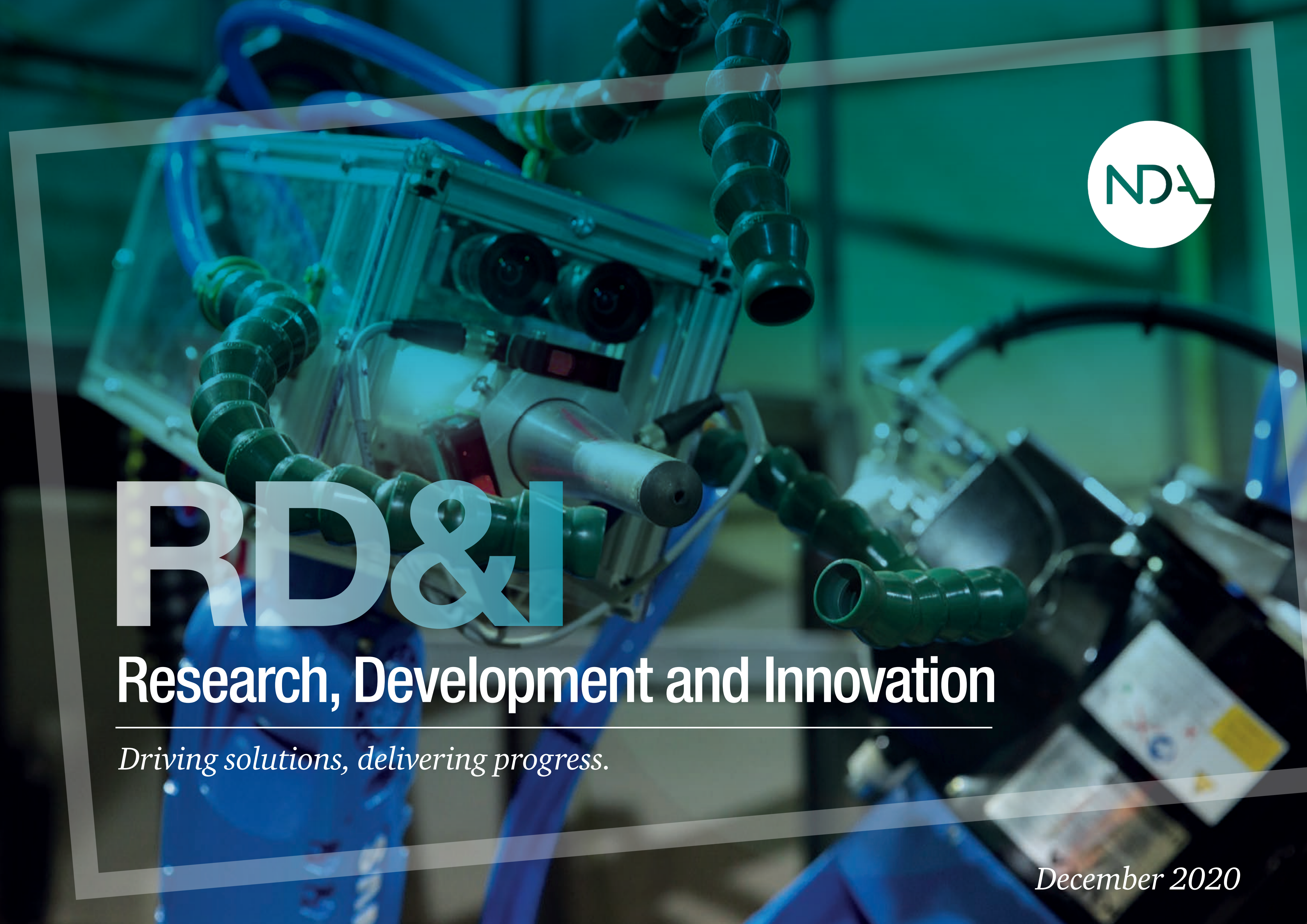


RD&I

Research, Development and Innovation

Driving solutions, delivering progress.

December 2020

more than £90 million a year spent on RD&I **across the group**

more than 60 supply chain **organisations in the UK and beyond** work on the NDA **Direct Research Portfolio**

working with sectors such as oil & gas, defence, space **and construction**

£13.5 million invested with **Innovate UK since 2012**

the NDA **sponsors 47 PhDs at 17 universities**

the NDA is a major funder of UK **nuclear RD&I**

Front cover image: Robotic system developed as part of a collaborative innovation competiton, see pages 15-17

The Nuclear Decommissioning Authority (NDA) is responsible for cleaning up the legacy from the UK's pioneering post-war nuclear programme.

From the late 1940s onwards, the country's scientists and engineers led the world with ground-breaking nuclear discoveries. The result was a diverse range of experimental facilities and early nuclear power stations, designed initially for the UK's defence but later to provide electricity for its citizens.

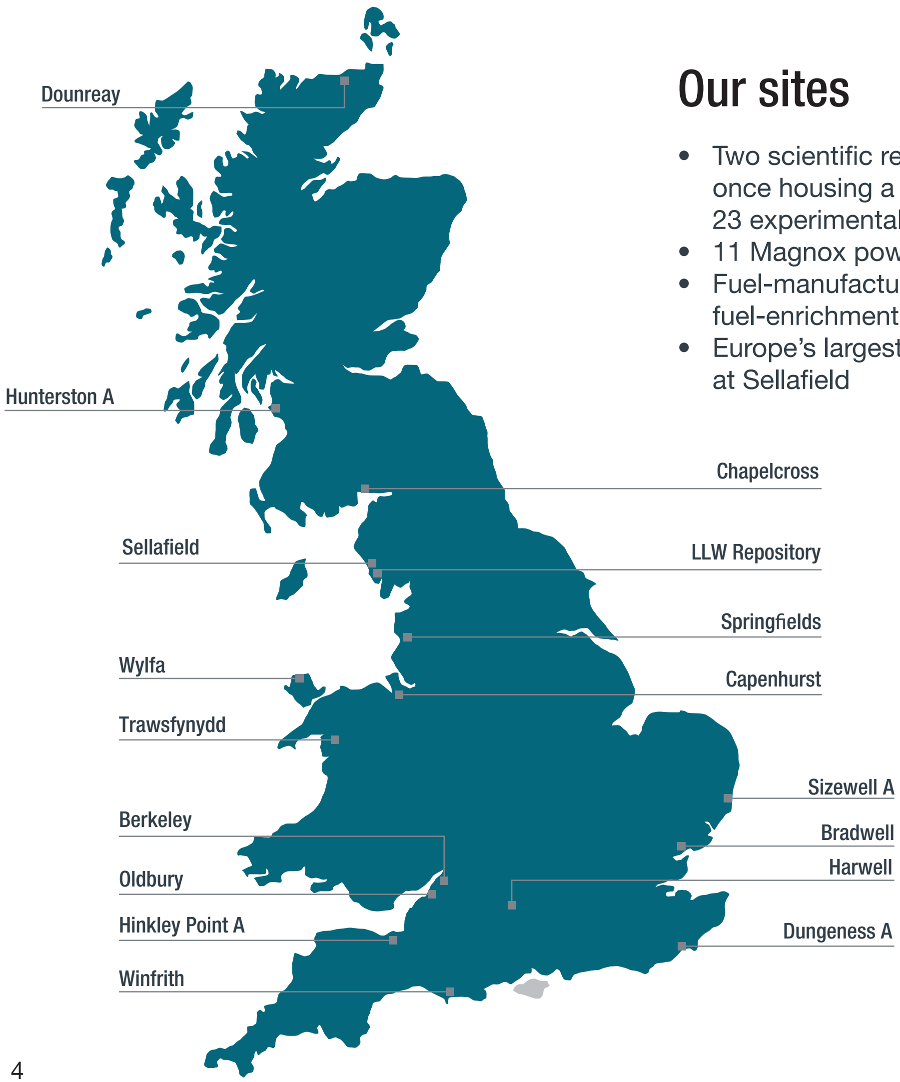
Many of the facilities were unique, producing radioactive wastes and spent fuel that no-one had ever dealt with before. Structures, pipework, container vessels and land became contaminated and were mostly left for a future generation to clean up. Today, the NDA is still dismantling this legacy, demolishing structures and preparing sites for future re-use. The mission stretches well into the next century and will cost more than £130 billion.

We are also responsible for developing a future deep Geological Disposal Facility (GDF) where higher-activity radioactive waste from England and Wales will be disposed of.

Dounreay was the site of early UK research into fast reactors

The bulk of research spending is targeted at the complexities and challenges at Sellafield.

Research, development and innovation across the NDA group



Our sites

- Two scientific research centres, once housing a total of 23 experimental reactors
- 11 Magnox power stations
- Fuel-manufacturing and fuel-enrichment plants
- Europe's largest nuclear site, at Sellafield

Delivering our mission involves dealing with a broad range of complexities and uncertainties. This requires fundamental science, innovative thinking and novel engineering. Progress depends on clearly understanding problems, finding solutions and ensuring costs remain acceptable.

Research, Development and Innovation (RD&I) are therefore essential to the mission, accounting for over £90 million of annual investment across the group.

The aim is to transform the approach of the NDA group and the industry as we move from operations to full-scale decommissioning. We seek solutions that are safer, more efficient and more cost-effective, while accelerating timescales. In the context of our challenges, innovation involves thinking creatively to generate novel solutions or re-assess current approaches. This often leads to the merging of new and existing technologies, as well as collaboration with non-nuclear industries.

A further role is to provide confidence that the high-level strategy options and advice we recommend to government are achievable.

We also need to develop technical decommissioning specialists for future work programmes, who will be able to deal with our own mission as well as challenges elsewhere in the UK and overseas.

Working together as One NDA, we seek to maximise opportunities across our industry.

Encouraging innovation

Our investments have resulted in:

- Innovative remote technologies, including laser-cutting, robotics and improved radiation detection, helping to create safer environments
- Risk and hazard reduction through simplified processes
- Reduced costs by bringing forward timescales and completing operations
- Development of a culture that nurtures innovation
- An ongoing programme of academic research, supporting a pipeline of future nuclear specialists

A vital part of our mission is encouraging innovation. We recognise the common barriers we face across the group, and how adoption of differing approaches will help unlock some of the constraints that often limit our ability to be innovative.

To encourage a culture where innovation thrives, we published a series of ‘Grand Challenges for Technical Innovation’. These bold, cross-cutting ambitions are wide-ranging, and apply to different market sectors as well as the NDA group. See page 22.

In some areas, such as radioactive waste and radiation-related safety, the nuclear sector excels and we would naturally want to take a lead in driving innovation.

For other topics, such as infrastructure management, construction and digital, we will actively seek to collaborate, leveraging investment and development by working alongside other sectors. As we benefit from shared learning, innovation communities are being successfully established across the group.

We will continue to develop and apply metrics to capture and share the benefits of innovation.

“We’re extremely proud of the progress brought about by our RD&I investments. Our challenges are unique and will continue to arise for many more decades, so we’re keen to harness the expertise of our workforce, suppliers, academia as well as other industries.

“We also work with other public and private-sector organisations to share and maximise the level of funding available, not just for our own mission but for all sectors of the nuclear industry.”

Professor Melanie Brownridge, Technology and Innovation Director

A drone in action at Winfrith in Dorset

Our approach

Flexibility

Our approach to delivering RD&I programmes is flexible, tailored to the circumstances and the particular challenge.

We take a group-wide perspective, ensuring that individual site programmes are technically robust and identifying technologies to apply across multiple sites.

If appropriate, we take the lead in commissioning work directly, but we might also opt to collaborate, seek funding partners, influence or observe other industry sectors.

- We are willing to explore the potential of conceptual ideas through to transfer of technology from other sectors
- We work with other public and private-sector organisations to increase the funds available
- We support collaborating and sharing between our sites and beyond to avoid duplication
- We are responsible for identifying specific topics for future research
- We seek to communicate both our challenges and progress

Oversight

The NDA's Research Board provides strategic guidance to help us identify and co-ordinate nuclear decommissioning RD&I.

Independently chaired, its membership comprises senior representatives from UK government, UK industry, NDA, regulators and overseas organisations, enabling us to access and share good practice.

On a working level, the Board is supported by the Nuclear Waste and Decommissioning Research Forum (NWDRF) which promotes collaboration across the NDA group and the UK. The NWDRF also ensures that innovation is delivered more efficiently, more cost-effectively, more rapidly, and avoids duplication.

NWDRF working groups focus on priorities related to waste, decommissioning, characterisation, effluents, land quality and university interactions.

Collaboration

We collaborate with other UK RD&I bodies to maximise available funding and bring benefits to the whole nuclear sector. We are also exploring potential collaboration with international organisations.

The collaborative approach has the potential to maximise the leverage on our own investment.

Our collaboration partners include:

- The Department of Business, Energy and Industrial Strategy (BEIS) and its research-funding arm UK Research and Innovation (UKRI).
- Innovate UK, a UKRI body
- The Engineering and Physical Sciences Research Council (EPSRC), also a UKRI body
- The Department for International Trade, which supports UK businesses globally
- Universities
- Other sectors, such as oil and gas, space, defence and construction industries

Sludge-dredging equipment, developed by a Cumbrian SME

We invest through two main routes

Via our group businesses

The bulk of funds are targeted at specific challenges faced by our sites, allocated as part of the annual budget set by the NDA. The majority of work is carried out by site workforces and supply chain contractors.

SLCs and subsidiaries use a detailed process to identify their specific on-site research needs and opportunities. The process ensures the NDA has a clear understanding across the group and confidence that plans can be achieved.

The plans are required to:

- Link RD&I needs to a site's overall lifetime plan
- Outline any links with other on-site work
- Provide estimated timeframes and costs
- Describe technical risks, their management and possible opportunities
- Monitor progress and how projects are governed
- Use a consistent system for assessing the maturity of a technology, known as Technology Readiness Levels (TRLs)

All sites have technical challenges requiring individual tailored solutions, however, the greatest needs are at Sellafield, which houses the UK's highest-hazard nuclear facilities and accounts for the bulk of RD&I spending. As the site with the greatest level of complexity and uncertainties, RD&I targeted at Sellafield also offers the most potential to transform decommissioning.

Group case studies follow on pages 11-13 and 20-21.

Via the the NDA

Separately, the NDA directly funds a strategic RD&I portfolio to:

- Help shape and underpin our strategy
- Deliver innovation across multiple sites
- Develop vital technical expertise for the future of our mission

The NDA Direct Research Portfolio (DRP) addresses issues that are expected to affect multiple sites or SLCs.

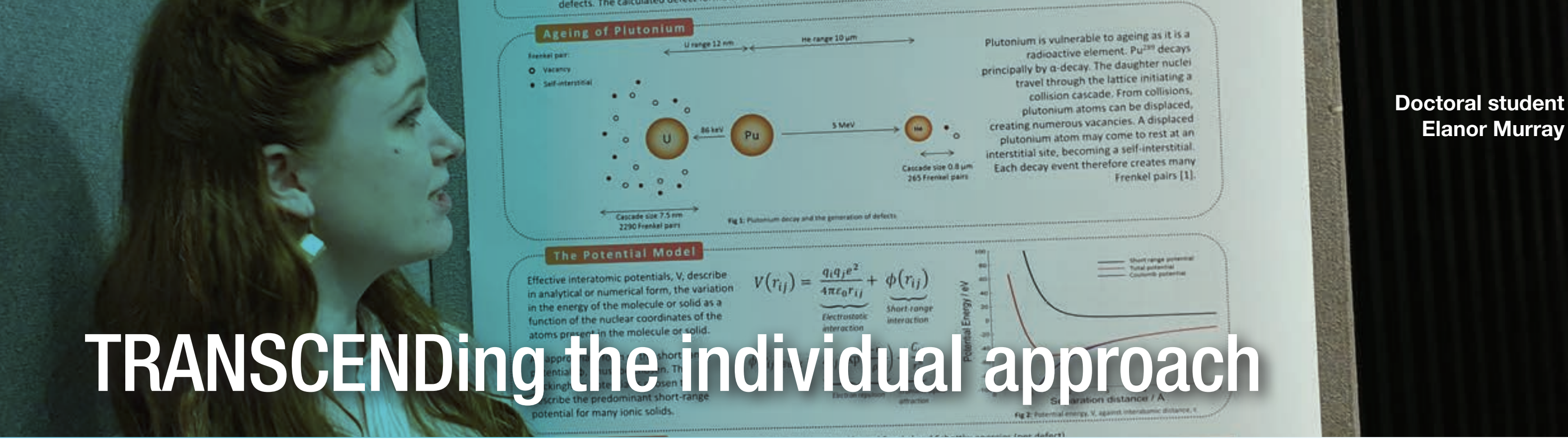
Projects are delivered through a wide range of organisations. Contracts lasting up to four years are awarded through a competitive tender process and focus on four themes:

- University-based work
- Managing waste
- Site decommissioning and remediation
- Managing spent fuel and nuclear materials

The latest contracts, awarded in 2020, involve 12 consortia (six led by SMEs) comprising more than 60 organisations, global corporations and UK universities. They will share in contracts worth up to £25 million in total.

The NDA also directly funds innovation work, including collaborative competitions, with other funders such as Innovate UK and BEIS. We are extending our RD&I portfolio, worth up to £8 million a year in total, to work with funders in other sectors and internationally.

NDA innovation case studies follow on pages 8-10.



Doctoral student
Elanor Murray

TRANSCENDing the individual approach

NDA DRP case study

Challenge: Developing solutions to technical challenges while securing high-level expertise for the future.

Solution: Collaboration with industry, universities and the Engineering and Physical Sciences Research Council to invest in a range of targeted and relevant university research projects.

Technology: Under development.

Status: Ongoing.

Research organisations: Multiple universities.

Innovation route: Collaborative public and private-sector initiative, supported by joint funding.

Link: www.transcendconsortium.org

The NDA is working with industry and funding partners to support a £9.4 million research programme that stretches over four years and involves more than 40 university studies.

The TRANSCEND consortium, launched in 2018, based its acronym on Transformative Science and Engineering for Nuclear Decommissioning and is the third joint initiative focusing on NDA technical priorities in radioactive waste, spent fuels, nuclear materials and site decommissioning and remediation.

Two earlier programmes, DIAMOND and DISTINCTIVE, ran from 2008-2019. Many of the PhD students and post-doctoral researchers have since taken up careers that support our decommissioning mission.

Earlier in 2020, DISTINCTIVE won a prestigious Royal Society for Chemistry award for industry-academia collaboration.

The DISTINCTIVE (Decommissioning, Immobilisation and Storage soluTIons for NuClear wasTe InVEntories) consortium ran between 2014-2019 with 10 academic and three industrial partner organisations.

TRANSCEND is building on the work of the previous consortia, as well as addressing new topics and will develop high-level technical specialists.

The wide-ranging topics include:

- New methods of decontaminating radioactive effluent
- Durability of new types of cement for encapsulation
- Improved understanding of solidified waste products
- Corrosion of spent nuclear fuel
- Predicting dose rates from buried pipelines where information is limited
- Corrosion behaviour of materials in a Geological Disposal Facility (GDF)
- Behaviour of stored plutonium over long timeframes

TRANSCEND brings together 11 universities and a range of industry experts. The programme is funded by a core grant of £4.6 million from the Engineering and Physical Research Council (EPSRC), with additional sponsorship from AWE, Cavendish Nuclear, LLWR, NDA, NNL, RWM, Sellafield Ltd and TÜV SÜD Nuclear Technologies. Their support is provided through funding or industrial expertise, use of facilities and guidance for the researchers.

A benefit of the consortium is to enable industry experts to work closely with UK academics and the research students, focusing directly on some of the problems in dealing with radioactive waste and other materials. Some challenges have long been anticipated while others arise during decommissioning activities.

Led by The University of Leeds, the consortium includes:

- Imperial College London
- Lancaster University
- Queen's University Belfast
- University of Birmingham
- University of Bristol
- University of Leeds
- University of Manchester
- University of Sheffield
- University of Southampton
- University of Strathclyde
- University of Surrey

The DoE's Jean Pablo Pabón Quiñones,left, and Dr Rick Short from the NDA

Hot Isostatic Pressing (HIP) for plutonium

As part of ongoing research into technologies for immobilising plutonium, the NDA has embarked on a collaborative project with the US to examine the feasibility of a can-filling treatment process in preparation for Hot Isostatic Pressing (HIP).

HIP could lock the plutonium into a glass-forming material, creating a solid that may be suitable for storage and eventual disposal.

The UK has large quantities of non-military plutonium, safely and securely stored in powder form at Sellafield. Potentially of value as a component in new reactor fuel, the UK government is in the process of establishing whether to take forward this option, or to dispose of the plutonium. Whichever option is selected, some will remain unsuitable for re-use.

Assessing technologies that are, or could be, available to deal with the plutonium is one of the most complex challenges facing the NDA as it provides information to the government on possible options.

HIP is a heat-plus-pressure treatment which has been used in industrial processes for a number of decades, including the nuclear industry, and can convert various materials into a glass-ceramic or ceramic form. The technology offers a potential future immobilisation solution if it can be successfully adapted and deployed on large-scale basis.

The US Department of Energy (DoE) is currently experimenting with HIP equipment to process an inactive simulant of calcined (heat-treated) radioactive waste. The NDA is collaborating with the DoE to develop a key aspect of the process: filling HIP cans. Collaboration supports knowledge sharing between the countries, recognising synergies in the requirement to deal with UK plutonium.

A non-radioactive simulated plutonium wasteform, containing a glass ceramic-forming mixer, was shipped to the US for trials. The alpha and gamma radiation characteristics of UK plutonium require complete isolation from any human contact, so all process steps must be applied using remotely operated technologies to avoid contamination of people or external surfaces/equipment. Among key issues to assess was how the powder would be fully contained as it is fed from a container through a fine tube into a canister for the HIP process.

NDA Research Manager Rick Short observed the work in progress: "The US trials were partially successful but further modifications are required to ensure the integrity of the process so that no residue remains outside the canister. Developing these steps on an industrial scale is key towards identifying a process as a potential final solution for plutonium immobilisation."

The trials will contribute to identifying the best technical solutions for immobilising UK plutonium.

Current research projects are focused on HIP technologies and include trialling HIP with real plutonium on a small scale and investigating industrial-scale HIP using an inactive plutonium substitute.

NDA DRP case study

Challenge: To identify a suitable technology for filling cans with plutonium and glass-forming materials, as part of ongoing research into Hot Isostatic Pressing (HIP).

Solution: Joint investigations into aspects of an existing HIP treatment currently used for other materials

Technology: Hot Isostatic Pressing (HIP)

Status: Analysis taking place of existing supplier's technology to establish if it can be successfully adapted

Research organisations: National Nuclear Laboratory, GeoRoc International Ltd and NuVision Engineering

Innovation route: Direct Research Portfolio contract

Web: www.nnl.co.uk
www.georoc.co.uk
www.nuvisionengineering.com

Right: Observers at the US can-filling demonstration

Concrete-based materials can generate highly alkaline and metal leachate when exposed to water

Concrete plans on rubble recycling

Research is under way to quantify the environmental implications of dealing with the huge quantities of concrete rubble that will arise as facilities across the NDA's 17 sites are demolished following decommissioning and clean-up.

Some rubble will be radioactive but the vast bulk will be conventional material that could be re-used, for example, in landscaping, void infill or as aggregate. Re-use on site will save time, costs and environmental damage by minimising the need to transport rubble off-site for disposal, or import material for voids and landscaping.

However, recycled concrete-based materials, or RCM, also generate highly alkaline and metal leachate when exposed to water. Leachate can enter groundwater, drains or surface water, affecting surrounding ground characteristics, vegetation and wildlife.This

Some rubble will be radioactive but the bulk will be conventional material that could be re-used

could undermine environmental and cost savings, potentially breaching regulatory guidelines. The NDA commissioned research to analyse the risks and consider methods for treating RCM before re-use.

Quantities are significant: the 10 Magnox reactor sites are estimated to generate 1.3 million tonnes of concrete in future decades. Transporting this to inert landfill sites will require 140,000 truck movements at an estimated cost of almost £150 million. Another 1.5 million tonnes will be generated by Sellafield.

Re-use of RCM is common in construction and demolition industries, but tends to occur immediately after it has been generated and is often used in shallow voids such as roads.

By contrast, demolishing cleaned-up nuclear facilities with deep foundations (for example, turbine halls or reactor buildings) will create large voids, and RCM stockpiles may require storage for decades before re-use.

Leachate characteristics vary depending on individual concrete compositions, coarseness, level of compaction, duration of exposure to air/water and surrounding land. Although the risks are well-known, a range of different regulatory protocols have created uncertainty and widely varying approaches to the options for management.

The research involved engagement with a range of industries, especially the demolition sector, as well as SLCs, together with analysis of technical literature and consultations with regulators.

The result is, for the first time, a comprehensive outline of the possible environmental consequences of RCM re-use in different scenarios. Recommendations are now being developed to support demolition planning and drafting of a consistent, rigorous approach.

NDA DRP case study

Challenge: Deal effectively with large quantities of concrete rubble generated by demolition activities across 17 sites.

Solution: Undertake research to analyse available technical evidence, current practices and regulations, with a view to developing protocols and guidance that will help avoid unintended environmental consequences, while reducing costs.

Status: First stage of research complete and published.

Research organisations:
AECOM, supported by NSG and KDC.

Innovation route: Direct Research Portfolio (DRP) contract.

Web: www.aecom.com, www.nsgltd.com and www.kdc.co.uk

Right: Demolishing facilities, such as the Dungeness turbine hall, will generate vast amounts of rubble

RWM's post-closure safety case team and, below, the ViSI digital system

Visual key to the deeper truths

Radioactive Waste Management Ltd case study

Challenge: Devise a user-friendly method of making accessible the wide range of information in a multi-volume safety case for the UK's future Geological Disposal Facility (GDF).

Solution: RWM designed and built an intuitive digital system that stores the safety case and allows it to be easily viewed, summarised and searched.

Technology: A new web-based digital system - ViSI

Status: System designed, tested and functional, with ongoing improvements

Research organisations:
Post-closure safety team at Radioactive Waste Management Ltd.

Innovation route: In-house concept and development.

Web:
www.gov.uk/government/organisations/radioactive-waste-management

Radioactive Waste Management (RWM) published a set of generic safety cases in 2016 for a GDF constructed in a range of geological environments.

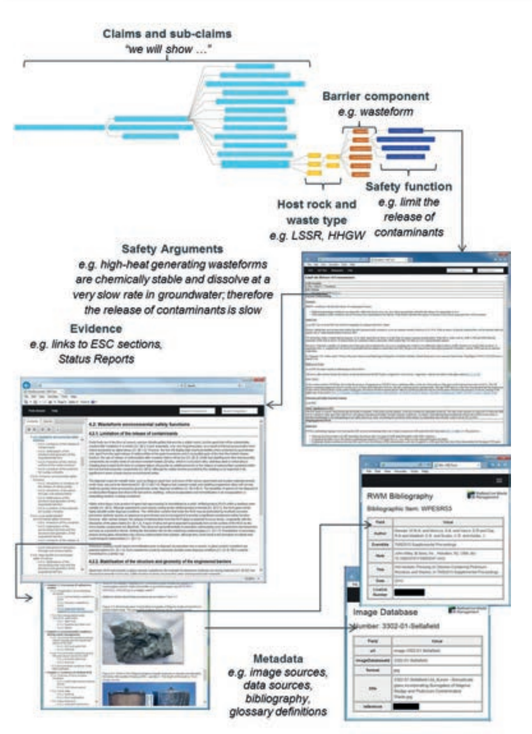
These explain how a GDF will operate safely and isolate and contain the waste, protecting people and the environment for hundreds of thousands of years.

Such safety cases can run to thousands of pages. In addition there is a wide range of underpinning information and research that provide the evidence. The information is of major importance to a wide range of audiences needing to trace the scientific and engineering basis for the safety case claims. However, sifting through such volumes of material poses a potentially overwhelming challenge. The diverse audiences likely to need an understanding of the contents include technical groups such as nuclear regulators, scientific and environmental experts and supply chain businesses - but also politicians at all levels, campaign groups and community residents. As the 2016 safety case was being written, it became clear that making the material more traceable would be of immense value.

Starting with hand-drawn 'spider diagrams', it was seen that visualisations would be key to realising the aim of displaying the logic flow through a safety case. Software tools for displaying flowcharts were exhaustively researched, trialled and then combined with digital publishing tools to create a set of diagrams that directly linked into the safety case documents, thus developing a multi-faceted digital system.

The result is ViSI: a unique digital tool developed in-house by RWM's post-closure safety team and now undergoing further development in the supply chain. In this tool, users can browse reports intuitively, much like a wiki, following lines of argument. Information can easily be accessed with easy-to-use, powerful search options.

The structure of the safety case's claims, arguments and evidence are visualised as a flowchart. Users can explore this diagram with different style options and expand or



contract content as they wish and directly navigate to underlying content in the safety case documents.

The tool has attracted interest from other waste management organisations in the UK and overseas, as well as from regulators.

Decommissioning Dounreay's DFR is one of the UK's most significant nuclear challenges

Odds are on the Monte Carlo system

Before the experimental Dounreay Fast Reactor (DFR) can be dismantled, a clear understanding is required of radiation levels, and their distribution, inside the shielded vault that houses the radioactive core.

DFR was the world's first fast breeder reactor to supply electricity to a national grid, playing an important part in research for fuel and coolant technology. Decommissioning the DFR is one of the UK's most significant nuclear challenges.

As workforce access to DFR's interior is impossible, measurements were taken using a variety of tools deployed through the dozens of openings. Among other items, the vault contains graphite, tanks, vessels, heat exchangers and ring main contaminated with residual sodium potassium liquid metal coolant, NaK.

Almost 70 tonnes of highly radioactive and chemically reactive NaK were destroyed over 10 years in a purpose-built plant, and dealing with remaining contamination is a key challenge.

The team opted to use the Monte Carlo N-particle (MCNP) code, a powerful and highly specialised simulation software

Four different systems were used to collect data, including the compact N-visage® gamma imaging scanner, which was developed by Cumbria-based Createc with support from the NDA's research budget and Innovate UK.

Senior Characterisation Specialist Vittoria Baldioli said: "Work to build a comprehensive picture of the vault's inventory, including radioactive hotspots, has been under way for a number of years.

"It's also important to predict how conditions will change once decommissioning starts and items are retrieved. This will enable us to assess the possibility of future workforce access."

Data from all techniques provided large quantities of information but did not represent the entire vault. The team opted to use the Monte Carlo N-particle (MCNP) code, a powerful and highly specialised simulation software developed by the Los Alamos national lab, used globally for safety, radiation and shielding problems.

A 3D MCNP model of DFR's vault was constructed using all available information, and gradually adjusted to achieve a match between measured and theoretical dose rate, indicating accurate modelling of activity distribution.

The model will support decommissioning, modified when necessary, and used to determine dose rate changes outside the vault, through the effects of shielding, and inside as components are removed. It will be of particular value for addressing contamination levels, and can also be applied at other decommissioning sites in the NDA group.

Dounreay case study

Challenge: Understand distribution and inventory of radioactivity in the Dounreay Fast Reactor's shielded vault, enabling decommissioning plans to be drawn up.

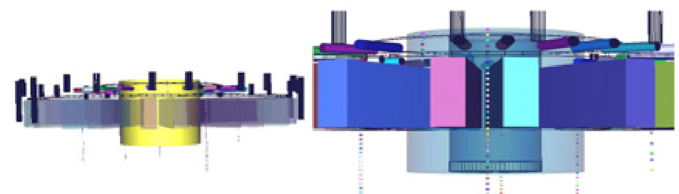
Solution: Collate data from all available radiation-measuring techniques and combine with specialised modelling to obtain a comprehensive dose rate map.

Technology: Monte Carlo N-particle code, spectroscopy, imaging and visual inspection devices.

Status: System designed, tested and functional.

Research organisation: Dounreay in-house team.

Web: www.dounreay.com
www.createc.com



Rigjt: A large scanner is lowered into the vault


The HPLC technique enabled a complexants monitoring strategy to be defined

Acid test leads to nuclear career

Former University of Manchester PhD student James O'Hanlon opted for a career in nuclear decommissioning after completing a project that led to a new leachate monitoring strategy at the UK's main repository for Low Level Waste (LLW).

When the repository first opened in 1959, waste was tipped into clay-lined trenches, a practice that ended in 1995. Today, highly engineered vaults receive LLW that cannot be diverted, recycled or subjected to alternative, more sustainable treatments.

As part of compliance with environmental regulations, the site regularly analyses all aspects of its treatment and disposal processes, including the condition of surrounding land and groundwater. James' doctoral study, sponsored by the NDA group, involved research into the latest procedures for assessing the precise concentration of organic complexants in leachate from the old trenches. Aminopolycarboxylic acids arise in waste due to their use as decontamination agents, however, these chemicals can become mobile, enabling transport of solid radionuclides to groundwater and the repository.

"It's vital to develop and recruit specialists like James to support some of the highly technical challenges in our mission."

NDA Research Manager, Dr Rick Short

As a result, their acceptance in consignments is restricted and their environmental concentration is monitored. In support of this, James successfully used high-performance liquid chromatography (HPLC) to identify and quantify individual complexants in trench leachate. James assessed the latest technologies and, with HPLC, established that samples from the trenches contained aminopolycarboxylic acids in concentrations well within the acceptable limits outlined in the Environmental Safety Case (ESC) approved by the Environment Agency.

He said: "There is an ongoing need to detect and quantify these complexants, using the latest and best technologies to ensure compliance with the limits for the entire site – these cover the vaults as well as the historic trenches. This is part of our work to protect both people and the environment."

The HPLC procedure enabled a complexants monitoring strategy to be defined, and also proved its cross-sector value for the Ministry of Defence, who needed to establish whether levels of aminopolycarboxylic acid complexants in incinerated resin waste from Rosyth naval base would meet criteria for disposal at the repository.

The NDA mission benefitted from both the research and sponsoring James, who is now a full-time technical specialist on LLWR's ESC team, adding to the expertise available for future decommissioning challenges.

LLWR case study

Challenge: Understand precise levels of potentially hazardous non-radiological species in leachate from historic trenches used for waste disposal at LLWR before 1995.

Solution: PhD research into the latest and most accurate technologies.

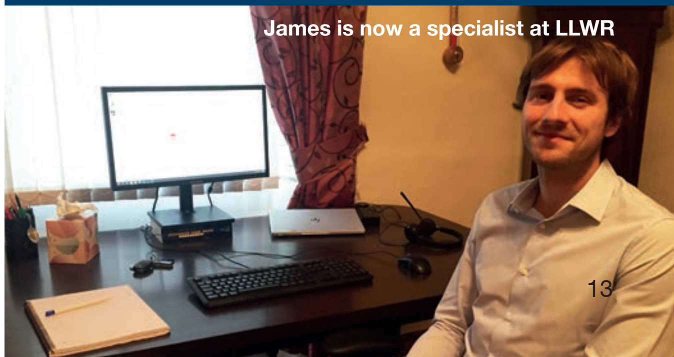
Technology: High-performance liquid chromatography, HPLC.

Status: Technology successfully tested and deployed, forming the basis for a new monitoring strategy.

Research organisations: University of Manchester doctoral student.

Innovation route: Research supported by Industrial Co-operative Awards in Science & Technology (ICASE), which provides funding for PhD studentships where businesses, in this case LLWR, take the lead in arranging projects with an academic partner.

Web: www.epsrc.ukri.org/skills


James is now a specialist at LLWR

Robotics

Robotics are becoming indispensable in tackling our mission, helping to safeguard the workforce, accelerate progress and save costs. We are collaborating with other research organisations and industries, as well as the supply chain, to harness opportunities for further developments and maximise funding.

Innovate UK

Department for Business, Energy & Industrial Strategy

Robotic adventures with our own IINDe competition

An £8.5 million competition was launched in 2017 to find technologies that could be combined into a single, seamless process to help dismantle some of the most radioactive facilities at Sellafield and other nuclear sites.

The Integrated Innovation in Nuclear Decommissioning (IINDe) competition was collaboratively funded by the NDA, Innovate UK and BEIS. Full funding was offered for collaborative projects to devise technologies that would access highly contaminated structures, efficiently manage waste, reduce risks to workers, increase productivity, reduce timescales and cut costs to taxpayers.

The challenge was to combine stand-alone technologies and integrate them into a single remotely operated system with smooth interaction between the different component parts. Robotics, artificial intelligence, virtual reality, autonomous navigation, and conventional engineering equipment all featured in the projects. The successful system, or systems, will first be deployed at Sellafield's Thermal Oxide Reprocessing Plant, which ended operations in 2018, and the Magnox Reprocessing plant which will also cease operations in the near future. The potential, however, could be far-reaching for industries operating in hazardous environments in the UK and overseas.

The integrated technology (or technologies) will establish what is inside scores of reprocessing cells, measure radioactivity, access spaces that have been sealed for years, cut up the contents (including large vessels and many miles of pipework), segregate the waste, then safely remove it for treatment and storage.

Entries came from existing nuclear suppliers, academic institutions and other research organisations, together with a strong interest from newcomers. Non-nuclear industries included gaming, sea fishing, medical imaging, fume extraction, space, defence, oil and gas.

An initial 15 projects were whittled down to a shortlist of five. Following demonstrations in non-radioactive environments, two were selected to carry out further trials in one of Sellafield's radioactive facilities.

"Through this competition, we wanted to harness the expertise of other industrial sectors and provide significant funding to the supply chain.

"We worked closely with Sellafield from the start, as the site will ultimately use the technology. This ensured the projects address every aspect of what would be needed.

"The joint initiative with Innovate UK and BEIS also helped to maximise the level of funding available and embrace a wider audience."

Prof Melanie Brownridge

NDA and Innovate UK case study

Challenge: Develop a seamless remote system to decommission highly contaminated facilities.

Solution: Development of new technologies, or integration of existing technologies, through funded open competition.

Technology: Varied but including robotics and virtual reality from different sectors.

Status: Two projects selected for demonstration in active Sellafield facility.

Research organisations: Barrnon Ltd and Jacobs.

Innovation route: Collaborative funding with Innovate UK and BEIS, plus working with Sellafield Ltd to identify technical scope.

Web: www.gov.uk/government/organisations/innovate-uk
www.barrnon.com
www.jacobs.com

IINDe case studies follow on pages 16-17

Barrnon

Based in Cumbria, Barrnon is a small business that provides bespoke engineering solutions to industries operating in hazardous environments.

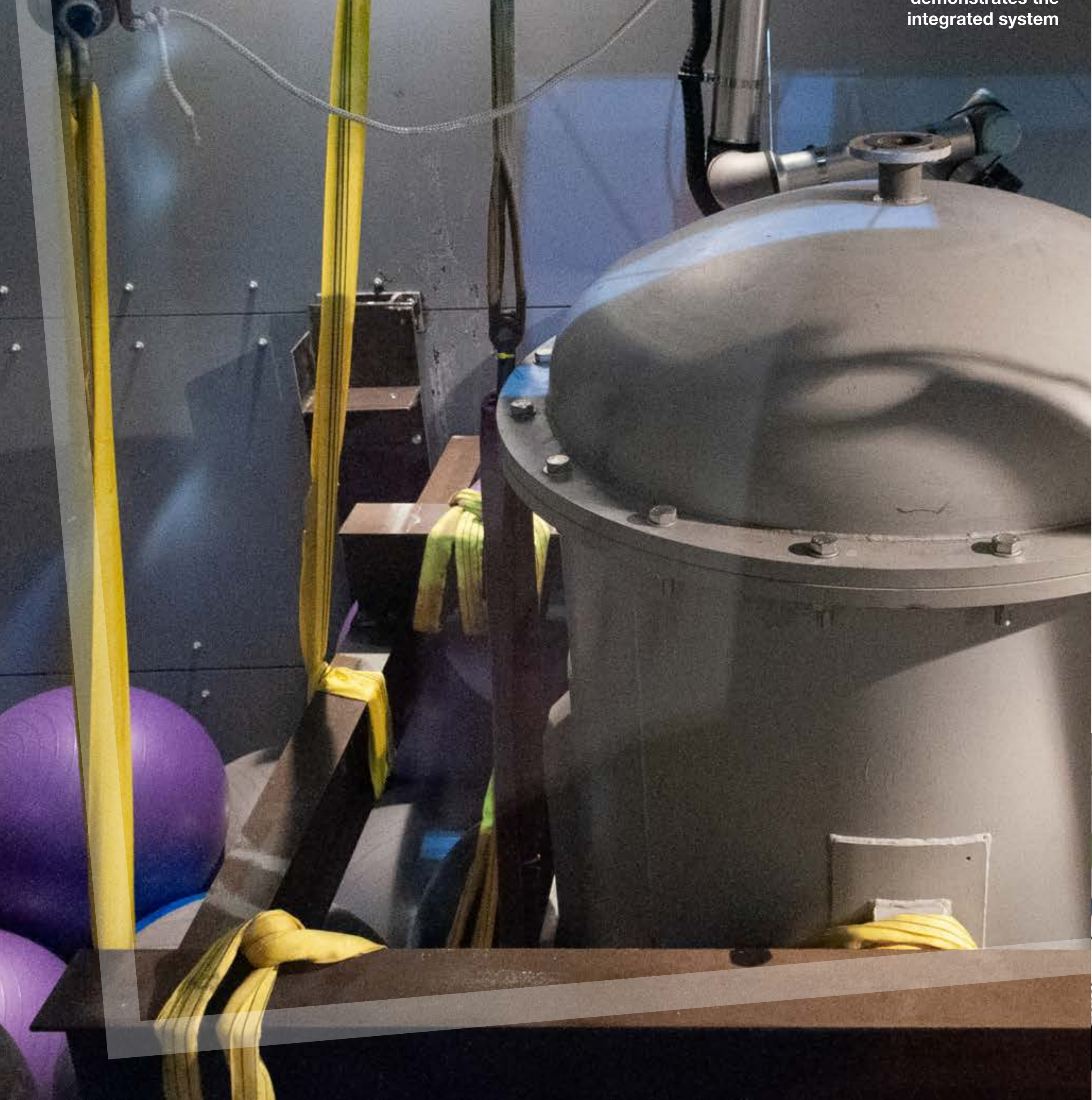
Barrnon's project comprises a tracked platform with hydraulic arms, each carrying a robot to operate a selection of tools that will characterise, decontaminate and dismantle cell contents up to five metres away. Once inside, a 360-degree scan with the Light Detection and Ranging process, or LiDAR, (using pulsed laser light) locates surfaces and senses gamma radiation. This builds up a map of radioactive contamination.

Located a safe distance away, the operator can view the 3D image, effectively walking around, analysing the layout and inspecting contaminated hotspots. A hand-held scanner, controlled by the remote operator, can check for alpha and beta contamination.

Advanced algorithms are used to analyse the surface contamination data, resulting in a plan for the most efficient way to segregate and pack the waste. The operator's array of tools includes laser-cutting, robots with mechanical arms, circular saw, stud welding and sludge removal.

Barrnon consortium: *Createc, Cambrian Intelligence, Atkins and IHI.*

Barrnon's David Main, right, with the Mantis robotic system



Ged McGill, below right, from Jacobs, demonstrates the integrated system

Jacobs

Multinational energy services business Jacobs operates across a broad range of industrial markets.

Jacobs' project enables planning and waste characterisation to take place on location, in real time, effectively bringing the laboratory onto site.

Located remotely, the operator wears a headset to remain in a 'mixed reality' that allows virtual objects to appear intuitively in a physical world. Interchangeable tools can be deployed, including laser-cutting equipment and a dexterous multi-fingered robot that grips and segregates objects. To enable autonomous mapping of cells where worker access is too hazardous, a navigation system, initially designed for space missions is integrated into this single system.

Large items located at height in the cells, such as vessels, will be size-reduced and gently brought to ground level with a novel system based on inflatable gym balls, reducing the risks of spreading contamination.

Jacobs consortium: *Airbus Defence and Space Ltd, Clicks and Links Ltd, Damavan Imaging SAS, Digital Concepts Engineering Ltd, IS-Instruments Ltd, I3D Robotics Ltd, The University of Lancaster, The University of Salford and TWI.*

Robotics and AI are being developed through the RAIN hub

Robots demonstrate collaboration at work

The Robotics and Artificial Intelligence in Nuclear (RAIN) hub was established in 2017 with £12.2 million from the government's Industrial Strategy Challenge Fund.

Led by Prof Barry Lennox at Manchester University, RAIN brings together academic experts in robotics and nuclear science from 10 universites together with the UK Atomic Energy Authority's (UKAEA) Remote Applications in Challenging Environments (RACE) centre.

RAIN now has 60 academic, technical and administrative staff. The motivation for RAIN came from the need to cut costs, improve productivity and reduce risks to the workforce. Deterioration of ageing nuclear facilities, where access is often problematic, added to the impetus. The Government's Nuclear Sector Deal also calls for action to reduce costs of decommissioning and new build by 20%-30%. In just over 2 years. RAIN's unique collaborative drive has already led to notable achievements while attracting interest from businesses working in other extreme environments, such as offshore industries and space exploration. Sectors such as agriculture, energy and food cleaning have also expressed interest.

To achieve success, RAIN operates very differently to other academic-led research programmes, with greater emphasis on collaboration and demonstrations to industry. From the outset, research programmes focused on alignment with industry needs. Three academic/industry working groups prioritised challenges as:

- Remote inspection
- Remote handling
- Safety case aspects, enabling regulator endorsement and, as a consequence, improving the potential for commercial uptake

RAIN is aiming to become a national centre of excellence in nuclear robotics, delivering world-leading research.

Some 'firsts' include:

- Deployment of a fully autonomous robot (CARMA) at Sellafield
- Deployment of a robot (MIRRAX) into Sellafield's active Magnox Reprocessing Facility
- Successful trial of small, low-cost radiation-mapping robot, Vega, in active waste store at Dounreay and non-active area at Dungeness A
- Remote mapping of LLW drum stores at Culham and Harwell
- Measurements, using a submersible robot, of neutron flux and gamma field inside an active nuclear reactor
- LiDAR scans at the Joint European Torus fusion project

Meanwhile, multiple technology demonstrations have taken place to hundreds of industry experts in the UK and overseas; more than £7 million of additional funding has been provided from industry and research councils for further research and development of commercial systems; a spin-off company has already sold 70 robots to universities in the UK and Europe.

Support in kind has been provided by NDA group businesses, sharing challenges to ensure research focuses on real challenges and providing access to facilities where appropriate.

Right: Radiation-mapping robot Vega has been trialled at Dounreay

Collaborating across government funders: case study

Challenge: Reduce risks to workforces involved in dismantling the UK's early nuclear legacy and minimise the costs of new build.

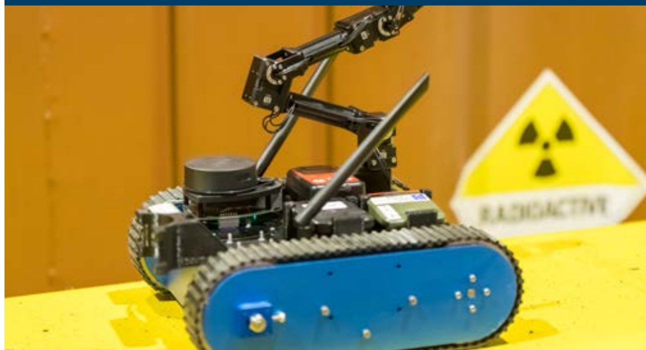
Solution: Establishment of government-funded Robotics and Artificial Intelligence in Nuclear (RAIN) body, that combines cross-UK academic research with industry expertise to stimulate development of cutting-edge solutions.

Status: RAIN consortium, established in 2017, has already seen a number of new robotic technologies and AI systems successfully deployed, while attracting additional funding and overseas interest.

Research organisations:
10 universities and the UK Atomic Energy Authority's (UKAEA) Remote Applications in Challenging Environments (RACE) centre.

Innovation route: Via the UKRI's Industrial Strategy Challenge Fund.

Web: www.rainhub.org




The SEID drone is available in several different versions

Small but perfectly formed

Unmanned aerial vehicles (UAVs), or drones, are now commonplace in many industrial environments, including nuclear.

Mounted with equipment such as cameras and/or radiation sensors, they can be deployed internally and externally at locations that are dangerous or difficult to access, for example, at height.

Workforce entries into hazardous conditions can be minimised, while savings in time and resources could potentially be significant.

Sellafield's Site Ion Exchange Effluent Plant (SIXEP), which opened in 1985, treats pond water from various fuel storage ponds, removing radioactive solids through a filtering and ion-exchange process before safe discharge into the sea. A vital facility for the entire site, SIXEP has operated successfully for decades, but its small-diameter access ports pose challenges for any maintenance work or regular inspections.

The University of Manchester has developed several UAV systems under the RAIN-funded Small Entry Inspection Drone (SEID) project

A detailed visual assessment of the interior, including pipework and storage vessels, will enable decisions on a potential extension to its operational life.

Hand-held pole-mounted cameras can provide visual information on areas near the access port, but are of limited value for comprehensive detail. UAVs can potentially provide far more detail, however, most commercial models are either too large or unable to carry sufficient payload.

The University of Manchester has developed several UAV systems under the RAIN-funded Small Entry Inspection Drone (SEID) project to provide capability in facilities such as SIXEP. The UAVs carry a high-resolution inspection camera and lighting systems, while 3D mapping and visual odometry (using data from motion sensors to estimate change in position over time) assist the pilot to navigate complex facilities and avoid obstructions.

A small platform holds the UAV as it slides through the port, taking flight once inside. In situ charging, via the platform, is being developed to allow for extended surveys without the need to extract the equipment. Several prototypes have now been tested, based on extensive modification of commercial off the-shelf equipment as well as bespoke designs.

Data from a successful SEID inspection would inform future decisions on a SIXEP upgrade, and on a contingency plant project that is currently under review.

SEID also has potential for deployment at other Sellafield facilities and across the wider NDA group.

Right: Small enough to fit through a restricted opening

Collaborating across government funders: case study

Challenge: Secure understanding of conditions inside highly radioactive nuclear facilities where access is restricted by small inspection and repair ports.

Solution: Design and build a small-scale aerial device (drone) that can operate remotely and deployed through ports of up to 25cm in diameter.

Technology: Airborne Small-Entry Inspection Device (SEID).

Status: SEID tested in a low-contamination environment at Sellafield. Further developments are under way.

Research organisations: University of Manchester in collaboration with Sellafield Ltd.

Innovation route: Through the UKRI-funded Robotics and Artificial Intelligence in Nuclear (RAIN) hub.

Link: www.rainhub.org

Robotics specialist Arron Griffiths working on CARMA

Clever CARMA follows its own path

The floor-mapping CARMA robot was the result of close collaboration between Manchester University's School of Electrical and Electronic Engineering and Sellafield.

Sellafield was seeking a remotely operated technology that would protect the health physics team from unnecessary exposure to contamination and measure radiation ground-level hotspots more effectively.

The team is responsible for the regular manual monitoring of roads, buildings, waste packages, equipment and people, often using hand-held devices to detect alpha, beta and gamma contamination.

Alpha contamination presents a particular challenge: to ensure reliable detection, sensors must be a few centimetres from the source, a process that is extremely time-consuming over large areas and dependent on operator vigilance during the survey.

The first prototype, designed to cover flat indoor surfaces, was able to carry highly sensitive pre-programmed radiation-monitoring equipment capable of generating geometric and radiological maps

The aim with CARMA was to reduce health risks, time and costs, while securing greater accuracy in radiation monitoring. Workers freed from repetitive routine activities would be able to focus on tasks requiring a greater level of complexity and skill.

The first prototype, designed to cover flat indoor surfaces, was able to carry highly sensitive pre-programmed radiation-monitoring equipment capable of generating geometric and radiological maps. The operator can be located in a separate facility, as the 2D map gradually builds on a computer screen.

Existing sensing technologies were brought together on the CARMA robot, which navigates autonomously and maps radiation but comes to a halt at contaminated areas to avoid further spreading of material, creating a visual exclusion zone. CARMA can also be programmed to travel across pre-determined areas.

A second-generation more rugged model was mounted on a four-wheel chassis for use outdoors, with a moveable camera mounted at height.

CARMA was successfully demonstrated at Sellafield's Thermal Oxide Reprocessing plant and was due to be deployed outdoors in the compound of the former Calder Hall power station. It is the first fully autonomous inspection vehicle to be deployed at the site.

The long-term vision is to have a fleet of CARMA robots continuously monitoring facilities like the Sellafield sites. Its development has already attracted interest from overseas, including Japan and Canada.

CARMA, right, maps ground radiation

Sellafield case study

Challenge: Identify areas of radioactive contamination across large areas of internal and external ground space at Sellafield.

Solution: Fully autonomous tool-carrying robotic vehicle.

Technology: Continuous Autonomous Radiation Monitoring Assistance (CARMA).

Status: Vehicle designed, tested and deployed in an active area, with potential for wider commercial deployment.

Research organisations:
University of Manchester and Sellafield Ltd.

Innovation route: Through the UKRI-funded Robotics and Artificial Intelligence in Nuclear (RAIN) hub.

Web: www.rainhub.org.uk

The Oldbury team cut up a skip in air

In-house teams ponder the tech options

All Magnox spent fuel ponds have individual configurations, with varying levels of contamination and complexities.

Sizewell A's single pond, with five bays, was designed to receive and store skips of spent fuel before they were dispatched to Sellafield for reprocessing. Oldbury also has a single pond with five bays but its different configuration effectively rules out straightforward replication of the same clean-up processes.

At Sizewell, specialist US divers cut up empty skips plus around 70 tonnes of pond equipment, collected miscellaneous items and pumped out most of the sludge. A small remotely operated submersible vehicle (ROV), acquired second-hand from Bradwell, assisted with inspections of remaining items and structures and led the team to opt for a newer model, equipped with additional grab and manipulator tools to retrieve lightweight items. Subsequently, this larger model, the Defender, was added to the toolkit for loads of up to 25kg. To remove the remaining sludge, the team designed an additional set of interchangeable sludge-removal tools and constructed them in-house using surplus equipment.

To protect workers from skip radioactivity, the team designed steel shielding, and sourced a local manufacturer

Extensive testing took place at a local dive pool and in a collapsible pool brought to site for trials. Sizewell's successful deployment of the uniquely customised Defender marked its first use for nuclear sludge in the UK. The equipment is now ready and available for other sites, as well as the wider nuclear industry.

While Sizewell's skips had been cut up by divers who were shielded from radiation by the water, Oldbury skips were lifted out whole by a conventional hoist before being size-reduced in air. The site's less cluttered and cleaner pond – benefitting from the operational experience of the older Magnox sites – allowed for conventional techniques.

To protect workers from skip radioactivity, the team designed steel shielding, and sourced a local manufacturer to follow their specification. This covered the skips as cutting operations took place. A bracing mechanism prevented the skip sides from collapsing when the shielding was removed. Once the water was drained, the Oldbury team deployed a miniature electric car, an innovation borrowed from Hinkley Point A, which cost a few hundred pounds and was fitted with a remote dose monitoring system to check conditions on the pond floor before people were allowed in.

Right: Tailor-made tools for the Defender were designed by Sizewell staff

Magnox case study

Challenge: Remove empty spent fuel skips, sludge and debris from Sizewell and Oldbury ponds before draining water.

Solution: Use learning from earlier pond clean-ups, modified for individual sites, to include in-house customised toolkit for sludge removal and tailor-made steel cover.

Technology: VideoRay Pro 4 and Defender vehicles, plus purpose-designed steel cover.

Status: Solutions designed, built, tested and deployed, now available for other nuclear sites.

Research organisations: Collaboration between Bradwell, Oldbury, Hinkley Point A and Sizewell A

Innovation route:
In-house engineering teams.

Web: www.videoray.com

“Innovation is also about taking a different approach to a problem, harnessing existing technologies in new combinations or working with non-nuclear industries – thinking more creatively in order to add value”

Sara Huntingdon, Head of Innovation

The NDA’s Grand Challenges for Technical Innovation

Huge potential exists to take advantage of technologies used in other sectors and the work of other government departments. Earlier in 2020, the NDA set out a series of ambitious innovation targets for the next 10 years. Based on four themes, the Grand Challenges for Technical Innovation are aimed at stimulating discussion, encouraging supply chain development of technologies and helping deliver the mission more effectively.

Challenge Theme	By 2025	By 2030
Reducing waste and reshaping the waste hierarchy	70% of all initial characterisation undertaken in situ, with results available within 24 hours.	Recycling 50% of waste produced from decommissioning and clean-up.
Intelligent infrastructure	All external monitoring of buildings carried out remotely.	All new buildings to be self-monitoring and energy neutral - with a 50% lifetime cost reduction.
Moving humans away from harm	Remote decommissioning of gloveboxes.	50% reduction in decommissioning activities carried out by humans in hazardous environments.
Digital delivery - enabling data-driven decisions	Accurate and up-to-date 3D virtual models for all key NDA sites.	All data captured at source and used in decision-making, planning and training.

Contractors currently supporting the NDA's Direct Research Portfolio

This table highlights the diversity of supply chain organisations bringing excellence in innovation to our R&D programme

<table>
<tr><th>Contractors</th><th>Consortium</th><th>R&D Objectives</th></tr>
<tr><th colspan="3">University Interactions</th></tr>
<tr><td>National Nuclear Laboratory</td><td>Frazer-Nash Consultancy Ltd, Arup, National Physical Laboratory.</td><td>To ensure the right level of academic technical capability is available</td></tr>
<tr><th colspan="3">Integrated Waste Management and Site Decommissioning and Remediation</th></tr>
<tr><td>DBD</td><td>AECOM, Amentum, Westinghouse (WEC), United Kingdom Atomic Energy Authority (UKAEA) and University of Sheffield including AMRC (UoS).</td><td rowspan="6">Integrated Waste Management
Higher Activity Wastes (HAW)

• Development and analysis of options for HAW management.
• Development of innovative technologies.
• Sponsoring R&D that enables the NDA to respond strategically to government policy and oversee SLCs' HAW work.
• Lower Level Wastes, non-radioactive and hazardous
• waste
• Sponsoring R&D that enables the NDA to respond strategically to government policy and oversee SLCs' work on these wastes.
• Site Decommissioning and Remediation
• Technical underpinning for the NDA's strategy on decommissioning, land quality and site end states.</td></tr>
<tr><td>Galson Sciences Ltd</td><td>National Nuclear Laboratory, Frazer-Nash Consultancy Ltd, Amphos 21, Lucideon, Mott MacDonald Ltd, Resolve Robotics Ltd, VTT Technical Research Centre of Finland, Orano, Veolia and Universities of Bristol, Lancaster and Sheffield.</td></tr>
<tr><td>Eden Nuclear and Environment Ltd</td><td>Cyclife EDF, Gardiner & Theobald, Golder Associates (UK) Ltd, Hydrock Consultants Ltd, Integrated Decision Management (IDM), University of Bristol, WSP UK Ltd,.</td></tr>
<tr><td>Jacobs</td><td>Andra, CL:AIRE, British Geographical Survey, NPL, AFRY, Arup, Brenk Systemplanung, Costain, Thornton Thomasetti, Urenco, Croft, Cogentus, Decision Analysis Services, Longenecker and Associates, MCM, Imperial College London, Universities of Birmingham, Bristol and Manchester.</td></tr>
<tr><td>NSG Environmental Ltd</td><td>Abbott Risk Consulting, KDC, Quintessa Ltd, RPS Consulting Services Ltd, SOCOTEC UK Ltd, The University of Sheffield including Nuclear AMRC (UoS) and Veolia Nuclear Solutions, Lucideon, Mirion Technologies, STERIS and The University of Manchester.</td></tr>
<tr><td>Nuvia</td><td>TÜV UK (TÜV NORD), CIEMAT, Createc, Cognition Land and Water, Lucideon, NucAdvisor, Empresarios Agrupados.</td></tr>
<tr><th colspan="3">Spent Fuel and Nuclear Materials</th></tr>
<tr><td>DBD</td><td>AECOM, Amentum, Westinghouse (WEC), United Kingdom Atomic Energy Authority (UKAEA) and University of Sheffield including AMRC (UoS).</td><td rowspan="5">• Sponsoring R&D that enables the NDA to set and monitor SLC delivery of our strategy on Magnox spent fuel, oxide spent fuel, exotic fuels and uranics.
• Ensuring skills in spent fuel management and plutonium handling are maintained over the longer term.
• To support NDA development of options for managing the UK's uranics inventory and stockpile of separated plutonium.
• Sponsoring R&D that enables the NDA to respond to government policy and oversee SLC activities on management of uranics and plutonium</td></tr>
<tr><td>Eden Nuclear and Environment Ltd</td><td>Integrated Decision Management (IDM), NSG-Environmental Ltd, Nuclear-21, TÜV UK (TÜV NORD) and the University of Bristol.</td></tr>
<tr><td>Jacobs</td><td>Andra, Pacific Northwest National Laboratory, British Geographical Survey, NPL, Arup, Brenk Systemplanung, Thornton Thomasetti, Urenco, Studsvik, Croft, StrataG, GRI Ltd, Decision Analysis Services, Longenecker and Associates, Thor Energy, Loughborough Materials, Integrity Corrosion Consulting, Gary Was Consulting, Nigel Donaldson Consulting, Imperial College London, Universities of Birmingham, Bristol, Cambridge, Manchester, Oxford and Sheffield.</td></tr>
<tr><td>National Nuclear Laboratory</td><td>Frazer-Nash Consultancy Ltd, Galson Sciences Ltd, GRI Ltd.</td></tr>
<tr><td>Orano</td><td>EDF Energy, Cavendish Nuclear, Lucideon, Galson Sciences Ltd, Universities of Manchester and Sheffield.</td></tr>
</table>

This brochure briefly outlines some examples of recent investments.
If you want to find out more, please visit our website www.nda.gov.uk or email: research@nda.gov.uk