challenging Environments): NNUF-HR's primary hub, which houses many robots and mock-ups of the environments where they would operate.
- NNL (the National Nuclear Laboratory) in Cumbria develops, tests, and demonstrates robotic solutions for the nuclear industry.
- A dedicated test space at the University of Bristol comprises a 245-acre site that focuses on environmental field surveying, with a focus on uncrewed aerial vehicles (also known as UAVs or drones) and mobile ground vehicles.
- The University of Manchester hosts another site in Cumbria, including a pond with an underwater positioning system.

Charlotte Wilkes, an apprentice mechanical design engineer at the UKAEA, controlling the remote manipulation system at JET
© This is Engineering

stationary platforms – like factory robots on a production line – are programmed to carry out very tailored tasks, such as safely packaging waste.

In the early days after Fukushima, robots sent to the reactors where the meltdown took place failed, as they were not designed to cope with such extreme levels of radiation. With this in mind, you would think that radiation hardness – how resilient components in a robot are to radiation – is a central challenge for nuclear decommissioning.

"In radioactive environments where there are medium to low levels of radiation, radiation hardness isn't that pressing. It may be radioactive enough you wouldn't want to send a person in there … but robots can work quite happily," says Megson-Smith. "I've been in radioactive places you wouldn't want to spend more than 10 minutes in, and robots have been fine, no sign of deterioration in their signal qualities." In fact, Boston Dynamics has reportedly exposed Spot to almost 250 years' worth of the allowable human dose of radiation, with no ill effects.

What can be affected, however, are navigation algorithms. If not properly radiation-hardened, ionising radiation can degrade sensor inputs, causing problems for control software, he explains. "If it has to navigate from a fuzzy picture – think of an old TV with a bad signal – can it still do it?"

If it can't get out by itself, you can't just send someone in to fix it. "How are you going to rescue or recover that robot?" Sykes asks. One option could be having twice as many motors as would normally be called for, so that if one stops working, the others can take over. "Or you can think about crude rescue mechanisms, such as tying a rope to the robot so you can simply drag it out."

Tackling the root cause might be a case of wrapping more shielding around electronic components. Another option is designing electronics that may not be quite as fast, but are less susceptible to radiation-induced corruption or bit flips, when a unit of memory data changes from a 0 to a 1 or vice versa, that cause errors.

PREPARING FOR FUTURE FUSION FACILITIES

Much of the effort at RACE is focused on JET, which ran its final experiments in December 2023. After 40 years of operation, it is now being prepared for decommissioning, a process that will take about 15 years.

For over 20 years, engineers at JET have maintained the machine using a remote handling system comprising two 12-metre-long snake-like booms. Controlled via camera and virtual reality, the booms reach through long, narrow maintenance ports reaching up to five metres into the vessel. Such equipment is essential for conditions in fusion plants, where components can reach temperatures of over 220°C and contain hazardous materials such as lithium and beryllium. Then, there's the level of radiation, which can reach up to 3 kilograys per hour at the start of maintenance. To put these units in perspective, this is over 4,200 times more than the total body exposure required to cause radiation poisoning (which is 0.7 grays or more). Because of safety precautions, personnel have not been able to enter the inner vessel of JET for over 30 years.

Furthermore, with such high levels of radiation, JET's remote handling robots must be 'wired out' to an area that's safer for electronics. "We have to take every motor and signal and have a cable leading out of that radioactive area so we can have all the electronics in a safe area," says Sykes.

Decommissioning JET will be an incredibly complex challenge. Newly-upgraded remote manipulators will be used to remove about 4,000 individual tiles and components, ranging from the relatively small up to tens of kilogrammes, from the machine's tokamak. These tiles and components are contaminated with tritium, a radioactive isotope of hydrogen essential for high-powered fusion plasmas. Tritium will need to be recovered both for re-use as fuel, and to reduce the volume of Intermediate Level Waste removed during the decommissioning process.

Tritium is very scarce, yet a critical fuel for fusion. "Every milligram is very important," explains Sykes. JET's decommissioning programme is therefore focused on recovering tritium for use in a future fusion machine or power plant, a process that could also involve remote handling capabilities. According to Sykes, this will inform an essential part of the fusion engineering and scientific planning and delivery process.

At the UKAEA, the future of hot robotics is closely connected to the global effort to produce fusion power. "Many countries are trying different solutions. In the UK we've got our own programme," says Sykes. This will be yet another acronym: STEP (Spherical Tokamak for Energy Production), a prototype fusion power plant that will be built in West Burton in Nottinghamshire, with a goal of being operational in the 2040s.

Fusion power plants aren't cheap to build, so the UKAEA aims to maximise the amount of time power plants can be generating. "Robotics have a really key part in making sure we do that maintenance of those machines and exchange critical parts in a very short period of time," says Sykes.

ROBOTIC COLLABORATION

Looking to the future, how much should robots be allowed to do independently, and how much should be controlled by humans? "If it's a very difficult or unknown task, a lot of human intervention may be needed," says Sykes.

Robots working with other robots is almost the next step, says Megson-Smith. "You don't want to throw robots in at the deep end and have them learn on the job, like you can do with a lot of AI training systems," he cautions. "Even in a collaborative system, it has to be about very gently leading them by the hand." He envisages AI systems supporting individual human operators over the next decade, to train and gain confidence in the AI. Once the trust is gained, semi-autonomous systems making more of their own decisions will become possible. "Then for the next five to 10 years, have a human watching it who can hit the stop button … until you have the evidence and confidence to make that fully autonomous. In nuclear, we have to move forward more slowly."

Robots are continually being perfected, he says. "As I see it, where we are with robots now is where we were in the 1990s with personal computers. We're at the cusp of that revolution now. They're going to slowly creep into our lives; in a decade, they will be everywhere; within two decades, you won't know how you ever did without them."

THE OTHER EXTREMES

How do the challenges of hot robotics compare to other sectors, such as space exploration and wind turbine maintenance?

According to Sykes, preparation across these operations can be very similar. "You create a sequence of events that you will go through and methodically work through those processes." Working undersea, for example, it's vital to think through the tasks in hand, just as you would in a radioactive environment: "How are you going to control the robot? What cameras are you going to use? How are you going to see [what it sees]?"

Radiation and control systems are two aspects the field shares with space exploration, he says: "Space is quite a radioactive environment, so making our robots resilient in terms of electronics is also needed in space. Space is difficult for humans to access, and conditions such as no air and freezing cold temperatures aren't particularly helpful either. But robots can deal with all those conditions."

The same applies to robots and wind turbines, where some of the most powerful are far out to sea, and difficult to access, especially in bad weather. "If a human has to, say, inspect the edges of a turbine blade, which get eroded on the trailing edge, they will have to land a boat, then climb pretty high up a ladder, which can be difficult and slow, and you've lost time when you could be producing electricity." Instead, drones can be used. "Drones are now very good at noticing changes and can assess when a blade needs a repair or replacing. And you're not putting a person at risk."

BIOGRAPHIES

Dr Dave Megson-Smith is a Hot Robotics Research Fellow at the University of Bristol's Interface Analysis Centre and has been on research visits to Fukushima Daishii and Chornobyl's New Safe Confinement.

Nick Sykes first joined the UK Atomic Energy Authority (UKAEA) as a senior mechanical engineer at JET, working on remote handling tooling. He was then appointed as a Unit Leader at RACE, before becoming Head of Operations and subsequently Director. At RACE, he has led the successful implementation of many projects for customers such as Sellafield Ltd, while also producing cutting-edge designs for JET, ITER and DEMO.

HOW ENGINEERS ARE FIGHTING MICROPLASTIC POLLUTION

Scientists estimate there are over 170 million microplastic particles in the ocean © Shutterstock

From the deepest reaches of the sea to the innermost tissues of our bodies, humans have found microplastics everywhere we've looked for them. Florence Downs speaks to the engineers who are trying to stop microplastics from getting into our water systems and the environment.

Did you know?

- Microplastics are fragments of any type of plastic smaller than 5 millimetres
- Most microplastic particles originate from larger plastic objects breaking down in the environment, with 35% shedding from synthetic textiles
- There are also even smaller plastic particles called 'nanoplastics'. These are between 1 nanometre and 1 micrometre wide – at least an order of magnitude smaller than the width of a human hair

7 May 2024 marked the 20-year anniversary of when marine biologist Professor Richard Thompson coined the term "microplastics". Now, scientists estimate that the ocean contains a "growing plastic smog" of over 170 trillion microplastic particles, with the extent of the harm it is causing marine organisms still not fully known. Meanwhile on land, scientists are urging further study on microplastics' possible harms to human health.

Further estimates from researchers suggest that 35% of microplastic particles from this oceanic smog are shed from synthetic textiles during washing, and another 28% erode from car tyres into road run-off. These are just two of the pathways that microplastics can take into wastewater.

When wastewater treatment plants are in good working order, they filter out the majority of microplastics from treated water. However, when untreated wastewater overflows into UK waterways – a risk during storms – microplastics can spill out along with the sewage.

Even when everything is functioning as it should, microplastics wend their way into sludge, the sterilised by-product of sewage. Sludge is spread on farmland as a fertiliser and researchers believe it carries a volume equivalent to 20,000 bank cards of microplastics into agricultural soil each month. The smallest of these particles, called nanoplastics, can be taken up into the roots of fruit and vegetables, while microplastics on the surface are in danger of being swept into rivers through agricultural run-off. Unfortunately, separating microplastics from sludge is not a straightforward process (see box 'Microplastics in sludge').

The obvious solution is to reduce plastic waste. While this is a massively complex ongoing challenge, one way that engineers are aiming to prevent microplastics from entering our waterways is by developing technologies to physically trap or break down the particles in our wastewater.

MICROPLASTICS IN SLUDGE

Conventionally, there are several steps in the water treatment where sludge and other bits of solid material are filtered, adsorbed and settled from treated water.

It's one thing separating water from solid organic matter, and with it any microplastic particles, during wastewater treatment. Sludge, however, is "sticky and messy," explains Dr Tom Bond, Senior Lecturer in Civil and Environmental Engineering from the University of Surrey. "Anything in the sludge is going to be difficult to filter out … The plastic fibres or particles would aggregate with the organic parts of the sludge." Tom also cautions that other pollutants, especially metals, can stick to microplastics during sewage treatment, with the risk of them building up in ecosystems and in people.

While wastewater companies do treat sludge before it is applied to farmland, the focus is on removing water, so that it is easier and cheaper to transport, and ensuring it is free of pathogens. "It's not the main concern of the wastewater companies to try and remove the plastics," adds Tom. One reason for this is that plastic pollution is not yet regulated in sewage. This means there's no regulatory driver for wastewater providers to filter out microplastics from sludge or the liquid component of sewage.

MECHANICALLY TRAPPING MICROPLASTICS

"We are trying to solve the problem of environmental microplastics," says Jess Middlemiss, Chief Technology Officer of Bristol-based engineering company Matter. Matter has developed a filter that mechanically captures microplastics to prevent them from getting into wastewater. Its first product fits to household washing machines, but the team is working on scaled up versions of the technology for wastewater and other industrial applications.

Jess explains how back in 2017, the company's founder and CEO, Adam

Root, who is a keen scuba diver, set his sights on the issue after seeing the problem of microplastic pollution firsthand. At the time, he was designing consumer products at Dyson, so decided to use his know-how to create a filter that could capture microplastics directly from washing machines. Armed with a £250 grant from The Prince's Trust, he built a prototype microplastic filter and tested it with a bucket, an old washing machine and a shredded-up pair of pants.

It worked, and seven years later, Matter has expanded to a firm of 40 and last year secured almost £8 million in investment. Its washing machine filtering system, dubbed 'Gulp', has gone through many iterations of feedback with washing machine manufacturers and the team expects it to hit the shelves next year.

A SELF-CLEANING FILTER FOR WASHING MACHINES

Like most types of conventional filter, the one inside Gulp captures fibres in a mesh, but the water flows towards it at an angle (rather than at right angles). This allows it to capture material even smaller than the 0.07-millimetre-wide holes in the mesh, including fibres as small as one micrometre wide and 10 micrometres long.

Unlike other filters, however, it is self-cleaning. Normally, such filters tend to become blocked over time and owners have to intervene to change the cartridges, to be either recycled or sent to landfill. When Gulp's sensors detect that the mesh is full, it flushes already-filtered water back towards the mesh to join the flow of incoming water from the dirty side (with a small power draw). Jess describes it as operating like rapids in a river, where trapped fibres "get blown back into the fast-flowing stream of fluid". This fluid flow eventually sweeps the collected fibres – resembling wet lint – into a capture area, which must be emptied every 15 washes on average.

In a perfect world, this "wet lint" would be recycled. But in reality, it is often made up of a real mixture of materials. "I, for one, will collect a lot of dog hair in [my Gulp] because I've got a very sheddy Labrador," says Jess. "I'm not sure how useful people would find dog hair-infested, mixed-material lint, if I'm honest." For now, it's destined for the bin. However, Jess explains that this is significantly better than it continuing to go into water systems, because landfill sites are bunded (sealed by a wall that prevents material from escaping). "The escape of microfibres from a landfill is much, much lower than if it's going into water systems or if it's landing straight on farmland."

Matter's first domestic-scale technology fits into the washing machine drawer and captures fibres in a mesh © Matter

While this is a definite improvement, it relies on every washing machine being fitted with a Gulp. Even just in the UK, that's already about 27 million washing machines. In the coming years, there will likely be legal requirements for new washing machines to come with built-in filters – something that France has been pushing hard for. But for older models, where the owner has not installed the add-on, microplastics will still be entering wastewater.

SCALING UP TO WASTEWATER AND TEXTILES MANUFACTURERS

With this in mind, Matter is collaborating with wastewater treatment companies, whose microplastics footprint is much larger than the individual washing machines in people's homes. "We always had an eye on the fact that it could be possible at a much larger scale," Jess explains. "You have to choose one thing to focus on first when you're a small startup, and it was easy for people to get the idea that you could put a filter on a washing machine." The team was careful to prove the filter worked at a larger scale before patenting it, building a proof-of-concept device Jess informally describes as "the Mega Gulp" at its Bristol facility.

That's not to say scaling has necessarily been easy. "Scaling any technology always comes with challenges," says Jess. It is, she says, like baking a cake. "If you triple the cake recipe, you can't bake it for the same amount of time. You need to adjust the cooking times; you need to adjust the temperatures." For Matter, the process has involved a lot of computer-based simulation, but Jess emphasises "there is absolutely no substitute for physical testing."

At the moment, Matter is helping one wastewater company map their facility and work out where the filter might be applied to capture the microplastics. "They know that the microplastics end up in their sludge, and therefore it must be coming into their facility," she explains. Matter's target for wastewater facilities is a filter that can cope with almost 60 times more water than for a home washing machine, with 700 litres passing through a minute – as much as a million litres a day.

Matter has other collaborations underway with textile manufacturers – another significant source of microplastic pollution. Jess explains that as much as 2% of input materials sheds during manufacturing: the equivalent of one in every 500 T-shirts lost as microplastic fluff. Annually, this could equate to tonnes of material reclaimed in Matter's filters.

What is especially interesting about this application is that wastewater from these factories has a much more controlled composition than that of a home washing machine. "If you're in a polycotton factory, you're catching a mixture of polyester and cotton, whereas if you're in my house, you're catching cotton, polyester, nylon, acrylic, polypropylene, dog hair, plaster, dust, soil, et cetera," Jess says.

The plan is to recycle the reclaimed material, with the help of partners specialising in materials reuse and emerging recycling technologies. Jess stresses that material recycling technology is not Matter's area of expertise. "We want to be part of this big circular economy ecosystem where we catch the material and then somebody else turns it back into monomers or processes it in a way that it can be reused as granules, then sells it onto somebody else who uses it."

The star player in this ecosystem might just be organisms too small for us to see, and the tools they've honed over generations of evolution.

THE MANY TYPES OF PLASTICS

- **Polyethylene terephthalate (PET)** is the plastic that makes up polyester clothing; it is also the plastic normally used for soft drinks bottles, for example. It is easily recycled.
- **High density polyethylene (HDPE)** is used for packaging applications, and also easily recycled.
- **Polyvinyl chloride (PVC)** is tough and often used for things such as drainpipes and packaging but is rarely recyclable.
- **Low density polyethylene (LDPE)** is flexible and found in films and plastic vegetable bags. It is recycled at supermarkets.
- **Polypropylene** is often used for bottle caps or containers that hold hot liquid and is easily recycled.
- **Polystyrene** is often used in takeaway containers and is very hard to recycle.

Source: London Recycles

CAN MICROBES AND ENZYMES EAT MICROPLASTICS?

At Imperial College London, synthetic biologist Dr Jose Jimenez and his team are searching for bacteria that will grow on – and break down – plastics.

In the wild, bacteria can divide (reproduce) in as little time as a few hours. This means they can evolve quickly, allowing them to adapt to whatever food sources are at hand. So far, they've adapted best to the plastic polyethylene terephthalate (PET). The most famous bacteria that does this – *Ideonella sakaiensis* – was discovered in 2010, breaking down PET at a Japanese recycling facility.

After discovering another promising candidate degrading the waxy coatings of leaves in compost with a special enzyme, scientists engineered it in the lab to break down PET instead. In April, French biotech company Carbios opened a facility that will break down 50,000 tonnes of PET a year with this enzyme. It works by breaking down PET into two constituent chemical components (called monomers), ethylene glycol and terephthalic acid. These are then purified and turned into virgin-quality PET.

To tackle such vast quantities of waste, the company purifies an enzyme extract from microbes grown in a reactor. As Jose explains, if you were to use microbes, there would be a lower concentration of enzyme, and thus a slower rate of plastic breakdown. This is one reason why *Ideonella* is not yet being used at this scale.

However, we don't yet know how well this enzyme can work outside of carefully designed conditions such as in Carbios' bioreactors. Jose cautions that conditions in wastewater treatment plants could be very different, including the pH, concentration of common ions in wastewater such as ammonia and phosphates, and temperature, too. He explains that although being exposed to higher temperatures could make the enzyme work faster, it could stop working if it's too high. "It's key to determine [which] enzymes are the most promising in real-world conditions of wastewater treatment," he says.

MICROBIAL MATTERS

In his own work, Jose is exploring engineered microbes. As microbes already play several key roles in sewage treatment, it is not too much of a stretch to imagine that engineered plastic-eating bacteria could join the party.

One advantage of the microbial approach is that it would save in the costs and materials associated with producing and purifying enzymes. However, an important caveat is that the mixture must be sterilised afterwards because regulations do not allow genetically modified bacteria to be released into the environment.

Jose is working on a bacteria that degrades both the PET and its by-products. But his team is not using *Ideonella*, which, he says, is difficult to grow in the lab and genetically engineer. Instead, they are taking the enzymes they want from *Ideonella* and other organisms and putting them into a microbe that naturally consumes the monomers for energy. They did not have to travel far to find such a microbe: in the garden on campus, they isolated a strain that can feed on terephthalic acid and ethylene glycol. Ultimately, they plan to engineer it to upcycle the monomers into more sustainable chemicals and materials.

There's still a long road ahead: studies suggest PET comprises about 11% of microplastic particles. What about the other 89% of microplastic particles? "Every plastic is different, and some are much harder than others," says Jose. "Pretty much everything that you see in the news … pretty much everyone is going to be doing PET. All of them are hard, but that's the easiest one."

Jose's group is also exploring how to break down a family of plastics called the polyolefins. These include polyethylene, one of the most widely used plastics that's mainly used for packaging, and polypropylene, a rigid plastic used to make items such as luggage and car dashboards. "With the polyolefins, it's really difficult. But it's really difficult by any method that you can think of," says Jose, referring to nascent chemical recycling approaches. (Critics say chemical recycling approaches are energy-intensive and create hazardous pollutants.)

In the hopes of meeting this challenge, the group is looking further afield than Imperial's back gardens. One of its collaborators, from the University of Northumbria, has brought one bacterial species consuming polyethylene for growth back from a recycling facility in Abu Dhabi. Other research groups all over the world are searching for similar microbes in the wild.

CHANGING OUR APPROACH TO PLASTIC WASTE

In a briefing paper in February, Jose and colleagues at Imperial set out recommendations for how microbes can successfully be used to combat microplastics in water and soil. Along with improving ways of measuring quantities of microplastics in the environment and working out what safe concentrations are, the authors argue microbiological approaches must be explored, feasibility tested, and proved in water treatment processes.

Users will be able to retrofit the Gulp technology on older washing machine models
© Matter

One of the Imperial team's final takeaways, however, was the importance of tackling microplastic pollution at source, giving microplastic fibre filters in washing machines – such as Gulp – as an example. Dr Tom Bond, too, agrees that separation at source is likely to be the easiest way to tackle the issue.

Clearly, there's no silver bullet, with the scale of the problem being so colossal. In 2021, petrochemical companies produced six million metric tonnes of new plastic – 120 times more than Carbios' facility can recycle in a year. So, while engineering solutions are vital, there's a lot to be said for more carefully considering how we consume plastics.

The 'godfather of microplastics', Richard Thompson, recently reflected in *The Conversation* on the two-decade anniversary of his discovery, in a year where the world aims to reach a global treaty on plastic pollution. He urged "reducing global production of plastic polymers and ensuring any plastic items we do produce are essential, safe and sustainable". For us as consumers, this means avoiding single-use plastics, consuming less in general, and where we can, stemming the flow of particles from our washing machines and choosing textiles made from natural materials. It will be an uphill battle, but one we must start as soon as we can.

BIOGRAPHIES

Jess Middlemiss is Chief Technology Officer at Matter. She studied materials science and engineering at Imperial College London. Her career has spanned aerospace, consumer goods and biopharma. She spent two years as Head of Operations at The Dyson Institute and is a Fellow and active volunteer for the Institute of Materials Minerals and Mining (IOM3). Jess, her husband and their two children are passionate about improving biodiversity on their six-acre smallholding and she enjoys making delicious food from whatever she can grow and forage. She also keeps bees.

Dr Jose Jimenez Zarco is a reader in synthetic biology at Imperial College London. He has worked on synthetic biology of bacteria as a postdoctoral researcher at Harvard University and the Massachusetts Institute of Technology, and as a lecturer at the University of Surrey. Jose is interested in the environmental applications of synthetic biology, such as turning plastic waste into valuable products.

Dr Tom Bond is a Principal Consultant at the Water Research Centre, an environmental consultancy based in Swindon. He is also a Visiting Senior Lecturer in the School of Sustainability, Civil and Environmental Engineering at the University of Surrey. His work is primarily concerned with engineering solutions to the impacts of hazardous pollutants, through investigating the underlying chemical pathways which define their fate in aquatic systems.

AN EXPERT IN THE AIR

Professor Catherine Noakes OBE FREng's engineering expertise goes from heavy duty ventilation down to how viruses move around in the air we breathe © thisisjude.uk 2020

When COVID-19 hit the planet, medical expertise was everywhere, but when it came to working out how the virus spreads Professor Catherine Noakes OBE FREng was one of a handful of experts in how air moves around in buildings. She spoke to Michael Kenward OBE about how ventilation proved crucial in understanding how to reduce the spread of the virus and continues to pose challenges.

When Professor Catherine Noakes OBE FREng was younger, engineering seemed liked an almost unavoidable career path. Her father was an aeronautical engineer and her mother worked on computers at the University of Manchester where she was involved in the early days of electronic publishing. "I guess STEM was always part of growing up," says Noakes. At school her favourite subjects were science, maths, and technical drawing. "We did graphic design. I really enjoyed that." Problem-solving was also something she took to as far back as primary school.

When it came to finding a degree course, Noakes opted to study mechanical engineering at the University of Leeds. Her course, in mathematical engineering, was "basically mechanical engineering with extra maths. I really enjoyed it because I could do more maths. I have probably forgotten most of it now," she laughs. But that seems unlikely. She latched on to fluid dynamics as an undergraduate, a topic that involves both engineering and maths. Fluid dynamics, and its application to different challenges, has been a constant in her career. It remains so in her work on how diseases spread in buildings.

DYNAMIC EQUATIONS

The appeal of fluid dynamics was in its use of "really complicated equations, but they then describe the things you see. It's physics, isn't it? I just found it fascinating." As an undergraduate she did modules on compressible flow for aerodynamics and non-Newtonian fluid dynamics. Noakes liked that the same equations can apply to the weather and its flow around the Earth and to micron-scale coatings on film.

Fluid dynamics took her into a PhD on thin-film coatings. That PhD, also at Leeds, added a new dimension to Noakes's experience: the use of computer power to tame those equations. "I learned about coding; I learned computational fluid dynamics." After her PhD, she spent time working as a knowledge transfer associate, in Delpro Ltd, a company that made machines to coat paper. Among other things, Delpro developed equipment to produce sticky labels and make bank notes.

"I came into that because I'd got the PhD around thin-film coating, but I then worked on drying because you dry it to coat," she says. "I quite enjoyed going to some of the sites where they'd installed machines. These things are huge. Metres and metres long, and they run at speeds of several 100 metres a minute. There's something about being involved with designing and developing machines like that. It was quite a challenging role."

Hoping to work in industry, Noakes applied for a few jobs until a civil engineer in the university asked her if she would be interested in a postdoctoral position at Leeds. "I almost said, 'No, not really, I want to do something different'." Not taking no for an answer, they invited her to drop by for a chat. The post turned out to be about controlling tuberculosis transmission.

A group of civil engineers at Leeds wanted to investigate using ultraviolet (UV) light in a room to inactivate bacteria. Noakes's immediate response was "I don't do biology"; but on reflection, she could see a fluid-dynamics problem, about air flow interacting with UV light in a room – a physics problem with a biological aspect. Somebody breathes out bacteria and where do they go in the room?

Noakes says: "I toyed with a couple of job offers and decided to go with that one. I've not looked back since then." Two decades later, that decision put her on the frontline of one of the biggest challenges that has faced society in decades: how to handle the outbreak of COVID-19, a clear case of engineering meets medical science and people. It took time to reach that stage, starting with her PhD. "I rapidly learned about building ventilation, the engineering side of that, but also the wider picture. I really enjoyed using the skills that I had built up around fluid dynamics to tackle something that had a societal impact." She started working with clinicians and microbiologists and, as her career developed, architects and social scientists. It turned out to be complex territory. "We can describe ventilation in a building as physics ... but it's very complicated physics that is influenced significantly by the people in the space. Capturing that human impact is incredibly challenging. Anybody who works in the field has to think through the complexities and limitations of what they do. It's too easy to just say, 'Hey, I've done a physics model'. But that physics won't be right. It's knowing how incorrect it is, how much you can draw from it, and how much you can't. That's where it becomes important."

IN THE AIR

Until recently, research on health and indoor air was down to a relatively small community, with focus on studying air quality and topics such as climate change, energy in buildings, and sustainability. "I was one of a very small number of people worldwide who worked on things around

As COVID-19 took hold, creating a need for more hospital beds and Nightingale Wards, the NHS sought advice from Professor Catherine Noakes on how viruses spread © thisisjude.uk 2020

infection transmission in buildings," says Noakes. "I would turn up at conferences and everybody else was talking about particles or gases in the air or temperature or humidity. And I'm the one who goes 'By the way people breathe out microbes that cause disease'."

This community focus began to change in the early 2000s, with SARS in 2003 and swine flu in 2009. "The number of people working in this area now has grown massively, but I could probably name 30 people worldwide who worked on it as their main topic prior to COVID-19." These people were, she adds, a mixture of engineers – civil, environmental, and mechanical – with others from backgrounds in public health or infectious diseases. "Where it gets really interesting is where those intersect."

This small community was suddenly in great demand when COVID-19 wafted in. Noakes had just stepped down as director of research in the School of Civil Engineering at Leeds. "I was thinking 'great, after six years in this role, I've got time to focus on my research again'." No chance, in March 2020 colleagues in the NHS got in touch. Scotland was quick off the mark. "They were trying to work out how to repurpose parts of the hospital estate and to create new isolation facilities, COVID-19 wards."

That was just the beginning. The Royal Academy of Engineering called early in April: the Academy and its partners in the National Engineering Policy Centre had been commissioned by the Chief Scientific Adviser Sir Patrick Vallance HonFREng FRS FMedSci to identify the interventions needed in the UK's built environment and transport systems to reduce infection transmission, including the Nightingale hospitals. Then, on 7 April there was a call from SAGE, the government's Scientific Advisory Group for Emergencies. "These dates are embedded in my head. They wanted a paper on the 14th." There wasn't time to assemble a

QUICK Q&A

Who influenced your engineering career?
A big thanks to Professor Clive Beggs who first got me into infection control engineering.

What's your advice to budding engineers?
Follow the things you are passionate about.

Best part of the job now?
I love seeing students develop and becoming experts in their own right.

Which record/book would you take to a desert island?
Any of David Bowie's music.

Most admired historical bit of engineering?
Fountains Abbey in North Yorkshire – even the monks understood ventilation and sanitation.

Overlooked engineering successes?
All the bits that make buildings work – we rarely see the heating/ventilation plant, but it is crucial to our everyday lives.

LESSONS FROM COVID-19

Schools and their role in the spread of infection are still teaching us long after closed classrooms made headlines during lockdown. "Schools are a great place to start learning about indoor air," says Noakes. "With a simple monitor you can start to understand how [the school] environment responds to different conditions and the weather." It is also a good way into education and promoting awareness about how the environment affects people.

Noakes is involved in two projects in schools. She is a member of the steering group for Schools' Air quality Monitoring for Health and Education (SAMHE). The project is about citizen science and measuring air quality at schools. SAMHE gives teachers real-world experiments for students along with teaching resources that tie in with the school curriculum. Supported by the Department for Education, it can also "help scientists learn how to make schools healthier places."

Schools in SAMHE get a free air-quality monitor to measure carbon dioxide, volatile organic compounds, particulate matter, temperature, and relative humidity. "If you've got an air quality monitor, you can start to do some really interesting explorations yourself," says Noakes. More than 1,000 air-quality monitors in schools across the UK are collecting data.

Funded by the Engineering and Physical Science Research Council and led by Imperial College London, SAMHE is a collaboration of five universities, including Leeds, and the UK Health Security Agency. "It's such a lovely project," says Noakes. "They've really thought about how to present data to different age groups and how you engage."

Noakes is more heavily involved in another schools project, supported by the Department of Health and Social Care. Class-ACT goes beyond monitoring air quality and is testing air-cleaning technologies (ACTs) in classrooms. The project has made high-efficiency particulate air (HEPA) filters available to 30 primary schools and added air-quality monitors in 540 classrooms in Bradford. As well as testing filters in schools, Class-ACT is also providing advice to policymakers on classroom ventilation and the practicalities of implementing and using air cleaners.

The project has studied the effectiveness of HEPA filters in reducing primary school absences related to illness. It has also looked into the feasibility of installing ACT in classrooms that had previously relied on opening and closing windows to control the classroom environment.

Class-ACT has yet to publish its final results, so Noakes can't say too much about the findings of ACT, but is positive about the outcomes. The project has already shown that installing it requires careful consideration, and, while HEPA-ACT may not be a panacea, it is a useful tool that could help schools, and other buildings, become healthier environments.

For Professor Catherine Noakes, engineering effective ventilation to create healthy indoor environments means combining physics, biology, and human behaviour

national group in just a week. "I just pulled together a few colleagues and PhD students at Leeds. We put together a massive, very, very rapid literature review as quickly as we could. We put this paper to SAGE on 14 April and Sir Patrick Vallance asked us to set up a subgroup to look at environment and transmission. We convened that group in about a week and had another paper out a week later. The timelines were just ridiculous."

That group, one of five key subgroups for SAGE, assembled experts in universities and public sector research organisations across the UK, to give advice around environment and transmission. This was an important issue at the time. The country was in lockdown, but that could not last for ever. "A lot of the government chief scientific advisers ended up on our SAGE subgroup because we were doing things that were very practical. We were looking at all the things that they were worrying about."

There were just so many questions about transmission of the virus. "Right at the beginning, we knew very little. Bits of evidence were starting to appear that pointed to 'super spreaders', and some of that being airborne. But we couldn't rule anything out. We didn't even know if it would survive outdoors. As lab evidence started to come through, it became quite quickly apparent that nearly all of the transmission happened indoors. That enabled us to be able to say, scientifically, we think that outdoors is considerably safer. But it was a real challenge."

It all came back to the science, and science that was changing, almost by the hour. "Even where you have things like your gut instinct, you can't use that as evidence to policymakers. You have to base this on some science. And you have to look at what we know from the science, and that changed over time. Communicating how it changed is quite hard. You get one message, and then, if that message changes, you have to try and explain that that message has changed because we've understood something new."

AIR FLOW THROUGH BUILDINGS

COVID-19 threw a light on the wider issue of ventilation and infection. "It has pushed the quality indoor environment, and the impact of environments on health up the agenda," says Noakes. It led to several research projects, including work on 'infection resilient environments' sparked off by a request from Sir Patrick Vallance to the Academy to look at the role that the environment played in the spread of COVID-19. This work included thinking about how you enable environments to be healthy, safe, and sustainable.

This thinking involved Noakes in writing major reports on buildings and health. The most recent, *Mandating indoor air quality for public buildings*, called for wider international use and national legislation on indoor air quality.

COVID-19 didn't just affect Noakes's work as an engineer, she became one of the public faces of science. At first SAGE participants were anonymous, when that changed, she became more careful about her own online security and "making sure that where I lived was not identifiable, making sure my son's school wasn't identifiable. Initially I didn't really want to talk to the media," she adds, "but I realised that there was a gap. And if you're not careful, other people fill the void. And they don't necessarily fill the void correctly." After all, there weren't many experts around on the science of transmission and the science of why ventilation mattered.

"I had my share of abusive emails and strange emails and things," she laughs. After she tweeted a cartoon, the *Daily Mail* dubbed her "the scientist who opposed the two-metre rule". Hardly the worst insult, she admits, but it made her realise that she was being watched. After that she was careful to steer clear of saying anything political on social media.

To make life less depressing, during lockdown Noakes returned to an earlier interest, music. She enjoyed music, playing flute and guitar at school but realised that she was "never going to be good enough to do it properly". Just before COVID-19 came along she had started to take piano lessons. When the disease hit, she worked out how to continue taking lessons online. "It was great, a really good way of having something else to take my head away. That was one of the things I think that kept me kept me sane."

For Noakes there are lessons to draw from COVID-19 beyond the obvious technical issues. She has concerns about what the pandemic did for equality, diversity and inclusion, and supporting early-career researchers. "It was inevitable that senior scientists got pulled in to advise. We did a lot of work, but we were also pushed across the media. We've had to go through an inquiry, for example. There's an awful lot to take in there. I was quite conscious that the next time this happens, hopefully I will have retired and somebody else will have to do it. And how do you build up that capacity?"

This is just one of Noakes's post-COVID-19 concerns. She worries that, as memories fade, "we're almost in denial about COVID-19. We could have learned an awful lot of lessons and put things in place. Whether it's building research capacity, whether it's changing guidance, whether it's updating our environments to be more resilient. Because there will be another pandemic." And like most pandemics that sweep the whole world, it will probably be an airborne respiratory disease. "I wish we were more readily thinking about resilience for the future."

CAREER TIMELINE AND DISTINCTIONS

Studied mathematical engineering, University of Leeds, **1993–1996**. PhD in mechanical engineering, University of Leeds, **1996–2000**. Postdoctoral researcher, **2002–2006**. Lecturer in environmental engineering, **2007–2010**. Director, Pathogen Control Engineering Institute, **2010–2014**. Director of Research, **2014–2020**. Professor of environmental engineering for buildings, **2014–present day**. Deputy Director, Leeds Institute for Fluid Dynamics, **2018–2024**. Chair, Environment and Modelling Group, UK government Scientific Advisory Group for Emergencies (SAGE), **2020–2022**. Appointed Officer of the Order of the British Empire, **2020**. Received a President's Special Award for Pandemic Service from the Royal Academy of Engineering, **2020**. Fellow, Royal Academy of Engineering, **2021**. Honorary Fellow, Chartered Institution of Building Services Engineers, **2022**. Chair, Science Quality Assurance Group, Health and Safety Executive, **2022–present day**. Received Gabor Medal from the Royal Society, **2023**. Pro-Dean Research and Innovation, Faculty of Engineering and Physical Science, **2024**.

THE SWEETS HELPING PEOPLE STAY HYDRATED

Inspired by his late grandma Pat, design engineer Lewis Hornby wanted to find a way to make staying hydrated easier for people with dementia. With his startup Jelly Drops, he's invented a jelly sweet that is helping thousands of people avoid complications relating to dehydration.

Lewis and Co-Founder Claudia testing Jelly Drops © Jelly Drops

Hydration is a real problem for people with dementia, who may not realise or be able to easily communicate that they're thirsty. According to the Alzheimer's Society, the sensation of thirst can actually change in older people, which means they might not feel thirsty if they're becoming dehydrated.

Design engineer Lewis Hornby first became aware of this issue when his grandma Pat was admitted to hospital while he was an undergraduate studying engineering at the University of Bristol. "She went downhill very fast, was hospitalised, and [we] didn't really know why," says Lewis. "Then [after] 24 hours on IV fluids, she was absolutely fine and went on to have a good quality of life for years after."

In 2018, Lewis was studying for his master's in innovation design engineering at the Royal College of Art (RCA) and Imperial College London. He had several successful group projects underway, but he decided that for his solo project he would head to Yorkshire and spend a month learning about the needs of care home residents. "I just thought it was a good excuse to go and spend a bit more time with my grandma, and see if I could help," he says.

DEVELOPING A PROTOTYPE

While there, he noticed that, among his grandma and other residents, he would become very popular if he brought in sweets. "I'd go to the care home most of the time and everyone would ignore me, which is fair," he says. "But if I had some chocolates, then everyone's your best friend, taking a handful and having a quick chat. I thought if I could make

EYES ON THE INNOVATORS

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

Microcomputer maker **Raspberry Pi** has started trading on the London Stock Exchange

Startup **WaterScope** has partnered with ARA International to take its innovative water-testing system to Pakistan and Afghanistan

Lewis Hornby (Left), Co-Founder of Jelly Drops, with his late grandma, Pat (right) © Lewis Hornby

a hydration version of a sweet then people would engage with it readily, enthusiastically, independently."

He developed a prototype in his kitchen and later applied for the James Dyson Award. To his surprise, the video he made for it went viral after someone posted it on Facebook. He describes how he was away on holiday and the group chat from his course started to go wild: "'oh, you're on the front page of Reddit!' And I was like, what's Reddit?" It made the *Evening Standard* and within a few weeks had reached 100 million views. "You couldn't really ask for a better start for your startup than having 50,000 people on your waiting list," he says. And so, Jelly Drops was born.

Compared to many early-stage businesses, Lewis and Co-Founder Claudia started off with an advantage: not only a huge customer base, but an excellent understanding of how their products would be used. For starters, Jelly Drops would need to be stable at room temperature, as people with dementia can forget to put them in the fridge. This would also make it much easier to store for another key group of customers, care homes, which typically prefer to order in bulk.

Meeting this very specific need was quite out of the ordinary for food manufacturers, and meant the team had to build its own production setup. Thankfully, through the media attention it had attracted, an investor who had reached out was able to connect the startup to someone who had been head of R&D at a large food manufacturer.

GETTING THE TEXTURE RIGHT

Jelly Drops are not, as you might imagine, an edible bubble filled with fluid that bursts when you bite into it. The team's user research had showed that sweets with this structure could become a choking hazard for people that weren't expecting it. Similarly, melt in the mouth sweets can cause issues for people with swallowing difficulties.

Instead, the solid, jelly-based sweets are designed to be very easy to chew – key for people with dentures – while also solid enough to hold their shape when you pick them up. They are 95% water: the rest is the vegan gelling agents, plus added flavours, vitamins and electrolytes.

With such a large waiting list, the team was keen to launch something quickly. Clearly, Lewis wasn't the only one with a loved one affected by challenges with hydration. "Having that close connection with our customers and our community allows us to develop and build a better version of the products," he says.

Often, when the team was developing Jelly Drops, team members would visit care homes to get feedback – which turned out to be enormously helpful. Initial tests showed the first product didn't quite meet the psychological expectations of customers; its crumbly texture somewhat unexpected. "If someone doesn't like it, they just don't like it," Lewis says. "So, we had to move quite quickly on that." The benefits of developing its own production process quickly became apparent when the team needed to make this change.

Another important design element was the packaging. The team has now settled on individual snack pots, each containing enough Jelly Drops to provide 50 millilitres of hydration. The idea is for people to have a few throughout the day, Lewis explains, perhaps with their cup of tea or with dessert after lunch.

While this doesn't sound like a lot, cumulatively, having five pots over the course of a day gives a 250-millilitre boost to people's hydration levels. This is significant when you consider that falling short of a 1,500-millilitre water intake can be enough for someone to go to hospital – just like Lewis's grandma Pat. "It's an extra tool for people," he says, emphasising that they are not designed to replace drinking for hydration altogether.

Another positive effect is that it reduces the strain on care home staff. "People are more independent when they're not suffering the effects of dehydration," explains Lewis.

HELPING PEOPLE

With a team of 10, Jelly Drops has built relationships with several NHS trusts and care homes. However, of its 68,000 customers, the company primarily sells to families. Amid the success of Jelly Drops for people with dementia, Lewis believes the company could help others too, including young people with learning disabilities, those going through chemotherapy, and some autistic people who don't like drinking plain water. The team has been working with Innovate UK for the past 18 months developing a nutrition product based on the same insights behind Jelly Drops.

"There's a lot of people out there that are really underserved by conventional forms of hydration and nutrition," says Lewis. "We're learning that we can really have a much broader impact and help a lot more people with challenges that we didn't even know were a challenge when we started."

Swytch, which manufactures a device that converts regular bikes to e-bikes, has won the Red Dot Design Award for the second year in a row

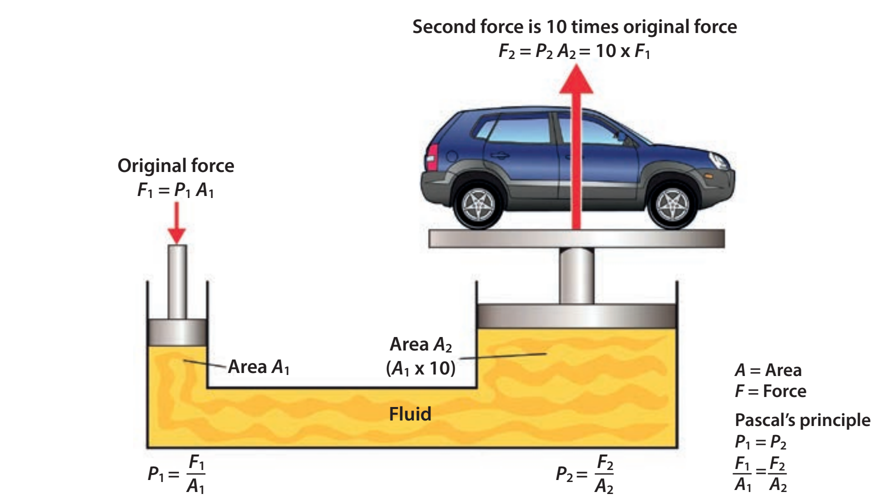
British company **Firefly** has received investment from Wizz Air to build a refinery in the UK to convert treated sewage waste into sustainable aviation fuel

Startup **AquaBattery** has closed a €6 million seed investment round, to support further development of a low-cost, sustainable energy storage solution based on salt water

HOW DOES THAT WORK?

HYDRAULIC PRESSES

Hydraulic presses are an integral component of manufacturing, used for assembling and disassembling tight components, moulding, forming, compacting, and more. Now, videos of a range of items – from gummy bears and Skittles to anvils – being squashed in a hydraulic press have gone viral across social media.



After a long day, what could be more relaxing than watching an assortment of everyday objects buckle, break, spaghettify, and even explode under intense pressure? With over nine million subscribers to the *Hydraulic Press Channel* on YouTube, perhaps not much.

On the channel, Lauri Vuohensilta and Hanna Korpisaari squash various fruit, toys, tools, and even concrete and metal under a 150-tonne hydraulic press in their workshop in Finland. It's captivating viewing, but what's actually going on? How is it that we can create these obscenely large forces, with relatively little input?

"The basic principle of the hydraulic press is that you can use a small force to generate a large force," says Adam Wojcik, associate professor at UCL's Department of Mechanical Engineering.

He explains that in its simplest form, the hydraulic press is two syringes connected by a pipe filled with an incompressible fluid, usually oil. When you press on one syringe, this force is transmitted through the fluid to the other syringe, in this 'hydraulic circuit'.

It's a demonstration of Pascal's principle, which states that pressure applied to a fluid will be transmitted evenly throughout the fluid and to the walls it's contained in. Where things get interesting, however, is that the force being applied can be increased at the other end of the hydraulic circuit, simply by changing a few dimensions.

Pressure on a surface is equal to the perpendicular force on it, divided by its area. As the pressure is the same throughout the fluid, the force applied to a relatively small area at one end of the system will multiply when applied to a relatively large area at the other end. So, if the area of the first syringe being pressed is half that of the second, you'll get double the force at the second syringe. "You don't get something for nothing, however – the force might be doubled, but the movement that the force creates will halve, so as to keep the overall work (energy) expended the same," Wojcik adds.

In a hydraulic press, this first 'syringe', where the smaller force is applied, is technically known as the pump, while the second, applying the larger force, is known as the ram.

This multiplier effect is why mechanics can raise a one-tonne car with a few pumps of the handle. Inside the car, another hydraulic system ensures that when you apply the brakes with a modest force, the car comes – with the help of friction, of course – to a stop.

Hydraulic presses are used to forge or shape materials including car parts and panels of domestic appliances, and to form concrete into different shapes for construction, as well as to punch out and join together different materials.

Andrew Pilkington, a senior research associate at the University of Oxford's Department of Engineering Science, notes that hydraulics can also be used to apply a large turning force for tightening bolts: "As the bolts get very large in diameter, you need a lot of force to tighten them," he says. "You'd either have to use a very, very long spanner, or a very, very large force. Hydraulic torque wrenches are a good way of providing that force without having to use an unwieldy 10-metre-long spanner, which would be unwieldy."

In Lauri and Hanna's videos, the presses generate compressive forces of between 150 and 300 tonnes, but hydraulic presses can go up to the order of thousands or even hundreds of thousands of tonnes.

The 100,000-tonne hydraulic press at GIVA's Forgiatura A Vienna facility in Italy, known as 'Tyson', forges turbine wheels for power generation and is thought to be the largest in the world.

To read more about hydraulic presses and find out how they could one day be used to date archaeological finds, read the full article at ***www.ingenia.org.uk***

Words: Leonie Mercedes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