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Nuclear Future

The professional journal of the Nuclear Institute
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"We have to make sure that we offer role models and career paths"

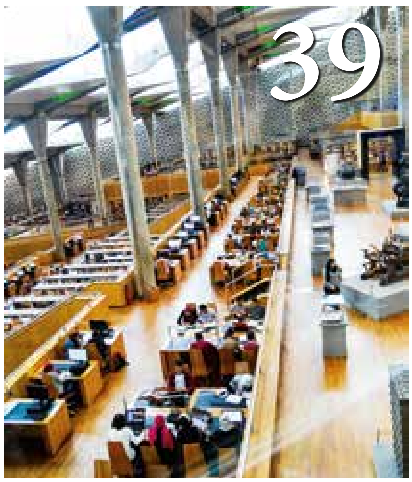
Gwen Parry-Jones, Chief Executive of Magnox and incoming President of the Nuclear Institute, is on a mission

ANALYSIS
Is it time for nuclear's digital revolution?

FOCUS
Safety and Security R&D project

YGN MYTHBUSTERS
Revisiting Chernobyl

• Network • Learn • Contribute •



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COVER PHOTO: Magnox ©2019

PRESIDENT'S PERSPECTIVE

And as I bow out...

Progress on renewing our nuclear capacity must still improve


John Clarke

It seems astonishing to me that this is my final contribution to *Nuclear Future* as President of the Nuclear Institute. My two-year term seems to have flown by and while not everything that I set out to achieve has been possible, I believe we have strengthened our governance arrangements and made progress on addressing our financial position and our member value proposition. But there remains more to be done.

September's AGM, timed to coincide with the very successful YGN speaking competition, focused largely on the challenges facing the NI and the actions we are taking to address them. Controlling costs is key to any organisation, but so too is driving up income – through increased membership, successful events, sponsorship etc. It is only through a combination of these that we will have the funds available to deliver on our charitable objectives and provide increased member value. A small working group has been established to review the actions currently being undertaken and to consider further actions we might take to further aid progress. I am grateful to those who are contributing to that work and intend to ensure that its output is shared early in the new year.

As I've mentioned in many of my columns over the past couple of years, progress on renewing our nuclear capacity in the UK has been disappointingly slow. That said, I remain confident that nuclear has a crucial role to play, now and into the future, in supporting a growing, sustainable, low carbon economy. Political will is required to make that happen. But, when circumstances do allow, I have no doubt that the professionalism, dedication and innovation shown by the nuclear community over many decades will enable real progress to be made.

It has been a huge honour to have been President of the Institute for these past two years. I am very grateful for the support I have been given by my fellow trustees, by members more widely and the NI's staff team. I very much look forward to continuing to serve as a trustee and particularly to supporting Gwen Parry-Jones during her term as President.

"It has been a huge honour to have been President... I am very grateful for the support I have been given by my fellow trustees, by members more widely and the NI's staff team. I very much look forward to continuing to serve as a trustee and particularly to supporting Gwen Parry-Jones during her term as President..."

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THURSDAY 13TH FEBRUARY 2020 18:30PM

Energus

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GUEST SPEAKER GWEN PARRY-JONES OBE

the nuclear institute cumbria branch

Standard ticket rate £80pp + VAT
Contact Nuclear.Institute@sellafieldsites.com for information about sponsor opportunities and tickets

Chief nuclear inspector gives view on industry performance

Mark Foy, the chief nuclear inspector, has published his annual report on the performance of the UK's nuclear industry

E news@nuclearinst.com

In the first report of its kind, the regulatory head at the Office for Nuclear Regulation (ONR) stated that he was satisfied that the nuclear industry had continued to meet the high standards of safety and security required to protect workers and the public.

In areas where shortfalls had been identified, the chief inspector said that ONR had focused its attention on securing commitments and plans from the industry to improve performance in a timely manner.

The report detailed good progress in several areas including continued hazard and risk reduction at Sellafield, the transition of Bradwell power station into a period of Care and Maintenance – marking a UK first, the piloting of new site security plans in line with ONR's Security Assessment Principles, launched in 2017, and the issue of consent for the first 'nuclear concrete' pour at Hinkley Point C.

The report also recognised a number of challenges which require continued focus over the coming year. These include:

- Increased attention at defence weapons and propulsion sites, notably Devonport naval base and the Atomic Weapons Establishment, where programmes to upgrade ageing facilities have experienced delays
- Continued scrutiny of Hunterston B power station which features the most advanced symptoms of graphite reactor core degradation in the Advanced Gas-Cooled Reactor fleet
- Enhanced regulatory oversight at Dungeness B where both reactors have been shut down during the last year due to a range of complex age-related issues which are being addressed by licensee EDF Energy
- Ageing plutonium storage facilities at Sellafield which require sustained investment and focus by Sellafield Ltd, the Nuclear Decommissioning Authority and government.

The chief nuclear inspector specifically challenged industry to deliver improved performance on three key themes in 2019/20 and onwards. These are:

1. Management of ageing facilities
2. Conventional Health and Safety
3. Delivering a holistic approach to nuclear security.

Foy said: "I am satisfied that the nuclear industry has overall continued to meet the requisite high standards of safety and security to protect workers and the public. Where shortfalls have been identified, we will focus our efforts in order to secure the sustainable improvements we require. In presenting this report, I highlight the importance of the industry applying increased attention in three key areas.

Mark Foy

"Firstly, there are significant challenges associated with ageing facilities, which require sustained focus and commitment to ongoing investment in plant, people and processes to ensure safe and secure operation, such that hazards are adequately controlled.

"We have also observed that certain sectors of the industry have experienced a reduction in conventional health and safety performance, and renewed efforts are required to ensure this performance improves. This is particularly relevant as considerable work is either underway or planned by the nuclear industry in new build construction, post-operational clean out, decommissioning and demolition.

"Thirdly, the implementation of our Security Assessment Principles across the sector is a real opportunity to deliver improved organisational ownership and cultural change on security matters. To this end, my inspectors will be seeking to ensure that dutyholders embed an effective security culture across their organisations.

"Our top priorities continue to be delivery of our core regulatory functions, holding industry to account on behalf of the public."

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SMRs expand energy choice, says US Energy Secretary

Nuclear power can help nations to attain energy security, diversity and decarbonise, and the USA is "ready and willing" to offer its technology to achieve this, US Energy Secretary Rick Perry told a US-EU High-Level Industrial Forum.

"By sharing our nuclear energy technologies, we are breathing new life into that great and noble vision first unveiled to the world by President Eisenhower. A vision to convert nuclear power into peaceful energy for the whole of humanity," Perry said in a keynote address to the first US-EU High-Level Industrial Forum on SMRs, held in Brussels on October 21, 2019. "We are reaffirming nuclear energy as an indispensable source of energy for the world," he added.

The USA is supporting this vision by efforts to increase the longevity and performance of today's nuclear reactors, developments including accident tolerant fuels and other technologies, and programmes such as the Department of Energy's (DOE) Gateway for Accelerated Innovation in Nuclear (GAIN) initiative to bring new reactor technologies to market. The DOE has long been involved in the development of small modular reactor (SMR) technology, Perry said, citing joint research between the Idaho National Laboratory and Oregon State University which ultimately led to the development of SMR company NuScale.

SMRs retain "every advantage" of existing large-scale reactors they are clean, reliable, and can store multiple years of fuel onsite – but also have "powerful advantages" of their own, Perry said: "They're smaller, they're more flexibile, they require less capital investment, they can be placed in remote locations...They can power everything from military bases to remote villages and islands beset by tropical storms and hurricanes."

–A longer version of this story appears on World Nuclear News

IRRS Mission experts scrutinise UK nuclear sector

E news@nuclearinst.com

A major international review of the UK's regulatory framework for nuclear and radiological safety has taken place.

Coordinated through the International Atomic Energy Agency (IAEA), the Integrated Regulatory Review Service (IRRS) Mission saw a team of 18 independent experts from across the globe scrutinising the regulation of safety across civil nuclear, radiological sources and the transport of radioactive materials.

The team concluded that the ONR has clear strategies for the regulatory oversight of nuclear facilities providing an effective regulatory framework for nuclear and radiation safety. It also provided recommendations to the regulatory authorities for further improvement, including a suggestion that the UK government should publish a single, formalised statement of its national policy and strategy for safety.

"The ONR has a mature regulatory framework that could be emulated by other countries' regulatory authorities to improve their understanding and implementation of IAEA safety standards in the oversight of nuclear and radiation safety," said team leader Ramzi Jammal, executive vice-president and chief regulatory operations officer in the regulatory operations branch of the Canadian Nuclear Safety Commission.

The Mission brought together senior nuclear regulators with the aim of identifying areas of good practice and opportunities for improvement.

This was the fifth IRRS Mission to the UK, but the first 'full-scope' Mission - encompassing occupational radiological protections, nuclear safety, medical and non-medical exposures, public exposures and environmental protection, transport of radioactive material, and emergency preparedness and response.

During their visit, the team carried out a wide-range of interviews and policy discussions and visited selected nuclear and radiological-related sites to observe inspection and other regulatory practices in the field.

The Mission was requested on behalf of the UK by the Department for Business, Energy and Industrial Strategy (BEIS). It is the culmination of months of preparation and collaboration between 15 regulatory bodies, five government departments and their equivalents in the devolved administrations.

The 11-day visit, which took place in October, was hosted and coordinated by the Office for Nuclear Regulation (ONR).

Dr Anthony Hart, ONR deputy chief nuclear inspector and project sponsor for the Mission, said: "Over recent months a considerable amount of preparatory work has been undertaken across the regulatory bodies and government departments to produce evidence for the Mission team. This included a detailed self-assessment of how well the UK meets IAEA standards and guidance."

Global firm backs Sunderland girls' team

E news@nuclearinst.com

Assystem, the world's third largest nuclear engineering firm, is sponsoring Farringdon Detached FC. The girls under-12 football team draws its squad from primary schools local to Assystem's Sunderland site at Quay West Riverside Business Village.

Assystem will be sponsoring the girls' blue away strip for the season ahead. Playing in the Russell Foster Youth League, the girls train at Silksworth Junior School. Their season's inaugural match took place at home on September 21, 2019.

"I'm really grateful for the support that Assystem has shown my daughter's team, and I am proud of the way it positively promotes girls' youth football," said David Hunt, father of one of the team's players and stress engineer at Assystem.

"Assystem's support for Farringdon Detached FC really shows that they are committed to the local community, while also positively reinforcing the company's gender diversity philosophy and the #IncredibleWomen programme. It sends a positive message to all these girls that the world is their oyster."

Diversity in the engineering industry is an important cause to Assystem.

Read all about it

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***Nuclear Future* is read by more than 3,000 people in the nuclear industry six times a year. We already carry a regular section of technical papers where you can explain your latest technologies and new concepts, practices and techniques.**

We are now introducing a new section that will profile latest R&D projects that may not yet be ready for a full technical paper. In just a few hundred words you can tell the industry about your newest project and perhaps even crowd source some real life, real time reviews and feedback.

We are particularly keen to hear from our company members, academic researchers and younger members who are working on exciting and innovative solutions to nuclear challenges.

Please send your contribution to **technical editor@nuclearinst.com**. We are still looking for high quality technical features that can be peer reviewed for the journal section. Please contact **Bethany Colling** on the same email address for guidance on how to submit your paper.

Think you're not ready for this step yet? Why not watch **Reuben Holmes'** YouTube video – a former Pinkerton prize winner – here: **https://youtu.be/aLXqsC2EIxE**.

Reuben has since moved on to become a key member of the Editorial Committee.

2019 AGM reports progress to members

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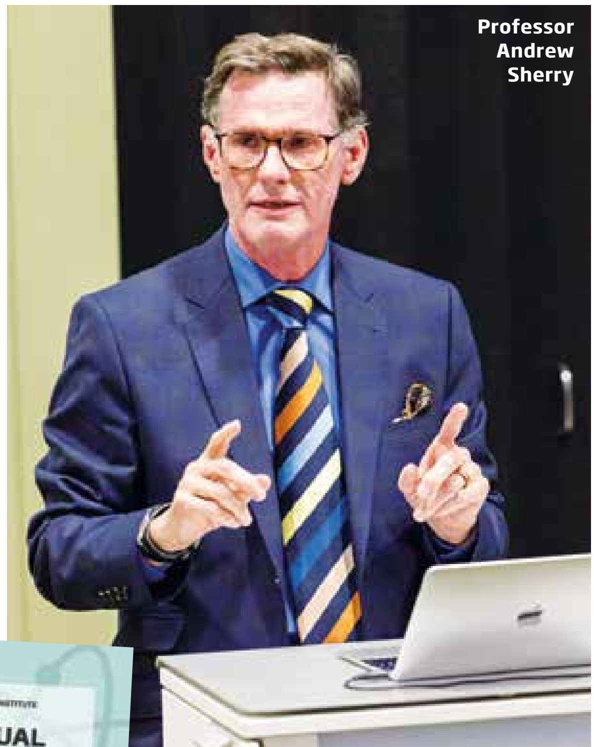
Our 2019 AGM took place in September in front of 29 members (both present and online) at The Engine Rooms in Birchwood. It was chaired by President Elect Gwen Parry-Jones who noted the all-female team presenting the 2018 results including Hon Treasurer Nicola O'Keeffe and CEO Sarah Beacock. Members heard a report on 2018 highlights, a summary of the financial report and some of the plans and activities for 2019 and 2020. A motion had also been put to the trustees regarding the future financial stability of the NI following a long period of declining reserves. A task and finish group was to be set up to consider future ideas to put to the trustees to arrest the decline and members would be kept informed in 2020. However it was noted that in the past few years the general direction of travel had been positive.

The full minutes of the meeting can be found on the Governance page of the NI's website, together with the new Articles of Association which were received and approved by the members.

For a full review of 2018 activities members are recommended to review our new format, user-friendly annual report which can also be found on the Governance page of the website.



Professor Andrew Sherry

The evening was concluded with an excellent presentation by Professor Andrew Sherry on what the future for UK nuclear might be if we are able to look at the innovations and successes taken forward in other industries and transfer these successfully to the UK nuclear industry.

We were also delighted to extend this new format for the AGM still further this year to include the National Final of the YGN Speaker Competition, a report of which you will find on page 26, and an Open Day to attract more potential members from Birchwood and the surrounding area to find out more about us. We showcased NI membership and key benefits such as professional recognition, the YGN, WiN and our branch network and staff were on hand to answer questions from members and non-members.

We already have plans for next year's event to be bigger and better so please let me know if your company would be interested in hosting or sponsoring our showcase of nuclear professionalism. As ever, I'm interested in your thoughts and questions so please contact me on s.beacock@nuclearinst.com or 020 7816 2601.

> **"We already have plans for next year's event to be bigger and better..."**

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2020 business plan

What we plan for 2020

- Develop the professional membership proposition further – increase the number of Members and Fellows
- Influencing policy – Policy Committee will be fully operational by end of 2019 which, along with collaborations with the Royal Academy of Engineering, will help to enhance our profile with stakeholders and present a positive image of the nuclear industry
- Events – repeat our most successful events and work with BEIS and others on making the most of topical content
- Nuclear Future – address the concerns of low advertising rates and make more of the digital advertising opportunities available, re-use older technical content to attract new readers and revenue, look at research ratings options

2020 business plan

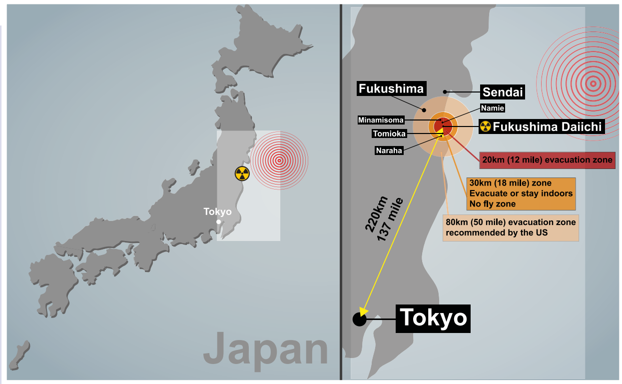
- Data – continue to drive our increases in social media followers and collect data on our members and customers for better understanding of our audiences
- Support NI Communities to thrive – provision of more accurate data and tools to market themselves and their programmes will help with delivering activities and attracting new talent
- Diversify – look to develop other income streams that can help us face uncertain times and reinforce our future financial position
- Be an institute of the future – increase the diversity and youth of our committees to ensure we develop services that are of value to the current and future nuclear workforce

News in brief

Japan nuclear shutdown did 'more harm than good', study finds

Increased electricity prices and greater use of fossil fuels have led to more deaths following the Fukushima accident in March 2011 than the subsequent evacuation from the area surrounding the nuclear power plant, a new study suggests. No deaths have been recorded as a direct result of the accident itself, but the decision to suspend nuclear power generation in response to it has contributed to loss of life, it says.

–World Nuclear News



Minister calls for EDF to revive French nuclear industry

French utility EDF must present within one month an action plan to the French government setting out how it will resolve issues, such as skills shortages, that have caused delays and cost increases at new nuclear power plant projects. Finance Minister Bruno Le Maire said these have damaged the reputation of the nuclear industry.

–World Nuclear News

Korean, Finnish waste organisations agree cooperation

The Korea Radioactive Waste Agency (KORAD) has signed a Memorandum of Understanding with Finnish waste management company Posiva to exchange technology and know-how related to the disposal of high-level radioactive wastes.

–World Nuclear News

IAEA: agency announces Argentina's Rafael Grossi as new director-general

Rafael Mariano Grossi of Argentina has received the majority required in an International Atomic Energy Agency board of governors ballot to be appointed new director-general of the Vienna-based organisation.

–NucNet

News

WiN Cumbria learn from a leader

A story from the inside

E news@nuclearinst.com

On a dark and tempestuous night at the end of July, 30 women braved the weather and joined WiN Cumbria's first evening event, 'Top Tips for Change'. It was a full house, with people attending from a variety of organisations.

The event was held at the new Women Out West (WOW) premises. This is a new collaborative venture hosted at the Haig Enterprise Park to help support and empower local women to fulfil their full potential and thrive in achieving their dreams, regardless of their background.

The speaker was Adriènne Kelbie, who impressed all those present. She was funny, driven, approachable and knowledgeable about all things – not just nuclear. Kelbie is the chief executive of the Office for Nuclear Regulation as well as the patron of Women in Nuclear (WiN). She was also awarded the rare distinction of Honorary Fellow of the Nuclear Institute in 2017 and is a Northern Power Women Role Model, together with Transformational Leader for 2019. This event was organised based on requests from the WiN Cumbria members for more meet-and-greet opportunities, and the demand for these sessions was demonstrated by audience numbers.

It was an extremely interactive and engaging session, where everyone felt included via questions and feedback. Kelbie explored concepts such as imposter syndrome, neuroplasticity, and the power of appreciation.

Group break-out sessions on different topics got everyone sharing experiences, plus interactive software let attendees submit their opinions anonymously for Kelbie to share and discuss. She was open and candid about some of her life experiences, explaining her interesting journey to where she is currently. Her talk ended by providing everyone with her top three tips for approaching organisational change – challenging those present to think about what makes people want to follow a leader. This was the first event since Lucy Barwise became the WiN Cumbria lead for skills development. At the end, attendees said the event was well organised and feedback included that they felt inspired, positive, motivated, empowered, supported, enlightened, re-energised, brave, driven, happy and ready to make a change.

After the event, Barwise said: "I'm so thrilled with how well the event went. Adriènne was such an inspiration to everyone there and the messages she conveyed will stay with me for a long time. It was an honour to be able to bring the event to the women of West Cumbria."

Women who attended reported that, for many of them, they took away ideas about how to progress their careers and make the most of themselves the people around them, a key point being the importance of giving colleagues and peers recognition for their work and contributions.

WiN UK and WiN Cumbria are grateful to Kelbie for taking time out of a hectic schedule to energise and inspire; Rachel Holliday from the Time to Change (West Cumbria) Project CIC for providing such a refreshing venue at WoW with plenty of tea, coffee, biscuits and smiles; and Barwise for organising such a valuable learning opportunity.

Thanks to WiN Cumbria members Sharon Platt and Emily Vincent for their work on this article.

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First Women in Nuclear regional teams conference a success

Members from the 10 WiN UK regional teams left their first conference feeling enthused and energised after learning about each other's recent successes and working together on initiatives to improve gender balance in the nuclear industry.

From the Scottish Highlands to North Wales, and from the East to the South of England, members of the different WiN regional teams travelled to EDF Energy's conference facilities near Bridgwater in Somerset.

Each regional team is at a different stage in their journey to attract and retain women to the nuclear industry, so this conference was organised to help members learn from others about WiN's overarching strategic approach, as well as what is working well in other regions. The aim of the day was to inspire and equip attendees with a clear sense of direction and ideas that could work in their own region.

An initial tour of the construction site for Hinkley Point C nuclear power station left everyone feeling extremely positive. Delegates heard that, of the 4,000 workers currently on site, approximately 20% are female. Even more encouraging is that EDF is taking action to achieve its target for a truly gender balanced workforce in the longer term.

With this positive view of the future in mind, the conference began with Jack Gritt, WiN UK's president, giving an overview of the new strategic plan. This document proposes a structured framework for WiN UK to help achieve the Nuclear Sector deal's vision of increasing the number of women working in UK's nuclear industry to 40% by 2030.

Gritt acknowledged that each WiN regional team faces its own distinct challenges. While each team is driving towards achieving the same thing, it's down to each region to decide what works best for their members and to tailor their activities to regional priorities. Each team should feel empowered, with their increasing number of volunteer ambassadors, to forge a way forward with activities that are right for their geographical area. The strategic plan sets out the objectives and offers various ways or toolkits to help WiN volunteers achieve the mission.

Jack Gritt

Gritt said: "You are all dedicated, busy, high volume individuals. That's why you have all volunteered to take lead roles in WiN UK. Your work for WiN further demonstrates your dedication to our industry, gender balance and wanting to make a difference. It also makes you doubly busy. You're building teams and extending the reach of our messages and activities within your areas, creating a 'fabulous critical mass'.

"Today is about making connections and sharing ideas. It's your networks, energy and conversations that will contribute to transforming our fascinating industry so that it has a thriving, diverse workforce."

Attendees split into three workshop sessions to focus on challenges the industry faces in attracting and retaining women in various roles, and promoting dialogue within the industry, government and with the general public. Each group identified quick wins that they will take away to develop beyond the event.

Loretta Browne, who organised the event, said: "I am really excited by the achievements over the two days and really looking forward seeing the impact this will have on our mission."

GET INVOLVED

If you're interested in getting involved with WiN, then make contact with your regional team. Below are the 10 Regional Teams, their regional manager, and the contact email address:

- **SCOTLAND HIGHLANDS:** *Fiona Bruce*, Dounreay, winscotland@nuclearinst.com
- **SCOTLAND CENTRAL:** *Gillian Morrison*, Jacobs, winscotland@nuclearinst.com
- **CUMBRIA:** *Claire Gallery-Strong*, Sellafield, WINCumbria@nuclearinst.com
- **NORTH EAST:** *Anita Lall*, Jacobs, winnortheast@nuclearinst.com
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- **WALES:** *Ashley White*, Magnox Ltd, winwales@nuclearinst.com
- **WESTERN:** *Lidia Bosa*, EDF Energy, WINWestern@nuclearinst.com
- **LONDON AND SOUTH-EAST:** *Illy Andrews*, Jacobs, WINSouthEast@nuclearinst.com

- *The WiN UK Executive and all attendees, from more than 16 different companies across the UK, were particularly grateful to EDF Energy for hosting this productive meeting at its Cannington Court conference facilities near Bridgwater and providing an inspiring tour of construction on the Hinkley Point C*

Is now the time for the nuclear industry's digital revolution?

E news@nuclearinst.com
Will Newsom
Digital engineering manager, Assystem

As nuclear facilities age, the need for high quality data on a plant's condition is critical.

There has never been a better time for the nuclear industry to embark on its own digital revolution. The need for plant life extension, decommissioning of aged facilities, mixed with the beginning of a new era of nuclear power, starting at Hinkley Point C, present the ideal moment for the Industry 4.0 paradigm to support nuclear facilities at either end of their life cycle.

Put simply, Industry 4.0, or the fourth industrial revolution, is when you connect machines to physical systems in order to create intelligent networks. It encompasses a range of sophisticated tools and data systems such as the internet of things, artificial intelligence, and autonomous systems. However, one example of its effective use in the nuclear industry is how intelligent networks can predict failures and trigger maintenance events.

The pharmaceutical industry uses 4.0 technology to perform continual process verification. Much of the manufacturing industry is operated using 'intelligent networks'. So, Industry 4.0 is changing the working environment of most major vertical industries and there are many opportunities to utilise these technologies in the nuclear industry as well.

Hinkley Point C, artist's impression

One aspect of Industry 4.0 is Machine Vision. Machine Vision is the process of providing automatic, image-based inspection and analysis for industrial processes. Machine Vision technologies can provide a means to obtain automated, metric information from the world around us. For example, we can use 3D cameras to detect objects for a manipulator to accurately grip and pick the object, or use spectral imaging cameras to determine the chemical composition of items.

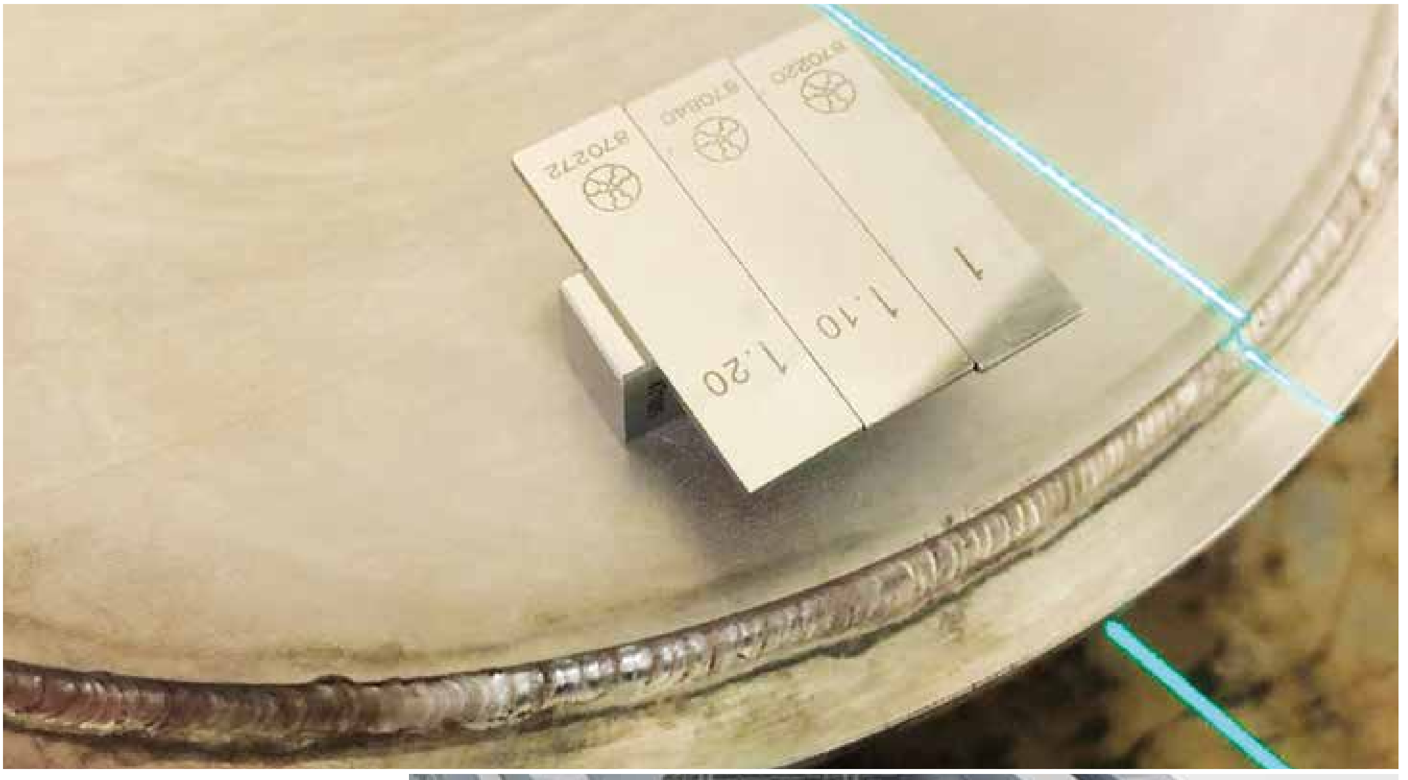
In the nuclear industry, Machine Vision can be used for remote inspections as part of periodic plant inspection or as part of a permanently installed condition monitoring system. The equipment is specifically designed to work in the harsh radiated environment.

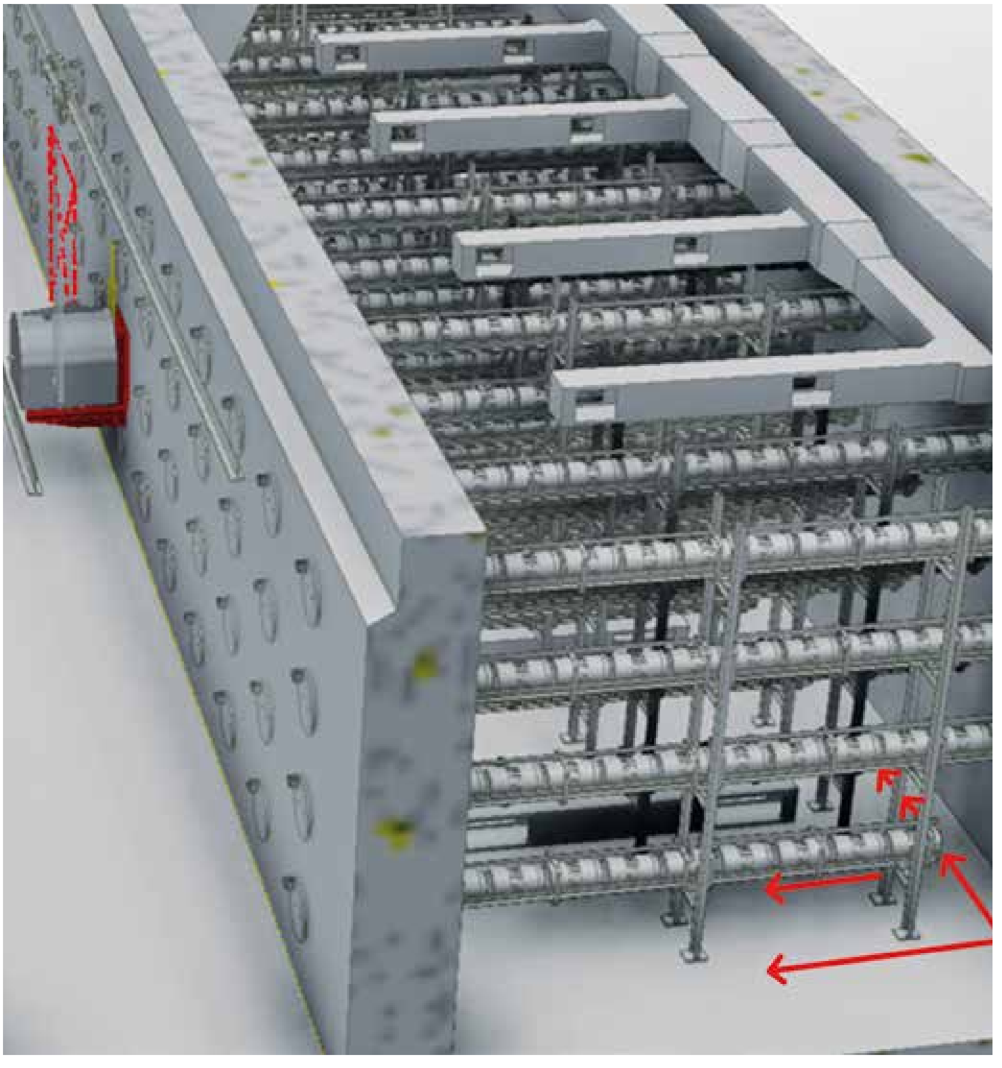
Currently, most remote inspections are either subjective visual examinations undertaken by staff, or Non-Destructive Examinations (NDE). The visual inspections do not provide metric information. They are usually from low resolution cameras which provide poor quality images from which an assessor must determine if the item under test is suitable for continued operations or not. With NDE inspections, a highly trained operator must deploy equipment into a facility and usually must make physical contact with the item under test. This can be a difficult and time-consuming task. Machine Vision can be a viable alternative to both methods as it can either be used in isolation or in conjunction with visual examination and NDE.

Through careful application, Machine Vision can provide many benefits to the nuclear industry. For example, instead of a visual examination, we could perform a laser line scan of structural steel in order to determine the size of surface-penetrating defects. This scan can be directly imported into a Finite Element Analysis (FEA) model where the effect of the defects can be analysed. Machine Vision can also identify and classify defects in nuclear waste packages and determine the following: the size of the package, the quantity of corrosion, as well as metrically quantify the contaminants identified.

Ultimately, using Machine Vision, we no longer need to rely on subjective analysis or have to contend with difficult equipment deployments. We can obtain high quality, metric data on almost any remote plant item. This data can then be directly fed into a digital representation of the plant

"In the nuclear industry, Machine Vision can be used for remote inspections as part of periodic plant inspection or as part of a permanently installed condition monitoring system. The equipment is specifically designed to work in the harsh radiated environment..."





[Above] Laser line scan calibration
[Right] Example facility where industry 4.0 technologies can be utilised

item where decisions can be instantly made on the effect of their condition. This allows us to not only speed up the inspection itself but also to speed up the post-processing and analysis of the inspection data. We are now able to obtain inspection data on items which were once impossible.

The effect of using Machine Vision is that it can cut down inspection times from days to minutes or weeks to hours and it can identify areas of risk that are invisible to the human eye, enabling safer assessments of plant. It also reduces the amount of human contact required near the hazardous area, which lowers the risks associated with maintenance in a radiated environment.

The more embedded Machine Vision and other 4.0 technology becomes to the nuclear industry, the sooner we can realise the cost savings and safety benefits. Now is the time for the nuclear industry to seize the opportunity for innovation that is in front of us, creating technology to suit our needs and creating our own digital revolution.

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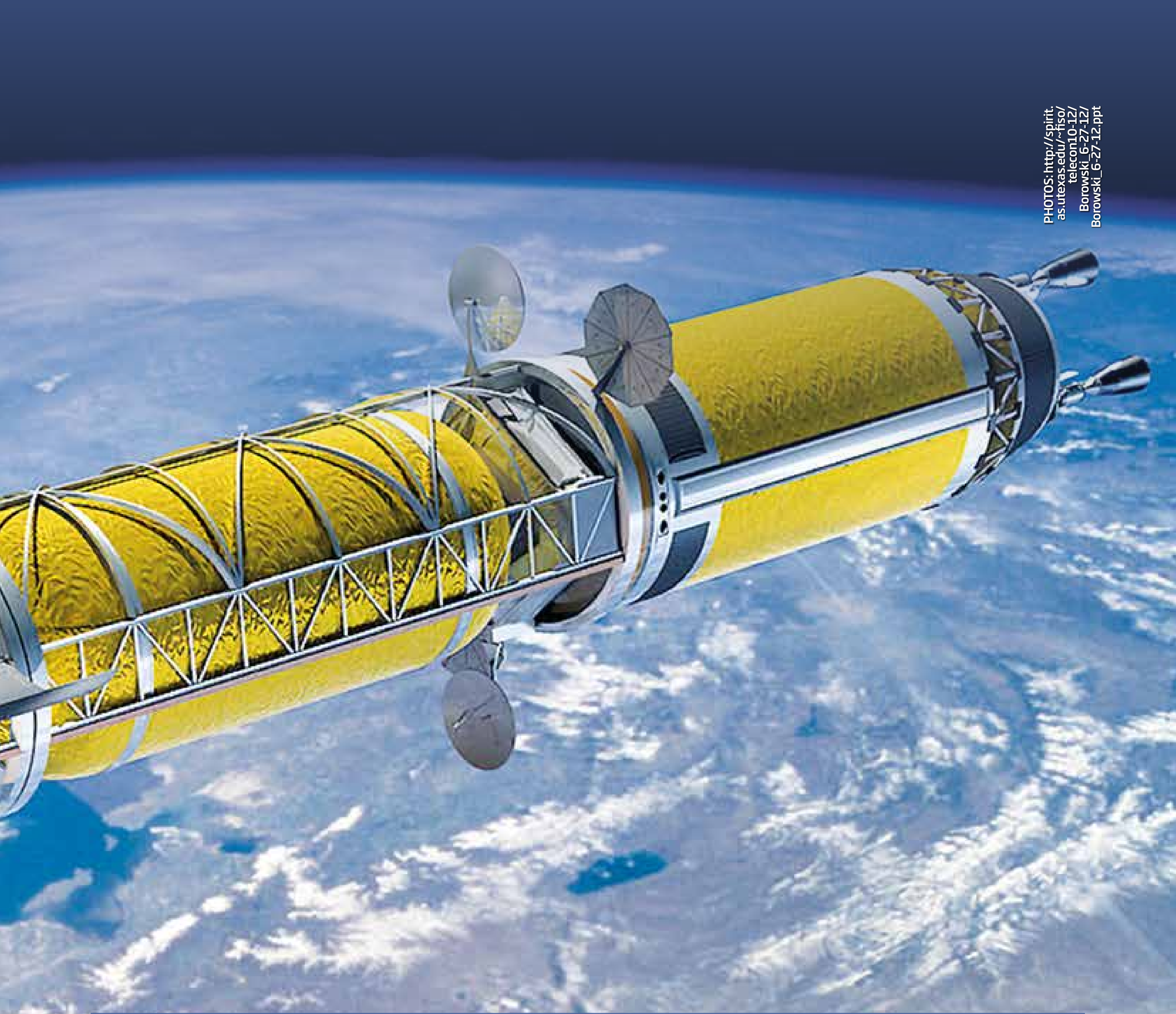
NASA'S MISSION TO MARS: NUCLEAR THERMAL ROCKETS



PHOTOS: http://spirit.as.utexas.edu/~fiso/telecon10-12/Borowski_6-27-12/Borowski_6-27-12.ppt

Nuclear-powered rocketry is making a serious comeback. Nuclear technology could enable travel from Earth to Mars – in only 100 days – a reality in the near future.

Nuclear thermal propulsion, being researched at NASA, is one way that could help the space agency meet its goal to send astronauts to Mars by the 2030s.

"That is absolutely a game-changer for what NASA is trying to achieve," said Jim Bridenstine, administrator of NASA. "[It] gives us an opportunity to really protect life, [if] we talk about the [high] radiation dose when we travel between Earth and Mars," Bridenstine explained.

Currently, using chemical-powered rockets, it would take approximately eight months to travel the average 225 million kilometre distance between the two planets. This is a long period of time for astronauts to be exposed to the radiation of space. A nuclear-powered engine could cut the travel time by more than half, reducing the time in space and therefore its radiation exposure levels.

Reduced travel time would also cut the amount of food, water and oxygen a crew would have to carry for the journey. *–Source: NASA*

YOUR JOURNAL

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***Nuclear Future* wants to hear from you. We are looking for occasional and regular contributors from the NI and beyond.**

If you have something new to say on topics like:

- professionalism
- diversity
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- workplace challenges and triumphs
- personal journeys in the nuclear sector
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The editorial board welcomes papers for publication in the *Nuclear Future* journal. Submitted articles will be considered by the board and the technical editor prior to publication. Part of this consideration process involves peer review of the article.

Authors will need to agree to the *Nuclear Future* copyright agreement for the article to appear in the journal or on the website. Please submit an abstract of 250 words to the technical editor or register your interest at technicaleditor@nuclearinst.com (include author name and contact email). The *Nuclear Future* will not have pre-set issue themes in 2020. For publication in a specific issue see the guidance dates below.

VOLUME 16 — 2020

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ISSUE		ABSTRACT	FULL PAPER
16.3	May/June	November 21, 2019	January 22, 2020
16.4	July/August	January 23, 2020	March 13, 2020
16.5	September/October	March 27, 2020	May 21, 2020
16.6	November/December	June 4, 2020	July 23, 2020
17.1	January/February	August 3, 2020	September 21, 2020

Contact the technical editor for our author guide, any queries regarding the paper submission/review process, and for other ways to contribute to the *Nuclear Future*. The tone of all articles should be informative rather than promotional and may be edited for publication.

JEFFERY DAVID LEWINS, 1930–2019

E news@nuclearinst.com

Jeffery David Lewins was born in Harrow in 1930. Following a family move to Sussex, he was educated at Brighton, Hove and Sussex Grammar School where he was a member of the Combined Cadet Force and also developed his talents as an actor and producer. He joined the army and was selected for officer training at Sandhurst where he came top of the 200 cadets and was awarded the King's Medal, the last awarded by King George VI who died just before his passing out parade.

He was commissioned in the Royal Engineers (the Sappers) and saw active service in Korea and Germany. Jeffery's service in Korea included dealing with old minefields, a hazardous operation requiring great skill and bravery. During his time in the army he went to Gonville and Caius College Cambridge to read Mechanical Sciences and then to MIT where he obtained a Doctorate in Nuclear Engineering. It was while he was at MIT that Jeffery met and married Sabrina. They had three children, Lloyd, Eugene and Shelagh, though sadly this marriage broke up in 1991. During his army service he was also a visiting professor at the University of Washington and had an attachment to the Battelle Northwest Laboratories at Hanford.

In 1968 he left the Sappers to be the first warden of Hughes Parry Hall for the University of London, which housed nearly 300 students, men and women, from all colleges of the university. He began teaching mathematics, computing and engineering at University College, Queen Elizabeth College and Queen Mary College. He obtained a second PhD from Cambridge and a London DSc (Eng).

Jeffery returned to Cambridge in 1980 to take up a lectureship in the Department of Engineering (CUED) Division A Thermodynamics & Fluid Mechanics, specialising in the teaching of nuclear reactor engineering. He was responsible for setting up a small nuclear laboratory where students could get used to handling radioactive materials and carry out simple 'counting' experiments. It is still in use today.

He was elected a fellow of Magdalene College in 1985 and became director of studies in engineering, then as now one of the biggest subjects in the college in terms of student numbers. In 1987 he was appointed praelector responsible for presenting students for graduation, a post to which he brought a touch of grand opera, and held it until 2006, long past his retirement as lecturer. He produced a booklet, Guide to the Customs of the Fellowship, which was a great help to all new Magdalene fellows outlining all the traditions and rituals.

During his period with CUED, he looked after many research students and published a number of books and more than 200 papers, mostly on nuclear reactor design and operation – some of his early work has been described by experts in the field as seminal. He was also the editor of two nuclear science journals and a regular contributor to the *Journal of the Royal Engineers*. During his time at Magdalene he built up the college undergraduate computing facilities from almost nothing without any professional IT assistance. He was a trustee of the ADC and a member of the University's Military Education Committee.

Jeffery was an active fellow of the Institution of Nuclear Engineers (INucE), now the Nuclear Institute, holding the office of president 1977-9. He was also a fellow of the American Nuclear Society and panel chairman for the Engineering Council's Quality and Audit Committee. He was twice awarded the INucE Pinkerton prize for the best paper published in the Institution Journal.

In 2001, Jeffery was given an award by the American Nuclear Society. The citation somewhat sums up his academic life. It read: *for his contribution to teaching and research, especially in reactor kinetics, to the advancement of knowledge through his publications and editing in the field of nuclear engineering and to the welfare of his students.*

Following the end of his first marriage, Jeffery married Judith in 1995 giving him two step-daughters, Louise and Sarah, and he had six granddaughters. Despite slowly losing his sight to macular degeneration he continued to play an active part in college, church and local life. He attended college functions and dinners until well into 2019 and performed in the local Gilbert & Sullivan Society. He also had a number of complex mathematical problems which not only kept his mind active but also challenged his colleagues.

Jeffery will be sorely missed by his colleagues at Magdalene and the Engineering Department, his friends in the local G&S Society, the members of the Kipling Society and of course by Judith and her extended family.

–Written by R L Skelton MA

@nuclearinst

Nuclear Innovation Programme

Making better decisions

James Cornish, consultant at Frazer-Nash Consultancy, writes about the Safety and Security R&D project

E news@nuclearinst.com

The UK's commitment to achieving net zero carbon emissions by 2050 is both an ambitious and necessary challenge that will require a fundamental change to our current energy mix. Nuclear technologies could play a significant role in meeting this commitment, not just by helping meet the demand of increasing baseload generation, but also providing process heat for industry, and supporting hydrogen production. Yet, the role of nuclear technologies as part of our carbon neutral solution is far from guaranteed – conventional nuclear technologies are unpalatable on cost grounds, no matter who the investor is.

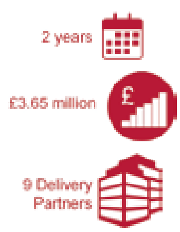
Refreshingly, this is a challenge our industry and the UK government are eager to solve. Advanced Nuclear Technologies, such as Small Modular Reactors (SMRs) or Advanced Modular Reactors (AMRs), could transform nuclear projects from a small number of large, high-cost projects to a product based approach, unleashing the cost savings of mass production. The UK government's recent consultation on the Regulated Asset Base (RAB) model as a mechanism for funding nuclear projects could significantly reduce interest costs of nuclear projects, lowering the overall cost. However, besides the financing arrangements and technology used, there is another significant area that is ripe for cost and risk reduction: how we go about designing and licencing our nuclear power plants.

INTRODUCING THE SAFETY AND SECURITY RESEARCH PROJECT

Frazer-Nash Consultancy, alongside our delivery partners, are leading the Safety and Security Research and Development (R&D) project as part of the UK government's Nuclear Innovation Programme. We are researching new techniques and technologies that provide engineers with a greater insight into their reactor technology's safety and security performance, empowering them to make risk informed decisions that reduce conservatisms driving cost and risk reduction. Our research will help engineers make better design decisions, no matter what the underlying nuclear technology is.

"We are researching new techniques and technologies that provide engineers with a greater insight into their reactor technology's safety and security performance, empowering them to make risk informed decisions..."

James Cornish



The £3.65 million project is composed of 20 individual research topics that are grouped around four key themes, including:

- **REACTOR DESIGN FOR SAFETY & SECURITY:** Investigating how safety and security can be integrated during design leading to increased performance at lower costs.
- **SECURITY MODELLING AND SIMULATION ASSESSMENT:** Exploring novel security assessment and modelling methodologies that improve the integration of nuclear security with safety.
- **ADVANCED SAFETY CASE METHODOLOGIES:** Developing a toolkit of advanced safety case methodologies that can drive down costs and support the adoption of novel nuclear technologies as a source of low carbon power.
- **CONTROL AND INSTRUMENTATION SAFETY AND SECURITY DESIGN CAPABILITY:** Enabling modern, off-the-shelf C&I to be used in nuclear installations by adapting alternative development, test and substantiation methods to support appropriate safety justifications.

The delivery team consists of more than 25 engineers and researchers

from a diverse range of academia and industry including Rolls Royce, Lancaster University, Jacobsen Analytics, National Nuclear Laboratory, Context IS, the University of York, EDF Energy and the University of Bristol.

Over the past 18 months our research teams have made a number of significant advances that have the potential to deliver real cost savings and performance improvements in both the safety and security domains.
Over the next four sections, we take a look at some of the exciting developments and how they can realise real cost savings for end-users.

MODEL-BASED SYSTEM ENGINEERING ENVIRONMENT FOR SAFETY CASES

Traditionally, multi-disciplinary teams have relied on a vast array of documents, spreadsheets and databases to manage design and safety case information. While these tools are capable of holding large amounts of information, they represent a fundamental barrier to understanding the entirety of the design, especially as the design matures and complexity increases. This lack of insight inevitably results in a build-up of unanticipated shortfalls, often requiring downstream changes that necessitate schedule delays and increased costs – ultimately eroding investor confidence.

At the forefront of the potential solutions is the application of Model-Based Systems Engineering (MBSE) methods which are being proven as highly effective in dealing with the technical and commercial complexity of modern systems. MBSE replaces the array of traditional tools with a single, visually programmed, relational database that presents ‘one version of the truth’. However, the practical implementation of MBSE requires the development of a MBSE environment suitable for a nuclear technology, which is the motivation for our research.

Our research is focused on how a modern nuclear safety case can be represented in an MBSE environment, leveraging real world examples, recognisable to safety engineers. We have developed the model ontology and nomenclature to represent a nuclear technology product breakdown in MBSE, how to represent safety principles and safety functional requirements relationship with Systems, Structures and Components (SSCs) and how to model plant operating rules. By combining these three features we can now auto-generate fault schedules and provide significantly enhanced flexibility and traceability that will help engineers determine the impact of design changes and assist the early identification of design shortfalls, de-risking nuclear development projects.

SECURE BY DESIGN

The ‘Secure by Design’ principle sets out a fundamentally different approach to conventional security design, integrating security requirements earlier in the plant design process, alongside safety, to build-in intrinsic features which provide inherent security benefits.

The joint Frazer-Nash Consultancy and Rolls Royce research team are developing a practical process to help guide both security professionals and wider engineering teams. The process describes the security informed input required at each design stage to enable the engineering team to understand security requirements and aspirations, and how they might be achieved without first resorting to classic security controls. Our research seeks to exploit alternative risk reduction techniques to enable improved security performance at lower construction and operating costs. Concepts such as ‘elimination’ and ‘passive engineering’ are prioritised to reduce the residual risk, ahead of more traditional security measures, such as operational arrangements.

OPTIMISING THE COMMUNICATION, PRESENTATION AND CONSTRUCTION OF THE SAFETY CASE

The methods, tools and techniques currently applied to the production of safety cases in the UK Nuclear Industry have been developed over the past 60 years as understanding of the technology and the associated challenges has increased, and in response to operating experience and nuclear incidents. As a consequence, while individual licensees have developed robust processes, there is divergence between approaches. The incremental development approach has also resulted in arrangements that are often considered too overly cumbersome or costly.

Our research is aimed at providing SMR/AMR vendors and requesting parties with innovative ways to present their safety case. Ultimately our vision is for our research to form a toolkit that will be developed into the go-to resource for use by current and future licensees to guide and supplement their own arrangements. So far we have developed guidance on a variety of topic areas including the key attributes of a fit-for-purpose safety case, defence in depth, template safety principles and a safety case data model that can be applied to both a traditional safety case and electronic safety case tools, such as MBSE. The toolkit will also provide links to existing guidance published by others as it is developed.

It is hoped that providing a common basis will improve consistency and reduce divergence in areas where it is not necessary, allowing licensees to focus time, effort and resource on the areas of their safety management system that are necessarily unique.

HUMAN FACTORS FOR FUTURE GENERATIONS OF CONTROL AND INSTRUMENTATION SYSTEMS

The vendors of future reactors are indicating a drive to change the control philosophy to allow for more automation, additional remote control locations and a need for operators to control multiple reactors simultaneously. Our research is focused on identifying the human factor challenges that this change to control philosophies will result in, to direct further research. The research topic includes a practical experiment as part of this exercise. So far our work has identified a number of issues:

1. The maximum number of SMRs that operators can manage.
2. Challenges experienced when moving quickly from low workload to high workload environments.
3. The number of displays required to efficiently and safely control a single SMR.
4. Integration of future technologies, such as Artificial Intelligence (AI), into control rooms.

As the research topic moves into the experimental stage, we are actively looking for current and former nuclear power plant or submarine operators to participate in interviews about future control rooms, covering areas such as increasing automation, remote control locations and individual operators potentially controlling multiple reactors simultaneously.

REALISING THE BENEFITS OF INNOVATION

Innovation is only of value if it is adopted by individuals and organisations to change the way they work day-to-day. That is why we have a dedicated team to ensure that the innovative techniques and technologies our team are developing are taken-up by end-users. We are helping end-users integrate our research into their organisation to deliver cost reductions by working with them to understand their organisations, programmes and nuclear technologies. We have a packed calendar of events, webinars and conferences planned, where you will be able to find out more about our research. In the meantime, if you would like to know more or get involved, please check out our website or get in touch.

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Cooling Towers nuclear power plant, Doel, Belgium

Belgian public support for keeping reactors running beyond 2025 on increase

news@nuclearinst.com

Support by the Belgian public for keeping the country's nuclear power plants in operation beyond 2025 has risen to 46% of those surveyed, up from 30% recorded in a 2017 poll.

The percentage of respondents who believe the share of nuclear power in Belgium's electricity mix should be reduced has fallen to 59% from 75% in 2017. Forum Nucléaire says the increase in support shown by the 18-month barometer survey is "remarkable".

The survey, which was carried out by Kantar TNS, is the seventh in a series begun by Forum Nucléaire in 2010 to track sentiment of the Belgian population towards energy issues in general and nuclear energy in particular. The questionnaire uses both recurring questions, to observe long-term trends, and new questions in response to current events. The poll, conducted between July 15 and September 6, had 756 respondents, who were aged over 16 and selected at random.

It found "more and more" Belgians are in favour of keeping nuclear energy, Forum Nucléaire said, with 83% of respondents agreeing the country should maintain its nuclear energy production, up from 80% in 2017. Although 37% want to maintain nuclear power plants until 2025, 46% of those interviewed believe that the country's nuclear power plants should remain open after 2025. This, says Forum Nucléaire, is a "remarkable" increase compared to the previous poll in 2017, when only 30% thought that nuclear power plants should remain open after 2025.

Some 63% said new nuclear power plants could be built to replace Belgium's existing fleet in the future.

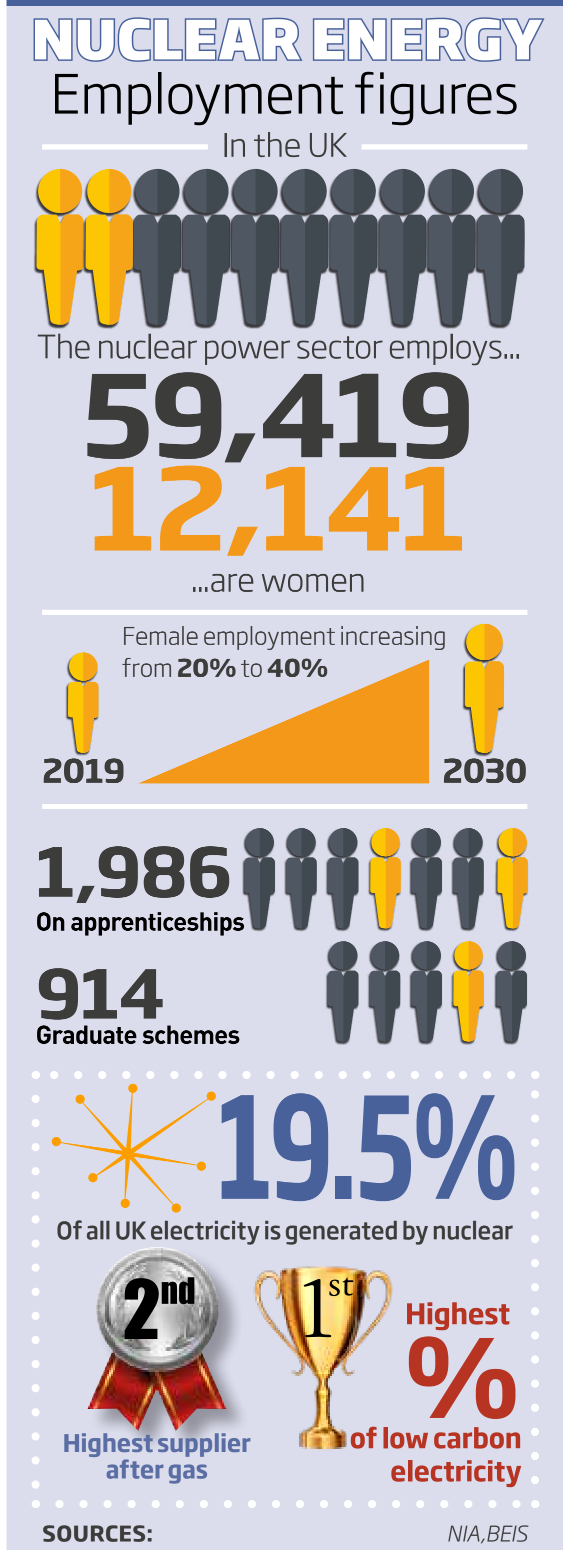
Seven nuclear reactors – four at Doel and three at Tihange – generate around half of Belgium's electricity, but government policy currently envisages phasing out nuclear by 2025. This was reaffirmed by the Belgian government in March 2018. A question on the government's plans to replace nuclear capacity with gas, which was asked for the first time in this year's survey, found 12% agreed, while 77% did not agree and 11% had no opinion.

These findings show the growing awareness in the Belgian population that a sudden nuclear exit in 2025 would make CO_2 reduction targets "almost impossible" for the country, Forum Nucléaire said.

–A longer version of this story appears on World Nuclear News

@nuclearinst

By the numbers



CENTRAL ENGLAND BRANCH ANNUAL DINNER 2019

A challenging year

More than 160 guests attended the Central England Branch's Annual Dinner at Oxford Spires Hotel on October 10, 2019.

In welcoming guests, the host and branch chairman Dr Mehdi Askarieh said: "There's no doubt that this has been a particularly difficult year, and I am relieved that this annus horribilis is coming to an end. We are still in midst of one the most challenging and entrenched constitutional and political issues this country has faced in peace time, perhaps with no parallel since the beginning of 20th century. Brexit has divided families and the country with no sensible and practicable solution in sight yet. As far as our industry is concerned, suffice to say it has not been a particularly successful and memorable year. And to top it all, England failed to win back the Ashes even after Ben Stokes' incredible and unmatched heroics. Let's look forward to a much better and successful year in 2020."

> "There's no doubt that this has been a particularly difficult year..."

After dinner and traditional toasts to the

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⬅23

Queen, the Royal Navy and the Nuclear Institute, Karen Sagar gave a short talk on the work of the NI Central England Branch's Women in Nuclear.

The main after-dinner speaker was Captain Philip Parvin. Captain 'Paddy' Parvin joined the Royal Navy in 1984 with the sole intent of becoming a submarine nuclear engineer. Graduating with First Class Honours, he successfully completed nuclear propulsion training and spent his seagoing time in TRAFALGAR Class Submarines. This time was interspersed with shore roles in safety management following completion of a Master's Degree in Marine Engineering. He also managed to spend three fulfilling years with the Royal Marines, doing acquisition and some much more active roles.

Captain Parvin returned to sea in HMS MONTROSE to complete a second charge appointment, and through this role he learned more about gas turbines and power electronics in support of operations in the Northern Persian Gulf. On completion of his sea time, he returned to acquisition in the Future Business Group at Abbey Wood, drawing new power and propulsion technologies into service, before joining the successor project (now DREADNOUGHT) as chief of staff.

Captain Parvin gave an engaging talk on the theme of 'Dreadnought to Dreadnaught but mostly the bits between'.

As usual, there was a charity raffle which raised more than £3,000. This year's chosen charities were the Stroke Association and the Pancreatic Cancer Research Fund. The Stoke Association helps people to rebuild their lives after a stroke as well as providing specialist support, funding critical research and campaigning to make sure those affected get the best care. Meanwhile, the Pancreatic Cancer Research Fund is dedicated to defeating pancreatic cancer by funding innovative research. Pancreatic cancer has the lowest survival rate of all cancers – just 3% of those diagnosed survive for five years. It is also the only cancer that has seen no improvement in this figure over the past 40 years.

This dinner, like all other regional Nuclear Institute dinners, relies on support from client and supply chain organisations. Dr Askarieh expressed the thanks of CEB Committee to all table hosts. Their support provides much needed funds to enable the Nuclear Institute to fulfil its charitable objectives at the national branch level. Special thanks were accorded to Nuvia (main sponsor), Veolia Nuclear Solutions and Framatome (pre-dinner drink sponsors) and Atomic Weapons Establishment, AWE (dinner menu sponsor) for being our generous sponsors this year.

Thanks also went to Central England Branch Committee members and to the Nuclear Institute staff, in particular Alison Hunt at the NI central office, who had invested a considerable amount of effort in organising this event.

Top Table Dinner Guests

- **Dr Mehdi Askarieh**
  Chairman of the NI Central England Branch
- **Keith Collett**
  CEO, Nuvia
- **Lyanne MacLean**
  Chief Operating Officer, UKAEA
- **Captain Philip Parvin**
  Chief Staff Officer Engineering, The Royal Navy
- **Hugh Radesk**
  Chief Engineer for Aldermaston and Burghfield Sites, Atomic Weapons Establishment (AWE)
- **Karen Sagar**
  Manager of Women in Nuclear at Central England Branch (NI CEB WiN)
- **Ian Scott**
  CEO, Moltex Energy
- **Richard Walker**
  Head of Site Engineering, Atomic Weapons Establishment (AWE)

NUCLEAR INSTITUTE

Meet the members

Anthony Shaw

Secretary of the NI Central England Branch

Anthony Shaw

Anthony Shaw is a plasma spectroscopist working on the Joint European Torus (JET) nuclear fusion reactor at Culham Centre for Fusion Energy (CCFE) as part of the United Kingdom Atomic Energy Authority (UKAEA). He is also the Secretary for the Central England Branch of the Nuclear Institute. In his role at CCFE, he is responsible for plasma diagnostics in order to better understand the behaviour of the complicated fuel and impurities of this different type of experimental nuclear reactor.

Following a well-received presentation on the basics of nuclear fusion designed as an introduction for scientists and engineers at the NI CEB YGN Young Speakers' Competition in 2017, he finished second in the national competition and subsequently became more involved in the NI at local level. He took over as Central England branch secretary in early 2018. Since then, Shaw has worked to maintain a high level of communication with branch members, especially with the large number of events and opportunities taking place in the local area. He has also worked alongside NI HQ to align the working practices with the new GDPR rules and guidelines.

Shaw continues to compose and deliver talks and presentations, in particular on nuclear fusion, to audiences around the country, including one to the Scotland Branch of the NI. This has also resulted in him appearing on BBC Oxford, as well as on television when he was interviewed by the BBC's Hannah Fry for a documentary investigating the nature and uses of mathematics, Hannah Fry's *Mysterious World of Maths*.

Shaw graduated from the University of Warwick in 2013 with a Master's in Physics, and moved immediately to CCFE onto their graduate scheme. Working in multiple roles at CCFE over the first three and a half years, he mostly focused on diagnostics and software with a physics background and then became responsible for one of the visible spectroscopy diagnostics in early 2017.

On a fusion reactor like JET, the hydrogen fuel is confined by large magnetic fields in order to allow it to be heated to around ten times hotter than the centre of the sun – about 200 million degrees Celsius. There are many different ways to measure and understand this plasma, and one of those is visible spectroscopy. To do this, light produced by the plasma is transmitted via optical fibres to various detectors which measure its intensity (brightness) and wavelength (colour). From this information many things can be inferred such as the density of the plasma, its elemental make-up, temperature, magnetic and electric field strengths and much more. This is the job of a plasma spectroscopist. This work is very varied and can involve being up on the huge fusion reactor with a spanner and some optics one day, to data analysis and calibration the next, and writing papers and studying plasma behaviour at the end of the week.

YGN NATIONAL SPEAKING COMPETITION FINAL

The last word

[FROM LEFT] Mike Roberts, Andrew Crabtree, Momchil Vasilev, overall winner Vicki Dingwall with contestants Neil Calder, James Gath, Jennifer Liley, Martin Rayner and Philippa Hawley

The YGN National Speaking Competition is a key part of the YGN calendar. This year did not disappoint, with six finalists coming from NI branches across the country with one thing in mind – to win the national competition and get the chance to present at the YGN Annual Day Seminar and Dinner, to be held in Bristol in November.

Over the evening attendees learned about diversity and inclusivity, small modular reactors, coated particle fuel, remote handling, quality and the cultural context of nuclear projects. Congratulations to Vicki Dingwall (Western Branch) for coming first with her talk on "*How Diversity and Inclusion contributes to a healthy Nuclear Safety Culture*". Well done to James Gath for placing second and Jennifer Lily for finishing third. Thank you also to Neil Calder, Philippa Hawley and Martin Rayne for rounding-off an evening of fantastic talks.

> "This year did not disappoint, with six finalists..."

The YGN, would like to express its gratitude to Ansaldo Nuclear for sponsoring the event and Andrew Crabtree for judging, along with our other judges, Mike Roberts (YGN Chair) and Momchil Vasilev (last year's winner).

MYTHBUSTERS

Сиэяпфьуl

Chernobyl

YGN's Pripyat correspondents **Tom Hughes** and **Jacob Home**

With a 9.6/10 rating on the popular entertainment website IMDB and a slew of Emmy Awards, including one for Outstanding Limited Series, *Chernobyl* has become one of the most discussed television shows of the year. It portrays the immediate aftermath of the Chernobyl nuclear power plant disaster of 1986 when a large explosion destroyed much of the containment of Unit 4 and caused a melt-down of the fuel within the reactor. The show was well researched and featured many dramatic scenes of heroism and tragedy. It has, not surprisingly, spurred debate on the safety of nuclear power and the decision to build new nuclear power plants in the UK. However, there were many scenes where artistic licence was taken to make the viewing more compelling. Let's take a closer look at the myths.

1. HEROES AND VILLAINS WERE NOT AS POLARISED AS PORTRAYED

In the dramatisation, there are very clear distinctions between 'good guys' (e.g. chief investigator Legasov) and 'bad guys' (e.g. supervisor Dyatlov and plant manager Bryukhanov). In reality, these depictions are likely to be skewed for dramatic effect. Worker testimonies reveal that, while Dyatlov and Bryukhanov were indeed leaders that engendered some fear and tension in their workforce, they were respected professionals that are perhaps undeserving of their 'villainous' portrayal in the show [1]. Likewise, Legasov was by no means the only Soviet scientist involved in investigating and publicising the incident, nor was he the world expert on RBMK reactors that was portrayed. He and his entire team deserve the credit for investigating the causes of the event.

Tom Hughes

Jacob Home

2. RADIATION IS CONTAGIOUS

The scene where Lyudmilla is told not to touch her husband Vitaly (the firefighter) implies it is because she will 'catch' radiation from him. In fact, this instruction would have

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been for his protection not hers, as his immune system was compromised and she was potentially introducing bacteria and viruses into his clean room. Later on she's told she lost her baby as "it absorbed all her radiation", but this is not how radiation works [2]. She would need to have been personally exposed to high radiation fields or picked up serious internal contamination from Vitaly, neither of which are feasible in the context of his (post-decontamination) treatment for radiation poisoning in Moscow.

3. RADIATION CAUSED THE HELICOPTER CRASH

One memorable scene depicts a helicopter dramatically plunging to earth as it flies over the open reactor core, implying that the fierce radiation field has paralysed its mechanical systems. Although a helicopter crash at the site did occur, this was actually six months following the accident and was due to the helicopter's blades contacting some chain dangling from one of the cranes employed in construction of the sarcophagus in poor visibility [3]. A video clip of this is widely available on online.

4. THE DIVERS WERE VOLUNTEERS WHO SACRIFICED THEIR LIVES

The three 'divers' tasked with draining the bubbler pools beneath the damaged reactor were hailed as heroes in the dramatisation after volunteering for the extremely hazardous foray underneath the plant. Not to take anything away from their heroic actions, but these men were plant engineers responsible for that area of the plant, one of whom was on-shift at the time, the others on-call. They viewed the task as simply part of their job, and as such did not receive (nor expect) the heroes' welcome and financial reward depicted on their return. One was quoted: "It was just our work. Who would applaud that?" [4] It should be noted that each of the divers lived for many years after the accident and two are still currently alive and living in Kiev.

5. EFFECT OF RADIATION ON THE HUMAN BODY

The final claim of a spike in cancer rates is difficult to prove as there is little data prior available prior to the accident. In addition, confirmation and selection bias could lead to an exaggerated number of reported cancers. There are several different sources that give different incidence rates.

Some of the deterministic effects of Acute Radiation Syndrome (ARS) were 'over-done' for dramatic effect in the series. The immediate bleeding or skin reddening shown after touching patients/objects in the first episodes are not scientifically feasible, and while many accounts talk of the longer-term (hours/days/weeks) effects of skin reddening/browning, the extreme cases of skin putrefaction shown in the patients at hospital #6 are likely the liberal use of artistic license [3]. Limited photographic evidence from that period shows men who are clearly seriously ill and in discomfort, but nowhere near the gory scenes shown.

"The trial was more about assigning blame and culpability than a technical investigation into the causes or progression of the accident..."

6. LEGASOV REVEALED THE DETAILS OF THE ACCIDENT AT THE TRIAL

Scenes in the final episode depicting Legasov putting his reputation on the line to explain the technical progression of the accident at a trial in Chernobyl are fictitious, presumably included as a way of explaining the accident to the viewer. In reality, this was more of a 'show trial', with a view to apportioning blame to Bryukhanov, Dyatlov and reactor operator Fomin – Legasov was not even present in the courtroom. The trial was more about assigning blame and culpability than a technical investigation into the causes or progression of the accident. While it is perhaps true to say that senior party officials had little interest in the technical reasons behind the disaster, these were already reasonably well-understood in the soviet scientific community at this time.

7. THE BRIDGE OF DEATH

Like many 'facts' about Chernobyl, the scene of individuals foolhardily observing from the 'bridge of death' as the black snow of fallout falls down around them can be substantiated by only one account. Other accounts make no mention of this and/or question its basis – after all, it was the middle of

the night and seems unlikely that many individuals would have gotten out of bed to walk to the bridge and watch the event unfold [4]. It is difficult to substantiate the claim made in the end credits that all those on the bridge died as a result of their exposure.

8. THE CONTROL ROD TIPS WERE MADE OF GRAPHITE BECAUSE IT WAS CHEAPER

In the trial scenes, Legasov explains a number of design decisions on the RBMK were made because "it's cheaper" (e.g. graphite control rod tips). In reality, while costs were a factor, there were sound technical reasons behind such decisions. In the case of the graphite followers, these had the effect of displacing water/steam with a neutron moderator, increasing reactivity toward the upper part of the core thus facilitating the use of natural uranium as a fuel, which was much more readily available in the USSR than enriched fuels required by other reactor types [5].

9. THE BLUE PILLAR OF LIGHT WAS CAUSED BY RADIATION

In the first episode depicting the aftermath of the explosion a bright blue shaft of light emanates from the burning reactor core. This can be interpreted as the glow of a radiation field spewing forth. While a blue glow can be seen emanating from nuclear fuel under certain circumstances (an effect called Cherenkov radiation that originates from the slowing of beta particles in water), this only occurs in water. It should be mentioned that one of the operators, Alexander Yuvchenko, reported seeing a "white-blue" light emanating from the reactor core when he went to inspect it in the immediate aftermath of the explosion. However, this report has not been substantiated by other accounts.

10. NUCLEAR POWER IS INHERENTLY DANGEROUS

The final impressions of the television series make it clear that the reactor operators were in an impossible situation, caught between Soviet bureaucracy and a process they did not fully understand – prompt supercritical fission. The scenes suggest a barely controlled process that is harnessed to produce power and that could at any moment unleash devastation. While nuclear power, like every other electricity generating source, has its hazards the truth is these are carefully controlled at all times through a number of safety measures. To achieve "defence-in-depth" nuclear reactors are designed, built and operated with safety as the overriding priority. The design of Chernobyl Unit 4 has not been repeated in reactors that have been built since and all remaining Russian RMBKs have undergone substantial safety modifications and improvements to operating practices to prevent a similar accident [5].

CHERNOBYL'S LEGACY

Nuclear power has an enviable record when it comes to safety; the few high profile accidents that have occurred have led to an industry that is safer and more aware of its responsibility to protect people and the environment.
In terms of deaths per TWhr nuclear is the least fatal of all electricity sources worldwide even taking into account both Chernobyl and Fukushima [6]. The Chernobyl mini-series has rekindled the discussion on nuclear power and nuclear safety in the public forum. As professionals within the industry we should be aware of how the public perceives our work and always be willing to improve understanding and correct misinterpretations. The show is perhaps best seen as a cautionary tale the consequences of political secret-keeping and the impact of the Soviet style of government on safety culture rather than a scientific documentary on nuclear power. Chernobyl has been invaluable in igniting interest in our industry: we should not let it define us.

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IN PERSON

"We have to make sure that we offer role models and career paths"

Nuclear Future talks to **Gwen Parry-Jones**, Chief Executive of Magnox and incoming President of the Nuclear Institute

Gwen Parry-Jones may only be a few months into her new job but, in a way, she has come full circle.

"I first worked for Magnox 30 years ago at the beginning of my career," she says. "So I started at Wylfa in 1989, and I left Magnox 24 years ago. After all that time I've come back again and I've been in post since July."

As chief executive of Magnox and incoming President of the Nuclear Institute, Gwen has a lot on her plate. But she is enjoying every minute.

"I've been reacquainting myself with all the stations and sites and the people but also refreshing my knowledge of where we've got up to in terms of their decommissioning missions. I've been delighted to find great progress in a lot of areas."

She adds: "It's quite a departure from what I was doing before because for all of my career I've either been involved in operating nuclear power stations or in future plans to build new nuclear power stations. So coming to the other end of the life cycle is quite different but, in some ways, very familiar. We all came from the same DNA effectively so a lot of the people and the issues and processes feel very familiar. In some ways it's a little bit like coming home. Hopefully I can bring what I've learned from other things back into this arena of decommissioning, and they can teach me a lot too."

NEW STRUCTURE

Magnox became a wholly-owned subsidiary of the Nuclear Decommissioning Authority (NDA) in September after ownership transferred from the parent body organisation, Cavendish Fluor Partnership. It marks a new approach to managing the UK's 13 Magnox sites – 10 former Magnox nuclear power stations, two nuclear research sites and a hydroelectric plant. But it's not just the approach which is new, as Gwen explains.

"It's quite a departure from what I was doing before because for all of my career I've either been involved in operating nuclear power stations or in future plans to build new nuclear power stations..."

"In terms of being a subsidiary of the NDA, we've got a brand new executive team in place because the previous team was supplied by the contract partner.

"I'm really pleased about the diversity in the team as well as the experience and capability of the whole team. There are four female members of a team so it's a good diversity ratio, and these are very experienced people."

DIVERSIFICATION

Needless to say, when Gwen began her career as a reactor physicist at Magnox's Wylfa power station in the late 1980s, diversity wasn't top of the industry's agenda. However, it didn't stop her from becoming the first woman in the UK to run a nuclear power station (at Heysham 1 in 2008) and nor did it hinder her progress which has included roles as a director at EDF Energy as well as operational development director for Horizon Nuclear Power. She was also awarded an Officer of the Order of the British Empire for services to science and technology.

As for the future, her focus is very much on Magnox.

"We have a clear mission which is to decommission the sites that we look after... What's in front of us is clear, it's hazard reduction work to enable decommissioning."

She continues: "I have three aspects to my job. The first is to decommission the Magnox fleet. The second is to look at the engagement and cultural aspects because we have to make sure that we keep offering the right things to our staff and people are feeling that they fit in here. The third part is potentially to earn the right to be involved in future things, whatever they may be, because if you think about it I have a couple of thousand of people who have a huge skill in decommissioning… How do we

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"We have a clear mission which is to decommission the sites that we look after… What's in front of us is clear, it's hazard reduction work to enable decommissioning…"

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leverage that for the UK?"

Licensed under the Nuclear Installations Act 1965, Magnox has played a pivotal role in the UK's energy requirements.

Gwen says: "Magnox was a great servant to the UK infrastructure. Quietly away, the units generated a huge amount of the UK's electricity for 50 years or more. That's almost been forgotten and I want to celebrate that with my staff because I'm really proud of what they did."

And what of Gwen's past? What made her want to work in the nuclear industry?

"I was always fascinated by physics and the science of why things work… I had a really good physics teacher who was an academic enthusiast. I also come from a family of scientists so everybody was interested in how things worked. It became a natural progression. I ended up being offered a job as a reactor physicist at Wylfa and I remember being so excited on my first day of work about the unique responsibility of something I feel is so important to do properly. I'm definitely a nuclear geek."

NEW PRESIDENT

Her self-confessed nuclear geekery will stand her in good stead as the new President of the NI. And it's also worth noting that Gwen is the first female President of the institute in its current form. Does she think it's important to encourage more women to work in the nuclear industry?

"I think we need the best of everything and we're not going to get that from just having 50% of the population involved. Therefore we have to make sure that we offer role models and career paths. People often look to see if there's "someone like me" in that organisation, for me it's really important that there is some visibility and people can see that there's someone like them there."

> "I was always fascinated by physics and the science of why things work… I had a really good physics teacher…"

The presidency is a two-year term and Gwen is looking forward to it.

"One of the key things that the institute offers is to do with connecting people. Where else in the industry has people who are just starting out on their careers having access to some of the nuclear icons of our generation? Where else would you have people sitting talking with people they normally wouldn't get access to?"

She continues: "That networking across generations and the knowledge transfer that can happen through something like the NI is one of its strongest attributes."

Meanwhile, Gwen is convinced that the nuclear industry has to continue to make its case to be included in a Net Zero future.

BIG CHALLENGE

"We have to work really hard on our reputation, our accident tolerance, our openness, our transparency to make sure that we earn our place in that future because I genuinely believe that we can play a very strong part in future systems, stability, security, reliability, affordability but we have to continue to work really hard on that. In particular, we have to make sure that we create affordable solutions. That is a big challenge.

"But the other side of the challenge is the human side where if you look at the expectations of the people entering the workforce now, they demand diversity and inclusion. They demand to be listened to, and so they should. And they demand to work in an environment where they can be the best version of themselves. I think that the nuclear industry has to work hard to meet these legitimate expectations of the new generation of workforce."

Gwen Parry-Jones

CHIEF EXECUTIVE OF MAGNOX

Gwen Parry-Jones OBE started her career in 1989 as a reactor physicist at Magnox's Wylfa power station. She then worked at several advanced gas reactors, pressurised water reactors, boiling water reactors and CANDU stations on both commercial and technical challenges, in the US, Canada and the UK. This culminated in being the Plant Manager at Sizewell B and then the Station Director at Heysham 1 where she was the first woman in the UK to have run a nuclear power station. She was subsequently a board director for EDF Energy, looking after safety, security and assurance for the nuclear, coal, gas, battery and renewables fleet. During her time at EDF Energy, she was awarded an Officer of the Order of the British Empire for services to science and technology.

Gwen was then appointed as the Generation Development Director, looking at future opportunities, including defuelling, deconstruction and decommissioning of the advanced gas reactor fleet. Subsequently, she became the Operational Development Director for Horizon Nuclear Power, developing the concept for a new reactor at Wylfa. She is a Fellow of the Institute of Physics and the incoming President of the Nuclear Institute.

QUICK-FIRE QUESTIONS

Q. Who is your professional mentor?

A. Andy Spurr was a really critical friend for me. He did more than mentor me, he sponsored me and pushed me forward when perhaps I was nervous about taking a step... He gave me both the challenge but also the confidence to act.

Q. What's been your nuclear career highlight to date?

A. Being the CEO of Magnox and having the great privilege and responsibility to do the best for the employees of Magnox and for the sites that we look after.

Q. If there's one thing could change about the nuclear sector, what would it be?

A. Probably the number of women who are retained into senior roles. You get really good people starting off and somehow, during their career, they get lost to the industry so they don't appear as the station directors or the board members.

Q. If there was one thing you wish more people knew about nuclear, what would it be?

A. People assume that somehow we're different or what we're doing is somehow secretive or very complicated. But we're just normal people doing a really good job.

Q. What advice would you give to young nuclear professionals?

A. I would say, never think that your question is in any way stupid because it's likely that many in the room are wishing that they'd asked that question. Speak up because there is absolutely no such thing as a stupid question.

See things differently

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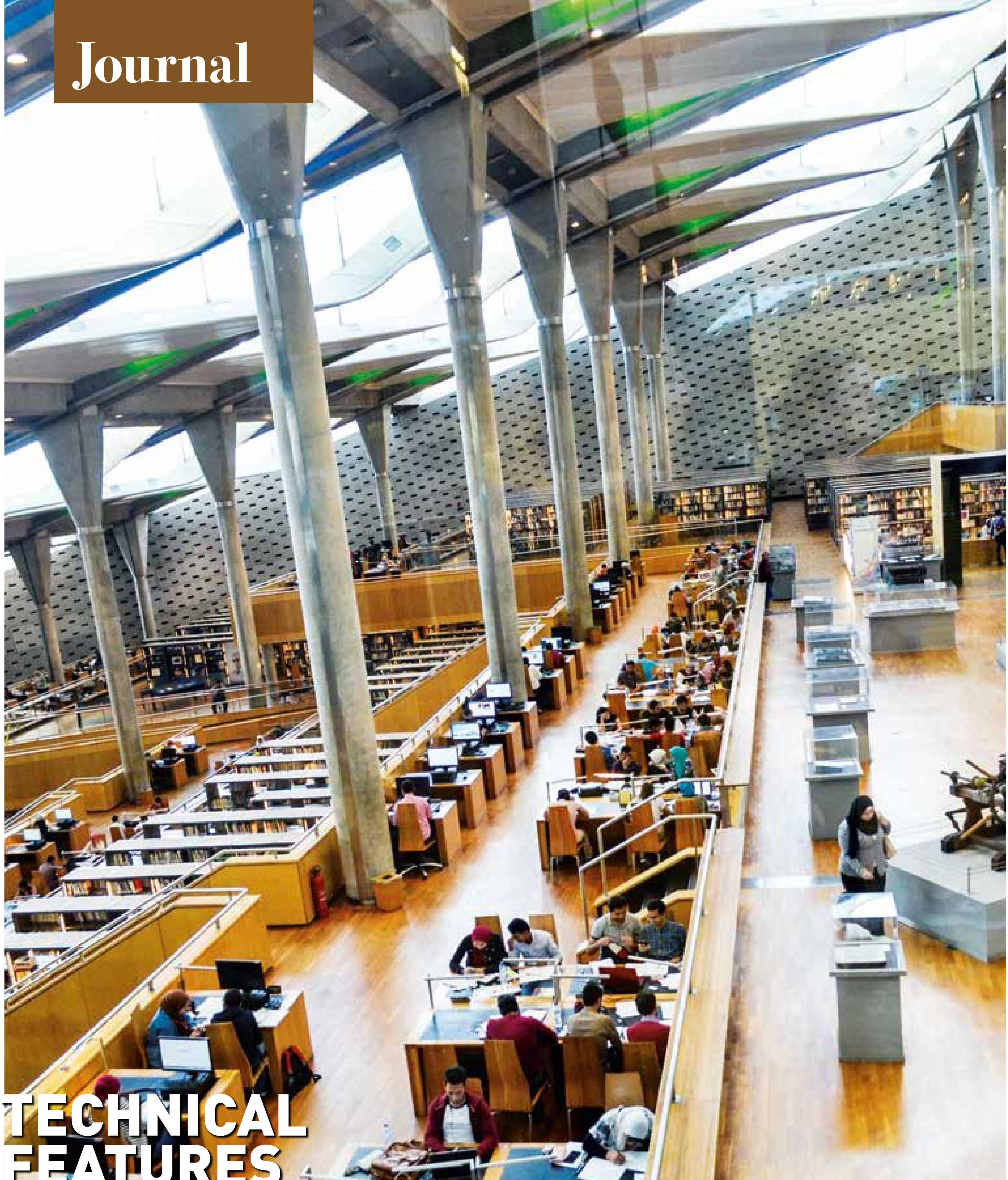


TECHNICAL FEATURES

Nuclear Innovation and the Road to 'Net Zero'

The role of government and the Nuclear Innovation Programme

SUMMARY

- Government has established a £505 million Energy Innovation Programme to support clean growth, of which £180 million is for nuclear technologies through the Nuclear Innovation Programme (NIP).
- This is the first significant public funding for future nuclear fission energy R&D in 20 years and follows advice provided by the Nuclear Innovation and Research Advisory Board (NIRAB).
- The NIP investment is already having an impact, including enabling UK organisations to engage with 54 organisations across 16 countries as it seeks to place itself, once again, at the top table of nuclear nations.

By **Paul Nevitt,** NIRO

INTRODUCTION

"In a few years' time there will be crucial gaps in capabilities". "The Government's view that the need for R&D capabilities and expertise in the future will be met without government intervention is troublingly complacent." So states the 2011 report from the House of Lords Science and Technology Committee looking at nuclear fission research and development funding [1]. In response to this finding from the House of Lords, part of government's response was to initiate funding through the commissioning of the Nuclear Innovation Programme (NIP); the first public funding of advanced nuclear fission energy research for over 20 years. This is timely, given the Committee on Climate Change's call for innovation and advancement in the deployment of all low carbon technologies towards a net zero future.

A brief history

In 2008, Parliament passed the Climate Change Act committing the UK to reducing carbon emissions by 80% by 2050. In part, to achieve this ambitious target, the UK nuclear industry responded by progressing with plans for the first new nuclear power station for a generation at Hinkley Point in Somerset, followed by Bradwell in Essex.

> "In response to the challenge of reducing carbon emissions by 80% by 2050 and following the Clean Growth Strategy, the Government established a £505 million energy innovation programme..."

In 2011, the House of Lords Science and Technology Committee carried out an inquiry into the UK's nuclear research and development (R&D) capability, identifying areas where improvements were needed. The Government responded in 2013 through the publication of the Nuclear Industry Strategy [2]. This recognised the contribution the nuclear industry made to the UK, including clean growth, a secure and reliable power supply and a source of high-quality jobs.

The strategy included a set of objectives and a number of recommendations, including the reconstitution of a Nuclear Innovation and Research Advisory Board (NIRAB) and the Nuclear Innovation and Research Office (NIRO) to provide independent and objective technical advice to the UK government.

In response to the challenge of reducing carbon emissions by 80% by 2050 and following the Clean Growth Strategy, the Government established a £505 million energy innovation programme [3] administered through the Department for Business, Energy and Industrial Strategy (BEIS). Of this £505 million, £180 million was earmarked for nuclear technologies following the 2015 government spending review under the auspices of the Nuclear Innovation Programme (NIP).

This was the first significant public spending on future nuclear energy R&D for over 20 years; a welcome change from the decline of spending that characterised previous decades. The money provided in the 2015 government Spending Review was part of an overall package of funding to help fund innovation in clean, low carbon energy.

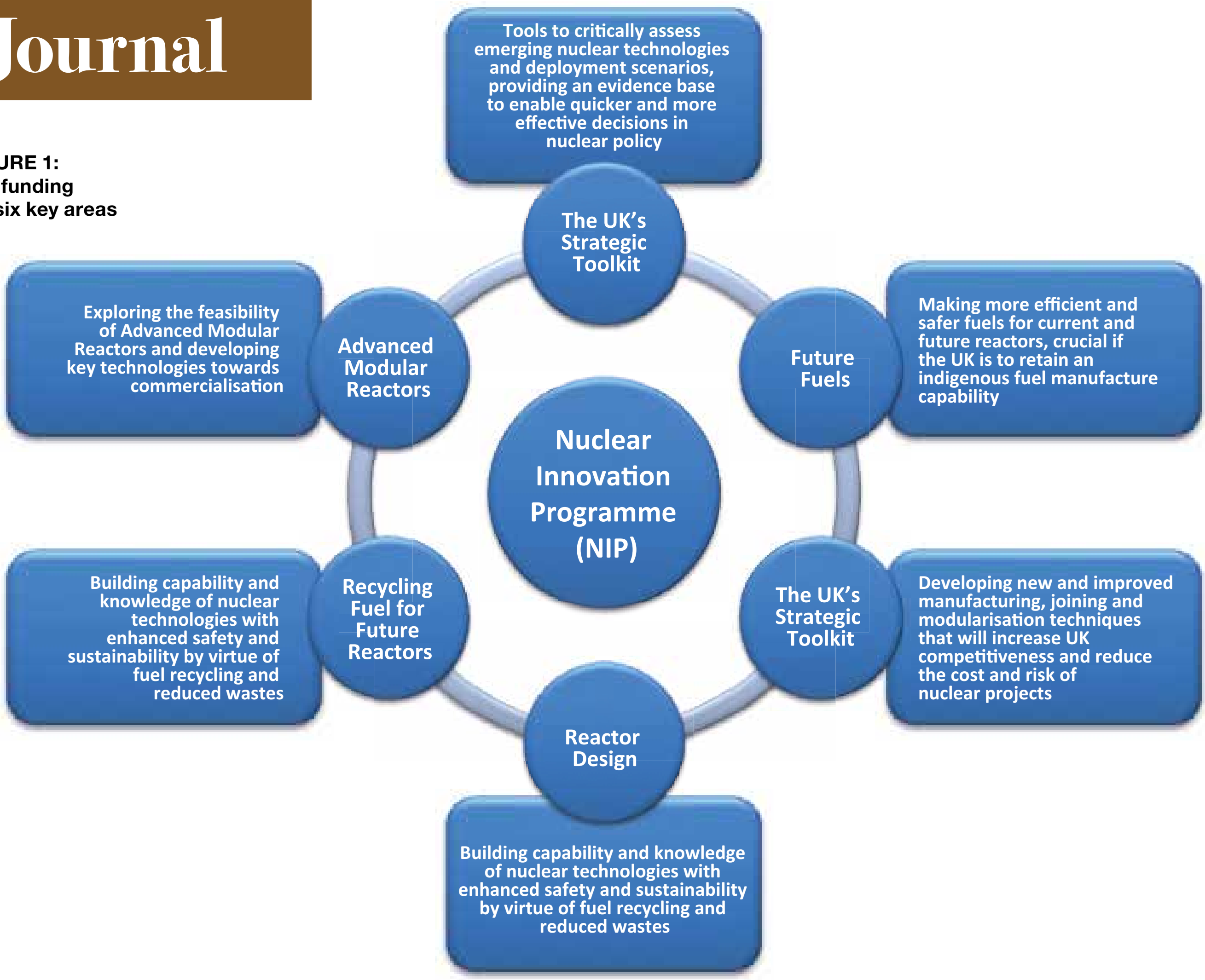
THE NUCLEAR INNOVATION PROGRAMME

From 2014 – 2016, NIRAB looked at the nuclear fission R&D landscape within the UK and concluded in its 2014 annual report to Government [4] that:

- Waste management and decommissioning research was commissioned by the Nuclear Decommissioning Authority (NDA) estate to support their ongoing mission.
- Fundamental nuclear research is well served by UK universities with UK Research and Innovation (UKRI) providing programme funding and infrastructure.
- UKRI funding helps stimulate the UK supply chain to provide smaller companies with a competitive edge within the domestic and international marketplaces.
- A gap existed in relation to future nuclear research technologies, providing an 'at risk' nuclear skills base and a diminishing presence in the international arena of nuclear R&D.

Following its 2014 report, NIRAB issued recommendations for research in 2015. This was followed by the launch of the NIP [Nuclear Innovation Programme] by BEIS, in 2016. The NIP looked to fund R&D in six key areas as shown in Figure 1.

**FIGURE 1:
NIP funding
for six key areas**



Advanced fuels

The advanced fuels programme looks to make advanced fuels for current and future reactors, to help safeguard the UK's indigenous fuel manufacturing capability.

It is split within R&D into:

- accident tolerant fuels
- fast reactor fuels
- nuclear data.
- coated particle fuels
- reactor physics

Reactor design

These reactor design tasks look to develop digital tools and fundamental scientific understanding needed to design and build future generations of reactors quicker and cost effectively. Funding for this area includes:

- development of thermal hydraulic modelling capability
- design, development and construction of a proposed new £40 million thermohydraulic test facility in North Wales in partnership with Welsh Government (subject to approval of business cases)
- reactor safety and security toolkits
- virtual engineering environments.

Spent fuel recycle

The spent fuel recycle programme is aimed at building the capability and knowledge of nuclear technologies with a view to a proliferation resistant, safe and secure nuclear fuel cycle.

Materials and manufacturing

Develop new and improved manufacturing and modularisation techniques that will increase the UK's competitiveness and reduce the cost and risk of nuclear projects in the future. It is divided into:

- materials test and development
- advanced component manufacturing
- large scale manufacturing and assembly
- pre-fabrication module development and
- codes and standards.

Nuclear facilities and strategic toolkit

This programme looks to generate the tools necessary to critically assess emerging nuclear technologies and deployment scenarios, providing an evidence base, upon which, quicker and more effective nuclear policy decisions can be made. This includes:

- strategic assessments
- fast reactor knowledge capture
- regulatory engagement
- access to irradiation facilities.

Advanced modular reactors

In its summary to the Clean Energy Ministerial in 2019, UK Government described AMRs and SMRs as potentially being "fundamental to any future decarbonised energy system". The AMR programme will provide a feasibility study and design

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development of certain AMR designs, and follows on from the Government's SMR competition which closed in 2017. The Government then commissioned an independent techno-economic assessment of SMRs [5], along with cost reduction studies [6,7] siting studies [8] and assessment of the UK regulatory regime with respect to SMRs [9]. Following the publication of these studies, BEIS announced the decision to invest £44 million under the NIP into an AMR feasibility and development project.

CURRENT STATUS OF THE NUCLEAR INNOVATION PROGRAMME

Phase 1 of the NIP is largely complete and, to date, has seen delivery of £6 million of R&D spending on advanced nuclear fuels, £5 million on reactor design, £6 million on advanced manufacturing, £2 million on spent fuel recycle and £2 million on strategic toolkits. Phase 2 of the NIP now underway and will continue work in these areas, building UK capability.

As Phase 1 of the NIP draws to a close, the results of the first R&D funding after two decades are bearing fruit. Knowledge capture from senior subject matter experts has been recorded and is being passed on to new researchers and entrants to the industry, including hands-on practical activities such as glovebox manipulation. Knowledge from the UK's fast reactor programmes has been captured and catalogued to enable future access and a set of toolkits produced to further streamline and improve future reactor design assessment.

Specific areas of the NIP are outlined in further articles in *Nuclear Future*.

INTERNATIONAL IMPACT

The NIP funding has also allowed the UK to re-join key international fora. These are vital in leveraging knowledge from other nation's R&D efforts and to provide access to facilities that the UK does not have at home.

So far, the NIP has enabled the UK to engage with 54 organisations across 16 countries as it seeks to place itself, once again, at the top table of nuclear nations.

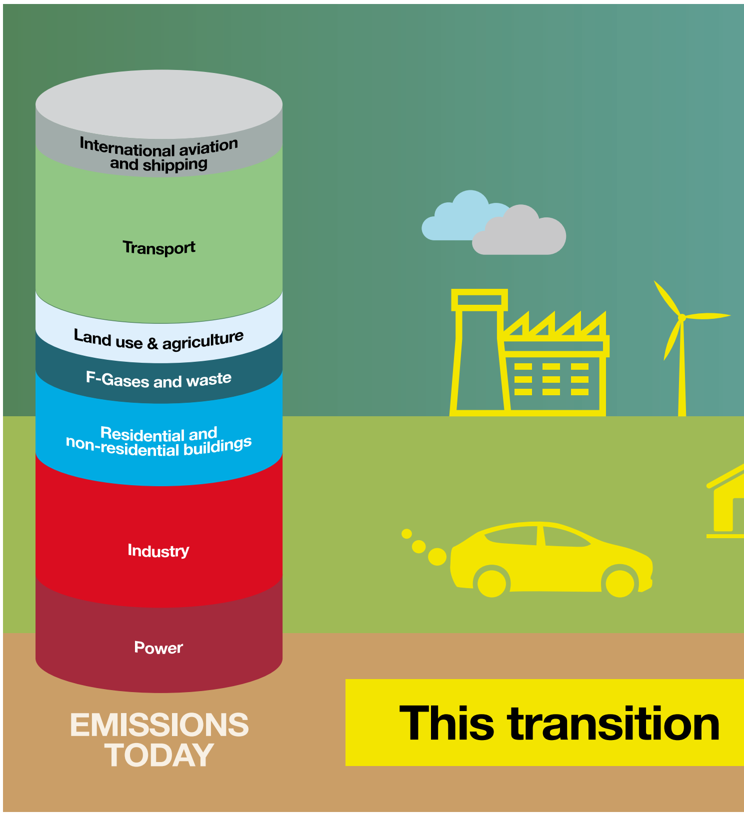
The UK acceded to the Generation IV International forum in 2018 and is, once again, a key part of international nuclear programmes such as the US-UK fission partnership, allowing it to share in key knowledge and skills for the next generation.

The US-UK fission partnership R&D action plan was signed in September 2018 and proposes the following strategic areas for cooperation:

- Nuclear reactor technologies having potential synergies with the advanced modular reactor (AMR) and small modular reactor (SMR) programmes in the UK.
- Radioisotopes for space technologies.
- Advanced fuels, with a clear link to the NIP's advanced fuels areas.
- Fuel cycle technologies, with potential collaboration with NIP work on fuel recycling.
- Advanced modelling and simulation, which could link with digital reactor work under NIP.
- Enabling technologies.

FUTURE INVESTMENT IN NUCLEAR R&D

In addition to entering the next phase of the NIP, the NIRAB are



looking to the future of research, development and innovation within nuclear fission. Under its remit of providing the Government with independent and objective advice on research and development of nuclear fission, NIRAB comprises 37 members from academia and industry. The group is supported by NIRO which provides a secretariat to NIRAB and provides independent and objective advice to BEIS on nuclear related topics, including R&D.

As described in NIRAB's latest report [10], there is a bright and broad future for nuclear, stretching well beyond the current level of 15 – 20 % of our energy production. This has the potential to be carried through to the provision of a much larger share of nuclear energy; up to and beyond 30%, including the production of nuclear heat for industry, domestic combined heat and power and even the production of hydrogen for our advanced, net zero carbon economy.

With the slowdown of new nuclear capacity rollout – down from the 16 GWe originally proposed across 6 sites, to 8 GWe across 3 sites – there is an urgent need to progress advances in nuclear technology, funding and support to help the UK achieve its ambitious net zero target by 2050. Providing an increased share of electricity production from nuclear power stations, be they large scale or small scale, is the relatively easy part. Using nuclear as part of a larger scale solution, and infrastructure to decarbonise transport or home heating, will take many years of research and investigation. Whilst 30 years may seem a long time by which to achieve net zero carbon emissions, it is a mere fraction compared to the lifetime of a nuclear or infrastructure project.

Government support is already having an impact now through the NIP programme; capturing knowledge, bringing on the next generation of nuclear specialist skills and preparing the UK and its regulatory authorities for the next generation of nuclear

technology. To help build on this, NIRAB has recommended that Government work with industry to define a roadmap for future nuclear new build to help meet net zero carbon emissions by 2050, and has proposed that following 2021 and the completion of the current NIP Government look to invest £1bn over the next spending review period, to include:

- £300 million for nuclear R&D to continue the work started under NIP
- £100 million to support infrastructure for new advanced nuclear technologies and
- £600 million to help bring nuclear technologies from the conceptual, through to the demonstrator phase.

The demonstration of concepts is a key part of the innovation cycle and is often where many projects fail. The Nuclear Energy Agency (NEA) – a specialised agency within the Organisation for Economic Co-operation and Development (OECD) – recommends a magnitude increase in funding to support technologies through these phases. There has not been a demonstration of a Generation IV technology in an OECD country for over 20 years; this may be surprising, but also offers opportunities for the UK to play a leading role moving forward.

Paul Nevitt

From 2016 until July 2019, Paul was a Senior Technical Advisor in NIRO (Nuclear Innovation and Research Office) providing advice to Government on the research and innovation required to underpin policy. Paul now works for the National Nuclear Laboratory (NNL) as Technical Director working on aspects of the Nuclear Innovation Programme investment in NNL.
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The story of the Nuclear Innovation Programme, whilst still in its infancy, provides hope for the future that the UK can continue to be a 'top table' nuclear nation and world leader in the slowing down of climate change in the global community. Identification of gaps in the UK's R&D funding of nuclear technologies has acted as an agent of change for the Government to deliver an ambitious, multi-faceted R&D campaign; the Nuclear Innovation Programme. Following the recommendations of NIRAB and alignment with the Committee on Climate Change's report [11], the UK is closer to achieving its target of net zero by 2050. This is only the beginning however; the UK and the NIP looks forward to strengthening and building upon the work already carried out as part of the first significant publicly funded future fission energy research in the UK in over 20 years.

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Innovation in the aqueous recycle of spent nuclear fuels

Results from Phase 1 of the Nuclear Innovation Programme

> "Phase 1 of the 'recycle programme' was approximately 22 months in duration, finishing in early 2019, and was delivered by a consortium led by NNL with partners from the universities of Lancaster, Leeds and Manchester and Wood plc..."

SUMMARY

- Spent fuel recycle and waste management is one of the main themes under the BEIS Nuclear Innovation Programme.
- Phase 1 of the recycle programme was delivered by a consortium led by NNL and completed in early 2019.
- Baseline flowsheets for an Advanced PUREX process to reprocess high burnup light water reactor UOX and MOX fuels have been developed for dissolution, chemical separations and product finishing stages.
- An assessment of wastes arising from the Advanced PUREX process has been made using NNL's Sim Plant tool and compared to Thorp.

By **Robin Taylor** and **Gemma Mathers**

INTRODUCTION

As described in the earlier article in this journal [1], to support the substantial role that nuclear energy could make in meeting the UK's 2050 net-zero carbon emissions target, the Department of Business Energy and Industrial Strategy (BEIS) have initiated a Nuclear Innovation Programme (NIP).

The National Nuclear Laboratory (NNL) are actively contributing to all six NIP themes and leading UK consortia to deliver innovation in the following three:

- advanced fuels
- fuel recycle and waste management
- nuclear facilities and strategic toolkit.

This article focuses on work undertaken as part of the fuel recycle and waste management theme.

Phase 1 of the 'recycle programme' was approximately 22 months in duration, finishing in early 2019, and was delivered by a consortium led by NNL with partners from the universities of Lancaster, Leeds and Manchester and Wood plc.

This article provides an overview of the recycle programme; initially looking at the background to fuel recycling and the objectives of the programme. The major results from the phase 1 project are summarised, including advances in the process chemistry, engineering and an assessment of the wastes arising from the processes under development. The wider benefits of the programme, such as maintaining skills, international engagement and knowledge management, are also noted before a short description of the likely future directions of the programme.

BACKGROUND – BENEFITS AND CHALLENGES IN FUEL RECYCLING

By the end of next year, the United Kingdom will have commercially reprocessed nearly 65,000 tonnes of spent nuclear fuel (SNF) from Magnox, advanced gas cooled (AGR) and light water (LWR) reactors since the 1960s at Sellafield with some of the recovered uranium and plutonium recycled as new fuel for reactors [2]. Fast reactor fuels, manufactured from uranium and plutonium recovered from reprocessing, have also been reprocessed at Dounreay in Scotland but, since the closure of the fast reactor programme in the early 1990s, the UK has accumulated a large stockpile of separated plutonium that is now held safely and securely in interim storage at Sellafield awaiting decisions on whether to re-use as mixed oxide fuel (MOX) or immobilise for disposal [3]. Fuel reprocessing at Sellafield is also now ending and from 2021 the UK will follow an open fuel cycle; that is, the remaining spent fuel from the current generation of AGRs, Sizewell B and new reactors will be stored, with the expectation that it will be directly disposed to a waste repository towards the end of this century [4].

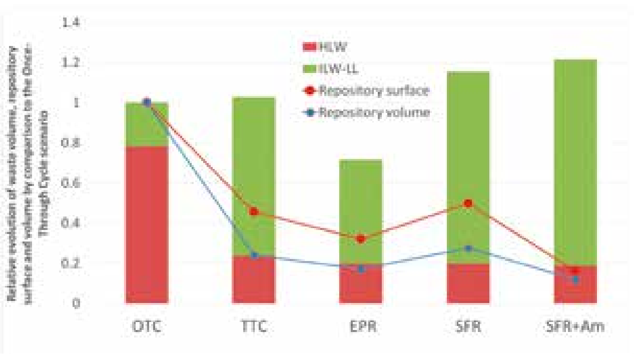

FIGURE 1:
Evolution of the relative volume of high level waste (HLW, including unreprocessed spent fuel), long-lived intermediate level waste (ILW-LL), repository surface and repository

volume between the various types of fuel cycles, normalized to the situation in the once-through cycle (OTC) – results from a study of French fuel cycle scenarios where TTC is the twice-through cycle (reprocessing with thermal MOX recycle); EPR is the TTC with Generation III pressurised water reactors; SFR is the sodium cooled fast reactor fuel cycle with plutonium multi-recycling and SFR+Am is the SFR cycle with the addition of americium recycling (reproduced from open access article J. Serp et al., Energies 10, 1445, 2017 [9])

In the UK, deep disposal in a geological disposal facility (GDF) is planned. However, the location, size and public acceptance of the GDF remains unclear and any significant expansion of low-carbon nuclear energy beyond the present 'new build' policy of up to 16 GWe will be challenging to dispose of in the GDF due to the heat loading and larger spacing that spent fuel disposal requires [5].

Fuel recycling, however, offers potential solutions as a waste management option, inter alia:

- Reduced long term heat generation by removal of plutonium and transuranic actinides enabling more compact loading in the GDF and hence a smaller overall size. For example, the reductions in footprint (surface area) and volume are illustrated in Figure 1 for various evolutions of the nuclear fuel cycle in France, compared to direct disposal of SNF (also called the 'once-through cycle').
- High level wastes (HLW) contained in a bespoke wasteform that is designed for geological containment (glass or ceramic) with a significant volume reduction compared to direct disposal of SNF. Again, Figure 1 illustrates this effect for the French fuel cycle.
- Reduction of the long term radiotoxicity of the HLW by removal of plutonium and transuranic actinides and hence the 'lifetime' of the repository from >100,000 years to <1,000 years. It should be noted that as the actinides are considered immobile in the repository environment, this reduction in hazard does not benefit the repository safety case, except in low-probability high-impact scenarios such as human intrusion [6]. As can be seen in Figure 1, recycling also increases the amount of secondary intermediate level waste (ILW) required for disposal [7].

Given the importance of public acceptance of nuclear waste disposal and likely concerns over the inventory, lifetime and size (or number) of repositories needed, the UK's ability to manage spent fuel could become a limiting factor on the contribution that nuclear can make towards the UK meeting its carbon emissions' targets and, hence, the fight against climate change. Recycling as a waste management option could, therefore, deliver significant public acceptability benefits and enable the expanded use of nuclear energy [8].

As well as new build of large Generation III reactors, there is interest in the UK and internationally in other reactor types including small or advanced modular reactors (SMR/AMR) or Generation IV (GenIV) systems, and new fuels (e.g. accident tolerant fuels (ATF), plutonium fuels, molten salt based fuels, thorium fuels). Some of these systems require fuel recycling and/or resources such as plutonium recovered from stocks of spent thermal reactor fuels. GenIV fast reactors could offer substantial advantages over current reactors in terms of sustainability by extending the available uranium resources almost indefinitely, with a concomitant reduction in mining and enrichment at the front end of the fuel cycle and hence benefits in reducing the overall environmental impact and proliferation risks of nuclear energy [9-11]. GenIV reactors also enable the multiple recycling and burning of plutonium and the minor actinides. For these reasons, the UK has recently re-joined the Generation IV International Forum (GIF – see https://www.gen-4.org/gif/) with specific interests in the sodium cooled fast reactor (SFR) and high temperature reactor (HTR) designs. Another prospective design is the molten salt reactor (MSR), originally developed at Oak Ridge National Laboratory in the 1960s [12, 13], and which is generating renewed interest [14]. Most MSR designs require an on-line salt clean-up process [15].

It is therefore clear that there are some substantial potential advantages to be gained from implementing closed fuel cycles and, specifically, recycling spent fuels from future reactors. However, there are a number of challenges that must be addressed for recycle to become an attractive option.

Firstly, the economics of the nuclear fuel cycle is a complicated situation. Most studies agree that the costs associated with the back end of the nuclear fuel cycle are a small percentage of the overall (levelised) cost of electricity (LCOE) – ref. [16] quotes 3.2%. Also, that the back-end costs are outweighed by the uncertainties and risks in the front-end – reactor build – costs and so there is little difference between the choice of open or closed cycles on this basis. However, fuel recycling requires nearer-term, up-front capital costs to build fuel cycle plants whereas interim storage and eventual disposal defers costs for several decades or more. The choice of SNF management also impacts operational costs once the reactors are built and generating electricity [16]. Offset against such costs are the potential economic benefits in terms of contracts for fuel recycling and creation of long-term skilled jobs.

Furthermore, fuel reprocessing creates secondary wastes and has environmental impacts such as radioactive aerial and liquid effluent discharges that must be managed, cost effectively and in compliance with regulatory limits. Eventual decommissioning of fuel cycle plants would also be required.

It is important to address any perceived proliferation risks of reprocessing activities and the circulation of nuclear materials within the closed fuel cycle, though most studies agree that all nuclear fuel cycles carry a level of proliferation risk – for example, in the open cycle, the decay of the fission products means that SNF loses its self-protecting radiation barrier within a century or so. More widely, it is concluded that physical protection, security and application of international safeguards are necessary and highly effective as the primary defence in addressing proliferation risks across all nuclear fuel cycle activities [15]. Additional barriers that add to the defence-in-depth are still beneficial and so should be part of the overall design of any new separation processes.

It is thus clear that to realise the benefits of fuel recycling, these challenges must be addressed. Current reprocessing technology is based on the PUREX process (see Box 1) and is essentially unchanged since the 1980s. Innovative approaches that reduce capital costs, reduce wastes and environmental impacts and address proliferation concerns effectively, are required to enable any future deployment of reprocessing later in this century. Moreover, reprocessing is only one stage of the closed fuel cycle

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and any improvements to be made need to be integrated with upstream and downstream activities so that overall fuel cycle solutions are fully optimised rather than, as in the past, optimising parts of the fuel cycle in isolation.

THE RECYCLE THEME IN THE NUCLEAR INNOVATION PROGRAMME

Fast reactors and the closed fuel cycle remain technologically immature and require sustained and long-term programmes of R&D to develop and implement; timescales that are outside the usual horizons of industry investment. The NIP is established to enable nuclear energy to play a full role in the UK's zero carbon future and, in line with the NIRAB recommendations, is focused to address challenges across advanced reactors, future fuels and spent fuel management. There is also the need to sustain the UK's world leading skills and reputation with the ending of industrial scale reprocessing operations at Sellafield next year. The NIP Recycle programme has, therefore, been designed to both maintain high level R&D skills but also to keep the recycle option open should this be needed to enable the growth of low carbon nuclear energy in the UK over the 21st century and beyond.

Based on the work of the Nuclear Innovation and Research Advisory Board (NIRAB) [17, 18], BEIS defined a two-part vision for a fuel recycle R&D programme, this being:

- "by 2020 to have demonstrated radical improvements in economics, proliferation resistance, waste generation and environmental impact of spent nuclear fuel recycle technologies
- by 2030 the UK to be engaged in national and international R&D programmes providing 'proof of concept' for future fuel cycles and reactors".

The NNL-led consortium have subsequently proposed that a goal-orientated R&D programme to meet these NIRAB objectives should have a technical mission "to provide by 2030 credible technical options for advanced reprocessing of SNF that are competitive with other fuel cycle options available to decision makers".

The NIP is a phased investment in nuclear energy R&D with Phase 1 having just completed (2017-2019) and Phase 2 (2019-2021) just starting. In Phase 1, the fuel recycle programme was focused on the development of advanced aqueous recycle of LWR fuels in order to maintain skills and build on existing programmes. Also, because in most scenarios the recycle of bulk quantities of LWR fuels – to generate nuclear materials for advanced reactors and to manage SNF inventories – will be the first stage in implementing a closed cycle. Phase 1 of aqueous recycle, therefore, laid the platform for the future R&D programme and, specifically, aimed to prove the concepts for the key reprocessing stages (fuel dissolution ⟶ chemical separations ⟶ product finishing) by defining and experimentally underpinning baseline flowsheets for these stages.

Beyond Phase 1 it is expected that the programme will expand to address the recycling of other fuel types, alternative processes such as dry pyrochemical processes and innovative means of dealing with the wastes arising from advanced SNF recycling technologies (see 'Next Steps' section later in this article).

RESULTS FROM THE PHASE 1 AQUEOUS RECYCLE PROJECT

Process chemistry and flowsheets

Initially, two reference fuels on which to base the flowsheet design were defined. These were typical fuels arising from probable UK new build light water reactors: 10 year cooled 65 GWd/t UOX (5%w/o initial enrichment) and 50 GWd/t MOX (8 %w/o Pu). The MOX fuel is based on the scenario that the UK's stored plutonium dioxide (PuO_2) is recycled as MOX fuel. Due to the age of this plutonium stockpile, there is ~0.3wt.% percent of americium-241 present in the fuel pre-irradiation with the consequence that the amount of trans-plutonium isotopes is significantly increased in the spent MOX fuel.

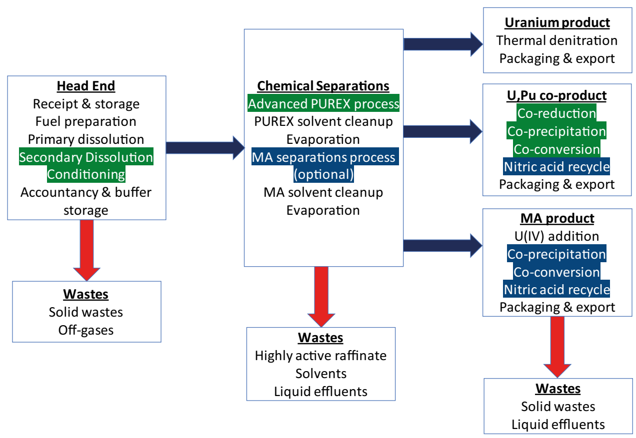

FIGURE 2:
Key stages in the advanced aqueous recycle process (green highlights indicate stages of lower technical maturity studied in Phase 1 and blue highlights indicate stages in the scope of the GENIORS project).

As in current reprocessing plants, the key stages of the advanced aqueous recycle chemical process are the head end plant, where SNF is prepared for reprocessing, the chemical separations plant, where the products are separated and purified from the dissolved fuel, and the finishing plants where the products are re-converted into solid products ready for fuel fabrication. The main chemical process steps for each of these stages are shown schematically in Figure 2. As Phase 1 was a relatively small project with a limited timeframe the whole end-to-end process could not be studied. Instead, we focused on parts of the process that are novel to the Advanced PUREX concept and hence of lower technical maturity, these are highlighted in green on the figure.

The head end plant consists of receipt and storage of SNF followed by mechanical disassembly and fuel preparation, e.g. by shearing, prior to the dissolution of the fuel in nitric acid [19]. In the Advanced PUREX process we have introduced a secondary or residues dissolver after the initial dissolution. This enables the reprocessing of high plutonium content fuels (such as thermal MOX) which cannot be routinely reprocessed in conventional reprocessing plants, as plutonium can form insoluble residues. The secondary dissolver uses the electrochemically generated silver(II) catalysed process. Although this is a well-known process, some uncertainties still exist before it can be industrially deployed. Specifically, in Phase 1 the effects of interfering platinum group metals on the efficiency of the electrochemically enhanced dissolution through trials with MOX and PuO_2 powders (Figure 3).

FIGURE 3:
MOX pellet dissolution in NNL's PuMA Lab

The role of the chemical separations plant area is to recover the actinide elements from the dissolved spent fuel with sufficient purities to enable their re-use in nuclear fuels or as transmutation targets. In Phase 1 the main focus has been on the development of an 'Advanced PUREX' process. This is a solvent extraction process still based on the extractant used in conventional PUREX reprocessing – tributyl phosphate (TBP, see Box 1 for details) – but with some key innovations, including:

- Reducing the process to one cycle of solvent extraction compared to three in current reprocessing.
- Replacing bulky mixer-settlers and tall, thin pulsed columns with small, low centrifugal contactors that have short residence times and intensified mixing-settling characteristics.
- Capability to reprocess high plutonium concentrations found in thermal MOX fuels.
- Full control of neptunium in the single cycle flowsheet.
- In the plutonium separation stage, replacing the reducing agent uranium(IV) used in current reprocessing with a complexing agent (acetohydroxamic acid) for Pu(IV). This also eliminates the need for hydrazine as a stabiliser for Pu(III) ions.
- Co-processing some uranium with the plutonium product to avoid fully separated plutonium at any stage of the process.

These innovations should lead to an Advanced PUREX process that is far more compact than the current PUREX process (hence reduced capital costs to build), is more flexible, generates less waste streams and demonstrates some technological improvements in both process safety and proliferation resistance.

In Phase 1, two flowsheet tests were made on the Advanced PUREX process, which is illustrated schematically in Figure 4, using surrogate feeds in a glove box housed centrifugal contactor rig in NNL's 'PuMA Lab' (Plutonium and Minor Actinides Lab). This rig is a cascade of 32 stages of 1 cm rotor diameter centrifugal contactors, and has been described in earlier Nuclear Future articles [20, 21].

The first test demonstrated the co-extraction of uranium, neptunium and plutonium from the fission products and separation of a mixed (U,Np,Pu) product from the majority of the uranium using acetohydroxamic acid. A U:Pu ratio of 1:1.3 was obtained, close to the output ratio predicted by process modelling in advance of the trial. This test proved, for the first time, the feasibility of co-processing uranium and plutonium using acetohydroxamic acid.

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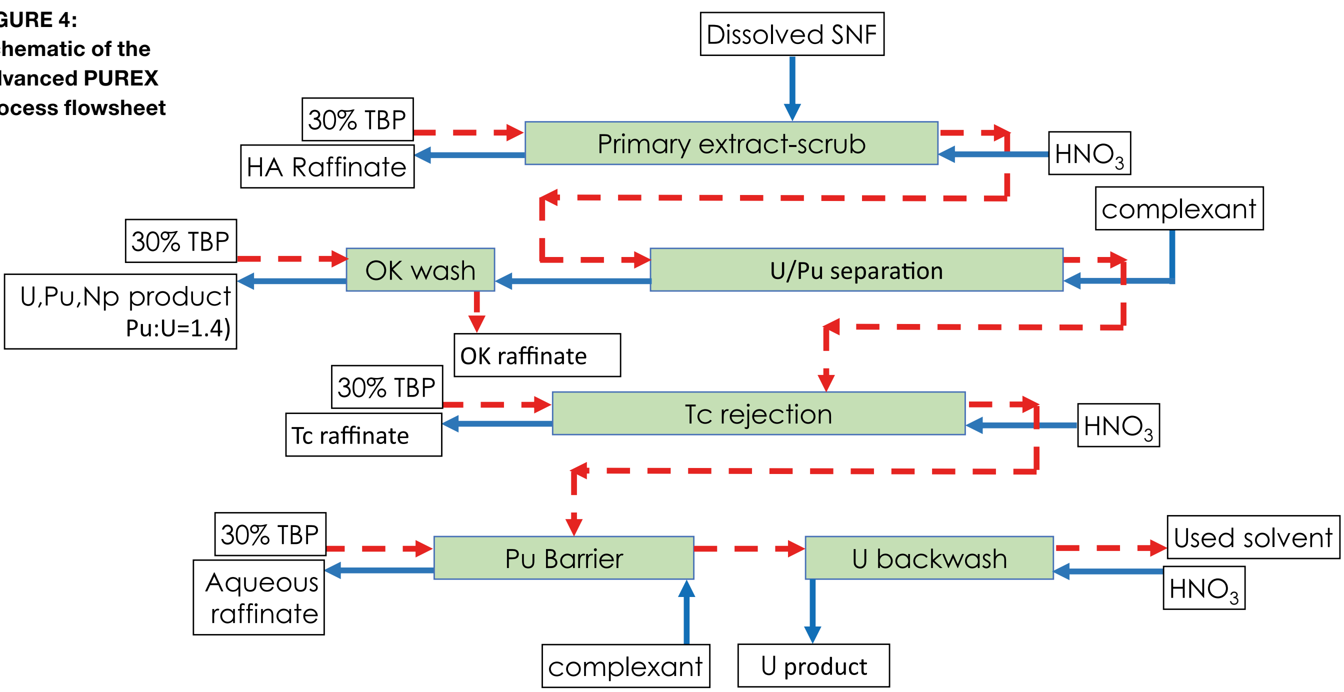
FIGURE 4:
Schematic of the Advanced PUREX process flowsheet



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The second test aimed to demonstrate that the bulk uranium product would meet product specifications for technetium and alpha content without the need for additional cycles of solvent extraction. Good results were obtained for the technetium decontamination stage but the decontamination factors measured in the alpha barrier contactor were too low. The reason for this is known and the flowsheet will now be optimised in the next stage of the project.

We are also interested in the option to incorporate a minor actinide separation process on the HLW stream should the heat generating americium and/or curium need to be removed from the wastes. However, no work was done on this in Phase 1 as the European 'GENIORS' project (see Box 2) is developing two reference process options: the innovative (or i-) SANEX process to recover americium and curium and the EXAm process to recover americium alone from the HLW [22]. This is a key example of the benefits of international collaboration to the UK programme.

The chemical separation cycles, therefore, lead to three product streams and consequently finishing processes needed:

1. **URANIUM** – the conventional uranium finishing processes (thermal denitration or ADU [ammonium diuranate] routes) to produce UO_3 or U_3O_8 products are industrially mature and, as this is a uranium-only process, not a priority for R&D.
2. **URANIUM-PLUTONIUM FINISHING** – assuming a U:Pu ratio of 1:1 and potentially containing neptunium.
3. **MINOR ACTINIDE (MA) FINISHING** – either americium and curium or americium alone.

In Phase 1 the focus has been on the (U,Pu) finishing process where we have taken the oxalate route as our reference process. This involves the co-precipitation of uranium and plutonium nitrate with oxalic acid and then the conversion of the mixed (U,Pu) oxalate to a mixed (U,Pu) dioxide powder product [23]. This is a modification of the process used in conventional reprocessing for the production of plutonium dioxide but the introduction of uranium causes some problems, i.e.:

- The need to reduce U(VI) to U(IV) in the nitrate product before precipitation as U(VI) oxalate has a high solubility.
- The reduction of U(VI) to U(IV), however, causes a concomitant reduction of Pu(IV) to Pu(III) and so a mixed [U(IV),Pu(III)] oxalate must be precipitated that incorporates a decomposable mono-positive counter-cation, such as the hydrazinium ion ($H_5N_2^+$), to maintain charge neutrality in the mixed oxalate complex.
- Avoiding uranium oxidation during the calcination stage to ensure a solid-solution stoichiometric $(U,Pu)O_{2.0}$ product is formed without excessive residual carbon contamination.

Phase 1 R&D focused on these issues. One of the major advances made has been in the development of a photo-chemical reduction to produce U(IV) prior to oxalate precipitation. Whilst chemical reducing agents or an electrochemical process were initially considered leading options, an upfront optioneering exercise also identified significant engineering benefits of using photochemistry for the reduction stage. A small-scale batch photo-reactor was designed and 3D-printed using an ultra-bright 6,000 mW LED array with a peak output wavelength of 405 nm as the light source.

Testing to date with mixed solutions of uranium and cerium (as an analogue of plutonium) in nitric acid has indicated near-100% conversion of U(VI) to U(IV) and Ce(IV) to Ce(III) can be rapidly obtained. Furthermore, the reduced product solution can be stabilised by the addition of hydroxylamine. This co-reduction step is a key technology gap in linking the chemical separations and product finishing processes together and there are good indications to date that this novel photo-chemical process will address this gap. The next step is to develop a continuous flow-through photo-reactor and to test the technology with (U,Pu) solutions to confirm its viability.

The MA finishing process again assumed an oxalate precipitation and calcination route as the baseline although the high specific activity of these isotopes will be problematic and an alternative to powder processing may ultimately be needed. The flowsheet was defined assuming blending with U(IV) is required to produce a $(U,MA)O_2$ product but further work is needed to underpin the concepts.

Process technology and engineering

To make step changes to plant layout that lead to reduced costs, the process engineering needs to be addressed together with the process chemistry. In Phase 1, work was initiated to underpin one of the key project assumptions: i.e. that compact, intensified centrifugal contactors can replace current pulsed column and mixer-settler technologies for the solvent extraction plant [24, 25].

The main drawbacks of centrifugal contactors are that they are rather complex engineered items that will have to be maintained and/or replaced in an active plant and that they are less robust to any solids or cruds in the process. To address these issues, an engineering-scale centrifugal contactor rig was installed and commissioned at the University of Leeds (Figure 5, left). This comprises three stages of 4 cm rotor diameter Rousselet Robatel BXP-040 centrifugal contactors and now presents a unique (in the UK) test bed facility for the programme.

It is anticipated that the rig will shortly be commissioned for use with uranium-containing solutions and supplemented with on-line analytical capabilities.

FIGURE 5:
New skills and capabilities developed by the programme – (left) the engineering scale centrifugal contactor rig at the University of Leeds and (right) plutonium glove box training at NNL.

Sim Plant modelling tool and waste assessment

As well as the development of the processes and technologies, it is critical that the impacts of the advances made through R&D on key drivers such as costs, safety, proliferation resistance, environmental impact etc. are evaluated. This evaluation can be at the reprocessing plant, recycle site or even UK fuel cycle scale. Whilst tools such as ORION are available to assess fuel cycle scenarios and options [26], there is a need to develop a simulation tool that evaluates the impacts at the plant or site scales in a clear way. We are, therefore, developing a new modelling tool, called 'Sim Plant', to make such assessments. Eventually, this will be 'gamified' to present easy to use input and visual outputs but in Phase 1 the focus was placed on making an initial waste assessment of the Advanced PUREX process compared to Thorp reprocessing.

TABLE 1 RESULTS OF SIM PLANT WASTE ASSESSMENT OF ADVANCED PUREX PROCESS COMPARED TO THORP REPROCESSING (ASSUMES A DAILY SPENT FUEL THROUGHPUT OF 5 tHM/d)

WASTE TYPE	UNITS	ADVANCED PUREX	THORP PUREX	% REDUCTION
Total HLW	m^3/d	27.1	28.5	5
	m^3/TWh_e	12.7	17.1	26
Total purged solvent	m^3/d	0.93	1.15	19
	m^3/TWh_e	0.44	0.69	36

Table 1 shows the results of the waste assessment. It is apparent that the Advanced PUREX process produces less HLW and solvent waste at source than Thorp both on a volumetric basis and when normalised to the electricity generated per tonne of the fuel reprocessed. This is despite the Advanced PUREX process being designed to reprocess a more challenging range of fuels in a simpler (single cycle) flowsheet. The Sim Plant assessment also highlighted the benefit of recycling nitric acid within the plant, from streams such as evaporator condensates, on the minimisation of ILW arisings.

International collaboration, skills and knowledge management

The NIP also has a range of more 'strategic' goals such as to maintain world leading expertise and develop the skills and capabilities that can drive economic growth for the UK in the future. Skills, knowledge management and international links were, therefore, key performance indicators (KPIs) for the recycle programme. In Phase 1, the main international collaboration developed was with the EURATOM Horizon 2020 programme funded 'GENIORS' project (see Box 2).

A strong focus was also placed on training and opportunities for earlier career researchers, including the development of 'alpha skills' – that is, the handling of special nuclear materials such as plutonium in radiochemical glove boxes (Figure 5, right). Another example was the secondment of a post-doctoral researcher from the University of Manchester to the United States Department of Energy's (US-DOE) Idaho National Laboratory (INL) to work with experts there on the effects of radiation on organic solvents.

Technology readiness levels

A technical objective of Phase 1 was to develop dissolution, separation and finishing processes towards technology readiness level (TRL) 3. The TRL scale is a widely recognised methodology to assess technical maturity of a component, product or process. The approach to assessing TRLs here was adapted from the methodology proposed by the Expert Group in Fuel Recycling Chemistry (EGFRC) of the Organisation for Economic Co-operation and Development's Nuclear Energy Agency (OECD-NEA) [15]. At TRL 3 there is proof of concept through lab scale tests of the technology applications (flowsheets) underpinned by fundamental data. These lab scale tests will have been performed with simulant feeds that include representative concentrations of nuclear materials such as plutonium. The dissolution, Advanced PUREX, i-SANEX and (U,Pu) finishing processes are all judged to have reached TRL 3 – noting that this is an assessment at the 'system' level even though some specific components of the overall system may strictly be at a lower TRL. The MA finishing flowsheet was not tested experimentally and so is assessed to be TRL 2. The TRL scale is provided in Table 2 for reference.

NEXT STEPS

During Phase 1 a roadmap was developed for the Aqueous Recycle project, with the end goal being to have by 2030 the technological demonstrations and impact assessments that could underpin strategic or policy decisions on the direction of the UK fuel cycle. Intermediate programme phases are based around climbing the TRL ladder. That is, reaching TRL 6 and demonstrating credible, competitive options for future recycling of SNF. It is likely that this eventually will require new facilities, including the capabilities to do demonstration 'hot tests' of processes using small quantities of actual spent fuels [27]. During this period, the development of wider international collaborations and realising 'spin-out' economic benefits are to be expected. One example is the separation of americium-241 from UK plutonium that can be used as a power source in deep space missions. By modifying PUREX and SANEX processes, NNL have already developed a flowsheet that can produce pure ^{241}Am – the AMPPEX process (see Box 3) [28].

More specifically, the next phase of the Aqueous Recycle project intends to continue the development of the flowsheets to reach TRL 4, addressing the issues identified in Phase 1 to ensure all novel process stages are properly underpinned by lab scale tests with representative materials. In parallel, there will be a greater

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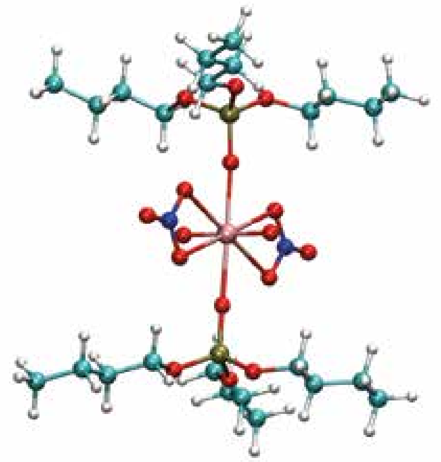
TABLE 2 SUMMARY OF TRL DEFINITIONS FOR SEPARATION PROCESSES (ADAPTED FROM REF. [15])

TRL	FUNCTION	DEFINITION
9	Proof of performance	Multiple years of operational experience established at industrial scale.
8		Full scale process demonstrated in a limited operational environment.
7		Prototype system demonstrated under conditions fully representative of operations.
6	Proof of principle	Engineering or pilot scale testing of technology component or process step. Process flowsheets proven through hot tests using spent fuel. Process models validated.
5		Technology component or process step validated at bench scale under relevant conditions. Process models developed. Proof of principle hot tests using spent fuel.
4		Technology component or process step validated under laboratory conditions. Tests performed using active materials in simulated feeds. Fundamental properties measured.
3	Proof of concept	Lab scale tests to prove concepts, fundamental data obtained
2		Technology application developed and options investigated
1		Initial concepts are proposed and basic principles established

BOX 1: Purex Process



Nuclear fuel reprocessing is generally used to describe the separation and purification of reusable uranium and plutonium products from irradiated nuclear fuel. The recovered uranium and plutonium can then be converted into new uranium oxide (UOX) or mixed oxide (MOX) fuels for recycle to reactors. The highly active (HA) fission product wastes are evaporated and then vitrified ready for disposal. By far the most successful reprocessing technology to date has been the PUREX process, which uses solvent extraction between aqueous nitric acid solutions and organic solutions of tri-n-butyl phosphate (TBP, $(C_4H_9O)_3PO$) diluted in a paraffinic diluent, such as Exxon D-80 [29].

The PUREX process was developed in the late 1940s in the United States and the latest generation of plants are designed to reprocess oxide fuels, i.e. Thorp (Sellafield, UK), UP2, UP3 (both La Hague, France) and Rokkasho-Mura (Japan). A PUREX reprocessing plant comprises a number of facilities: (a) a head end plant to receive and store SNF and to convert the fuel to a solution in nitric acid ready for (b) chemical separation using solvent extraction to produce separate aqueous nitrate products that can be (c) converted to solid oxide products.

A substantial supporting infrastructure is necessary to treat solid wastes and liquid and gaseous effluents arising from reprocessing operations. The Thermal Oxide Reprocessing Plant (Thorp) at the Sellafield site exemplifies current reprocessing technology. Following disassembly, shearing and dissolution of the SNF in nitric acid, uranium and plutonium are purified by solvent extraction.

Thorp uses three solvent extraction cycles with an early split flowsheet where uranium and plutonium are extracted away from the fission products and then separated from each other in the first highly active (HA) solvent extraction cycle. The organic soluble complex formed between TBP and uranium(VI) ions, $UO_2(NO_3)_2(TBP)_2$, is shown in the illustration. There are then two further solvent extraction cycles to purify the uranium product stream and the plutonium product stream. Salt free reagents, tetravalent uranium (U^{4+}), hydrazine (N_2H_4) and nitrogen oxide gases (NO_x) that do not add to waste volumes are used to change plutonium oxidation states through the process.

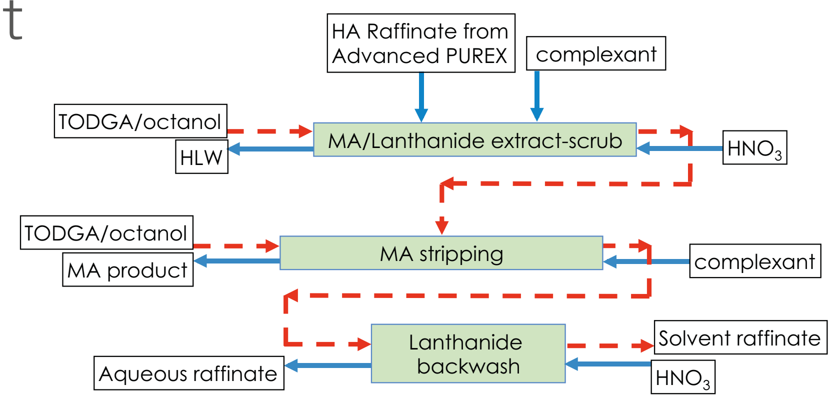
For improved criticality safety and to reduce solvent degradation, tall pulsed columns are used for the plutonium bearing streams whereas large mixer-settlers are used for uranium-only streams after the U/Pu separation. Following solvent extraction, uranium and plutonium products are converted into solid oxides suitable for interim storage before manufacture into new fuels. The conversion processes used are a thermal denitration (TDN) process for uranium finishing and an oxalate precipitation and calcination process for plutonium finishing. As well as the surrounding waste treatment infrastructure, the Thorp plant was integrated with the other supporting operations such as SNF storage, plutonium product storage and MO_x fuel fabrication.

BOX 2: GENIORS Project

GENIORS ('GENeration IV Integrated Oxide fuel Reprocessing Strategies') is the latest project in a series of European projects related to actinide partitioning and recycling that stretch back to the EURATOM Framework Programme (FP) 4.

GENIORS, which is coordinated by the French Atomic Energy Commission (CEA), started in July 2017 and is funded under the EURATOM Horizon 2020 programme with a total value of over €7.5M. There are 24 European partners in GENIORS covering national nuclear laboratories, the EU's Joint Research Centre, universities, nuclear companies and technical safety organisations. There is also a collaboration agreement between the US-DOE and GENIORS.

The GENIORS project is directed towards the development of advanced separation processes for recycling actinides from mixed oxide fuels in future sustainable (fast reactor) fuel cycles focusing on the further development of the European 'reference processes' that have been selected for heterogeneous recycling of minor actinides – 'i-SANEX' and 'EXAm' processes – and homogeneous recycling – the 'EURO-GANEX' process. Thus, the technical scopes of the NIP recycle programme and the GENIORS project are well aligned and the additional leverage will enable accelerated development across both programmes. In fact, several steps in the process are within the scope of the GENIORS project (Figure 2) including development of the i-SANEX process (*process flowsheet illustrated above*). UK partners in GENIORS are NNL and the universities of Edinburgh, Lancaster, Leeds, Manchester and Reading. For further information see the website: http://www.geniors.eu/



BOX 3: AMPPEX Process

The UK has a large stockpile of civil plutonium dioxide, mainly from Magnox and Thorp reprocessing operations. Some of this PuO_2 is now several decades old where a substantial fraction of the ^{241}Pu content has decayed to ^{241}Am (the half-life of ^{241}Pu is 14.35 years). This presents the opportunity to recover isotopically pure ^{241}Am from the plutonium in gram or even kilogram quantities. The European Space Agency (ESA) are interested in the potential use of ^{241}Am to replace ^{238}Pu in radio-isotope thermo-electric generators (RTGs) for space power. NNL have, therefore, developed a new separation process – the 'americium plutonium purification by extraction' or AMPPEX process. The development of this process has been described in detail in ref. [28] but, in brief, it comprises the stages below. A key point to note is that AMPPEX is in essence a modification of the aqueous recycle chemistry and thus a notable example of how alternative applications and commercial opportunities can be spun-out from the core programme. Steps in the AMPPEX process are:

esa space for europe

- Dissolution of aged PuO_2 in nitric acid using the electrochemically generated silver(II) catalysed dissolution method.
- Solvent extraction using 30% TBP to separate plutonium from americium and silver. Plutonium is back-washed by a hydroxylamine (NH_2OH) reduction.
- Solvent extraction using an organic phase of 0.15 mol/L TODGA [tetra-octyl diglycolamide] with 0.5 mol/L DHOA [dihexyloctanamide] diluted in odourless kerosene (OK) to separate americium from silver. Americium is back-washed by changing the nitric acid concentration (note that both solvent extraction processes were carried out in the NNL PuMA Lab glove box centrifugal contactor cascade).
- Both americium and plutonium nitrate products are converted to dioxides by oxalate precipitation and calcination.
- AmO_2 is pelletised and sintered with conversion to Am_2O_3.

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focus on the development of process models for the chemical separations that can be used to both explain experimental results and to design further tests. These process models will be essential in understanding sensitivities to process upsets in future phases – an essential requirement of demonstrating safety. Phase 2 will also broaden the engineering studies to cover on-line analysis for process monitoring and near real time accountancy (NRTA). The Sim Plant tool will be extended to make a plant footprint assessment of an Advanced PUREX reprocessing plant compared to conventional reprocessing (i.e. Thorp). This will provide an initial perspective on possible cost savings if building an Advanced PUREX plant compared to a conventional reprocessing plant.

As well as continuing the development of Aqueous Recycle, other aspects of SNF management need to be considered including reprocessing and recycling of advanced reactor fuels (including GenIV fast reactors), pyro-processing options for solid and molten salt fuels and improved management of recycle wastes: inter alia, HLW immobilisation, solvent and liquid effluent treatments, off gases and used salts. We also expect to engage academia and industry more widely in the broader programme. One pressing need, for instance, is to initiate a reprocessing knowledge capture exercise, particularly since the Thorp plant at Sellafield has already completed its operations [2].

CONCLUSIONS

In conclusion, thanks to the first government investment in nuclear R&D in a generation through the BEIS funded NIP, good progress is being made in developing the chemical flowsheets for key stages of an Advanced PUREX reprocessing plant with most process stages now in the range of TRL 2 to 3. A new tool, Sim Plant, has been developed and used to show significant savings in waste arisings are achievable compared to current reprocessing technology. The project is also enhancing UK skills and capabilities and developing international collaborations in Europe and the USA.

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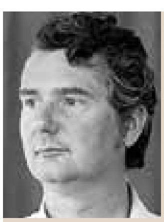

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NUCLEAR PROFESSIONALISM

All people working in the nuclear sector, irrespective of their level or grade of employment, can be characterised as nuclear professionals. All require specialist education and training to develop the skills and expertise needed to perform their jobs safely, securely and effectively in a nuclear context.

In addition to role-specific technical skills, all nuclear professionals demonstrate something extra – what we call in the United Kingdom the Nuclear Delta®. This is the understanding of nuclear specific standards and requirements, especially the importance of nuclear safety culture, nuclear security culture and nuclear technology.

Employer responsibility

Promoting nuclear professionalism brings together the responsibilities of the employee and the employer to create an environment and culture in which nuclear professional practice is highly valued and expected as the norm.

Continuous professional development

In most professional disciplines it is normal practice for individuals to maintain and record their professional status independently of their employment through the appropriate professional body. Professional status is maintained by reporting continuing professional development, accumulated experience and on-going commitment to uphold the profession’s standards and codes of conduct.

As the professional membership body for the UK's nuclear industry, the Nuclear Institute has developed the Nuclear Delta® to support professionals in meeting and maintaining the specific attitudinal, competence and behavioural requirements of the nuclear industry. Achieving the requirements of the Nuclear Delta® is central to professional membership and accreditation by the Nuclear Institute.

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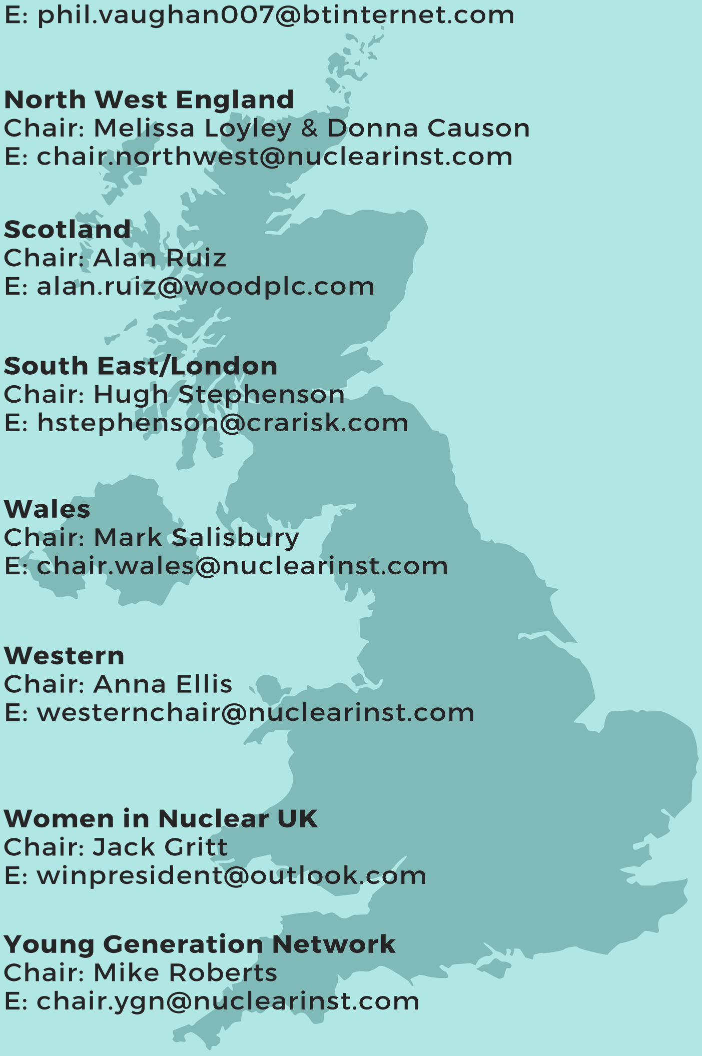

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Implementing the NDA R&D strategy for robotics and artificial intelligence

SUMMARY

- The benefits of wider deployment of robotics and artificial intelligence (RAI) in the nuclear sector are many and include removal of the operator from dangerous environments, productivity improvements and reductions of secondary waste, both radioactive and non-radioactive.
- Sellafield Ltd is leading a RAI R&D programme on behalf of the Nuclear Decommissioning Authority (NDA).
- The R&D programme is managed by the National Nuclear Laboratory (NNL) and delivered in collaboration with UKAEA's Remote Applications in Challenging Environments (RACE) group, industry and academia.

By **Elisa Cucco[1], Katherine Eilbeck[2], Darrell Morris[3], Darren Potter[1]** and **John-Patrick Richardson[1]**

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INTRODUCTION

The UK's nuclear energy programme, dating from the post-war years, has left a mixed legacy: numerous prototype reactors, fuel-manufacturing plants, research centres, reprocessing plants and 11 power stations.

To give some scale to the challenge, at 1st April 2016 the total amount of radioactive waste held within stores and forecast up to 2125 would occupy a volume of about 4.77 million cubic metres (as a final volume after all wastes had been packaged), similar to the volume of Wembley stadium inside its walls and under its roof [1].

Robotics and artificial intelligence (RAI) technologies have undergone rapid technological growth in recent years and have therefore been identified as an area that could significantly improve the existing technical baseline for decommissioning the UK's nuclear legacy [2].

Several nuclear decommissioning and waste management challenges have been identified to be targeted by the RAI research and development (R&D) strategy. These include restricted access, waste management, size reduction, glovebox decommissioning, pond visibility and waste retrievals.

The Nuclear Decommissioning Authority (NDA) maintains strategic oversight of the resulting R&D programme that is led by Sellafield Ltd, managed by the National Nuclear Laboratory (NNL) and delivered in collaboration with UKAEA's Remote Applications in Challenging Environments (RACE) group, industry and academia. This programme has been developed for the purpose of RAI R&D development, demonstrations, communication and training.

The initial activities of this research team are focused on understanding Sellafield Ltd's challenges and constraints, including timescales and key decision points; engaging across the NDA group and externally to identify opportunities for collaboration; understanding where the gaps are in the R&D that is being undertaken; and delivering R&D between technology readiness levels (TRL) 3-6 while influencing work at either ends of the TRL level.

This paper highlights the approach taken to implement the RAI R&D strategy and the progress thus far.

ROBOTICS ACTIVITIES AT SELLAFIELD LTD

There are numerous RAI R&D activities across Sellafield Ltd, industry and universities in support of nuclear decommissioning and waste management. Some are funded directly by Sellafield Ltd, whilst some are jointly or wholly funded via UK Research and Innovation (UKRI) funding and grants. An overview of some of these projects is presented in this section, outlining RAI technologies at different stages of development, ranging from inactive testing through to active deployment.

Box Encapsulation Plant (BEP) waste handling robots

NNL supported Sellafield Ltd in the technical work, including design and proof of concept trials, to develop a full-scale test facility at NNL's Workington Laboratory, where robots could be put through their paces handling a range of simulant miscellaneous beta gamma waste (MBGW) items from different types of imported skips [3].

The developed rig uses commercial off the shelf equipment, including tele-operated industrial KUKA KR500 robotic arms (see Figure 1), extensively adapted to the requirements of BEP, and tested to ensure they fulfilled the requirements. The robots' tools include two different sizes of hydraulic grab for the main waste recovery activities, hydraulic shears for waste disruption and a set of tools for minor activities, such as housekeeping.

The BEP robots are operated remotely to handle all the waste, including heavy and bulky items, with associated tooling to perform handling, disruption and house-keeping tasks. The benefits of remote handling and processing of materials include the reduction of the radioactive dose to the operator, but also the increased efficiency of waste processing from legacy facilities.

This project provided confidence that the robotic system can perform waste processing operations. Furthermore, the achievement of TRL 6 allowed the project to initiate procurement activities for the plant system.

FIGURE 1:
BEP waste handling robots

RoMaNS

The European Union (EU) Horizon 2020 RoMaNS (Robotic Manipulation for Nuclear Sort and Segregation) project aimed to advance the state of the art in autonomous, tele-operative and shared control for remote manipulation, with inspiration coming from the BEP Project at Sellafield. Where many robotic projects, such as BEP, are primarily controlled by tele-operation (robot and tooling manually controlled by operators), RoMaNS aimed to be as autonomous as possible in an unstructured environment.

RoMaNS consortium consisted of the University of Birmingham, NNL, the University of Darmstadt, the Commissariat à l'Energie Atomique (CEA) and French National Centre for Scientific Research (CNRS).

Each partner had a specific focus area in developing a semi-autonomous sort and segregation capability. The University of Birmingham focused on vision-based manipulation algorithms and collision-free trajectory planning [4]; the University of Darmstadt focused on learning algorithms [5]; CEA and CNRS focused on haptic sensors, assisted telepresence system and shared control algorithms [6]; whilst NNL provided the industrial and nuclear background and the industrial testing facility.

The demonstration at the NNL Workington Laboratory rig included two KUKA robots programmed using the KUKA Robot Language, and other hardware, such as grippers, being Programmable Logic Controller (PLC) devices (see Figure 2).

FIGURE 2:
RoMaNS rig in NNL Workington

The RoMaNS project has far reaching cross-sector applications in nuclear, aerospace, oil and gas, space, food and agriculture – and within the nuclear industry itself the research aims to advance waste processing, decommissioning, asset care, maintenance, repair, characterisation and sampling techniques.

"Sellafield Ltd, the University of Manchester and Forth Engineering Ltd have developed Aqua Vehicle Explorer for In-situ Sensing (AVEXIS) [7]. AVEXIS is now part of a new class of small, low-cost underwater vehicles deployed on the Sellafield site..."

AVEXIS: a submersible for underwater exploration of facilities with restricted access

It is difficult to survey the underwater legacy facilities at Sellafield due to several challenges within these extreme environments. Although commercially available remotely operated vehicles (ROV) have been used to explore Sellafield ponds, there is a need for a platform able to address the physical challenge of entering existing access points which are only 150mm wide.

Sellafield Ltd, the University of Manchester and Forth Engineering Ltd have developed Aqua Vehicle Explorer for In-situ Sensing (AVEXIS) [7]. AVEXIS is now part of a new class of small, low-cost underwater vehicles deployed on the Sellafield site, to monitor challenging areas with restricted access points (see Figure 3).

The AVEXIS vehicle consists of a central cylindrical tube containing the control electronics and the camera. The available payload weight is 1.5 kg, enough to also add sensors on-board [6].

FIGURE 3:
AVEXIS

CARMA

Radiological protection monitoring is currently carried out using commercially available and handheld radiation monitors. These surveys are very often repetitive, thus adding autonomy to the current manual process would increase productivity, improve safety and reduce costs. The University of Manchester and Sellafield Ltd cooperated to develop the Continuous Automated Radiation Monitoring Assistance (CARMA) platform. This mobile platform offers autonomous and wireless radiometric floor mapping in nuclear facilities; can autonomously navigate and avoid obstacles; and survey large areas replicating the

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radiometric procedures currently used on the Sellafield site.

A proof-of-concept demonstration in the Thermal Oxide Reprocessing Plant (THORP) at Sellafield allowed for some improvement in a second design, with a better situational awareness and faster acquisition time. The CARMA 2 platform was deployed to carry out complete floor surveys in active facilities at Sellafield in 2018, being therefore the first autonomous platform deployed on the site.

MIRRAX: a reconfigurable robotic platform for the survey of access-limited areas

Several buildings on the Sellafield site require geometric and radiological characterisation before decommissioning. Currently characterisation is carried out by workers in protective suits however, this is expensive and time consuming. Furthermore, many of the facilities at Sellafield have been sealed for an extended period, and initial access is often restricted to 140mm or 270mm diameter entry ports.

To overcome these challenges, Sellafield Ltd and the University of Manchester have been developing 'mini robots for restricted access exploration' (MIRRAX). This platform can enter hazardous environments through restricted access ports, but also the innovative design, combining omnidirectional drive wheels and a reconfigurable footprint, enables the platform to navigate through difficult environments.

MIRRAX is also able to carry mid-size sensors such as light detection and ranging (LIDAR) and has enough battery charge to conduct 1-hour surveying through the restricted port. Due to those requirements, the robotic platform has been designed to be long and narrow, and with two additional joints to be reconfigured in more stable configurations [8].

The robot has been trialled in the First-Generation Reprocessing Plant (FGRP) at Sellafield, in an area that has not been surveyed before. The robot is currently undergoing further development (see Figure 4).

FIGURE 4: MIRRAX

Alpha glovebox decommissioning

Sellafield has alpha contaminated gloveboxes to be safely decommissioned. The traditional method for decommissioning the alpha contaminated gloveboxes is to use manual methods and mechanical size-reduction tools to breakdown the items and dispose in 200-litre drums. Currently, operators must wear air-fed suits; which is cumbersome, can create hazards to the operators, is inefficient, and generates significant amounts of secondary waste.

Thus, the feasibility of using tele-operated industrial robots and laser cutters for size reduction and waste disposal has been investigated by designing and building a full-size test rig and carrying out several trials (see Figure 5).

With the system trialled, operators are removed from the contaminated area during cutting operations; furthermore, smaller cut sections can be produced for more cost-effective waste packing. As this technology is scalable and adaptable, Sellafield Ltd benefits from the application of a proven tele-operated robotic laser cutting system into other decommissioning projects.

FIGURE 5:

Alpha glovebox laser cutting robot

In support of addressing the challenge, a project was funded by Innovate UK, allowing NNL, the University of Strathclyde, I3D Robotics, Shadow Robot Company and TWI to collaborate to optimise the current Alpha Active Demonstrator process, advancing the technological capability and ensuring that state-of-art functionality is tested for future implementation on the Sellafield site. The aim of this Innovate UK funded project was to carry out a feasibility study to establish an autonomous capability for size reduction of alpha-contaminated gloveboxes, that could potentially deliver significant benefits to the NDA group. These benefits include removing the operators from the area during cutting operations, and smaller cut sections produced allowing a more cost-effective waste packing.

NNL provided the challenge statement, background to allow integration and end-user requirements, while the other partners worked on separate technical aspects:

- The University of Strathclyde developed semi-autonomous path planning for laser cutting and cut-piece grasping, which has been shown in simulation and physically demonstrated at NNL's Workington Laboratory.
- I3D Robotics provided a camera system to image and develop a 3-dimensional mesh of assets in near real-time. This mesh of the asset could then be used by an operator to point and click on a node and assign a cut path or grasping position. The image system and path planning were integrated in a virtual demonstrator (see Figure 6).
- Shadow Robot Company demonstrated autonomous grasping of cut sections using a 3-fingered griper using the MuJoCo physics engine [9].
- TWI developed a novel laser cutting head for both metallic and non-metallic components. Results were successful for metallics and promising for thin non-metallics.

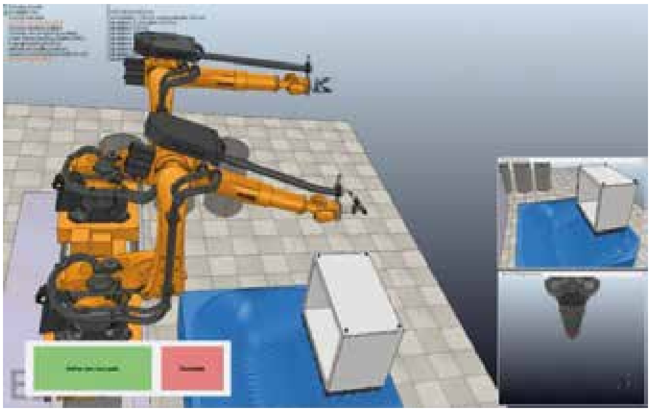

FIGURE 6:
Virtual demonstrator including path planning and camera system

Variable buoyancy heavy lift remotely operated vehicle
The Sellafield site has several fuel storage ponds that operate beyond their design intent, contain corroded nuclear material, and were not designed for retrieval of this material. In addition, due to the levels of radioactivity operators of these facilities have limited or no access. Due to the condition of the ageing infrastructure and continuing deterioration of the material contained within the ponds, this material must be removed and transferred to modern storage facilities.

The use of ROVs in nuclear ponds has proven to be a safe and efficient solution; however, ROVs already used in nuclear are usually small and for visual surveys, while nuclear pond operations require capability to move and retrieve various objects. The Closed-Loop Variable Buoyancy System (VBS) is the first such system developed ready for deployment in active ponds at the Sellafield site, to support routine underwater lifting operations within harsh nuclear pond environments (see Figure 7). Commencing with initial funding from Innovate UK, the system has been developed in a truly collaborative process between NNL, ROVtech Solutions Ltd, and the system end user Sellafield Ltd; accelerating the successful progression of the unique prototype (an integrated ROV-VBS) through the TRLs, towards future trials in active ponds at Sellafield.

A consequence of using ROVs is that thrusters (those with motor/propeller drives) generate motive force flows downstream. This combined with the silty nature of the corroded fuel can result in these materials being dispersed around the pond. This increases local radiation and reduces pond visibility, leading to delays in pond operations.

To overcome this issue, a variable buoyancy system was added to a ROV. The system allows vertical movement of the ROV without the use of propellers or jets, that would disturb the silt or the release of air from any ballast system that create aerosols which could transport radioactive silt to the pond surface.

FIGURE 7:
Inactive trial of closed-loop variable buoyancy lifting system at NNL's Workington laboratory

CONCLUSION

RAI technologies have the potential to significantly improve the efficiency and effectiveness of decommissioning the UK's nuclear legacy. They can remove operators from dangerous environments, increase productivity and reduce secondary waste generation.

At Sellafield, an R&D programme has been started that is identifying the specific opportunities and working with the supply chain and academia to development, demonstrate and deploy new RAI technologies.

Acknowledgements

- We would like to thank the members of the NDA Research Board for advice on developing and implementing our R&D strategy for RAI.

Glossary

- **AVEXIS:** Aqua Vehicle Explorer for In-situ Sensing
- **BEP:** Box Encapsulation Plant
- **CARMA:** Continuous Automated Radiation Monitoring Assistance
- **CEA:** Commissariat à l'Energie Atomique
- **CNRS:** French National Centre for Scientific Research
- **EU:** European Union
- **FGRP:** First-Generation Reprocessing Plant
- **IRT:** Integrated Research Team
- **LIDAR:** Light Detection and Ranging
- **MBGW:** Miscellaneous Beta Gamma Waste
- **MIRRAX:** Miniature Inspection Robot for Restricted Access eXploration
- **NDA:** Nuclear Decommissioning Authority
- **NNL:** National Nuclear Laboratory
- **PLC:** Programmable Logic Controller
- **R&D:** Research and Development
- **RACE:** Remote Applications in Challenging Environments
- **RAI:** Robotics and Artificial Intelligence
- **RoMaNS:** Robotic Manipulation for Nuclear Sort and Segregation
- **ROV:** Remotely Operated Vehicle
- **THORP:** Thermal Oxide Reprocessing Plant
- **TRL:** Technology Readiness Level
- **UKRI:** UK Research and Innovation
- **VBS:** Variable Buoyancy System

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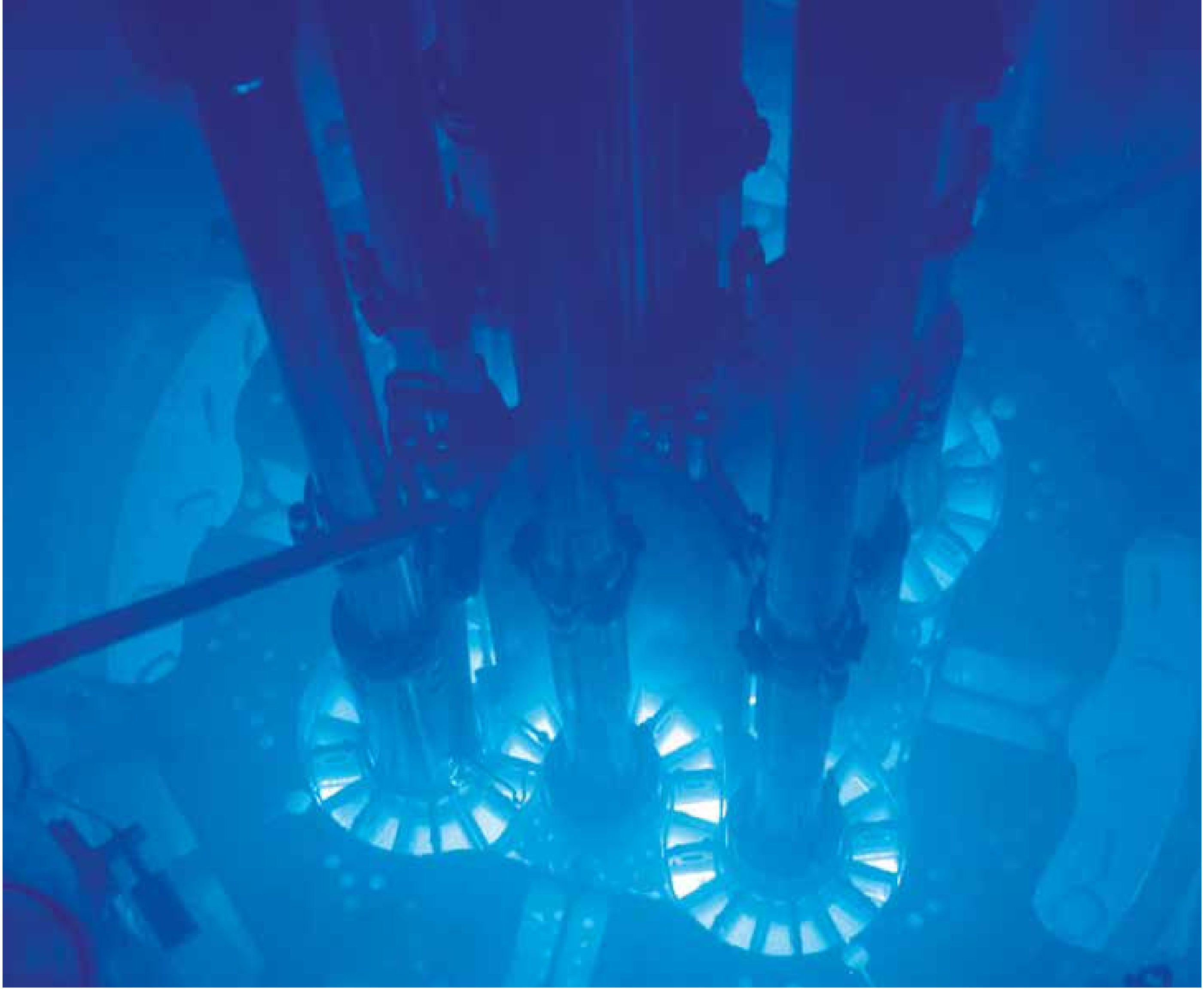

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Katherine is Head of R&D in Central Technical and Strategy at Sellafield Ltd. After completing her PhD in Environmental Chemistry at UEA, Katherine has worked on Sellafield site for over 20 years in a variety of roles over the years, after starting in BNFL R&T working on the post closure safety case for LLWR and various contaminated land projects. Katherine has worked on predicting Sellafield long-term clean-up costs, in Sellafield strategy teams, and spent several years managing the Sellafield Land Quality team; as well as a secondment to the NDA managing their Direct Research Portfolio.

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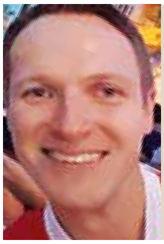

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Darren is the Capability Leader of the Plant Intervention and Modelling areas within the NNL. Darren is directly responsible for many of the robot operators within NNL. Darren has many years of project experience in both academia and industry and has managed NNL's successful completion of numerous robotics projects. Darren acts as the interface between roboticists and the nuclear decommissioning domain experts within NNL.

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