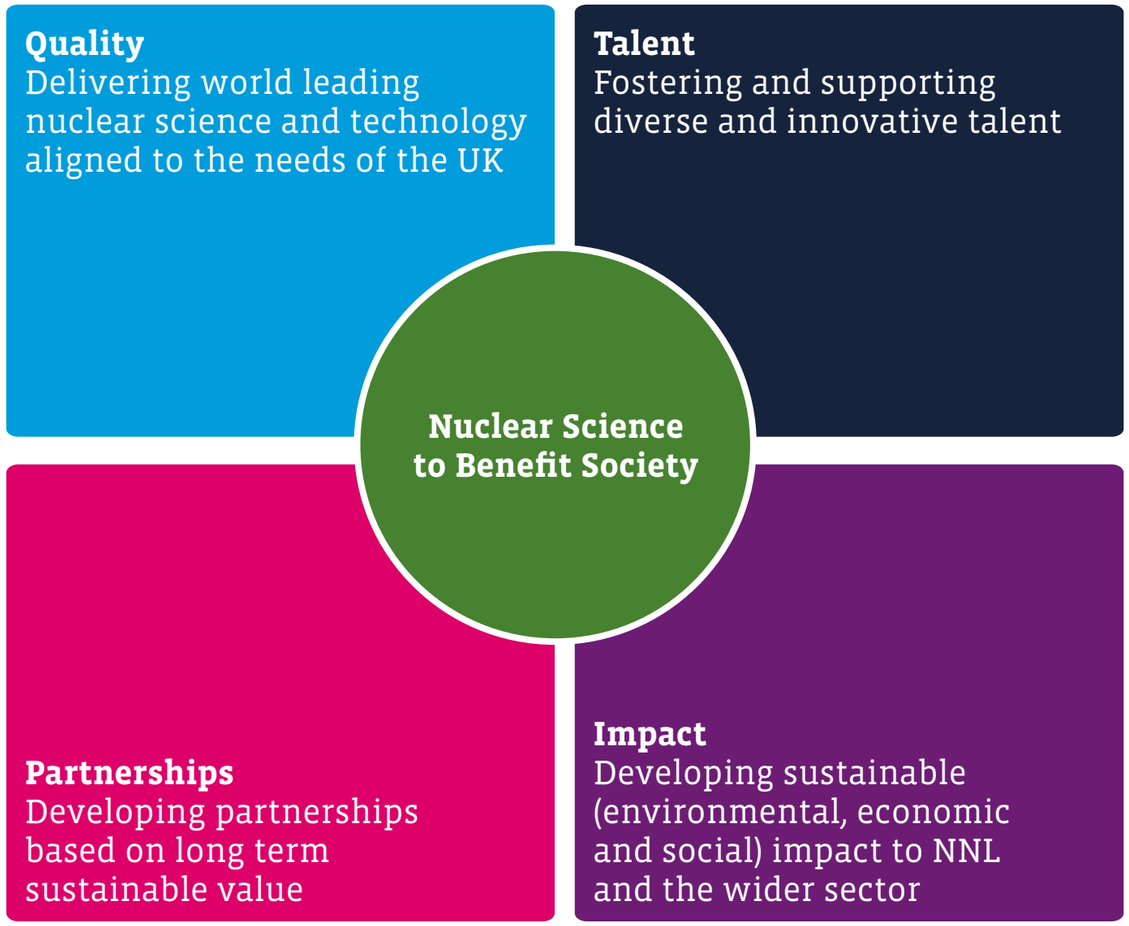
NATIONAL NUCLEAR LABORATORY

Science and Technology Agenda

Case Study Series
2021–22

NNL S&T Agenda Value Framework



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

Investing in scientific research and unleashing innovation is vital to our work as a national laboratory; allowing us to serve our customers, our partners and our nation better, and reposition 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 publication is a selection of case studies showcasing six highlights from the past twelve months across this portfolio of work. These emphasise the value generated by working in partnership with a range of national and international stakeholders from across academia, industry and government.

Dr Fiona Rayment
NNL Chief Science and Technology Officer (CSTO)

Dr Paul Nevitt
NNL Science and Technology Director

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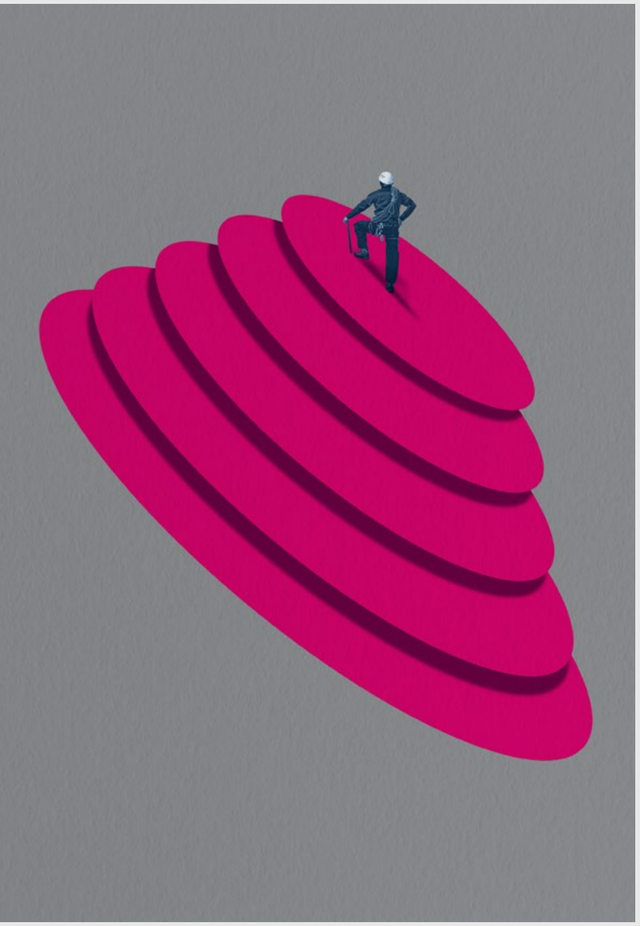
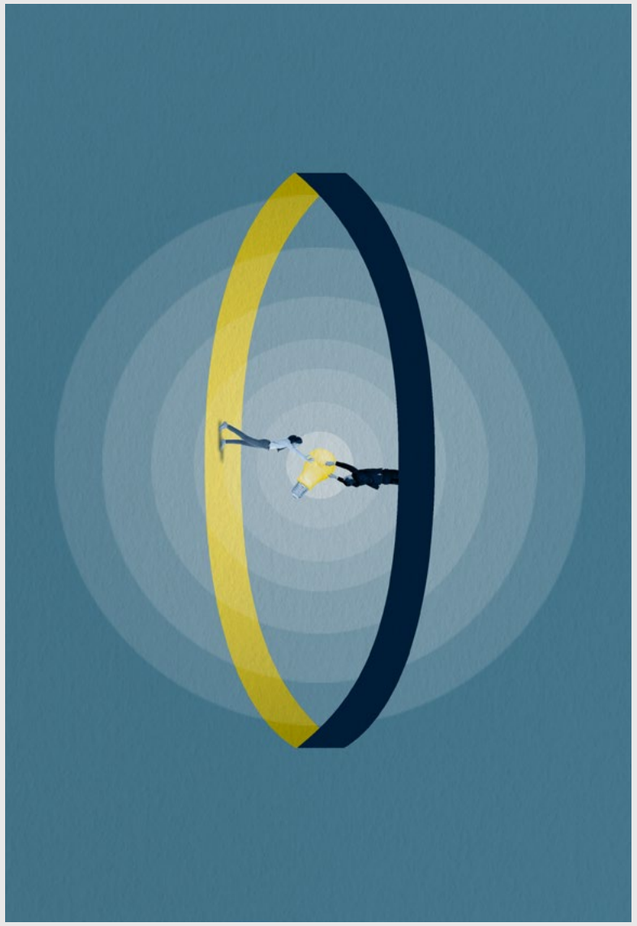


Core Science



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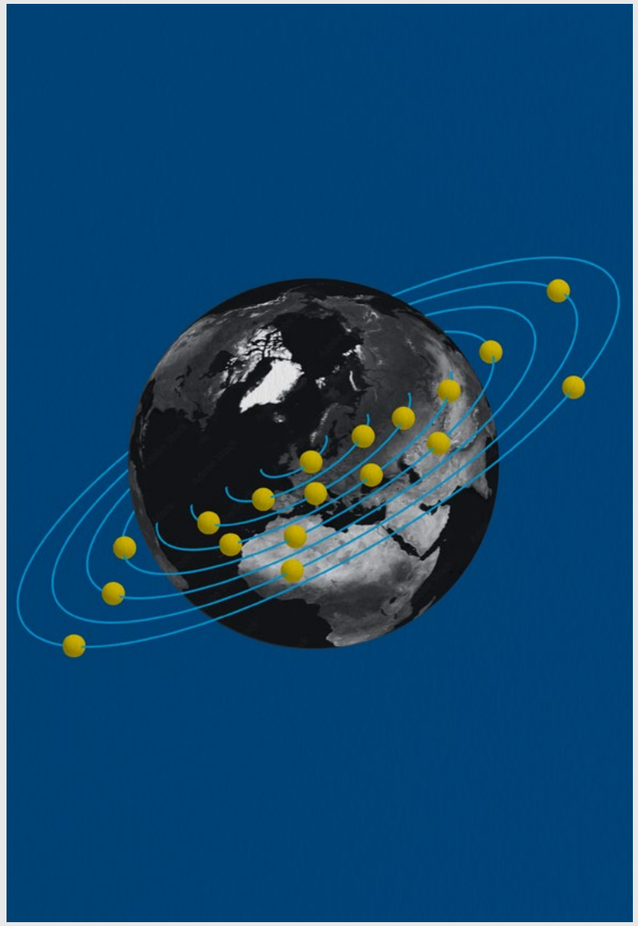
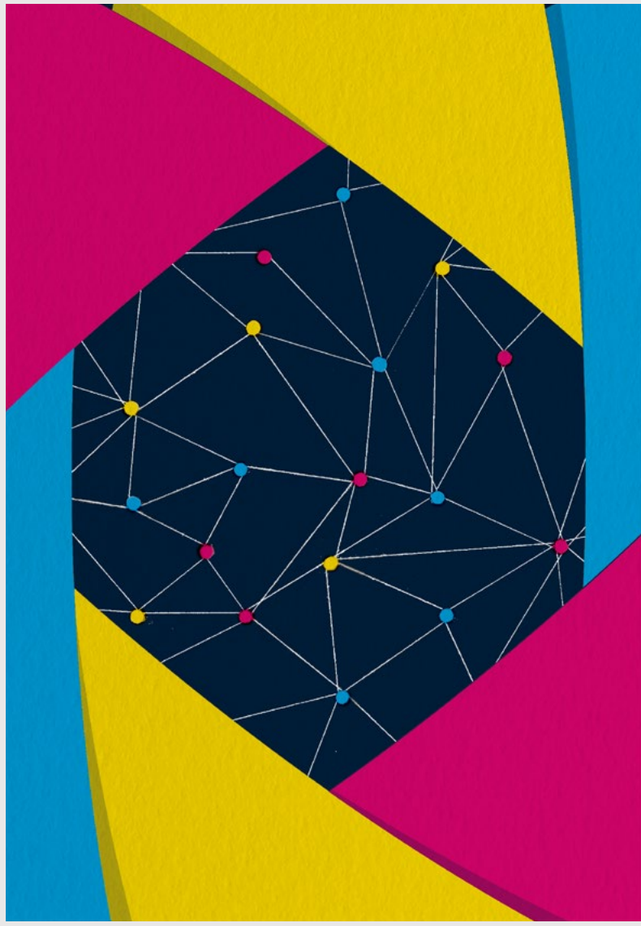


Strategic Research



Collaboration

01 | Core Science

Driving capability in nuclear-enabled **hydrogen,** on behalf of our sector for the whole of the UK.

Recognising the potential for nuclear enabled hydrogen, NNL has invested through the Core Science pillar of our Science and Technology Agenda to develop the capability and technical underpinning needed to support the UK's ambition to become a world-leading hydrogen economy.

Over the past year, the Hydrogen Core Science Programme has:

Generated capability that has enabled us to break new ground in our partnerships and ability to collaborate across the energy space and beyond, paving the way for nuclear to play a crucial role in delivering the UK's ambition to become a leading hydrogen economy;

Enabled us to partner in projects that will drive forward energy applications from nuclear at a significant pace, and pave the way for hydrogen production using high temperature reactors;

Pivoted capabilities and talent from across the lab into a new application that provides interesting and challenging work for colleagues and brings valuable long-term skills into our sector.

The production of low carbon hydrogen has been prioritised by UK government and industry as a promising solution for decarbonising heat, long-distance transport such as shipping and aviation, and heavy industry including cement, steel, chemicals and aluminium. These sectors are vital to living standards and our economy, but they are energy intensive and hard to decarbonise through electricity alone. The challenge of this is addressed in the UK's *Hydrogen Strategy*, published by the government in 2021. This set out a vision and plan for kickstarting a world-leading hydrogen economy. It recognised the role of current and advanced nuclear reactors alongside other technologies in delivering what is needed, but these pathways are yet to be fully modelled and demonstrated. Now we are helping to close this gap.

Our technical lead for this programme, Allan Simpson, explains our role in this area: "As the UK's national laboratory, our role is to provide credible and robust support in the delivery of low carbon hydrogen production from nuclear. This involves developing the science and technology evidence base and communicating this effectively to stakeholders. Our aim is to enable nuclear to play a crucial role in delivering the UK's ambition to become a leading hydrogen economy. In doing so, we are pivoting capabilities from across the lab into a new application that provides interesting and challenging work for colleagues and brings valuable long-term skills into our sector."

Counting down to net zero
What is the role of nuclear power?

3 Classes of reactor

Large – Ready Now
Small – Early 2030s
Advanced – Early-mid 2030's

2 Forms of energy

- Heat & electricity to help decarbonise the electricity grid to meet the step change in demand as UK electrifies to meet net zero
- Produce low carbon heat and hydrogen to support decarbonisation of applications such as domestic heating, transport (e.g. shipping & aviation) and industrial processes

1 Stop energy shop

Co-generation of low carbon heat and electricity in a low cost, net zero integrated energy system

Talent

Creating a strong nuclear pipeline: the team delivering for NNL

Through NNL investment in Core Science, Kate Taylor is part of a virtual team of twenty-five engineers and scientists delivering our work to drive the UK's capability in nuclear enabled hydrogen.

"Being part of this team, and having the opportunity to change the course of how the nuclear sector delivers for net zero, has been an eye-opening opportunity that I truly believe will make a difference to the world. Nuclear-enabled hydrogen is a proven technology, but there are still missing pieces of the jigsaw; we are making much-needed, rapid progress towards finding these, and our work is driving many new and necessary collaborations beyond our sector.

"My day-to-day job is chemical process modelling but within this programme I am modelling the economics of hydrogen generation. All of our team come from different parts of NNL, so through our involvement in NNL's hydrogen programme we have developed a whole new area of capability for ourselves and collectively for the lab. One year in, we have delivered some powerful outcomes and our plans for the coming year are even more exciting."

Quality

Known by partners for our science

The capability derived from our investment in the NNL Hydrogen Core Science programme has led to much collaboration with a range of partners, public and private, to strengthen the pathway to nuclear enabled hydrogen.

As well as being invited to join working groups for the government's Hydrogen Advisory Council and its Jet Zero Council, we have delivered seminars across the energy sector including for Ofgem and the National Grid, and opened up new links with academic institutions such as the University of Chester and Energy Research Accelerator, a group of eight Midlands universities.

Partnerships

The 'nuclear derived hydrogen to gas networks' collaboration is an example of partnership in practice

Converting national and regional natural gas networks to hydrogen could enable consumers to continue using gas in homes, businesses and industry, reducing risks to the net zero transition.

Working with DNV, who are a technical authority on a gas network transition in the UK, our work has explored the potential of nuclear to support the conversion of UK gas networks to hydrogen. We have been able to understand the progress already being made in both sectors and build valuable connections between the sectors.

Capability built through the NNL Hydrogen Core Science programme enabled the project, which took place as part of the Advanced Nuclear Skills and Innovation Campus *(ANSIC)* pilot, located at our Preston Laboratory and funded by the Department of Business, Energy and Industrial Strategy *(BEIS)*.

The findings will enable both the nuclear and gas sectors to gain a deeper understanding of priorities and assess barriers and next steps on matters including regulation, safety, siting and economics.

Blue Hydrogen filled H_2 commercial Aeroplane flying in the sky - future H_2 energy concept.

Converting national and regional natural gas networks to hydrogen could enable consumers to use hydrogen in their homes.

Impact

One year in, already delivering successful outcomes

Just one year in, this unique programme of work has delivered a series of outcomes that will be critical to the UK's future capability in nuclear enabled hydrogen.

This is a new and vital area of work for NNL, building the capability of NNL and the whole of the nuclear sector to help ensure the UK delivers on its ambition to become a world-leading hydrogen economy. Some of the key outputs of the programme, which was shaped around the needs of potential nuclear enabled hydrogen consumers, are:

An economic assessment demonstrating that, under the new Regulated Asset Base financing model, the cost of hydrogen from nuclear is competitive with wind;

A safety review to identify the hazards that could be created through the co-generation of hydrogen on a nuclear-licensed site and understand how each of these has been successfully contained in the past – this review confirmed a proven and viable route through each of the safety implications of co-generation;

Process modelling to build a picture of what is needed to bring each hydrogen production technology to commercial maturity, enabling NNL to provide credible commentary and advice on each.

The expertise, talent and credibility generated by these projects, and others like them, has led to new relationships between NNL and some 40 organisations across the energy space and beyond.

The collaborations that have followed are already helping to define nuclear's contribution to the hydrogen economy and growing our capacity to contribute to this.

> "NNL has invested in an area key to the sector delivering on its decarbonisation potential. As a leader in bringing forward innovative solutions, NNL is providing the technical underpinning required for a more expansive nuclear sector supporting a future hydrogen economy. This work is therefore supporting the nuclear sector to bring forward new climate change solutions and enabling UK industry to play a key role, including as part of the High Temperature Gas Reactor demonstration programme."

Tom Greatrex
CEO of the Nuclear Industry Association

That our Core Science Progamme is internally funded enabled the freedom to innovate and move quickly, and the outcomes of this have directly resulted in our ability to engage with a series of externally funded projects that will drive forward energy applications from nuclear at a significant pace.

This includes GEMINI 4.0, a European research collaboration on the development of high temperature gas reactors.

02 | Core Science

Establishing a centre of excellence in **thermal treatment** technology.

Environmental restoration is a challenge that the UK is tackling with allies around the world. This is why, at NNL, we are constantly driving new research routes into the way legacy wastes and future used materials are processed. Our foundations as a laboratory lie within this vitally important work, helping to leave the planet stronger and more sustainable.

We have pioneered the use of thermal treatment which forms one of the twelve areas of Core Science within our Science and Technology Agenda. Thermal treatment involves mixing nuclear materials with glass or ceramic precursors and consolidating by heating at high temperatures. It offers several advantages over conventional processes, including reducing the final volume of waste and improving stabilisation – making it more affordable as a result.

"I am proud to be involved in work that is helping to create a more environmentally sustainable future for the UK and benefiting the wider nuclear industry. Being in the early stages of my career, it is a fantastic opportunity for me to be a part of this world-leading team and learning from colleagues who are experts in the field of thermal treatment."

Beth Sunderland
Hot Isostatic Pressing (HIP) Laboratory Technician at NNL

Quality

What we have achieved:

Key Highlights

Thermal treatment isn't a new technology but it hasn't yet been deployed at scale across the nuclear sector. Typically, vitrification is the *de facto* process used around the world to stabilise the highly radioactive liquid arising from reprocessing. Thanks to the innovative and quality science we're undertaking at our Central Laboratory, key industry partners including Sellafield Ltd and the Nuclear Decommissioning Authority *(NDA)* are now looking to incorporate thermal treatment as part of their broader waste management toolkit.

To demonstrate the significant benefits of this transformative technology, a crucial part of our work involves thermal product sampling, characterisation and analysis, for which we are establishing a Centre of Excellence. Not only does this enable us to qualify the process, ensuring that the final products are as expected, but it means we can provide Nuclear Waste Services with the essential information they need to manage these materials.

Through trials of a Resodyn Acoustic Mixer *(RAM)*, we have confirmed that this technology improves the consistency of precursor materials before they undergo Hot Isostatic Pressing *(HIP)* – a specialised thermal treatment process that applies heat and pressure to transform powders into a highly robust and durable ceramic. HIP is currently being developed to help immobilise our nation's supply of surplus nuclear material. By improving the precursors, we can produce a higher quality product faster helping to reduce the surplus more quickly.

We are also investigating new techniques to assess this final product, along with vitrified nuclear material produced through vitrification, which includes the novel use of Raman spectroscopy. This technique enables us to scan across solid samples to assess their uniformity and confirm whether they contain any unwanted species or unreacted precursor material.

As well as pioneering technical advancements, in the past year we have made five journal submissions, presented our learnings at several international conferences and become a member of the prestigious Society of Glass Technology's Basic Science and Technology Committee.

Partnerships

Working with experts in the UK and across the globe

To ensure we are building a new clear future of the UK and for our planet, it is important that we work in tandem with specialists all over the world.

Examples of our recent collaborations include:

Working alongside nine other international laboratories to assess a new leach test method being developed by Pacific Northwest National Laboratory *(PNNL)* in the US. Collectively, our findings will feed into the publication of a new international standard to ensure radioactive species that have been immobilised within glass or ceramic materials are not rapidly released when they come into contact with water.

Partnering with the French Alternative Energies and Atomic Energy Commission (*CEA)* to build a UK model for glass dissolution. Based on the CEA's own state-of-the-art model, this has the potential to enable us to predict the behaviour of thermally treated glass or ceramics in water over tens of thousands of years.

We also have long-established partnerships with the NDA and Sellafield Ltd which extend to this area of work. Our advancements in thermal treatment have helped to develop the HIP capability that is now part of a multi-year NDA programme to ensure the long-term security of the UK's special nuclear material.

It has also supported experimental trials on new vitrification technologies as part of a collaborative project between the NDA and Theramin – a consortium of twelve European partners of which NNL is a part. These technologies are now being used by Sellafield Ltd to develop full-scale demonstrators for the treatment of key waste streams supported by NNL personnel and establishing the thermal product analysis Centre of Excellence.

Top
RAM trials taking place at our Workington Laboratory.

Bottom
An in-situ image of the GeoMelt® process showing a mixture of molten materials, with electrodes in each corner used to generate heat.

"Working within NNL's CINDe framework has enabled me to gain access to state-of-art technology and key technical knowledge offered by subject matter experts, both of which have been invaluable to me during my PhD. This programme has also given me the opportunity to see what it is like to work in an industrial facility in rural Cumbria. I can definitely say that the importance of the work, coupled with the general team atmosphere, has inspired me to want to continue working here."

Einan Solomon
PhD student at the University of Liverpool, who is in place at The Centre for Innovative Nuclear Decommissioning (CINDe), our PhD hub at Workington Laboratory

Talent

Creating a collaborative workforce with the necessary nuclear skills and experience

As the UK's national laboratory for nuclear fission, we want to give our nation's brightest young minds an avenue where they can develop their scientific curiosity and make a positive difference to society.

Within our thermal treatment programme, several early careers team members have taken a lead on the main technical tasks. They, along with some of our apprentices, have received training on our state-of-the-art equipment in the laboratory, including a new desktop scanning electron microscope *(SEM)* and associated grinder/polisher used for sample preparation, developing their practical, hands-on experience.

As well as progressing our own people, we are also fostering talent outside of NNL by providing individuals from other organisations and sectors with access to our specialist facilities. Three PhD students from the Universities of Sheffield, Manchester Dalton Cumbria Facility and Liverpool have been working with our experts at NNL on various research projects relevant to this field of work.

Impact

The future of thermal treatment

Our ambition is to establish a Centre of Excellence in active thermal product sampling, analysis and characterisation. This is key to enabling NNL to successfully support the deployment of thermal treatment on the Sellafield site and more broadly across the NDA estate, and ensure we're continuing to deliver sustainable impact.

We will continue to build our capability in this area of Core Science, exploring the application of existing and new analytical equipment and identifying and finding solutions for needs as they arise.

Our technical work will focus on the following three areas:

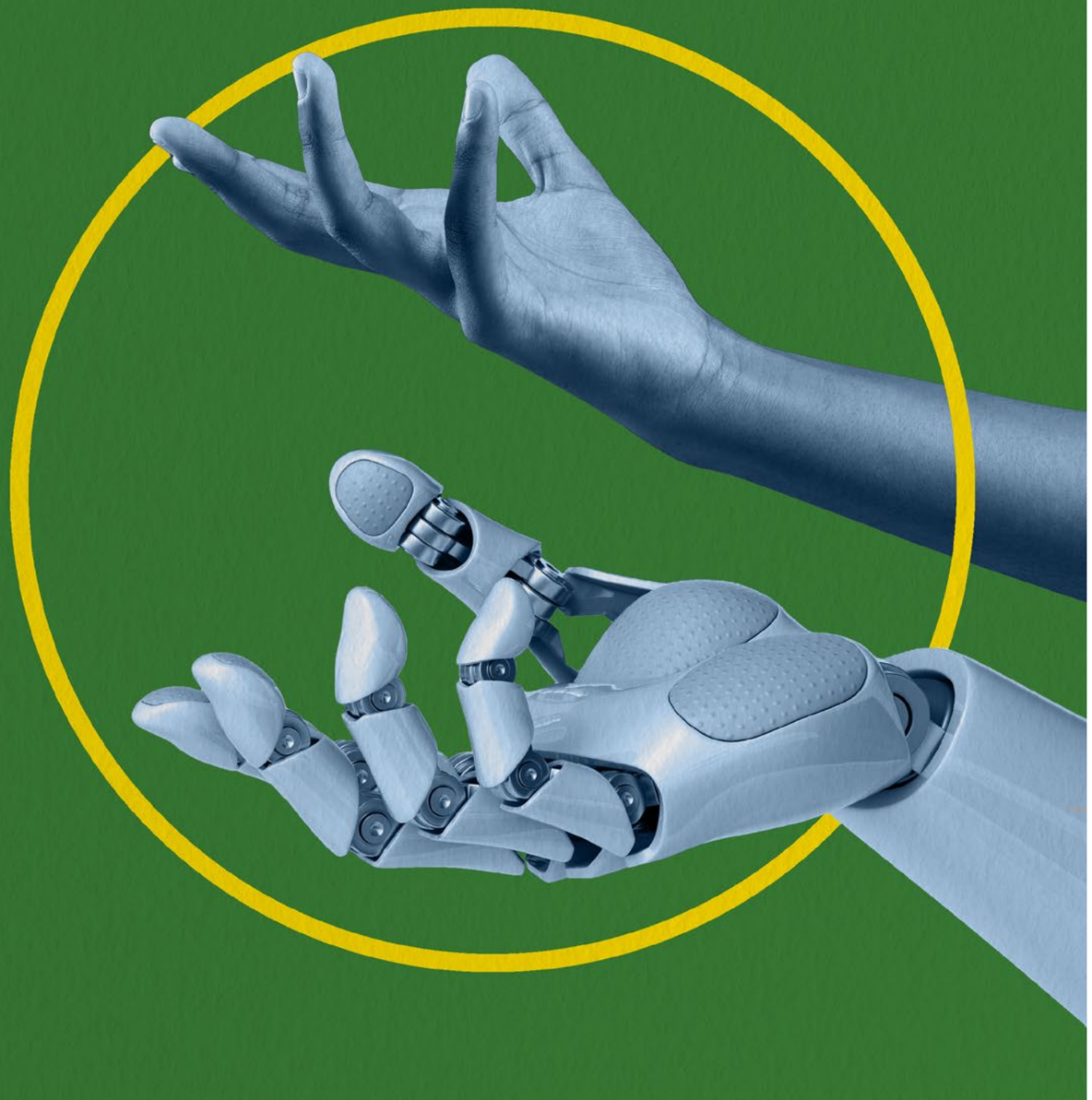
Thermal product performance – exploring advanced microscopic techniques, developing glass/ceramic dissolution models and new leach test methodologies, and supporting capability for the UK's Geological Disposal Facility;

Thermal product analysis – developing our alpha thermal treatment capability in Central Laboratory, supporting Sellafield's thermal demonstrators, and carrying out vitrified product compositional analysis and Raman measurements;

Providing the necessary technical underpinnings to NNL's Advanced Fuel Cycle Programme (AFCP), developing thermal processes and advanced glasses and ceramics for immobilising nuclear material.

03 | Innovation

Engaging in **open innovation** to provide nuclear power for **space exploration**.



At NNL, we have built a distinct identity as the UK's technical authority on nuclear fission but no single area of expertise resides in just one organisation.

Engaging in open innovation is fundamental to our work in science and technology. By partnering with the brightest minds across academia, government and industry, we are able to find solutions to some of the world's most pressing scientific challenges, keep our scientists and researchers at the cutting-edge and ensure we're delivering impact.

Across the nuclear sector, we are developing new and pioneering solutions to minimise the contact dose to operators when handling radioactive materials. As part of this, over the past year, we have been working with Cumbrian small and medium-sized enterprise *(SME)*, Resolve Robotics, to build a pair of mechanical hands. Created to support the European Space Agency's *(ESA)* forthcoming lunar mission in the first instance, the mechanical hands will in future be deployed in applications beyond space.

A model of the Mars Perseverance rover; powered by Am-241 power cells

Quality

Science and technology to fuel the European Large Logistic Lander on the moon

"Previously, the European space programme lacked an independent capability in nuclear power sources. Such systems are vital enabling technologies for many exciting missions to the outer solar system or to the moon and Mars surface. NNL has developed and proven a process to create radioisotope fuel in a sustainably affordable way, and has provided the foundation from which a European space nuclear power programme can be launched. It's essential for ESA that such activities are conducted with the highest standards of safety and technical rigour. NNL is a valuable partner in this regard."

Keith Stephenson
European Space Agency

Nuclear fuel, through Radioisotope Power Sources *(RPSs)*, is critical for deep-space exploration. It remains the only way to fuel long-term, long-distance missions which are key to furthering global understanding of the solar system and Earth's creation.

In the late 2020s, ESA will launch the maiden flight of its European Large Logistic Lander *(EL3)*. EL3 aims to deliver payloads ranging from 1,500 to 1,700 kg anywhere on the lunar surface. It will conduct both science and logistic cargo missions and will provide survival and operation through the two-week long lunar night.

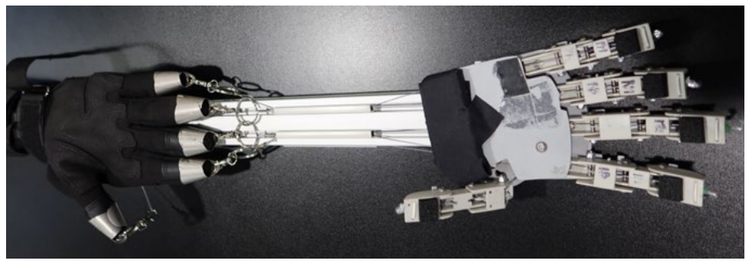
This capability is contingent on securing a volume of americium-241 *(Am-241)* and NNL is uniquely placed to provide it.

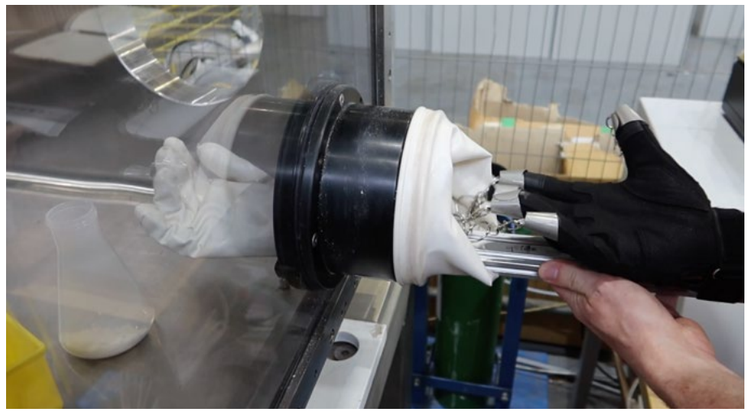
Typically, RPSs are fuelled by plutonium-238 *(Pu-238)*; however, supplies of this isotope are limited, costly and entirely dependent on the United States of America and Russia as producers. In partnership with ESA and the University of Leicester, our experts at NNL have identified a new and more affordable alternative – Am-241.

With a half-life of around 430 years, compared to around 90 years for Pu-238, Am-241 can be separated from aged plutonium dioxide, of which the UK has a civil stockpile on the Sellafield Ltd site. As well as producing an indigenous supply of Am-241, boosting our national reputation as a sovereign space-faring nation, we are helping to recycle used nuclear materials.

"Americium-241 based radioisotope power systems will be transformational in providing a power source, complementary to Pu-238 and other larger reactor-based systems, for planetary surface and deep space exploration missions. The UK has the expertise, know-how and facilities to be at the forefront of space nuclear power enabled science and exploration missions."

Prof. Richard Ambrosi
Space Park Leicester
Executive Director

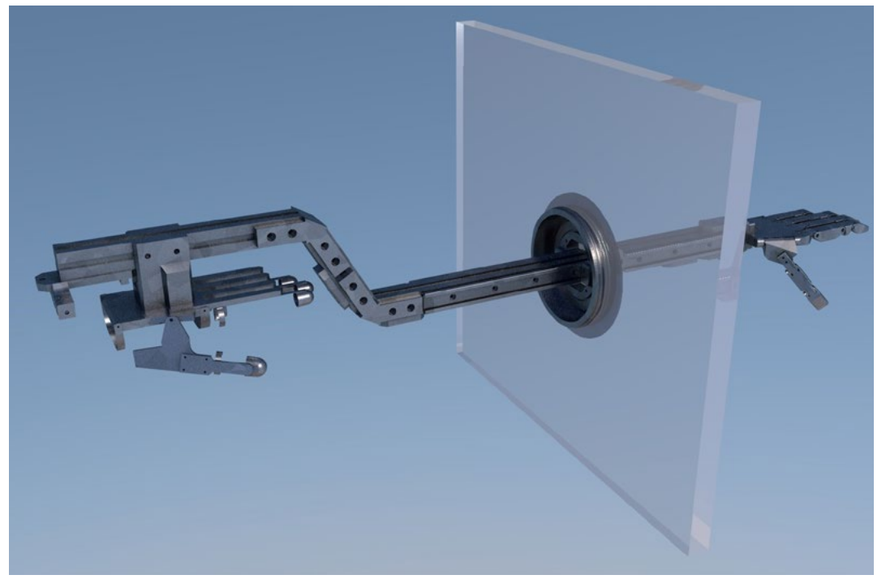




Top left
Early prototype unit of the mechanical hand developed with Resolve Robotics

Bottom left
The mechanical hand prototype being demonstrated to glovebox operators at our Workington Laboratory

Right
3D CAD drawing of the deployable units



To perform the separation of Am-241, operators typically place their hands in a pair of gloves attached to the glove box and directly handle part of the radioisotope. In doing so, the operator receives a safe and small contact dose, regulated by our robust dose-management procedures.

However, to extract the volume needed for the mission, around 500g per year, continuous hands-on operations are required. Our primary challenge was to find a way to maintain this, whilst guaranteeing the operator's contact dose remains at a safe level. We also wanted to ensure the solution would be cost effective, low carbon, durable and quick to design and deploy. needed for the mission, around 500g per year, continuous hands-on operations are required. Our primary challenge was to find a way to maintain this, whilst guaranteeing the operator's contact dose remains at a safe level. We also wanted to ensure the solution would be cost effective, low carbon, durable and quick to design and deploy.

Partnerships

Our solution: driving innovation through collaboration

In 2020 we launched an Open Innovation campaign to promote our challenge to over 50,000 cross-sector innovators, internationally.

Following a 12-week feasibility study, the technology put forward by Resolve Robotics was selected as the winning solution. Crucially, as well as addressing the challenge, this solution met our criteria for cost, carbon, durability and deployability.

Leveraging Resolve Robotics' experience in puppetry and animatronics and our capabilities in handling radioactive materials, together, we have developed two mechanical hands – a left and a right – that allow the operator to carry out the separation of Am-241 whilst reducing their contact dose.

With smooth edges and quick-release functionality, the mechanical hands act as an extension of the operator's own hands. Importantly, this solution also enables the operator to retain their line of sight so they can directly see what they are doing. Throughout the development phase, we were able to use a mock-up glovebox at our Workington Laboratory to demonstrate prototypes of the mechanical hand.

"Collaborating with Resolve Robotics has been incredibly fruitful, with working prototypes developed and tested in a matter of months. The innovation of applying puppetry more typically seen in film industry applications, to allow safer handling of active material, cannot be understated. Working with an external company has enabled me to develop ideas with engineers from an entirely different industry and look to solve a real nuclear handling related issue."
James Rigby, Mechanical Engineer, NNL

The mechanical hands are set to be deployed in an active glovebox in 2022.

"Working with NNL has been transformative not just for our business but also for our ability to create innovative solutions for the nuclear sector. Our background is in robotics but aligning this with NNL's expertise in handling radioactive materials means that we've been able to deliver a new product that is fit for purpose and will directly contribute to future space exploration."

Andrew Ludar-Smith
Technical Director of Resolve Robotics

Impact

What we have achieved:

Embraced open innovation to create an entirely new and cost-effective solution that both meets the contact dose management challenge at hand and, as a sign of its quality, supports the delivery of a multi-million pound programme for ESA;

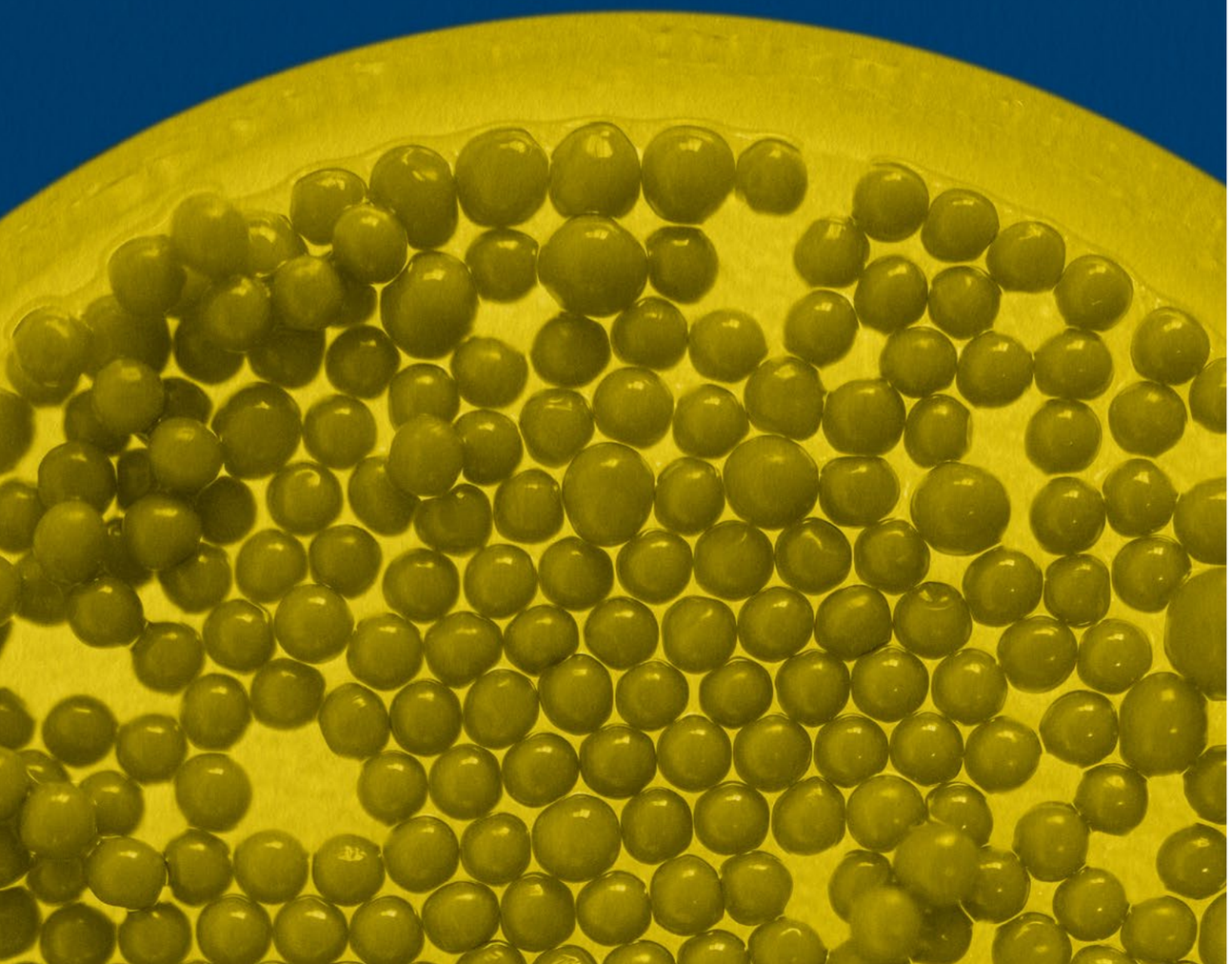
Stimulated the supply chain by partnering with a Cumbrian SME, helping to promote regional growth and ensure the North West of England can continue to offer high-quality and high-skill employment;

Built a positive and collaborative working relationship with a partner organisation who bring expertise beyond just the nuclear sector. As part of this, we worked with the team at Resolve Robotics to ensure a fit-for-purpose solution was delivered in less than a year, providing them with access to our facilities at Workington where they were able to test, trial and demonstrate the solution;

Employed technology and expertise from the film and TV special effects industry to solve a unique, nuclear challenge. Through this cross-sector collaboration, we have been able to produce a technology which has the potential to be deployed more widely across other glovebox scenarios, including in the handling and repackaging of cans of plutonium for longer-term storage.

04 | Strategic Research

Leading **ground-breaking research** and partnerships to enable a UK advanced fuels and fuel cycle capability.



A flagship of NNL's Strategic Research work, the Advanced Fuel Cycle Programme (AFCP) is successfully rebuilding the UK's sovereign capabilities in the manufacture and recycling of fuels for the next wave of nuclear technologies.

Through its uniquely collaborative model, the programme unites the expertise, facilities and knowledge of over 100 organisations worldwide to help accelerate the UK's net zero ambitions, maximise domestic opportunities for jobs and growth and support the global clean energy transition.

Over the past year, AFCP has:

Delivered technical UK 'firsts' in the development and demonstration of advanced solutions, including for Coated Particle Fuels for High Temperature Gas Reactors (HTGRs);

Leveraged NNL's specialist nuclear facilities to conduct active experiments that would not be possible elsewhere in the UK and grown skills and expertise across the programme to support the future talent pipeline;

Strengthened existing relationships across industry and academia, maximising the input, skills and opportunities of all partners and continuing to ensure that investment is spread across the UK value chain;

Enabled the UK to influence global research and development by providing significant contributions to bi-lateral and multi-lateral international programmes, including with the International Atomic Energy Agency (IAEA), the OECD Nuclear Energy Agency and the US/UK Civil Nuclear Energy Research and Development (R&D) Action Plan.

Led by NNL as part of the Department for Business, Energy and Industrial Strategy's *(BEIS)* Energy Innovation Programme – now the Net Zero Innovation Programme – AFCP represents the biggest investment in future nuclear fission fuel cycle research in a generation. Further, it reflects the essential role nuclear must play in a secure, affordable, low-carbon future.

Over the past three years, AFCP has leveraged over £130million in investment across national and international programmes to drive nuclear fuel cycle innovation, ensuring we have the capabilities to underpin advanced nuclear technologies for net zero. This has involved over 100 partnerships worldwide and more than 90 in the UK alone – bringing together universities, industrial heavyweights and small and medium-sized enterprises *(SMEs)* – to pioneer new solutions and begin to establish a UK supply chain for advanced fuels development and manufacture.

Recognising the value, impact and quality of this work, in 2021 the programme received a £10million extension from government, which we have combined with over £500,000 of NNL's own Science and Technology investment in advanced fuels and fuel cycle. Through this, we have been able to dovetail priority research areas with the UK government's 2021 Net Zero Strategy. This includes greater focus on Coated Particle Fuels for HTGRs, which were announced as BEIS's Advanced Modular Reactor *(AMR)* technology of choice for demonstration by the early 2030s.

Quality

UK Foundations for a net-zero future

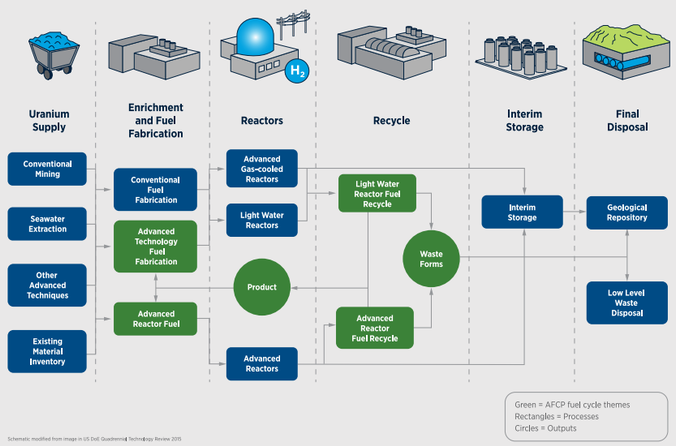
Over the past year, AFCP has re-prioritised its strategic research towards the advanced fuels that will power new HTGRs, as the UK progresses development of these technologies ready for deployment. This has been combined with a continued focus on and investment in advanced fuels for light water reactors and sustainability within the fuel cycle, recognising the importance of new products for existing reactors and maintaining our world-class capabilities in recycle science. Through ongoing trials in our unique active laboratories, we are providing credible technical options for reprocessing spent fuels that are cost-competitive with other fuel cycle options – maximising our valuable resources and continually improving processes for the future.

By growing this base of knowledge, AFCP is helping to maintain and develop a future UK fuel manufacturing capability focused on fuelling nuclear for net zero – building on the decades of success in fuelling the AGR fleet. Doing so successfully will not only unlock future export opportunities but will also retain necessary skills and talent, high-value jobs and supply chain growth for decades to come in the UK.

"I was delighted to visit the National Nuclear Laboratory at their world-leading laboratory for scientific research and innovation in the North West of England. The work they are doing to develop advanced fuels for the next generation of nuclear reactors will be essential to the UK's ambitions to build our national capabilities to secure our position as a global leader in these clean energy technologies. It is fantastic that we have a national laboratory in the NNL that is driving the key research and development we need to meet our net zero goals, whilst promoting UK skills."

Rt Hon Greg Hands MP
Minister for Energy, Clean Growth and Climate Change

AFCP fuel cycle themes



Schematic modified from image in US DoE Quadrennial Technology Review 2015

Quality and talent

Building technical capability and capacity

Over the past year, AFCP has continued to deliver technical UK 'firsts', demonstrating the potential for advanced fuels and fuel cycle, and supporting the wrap-around structures which will be needed for future delivery.

This has included:

Demonstration in the UK of the technology to manufacture uranium oxide (UO_2) kernels for Coated Particle Fuels for HTGRs and installation of the scale-up manufacturing facilities required for the next stage of its development – delivered alongside the Universities of Bangor, Bristol, Lancaster and Manchester;

Production of full-length fuel cladding coating technology for Advanced Technology Fuels, working with Worcestershire-based SME Teer Coatings, to be installed on the Springfields site;

Also with Teer Coatings and Westinghouse, completion of irradiation testing on a UK advanced fuel concept completed at the Massachusetts Institute for Technology test reactor;

Demonstration of flash sintering of UO_2 fuel pellets in the UK for the first time, representing a novel technology that is faster and operates at lower temperatures than existing methods, thus providing potential cost benefits in the manufacture of a range of nuclear fuels. This work has been delivered in partnership with Lucideon, an SME based in Stoke-on-Trent, and the University of Manchester;

Increasing the technical maturity of advanced fuel recycle processes by conducting world-leading specialist scaled rig trials in NNL's active laboratories and working collaboratively with partners to build the modelling and 'non-active' base to retain our world-class capabilities in fuel recycle science;

Supporting the development of international best practice by establishing collaborations under the US/UK Civil Nuclear Energy Research and Development (R&D) Action Plan with several US national laboratories, driving advancements and efficiencies in recycle processes – including in uranium recovery – to reduce overall environmental impacts.

This ground-breaking work is enabling us to move up the technology-readiness scale and growing the UK knowledge base in these areas of research, priming the talent pipeline with higher level skills.

Judgement on technology readiness level of advanced fuel and fuel cycle areas developed as part of AFCP in the UK

(based on expert opinion from within AFCP)

The UK Advanced Fuel Cycle Programme (AFCP) (2016–2022)		**TRL at start of AFCP**	**TRL at 2022**
Accident tolerant fuels (ATF) or advanced technology fuels for light water reactors (LWRs)	High density fuels	1	3
	Coated Cladding	2	6
	SiC cladding	2	3
Coated particle fuels (CPF) for high temperature reactors (HTRs)	Kernels	3	4
	Coating	3	3
Fast reactor fuels		3	3

Partnerships

Greater impact through collaboration

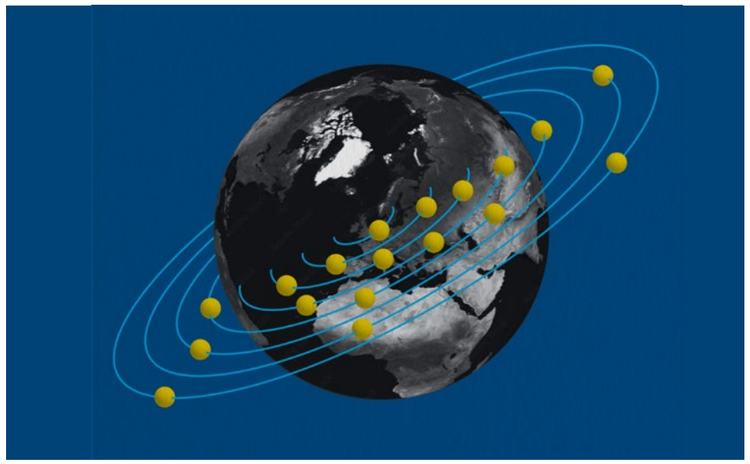
The success of AFCP to date, and the quality of its outputs, are thanks to its collaborations across leading academic, industrial and research institutions – both in the UK and globally. In leading these partnerships, we have been able to leverage our existing capabilities – the skills of our people, our decades' expertise in fuel cycle science and our specialist active facilities – to enable others to progress ideas, concepts and strategic research.

"As a work package leader within AFCP's aqueous recycle research programme, I had my first opportunity to organise and run a major project which has been hugely valuable experience – both in terms of new techniques developed in the laboratory and skills gained across the whole team. For example, we were able to train early careers researchers in plutonium active operations which are vital for maintaining alpha skills in this area of work, ensuring we are continually building expertise and capacity for the future.

"Additionally, because partnerships are at the heart of AFCP, I had the opportunity to network with a wider range of individuals and organisations from the global nuclear community. This was an excellent way to engage with international work and perspectives, share ideas and showcase AFCP's ambitions and achievements. It is fantastic to know that the programme is driving crucial research in the fuel cycle, whilst also feeding into other future projects and capabilities." *Hannah May Colledge, NNL Senior Research Technologist, Separation Science & Special Nuclear Materials*

"Through our bilateral collaboration with the UK, we hope to enhance state-of-the-art technologies that promote the unique expertise and facilities each country brings. Currently, we are collaborating on radioisotopes for use in space technologies, advanced reactor technology, advanced fuels, fuel cycle technologies, modelling and simulation, and enabling technologies. It is great to see the role of national laboratories in driving forward the collaboration in all areas. The work on fuel cycle technologies has seen real progress underpinned by the work of the US national laboratories and NNL in the UK through the U.K. Advanced Fuel Cycle Programme (AFCP)."

Andrew Griffith
Acting Assistant Secretary for Nuclear Energy, Office of Nuclear Energy, US Department of Energy



Impact

Mapping out future systems

Alongside specific research programmes, we have also developed modelling of the whole energy landscape – looking at the projected demand for clean energy, the resourcing required to meet this and the gaps that therefore need to be filled in the UK.

Over the past year, this has contributed to several transformative reports, including:

Whole energy system modelling with Energy Systems Catapult, which enabled nuclear deployment scenarios to be produced for the first time to show the role of nuclear in a UK net zero energy system. This allowed us to develop detailed fuel cycle modelling to understand resource demand for future systems, including HTGRs;

Detailed technology development roadmaps – building on the energy system modelling – as guidance for policymakers and the wider sector;

Joint publications with the University of Manchester on the environmental and economic implications of advanced fuel cycles, providing crucial underpinning evidence for industry and policymakers to support future strategic fuel cycle decisions;

An assessment of a number of future fuel cycle scenarios using life cycle analysis *(LCA)*, working with academic partners including University College London. LCA is a method used to evaluate the environmental impact of a product through its life cycle, encompassing extraction and processing of the raw materials, manufacturing, distribution, use, recycling and final disposal. Once again, this is enabling a strategic assessment of future fuel cycle decisions.

All of this modelling work is underpinned by our sophisticated modelling capabilities, created by NNL with the support of our partners – ranging from Orion, our internationally-recognised fuel cycle modelling tool, to Sim Plant, which models what future advanced fuel cycle industrial complexes could look like based on the latest underpinning technical data from AFCP experimental programmes.

Targeting 2050 and beyond

Due to the size and scale of the programme, it is impossible to highlight all the achievements and successes that have been secured so far. Further information on the work that has been undertaken and delivered through AFCP is available on the programme website.

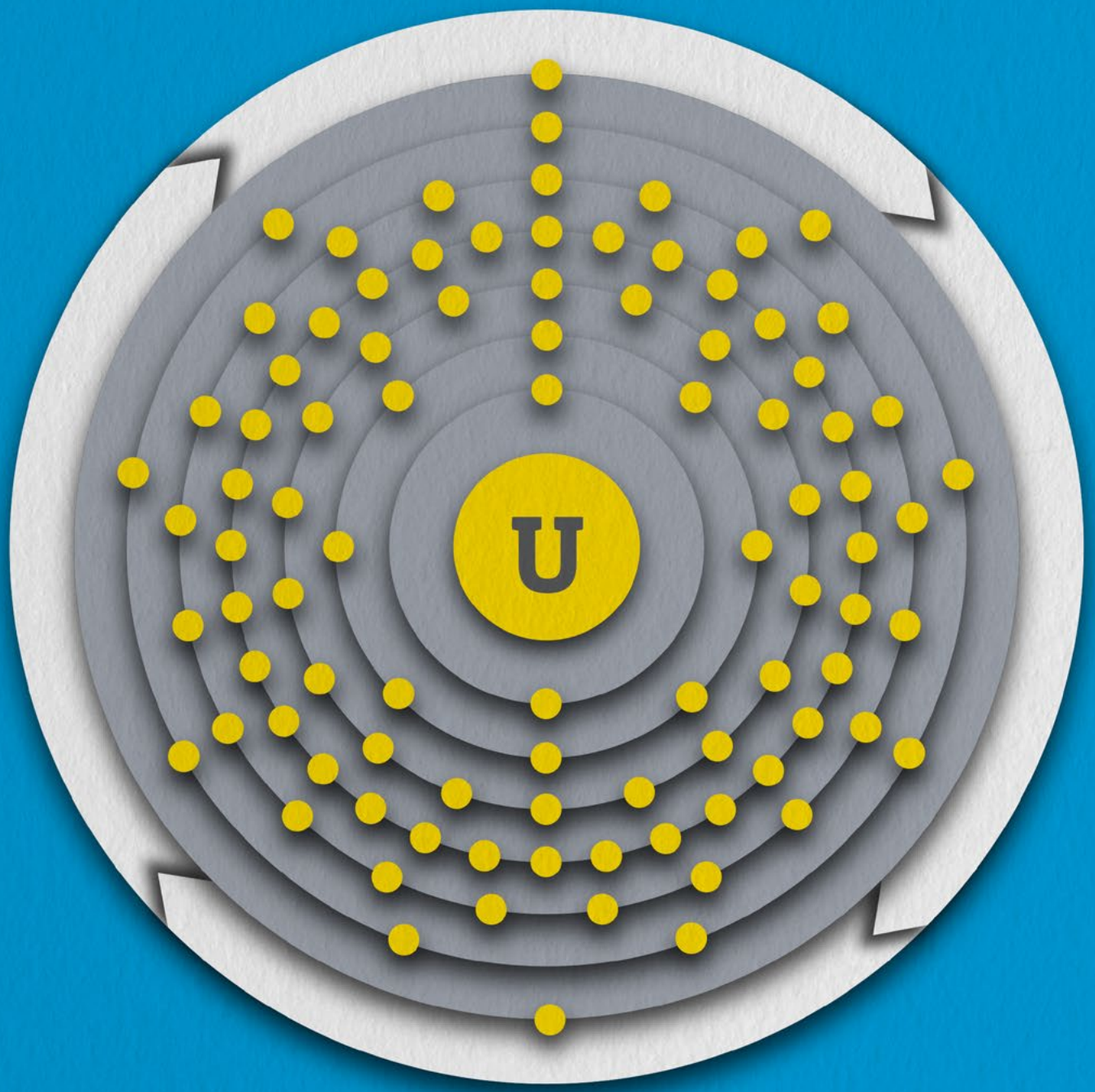
As we look ahead, we are pleased that the importance of ongoing research and development on the future UK fuel cycle is recognised by the UK government's Net Zero Research and Innovation Framework, as essential to achieving net zero by 2050. Building on this, however, we recognise our role as a national laboratory stretches further than this key milestone. So, whilst we continue to drive the research needed to fill current gaps in UK technical expertise, using our extensive technical and modelling capability, we are looking at the impact and opportunity of advanced fuels and fuel cycle for future generations. This means considering what, for example, 2100 could look like and enabling strategic decision-making in support of the future role of nuclear in mitigating climate change.

"My research team has had a long and very productive relationship with the scientists, technologists and engineers at NNL – a relationship that has had a major influence on our research strategy for more than two decades. However, it was ACFP that allowed us to take that relationship, the work produced and its impact, to another level. It is in the area of product finishing where the work has been most rewarding and probably made the most significant contribution to the generation of new intellectual property for the UK. Through the programme, innovative technologies have been developed and nuclear-relevant skills inculcated in more than a dozen researchers. Driving step changes in technology and capability, AFCP has been a real UK success story."

Professor Colin Boxall
The Lloyd's Register Foundation Chair in Nuclear Engineering, Lancaster University

05 | Collaboration

Creating a global hub of expertise on advanced **fuel cycle science**.



A thriving nuclear power sector is an essential component of the UK's path to net zero. NNL has a long and proud history of collaborating and working in partnership with the International Atomic Energy Agency (IAEA), with our experts working together across many areas of nuclear science and technology.

In September 2020, NNL and the IAEA jointly launched the UK's first IAEA Collaborating Centre. The first Centre of its kind anywhere in the world, it is creating a global hub of expertise on advanced fuel cycle science and is making an essential contribution to realising the vital role of advanced nuclear technologies in achieving net zero goals.

David Hall, UK Permanent Representative to the IAEA at the signing ceremony to formalise the new Collaborating Centre in September 2020.

Impact

Building understanding of advanced fuels and fuel cycle development.

Through the Centre, we seek to strengthen international understanding of a range of advanced fuels and fuel cycles.

In partnership with the IAEA, the impact we have had:

Organising and participating in national and international events, convening communities of experts in valuable forums for technical exchange. This included a meeting on Advances in Post-Irradiation Examination Techniques for Power Reactor Irradiated Fuels and Innovative Fuels and a roundtable exploring the fuel cycle opportunities and challenges associated with the deployment of advanced modular reactors. NNL experts also participated in the drafting of IAEA technical reports on fuel development and waste management;

Sharing our joint experience of modelling, comparing tools and applications. We have also combined our advanced reactor knowledge to develop materials that will ultimately enhance understanding across the sector;

Receiving nominations for our scientists at NNL to represent the UK on important IAEA Technical Working Groups *(TWGs)*, including Nuclear Fuel Cycle Options and Spent Fuel Management, and Fuel Performance and Technology. An essential mechanism for creating international consensus and vision across key research areas, these TWGs play a central role in informing the IAEA's future priorities.

To successfully develop, and ultimately deploy, advanced nuclear clean energy systems, countries around the world must have a holistic understanding of the full fuel cycle, including how to manage future legacy.

Together with IAEA, we will be jointly conducting training courses and seminars on the modelling of advanced nuclear fuel and fuel cycle performances, using our own ORION fuel cycle analysis software and IAEA's Nuclear Fuel Cycle Simulation System. Importantly, we are also partnering to drive forward research into waste management issues, helping to evolve recycling concepts and support sustainability efforts.

Talent

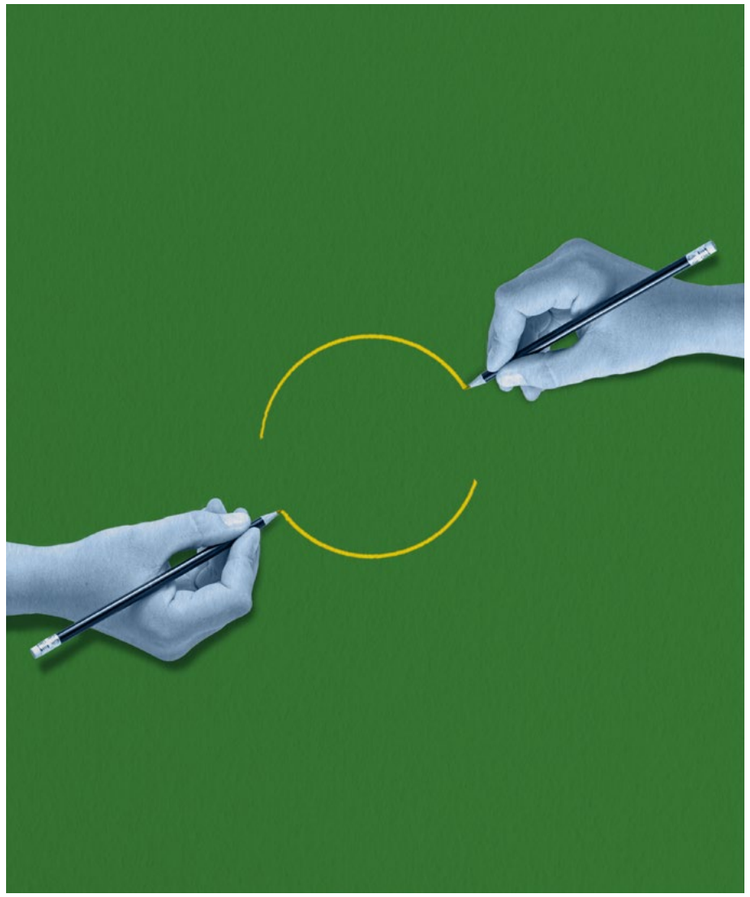
Developing the next generation of nuclear experts

People are the currency of the nuclear industry; it is only by investing in our national talent pipeline that we will retain the critical skills and knowledge base the UK needs to develop new nuclear capabilities.

By encouraging the participation of early career research scientists, the Centre is providing an opportunity for them to work closely with those who have decades of experience in the field whilst giving them unparalleled insight into the international nuclear sector.

NNL is also engaging in specific activities to develop the next generation of nuclear scientists, both in the UK and globally, as part of the Centre's e-Learning workstream. Leveraging our national nuclear expertise, we have helped to create a suite of online materials, hosted on the IAEA's e-Learning platform, designed for early careers individuals at NNL and the IAEA. So far, content has been produced for a module focused on fast reactor fuel cycles and potential challenges to deployment, with further materials set to be developed in the future.

Additionally, in 2020 NNL joined UK Government in supporting the IAEA's Marie Sklodowska-Curie Fellowship Programme *(MSCFP)*. This aims to increase the number of women in the nuclear field, helping to foster an inclusive workforce which contributes to and drives global scientific and technological innovation. The Centre will explore opportunities to host participants of the MSCFP, offering internship placements for up to 12 months.



Quality

Delivering leading pioneering advancements on a global stage

As the UK's national laboratory for nuclear fission, we are working to secure the country's place as a global leader in the clean energies of the future.

The IAEA Collaborating Centre has created a platform for NNL to be internationally recognised as a convener of advanced fuel cycle expertise, made possible through our investment in AFCP. As the Centre continues to grow and expand, NNL will further cement its position in this strategically important field, taking a leading role at international events, presentations and conferences and creating joint publications with the IAEA to share information and learning.

Partnerships

What's next: future Collaborating Centres

Over the coming years, we will create more Collaborating Centres. These will allow us to explore partnership opportunities with other like-minded organisations, advancing globally significant research across our four Focus Areas and ensuring we're delivering on our purpose of *nuclear science to benefit society.*

The first of these will be a UK Collaborating Centre on Integrated Energy Systems, which we recognised as a fundamental area of work through our Science and Technology Agenda. Following our commitment made at the Global National Laboratories Summit 2022, the Centre, which is set to be established in Spring 2022, will bring together UK industry, national laboratories and academia across energy sectors to advance our knowledge in this area.

"The opportunity to work in the Collaborating Centre has allowed me to develop my skills in presenting and communication and given me the opportunity to interact with international experts across all areas of advanced fuel science. My ambition for the future is to become a technical expert in reprocessing, so gaining this insight into how we, as nuclear scientists, can collaborate across borders is invaluable. One day, I hope to be a key contributor to the Centre's work."

Billy Keywood
Technical Graduate at NNL who acts as Secretary for the IAEA Collaborating Centre

06 | Collaboration

Establishing a new **global forum** of national laboratories to progress an integrated approach to decarbonisation.

In January 2022, NNL convened the world's first global summit of national laboratories working on energy research to progress a holistic understanding of what is needed for net zero and develop an integrated energy systems approach – across borders and energy vectors alike.

The Global National Laboratories Energy Summit 22 has:

Established a first-of-its-kind global forum of national laboratories working on energy research, combining nuclear, renewables and other low-carbon sources;

Brought the importance of an integrated energy systems approach to the fore, as nations strive to balance decarbonisation efforts with energy demand, security and cost;

Laid the foundations for a long-term legacy of collaboration between national laboratories, following the UK's presidency of COP26, to drive the research and innovation required for net zero by 2050.

We seized the opportunity, in the year of the UK's presidency of COP26 – the United Nations Climate Change Conference hosted in November 2021 – to build the foundations of a long-term legacy of collaboration with our global counterparts. With the Global National Laboratories Energy Summit 22, we highlighted the importance of an integrated approach if we are to maximise the efficiency of future clean energy systems, something which is already recognised in NNL's Science and Technology Agenda and Clean Energy Focus Area.

The summit also signified the part played by national laboratories worldwide in enabling the science, innovation and research and development *(R&D)* that will be required for net zero, with our unique positioning across the public and private divides. Ensuring the event included both nuclear and non-nuclear national laboratories, all confirming their intent for future collaboration, we have paved the way for greater impact in the policy and technical debate with this new forum going forward.

"With the transition to net zero driving fundamental changes globally to energy supply, demand, transmission, distribution, storage and use, research and innovation is required to help us develop, design and operate the right systems for a net-zero future.

As national laboratories we have a unique role to play in enabling the successful energy transition, by providing global leadership and scientific expertise, bridging the gap between academia and industry and driving the innovation required for future technologies to deliver."

Dr Paul Howarth
NNL Chief Executive Officer (CEO)

Partnerships

Global collaboration for a global challenge

National laboratories exist across the world to deliver cutting-edge science to solve some of society's biggest problems; with respect to urgent climate mitigation efforts, working together *(one of the four aims of COP26)* has the potential to deliver greater, faster outcomes for the planet as a whole.

This first summit therefore brought together national laboratories from Canada, France, Japan and the USA, as well as colleagues at the UK's Energy Systems Catapult, who are all pioneering clean energy systems but encompassing nuclear, renewables and other low-carbon solutions.

The creation and the planning of the summit involved several months' joint working to determine the best framework and approach to deliver our collective aims, as well as set in motion aims for the forum's legacy. This allowed us to build on existing and new bilateral partnerships as we developed a steering committee to advance the summit's aims.

The event itself saw presentations on existing work streams towards integrated energy systems from each delegate and closed with a document signifying agreement to collaborate across a series of key themes including enabling and preparing for energy flexibility and identifying energy needs across industry sectors. *Watch a recording of the event here.*

Quality

An ambitious new forum to progress work

"We know that the very best solutions in history come from collaboration. The S&T infrastructure is pretty impressive in a lot of places around the world and so I think unless we work together, we all won't survive. It's either everybody or nobody." *Dr Peter Green, Deputy Laboratory Director, US National Renewable Energy Laboratory (NREL) Video clip of Dr Green.*

"If we're to unleash the innovation we need to get to a net zero global economy, it's essential we take an integrated approach that understands the roles of different technologies, of markets, of digital technology and, crucially, of people. That's why we're delighted to support this initiative. It puts a whole system, integrated approach at the heart of our future innovation. COP26 showed what global collaboration can achieve in the push towards net zero – through this initiative we have an opportunity to work together to help deliver our shared ambitions for a cleaner, more affordable energy future." *Guy Newey, strategy and performance director, Energy Systems Catapult*

"We are already partners in nuclear research and innovation to move forward towards a future net-zero carbon society, and we all have solid grounds to design, develop and deploy nuclear-renewable hybrid systems. This summit will lead us to a shared vision of future integrated energy systems as well as enhanced international collaboration." *Mr. Kentaro FUNAKI, Executive Director for International Affairs, JAEA*

"Canadian Nuclear Laboratories (CNL) welcomes a new era of international collaboration to accelerate the global adoption of clean energy and the critical role of integrated energy systems. […] Collective knowledge is a powerful tool, and we look forward to sharing our expertise, research and learning to help shape the energy systems of the future." *Dr Jeff Griffin, VP, Science & Technology, CNL*

> "Transitioning to a low-carbon energy system is critically important for global sustainability, and integrated energy systems can harness the benefits of clean energy sources working together, including nuclear and renewables. Idaho National Laboratory is pleased to engage with labs around the world to discuss how to achieve this ambitious goal."

Dr Marianne Walck
Chief Research Officer, Idaho National Laboratory

Stills from the Global National Laboratories Energy Summit 22 film.

Impact

Sharing science and maximising investment

The summit began to consider what the future integrated energy system will look like and how national laboratories can accelerate countries towards this target. As a new global collective, we have an opportunity to leverage our talent and respective investments in S&T to share and develop best practice, so we can evolve technologies to be fit and ready to deliver. Ultimately, we want to ensure countries can maximise the benefits of each form of technology and their mode of operation to provide reliable, sustainable and affordable low-carbon energy for their citizens.

To set this in motion, over the course of 2022, the forum will look to deliver a series of united interventions towards an urgent integrated energy approach. This will include a joint technical workshop, impact study and a presentation of these findings to support an evidence-based view of how low-carbon technologies can deliver in a global net-zero energy economy.

Further, over the coming months and years, we will look to communicate our collaborative approach across the globe to inspire further partnerships that advance knowledge around integrated energy systems in mitigating climate change. The forum will meet again, formally, with the Global National Laboratories Energy Summit 23.

Impact

Demonstrating UK leadership

Following COP26, which saw the UK lead calls for urgent and tangible actions towards net zero, we wanted the summit to represent a continuation of this ambition – promoting UK interests and strengths whilst engaging global partners. In convening thought leaders from the UK and allied nations, the summit spotlighted not only the issue of energy system integration but also the value of research and innovation in unlocking barriers to deep decarbonisation.

Keynote welcomes from the UK Government's Chief Scientific Adviser, Sir Patrick Vallance, and UK Energy Minister, the Rt Hon Greg Hands MP, helped to set the scene for the value and impact such a summit can have.

> "Nations are going to have to harness all the resources they have and, particularly in respect of this Summit, to think about the role of national laboratories, which have been absolutely crucial to support translation, adoption and deployment of technologies that will make a difference.
>
> So with this meeting, it's important that it is international in scope, it's important that it is national laboratories coming together with all the resources and insights they can bring and it's important that it reflects the urgency of the work ahead."

Sir Patrick Vallance
Government Chief Scientific Adviser
Video clip here

National Nuclear Laboratory
5th Floor, Chadwick House
Warrington Road, Birchwood Park
Warrington WA3 6AE
T. +44 (0) 1925 933 744
E. customers@uknnl.com
W. nnl.co.uk