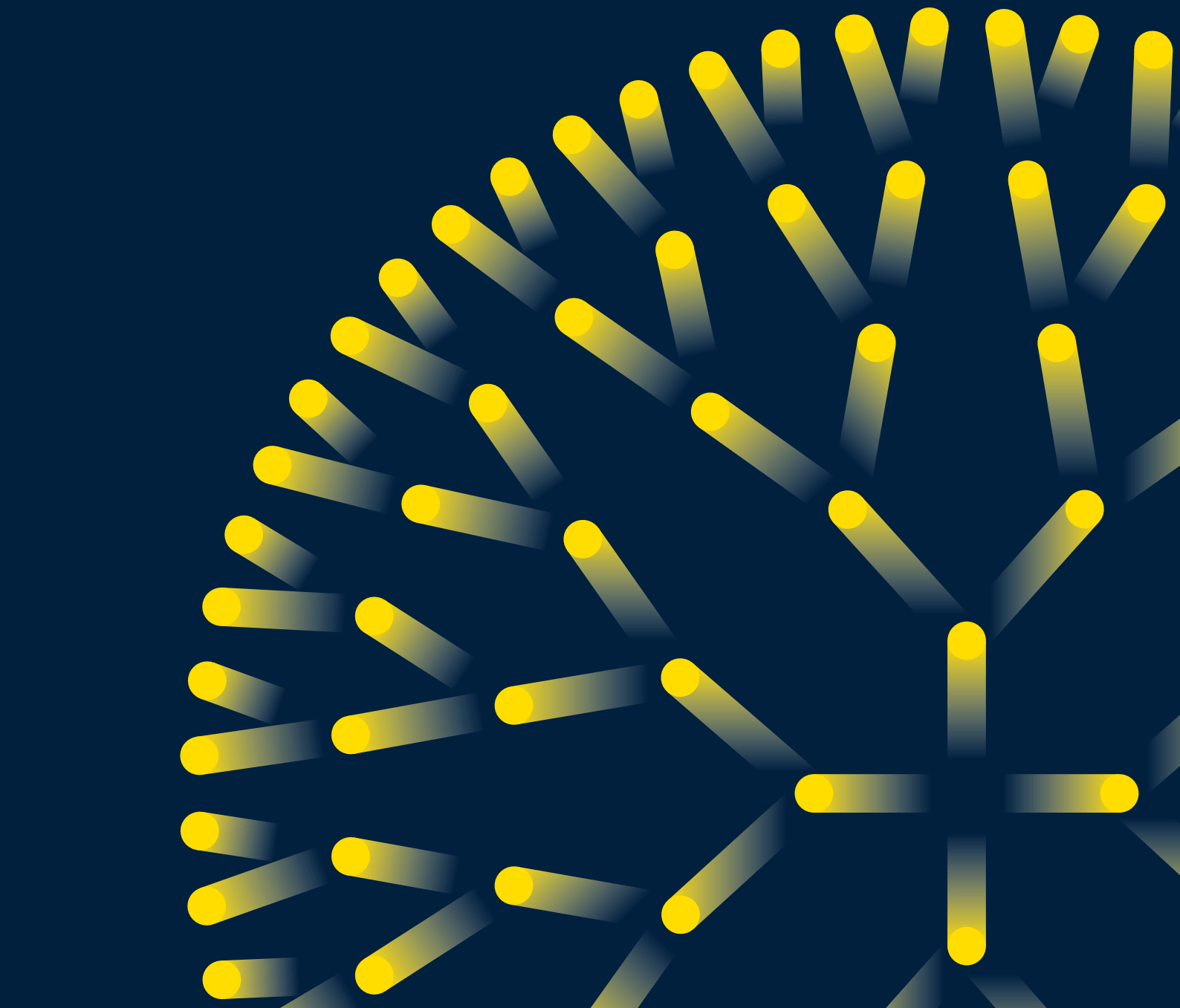
NATIONAL NUCLEAR LABORATORY

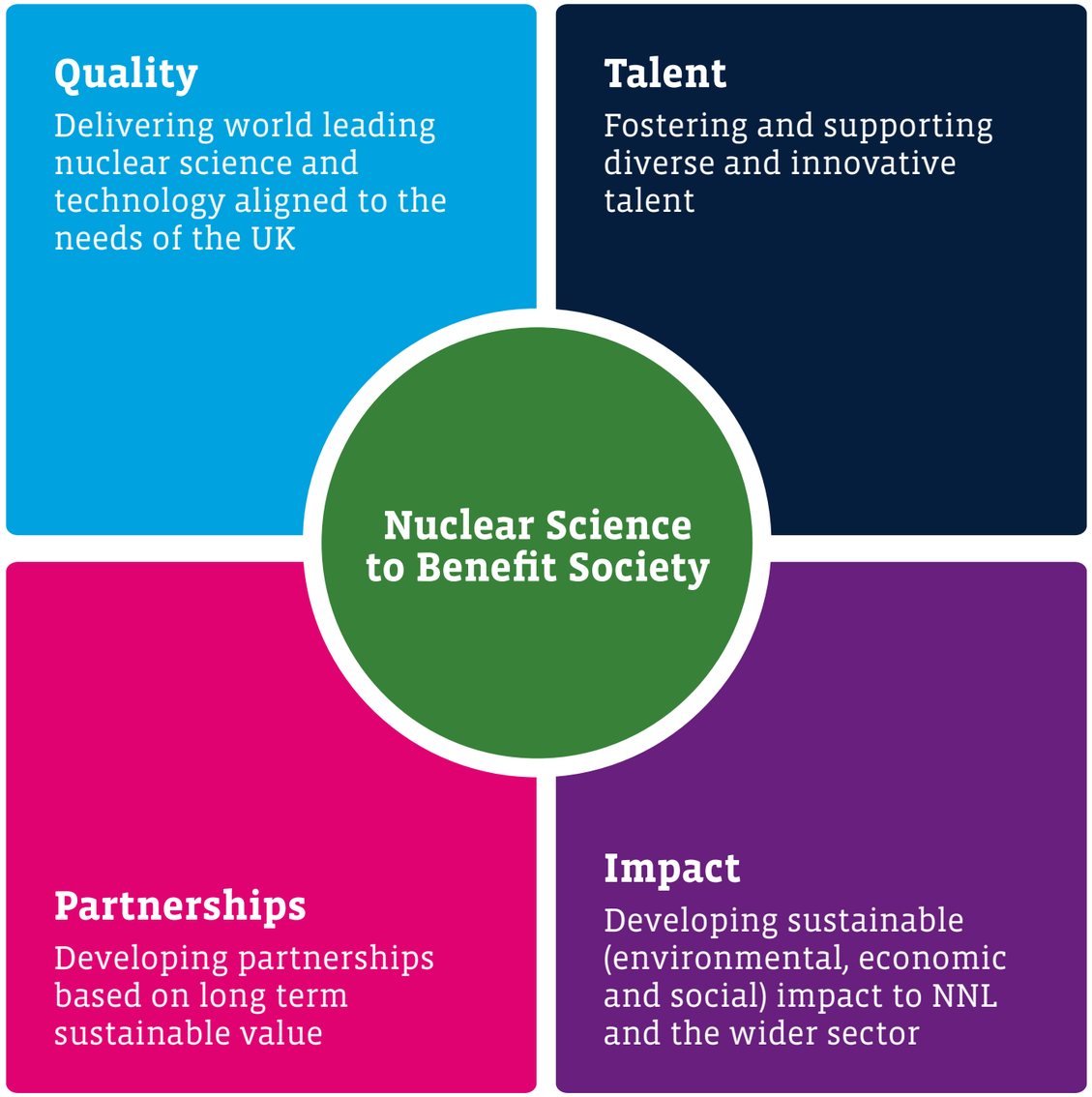
NuClear Science: Case Studies

2023–2024

Part of the S&T Agenda



NNL Science & Technology Agenda Value Framework



Science and technology is, and always has been, the beating heart of NNL.

We continue to be committed to communicating the world-leading science and technology we deliver for our partners and stakeholders through our Science and Technology Agenda.

We invest in scientific research and unleash innovation, building capability for the UK. This investment is a key part of our work as a national laboratory; it enables us to serve our customers, our partners and our nation better, and play our part in positioning the UK as a global leader in nuclear technology.

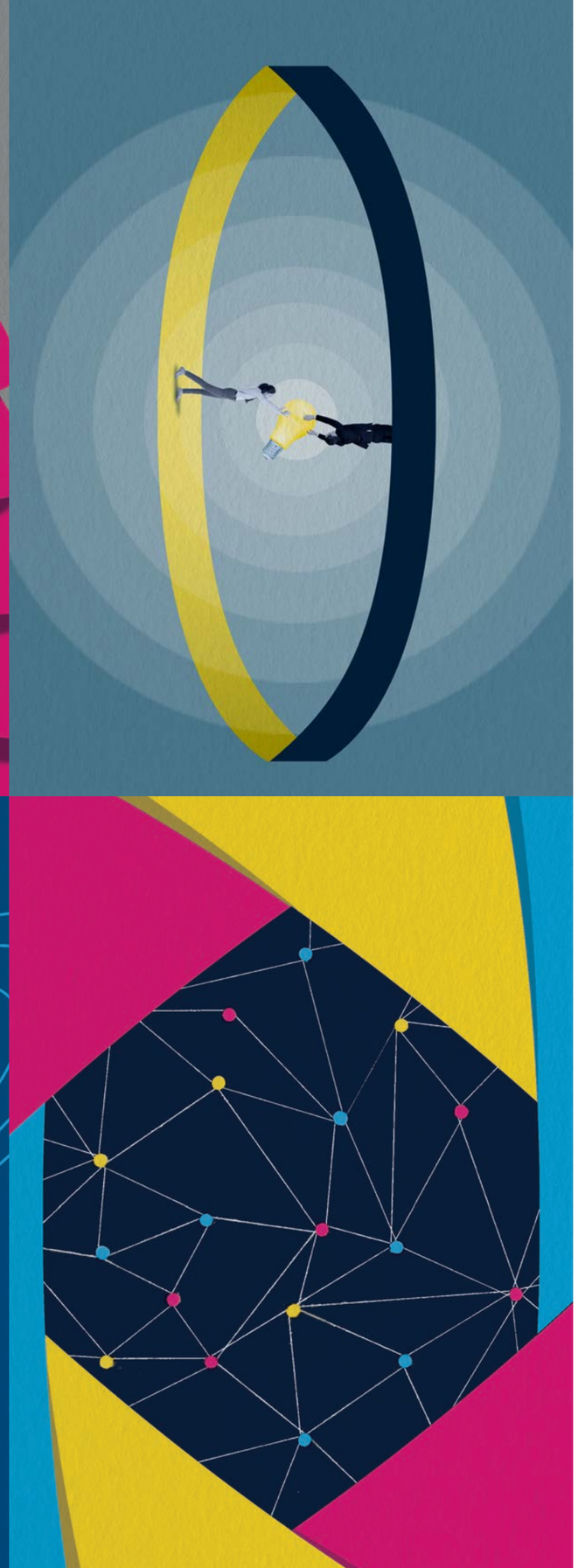
Our Science and Technology Agenda is defined by three key pillars – Core Science, Innovation and Strategic Research – all of which are underpinned by Collaboration. Within this **NuClear Science: Case Studies** publication, which is an evolution of the science and technology case studies we have published in previous years, we have selected examples that showcase the breadth of work undertaken under these pillars over the past twelve months.

In each case study, we describe the value generated against our Science and Technology Value Framework: Quality, Talent, Partnerships and Impact.

This is the first instalment in our new **NuClear Science: Case Studies** series, complemented by our NuClear Science: Webcast series that launched early in 2024. It's exciting to share these case studies and the value we are delivering in partnership with a range of national and international stakeholders from across academia, industry and government.

Dr Gareth Headdock
NNL Chief Science and Technology Officer (CSTO)

Dr Paul Nevitt
NNL Vice President Science and Technology



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1 | Our people

The NNL Fellowship - world-leading experts and ambassadors **pushing the boundaries** of science

Science and technology is the beating heart of NNL and it's our world-leading scientists who continue to drive forward advances with their expertise and innovative thinking.

Recognised as leaders in their respective fields, whether in science, technology or engineering, our Fellows help to promote technical excellence and shape national and international policy.

They are outstanding role models to our teams across NNL, as well as to collaborators across the sector, and are key to shaping a clean, sustainable nuclear future for the UK.

Dr Deborah Hill receiving the Distinguished Service Award from the Chair of the Nuclear Criticality Safety Division of the American Nuclear Society.

" An NNL Fellowship award is a prestigious appointment that recognises the important technical leadership role that those individuals fulfil within both NNL and the wider industry.

I'm proud of the role our Fellows play in shaping and driving the technical direction of the laboratory, enabling us to collaboratively deliver on our strategic ambitions whilst nurturing the next generation of subject matter experts. "

Dr Deborah Hill
Head of NNL Fellowship

Quality

Celebrating our subject matter experts

The NNL Fellowship currently has 18 members across Senior Fellows, Fellows and Associate Fellows. These are experts with individual expertise in materials science, environmental radiochemistry, fuel manufacture, actinide chemistry, decommissioning, statistics, nuclear safety and more. All have leading international roles and reputation; they are mentors and represent NNL and the UK at prestigious scientific conferences and meetings around the world.

David Hambley is a Fellow in spent fuel storage and disposal. He holds prestigious advisory roles with other international organisations such as the Electric Power Research Institute (EPRI) and the World Nuclear Association (WNA). David works with respected organisations such as the Organisation for Economic Co-operation and Development's Nuclear Energy Agency (OECD-NEA) and the International Atomic Energy Agency (IAEA). His view is being increasingly sought on the best techniques to manage spent fuel from advanced modular reactors, an area in which he has significant influence to shape the international landscape. Insights gained from these international collaborations help form the UK strategy for developing and managing nuclear fuel.

This year, David has led a major international programme to evaluate strategies for advanced fuel cycle options for future reactor technologies and developed a groundbreaking new joint project with OECD-NEA in relation to managing used fuel from advanced modular reactors. These activities are vital for shaping future policy on nuclear technologies, to put NNL and the UK at the forefront of defining the future of nuclear around the world.

Partnerships

Building collaborations that have real impact

Our Fellows strive to make new scientific discoveries, and to apply their knowledge and understanding to meet challenges. Part of this involves sharing information with other experts and building collaborations. Dr Tom Carey is an Associate Fellow in decontamination and decommissioning.

The Associate Fellow scheme was introduced in 2022 as a key new step in the NNL technical career pathway, to acknowledge and support our future technical leaders.

Dr Carey's collaborations with European partners and UK academic institutions such as The University of Manchester and Lancaster University are uncovering fundamental mechanisms behind the contamination of materials. He has been recognised as an associate professor by the University of Birmingham, where he is developing new methods for the treatment of radioactive liquids. Dr Carey is also building partnerships with national bodies and regulators such as the Environment Agency and Public Health England, to develop strategies for post-emergency situations.

Opposite page:
David Hambley presenting at Global 22.

This year, Dr Carey has

supported four PhD projects and seen two other PhD researchers graduate, following which they took on jobs in the industry to further build on the skills developed in academia

established quarterly Decontamination Centre of Excellence meetings with Sellafield Limited, where PhD researchers are invited to present and share their work directly with industry

delivered a training course on decontamination techniques to stakeholders in Europe and to the UK's emergency responders to share best practice in this arena

presented at the International Conference on Environmental Remediation and Radioactive Waste Management (ICEM 2023) and published research in several journals to share the latest research findings with the wider scientific community.

Read Dr Carey's recently published work:

Methods for the destruction of oxalic acid decontamination effluents

J. Blenkinsop *et al, Front. Nucl. Eng. (2024) 3, 1347322*

Read the research article on the Frontiers in Nuclear Energy journal website

A review of contamination of metallic surfaces within aqueous nuclear waste streams

D.N.T. Barton *et al, Prog. Nucl. Energy, (2023) 159, 104637*

Read the research article on the ScienceDirect website

Dr Tom Carey (centre) facilitating a tour of NNL's Workington Laboratory.

Dr Steve Graham teaching on the Science and Technology Leadership Programme.

Talent

Fostering the next generation of subject matter experts

The very best scientists use their leadership skills to mentor and encourage others. Being an influential expert in your field means you have great power to help shape other experts. Dr. Steve Graham, Fellow in nuclear thermal hydraulics, has pioneered a new educational programme to develop scientists and engineers at an early stage of their career. The Science and Technology Leadership Programme is a postgraduate qualification that introduces course participants to key leadership skills and enables them to put them into practice under the guidance of a mentor.

The programme evolved into an accredited academic course run in conjunction with the University of Liverpool, following the success of the original course developed within NNL. Skills taught include leadership, communication, impact and influencing. Over 50 future leaders from NNL have participated in the course, alongside a further 44 participants from other organisations.

This year the course has seen all seven participants receive a distinction: the highest grade possible for this type of course. These included external delegates from the UK's National Physical Laboratory (NPL), the Atomic Weapons Establishment (AWE) and Nuclear Waste Services (NWS). Feedback from line managers of attendees has been positive and indicate a noticeable increase in technical gravitas.

> "The course was very thought-provoking, it provided insights that made me view things from different perspectives. This course has enhanced skills that will shape my career and guide me through challenges ahead."

Sarah Forder
Team Leader (Radiation Protection Advisers) and Deputy Group Leader (Radiation Protection & Dosimetry), AWE

> "The final project was challenging, but the support of programme mentors enabled me to plan effectively – skills I am now putting into practice."

Alex Cackett
Materials Scientist at NNL

Impact

Influencing world-leading organisations to shape a nuclear future

Our experts are well-respected in their fields and form part of a thriving community of dedicated technical specialists. The communities have a common aim: to work together to generate new scientific knowledge that can improve how we live.

Dr Deborah Hill is a Senior Fellow in criticality safety. Soon after receiving the Distinguished Service Award from the Nuclear Criticality Safety Division of the American Nuclear Society (ANS) in 2019, Dr Hill was invited to chair the ANS Professional Divisions Committee, the key technical governance committee for the Professional Divisions within the Society. A voluntary role, Dr Hill recently received a highly prestigious ANS Presidential Citation from the Society for her work in transforming the Committee. Through her leadership, an environment has been created where Divisions of the Society can effectively collaborate with the wider ANS leadership on both a strategic and tactical level, to add value to the work of its members. Driving these significant enhancements in a well-respected professional body can make a tremendous difference to the global nuclear industry.

A key success this year is the creation and delivery of an extensive set of onboarding resources for the new Division leadership, which enables them to quickly maximise their impact in their new roles.

International impact

More widely, the NNL Fellowship is currently involved in a range of working groups and other technical leadership roles. The following are some examples of members' broader impact.

Chairing the OECD-NEA Expert Groups on Fuel Materials, Fuel Recycling and Waste Technology.

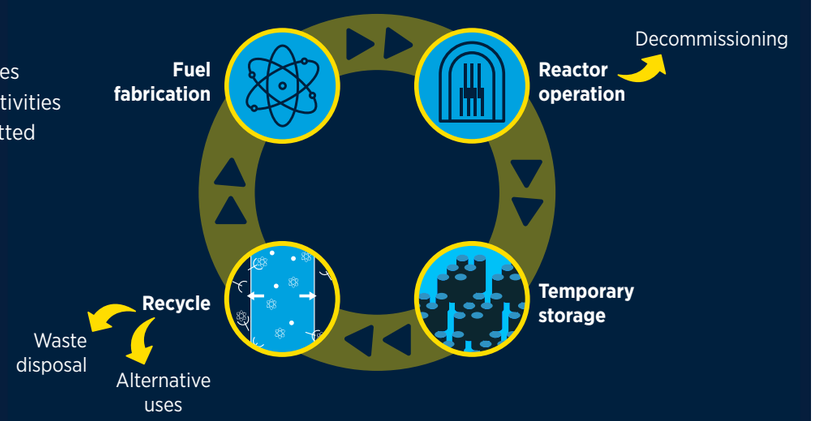
Chairing the Board of Management for the Halden Reactor Programme. The reactor, based at the Institute for Energy Technology in Norway, has been an asset for testing fuel and reactor components.

Chairing the ASTM (American Society for Testing and Materials) International Committee that approves the test methods for manufactured carbons and graphites.

> "The American Nuclear Society is indebted to Deborah for her hard work and dedication. As Chair of our Professional Divisions Committee, she has played a pivotal role during our organizational transformation in mending and strengthening the relationship between the Society and the elected leadership of its divisions. Her ability to manage a group with diverging interests to forge a set of common objectives is a rare talent."

Craig Piercy,
Chief Executive Officer, American Nuclear Society

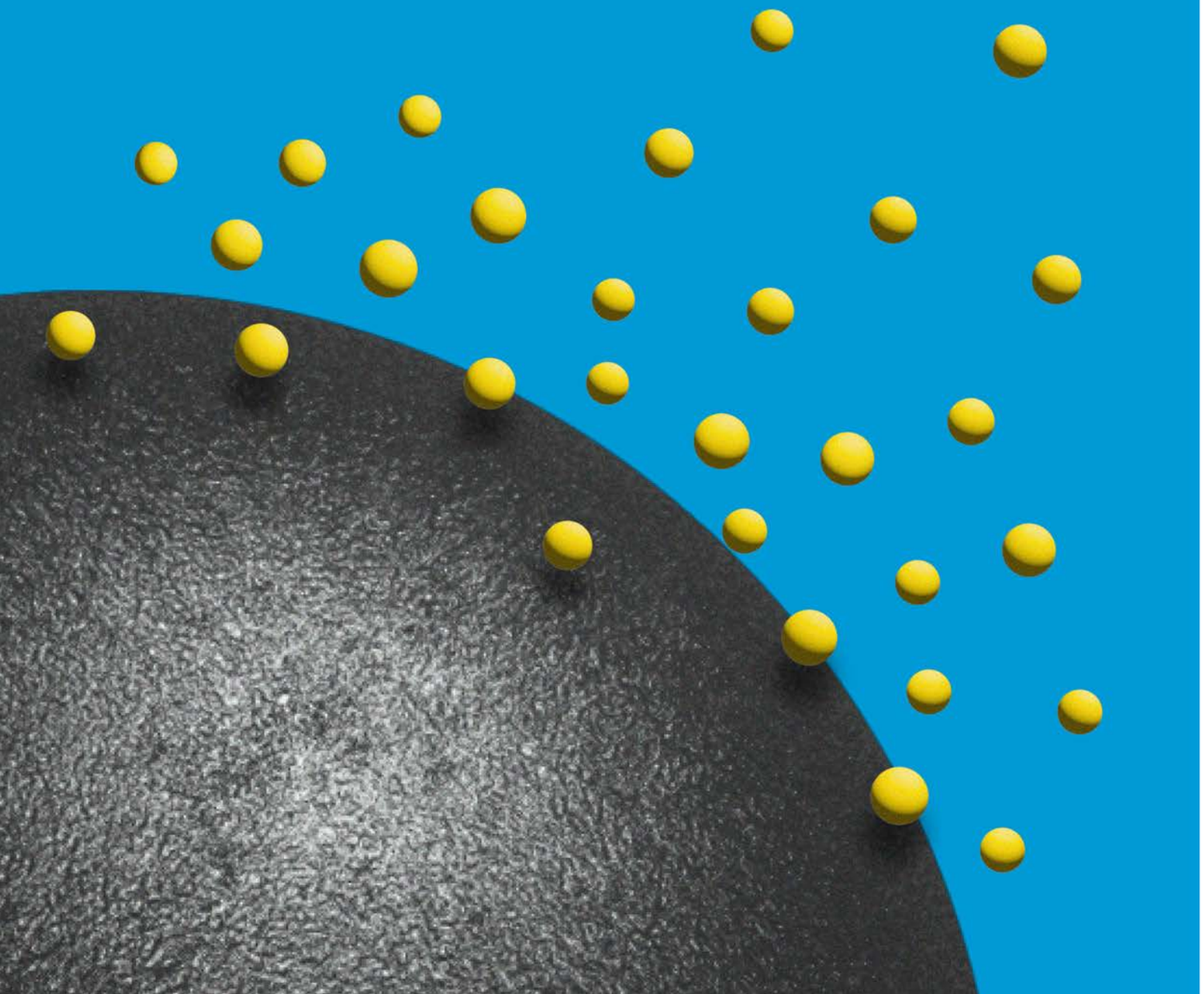
Activities this year:
18 Fellows
45 national leadership activities
58 international leadership activities
27 journal publications submitted
35 PhD students



The NNL Fellowship works across all aspects of the fuel cycle.

2 | Innovation

Driving towards **a sustainable future** through a novel approach to decontamination



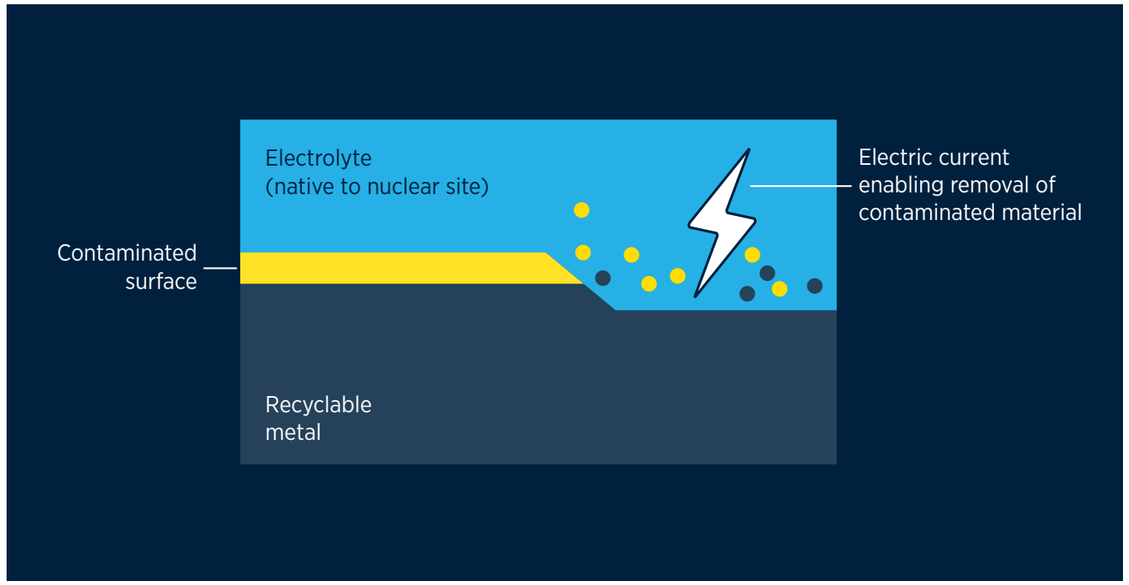
As our global industries move towards a future of zero waste, approaches to managing all materials as valuable assets are evolving. In the nuclear industry, removing contaminated portions of materials that have reached the end of their useful life will enable the uncontaminated portion to be reused.

High-quality metalwork is used extensively in the nuclear industry, as pipework, storage tanks and more. Over the long timeframes associated with nuclear operations, the surfaces of these metals can become embedded with radionuclides. If these radionuclides are not removed, large volumes of metallic waste must be handled, treated and stored.

Removing this contaminated surface layer can dramatically reduce the amount of waste and means that the vast majority of the metal can be returned into the supply chain for reuse.

As part of NNL's environmental restoration work, we research technologies that can tackle this challenge, and are developing Electrochemically Assisted Surface Decontamination (EASD) with our partners. EASD is an innovative technology that enables decontamination work to be carried out in situ, which enables decommissioning operations to be accelerated and supports sustainable nuclear operations.

Schematic representation of electrochemical surface decontamination.



Quality

Providing an effective solution to a key decommissioning challenge

Specialised metallic components are routinely used in industry as they are corrosion resistant and perform well in a variety of extreme environments. In some environments, such as inside nuclear reactors, corrosion resistance is essential. In steel, this can be achieved by adding chromium to the metal alloy. The chromium on the surface interacts with oxygen to create a corrosion-resistant surface. This surface successfully resists degradation and ensures that the steel is long-lasting.

The final stage in the life cycle of any industrial plant is decommissioning. The parts can be dismantled, useful components can be reused, and other materials disposed of. During the decommissioning of nuclear facilities, radioisotopes must be separated from non-radioactive materials so that the non-radioactive materials can be handled safely, giving them the potential to be reused. The robust nature of the surface of metals means that radionuclides embedded in the surface require special consideration.

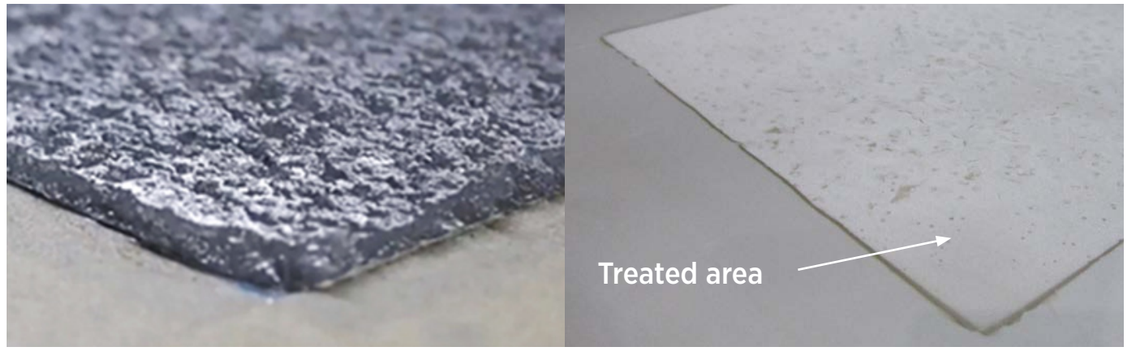
We have worked with C-Tech Innovation and Sellafield Limited to develop a novel, cost-effective solution to remove the corrosion-resistant surface layer, thereby separating the radionuclides from the non-radioactive metal and reducing waste volumes. The technology relies on a technique known as electrochemistry. Here, an electric current is passed through the metal surface, enabling the surface to rapidly dissolve into a liquid or gel that is applied at the same time. Both the liquid and gel used are compatible with existing on-site waste management practices, which ensures that new waste streams are not produced and that EASD can be deployed in a wide range of settings.

Prototype of the EASD jet system for cleaning vessel walls.

"The EASD technology has many benefits. The electric current can be passed through nitric acid, a reagent commonly used on the Sellafield site. This makes waste routing straightforward as a new chemical process does not have to be developed. With EASD the treatment is fast and decontamination is very thorough. The technique can be employed in different ways which means we can work on sections of our historic reprocessing plants that are hard to access. This helps speed up Sellafield's mission to clean out redundant facilities safely, securely, and at pace."

Sarah Bibby
Technical Manager for Sellafield Limited

EASD gel can remove localised spots of contamination. The gel turns dark during the treatment process. Once it's removed, you can clearly see the difference it makes to the surface of the metal.



Partnerships

Working locally and internationally to drive innovation

Our expertise in the management of materials and chemicals that are widely used in the nuclear industry has been combined with the expertise of C-Tech Innovation, a small–medium enterprise based in the North of England, to deploy electrochemical techniques. The success of this partnership has been assured by our collaborative approach in which our scientists have worked alongside C-Tech scientists and engineers to develop different deployment methods and demonstrate these within a nuclear setting.

Investment in EASD has led to numerous opportunities to deploy the technology, helping to drive value for the industry. We have worked with industry partners to develop the right solution for them and to train their technical experts to operate EASD prior to deployment. Different deployment techniques have been developed from the core technology. Where localised 'hot spots' of surface contamination are detected, a gel can be applied to mediate the electrochemical reaction. For larger areas of contamination, a jet of liquid can be used instead of the gel and a pipe-crawling robot has also been developed.

We have also fostered international collaborations to benchmark EASD against other decontamination technologies deployed in a range of nuclear operational scenarios. More widely, we have partnered on international research programmes such as the EU PREDIS (pre-disposal management of radioactive waste) programme and developed discussion of an alliance across other national laboratories.

"It was only by working in partnership with NNL that the development of the EASD technology (Electrochemically Assisted Surface Decontamination) was made possible. The combination of NNL's comprehensive understanding of the decommissioning requirements coupled with C-Tech Innovation's electrochemical expertise was the ideal platform on which to develop the technology. We now have a jointly owned patent portfolio that will support commercialisation in the UK and around the world."

Bob Crawford,
Technical Director for C-Tech Innovation

Talent

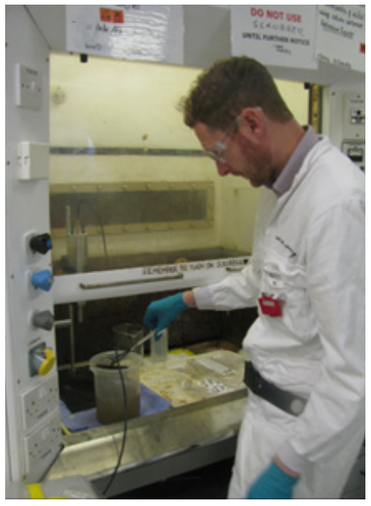
Providing opportunities for the next generation of experts to flourish

Collaboration with project partners has led to unique opportunities to develop our people. Working with Sellafield Limited to build on initial development work at C-Tech's facilities in addition to our Central and Preston Laboratories, we designed a project that saw a researcher augment the core electrochemical technology. The researcher deployed the technology, and proved its effectiveness, at our Workington Laboratory. Further work will see the technology deployed on the Sellafield and Dounreay sites. This project, funded by the Development of Alpha Resource and Technical Skills (DARTS) programme, enables the researcher to gain significant experience in deploying new technology, thereby helping to retain key skills in the nuclear workforce.

Deployment at our Workington facility also enabled technical experts who will use the EASD technology to be trained in an environment that comes close to actual conditions experienced on a nuclear licensed site, and further deployment at our Preston Laboratory proved the technology on contaminated materials gathered from decommissioning of nuclear facilities. Not only do these experiences build confidence in the technology, but they expand the skill sets of many key workers on nuclear sites.

> " I had the opportunity to learn about electrochemistry and how it can be beneficial for decontamination projects. I was also in the unique position to be the first to deploy the EASD technology on a nuclear licensed site so it was great to pioneer something new. I verified the technology on a real-life example of contaminated material and it was satisfying to see how effective the technology is. Separately, I demonstrated the technology to others which was a very rewarding experience. "

Peter Durham,
Senior Research Technologist,
NNL



Peter Durham testing the EASD technology at our Preston Laboratory on materials gathered from decommissioning of nuclear facilities.

Impact

Driving sustainability by fostering a circular economy

The 2022 UK Radioactive Waste inventory shows that approximately 26,000 cubic meters of material is contaminated metallic intermediate-level waste. These metallic items were developed to meet exacting standards for strength and durability. Decontamination means that they can retain classification as high-value items and be returned to the supply chain, rather than being disposed of as waste.

This avoids the high costs associated with building interim storage and reduces the size of the geological disposal facility (GDF). In the future, new-build reactor components could be made from recycled steel that previously operated in a nuclear setting for decades.

Recycling of used metals means that fewer natural resources need to be mined from the Earth. This means that the environmental impact of metal production can be reduced as land does not need to be disrupted for mining operations. Recycling also represents a significant cost saving if waste is diverted from long-term disposal facilities such as the GDF.

Specifically, this year the EASD project has achieved

progress towards active demonstration on the Sellafield site for waste treatment

practical evaluation alongside other commercially available decontamination approaches by a researcher under the Development of Alpha Resource and Technical Skills (DARTS) programme, providing the early career researcher with a unique development opportunity early in their career.

The science

Contamination of metals is usually limited to the top few micrometres near the surface.

Metallic vessels and pipework can be much thicker than this. Removing a very small fraction of the thickness can enable reuse of most of the material. The ratio of the original volume of material to final waste volume, known as the waste volume reduction factor, is high (approximately 1000:1).

Metals used in the industry have a protective layer on the surface which makes them corrosion resistant; conventional chemical treatment will not be effective in removing surface layers.

Applying an electrical current facilitates a chemical reaction that temporarily disrupts the protective layer and leads to rapid, controlled dissolution of the surface without the need for aggressive chemicals or the creation of challenging secondary waste.

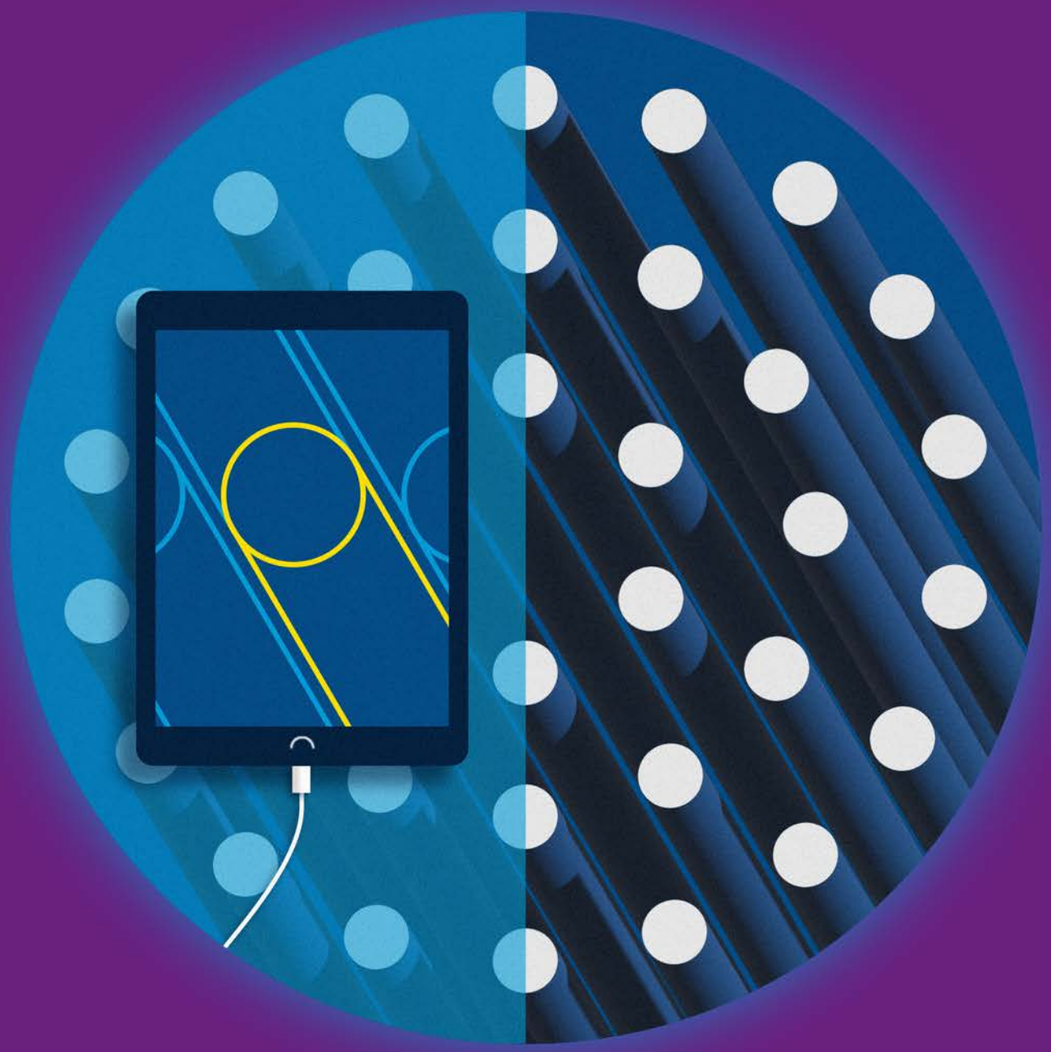
EASD technology enables the surface to be removed using non-contact electrochemical treatment; electrodes do not need to be in contact with the metal. Treatment can take between 5 and 30 minutes.

The technology is scalable and can be applied in a range of formats including

- *immersion baths for treatment of items that have been removed from the operating environment*
- *pipe crawlers that can treat the internal or external surface of pipework or ducts*
- *a 'jet' version that passes a current through pairs of hoses to treat surfaces at a distance without the need for immersion of the target areas*
- *gel application for treatment of hotspots in operational environments that do not permit the use of liquids.*

3 | Innovation

An **innovative new app** to support inspection of nuclear fuel



Decades of experience managing nuclear materials safely has equipped us with the knowledge and expertise to explore new techniques, such as our DEPEND mobile app, which enables safe inspection of used fuel.

Inspection of nuclear fuel stored underwater in engineered ponds is vital for ensuring safe operations on reactor sites.

The ponds keep the used fuel cool and provide radiation shielding. NNL's endoscopy team surveys in-pond fuel at all the UK's advanced gas-cooled reactor (AGR) power stations, operated by EDF. This involves using a video camera underwater to assess the integrity of the fuel and look for deposits that may have formed while the fuel was inside the reactor core. During the inspections, information is recorded by the pond-side endoscopy team, using pen and paper.

Keeping track of the paperwork, collating the information and consolidating it into a valuable report for the reactor operator is a significant and important part of the work. Making a move to using a mobile device that collates the same information pond-side will streamline data collection and ensure robust data management while also helping to retain expert knowledge from an incredibly experienced workforce.

As a result of this innovative work, the DEPEND (DEPosit recording from ENDoscopy surveys) app captures this expertise, thereby safeguarding this important aspect of nuclear safety and facilitating efficient delivery of work by the endoscopy team.

Quality

Upholding our strong track record in safety and security

Endoscopy is specialist work and is vital for operators to meet regulatory requirements, by ensuring safe storage of the fuel as it cools in-pond and enabling safe and efficient operation of the reactor. The DEPEND app was developed in partnership with experts in app development, tested during site surveys and modified based on feedback from our expert endoscopy team.

Inside the core of a nuclear reactor, coolant circulates to remove the useful heat generated. The chemistry of this coolant can be adjusted to minimise the formation of deposits on the surface of the fuel. These deposits can affect heat transfer from the fuel to the coolant which reduces the efficiency of the reactor. Understanding what these deposits look like, and how thick they are, helps reactor operators understand the conditions that lead to their formation.

"As the UK's AGR stations are nearing the end of their life, the endoscopy work is still providing high value information to support continued generation. The results have been used to help to substantiate relevant safety cases and give assurance to the Office for Nuclear Regulation {ONR} and Sellafield Limited on the condition of fuel which is important for both operations and future storage of fuel. The build-up of carbonaceous deposit on AGR fuel pins reduces heat transfer and affects the reactor efficiency, so the work of the endoscopy team to assess the deposit and understand the deposit properties supports safe continued operation of the reactors."

Laura Jenkins
AGR Fuel Post-Irradiation Examination Co-ordinator for EDF

Partnerships

Combining unique skill-sets to deliver a valuable solution

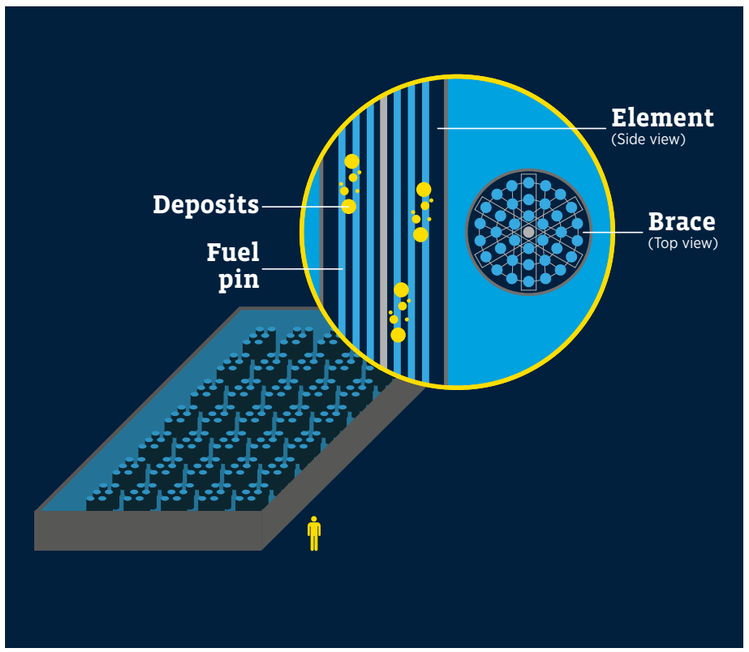
The DEPEND app was created in close collaboration with Cumbrian-based small-medium enterprise, Mobetrics, who are experts in delivering intuitive mobile solutions. The endoscopy team worked closely with Mobetrics at every step of the journey to design, build and test the app.

A member of the endoscopy team identified an opportunity to innovate and move to a digital solution for recording and processing inspection data. Through NNL's innovation programme, the concept was developed into a partnership opportunity. This innovation process has enabled our people to highlight a challenge and work with external experts to find a solution. In doing so, NNL has combined nuclear know-how and experience with Mobetrics' expertise in coding. The outcome is a fantastic solution that will deliver significant value for nuclear power plant operators.

This innovation project has led to the digitisation of a manual process and resulted in the development of an entirely new tool which will be ready for use in the near future. The endoscopy team used their vast experience and knowledge of the current method for recording endoscopy inspection data and, in partnership with Mobetrics, came up with a creative approach that is both quick to use and easy to learn.

"As mobile app developers, it is always exciting to be offered an opportunity to collaborate with a world-class specialist such as NNL and see software making a real difference in the workplace.
By working closely with their endoscopy team we were able to establish what features would make the greatest improvements to their existing workflow and develop an app that was easy to use in a challenging environment.
The NNL team were always looking to take advantage of the possibilities that a mobile digital platform would offer them and develop a template that could be reused for future projects within the business.
It was particularly great to see that NNL were keen to work in a flexible, agile manner that delivered the best possible product."

Marc Morrison
Co-founder of Mobetrics



Fuel pins stored underwater are inspected for deposits and wear on the brace which holds them in the fuel assembly used in the reactor core.

Talent

Sustaining vital expertise to assure reactor performance

The expertise of our endoscopy team had been gained over decades. There is a need to train new experts to continue to uphold the high standards that the industry sets itself. The DEPEND app can assist in skills and knowledge retention.

The traditional method of managing and collating the inspection data that the team currently uses is labour-intensive, requiring expert knowledge of the data and the reporting process to manage the workload effectively. This expertise has been incorporated into the app, to free up time so the team can focus on other vital aspects of work in the future.

Analysing the deposits during an endoscopy inspection requires familiarity with the fuel elements. Images from the camera are displayed on a screen and the team must use their expert judgement to decide on the texture, coverage and thickness of the deposit.

Their findings are recorded in the DEPEND app, along with images of the deposits.

"The DEPEND app can make a huge difference to the team. Right now, transcribing the information from inspection sheets to reports is a lengthy process that requires verification. Having an app to do this not only saves a substantial amount of time, but it also removes the risk for transcription errors that arise from transcribing large amounts of data."

Dave Wilkinson,
Endoscope Survey Team Leader for NNL

Dave Wilkinson carrying out an inspection pond-side

Impact

Innovation makes excellent use of resources

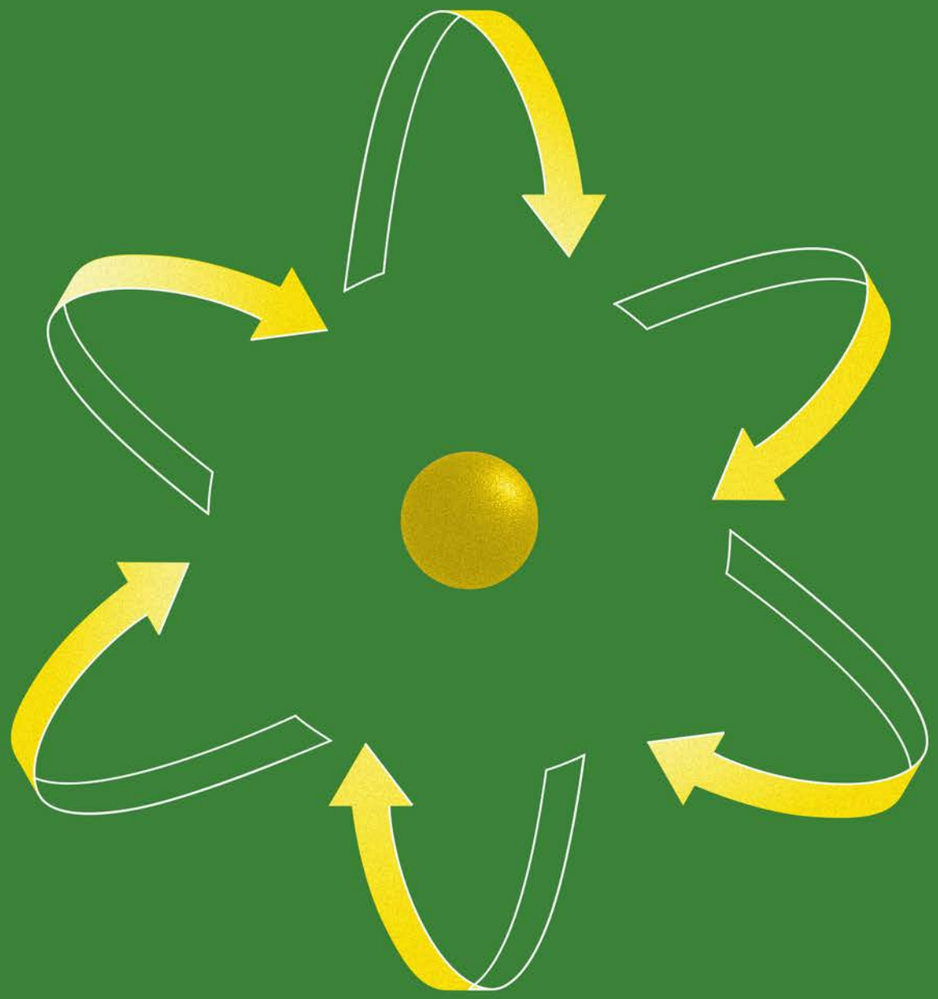
The inspections carried out by the endoscopy team have enabled the UK's fleet of currently operating AGRs to safely extend their operations. This directly leads to a saving in greenhouse gas emissions compared with using fossil-fuel-based forms of energy. Keeping reactors operating also safeguards jobs.

Additionally, the inspections generate vast amounts of paperwork. Stretching back decades, this paperwork is currently archived by NNL. Moving to a fully digital method of handling information will not only provide our experts with more time, but it will also deliver results to plant operators quickly and efficiently while reducing the environmental impact.

Integration with reporting systems is now being finalised, ready for full deployment of the DEPEND app. The endoscopy team is also considering additional features to be developed in the future.

4 | Collaboration and strategic research

Contributing **world-leading research** to benefit global challenges



NNL is home to some of the world's experts on the nuclear fuel cycle. As part of our ongoing commitment to share our science, our research regularly features in journal publications which are recognised by the international scientific community.

Our experts have unique insight, garnered over decades spent researching solutions to engineering challenges. At the heart of this is a thirst for knowledge that can benefit society. We recognise that this ambition cannot be achieved by us alone; science moves forward rapidly when we work together and share what we discover.

Journal publications are a time-honoured way of sharing discoveries between scientists, pushing the boundaries of understanding in physics, chemistry and more. At NNL, our world-leading scientists regularly contribute to the wider research community by publishing their work. Significantly, in 2023, our researchers saw their work captured in a special edition of Progress in Nuclear Energy.

An invitation to lead on a special edition of a scientific journal is a rare privilege only extended to experts at the pinnacle of their field. This forum has established strong foundations from which to deliver future impact.

Quality

Raising Raising the profile of our work on the global stage

At NNL, we deliver world-leading nuclear science and technology aligned to the needs of the UK. The Advanced Fuel Cycle Programme (AFCP) was the UK Government's leading research programme for developing the nuclear fuel cycles of the future, part of a £505m Energy Innovation Programme designed to help expand the potential of clean energy technologies in the UK. The Recycle theme under this programme delivered a substantial body of work which was captured in a special edition of the Progress in Nuclear Energy journal, ensuring high impact among the relevant scientific community.

Special issues of scientific journals often involve invited guest editors, recognised as experts in their field.

NNL researchers led on four of the articles in the special edition of the journal, covering future options for recycling of nuclear fuel, delving deep into the chemistry of environmentally friendly techniques to extract multiple useful components of used fuel, providing expert review of how these extracted products could be further modified, and focusing on capturing trace materials from waste streams.

The special edition of Progress in Nuclear Energy – "Development of Advanced Nuclear Fuel Recycling Options" is available on **Science Direct.**

"Anthony Banford, NNL's Waste Management and Decommissioning Chief Technologist, was an instrumental member of the guest editorial team. Along with Professor Colin Boxhall from Lancaster University and Professor Bruce Hanson from the University of Leeds, Professor Banford's significant expertise and unique industrial perspective was immensely helpful in shaping the scope of the special issue and really elevated the quality of articles that appear in the special edition. Special issues in **Progress in Nuclear Energy** have higher impact than ordinary articles and this particular issue spotlights the excellence in the UK research community, focused on next generation development for our nuclear industry."

Professor Simon Middleburgh, Bangor University and Editor of Progress in Nuclear Energy.

Partnerships

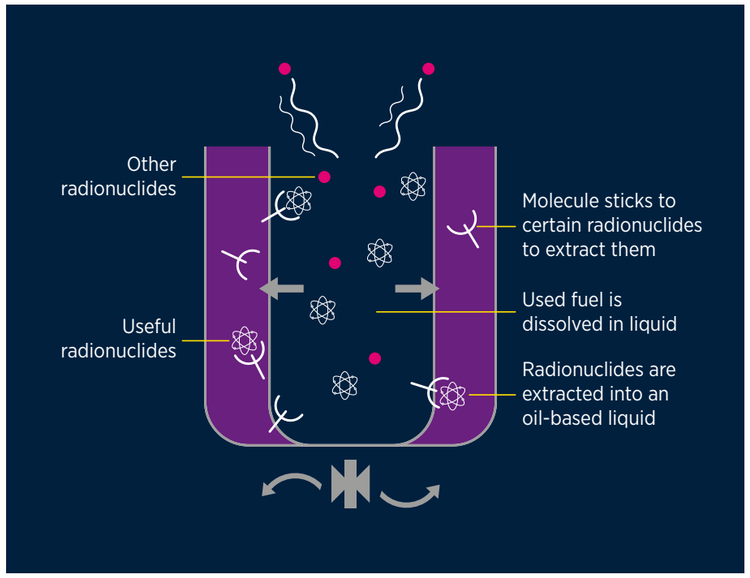
Science leaps forward when collaborations form

The special issue brings together insights into many key areas vital for long-term, sustainable recycling of nuclear fuel. These insights are only possible when researchers with diverse backgrounds come together. Some of the key research collaboration features in the special issue are with universities located throughout the UK.

Alongside The University of Manchester, we have developed a robust model of a key aspect of the fuel recycling process. The model accurately predicts how certain radionuclides can be retained in the liquid, thereby preventing them from being extracted along with the uranium. The outputs of the model can be used to produce high-quality uranium to produce new nuclear fuel.

In collaboration with Lancaster University, we have looked at a novel method to convert uranium into a form suitable for manufacturing. This novel method uses light to convert the uranium and is rapid, taking less than two minutes to convert 98% of the uranium. Not only is this method quick, but it is clean as it doesn't generate additional waste, safe to use and cost-effective to implement.

We have also looked at the sustainability of recycling used nuclear materials. In partnership with University College London, we have assessed the lifecycle of two materials and found that not only does recycling or reusing them significantly reduce the depletion of natural resources, but there are also other environmental benefits such as avoiding greenhouse gas emissions.



Schematic representation of key processes in used fuel recycling.

Talent

Training the next generation of experts

Our experts are in a unique position to bridge the gap between an industry that values practical solutions to existing challenges, and academics who focus on fundamental science and discovery. The expertise and insight gained by our experts can be passed on to researchers early in their career, helping shape future research that can have immediate impact.

Together with our university partners, we have, therefore, helped to train several PhD and post-doctoral researchers over the year, giving them unique insight into the nuclear industry. A significant number of PhD and post-doctoral researchers have, likewise, been involved in writing the articles that formed the special edition with NNL experts as co-authors.

"As part of the Advanced Fuel Cycle Programme, I completed a literature study on alternative finishing processes for uranium/plutonium and minor actinide nitrate products from thermal and fast reactor fuels reprocessing. I was then offered the opportunity to publish this research in the special edition of **Progress in Nuclear Energy**. Being the lead author gave me an insight into the journal publication process for the first time and the opportunity to work with industry experts not only within NNL but also in academia."

Hannah College
Senior Research Technologist at NNL

Impact

Ensuring a sustainable fuel cycle for the future

The work published in the special edition delves into the nuances of myriad chemical interactions, engineering plant process conditions and technologies that can focus on individual chemical bonds. Such a detailed, careful approach is exactly what is needed to build robust, sustainable industrial processes.

The nuclear industry has a history of recycling fuel which stretches over decades. Building on this history, modern techniques applied by experts can help us understand whether something is truly sustainable.

Following a process all the way from start to finish – a technique known as lifecycle analysis – aids this understanding. The special edition has shown that proposed approaches to recycling nuclear materials have a lower environmental impact compared with current approaches. Lifecycle analysis enables aspects of fuel cycle strategies to be compared objectively, thereby aiding future decision-making. Analysis conducted so far is beginning to show that recycling used fuel contributes to a circular economy which will positively contribute to a sustainable future.

Mixed oxide fuel dissolution taking place in a glovebox. Taken from: R Taylor, G Mathers, A Banford, **Progress in Nuclear Energy** (2023) 164, 104837

"The research presented in this special issue is vital for the industry and can help inform future UK policy on options for future sustainable nuclear energy systems.

Each study contributes to our understanding of what innovative nuclear fuel cycles could look like, where we can extract all the useful actinides and fission products from used nuclear fuel while safely locking away a much smaller volume of wastes.

In doing so, we can contribute to a sustainable circular economy that benefits future generations."

Dr Robin Taylor
Principal Radiochemist at NNL

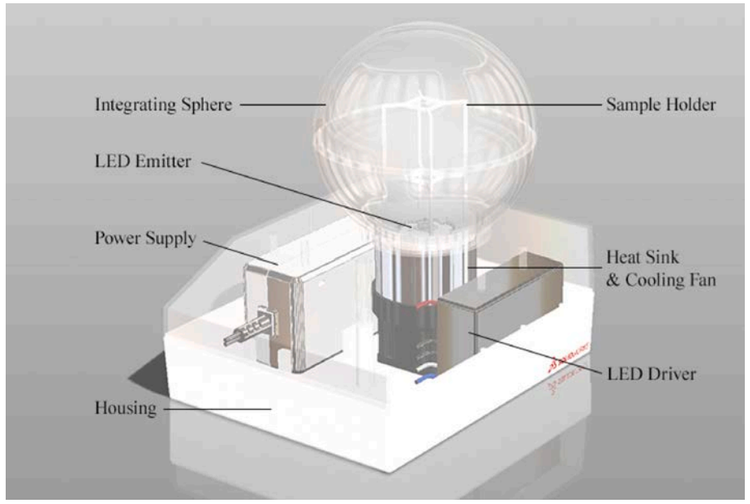
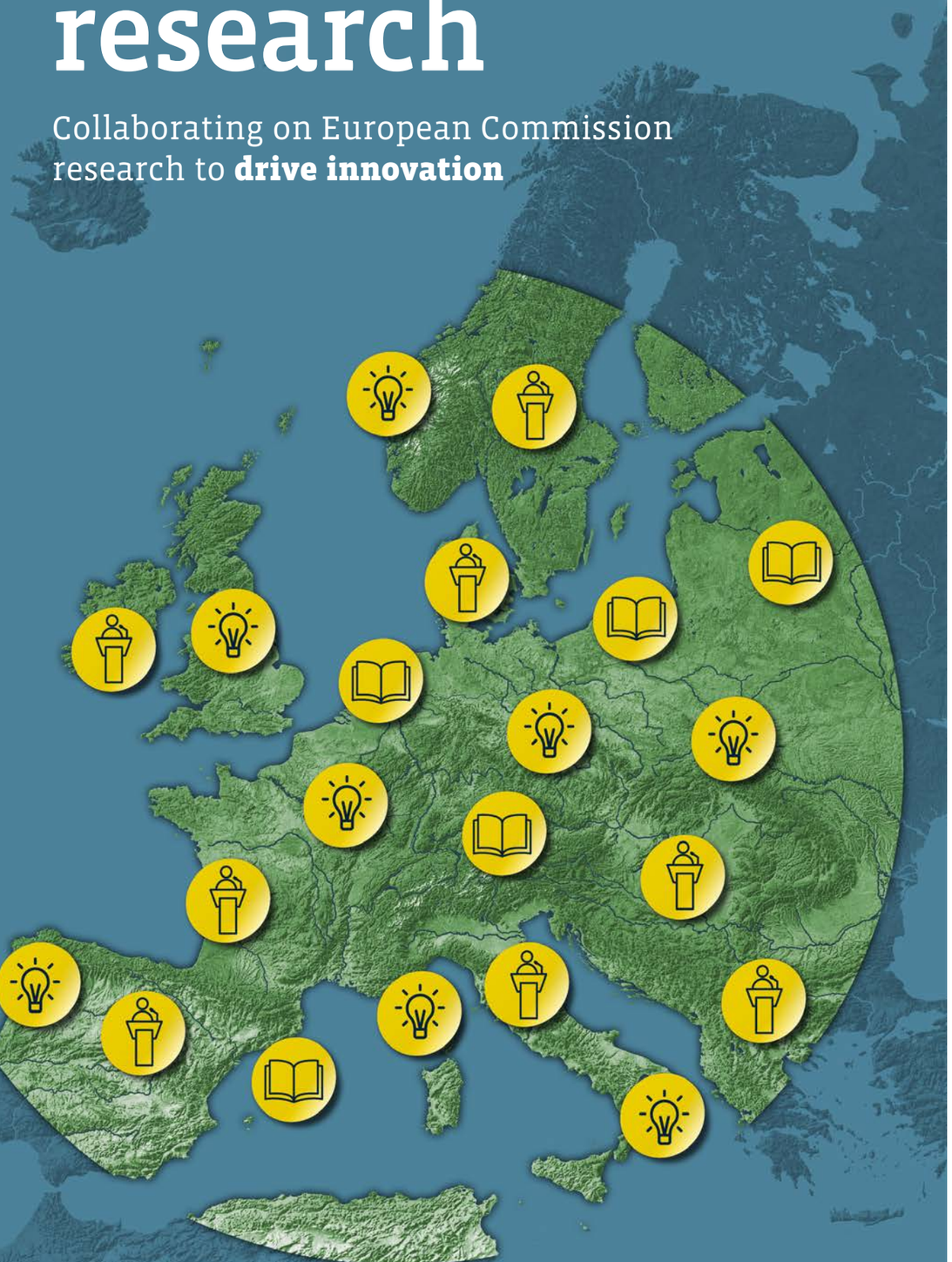


Illustration of the equipment used to convert uranium using light. Taken from: MA Bromley, C Boxall, R Taylor, M Sarsfield, **Progress in Nuclear Energy** (2023) 164, 104853

5 | Strategic research

Collaborating on European Commission research to **drive innovation**



Research programmes initiated by the European Commission enable collaborative work that has significant impact internationally. NNL's involvement in multiple projects demonstrates the value NNL scientists add to these collaborative programmes. To accelerate nuclear research and innovation, the Euratom Research and Training Programme complements projects funded by Horizon Europe.

NNL has a long-standing history of collaborating with European colleagues. European research programmes enable this collaboration, strengthening the impact of research.

They also enable effective dissemination of expert knowledge and vital technologies. Continued engagement in these programmes recognises the value of collaboration in advancing nuclear science and technology.

NNL's involvement in multiple projects, spanning the breadth of the nuclear fuel cycle, demonstrates the value NNL puts on these programmes and the value NNL scientists add to these collaborations. One of the most significant projects for NNL this year is PREDIS, which focuses on the pre-disposal management of radioactive waste.

Quality

World-leading science driven by the greatest minds

NNL has participated in over one hundred European Commission-funded programmes spanning all aspects of the nuclear fuel cycle, from fuel manufacture to reactor operation and design, recycling and disposal of used materials. The PREDIS programme – funded by Euratom – is one of the largest, involving 47 partners across 18 nations. As the programme, initiated in 2020, draws to a close, much has been learned that can support management practices for radioactive waste.

Many types of used nuclear material are well understood and have well-defined management solutions. The PREDIS programme focuses on those that require additional research so that they can be conditioned into a form suitable for disposal. NNL has led on a key milestone to define the future Strategic Research Agenda for essential waste management research and development activities across Europe. This will inform future European collaboration opportunities.

Working in partnership with The University of Manchester, we have applied life cycle assessment (LCA) and life cycle costing (LCC) approaches to evaluate the sustainability of waste management technology options. The tools produced by the project will guide future decision-making and the detailed assessment will soon be published as a series in scientific journals.

Other key outcomes are

development and implementation of holistic lifecycle assessment approaches to evaluate the environmental benefits of different technologies

advances in technologies for treatment and immobilisation of certain types of waste, including solid and liquid organic wastes

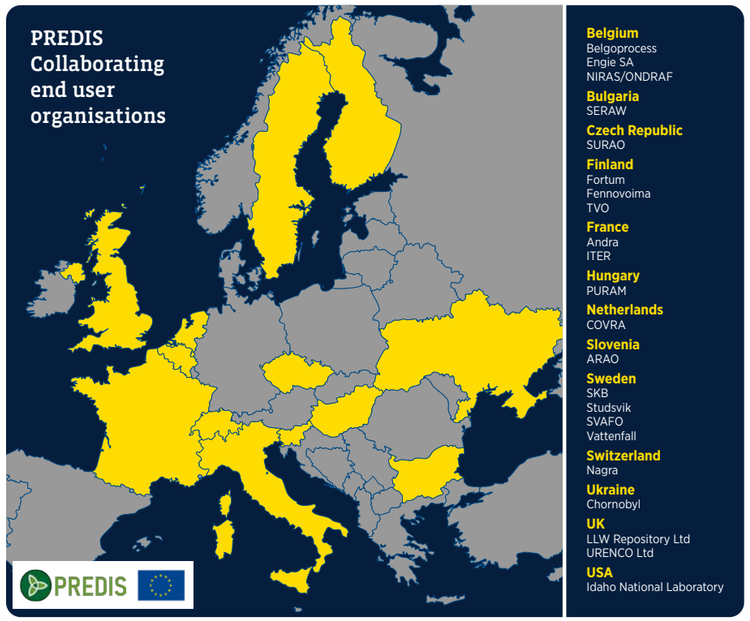
innovation and optimisation of novel decontamination technologies to reduce the volumes of radioactive waste from decommissioning

digitalisation solutions for improved performance and efficiency in handling and assessing cemented waste packages.

> “ International collaboration is critical to deliver solutions to sector-wide challenges, helping NNL to deliver to UK national needs but also contribute to solutions to global challenges.”

Anthony Banford
Chief Technologist for NNL

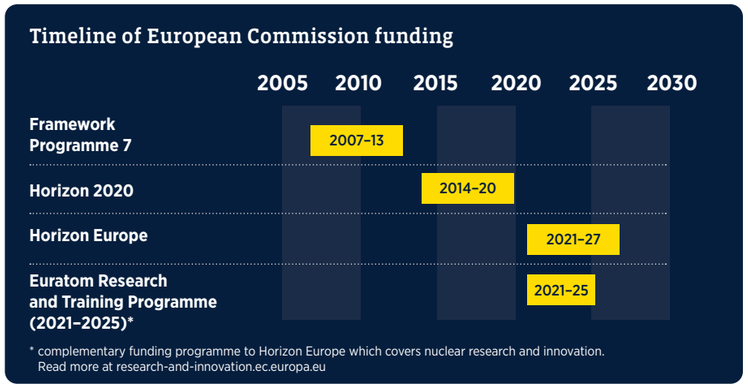
Collaborating end user organisations in the PREDIS programme. This project has received funding from the Euratom research and training programme 2019–2020 under grant agreement No. 945098.



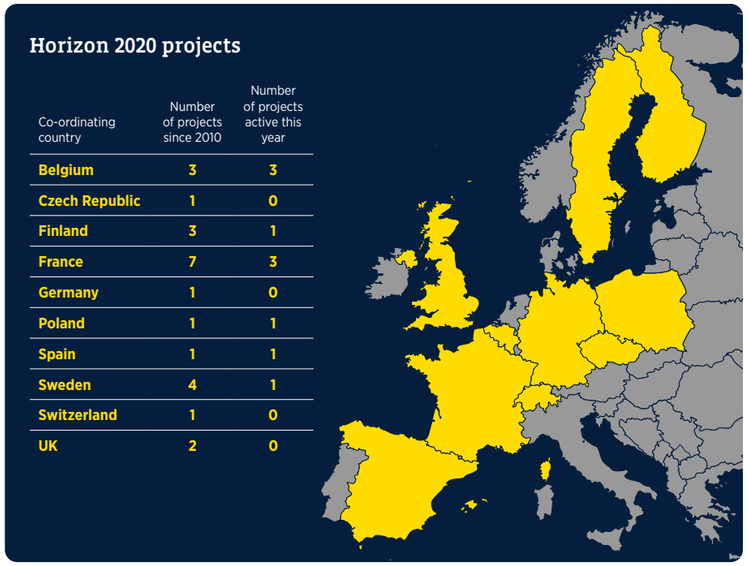
> “ NNL’s deep involvement in PREDIS, including the leadership on the Strategic Work Package and expert contributions to the Technical Work Packages, has been pivotal to ensure the success of the project.”

Maria Oksa
Co-ordinator of the PREDIS project and Research Team Leader at VTT, Finland

Timeline of European Commission funding between 2005 and 2030.



Location of lead organisation of Horizon 2020 projects that NNL has been involved in over the last ten years.



Co-ordinating country	Number of projects since 2010	Number of projects active this year
Belgium	3	3
Czech Republic	1	0
Finland	3	1
France	7	3
Germany	1	0
Poland	1	1
Spain	1	1
Sweden	4	1
Switzerland	1	0
UK	2	0

Partnerships

Collaboration leads to greater insight

Working with other experts from around the world leads to a mutual understanding. Expertise can be rapidly shared and results quickly disseminated, to drive research programmes forward at a faster rate. It also leads to access to a much wider range of resources. A prime example of this in the PREDIS project has been the close co-operation between multiple international research laboratories in the development of novel formulations for the encapsulation of certain types of wastes.

Encapsulation is the method used to immobilise legacy wastes which are derived from historic operations, thereby enabling them to be stored. Currently, a specifically formulated cement is used but some types of waste are not chemically compatible with the cement. A new type of encapsulant known as a geopolymer is being developed to improve chemical compatibility with these types of waste. Advances were rapidly made because of the combined experience and knowledge of multiple organisations and an international team of leading scientists. These advances in geopolymer technology directly feed into our UK programmes for Sellafield and the Nuclear Decommissioning Authority (NDA) estate.

More widely, since our initial involvement in European Commission-funded research almost 20 years ago, beginning with Framework Programme 7, we have built over 200 collaborations with dozens of partners to leverage significant research investment. Within the Horizon 2020 and Horizon Europe frameworks alone, we have been involved in 24 projects led by organisations in ten different nations, which have leveraged €128 million. This year, including the PREDIS project, we are involved in ten Horizon 2020 projects totalling €65.4 million.

Talent

Expanding the horizons for research

Working with leading organisations across Europe broadens the horizons of NNL researchers. The Euratom Research and Training Programme draws on cutting-edge, international research collaborations to attract and retain talent in the nuclear industry and enables cross-fertilisation of ideas and knowledge from world experts. This ethos is reflected in all our European research projects.

The PREDIS programme has given researchers the opportunity to travel to partner locations and work alongside their experts, to gain first-hand expertise relating to the latest advanced techniques. Drawing on the experience of almost 100 scientists, engineers and technicians from NNL, approximately half of this technical work has been delivered by researchers who are in the early stages of their career, providing them with opportunities to expand their skill set. In addition, five PhD students across British universities, co-supervised by NNL's experts, have been trained. These experiences have given these researchers unique insight into international collaboration.

NNL scientists and engineers have benefitted from collaborating with organisations from the European Union and bringing specialists skills and knowledge to the UK. Several specialists from NNL have travelled to collaborators, including Subatech and La Hague in France, to learn the latest techniques in sample preparation and analysis. These activities have led to presentations at conferences such as the International Conference on Environmental Remediation and Radioactive Waste Management (ICEM) along with several publications in scientific journals. Not only do these experiences help safeguard the skills of a British workforce, but they also position our researchers as subject matter experts.

> "I came into NNL's Decontamination team 3.5 years ago, relatively new to the technical field. Being part of the PREDIS project has allowed me to adapt my knowledge and skill set from nuclear materials to tackle challenges in decontamination – which has resulted in new science."

Anne Callow
Research Technologist for NNL

Impact

Science drives sustainable development forward

The United Nations' Sustainable Development Goals focus on global peace and prosperity, encompassing social value and environmental improvement. The European programmes demonstrate how nuclear technology can play a significant role in meeting these goals.

In the PREDIS programme, our research directly aligns with our partnerships with Sellafield Limited and the NDA to work towards their goals for environmental restoration. Collaborative work around the development of novel methods for the immobilisation of challenging waste types supports long-running work with Sellafield Limited. Meanwhile, work on robotics supports Sellafield Limited to progress plans for the automation of stores, enhancing safety and increasing efficiency.

Overall, the European research programmes bring together the best scientists, engineers and facilities across geographical Europe to accelerate research and development and reduce costs, as we pursue our sustainable development goals. For PREDIS, this has focused on the development of more sustainable solutions to some of the most challenging radioactive waste management issues, while striving to reduce waste and enable a circular economy.

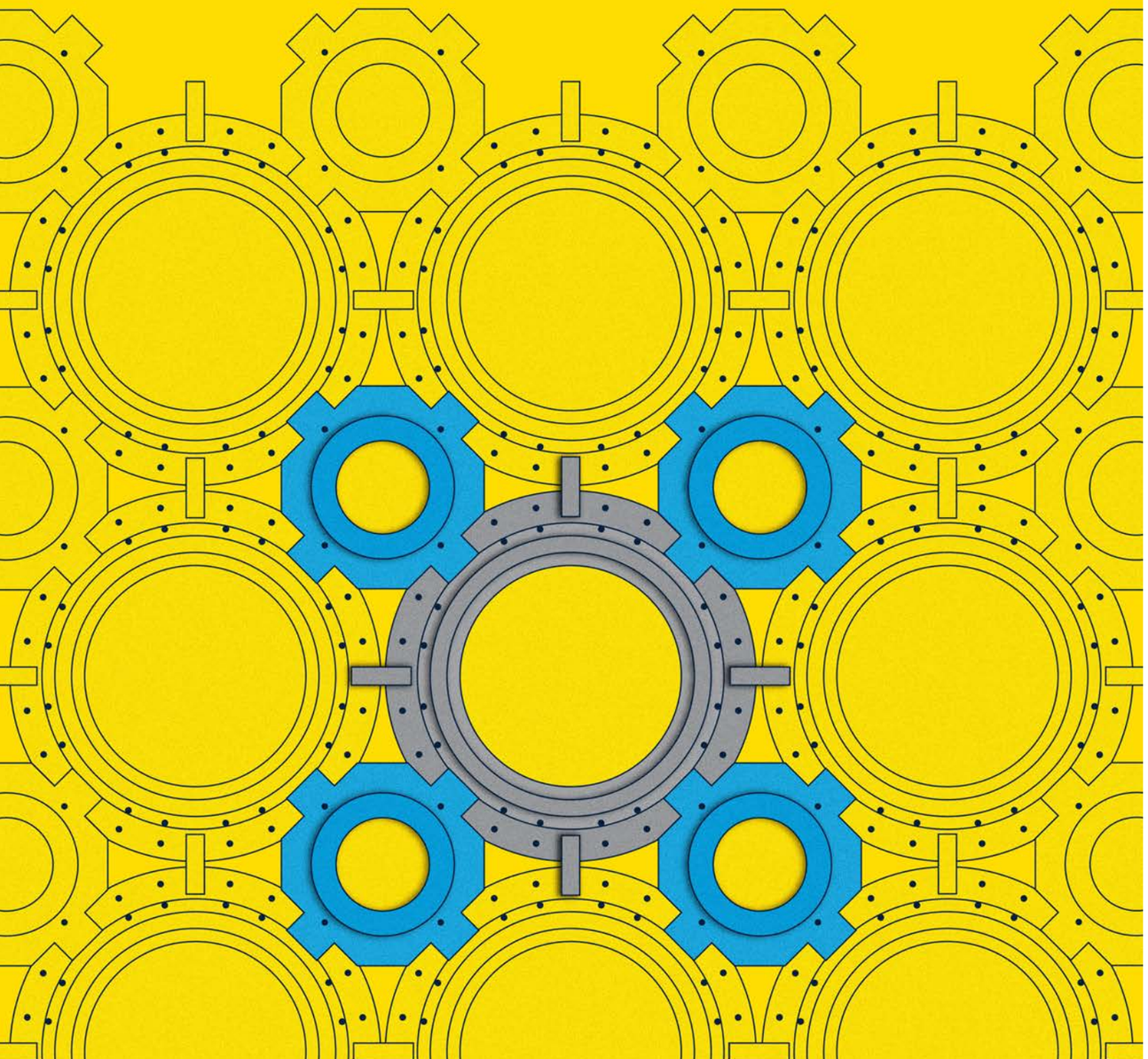
Funding provided by UK government ensures that we will continue to participate in these vital programmes so that we can maintain our ongoing commitment to contributing to international research, growing the skills and expertise of our scientists and making scientific discoveries to benefit society.

Anthony Banford and PREDIS project co-ordinator and Principal Research Scientist at VTT, Finland, Erika Holt, presenting at the International Atomic Energy Agency.

Members of PREDIS taking part in an international conference panel session.

6 | Core science

Materials science enabling a **low-carbon future**



Materials science is integral to modern life and draws on a fundamental understanding of matter to develop advanced materials.

Many of the reactors that contribute to the UK's current low-carbon energy mix are safely operating well beyond their original design lifetimes because of improvements in our understanding of how materials change during service.

Based on this understanding, new reactors are currently being designed to operate for longer.

These new designs mean that components could need to withstand higher temperatures, pressures and radiation fields. A longer reactor operating lifetime is underpinned by robust standards which are maintained by highly regarded international bodies. The standards are developed by panels of experts, including our experts at NNL.

These standards, which support international regulations, are regularly reviewed and updated to reflect new understanding as well as new developments in methods to assess material properties. These developments are a result of high-quality research. At NNL, we have a long history of developing this knowledge.

Post-irradiation examination takes place at our Windscale Laboratory.

Quality

In-depth understanding of materials performance sets the highest standards and assures performance

Graphite is a key component of the designs of existing and some future reactors. This material acts as a moderator, helping to control the nuclear fission reactions, and is the main structural component of the reactor core. For this reason, before they are placed in the reactor, graphite components undergo extensive qualification using materials specifications, test methods and practices maintained by American Society for Testing and Materials (ASTM) International via a committee of world experts.

At NNL, we have pioneered new testing methods which can produce a wealth of detailed information relevant to reactor operations. Carried out at our Windscale Laboratory, the tests analyse the fracture properties of the graphite as well as changes in density and porosity. The results are compared with model predictions and confirm that any changes in the graphite do not affect the performance of the reactor. It is, therefore, very important that the data from these small samples are accurate and representative of the large graphite components in the reactors. Based on our 50 years of experience, we have developed an ASTM guide to support other laboratories in ensuring that data from small graphite samples, taken from the reactor or from separate irradiation experiments, can meet these criteria.

Future reactor technology, such as the high-temperature gas-cooled reactor (HTGR), will require new materials that can perform well in the high temperatures and radiation fields found in the reactor core. New graphite grades and metallic structural materials are being developed, which must be proven to meet these high standards. This year we published our research into new grades of graphite using a novel method that can determine the porosity of the material. With unparalleled experience in this area for the UK, we are also supporting The American Society of Mechanical Engineers (ASME) to develop the design code for HTGR graphite components.

The standards and journal publications include:

- ***Behavior and Use of Nuclear Structural Materials***
  The American Standards and Testing (ASTM) International.
- ***Graphite Testing for Nuclear Applications: The Validity and Extension of Test Methods for Material Exposed to Operating Reactor Environments***
  Editor(s): Athanasia Tzelepi, Martin Metcalfe, DOI: 10.1520/STP1639-EB
- ***Graphite Testing for Nuclear Applications: The Significance of Test Specimen Volume and Geometry and the Statistical Significance of Test Specimen Population***
  DOI: 10.1520/STP1578-EB. ISBN-EB: 978-0-8031-7602-7. ISBN-13: 978-0-8031-7601-0 STP1639-EB
- ***Boiler and Pressure Vessel Code (BPVC)***
  The American Society of Mechanical Engineers (ASME).
- ***Research on new grades of graphite is reported in***
  A. Tzelepi, J. McGladdery, I-H. Lo and G. Copeland, Nuclear Engineering and Design, (2023) 411 , 112421

View the research article on the Nuclear Engineering and Design journal's website.

Talent

Upskilling our researchers to develop advanced nuclear materials

Analysis and understanding of the behaviour of irradiated material is vital for the nuclear industry and will help develop the next generation of nuclear technologies. This is made possible when highly skilled researchers perform the analysis and interpret the results.

Working across our wider materials science portfolio are more than 30 scientists and technicians. Many elements of the work are led by early or mid-career scientists to support their growth as technical leaders. We also support 14 PhD students across 8 universities to develop vital skills and expertise in materials science. Many of these students have accessed our facilities at our Central and Windscale Laboratories, which has afforded them unique opportunities to work with material in actual nuclear settings. These experts of the future will continue to make new discoveries of materials that can last for longer, widening the possibilities for nuclear technology.

NNL's Core Science Themes, such as materials performance, led by Dr Paul Styman, push the boundaries of many aspects of nuclear science. Dr Styman originally worked on a PhD project supervised by NNL and joining NNL enabled him to continue working with internationally recognised experts in the field of nuclear materials and further develop his skills. He is now a recognised expert in his own right, holding a visiting position at the University of Oxford and participating in the OECD-NEA Expert Group on Structural Materials. Within this group, he leads the development of best practices for an advanced analytical technique, atom probe tomography, that can explore materials at the atomic scale. This type of analysis enables the effect of minute changes in composition to be determined, thereby helping to inform the manufacture of future materials for nuclear applications.

To further build future capability, this year we are actively participating in an exciting UK/US programme: the Neutron Irradiation as a Function of Temperature (NiFTE) irradiation campaign. This campaign, between the UK's National Nuclear User Facility (NNUF) and the US Nuclear Science User Facilities (NSUF), brings together experienced and early career scientists from NNL, The University of Manchester, UK Atomic Energy Authority and Idaho National Laboratory, to look at a wide variety of materials including stainless steels, nuclear graphite and novel materials.

For the first time in the UK, we have characterised the pyrocarbon layer of advanced fuel particles, which will have a significant impact on refining the fuel's performance. Continued research into the effects of radiation on materials is essential for developing and licensing nuclear technology and will help build skills.

"The NSUF/NNUF NiFTE irradiation campaign planned to start in 2025 is the first major US/UK materials damage study in many years and involves a carefully planned campaign with partners from several national laboratories and universities on both sides. We have been very pleased to include NNL staff both in the management of the project and in the selection and provision of some of the sample sets for this ambitious programme of work."

Dr Brenden Heidrich
Director, Nuclear Science User Facilities, Idaho National Laboratory

Prof. Chris Grovenor
Oxford University

"During my PhD at University of Liverpool, I was very fortunate to be supervised by some of the world experts that work for NNL. The opportunity to work on graphite post-irradiation examination (PIE) analysis at Central Laboratory was crucial to develop my skills. I feel that my work is really making a difference to the industry and I'm excited to keep challenging myself and maybe be recognised as a world expert myself one day."

Dr Chloe McElvaney
Graphite Scientist for NNL

Partnerships

Far-reaching research delivers vital insights

Science moves forwards rapidly when researchers come together to work on common interests. Our materials scientists are involved in numerous collaborations with universities and other national laboratories around the globe. This in-depth research improves our understanding of materials behaviour, which in turn leads to advancements in the standards that support high-quality materials and testing methods. Some of the international collaborative projects our researchers are working on are detailed below.

The Horizon 2020 project II Trovatore will develop innovative cladding materials for advanced reactors. These materials will be more robust and so able to withstand a wider variety of conditions compared with previous materials. Many candidate materials are tested in the Belgian research reactor, BR2, and we are leading on the post-irradiation examination to understand their stability under irradiation. To date, we have characterised materials using state-of-the-art techniques which will serve as a benchmark for the irradiated materials.

The collaborative EU Horizon Europe project, FRACTESUS, takes a detailed look at the steel used in reactor pressure vessels using small-scale samples. This vital component of a reactor can measure several metres across and is 10–20 cm thick. The pressure vessel contains the fuel and the coolant which is under high pressure. It is designed to last for the entire life of the reactor and so must meet incredibly high standards to ensure continued safe operation over its lifetime. Our collaborative work has helped develop new techniques to test small specimens, thereby optimising the use of resources while maintaining scientific accuracy.

Small samples, which replicate the materials used to make the entire pressure vessel, are put inside the reactor. The results of tests to understand strength and fracture toughness are fed into increasingly advanced computer models to predict the performance of the pressure vessel as accurately as possible. Small-scale samples provide a wealth of high-quality data to ensure this impressive level of accuracy. These models are used to validate the operational lifetime of current reactors and will help predict the lifetime of future planned reactors.

We are involved in a European collaboration to create a database which collates data obtained from multiple projects where the effects of radiation on reactor pressure vessels was researched. This project, called ENTENTE, is significant as it draws together data collected by diverse, specialist characterisation techniques, which require careful consideration by experts. In this collaboration, NNL leads on the specialist atom probe tomography technique.

In another European collaboration, JHOP, we are contributing to the Jules Horowitz Materials Test Reactor which will be built in France and will allow UK-based materials researchers access to this ultramodern facility. During the current development phase, we are influencing roadmaps for essential materials and nuclear fuel research.

Read more about FRACTESUS at www.fractesus-h2020.eu

and II Trovatore at www.iltrovatore-h2020.eu

Read about ENTENTE and JHOP at the EU research and development information website: cordis.europa.eu

Impact

Developing high-quality materials for a sustainable future

The UK's gas-cooled and pressurised water reactors have supplied clean, safe power to the national grid for decades. New, advanced reactors will supply the UK with clean, safe power for generations to come, thereby contributing to a net-zero energy economy that minimises resource use while providing job security for a highly skilled workforce. These advances are supported by in-depth materials research.

NNL's materials performance Core Science Theme has been reviewed as being world-leading by a panel of international experts. In addition to publishing over 100 articles in scientific journals, our experts are involved in international steering groups and committees which place them at the heart of international programmes pushing the boundaries of materials science.

We have pioneered methods to analyse the microstructure of materials that have become the de facto standards worldwide to investigate irradiation-induced nanometre-scale clusters of atoms in steels and relate these to changes in the properties of the material. The resulting mechanistic understanding has influenced regulators and materials standards in the UK and internationally

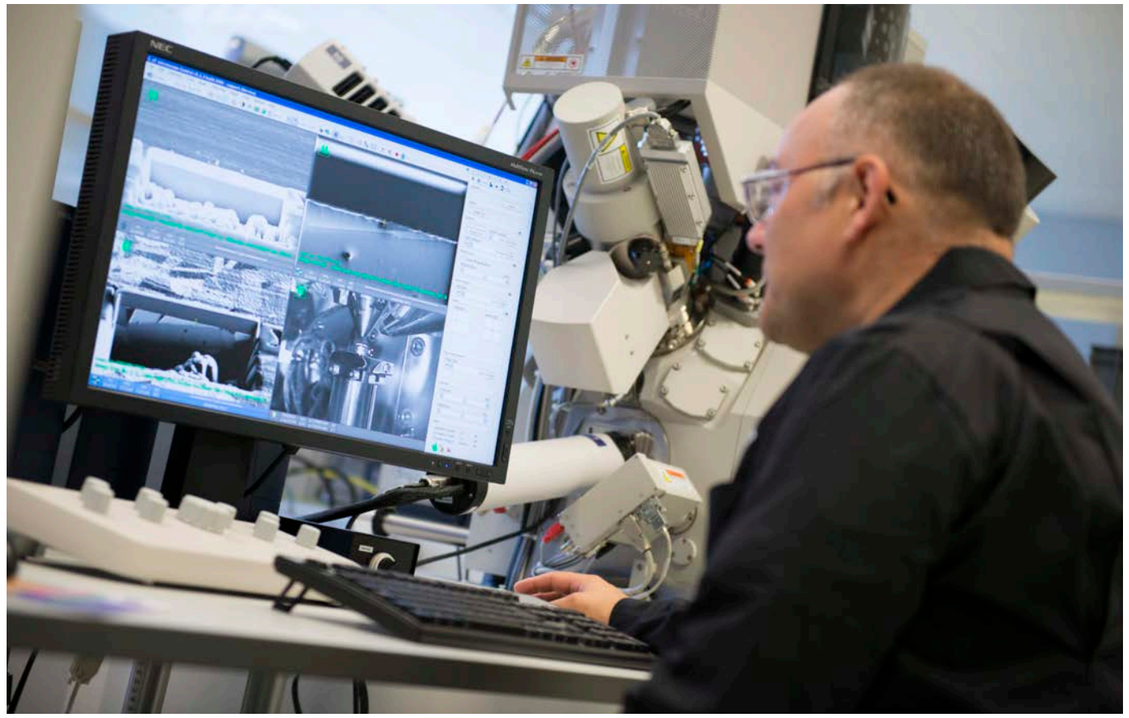
Key member of the materials performance community

Since 2018, Jonathan Hyde, Senior Fellow for materials, has represented the UK on the Board of Management for the Halden Reactor Project. He was appointed chair in 2023. Over the last year, the board has ensured that more than 50 years of operational experience on material irradiations has been captured and made available to the international community.

Nassia Tzelepi's work on the international standards for graphite has influenced regulators in the UK and internationally.

Susan Ortner, Principal Materials Scientist at NNL, is the UK representative on a sub-group of the Generation IV International Forum, where she is helping to define the specifications for metals used in very-high-temperature reactors.

Advanced analytical techniques can look at the structure of materials with nanometre accuracy.



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