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Nuclear Future

The official journal of the Nuclear Institute

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NUCLEAR FUEL CYCLE AND RADIOACTIVE WASTE MANAGEMENT

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Nuclear Future

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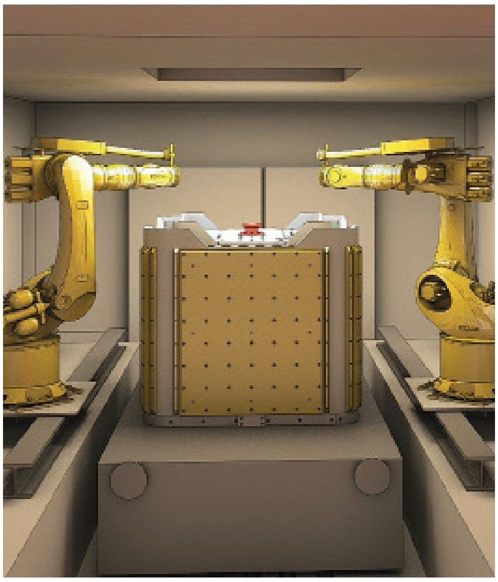

ON THE COVER:
Nucleus: The Nuclear and Caithness Archives are based at Wick Airport and are home to the archives of the UK civil nuclear industry
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Nuclear Future: Call for papers 2018

Paper submission

The editorial board welcomes papers for consideration 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 in order for the article to appear in the journal or on the website.

For a paper proposal to be considered please submit an abstract of 200-300 words to the technical editor at *NIEditor@centuryonepublishing.uk*, including author name and contact email.

Issue	Theme	Abstract deadline	Paper deadline
14.1 – Jan/Feb	**Nuclear fuel cycle and radioactive waste management**	–	–
14.2 – Mar/Apr	**Radioactive waste management and disposal**	–	–
14.3 – May/Jun	**Defence**	–	–
14.4 – Jul/Aug	**Nuclear reactors (incl. new build, reactor operations, next gen and SMRs)**	ASAP	19 Mar 2018
14.5 – Sep/Oct	**Transport of radioactive materials**	2 Apr 2018	14 May 2018
14.6 – Nov/Dec	**Workforce, education and training**	4 Jun 2018	16 Jul 2018

The editorial board welcomes papers on any of the key themes, topical issues and R&D. Although there is no specific Young Generation Network issue, members are encouraged to submit papers to any of the 2018 issues.
Please contact the technical editor for the guide for authors, or with 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.
For advertisement and promotional features please contact *Alex@centuryonepublishing.uk*.

President's page

You can contact the President by emailing *president@nuclearinst.com*

Let byproducts be byproducts

The Nuclear Institute's new president, John Clarke, reflects on the waste management and decommissioning legacy in the UK, and looks toward the future

I am hugely privileged to have been asked to become the president of the Nuclear Institute (NI).

Looking back at the names of past presidents of the institute and its earlier incarnation adds to that honour, but it also brings more than a little pressure. I hope I am able to serve the NI and its members, and help to drive the organisation forward to respond to the pressures on and opportunities for the industry and nuclear professionals working within it.

This edition of Nuclear Future focuses on waste management and decommissioning. That seems particularly appropriate for my first edition as president as I've spent the bulk of my career in the industry involved with the 'back-end' of the nuclear fuel cycle—spent fuel treatment, waste treatment for storage and disposal and decommissioning.

Pretty much every part of the nuclear industry (or indeed any industry) produces waste and byproducts. The early days of our industry (again like most industries) were characterised by either setting waste to one side or discharging it directly to the environment. Those days are long gone, however we are still dealing with that legacy and this edition covers some of the challenges and opportunities that it presents.

While we can and must focus on reducing, reusing and recycling waste products, it is inevitable that there will be waste that ultimately needs to be disposed of. Current UK policy for the higher activity waste is for deep geological disposal. While this presents considerable technical challenges, perhaps the greatest challenges are socio-political. It's a great example of where nuclear professionals need to be involved—not just the technical aspects of an issue, but also in the wider discussion and explanation of these issues with the public.

> "Higher activity waste is a great example of where nuclear professionals need to be involved—not just the technical aspects of an issue, but also in the wider discussion and explanation of these issues with the public"

I will close my first column with a couple of thank yous. First, I'd like to thank Neil Thomson for his work during his time as president and for his handover to me. Second, I'd like to thank the team within the NI who put so much effort into making December's annual dinner the success it was. I very much look forward to working with the team and to serving the membership over the next couple of years.

UK news

Please send your news to *NIEditor@centuryonepublishing.uk*

Government to support development of next-generation nuclear technology

The UK government announced significant support in December 2017 to help the UK become a world leader in developing the next generation of nuclear technologies.

The government said funding of up to £56 million is available over the next three years to help support R&D into innovative advanced and small modular reactors, and to assess their feasibility and accelerate the development of promising designs.

The government will also support regulators in building the capability and capacity needed to assess and license small reactor designs. It will establish an expert finance group to advise how small reactor projects could raise private investment.

In addition, the government plans to launch the second phase of its Nuclear Innovation Programme, including up to £8 million for work on modern safety and security methods and studies in advanced fuels.

Business secretary Greg Clark said the UK's civil nuclear sector contributed £6.4 billion to the UK economy last year.

UK fusion researchers welcome government support

The UK Atomic Energy Authority (UKAEA) has welcomed the government's investment of £86 million that will fund the building and operation of a National Fusion Technology Platform (NaFTeP) at Culham Science Centre, which is expected to open in 2020.

The Department for Business, Energy and Industrial Strategy announced the new funding as part of a series of measures that aim to support the development of 'next-generation nuclear technology', which follows publication of the government's Industrial Strategy whitepaper in November 2017.

UKAEA said the new facilities will support British industry and help to secure around £1 billion in contracts from the key international fusion research experiment ITER and other global fusion projects.

Looking further ahead, it added, the facilities will enable UKAEA to develop technology for the first nuclear fusion power plants and put UK industry in a strong position to exploit the commercialisation of this highly promising low-carbon energy source.

Ian Chapman, CEO of UKAEA, said: "Fusion is entering the delivery era, with an increasing focus on the key technologies that will be needed for the first power stations. The National Fusion Technology Platform will help British industry to maximise growth from opportunities provided by ITER. In the longer term it means the UK will be at the forefront of developing fusion and bringing cleaner energy to the world."

Ian Chapman, CEO of UKAEA (Credit: Lancaster University, www.lancaster.ac.uk)

NaFTeP comprises two new centres of excellence: Hydrogen-3 Advanced Technology (H3AT), which will research how to process and store tritium, one of the fuels that will power commercial fusion reactors; and Fusion Technology Facilities (FTF), which will carry out thermal, mechanical, hydraulic and electromagnetic tests on prototype components under the conditions experienced inside fusion reactors.

"NaFTeP will enhance the UK's expertise in critical areas of fusion research, with significant benefits to the economy as part of the government's Industrial Strategy. It will also provide a powerful signal of the UK's intent to continue its participation in international science collaboration after leaving the European Union," UKAEA said.

Source: World Nuclear News

UK regulator moves to second stage of Hualong One GDA

The UK's nuclear regulator is beginning the second stage of the generic design assessment (GDA) for the UK version of China's Generation III HPR1000 nuclear plant, known as the Hualong One, that China General Nuclear Power Corporation (CGN) wants to build at Bradwell B in Essex.

The Office for Nuclear Regulation (ONR) said on 16 November 2017 that CGN will also launch a consultation process for comments.

Stage one of the process was the preparatory phase, the ONR said.

Mike Finnerty, the ONR's deputy chief inspector and director of the ONR's new reactors division, said the purpose of GDA is to determine whether the design meets the robust safety and security standards to make it suitable for use in the UK.

He said: "I am satisfied that there are adequate project management and technical provisions in place to enter step two of the process and, as regulators, we can begin our technical assessment phase."

CGN, which holds a one-third stake in the French-led Hinkley Point C EPR nuclear project, said recently it is confident that the HPR1000 will be approved by UK authorities for construction at Bradwell.

The company hopes the GDA will be completed in less than five years. The costs of the GDA, which have not been disclosed, will be footed by French nuclear operator EDF and CGN, which have formed a joint venture called General Nuclear Systems Limited to develop the Bradwell plans.

They are also behind plans for Hinkley Point C in Somerset and Sizewell C in Suffolk. EDF said the reference plant for Bradwell B is CGN's Fangchenggang Plant Unit 3 in China, which is under construction and on schedule.

Source: NucNet

UK government funding to tackle challenges of large-scale manufacturing

The Nuclear Advanced Manufacturing Research Centre (AMRC) is leading two new R&D projects to address fundamental challenges in nuclear manufacturing.

The Inform and Simple projects, backed by government funding of almost £2.5 million, will investigate two contrasting approaches to producing large-scale nuclear components.

Inform aims to improve the process of moving large parts between multiple machines, while Simple aims to do more operations on a single platform.

Professor Steve Jones, chief technology officer of the Nuclear AMRC, said: “Simple and Inform are based on the two different philosophies of manufacturing large high-value components—taking the part to the machine, and taking the machine to the part. Both projects aim to provide significant improvements to UK productivity, potentially cutting manufacturing time and cost by half for a variety of large nuclear components.”

“By developing innovative approaches to the fundamental challenges of manufacturing, these projects will help the UK's nuclear supply chain to compete globally. These technologies could also provide major benefits to other high-value manufacturing sectors, such as offshore renewables or oil and gas.”

The Inform project (intelligent fixtures for optimised and radical manufacture) will develop an adaptive fixturing system to ease the movement of large parts around a factory, and ensure precision throughout forging, machining, welding, inspection and assembly.

The second project, Simple (single manufacturing platform environment), aims to integrate a range of manufacturing operations onto a single machining platform.

The Simple and Inform projects are funded by the Department for Business, Energy & Industry Strategy through the Small Business Research Initiative, which is managed by Innovate UK.

Both projects are supported by a range of nuclear industry partners—including reactor developers and operators, and decommissioning site owners—who will ensure the research is addressing industry challenges.

The results will be shared with UK industry, including the Fit For Nuclear network of companies from among the supply chain.

UK news

Please send your news to *NIEditor@centuryonepublishing.uk*

New AREVA becomes Orano

New AREVA has completed its rebrand and will now be known as Orano.

The announcement of the Orano brand marks an important milestone in the transformation of New AREVA.

Refocused on nuclear materials development and waste management, Orano's activities encompass mining, conversion, enrichment, used fuel recycling, nuclear logistics, dismantling and engineering.

"Orano's unique and internationally-recognised expertise in the nuclear fuel cycle enables it to offer clients efficient products and services that are adapted to their needs, right across the cycle," the company said in a statement.

In the UK, Orano will continue to provide expert, local services to its clients and projects across the country.

Working on the majority of the UK's nuclear licensed sites, Orano is able to deliver solutions to suit all types of project, from site management and operations through to technical consulting and engineering services.

Combining this local presence with a global capability that spans the entire nuclear fuel cycle, Orano offers a sustainable and expert services platform to UK clients, well-equipped to address today's most complex technical challenges.

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International news

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Ichos consortium will build the Pallas research reactor in the Netherlands

The Ichos consortium will design and construct the Pallas research reactor destined for Petten in the Netherlands.

The agreement was signed in The Hague by Pallas Foundation CEO Hermen van der Lugt, Invap CEO Vicente Campenni, Croonwolter&dros director Lennart Koek and Mobilis director Robert jan Feijen.

The Ichos consortium comprises Argentinean nuclear technology firm Invap, Croonwolter&dros and Mobilis, both of which are a part of TBI Holdings of the Netherlands.

The project's contract value is up to €40 million for the current preparation phase and up to several hundred million euros for the consecutive phases.

The Netherlands launched a tender for the Pallas reactor, which will replace the existing high flux reactor (HFR), in December 2007. Three companies participated: Areva TA of France, the Korea Atomic Energy Research Institute (KAERI) and Invap.

Invap's offer was selected in June 2009, but authorities in the Netherlands decided to discontinue the project due to the global economic crisis.

The project was relaunched in 2015 and the Pallas Foundation issued a new tender, dividing the project into two phases. The first phases consist of engineering, obtaining the construction licence, perfecting the business plan and obtaining finance.The second phase involves construction of the reactor.

The same three companies participated in the new tender, with Invap partnering with TBI Holdings. The bids were presented in March 2017. Following two rounds of negotiations, a request for final offers was issued in November.

The Pallas reactor is to be of the 'tank-in-pool' type, with a thermal power of around 55MW, and able to deploy its neutron flux more efficiently and effectively than the HFR.

Source: World Nuclear News

Objective Engineering, Optimised Results

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International news

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ITER fusion project passes construction milestone

Construction of the ITER fusion reactor, being built at Cadarache in the south of France, is now 50% complete, the ITER Organisation has announced.

The reactor—construction of which began in 2010—is scheduled to achieve first plasma in 2025.

The ITER Organisation said that almost 53% of construction activities (on the ITER site at Cadarache) and manufacturing activities for components and systems needed for first plasma have been completed.

"The performance metrics used in ITER assign a relative weight to every activity category within the project," the organisation said. "Design, for instance, accounts for 24%; buildings construction and manufacturing for 48%; assembly and installation for 20%."

"After having compounded the percentage of completion of each category, the metrics produce a figure for the totality of the work scope through the launch of operations ('first plasma')."

Design, which accounts for approximately 25% of the scope, is now close to 95% complete. Manufacturing and building, which represents almost half of the total activities, is close to 53% complete.

ITER director general Bernard Bigot said the passing of the 50% milestone reflects "the collective contribution and commitment of ITER's seven members".

Source: World Nuclear News

Chinese Hualong One unit gets reactor vessel

The reactor pressure vessel has been installed at the demonstration Hualong One being constructed as unit 5 of the Fuqing nuclear power plant in China's Fujian province.

The reactor is expected to start up next year.

The vessel was introduced into the 16.5-metre platform of the reactor building on 17 January. In an operation lasting almost nine hours, the component was moved into position on its support ring, according to China National Nuclear Corporation (CNNC).

The pressure vessel was independently designed by China Nuclear Power Research and Design Institute and manufactured by China First Heavy Machinery. The vessel completed hydraulic pressure tests in April last year. These tests confirmed the integrity of the vessel's welds and seals.

Installation of the reactor pressure vessel marks the completion of the installation of the unit's major components, CNNC said. Installation of the three steam generators and pump casings was completed in January.

Source: World Nuclear News

Nuclear Institute news

ONR's Mark Foy joins Nuclear Insitute as fellow

The Nuclear Institute (NI) is delighted to welcome Mark Foy, the Office for Nuclear Regulation's (ONR) chief nuclear inspector, as a fellow.

The institute was pleased to be able to present Foy with his fellowship certificate at the opening of the prestigious new ONR Academy on 29 November 2017.

Speaking during the event, he commented: "I am delighted to be elected a fellow of the NI. The NI plays an important role in promoting and supporting nuclear professionalism across the industry which, in turn, helps ensure a safe and secure industry in line with ONR's core purpose."

"I look forward to working closely with the NI and the professional community to help drive this important agenda."

The grade of fellow is awarded to nuclear professionals who meet the Nuclear Delta professional standard and who have made a significant contribution to the sector.

Nuclear Institute news

Please send your news to *NIEditor@centuryonepublishing.uk*

YGN focus

Busy 2018 in store for the YGN

After a couple of years away from running a full complement of annual events due to organising and then hosting the hugely successful European Nuclear Young Generation Forum (ENYGF) in 2017, the YGN is back in full force for 2018.

This year's programme includes the ever popular 'Intro To' series (including a brand new event for 2018, 'Intro To Project Management'—further details below), Annual Day Seminar and Dinner, and speaking competition, to name but a few. The YGN's membership has continued to grow year on year and is now operating at record levels.

Due to the increasing demands on its exceptional volunteers, the YGN committee has restructured for 2018, formalising roles and sub-committees in order to continue delivering on its objectives as the Nuclear Institute's most active branch/network (see the YGN's new value, mission and objectives for more information). The new committee structure will be led by 2018 chair, Michael Bray.

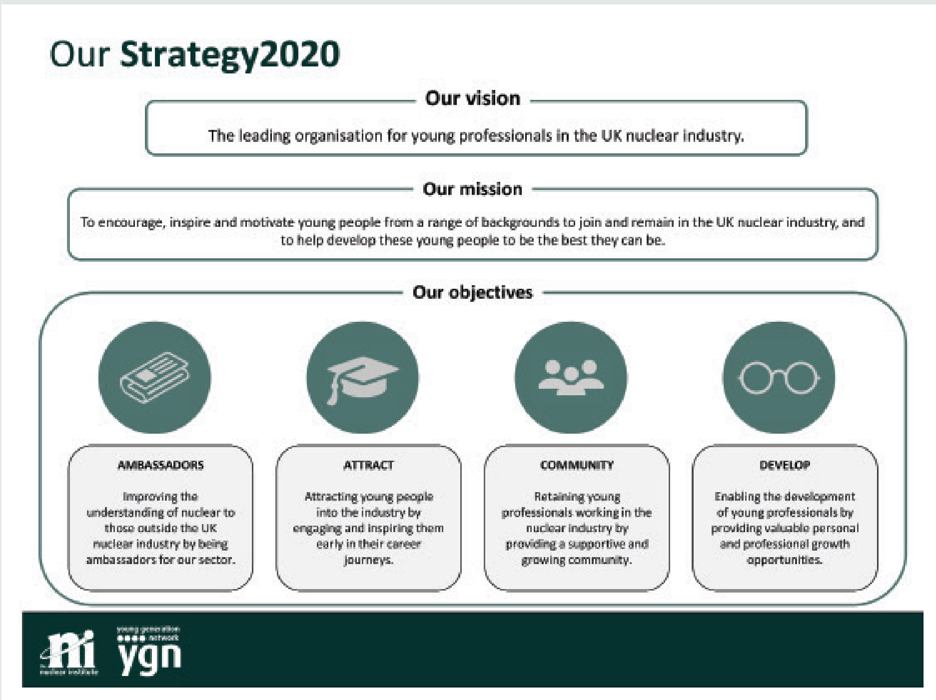
The new and formalised committee roles have been created to better serve the needs and objectives of the YGN, with extra emphasis on how it interacts with the industry and how it reaches out to young talent in schools and colleges. This is an important objective for the YGN as the young people that it reaches out to through its science, technology, engineering and mathematics events and graduate and apprentice workshops will be leaders and future ambassadors of the nuclear industry. Attracting and retaining YGN members is another key objective for the committee as it continues to provide members with technical and professional opportunities to aid their advancing careers, in order to both introduce them to and then keep them working in this expanding industry.

The 'Intro To' series is expected to be very popular again this year, with more seminars incorporating tours with fascinating talks from industry experts. The series will cover topics ranging from new build to regulation, defence to project management, and legal to generation. Expect there to be exciting and influential speakers at every event, where you can learn from key industry figures in manufacturing, design, government, law and business, as well as network with peers and speakers.

It's safe to say that the YGN is in a strong position to reap the rewards of 2017's ENYGF and to remain resilient and true to its trusted and recognised brand through this exciting time of expansion. The restructure of the committee and its new focus represents a really exciting change for the YGN. Each lead and their team is extremely committed to the success and the future of the YGN, which wouldn't be possible without the efforts of the previous committee members, the volunteers and, importantly, the YGN community. The new structure also has a number of sub-committees and less formal volunteering roles so if you are interested in getting involved, please get in touch via chair.ygn@nuclearinst.com.

Strategy 2020

This year, the YGN is excited to launch Strategy2020! The YGN has refreshed its vision, mission and objectives so it can continue to support and nurture the UK's younger generation into becoming the world's leading nuclear workforce. By encouraging younger members to act as nuclear ambassadors, through attracting talented young people and by providing opportunities for professional growth, the YGN aims to play a key role in building a nuclear sector that the UK as a whole can be proud of. If the YGN's new strategy excites you too, get in touch via chair.ygn@nuclearinst.com to find out how you can help the YGN to accomplish its mission.



Event news

Please send your news to *NIEditor@centuryonepublishing.uk*

Conference preview:

Stage set for Integrated Waste Management Conference

The 2018 Integrated Waste Management Conference will be held in Rheged, Penrith, on 24 and 25 April

A continuing challenge to the nuclear industry is to 'sort out' its waste. The industry has implemented various measures to meet this challenge, but it would be misleading to claim that every nation and organisation has truly done all that it can to address this very challenging problem.

The Nuclear Institute (NI) is playing its small part in addressing this issue by introducing what is hoped will become an annual fixture that has a significant impact on tackling the issue of radioactive waste and embracing a fully integrated waste management approach. Although much more concerted effort has been applied worldwide in recent years, this problem has yet to be fully resolved.

The 2018 Integrated Waste Management Conference provides a European hub for waste management discussions that will complement other conference discussions, particularly in the US, such as the well-established Phoenix Waste Management Conference.

It is acknowledged that conferences provide a platform for practitioners, academics and experts to come together and apply an aggregated capability to a problem and share challenges and solutions. The solution to this particular problem requires a more integrated approach across the radioactive waste spectrum.

The UK, via the strategic guidance of the Nuclear Decommissioning Authority (NDA) and the drive and delivery of its site licence companies, has begun to make major in-roads into this challenge. Both Sellafield and LLW Repository (LLWR) are sponsoring this conference because of the importance of integrated waste management to their individual businesses and the industry as a whole.

LLWR has already demonstrated what can be achieved when an integrated approach to low level waste is adopted and how incorporating the supply chain in the delivery mechanism can provide efficiencies and value for money.

An integrated waste management approach would challenge the current baseline and seek alternatives. It could also challenge the method we choose when determining waste management routes, considering a lifecycle risk-informed approach in preference to current practices.

Dennis Thompson, managing director at LLWR, says: "My vision is to build on the success of LLWR's annual Customer Forum and use it as a stepping stone to an international forum and as a platform for further positive change."

Rebecca Weston is strategy and technical director at Sellafield, and a chair of the 2018 Integrated Waste Management Conference

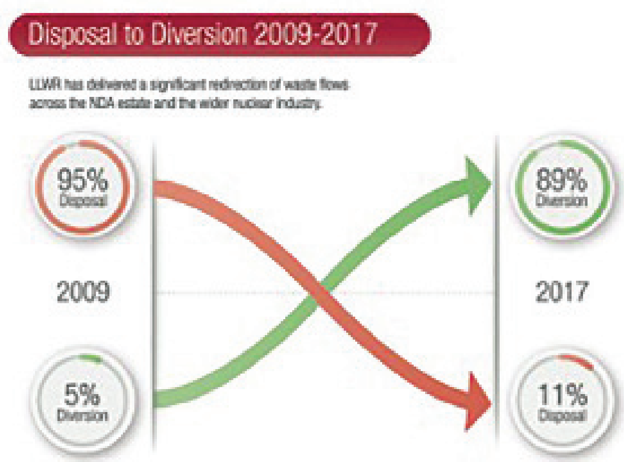
"The success we have encountered during the past 10 years relies on having a robust waste treatment and diversion infrastructure in place, but more importantly, required a change in attitude, behaviours and practices, not only within my own organisation but across all UK nuclear waste consignors."

Dennis Thompson is managing director at LLWR

Thompson adds: "Historic practices saw almost 1000 waste containers a year arriving at the LLWR site for disposal. Implementing the waste management hierarchy, securing routes to services and embedding the right behaviours has resulted in nearly a 90% reduction in the volumes of waste requiring disposal at the LLW Repository. It has also created the opportunity to explore optimisation and standardisation utilising international guiding principles."

Thompson went on to say: "Whilst low level waste management may appear to be 'in the bag' it is only one component of the bigger waste management issue. The NDA's 2016 strategy advocates an integrated approach to radioactive waste management in support of their decommissioning and clean-up programmes. We already see waste producers thinking in this way, however, we cannot rest on our laurels. New techniques, technologies, standards, learning are always emerging, and there's always a tricky problem to be solved—it's the nature of the business. We are at the beginning of a journey and like many of our colleagues within the industry, have a valuable contribution to make."

"My hope is that the 2018 Integrated Waste Management Conference gains recognition as a collaborative platform that grows in stature, attracts the right people who can contribute to the discussions, become involved in developing solutions and progress the dialogue."



LLWR diversion 2009-2017

Rebecca Weston, strategy and technical director at Sellafield, described the event as an opportunity to truly start thinking about the full scope of the integrated waste management challenge.

"The magnitude of the challenge can be seen by considering the range and volume of wastes at Sellafield that all need safe treatment and storage and ultimately disposal," Weston explains. "We've already come a long way. A decade ago removing bulk sludge from our legacy ponds or cutting holes to remove waste from one of our silos seemed light years away. Over the last 10 years we have removed more than 100 buildings from the Sellafield skyline, including the hurricane buildings, which were built to process plutonium for the first atomic test in 1952, the filter gallery from the top of the Windscale Pile Chimney and a uranium purification plant."

"In order to achieve our ambition to transform Sellafield, so that it is recognised as a world leader in solving complex nuclear problems, we need to be bold and ambitious, and think differently. The complexity and diversity of waste management at Sellafield means that working with the UK and worldwide industry is critical to delivering effective integrated waste management. We will continue to seek solutions from across the wider industry and embed fit-for-purpose approaches. This conference is one step on that journey."

John Clarke, president of the NI, will support Thompson and Weston as the chairs of the conference.

To find out more, visit: www.iwmeurope.com/programme

Branch news

Please send your news to *NIEditor@centuryonepublishing.uk*

NI Cumbria visits Nuclear AMRC

The Nuclear Institute (NI) Cumbria organised a Technical Tour to the Nuclear Advanced Manufacturing Research Centre (AMRC) for 36 members on 30 November.

More than 10 nuclear companies, including Sellafield, NuGen, Jacobs and Low Level Waste Repository (LLWR) were represented. The visit included a presentation on the Nuclear AMRC from business development manager Johnny Stephenson, a tour of the manufacturing workshop with a question and answer session, and a factory 2050 virtual reality model demonstration.

Shaun Lewis, associate member of NI at the National Nuclear Laboratory, shared his highlights: "I thought the tour was fantastic. I was very impressed with the scale of the machinery being used and the huge time and cost savings that could be achieved through processes that the Nuclear AMRC are developing, such as electron beam welding of pressure vessels. I learned a lot, and found the event very useful for meeting other people in the industry doing similar work to myself."

Lead organiser Hannah Paterson expressed her thanks to the Nuclear AMRC for hosting the visit. She said: "The open environment for asking questions was brilliant. We have come away having learnt about the opportunities the Nuclear AMRC offers for the nuclear supply chain and having made contacts across the industry."

Spainish trip promises international learning and networking opportunity

The London and Southeast branch of the Nuclear Institute (NI) has collaborated with Enresa to offer guests an international learning and networking opportunity.

Between 18 and 20 April, a party of 25 delegates will travel between Spain's only nuclear waste repository, El Cabril, and one of the country's successful pressurised water reactor decommissioning projects, José Cabrera Nuclear Power Station.

The visits will include a tour of the facilities and educational talks from experts in the fields of decommissioning and waste management. Time will also be permitted for refreshments and networking at each facility.

Two overnight stays are included in the cost of the trip. The first will be in the Andalusian city of Cordoba, a designated world heritage site and award winning gastronomic centre. On the second night, guests will stay in the heart of Madrid, just a short walk from the city's main tourist attractions.

This event is open to all, however, places are strictly limited to 25 and will be filled on a first-come, first-served basis, so register your interest early.

The trip is priced at £300 for NI members and £350 for non-members. This covers site visits, domestic transport and hotel costs.

In the interest of flexibility, guests will be asked to make their own arrangements for travelling to and from Spain. Travel expenses are not included in the event delegate price.

To register your interest or for more information, please email southeast@nuclearinst.com.

Keeping our options open in the UK

Dr Fiona Rayment OBE tells Nuclear Future why subject matter experts are crucial to the UK's future decisions about the fuel cycle

Dr Fiona Rayment OBE, Chair of NSSG and Executive Director, NIRO National Nuclear Laboratory

For half a century, the UK's nuclear industry has been involved in all stages of the fuel cycle (except mining), from front-end activities: uranium enrichment and processing, through to back-end processes of storage, reprocessing, waste management and disposal. With the decision to close Thorp this year and Magnox in 2020, the UK will transition from a partially closed to a fully open fuel cycle with interim storage and other methods of disposal and re-use.

International subject matter expert Dr Fiona Rayment OBE discusses this transition and the critical importance of investing in subject matter experts to support future decisions about the fuel cycle.

The fuel cycle context

In the early years of nuclear energy development—up to the late 1980s—a fully closed fuel cycle was pursued as the optimum solution internationally, with the UK, France and Japan having played leading roles historically with respect to this. Using this approach, uranium and plutonium were separated from spent fuel, using commercial aqueous reprocessing technology, for future use in fast reactors. France, for example, has pursued a long-term strategy for a fully closed self-sustaining fuel cycle based around its prototype fast reactor technology (Astrid), with an integrated short-term objective of reprocessing spent fuel for mixed oxide fuel manufacture for use in its existing fleet.

The USA, on the other hand, has a clear 'no reprocessing' policy and a 'once through' fuel cycle, using uranium oxide fuel in its existing fleet, followed by storage onsite, and ultimate disposal in a repository, is the preferred approach.

Historically, the UK developed a partially closed system, with reprocessing facilities at the Magnox and Thorp facilities on the Sellafield site, in Cumbria, enabling the production of uranium, uranium oxide and mixed oxide fuels for commercial customers. In addition, the UK was also involved in fast reactor technology research, and in particular, sodium fast reactor technology, where two fast reactors were designed and operated at Dounreay (Dounreay Fast Reactor, and latterly, the Prototype Fast Reactor).

However, following events in Japan in 2011 and the closure of the UK Magnox stations, the requirement for the UK to produce Magnox fuel for domestic customers and mixed oxide fuel for overseas customers has come to an end. Now, the UK is moving to an open fuel cycle, which will happen after 2020 when the last reprocessing facilities close. Spent fuel will then be stored at various central and local facilities for a period of time prior to being disposed of in a geological disposal facility.

This outcome, says Dr Rayment, is "the logical conclusion" for the UK at this time, but she adds that we also need to keep options open for the future. Much of the UK's reprocessing work has been "pioneering", she says, especially the research and development (R&D) associated with fast reactor fuel technology, and the separating of radionuclides from waste. However, Dr Rayment adds: "It is also clear that at this point in time the UK no longer has the same requirement it once had for reprocessing and will require a different approach to managing the fuel cycle."

Nuclear in the future energy system

The fuel cycle route that the UK takes will be determined, ultimately, by the future size and shape of the UK energy system, together with the role that nuclear energy plays within the mix.

"It is clear that decisions about our nuclear future and the long-term fuel cycle cannot be taken in isolation," says Dr Rayment, who, as one of her many other roles, until recently was a member of the board of the Energy Systems Catapult, a catapult set up to help the UK navigate the transformation of the energy system.

"We have to see these decisions in the context of the wider energy system and we have to keep our options open about the direction of the fuel cycle, too," Dr Rayment explains.

The challenge for the UK and other signatories to the Paris Agreement of 2015 (COP21) is how to balance the needs of the energy trilemma for secure, affordable, sustainable energy for its citizens, with global commitments to reduce greenhouse gas emissions to a level that will limit the global average temperature to a rise "well below" 2°C.

The UK is committed to reducing carbon emissions by 80% on 1990 levels by 2050 and the direction of travel has been towards low carbon sources for the last decade. The most likely future scenario is an energy mix consisting of renewables, nuclear and gas (with carbon capture and storage). Nuclear is projected to be around 30% of this energy mix by 2050, with renewables and gas, according to the National Grid's Future Energy Scenarios (July 2017). The low carbon transition includes heat and transportation (electric vehicles in particular) and while this is good news for the environment, these changes also pose significant challenges to the UK energy system, which the government, the energy industry and consumers will need to manage.

The Nuclear New Build Programme is based on scenarios of 16-18GW of new capacity on the grid by 2030 alone, depending on the impact of demand from electric vehicle charging, and the high-end scenario is that nuclear could increase to 75GW by 2050. Even a mid-range scenario of 35GW of nuclear would also have enormous consequences for the fuel cycle.

Dr Rayment believes that it is critical for the R&D community and wider industry to understand the impacts.

She says: "We have to start thinking about the types of technology that might be required beyond the current new build programme [16-18GWe] and what fuel cycle will be needed. We don't know what those technologies will be—it might be that we go with existing ones, or it might be new. It is hard to predict what fuel cycle you will need until the reactor technologies are understood."

"So beyond 2020, even though we say we are moving towards an open fuel cycle and storing spent fuel from the existing fleet, we need to make sure that we keep future options open for our fuel cycle depending on the size and type of the future nuclear energy mix. This could mean moving to a closed fuel cycle once again with reprocessing playing a key role."

The role of R&D

From an R&D perspective, understanding the behaviour of radionuclides within a fuel cycle is of course crucial. Dr Rayment says that any expansion of nuclear capacity will result in waste management challenges and R&D can help us to understand and plan for the best approach, especially in relation to long-term geological disposal. The UK's National Nuclear Laboratory (NNL) is supporting long-term nuclear options through its expert work on the fuel cycle with modelling tools such as Orion, which tracks radionuclides through the fuel cycle and is used to develop scenarios to understand the UK's spent fuel inventory (see Orion: Nuclear fuel cycle modelling).

Orion is one of a small number of internationally available fuel cycle modelling tools that can predict the radionuclide transport and associated radiotoxicity within a fuel cycle. It can be used to plot an energy system and different scenarios, such as the impact of using one fuel instead of another, as well scenarios with different types of reactor.

NNL has mapped a number of scenarios over time and then looked at the decay in heat output from the spent fuel to understand the associated impacts on the amount and type of spent fuel produced. Scenarios included 16GW, 40GW and 75GW, with spent fuel inventory outcomes in tonnes of heavy metal of 23,000, 50,000 and 90,000 for each scenario, respectively. This has enabled an understanding to be reached on the storage capacity requirements for spent fuel and associated wastes for each energy scenario with and without reprocessing.

Commenting on the Orion studies, Dr Rayment says: "Using Orion, we have shown through direct comparisons of an open fuel cycle with a closed fuel cycle (where long lived radioisotopes have been removed) that the radiological and volumetric storage requirements can be reduced by as much as two thirds by choosing a closed fuel cycle (reprocessing). This provides us with a significant evidence base, which we can use to inform decisions about fuel cycles of the future."

The role of experts

The discussion about R&D led inevitably to a discussion about how to retain knowledge and skills when the UK is moving away from reprocessing and towards an open fuel cycle. Doesn't this pose a dilemma and a challenge? Unsurprisingly, given Dr Rayment's own position as an internationally renowned subject matter expert, and her role as chair of the Nuclear Skills Strategy Group (NSSG), she was keen to discuss skills, flagging it is one of the most important issues in the whole debate.

Dr Rayment says: "In order to make a decision about the fuel cycle, we need to have an intelligent scientific capability to enable us to understand and underpin what the best options are. To do that you need to make sure people are practicing in that field and through engagement in R&D programmes that capability can be maintained."

NSSG estimates that the UK will require up to 4,000 subject matter experts over the next decade, in line with the projected growth of the whole industry to more than 100,000 professionals.

Dr Rayment explains that subject matter experts are not people who can be plucked from trees. "These are professionals who have spent their life researching a topic in order to become a domain expert, capable of offering deep insight from any and every angle," she says, and often, like her, they are recognised on an international level. The industry needs to understand what the gap is and where subject matter experts are needed—then invest in developing that expertise.

She is aware that maintaining skills such as reprocessing in the UK will remain challenges in the absence of a mature commercial technology and the closure of facilities from 2020. However, she cites the US example, which has retained its skills base even though it isn't actively undertaking reprocessing. Idaho National Laboratory has been "very successful" in maintaining a reprocessing skills base in the US through the Department of Energy's Nuclear Energy Programme, even though it has no commercial facilities. At Idaho National Laboratory, people have engaged in reprocessing R&D for decades.

Dr Rayment is a practical problem solver in this as in other areas of her work, concluding that while possible, it is still challenging, but also: "It is about making the most of the money you have available and how you engage with international partners to share best practice to focus on top priority options. At the end of the day, this will give you a better product because you are working with the best people out there. That is a good thing, and there is no reason why we can't do that here with R&D facilities like NNL's."

NNL nurtures core skills and its own subject matter experts through partnerships with key organisations, such as NDA and Sellafield, as well as various other companies and institutions, including the Nuclear Institute, with its focus on nuclear professionalism and its fellowship programme. It also supports international exchanges and facilitates access to its laboratories for others to carry out R&D, something she is particularly proud of.

"We have enabled students and researchers from universities to come in and carry out work, including with radioactive materials. So the fuel cycle is not just a theory—students can see how materials behave over time and what it is like to work with the material and how challenging some of the operations are when you are dealing with radioactive materials. This is absolutely invaluable to their development."

Dr Rayment also welcomes the UK government's support through its Nuclear Innovation Programme, which includes a work stream on reprocessing, enabling the industry to keep that option open. A number of universities and NNL will take the innovation programme forward and continue to develop new flow sheets and fuel cycles through the money that comes in through this, and by accessing European framework programmes.

The ultimate expert

Dr Rayment is a nuclear professional at the top of her field with an excellent breadth of knowledge. Before she took on the role with the Nuclear Innovation Research Office (NIRO), which is hosted within NNL, Dr Rayment was for six years director of fuel cycle solutions at NNL, which she describes as "her bread and butter". She ran the teams that carried out the fuel cycle scenarios in Orion, developed reprocessing options and also ran the teams involved in fuel manufacture. Her international commitments took up around 20% of her time.

Her focus now is very much on NIRO, whose role it is to provide the UK Department for Business, Energy and Industrial Strategy with strategic technical advice on nuclear-related topics, of which reprocessing and the fuel cycle are still a part. She is still engaged as a spokesperson on these topics in the media and regularly participates on many related international panels and conferences. She is a powerful representative of many areas, championing skills, industrial strategy and R&D. Skills are, however, a real passion and interest, both professionally and personally. In her own words: "Close to my heart is the maintenance and growth of subject matter experts. We have highlighted this both at NSSG and also as part of the discussions around industrial strategy with the government. I and my colleagues are determined to keep this on the agenda."

When asked how she began her own journey, Dr Rayment harks back to a very early interest in chemistry—"my parents gave me a chemistry set when I was 10!"—an interest that was maintained throughout university, and into her first role at British Nuclear Fuels Limited (BNFL).

Dr Rayment says: "I was very good at science and chemistry. I liked testing my assumptions in the lab and I was always interested in finding ways to cut the steps down in a process and find a better way of doing something. If a process doesn't work, I want to get to the root cause and find a better way. I loved what I did at university and have loved all my jobs, including my current role. I always loved energy too."

If you add all of these elements together—a passion for her subject, being exceptionally good at it, and a tireless effort to always get to the bottom of an issue and find a better solution—that is perhaps the je ne sais quoi of the ultimate expert.

By Dr Rachel Roffe

Orion: Nuclear fuel cycle modelling

Orion is a fuel cycle modelling tool that provides a holistic view of the fuel cycle. It is an important tool providing fuel cycle scenario assessments to measure impacts. Understanding these impacts is a critical component of long-term nuclear energy policy development.

Orion can track just over 2,500 nuclides through any time-dependent nuclear fuel cycle. Typical results include: material flows, high level waste projections, decay heat and radiological impact on process design and repository, and the practicalities of transitioning to a different reactor technology or fuel cycle.

The modelling tool is easy to use and based on robust and accurate physics methods. It is general enough to model virtually any fuel cycle (steady state or at equilibrium).

NNL's next generation: Aiden Peakman

Aiden Peakman, a nuclear physicist focused on future reactor technology at NNL, is a great example of one of tomorrow's fuel cycle experts. Passionate about his subject, it appears that he has "landed" in the right place at NNL, which has given him the opportunity to develop his expertise in future reactor technology, and to continue his long standing personal interest in alternative energy sources.

From his early days at university, Peakman found research into alternative energy sources interesting.

"During my undergraduate course, topics on semiconductors (for harnessing solar energy), nuclear fission, nuclear fusion and pretty much anything related to the physics of electricity generation were always at the top of my course list," he says.

This interest inspired him to move to the University of Manchester for an interdisciplinary post-graduate degree in nuclear energy. There he carried out research into accelerator-driven subcritical reactors, small high-temperature reactors for industrial heat and alternative fuels to uranium. His PhD focused on small light-water reactors to power commercial container ships, a topic he says "isn't quite as wacky as it sounds".

During his PhD he also undertook various secondments at Rolls Royce and on a project for the UK government identifying the technology challenges of advanced reactors. He also spent time with NNL's core design team at Preston, which he joined in 2014 on completion of his PhD.

NNL has given him the opportunity to build his expertise in core design by working with UK experts in reactor physics and fuel performance. He has been involved in commercial work, supporting nuclear new builds in the UK, and also non-commercial research, including modelling experimental fuels in research reactors.

Peakman has also been able to continue his interest into alternative energy sources, including leading a project with utilities in the UK, exploring how reactors will need to operate to accommodate future energy mixes. "This is a really important area nowadays and I am pleased that I had this opportunity," he says.

His research is also winning him some well-deserved recognition, too. Peakman was recently appointed the UK representative on the Organisation for Economic Co-operation and Development's Nuclear Energy Agency expert group on advanced reactors and future energy market needs.

It does indeed appear that Peakman has not only landed, but that he is also poised to take off, too.

MOX fuel laboratory facilities at the National Nuclear Laboratory. Credit: NNL (www.nnl.co.uk)

Lifecycle management options for large PCM crates and gloveboxes

Jenny Kent and **Marc Rigby** discuss the tools available for the development and optimisation of decommissioning and waste management strategies

Radioactive Waste Management Ltd (RWM), working collaboratively with waste packagers, has developed a range of alternative lifecycle management options for larger plutonium-contaminated material (PCM) waste items. PCM is defined as: "Wastes containing plutonium material that is not practicable to recover, with radioactivity levels exceeding the upper boundaries for LLW [low level waste], but which do not require self heating to be taken into account in the design of the storage and disposal equipment." [1]. A larger PCM waste item is defined as an item that cannot fit into a 3 cubic metre box without challenging disposal requirements or requiring a form of size reduction and for which size reduction into 200 litre drums is not deemed practicable by the waste packager.

Larger PCM waste items pose challenges associated with the physical characteristics of the waste item (for example, mass, size and geometry), the fissile mass of the item and the availability of characterisation data. The range of larger PCM waste items that will need to be managed include items currently stored on a number of UK nuclear-licenced sites and items that will be generated during future decommissioning activities, ie, legacy and future arisings respectively. Examples include legacy crates containing gloveboxes and process equipment, tanks and pipework that will be packaged during decommissioning of plutonium-handling facilities [2]. RWM is responsible for preparing waste package specification and guidance documentation (WPSGD), which provides a 'user-level' interpretation of the RWM packaging specifications, and other aspects of geological disposal, to assist UK waste packagers in the development of plans for the packaging of higher activity waste in a manner suitable for geological disposal.

Current baseline

The current baseline for operational PCM at Sellafield is size-reduction into 200 litre drums, which are supercompacted in the on-site WTC. The supercompacted pucks are then placed within a 500-litre stainless steel drum and grouted, prior to being placed into interim storage. These drums will be transported to and disposed of within a GDF, once this is available. For larger PCM waste items, Sellafield plans to build a crate breakdown facility, but the design for this has not yet been specified and alternative technologies are being considered [3]. Use of the current baseline for all PCM would result in the generation of ~230,000 200 litre PCM drums at Sellafield [4]. Larger PCM items are also being managed by Dounreay Site Restoration Ltd (DSRL) and the Atomic Weapons Establishment (AWE).

Potential benefits and the case for change

Alternative options for larger PCM waste item management may offer several potential benefits to waste packagers and the Nuclear Decommissioning Authority (NDA), including reducing worker risk exposure, informing future decommissioning strategy and tactics, and reducing the number of waste containers needing to be handled and disposed of at a geological disposal facility (GDF). Size reduction of larger PCM waste items to enable packaging within containers smaller than a 3 cubic metre box may require extensive, long-duration manual operations. The main risk from a safety perspective is considered to be from wounding of workers wearing pressurised air-fed suits, resulting in the absorption of plutonium. Regardless of the steps taken to minimise exposure to risk during such activities, hands-on decommissioning remains inherently hazardous.

The development of a toolkit of potential alternative management options for larger PCM items, including use of larger waste containers (constructed from stainless steel or glass-fibre composite materials) and remote or semi-remote size-reduction technologies, or a combination of the two approaches, would increase the options available during strategic decommissioning planning. The removal of whole plant items or larger sections could also significantly reduce the cost and duration of decommissioning activities. Standardising approaches to size reduction, tooling and waste handling may introduce operational efficiencies and help to avoid issues relating to the disposability of future larger PCM waste items.

Addressing the challenges

RWM engaged the Nucleus consortium (TÜV SÜD Nuclear Technologies and NSG) to support the development of thematic guidance on the management of larger PCM items, as a new addition to the suite of WPSGD. The team identified a range of representative larger PCM waste items and suitable packaging and treatment options, then convened an industry workshop to qualitatively evaluate these options and identify the benefits and limitations that applied to each option for the representative (example) items [5].

Larger waste containers

The LWC was designed to fit within a larger waste transport container (LWTC) that meets the requirements of the UK rail network (gauge W6a) and enables waste that does not meet the requirements for transport as a Type IP-2 package to be transported as a Type B package.

The LWTC is a conceptual design for a Type B transport container, based on the largest item that can be transported by rail (W6a gauge), so has constrained external dimensions of (l) 4.8m x (w) 2.65m x (h) 2.025m—the internal dimensions will be dependent on the exact design [6] To enable potential opportunities to be identified, a conceptual design, user and system requirements and an implementation plan have been developed for the unshielded LWC by Amec Foster Wheeler for RWM's higher activity waste (HAW) programme in 2016/17 [7, 8]. The LWC is not currently included in RWM's list of approved containers within the Disposal System Specification Part B [9] and the work completed to date has not identified waste- or facility-specific user requirements.

The implementation plan identified that it would take approximately five years to progress the LWC concept to a level of maturity suitable for implementation, including concept, preliminary, detailed design and prototype manufacture and testing, and development of a reference design [8]. The budget for this work, including prototype manufacture and tooling, would be approximately £2 million, and Graham Engineering Limited developed a scoping Class D (-50%, +100%) cost estimate of £35,000 per unit (based on manufacturing a batch of 1000 units, extrapolated from the cost of developing and producing 3 cubic metre boxes) [8].

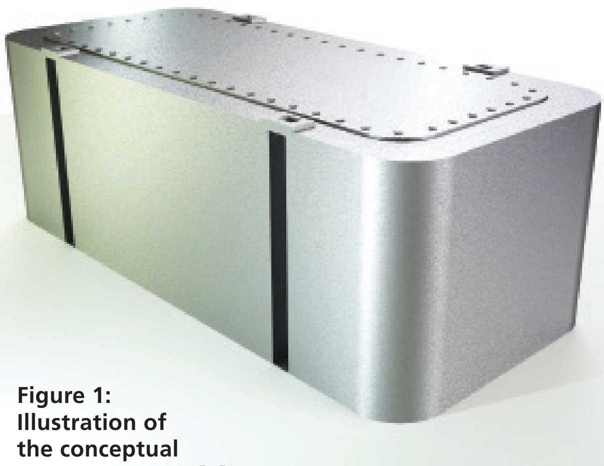


Figure 1: Illustration of the conceptual unshielded LWC [8]

RWM, through engagement with waste packagers, has identified the demand for, and requirements on, an unshielded larger waste container (LWC) and scoped the work that would be needed to develop such a container. In parallel, Sellafield has developed a programme of technology identification, development and testing for decommissioning of alpha-contaminated areas (known as the 'alpha demonstrator'), which is focused on practical implementation, testing and demonstration of remote and semi-remote size reduction technologies to reduce worker risks and improve efficiencies in decommissioning alpha facilities.

Drivers for alternative management options

Taking a legacy glovebox contained within several layers of packaging [1] as an example larger PCM waste item, the alternative management options for each lifecycle stage are shown in Figure 2. The following drivers will direct which of these alternatives are best available technique (BAT) or as low as reasonably practicable (ALARP) for this generic item:

- The quality of the available characterisation data: Further data may be required if historical records are incomplete, or if records are insufficient to demonstrate compliance with safety cases for transport or disposal, and to inform decisions on the most appropriate management route. However, the level of additional characterisation required would be dictated by the provenance, the type of packaging and the storage conditions, with intrusive or disruptive characterisation potentially being necessary for a poorly characterised glovebox that is contained within multiple layers of packaging.

- The presence of contaminants and hazardous materials: If it is deemed necessary to remove residual acid, oils, powders and lead shielding, segregation and/or passivation of potentially hazardous materials may be required to generate a waste package that complies with transport and disposal requirements.

- The level and nature of activity: Gloveboxes or sections of gloveboxes with high and mobile activity may require more extensive conditioning compared to glovebox sections with lower, or fixed, activity. It may therefore be possible to segregate sections of the glovebox that have higher activity and condition the segregated sections separately to optimise packaging and conditioning.

- The viability and benefits of decontamination: Sections of the glovebox may be amenable to decontamination to reduce the level of surface activity, residual acids and oils. However, there should be a clear benefit associated with decontamination and a management route available for the secondary waste that will be generated. For example, where decontamination would reduce the surface contamination significantly to the extent that waste could be reclassified, packaged differently or consigned as LLW or very low level waste (VLLW).

- The size of the selected waste container: The size of the waste container will dictate the extent of size reduction necessary to successfully package the glovebox. The use of a 3 cubic metre box or an LWC will result in fewer size reduction activities compared to the use of 200 litre drums in the baseline PCM strategy.

- Ability of the waste packaging site to handle containers: The site packaging the waste may have limited space or restricted access such that it cannot accommodate certain larger or heavier waste containers.

- Staged containerisation and conditioning: There may be benefits in containerising the waste for a period of interim storage, pending future conditioning. If existing storage arrangements for the legacy gloveboxes are acceptable, this may mean that no change is made until extant uncertainties surrounding the acceptability of particular treatment and conditioning options have been resolved.

If further waste conditioning is necessary, timing will be an important consideration. Treatment and conditioning may be performed before, during or after interim storage for an extended period. This presents both opportunities and challenges with respect to waste management. It is assumed at present that, for HAW, these activities will be completed before transport to a GDF, and significant technological advances may provide a range of alternative options with respect to how the waste is managed over such a time period. In addition, the GDF siting process and concept designs will mature, providing greater clarity with respect to disposal requirements, which may present further opportunities for new approaches which cannot be applied at present. If components of the larger PCM items are successfully reclassified as LLW or VLLW, these may be able to be transported to alternative sites prior to onward treatment and conditioning for disposal in the near term.

For each waste management lifecycle stage, the key implementation requirements, benefits and limitations for each of the alternative waste management options shown in Figure 2 were identified using a process of evaluation against the NDA's Value Framework [10] criteria, modified to recognise PCM-specific differentiators identified in previous Sellafield PCM options studies [11, 12].

These are presented within the thematic guidance [1] as case studies that demonstrate the approaches that could be applied to the lifecycle management of larger PCM waste items, including the options that could be considered at each stage. To support decision making, the case studies included flow diagrams that walk through the waste management lifecycle, providing different options depending on the answers given to each question. As an example, the results for characterisation of a legacy glovebox are presented in Table 1 and Figure 3. The implementation requirements will vary depending on the type of item, whether it is legacy waste or an operational item awaiting decommissioning, the location and strategic considerations at the site. Not all lifecycle stages are compulsory and the stages do not necessarily have to be completed sequentially.

Conclusions

The thematic guidance on the management of larger PCM waste items [1] supports the development of BAT arguments and the business case for further work, if needed, to implement the preferred option(s). It also provides waste packagers with additional tools for the development and optimisation of their decommissioning and waste management strategies.

RWM and Sellafield have collaborated on the development of this guidance, but information was also provided by DSRL and AWE, where similar waste is also located. Learning from experience was shared between these sites as part of this work. The thematic guidance emphasises the importance of considering the full lifecycle, including transport and disposal, when developing decommissioning strategies. Due to the wide variety of forms of waste and potential packaging methods, waste packagers are encouraged to discuss their detailed waste packaging plans with RWM at an early stage, in order to obtain independent advice based on its knowledge of waste package behaviour during transport and the operational and post-closure periods of a GDF, and from its experience obtained during the research and development of transport and disposal systems.

The authors would be keen to hear from any organisations with interest in using the LWC for the management of similar waste.

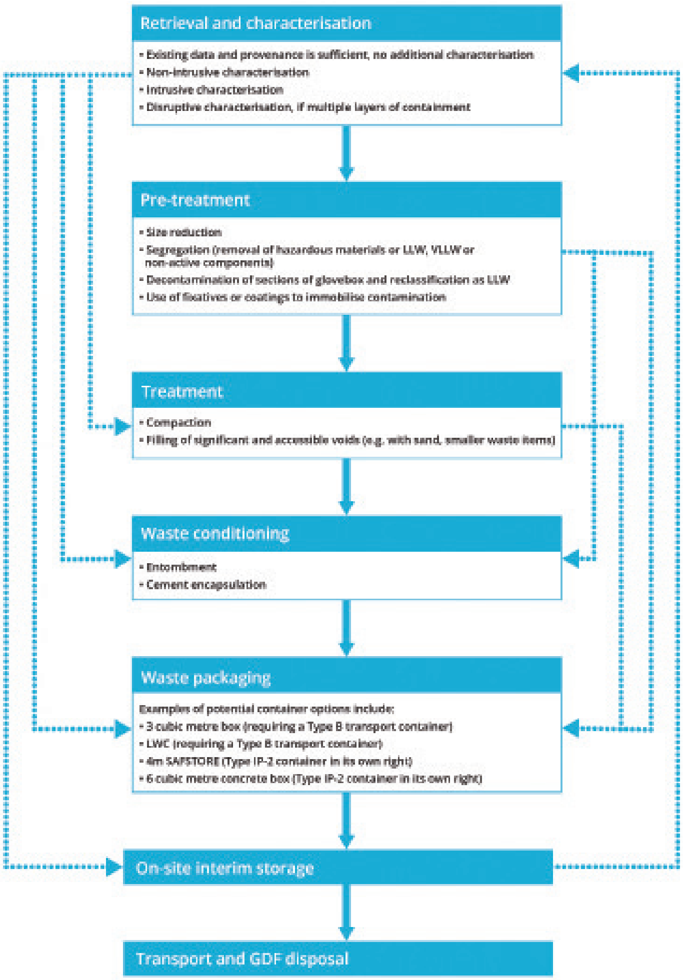


Figure 2: Generalised larger PCM waste item management lifecycle (adapted from [1])

What would be required for Implementation?	Benefits	Limitations
Non-intrusive characterisation		
• Historic records to understand provenance • If existing records are not sufficient to support the onward management of the glovebox, non-intrusive characterisation would be required • A toolbox of in-situ characterisation techniques (for example, radiography, X-ray, γ-spectrometry, X-ray fluorescence)	• No loss of containment so minimal exposure and risk to operators • Higher throughput rates • Lower capital cost compared to the baseline	• Hazardous materials, or regions of higher activity (for example, within corners of the glovebox), may not be identified • Limited opportunity to segregate hazardous materials or lower activity sections • Financial risk in the longer term if the package needs re-work at a later date to ensure compliance with disposal requirements*
Intrusive and disruptive characterisation		
• Required if non-intrusive characterisation is inconclusive (for example, if the glovebox is stored in multiple layers of wrapping) • In-situ characterisation techniques for the more accessible surfaces • Ability to remotely disrupt the glovebox, recognising that primary containment will be broken • Ability to remotely observe and swab internal or difficult to access areas of glovebox (for example, endoscopes/ borescopes) • Provision to analyse swabs or samples in a laboratory to provide more representative assay data	• Identification of hazardous materials, or regions of the glovebox that are more contaminated • Opportunity to identify and segregate lower activity items and problematic items • Increased likelihood of the waste package being acceptable for disposal	• Breaking containment (for example, removing wrapping, accessing internal surfaces) could release contamination and increase operator exposure and risk • May have to undertake several intrusive characterisation steps to ensure that representative results are obtained (for example, contamination build-up may be higher in the glovebox corners) • Secondary waste generated through sampling • May require investment in new/ additional sampling or characterisation technologies

Table 1: Implementation requirements, potential benefits and limitations of alternative options for characterisation of a legacy glovebox (adapted from [1])

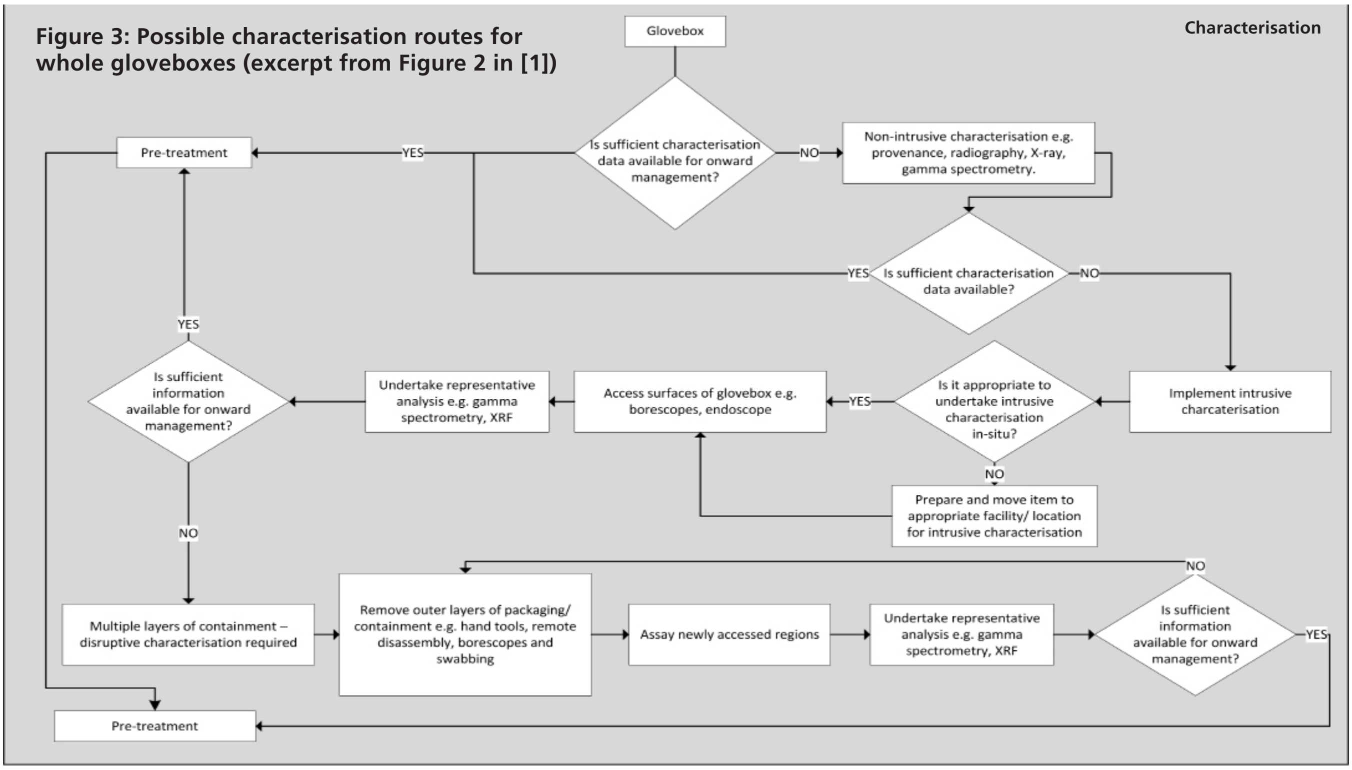


Figure 3: Possible characterisation routes for whole gloveboxes (excerpt from Figure 2 in [1])

***Non-intrusive characterisation may not provide representative data (due to some regions of the waste being inaccessible). If the full characteristics of the item are not known, there may be greater risk of needing to re-work the waste package at a later date to ensure compliance with disposal requirements.**

Jenny Kent is a senior scientific consultant at Galson Sciences, where she has worked on a wide variety of projects relating to the packaging, interim storage and disposal of radioactive waste. She has a geological background and a PhD in environmental radiochemistry.

Marc Rigby is a chartered scientist and has worked in the nuclear industry for eighteen years in both operational and technical roles. He manages the higher activity waste innovation and delivery programme at Radioactive Waste Management Limited, enabling the implementation of near-term waste management solutions in collaboration with Site Licence Companies.

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- Attendees at an industry workshop in Warrington on 12 July 2016 to evaluate options for the management of larger PCM items, including representatives from AWE, Cavendish Nuclear (on behalf of DSRL), Eden, NSG, Quintessa, RWM, Sellafield and TÜV SÜD Nuclear Technologies.

Acronyms

ALARP: As low as reasonably practicable
AWE: Atomic Weapons Establishment
BAT: Best available technique
DSRL: Dounreay Site Restoration Limited
GDF: Geological disposal facility
HAW: Higher activity waste
LLW: Low level waste
LLWR: Low Level Waste Repository
LWC: Larger waste container
LWTC: Larger waste transport container
NDA: Nuclear Decommissioning Authority
PCM: Plutonium-contaminated material
RWM: Radioactive Waste Management Ltd
VLLW: Very low level waste
WPSGD: Waste package specification and guidance documentation
WTC: Waste treatment complex

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Nuclear Professionalism

the nuclear institute

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.

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New shielded package design presents opportunities

Rob Ward of REACT Engineering discusses the strategic benefit of self-shielded boxes for storage and disposal of metallic uranic material

Sellafield is facing a complex nuclear clean-up challenge for which there is no precedent. Sellafield led the development of the UK's nuclear industry, from the production of plutonium for the country's nuclear deterrent programme, to the development of nuclear power generation. Today, we face the challenge of cleaning up the legacy of the site's early operations, including some of the most hazardous nuclear facilities in Europe, with the world's largest inventory of untreated nuclear waste [1].

"*Our* legacy will be a demonstrable positive impact on *the* legacy."

Crucial to this mission is the strategy for management of uranic fuel and fuel bearing material (FBM) from across the Nuclear Decommissioning Authority (NDA) estate. The development of a new shielded package design for retrieval of uranic materials from legacy storage facilities presents the opportunity to derive wider benefit through an integrated approach to strategy development, in order to facilitate risk reduction and potentially significant cost saving. The technical aspect concerning the development of this new package poses challenges to the status quo at Sellafield and brings with it interesting regulatory issues around transport and disposability.

This paper presents the means by which these challenges are being overcome in order to achieve strategic benefit for Sellafield and the NDA, which might inform other operators and nuclear site licensees in development of spent fuel or legacy waste management strategies.

Context

The two legacy pond storage facilities on the Sellafield site are aging structures, which will continue to deteriorate with time, both of which contain inventories of metallic uranic material, including sludge and degraded Magnox fuel, the retrieval capability for which was not built into the original plant design. This inventory, combined with the deteriorating nature of these facilities, ranks one of them among the highest hazard plants in the UK. There is an urgent need to retrieve the hazardous inventory from the facility and place it into modern containment and as such, this is a pressing NDA strategic objective for risk reduction [2].

Under Sellafield's risk-based management approach, this facility falls under Region B of the risk management profile shown in Figure 1, indicating that the current potential level of detriment to the workforce, public or environment is unacceptable. Intervention is required in order to prevent the risk associated with facilities in Region B from increasing in the long term [3]. In order to comply with nuclear site licence conditions and in order to demonstrate that risk is as low as reasonably practicable (ALARP), a programme of hazard and risk reduction is being implemented.

In order to grant access and retrieve the inventory of fuel and sludge from the ponds, other intermediate level waste (ILW) and pond solids must be removed. The approach being taken is to buffer store some of this material in unconditioned form in self-shielded boxes in a dedicated storage facility [4]. Following the principles of the decommissioning mindset, the transient increase in risk is balanced against overall time at risk in order to reduce the area under the risk curve, until the facility falls within Region A, where risk is considered to be acceptable given the application of nuclear safety management practices.

There are similar considerations around retrieval of Magnox fuel from pond storage. The current NDA strategy for management of spent Magnox fuel is reprocessing via the Magnox operating programme (MOP), with the intention to process all material currently held in wetted storage by 2020. It is recognised, however, that the Magnox reprocessing plant is a complex, aging facility, and that the economic viability of recovery from catastrophic failure of critical plant or equipment could bring the programme to a close at an earlier time. It is also recognised that Magnox fuel is not suitable for extended pond storage, meaning that a strategy is required for management of any material remaining post-MOP [5].

The NDA is responsible for additional fuel and fuel bearing materials, some of which are similar to the Sellafield-managed inventory and others present different management challenges. Some of this fuel is destined for reprocessing at Sellafield, but it is known that a portion of this will be timed out by MOP completion. Consequently, a management option is required for this, and any material that is out-of-specification for reprocessing.

Enterprise fuel study

The enterprise fuel study (EFS) was instigated in order to identify full lifecycle management strategies for metallic uranic material from an enterprise perspective. The EFS considers a range of metallic uranic fuel and FBM of mixed origin, in a wide variety of forms, in varying states of condition. Some of the material originated from the current UK advanced gas-cooled reactor (AGR) fleet and is stored in a modern facility under tightly controlled conditions.

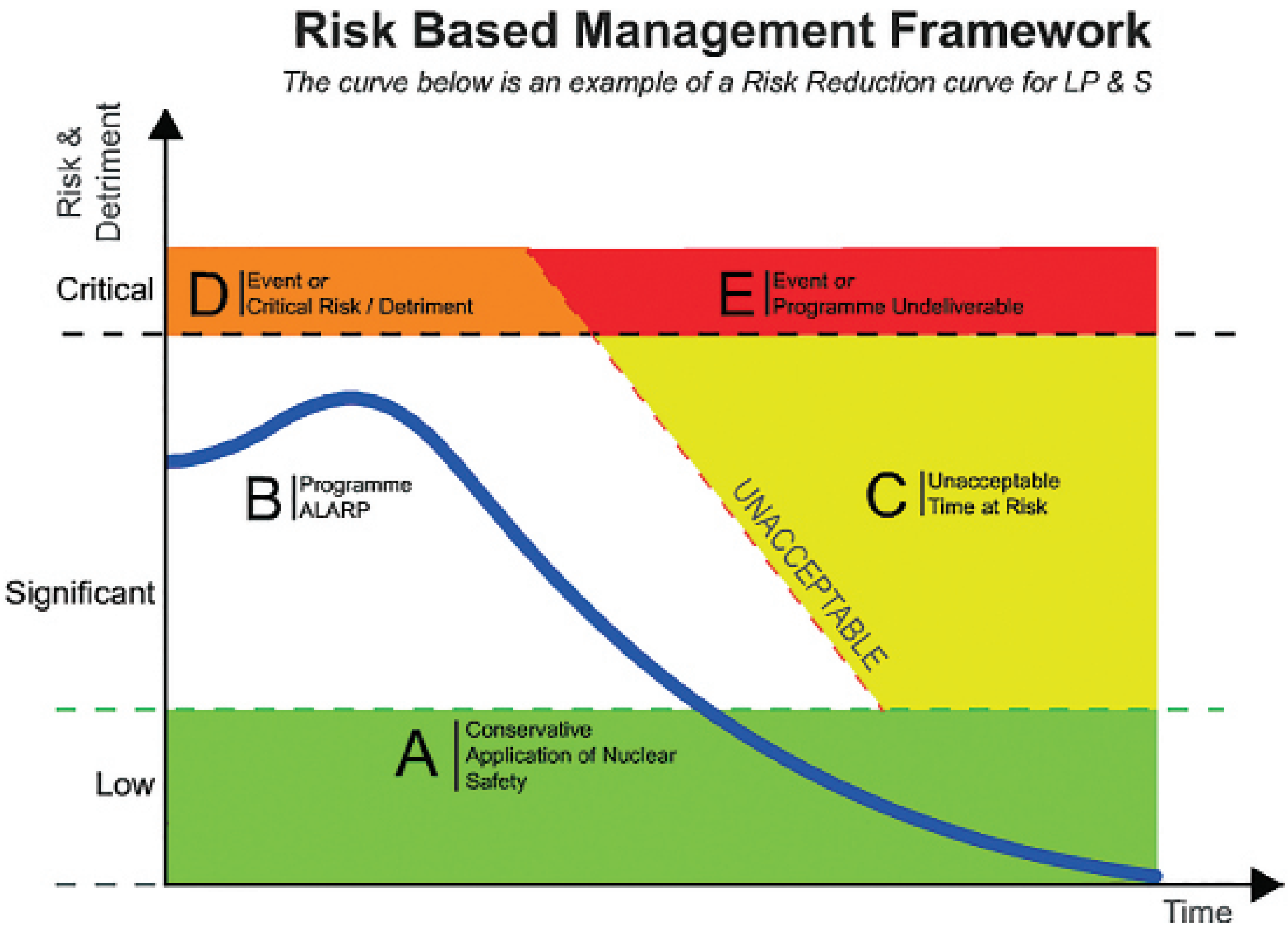


Figure 1: Risk-based management curve (Sellafield, 2016)

On the other hand, there is a large amount of 'legacy' material that represents a higher risk, due to its condition and the hazards associated with its storage in aging facilities, which are no longer fit for purpose. The material from the legacy storage pond facilities is less well characterised than that held in more modern plants. These facilities are open to air and have been subject to less well-controlled water chemistry for periods of their operation, which has resulted in more significant degradation of the stored fuel. Some of the metallic uranic material is considered to be an asset destined for reprocessing, while other material is included in the UK Radioactive Waste Inventory (UKRWI), and, and therefore will not be reprocessed [6].

Specific details of the inventory are not recorded here but at a high level, the material considered by the study (hereon referred to as EFS scope material) broadly comprises [7]:

- Un-reprocessed AGR fuel remaining on completion of reprocessing operations
- Legacy Ponds metallic uranic fuel and FBM
- Other metallic uranic fuel and FBM
- Aluminium clad fuel
- Samples contained in post-irradiation exam (PIE) bottles and other bottled fuel
- Residuals and Pond floor debris
- Dounreay fast reactor (DFR) fuel:
  - Material that is planned to be reprocessed prior to completion of reprocessing operations (in the event of catastrophic failure of reprocessing capability)
  - Material that will not be reprocessed prior to completion of reprocessing operations (due to either being out of specification or due to timing incompatibility with the planned reprocessing end date)

Shelf-shielded boxes

Shielded waste packages have traditionally been used for the transport of low specific activity materials and surface contaminated objects. In order to substantiate the safety case for transport, storage and disposability of waste packages, robustness to fire, impact and fault scenarios are normally achieved through a combination of package performance and immobilisation of the inventory by encapsulation. The new generation of robust shielded containers (RSCs) provide robustness against impact and fire,

Figure 2: Self-shielded box concept (Sellafield Ltd, 2017)

without the requirement for immobilisation of wastes. The ability to interim store material that would otherwise have been immobilised and stored in an unshielded package represents an opportunity to reach a passively safe condition sooner, awaiting final disposal, without foreclosure of onward retrieval and conditioning routes [8].

So as to accelerate urgent hazard and risk reduction associated with the legacy waste inventory at Sellafield, one of the legacy storage facilities has led technical work into the development of shelf-shielded boxes (SSBs) (see Figure 2) for storage of spent fuel and ILW. The self-ventilating ductile cast iron containers have been designed to receive skips containing degraded fuel from legacy ponds and to provide robust containment and shielding for on-site transport and interim storage. Detailed design of the boxes is due to be complete by early 2018, with the first production box available around a year later. Technical work is underway to substantiate the storage of metallic uranic material in SSBs for up to 100 years [9, 10].

Opportunity

While SSBs are not the only consideration for management of EFS scope material on the Sellafield site, their development in order to address the hazard risk reduction (HHRR) imperatives of one programme prompted the study into the potential utilisation of SSBs in order to derive benefit for the wider enterprise and NDA estate. This might involve enabling early retrievals from legacy facilities, management of material remaining once reprocessing operations cease, or management of material from across the wider NDA estate, such as the DFR fuel.

The potential for buffer or interim storage of unconditioned material in SSBs is a change of direction from the existing baseline plan, and therefore the wider implications of any new strategy focused around the use of SSBs must be understood. The combination of this strategic work and ongoing technical work will underpin a series of decisions to divert sub-groups of uranic material away from baseline routes in support of earliest practicable hazard and risk reduction.

BUFT deferral

Under the current baseline plan, the bulk uranic fuel treatment (BUFT) capability is identified for treatment and packaging of fuel and FBM (EFS scope material) into a form suitable for safe surface storage, pending the availability of the geological disposal facility (GDF). It is currently assumed that this capability is provided as a single new build facility with an estimated capital cost of up to £1 billion.

Further technical work is planned, leading to a series of decisions to underpin the use of SSBs for interim storage of up to 90% of BUFT scope material. Each decision relates to a specific type of material, and the rolling deferral of BUFT capital spend will be linked to programme planning dates for completion of the technical underpinning work for each material type, with consideration of required export dates from donor facilities. Each decision will reduce the scope of BUFT, which will diminish the associated capital cost and permit focus on high hazard and risk reduction activities in the near term.

This has the potential to release the associated budget to be diverted elsewhere or to achieve cost savings. To date, around two thirds of the BUFT scope material has been diverted into storage in SSBs. Deferring the capital expenditure components of BUFT will allow time for the legacy ponds programme to gain a better understanding of the legacy materials held in storage such that, if a new build capability is ultimately required, its scope will be based upon better knowledge [11].

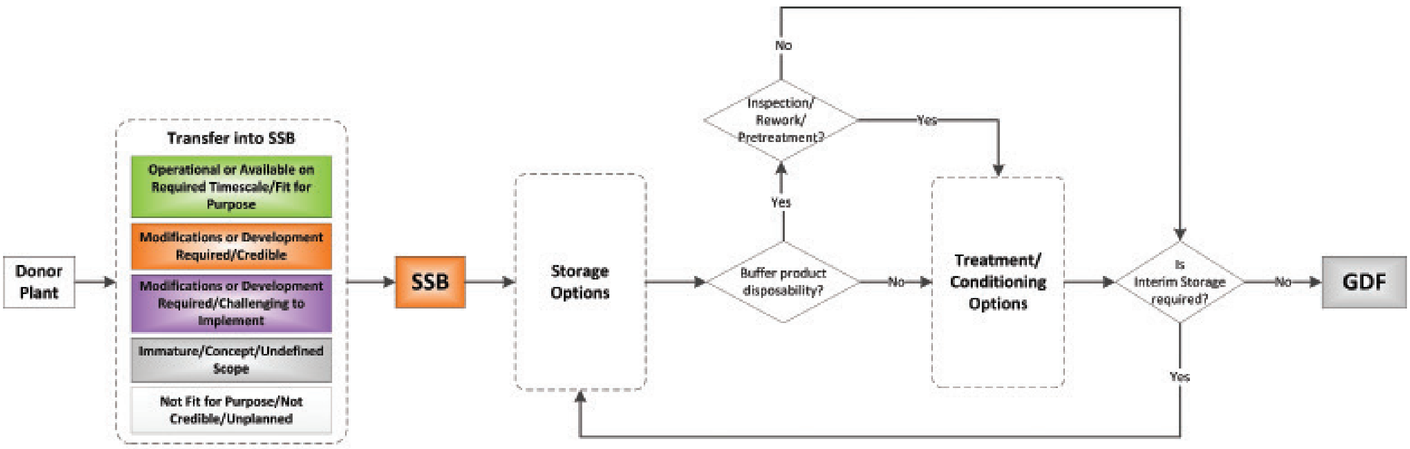
Transfer, conditioning and storage of shelf-shielded boxes [9]

An understanding was required of the scope for defining optimal routes for each metallic uranic fuel and FBM group for safe transport and storage commensurate with current final disposal assumptions and risks. Under the EFS, a piece of work was undertaken to understand potential routes for this material in SSBs, from donor plant to final disposal. A route can be divided into the following five stages: (i) transfer of material into SSBs; (ii) buffer storage locations/facilities; (iii) final treatment/conditioning; (iv) interim storage prior to GDF availability; and (v) transport to GDF.

The path for EFS scope material in SSBs, including key decisions related to timing of exit from storage, timing of conditioning and timing of GDF availability, is highlighted in Figure 3 and each stage of the process is described in the subsequent sections.

Buffer storage

Consideration of buffer storage options takes into account the availability (space, capacity and interaction with other operations/programmes) of current and future facilities, cognisant of operational lifetimes and timescales for delivery of new facilities



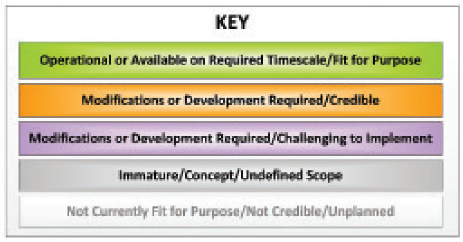


Figure 3: SSB route options process flow

based on corporate norms. Key factors specific to SSBs are handling capability, lifting capacity and structural capacity of floor slabs, due to the high loads associated with the packages. Transfer of fuel into waste facilities will have implications around safeguards, planning and regulatory acceptability, and appropriate CM&I arrangements will be required.

The interim storage facility (ISF), a dedicated store for SSBs based on the design used by Magnox, is being progressed at an accelerated rate and is due to be available in 2018. Further work will be required in order to make the best available technique (BAT) and ALARP cases for transfer of a wider group of materials to the interim store and a series of decisions has been identified in order to secure these routes. The potential for higher activity and/or burn up associated with the wider NDA estate materials may preclude storage in an ISF without a change to existing SSB/ISF conditions for acceptance.

Conditioning/treatment

High-level options were considered for treatment or conditioning of metallic uranic materials in order to produce a wasteform consistent with the Radioactive Waste Management's (RWM) requirements for package integrity of 150 years and in order to be consistent with the longer target period of 500 years. If the buffer storage product can be justified for direct disposal to GDF, the requirement for retrieval of material from SSBs would be avoided and the complexity of the final conditioning step would be reduced, with perhaps only a requirement for final inspection of the boxes.

The timing of final conditioning (early/late) will influence whether the material will require a further period of interim post-treatment storage. Early conditioning essentially describes conditioning at any time prior to availability of GDF, after which the material may or may not remain in SSBs while it is interim stored until GDF becomes available. Late conditioning refers to conditioning immediately prior to final disposal.

Interim storage

The requirement for further interim storage will be determined by the timing of conditioning (early/late) with respect to GDF availability and pending justification of direct disposability. In the case of "early" final conditioning, a further period of interim storage will be required until a route to final disposal becomes available.

Transport and disposal

With regards transport disposability of the packages, RWM's approach is being followed, which is described as such: "Where a waste producer's packaging proposals are compliant with RWMD packaging specifications and safety cases, it endorses their proposals with a letter of compliance (LoC). A LoC indicates that RWMD considers the operator's packaged waste is likely to meet the waste acceptance criteria for any future GDF. LoCs can be issued at conceptual, interim and final stage (cLoC, iLoC, fLoC). RWMD undertakes periodic reviews to ensure previously issued fLoCs remain valid [13]."

There is currently no LoC for transport or disposal of fuel and FBM in SSBs. Development of a transport safety case for metallic uranic material in SSBs relies upon Type B (M or U) licensing of the package. For a package to be used solely in the UK, a type B(M) approval would be adequate for the intended use [14]. It is not considered feasible to redesign the SSB to fulfil all of the requirements for off-site transport in the short term, so there are potential advantages to developing an overpack design to fulfil Type B requirements, particularly in order to enable transfer of material for which there are immediate programme imperatives.

The SSB route will be pursued without a cLoC so as not to impede the Sellafield strategic mission or programme of hazard and risk reduction, delaying the request for endorsement until a later date. Sufficient confidence is required in ascertaining the disposability case in the future, and technical underpinning work is underway by Sellafield to develop the Type B transport arrangements for SSBs consistent with regulatory requirements, sufficiently to allow formal disposability assessment.

Key challenges

Due to their strategic significance in accelerating HHRR programmes at Sellafield, direct disposability to the GDF was not explicitly considered in the SSB design but early input was gained from RWM so as to avoid inadvertently foreclosing disposability. Further work is underway to ascertain the credibility of direct disposal of SSBs containing EFS scope material.

The disposability assessment process considers the compatibility of the proposed packages with the requirements for safe long-term management, including interim storage at the site of arising, transport, emplacement and disposal. Therefore, the credibility of implementing a strategy predicated on storage and potentially disposal in SSBs relies heavily on a disposability case being made. The general requirements placed on waste packages for disposal in a GDF are embodied in the generic waste package specification (GWPS).

The key outstanding issues for development include [15]:

- Lifecycle justification: Compelling arguments that the proposed use of SSBs as an alternative to uranic fuel treatment capability is based on full lifecycle considerations and not just the immediate operational or financial benefits.
- Reliability of information and records: It is important to develop an adequate understanding of the inventory (particularly the legacy material) and associated uncertainties to underpin the disposability case.
- Post-closure performance: Sensitivity of the calculated post-closure risks (to the groundwater and gas pathway) to changes in the inventory as may be brought about by the disposal of bulk Magnox fuel in SSBs.
- Wasteform evolution: Understanding is required of the risk presented by UH3 evolution to underpin transport, handling and disposability safety cases.
- Thermal performance: The SSBs could contain wastes with heat outputs that are significantly greater than typical LHGW and consideration needs to be given to the impact of such higher thermal loadings on GDF performance
- SSB design: Sellafield must share detailed technical design information on the SSB, with a long-term view to RWM developing a waste package specification and influencing GDF engineering design.
- Criticality safety: EFS material in SSBs does not fit within any of the existing generic criticality cases that have been developed for GDF's LHGW vaults. Joint working is required between Sellafield Ltd and RWM to develop a package-specific case.
- Transport: There is uncertainty that the box would retain its Type B transport package status following a prolonged period of interim on-site storage due to ageing of the container, particularly for wet wastes The criticality case for transport would be reliant upon Sellafield making an ALARP justification to the Office for Nuclear Regulation to explain that attaining fully optimised conditions within the SSBs would represent a low and tolerable risk, when judged against the alternative options such as reducing the package payload, which would not be reasonably practicable as it would increase overall risk.
- Security implications: The disposal of fuel-bearing wastes, particularly if unconditioned, could challenge the current assumptions regarding the physical protection requirements for the disposal vaults.

The challenge is compounded by the imminent need to commit to the use of SSBs so as not to impede HHRR programmes of work, given that the detailed design of the boxes is ongoing, precluding a disposability assessment. The nature of material consigned to the boxes is varied, hence either separate disposability cases will be required per material type or a bounding case must be made. Application of a conservative bounding case to underpin the transport and disposability cases for all EFS scope materials could drive very restrictive package payloads and lead to a significant increase in package numbers, with knock-on impact on required storage capacity, cost and programme.

Strategic benefits

The strategic benefit gained from implementation of SSBs for metallic uranic material can be summarised as follows:

- Enable near-term focus on HHRR activities.
- Facilitate early retrievals from wetted storage, avoiding increase in risk associated with long term storage in aging facilities. This creates working space in the facilities, which enables sludge retrieval, which represents a significant proportion of the uranic inventory of the ponds [16]. Sludge retrievals are a pre-requisite to dewatering of the ponds, and achievement of a safe, quiescent interim end state.
- Reduce scope of and defer capital spend for future BUFT capability.
- Release up to £1 billion of near/medium term budget to be diverted elsewhere, or to achieve cost saving,
- Buy time to develop a better understanding of the legacy inventory, to inform future conditioning requirements.

The boxes offer the opportunity for an enterprise-wide approach to other issues, too. For example, the scope of planned storage or conditioning facilities to be delivered under other programmes of work might be reconciled against the requirements for storage or conditioning of metallic uranic materials in SSBs, in order to reach one mutually beneficial solution, in terms of overall cost, programme and land use on the spatially constrained Sellafield site.

In line with Region B risk management principles, and to address the balance between 'safer sooner' and future liability creation, the EFS scope material in the SSB route will be progressed without a disposability case, in order to balance the overall business benefit against the transient risk associated with early retrievals and time at risk in terms of ongoing storage in aging facilities. The approach is to pursue this route at risk, mindful of the technical gaps and design immaturity, or to provide funding and scope to initiate work to close knowledge gaps to support the full assessment of a disposability case.

Conclusion

Whereas technological advancements at Sellafield once led the development of the UK's nuclear programmes, Sellafield is now leading the way in the decommissioning and radioactive materials management space. The complexity of the nuclear clean-up challenge posed by the legacy storage facilities at Sellafield has driven technical innovation in the development of SSBs. Clearly these packages offer opportunity to reduce the risk associated with the site's highest hazard facilities by enabling accelerated retrieval of the legacy inventory and progressing towards a safe interim state for the site.

The change to the status quo also presents significant challenge, not only to the strategy for nuclear materials management on the Sellafield site, but in terms of the need for close collaboration with RWM and the regulator in order to ascertain a credible disposal route in line with current assumptions around GDF availability. With confidence in a future disposability case for metallic uranic materials in SSBs, the route is being pursued so as to achieve the significant enterprise-wide strategic benefits.

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Acronyms

AGR: Advanced gas-cooled reactor
ALARP: Low as reasonably practicable
BAT: Best available technique
BUFT: Bulk uranic fuel treatment
DFR: Dounreay fast reactor
EFS: Enterprise fuel study
FBM: Fuel bearing material
ILW: Intermediate level waste
ISF: Interim storage facility
HHRR: Hazard risk reduction
GDF: Geological disposal facility
GWPS: Generic waste package specification
MOP: Magnox operating programme
NDA: Nuclear Decommissioning Authority
RSC: Robust shielded container
RWM: Radioactive Waste Management
SSB: Shelf-shielded box
UKRWI: UK Radioactive Waste Inventory

Within the Sellafield decommissioning strategy and technical team, Rob Ward progressed the development of the approach to defining strategically coherent lifetime management options for uranic materials from across the Nuclear Decommissioning Authority (NDA) estate. Ward, on behalf of REACT Engineering, is now leading a team of supply chain companies in delivering support to the Sellafield Enterprise Fuel Study, upon which this article is based.

For the record

K Sihra discusses the role that waste package records play in radioactive waste management and disposal

The Nuclear Decommissioning Authority (NDA), through Radioactive Waste Management (RWM), is responsible for implementing UK government policy for the long-term management of higher activity radioactive waste, as set out in the Implementing Geological Disposal White Paper [1]. The white paper outlines a framework for managing higher activity radioactive waste in the long term through geological disposal, which will be implemented alongside the ongoing interim storage of waste packages and supporting research.

As implementer and future operator of a geological disposal facility (GDF), and therefore as the ultimate receiver of waste for disposal, RWM will be responsible for the production of waste acceptance criteria (WAC) for the facility. It is expected that the WAC will be a combination of physical attributes of the waste package and empirical evidence of its contents, as demonstrated through the package records. While plans for a GDF remain at an early stage, the information necessary to define final WAC is not available. In the meantime, and as a precursor to the final WAC, RWM produces generic specifications for both the waste package and its record.

For the waste package, a key purpose of the publication of related packaging specifications is to provide a baseline against which the suitability of the packaging proposal can be judged. By providing such a baseline, RWM is able to assist packagers of radioactive waste in the development and implementation of such plans, by providing confidence that the resulting waste packages would be compatible with the anticipated needs for transport to and disposal in a GDF. This process is known as the disposability assessment process and, if successful, results in a letter of compliance (LoC).

For the waste package record a key purpose of the publication of related record specifications is to enable waste packagers to design their own data and information recording system to allow demonstration of compliance of waste packages with relevant legislation and regulatory guidance, and conformance against all relevant RWM specifications, at all stages of waste package management. This includes compliance with the needs of interim storage (under site licence conditions), nuclear material accountancy and consignment for transport either to off-site storage or a GDF. The specification is the waste package data and information recording requirements [2], and it is supported by explanatory material and guidance [3].

To date, the 17 sites within the NDA estate have produced approximately 70,000 waste packages. Each has been produced following evaluation of the proposed packaging proposal by RWM and following consistent guidance on the requirements for the waste package record. Associated with each record is actually a wide range of data and information held in differing formats in diverse locations, together with a similarly diverse and dispersed range of supporting information and documents. These data and information can be shown to comply with relevant legislation and regulatory guidance, but cannot be shown to comply with RWM's requirements for disposal and are not actively being preserved for the long-term timescales required for geological disposal, associated with the identification of a site, construction of a facility and the duration of its operation.

Recognising the challenge presented by the current position, the NDA has charged RWM to develop, maintain and implement an estate-wide programme to address this challenge. The NDA's target, which is supported by UK regulators, is to have RWM-approved waste package records for existing waste packages by March 2021, and for all new waste packages in new packaging facilities to have RWM-approved waste package records within 12 months of the package entering interim storage (ie, storage prior to disposal at a GDF).

This paper describes the regulatory drivers for maintaining package records, the defined structure of a package record and the newly instigated records approval process. All records will now be maintained at Nucleus (Nuclear and Caithness Archive) in Wick; a description of this facility is also given.

Regulatory drivers

UK legislation, policy and regulatory guidance documentation provide the legal framework for the derivation of waste package data recording requirements. The provision of a package record specification has focussed on those associated with the transport of waste packages to a GDF, the operation of that GDF and its intended use as a disposal facility.

The UK regulations that govern the transport of radioactive material are the Carriage of Dangerous Goods and use of Transportable Pressure Equipment Regulations 2009 (and amendments) CDG2009 [4]. The regulations place the main responsibility for compliance on the consignor and carrier, and these have been incorporated into the specification for waste package records, since within the NDA estate, these need not necessarily be the generators or packagers of the waste. It is expected that conformance with the specification [2] will allow the consignor to demonstrate to the competent authority that the transport package design fulfils all of the requirements of the regulations.

The white paper [1] states that a GDF would be a nuclear installation under the Nuclear Installations Act (NIA) 1965. This will require RWM to have been granted a nuclear site licence by the Office for Nuclear Regulation (ONR) before it can begin to construct or operate a GDF.

The NIA (as amended by the Energy Act 2013) requires the appropriate national authority to, "when it grants a nuclear site licence, attach to it such conditions as the authority considers necessary or desirable in the interests of safety".

A standard set of 36 site licence conditions has been developed by the ONR and these are attached to all nuclear site licences [5]. Of the 36 standard site licence conditions, Conditions 5, 6, 14, 17, 25 and 32 are of most relevance to data and information. The most broadly encompassing is Condition 6: "The licensee shall make adequate records to demonstrate compliance with any of the conditions attached to this licence."

A GDF is a disposal facility and radioactive waste disposal is regulated under the Environmental Permitting (England and Wales) Regulations 2016 (EPR16) [6] and in Northern Ireland under the Radioactive Substances Act 1993 [7]. RWM must therefore apply for and be granted an environmental permit to dispose of radioactive waste at a GDF.

The permit requires the operator of a site transferring waste to another site to ensure that such a transfer is in accordance with the directions of the representative of the organisation to whom the radioactive waste is transferred, to enable that organisation to comply with all relevant regulatory requirements (Condition 3.1.5). It also requires that the representative receiving the waste is provided with the radionuclide inventory of the waste (Condition 3.1.6). As such, the importance of records in this process and RWM's right to dictate the structure and content of the record for disposability is established. The waste consignor will also be required under their environmental permit to provide the information stipulated by RWM in order for RWM to meet its requirements for on-going management of the waste packages and associated records (see paragraph 345 [8]).

The waste package record

The relevant requirements for data and information required to produce a waste package record is structured in a hierarchical structure based on classes, categories and fields. The collation of this information would produce a record that would:

- Describe the physical, chemical and radionuclide content of a waste package, thus providing an accurate and trustworthy record of the nature and contents of the package.
- Identify and define waste package properties and performance that are relevant to future management options.
- Provide sufficient data and information relating to the provenance of the waste to:
  - Allow the radionuclide inventory to be extended as required (through the application of suitable extrapolation methods); and
  - Predict the likely evolution of the package with time, the effect of interactions with other packages and disposal system components and the effect of environmental conditions on package integrity.

To facilitate the development of a data and information recording system, the means of recording the information and its subsequent management should also be considered. The data and information should be considered as falling into two categories:

- Recorded information: Information directly associated with a waste package that would accompany the waste package electronically, and to which access is likely to be required throughout all periods of waste package management.
- Traceable information: Information or documents referenced from the recorded information, and to which access would be required by exception.

Recognising the sources and different functions that the data and information may fulfil, the package record is separated into classes, as follows:

- Class A: Underpinning and justification—information that applies to the waste type as a whole, in particular the documents that define the origin of the waste, the packaging process, the results of a development programme, waste container manufacturing specifications, the anticipated properties of the waste package and the waste package record. This information provides the basis for, and justification of, the specification documents that form class B.
- Class B: Specification—a concise statement of the precise requirements to produce a waste package that would be compliant with the obligations for storage, transport and disposal.
- Class C: Compliance—information collected about the as-manufactured waste packages, primarily required to demonstrate compliance with the specifications. In general, information required for classes A and B is expected to be traceable, while class C compliance data are expected to be recordable.

It is recognised that some data and information may apply to a subset of waste packages, regardless of which class of information it belongs to. This may be termed as 'batch specific' information. Examples may include manufacturing and purchasing information for a batch of waste containers, or analytical data pertaining to a quantity of waste that would be distributed between several packages. Such data may be duplicated in individual disposability records or, preferably, referenced as traceable information. The appropriate means of recording such information would depend on the nature of the information and is at the discretion of the waste packager.

In terms of defining the record, the package record specification (PRS) provides a concise statement of the overarching data and information recording system and defines the documents containing the data and information that are required for a compliant waste package record. It should therefore include references to all documents that contain the required underpinning and justification information, as well as the relevant specifications under which each waste package was manufactured. The PRS should also specify the package-specific compliance data and information that will be produced during and following package manufacture. The PRS will be used as an index of all the package records associated with a package, and must be maintained and preserved.

Disposability assessment

When requested by waste packagers, RWM provides packaging advice through the disposability assessment process, in order to minimise the risk that waste packaged now will not be compliant with future transport and disposal system requirements. RWM's disposability assessment process consists of a series of technical evaluations and safety assessments, including an evaluation of the data recording requirements, from which the content of the package record will be established.

Where packaging proposals are compliant with its packaging specifications and safety cases, RWM endorses a waste packager's proposal with an LoC. This document indicates that RWM expects the packaged waste will meet the waste acceptance criteria for any future GDF. LoCs can be issued at the conceptual, interim and final stages. It is expected that for new waste packages, the content of the PRS will be agreed by final stage endorsement and changes are subsequently managed through a prescribed change control process.

For the 70,000 legacy waste packages, the PRS needs to be agreed retrospectively to establish the content that is available and to assess the implications of any data and information not or no longer available.

Records approval process

The principal aim of the RWM package records process is to ensure that package records will be sufficient to fulfil all relevant purposes throughout the lifecycle of the waste packages, up to and including demonstration that the packages are consistent with the extant RWM safety cases. Ultimately, at the time of consignment to a GDF, the package records would be required to demonstrate that the corresponding packages are acceptable for disposal through any waste acceptance process that would be applied.

Further objectives of the package records process are:

- To ensure that an endorsed PRS is available as the basis for generating and approving the package records for each identified packaging operation.
- To confirm that package records have been produced under a suitable system of verification, implemented by the waste packager.
- To approve completed package records as fulfilling the requirements agreed through the endorsed PRS.

In approving the package records, RWM will confirm that all the documents detailed in the PRS are present and accessible, and are subject to adequate arrangements for retention and retrieval.

The package records process requires collaboration between the waste packager and RWM. Nevertheless, the waste packager is responsible for the provision of records and supporting documentation to RWM to demonstrate fulfilment of the requirements. RWM is responsible for the conduct of records process, including approval of package records, based on the documentation made available to RWM.

The package records process applies to the package records for waste packages already in store at the time of defining the process, or packages that continue to be produced under existing arrangements (existing packages), and for those waste packages to be produced subsequent to the implementation of processes that are fully compliant with RWM expectations (new packages).

For existing waste packages, some data and information may no longer be available. The records process therefore includes the option to recognise omissions, provided the absence of such data and information do not compromise the case for safe disposal. Recognised omissions should be recorded in the PRS and endorsement of the position traceable through the disposability assessment process, where the significance of the omission is evaluated.

Package records are assembled by the waste packager. For existing packages, the NDA has given waste packagers and RWM until the end of financial year 2020/21 to submit and receive approval for all records for these waste packages. For new packages, the NDA has stipulated that the records for these waste packages will be approved by RWM within 12 months of the packages entering interim storage (ie, storage prior to disposal at a GDF).

Approval of a batch of package records shall be subject to the satisfactory conclusion of a review of a suitable sample of those records and requires the following prerequisites:

- An LoC is in place, with no outstanding conditions, and an endorsed PRS is available.
- Confirmation that the data and information recorded during production of a waste package have been subject to verification by the waste packager and that the package records comply with the agreed process for producing them (RWM may audit the waste packager for confirmation).
- Confirmation that each waste package record includes a statement of compliance with relevant specifications (class B documents).
- Confirmation that the package records have been collated, in

> The principal aim of the RWM package records process is to ensure that package records will be sufficient to fulfil all relevant purposes throughout the lifecycle of the waste packages

preparation of their transfer to the NDA Archive, and are being stored in a manner appropriate to vital records. Fulfilment of these prerequisites ensures that the quality management system has been correctly implemented and is robust, and gives confidence that the sampled records are representative of the batch of packages. Without this, all records would have to be checked.

The sample size for review is governed by agreed processes (currently expected to be ISO 2859-1) and is intended to provide assurance to defined acceptance quality levels (within the standard). Where the number and extent of any nonconformities found in the sample are small and/or minor, the risk that appropriate data and information are not being preserved is low and therefore the records would be approved subject to all required corrective actions being implemented and demonstrated.

Where the number and extent of any non-conformities found in the sample are large and/or major, then the risk that appropriate data and information are not being preserved can be accepted only after the underlying causes of those nonconformities has been understood and rectified. It is expected that such records would be re-sampled through a subsequent records review in order to resolve the nonconformities.

Following approval the package records will be suitable for transfer to Nucleus for archiving.

Nucleus

Located near one the UK's earliest nuclear research sites, Dounreay in Scotland, the Nucleus archive will house both nuclear records from across the NDA estate and a collection of local Scottish records. Nuclear records will include many thousands of important plans, photographs, drawings and other records dating back to the late 19th century. The Caithness collection contains records dating back to the 16th century.

Waste package records will be included in the nuclear records and are defined by the NDA as the only records that are both permanent and vital to the nuclear industry. This requires the package records to be stored in three formats: paper, electronic and microform. All three formats can be accepted for preservation at Nucleus.

The archive has approximately 26km of shelving in a series of secure pods, placing limits on the amount of material for archive to ensure those archived are readily accessible, secure and can be managed in the manner required. Archive material will be catalogued, indexed and stored in a carefully controlled environment, with humidity and temperature kept stable to minimise the potential for deterioration. Documents will be transferred to archive-quality paper and digitised for improved accessibility and to avoid risk of damage to the original material.

It is hoped that Nucleus will be granted Place of Deposit status by The National Archive at Kew. Once achieved, it will become one of the largest accredited repositories outside of London. In so far as possible, this central repository will safeguard the waste package records until a GDF is constructed and while it is in operation.

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Acronyms

EPR16: Environmental Permitting (England and Wales) Regulations 2016
GDF: Geological disposal facility
LoC: Letter of compliance
NIA: Nuclear Installations Act 1965
NDA: Nuclear Decommissioning Authority
ONR: Office for Nuclear Regulation
RWM: Radioactive Waste Management
WAC: Waste acceptance criteria

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Characterisation of plutonium dioxide

Robin Taylor, Jeff Hobbs, **Robin Orr** and **Helen Steele** report on a new R&D facility for characterisation of the UK's plutonium dioxide, supporting safe storage of plutonium at Sellafield

Arising from more than 50 years of reprocessing of used nuclear fuels, the UK has the world's largest stockpile of separated civil plutonium [1]. This plutonium, estimated to reach 140 tonnes by the end of UK reprocessing operations [2], is held in safe and secure interim storage at the UK Sellafield site, primarily as dioxide powder (PuO_2) or (U,Pu) mixed oxides, prior to UK government decisions on its ultimate disposition [3]. Whether this disposition is to recycle the plutonium as new fuel for reactors or to immobilise and dispose of it in a waste repository [4], an extended period of interim storage is inevitable [1].

There is, therefore, a requirement to underpin the safety case for storage through technical assessments of both the storage environment and package integrity under storage conditions [5]. There would be further benefits to plutonium management if a predictive capability can be developed based on a more fundamental understanding of the chemistry occurring within plutonium packages. Of particular interest, to ensure that internal conditions remain within a safe and stable envelope over periods of several decades, are the potential mechanisms for gas generation and pressurisation [6]. Additionally, there are some 'out-of-specification' legacy materials that must be re-packaged to meet modern standards for long term storage. Some of these legacy materials may need additional treatment to re-stabilise them before packaging in new containers [7].

Current R&D needs

In the UK, plutonium arising from spent nuclear fuel reprocessing operations is stored as the stable oxide (PuO_2) in nested stainless steel containers with the outer can sealed by welding (see Figure 1). There are slight variations between plutonium packages arising from Sellafield's Magnox and Thorp reprocessing plants but as noted above, when storing PuO_2 in welded containers, one of the most important aspects of the storage safety case is avoiding conditions under which the packages may pressurise due to gas generation, as this is clearly a hazardous condition and incidents have occurred elsewhere [8, 9].

In practice, safety is achieved by controlling processing conditions during the production and packaging of the oxide, and this operational control has been very successful since welded cans were first introduced in the 1970s. However, with long storage timescales before eventual disposition, there may be 'ageing' effects due to the accumulated effects of radiation on the PuO_2 powders. Better understanding of the envelope of safe storage conditions potentially enables greater flexibility in conditioning and storage arrangements, including needs for reassurance monitoring [10].

Specifically, understanding processes that could lead to gas generation are highly relevant to safe storage [6]. These processes include:

- Radiolysis of water adsorbed on the PuO_2 surface to form hydrogen gas. Studies of water radiolysis have shown that the rate of hydrogen generation (conventionally described by a G-value that is defined as the number of molecules formed per 100 eV of energy absorbed) depends on the number of surface monolayers (ML) of water present. Figure 2 illustrates the relationship between $G(H_2)$ and $ML(H_2O)$, based on recent data obtained at the National Nuclear Laboratory (NNL), and it can also be seen that hydrogen generation on PuO_2 is very different to UO_2 (and most other metal oxides) where the water layers closest to the surface generate the highest yield of hydrogen [11]. However, while $G(H_2)$ for PuO_2 is low with <5 $ML(H_2O)$, it is not zero under the experimental conditions. Both practical experience and models show that, in sealed systems, hydrogen generation by radiolysis must, therefore, be in a steady state with either the reverse reaction reforming water or that there is a gradual transition of water to a form that is not radiolysed during storage. While the forward reaction is a radiation driven reaction, the reverse reaction(s) could take a number of forms including chemical recombination of molecular hydrogen and oxygen that is catalysed by the PuO_2 surface [12, 13], reaction of hydrogen with a surface oxygen species, or radiolytic recombination processes. Research is therefore needed to understand both forward and back reactions.

- Thermal desorption of physi-sorbed water from PuO_2 in a sealed vessel (see Box 1).

- The degree of helium release from the PuO_2 matrix. Helium

Figure 1: Multiple barrier containment PuO_2 storage cans. Clockwise from top right are containers for Thorp PuO_2, Magnox PuO_2 and a cutaway diagram of the assembled Magnox package

is inevitably formed from α-decay of plutonium isotopes but it is likely that a portion is held up in the PuO_2 matrix [14]. Quantification of the rate of helium release from PuO_2 to the can atmosphere would enable more accurate modelling of plutonium cans which could extend package lifetimes

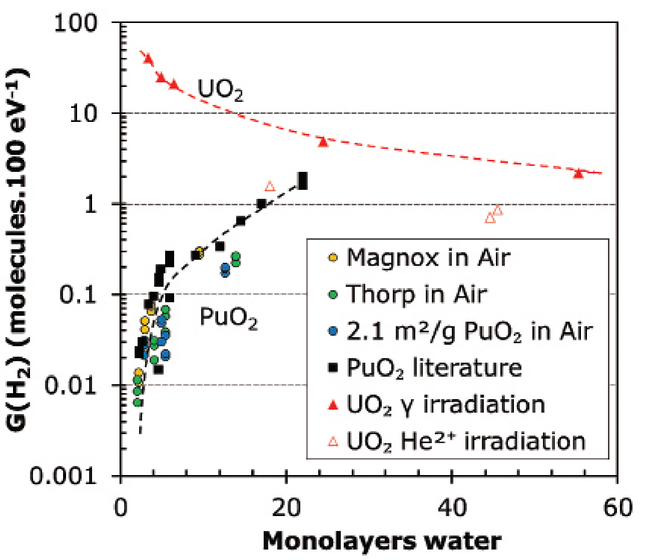


Figure 2: Experimentally measured hydrogen yields (represented by $G(H_2)$ values) from water adsorbed on PuO_2 (adapted from ref. [11]) compared to values reported for UO_2 in the literature

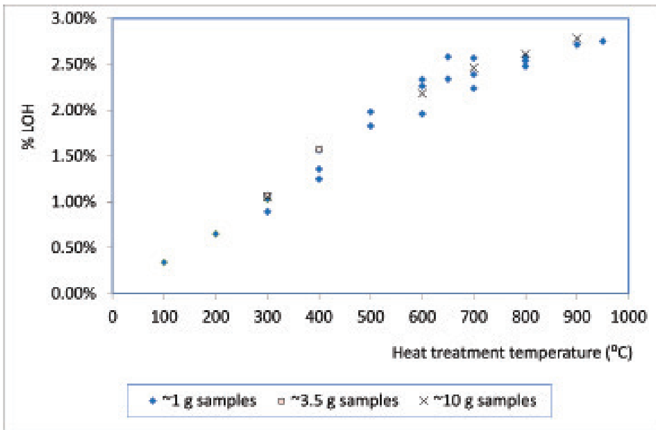


Figure 3: Percentage mass loss from chloride contaminated PuO_2 samples retrieved from a legacy plutonium package after heating in air for two hours at the set temperature (selected data at 3 different sample masses)

compared to current conservative assumptions that 100% of helium generated is released.

While the bulk of the PuO_2 stored at Sellafield is high purity oxide powder stored in welded cans, there are some 'out-of-specification' materials that must be dealt with as part of the UK's nuclear legacy clean up programme. Of particular significance is PuO_2 from reprocessing operations in the early 1970s that was packaged in non-welded nested metal cans [7]. These packages also contained an intermediate polyvinyl chloride (PVC) layer that has decomposed under the influences of heat and radiation generating hydrogen chloride gas.

This has led to contamination of PuO_2 powders in these packages with high levels of chlorine. Our recent analyses suggest that the extent of degradation and contamination is between 2000 and 8000 parts per million (ppm) chloride, although chloride levels over 10,000 ppmCl have been measured in some PuO_2 packages in the past [15]. As the packages are 'breathable', moisture contents are also relatively high since PuO_2 itself is hygroscopic [16] and there is an additional co-adsorption of water with surface chloride [17]. These historic materials must now be retrieved from storage and stabilised ready for repacking in welded cans for safe long-term storage.

While ideally the chloride would be totally removed, the key risks to long term storage can be mitigated simply by drying the powders to suitably low moisture contents. Figure 3 illustrates some selected results from a series of small scale heat treatment experiments conducted in NNL laboratories on a series of samples taken from a package of chloride contaminated PuO_2 retrieved from the Sellafield stores. Since it was manufactured in 1974, the PuO_2 in this package absorbed ~3 wt.% of volatile species, ie, water, carbon dioxide, nitrogen (as nitrogen oxides) and hydrogen chloride. It can be seen that the mass loss on heating in air is dependent on the heat treatment temperature and that temperatures above ~650 °C are effective at 'drying' the powder. There was no real difference when treating samples between 1 and 10g mass (approximately 0.3 to 3cm bed depth). However, while

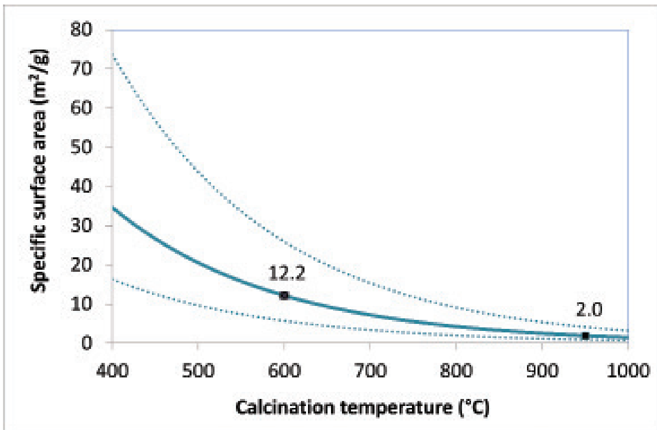


Figure 4: Correlation between specific surface area and calcination temperature for plutonium dioxide produced from plutonium (IV) oxalate showing 95% confidence limits (for the derivation of these curves see ref. [20]). SSA values for PuO_2 calcined at 600 °C (UK reprocessing) and 950 °C (US-DOE 3013 standard [19]) are marked

a heat treatment process is considered essential to dry these high chloride powders, the distribution of chloride between the residual solid and off gas streams also needs to be known to support design and engineering of the 're-treatment plant' and to inform future disposition options [18]. This requires an understanding of the speciation of chloride on the PuO_2 surface.

The international perspective

The UK is not alone in needing to manage separated plutonium stocks and so understand the chemistry occurring within sealed packages of PuO_2. The US, in particular, has a long running programme to stabilise historic stocks of separated plutonium for long-term storage in nested, welded cans—their packaging requirements are detailed in the US-DOE 3013 standard [19].

There are some key differences, however, with the UK programme including stabilisation by heating at 950 °C compared with UK PuO_2 which is generally produced at ~600 °C to ensure suitable properties for subsequent fuel fabrication. Higher calcination temperatures lead to lower specific surface areas and, therefore, less adsorption of gases and moisture [6]. The relationship between surface area and calcination temperature has recently been re-assessed [20] and is illustrated in Figure 4, where the best fit to the data together with the 95 % confidence intervals are shown.

It can be seen from the figure that the predicted surface area falls from 12.2 m^2/g at 600 °C to 2.0 m^2/g at 950 °C (although at lower calcination temperatures there can be a wide range in surface areas obtained in practice). Also, due to differences in plutonium isotopics, US materials tend to be lower power than UK civil PuO_2 (therefore, they are cooler due to less self-heating from radioactive decay) and some contain alkali metal salts from pyro-processing operations mixed with the PuO_2 [21].

For many years now, the US-DOE has sponsored long-term R&D studies on behaviour of PuO_2 under storage conditions, much of which has been published in the open literature (for instance, see [22. 23]) and these data have been extensively used by NNL and Sellafield to support the development of computer-based process models that describe the behaviour of water and generation of gases within a plutonium can in order to demonstrate compliance with the storage safety case [5]. As well as basic research, the US programme has run 'shelf life' or 'materials surveillance' studies in which representative packages have been monitored for gas generation over long periods [22, 24].

Although the US programme is most closely related to the UK situation, basic studies of water radiolysis, helium generation and plutonium dioxide chemistry have been published by other international nuclear research centres, for example, [25-28]. All of these studies indicate there is a complex mix of physical processes and chemical and radiation driven reactions occurring at the PuO_2 surface and in the gas phase above the PuO_2 that make predictions on long term behaviour based on fundamental chemistry difficult, thus far necessitating a reliance on empirical observations with suitably conservative assumptions. Nevertheless, the overwhelming operational experience is that PuO_2 produced and packaged under normal plant conditions is stable.

New facilities for UK plutonium R&D

A common theme cross-cutting current and future plutonium R&D programmes is the need for characterisation of the PuO_2 powders [10]. Unsurprisingly, given the highly radioactive nature of plutonium and need for specialised facilities on nuclear licensed sites, little information exists in the published literature regarding the effects of ageing on the chemical and physical properties of PuO_2. With the exception of mixed oxide (MOX) fuels development, there was a hiatus in civil UK plutonium R&D in the first decade of the 21st century with old R&D facilities at Sellafield for opening and examining plutonium cans decommissioned. For these reasons, over the last few years the NNL and Sellafield have collaborated on the installation and commissioning of new facilities for plutonium

Figure 5: A glove box operator opens a plutonium can in the PCP facility

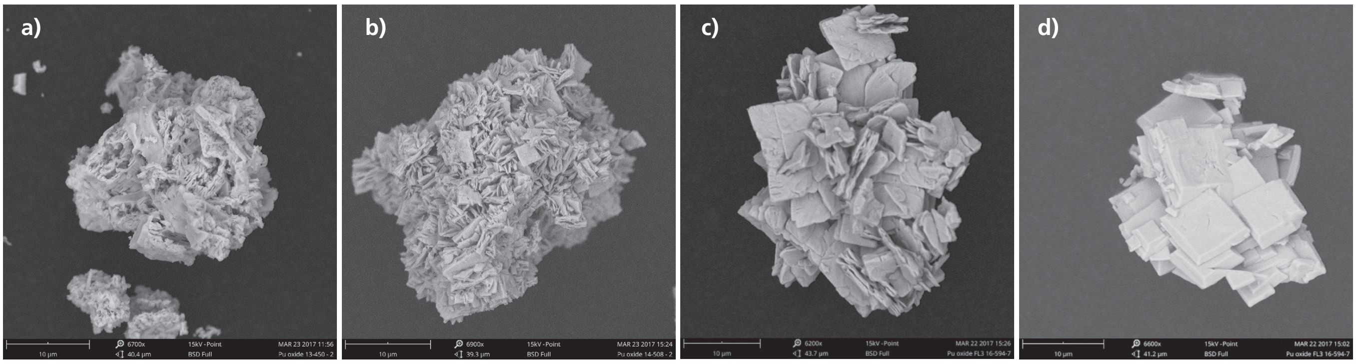


Figure 6: Example SEM images of (a) high surface area PuO_2 produced from decomposition of plutonium oxalate; (b) low surface area PuO_2 re-calcined from Magnox PuO_2; and (c)-(d) images from a sample of legacy Magnox PuO_2 produced in 1974 and contaminated with chloride from PVC degradation

R&D at NNL's Central Laboratory complex, co-located on the Sellafield site.

Firstly, the Plutonium and Minor Actinides (*PuMA*) Laboratory is a flexible R&D capability that concentrates on plutonium experiments in the multi-gram scale, both 'dry' (powder and pyrochemical separations) and 'wet' (dissolution, hydrometallurgical separations and analysis). It has the useful capacity for plutonium experiments in radiochemical glove boxes under air, nitrogen or argon atmospheres. Both the Central Laboratory and NNL's PuMA Lab capabilities have been described in detail in previous articles for *Nuclear Future* [29, 30].

Within the *PuMA* Lab, two glove boxes have been equipped with furnaces for calcining PuO_2 in either air or inert (nitrogen or argon) atmospheres. These furnaces have been extensively used to develop a thermal treatment process for the chloride contaminated PuO_2 and also to do standard loss-on-heating (LOH) analyses for PuO_2 samples (the mass change after heating at 950 °C is used as an upper limit for volatile content). We have

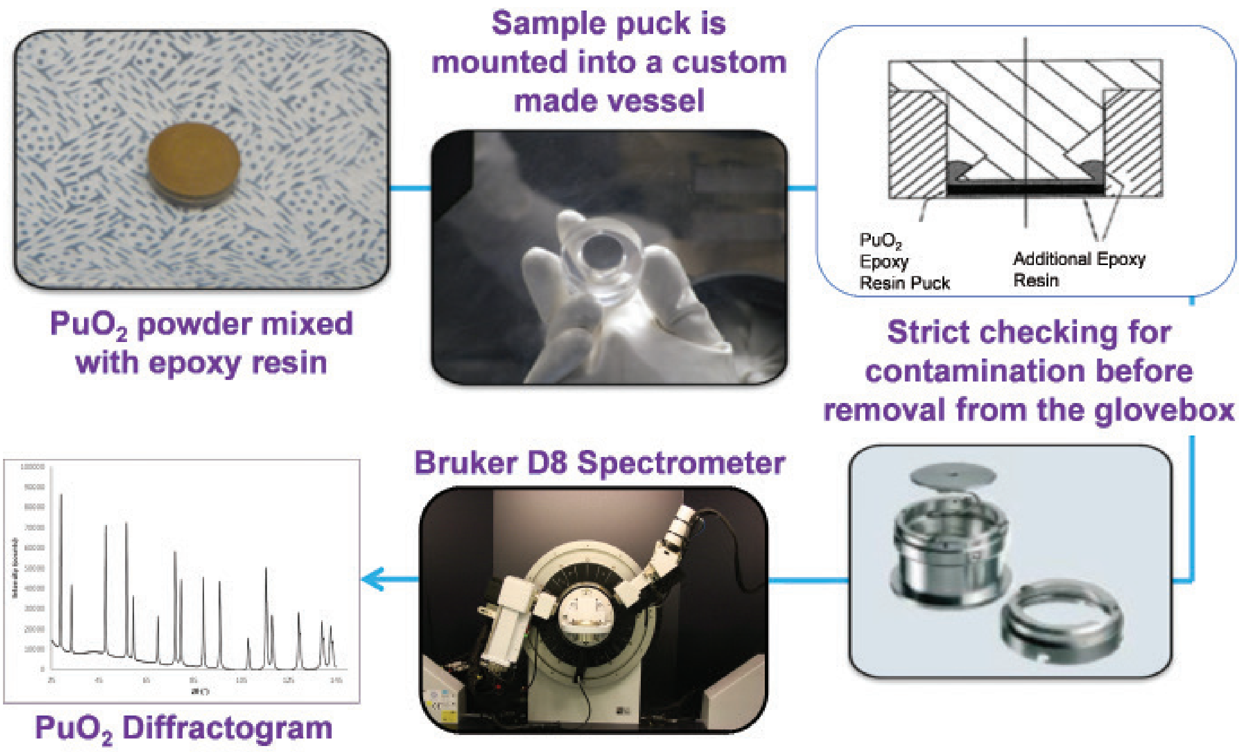


Figure 7: Scheme showing the analysis of PuO_2 by powder XRD

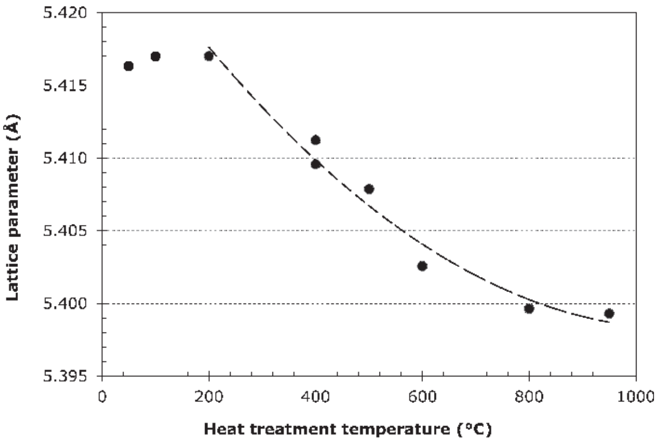


Figure 8: Variation of lattice parameters measured by XRD from an aged PuO_2 sample after heat treatments

also installed a bespoke designed stainless steel reaction vessel to record pressure-temperature (P-T) curves as PuO_2 is heated in the presence of water up to ~250 °C (see Box 1) and vibrational spectroscopy for surface characterisation (infrared and Raman). Raman spectroscopy has proved to be a particularly interesting characterisation tool with changes in spectra attributed to defect formation as PuO_2 ages [31].

Secondly, in a major phase of facility development, NNL has actively commissioned a new area within the Central Laboratory, the High Alpha Labs Facility, to support the Sellafield plutonium storage mission [32]. This facility came on-line in 2016 and has been ramping up to full operational capabilities through 2017-18. The focal point of this area is the plutonium can processing (PCP) facility in which plutonium cans imported from the Sellafield site stores can be punctured and head space gases sampled and sent for analysis by gas chromatography (GC). This gives us the capability to evaluate the atmosphere that has evolved inside plutonium cans during storage thus validating predictive models and increasing confidence in long term storage.

The first package punctured in the facility under this 'can surveillance' programme was a 15-year-old Magnox type that initially contained a mixture of argon and air. The measured gas composition is given in Table 1 and of note is the absence of both hydrogen and oxygen at detectable levels, illustrating the normal production condition leads to non-flammable atmospheres within packages. During storage, the pressure within the package initially decreased because radiolysis leads to nitrogen oxides forming that adsorb on the oxide surface and reduce the oxygen content of the atmosphere [33]. Over the longer term, helium from alpha decay is released to the gas atmosphere, raising pressure.

After puncturing, there is a can cutter to open cans so that the powder can be sampled and dispensed for further characterisation or experimental programmes (Figure 5). Can materials can be retained for size reduction for metallographic analysis elsewhere. The PCP glove box line also contains an integrated batch furnace capable of heating full can contents up to 1000 °C. This is necessary to ensure the PuO_2 is dry enough to meet the conditions for acceptance (CFA) for exporting the materials back to the Sellafield stores. The PuO_2 can then be repackaged in an inner can, intermediate polythene bag and outer welded can ready for export out of the NNL facility.

The High Alpha Labs facility also contains a range of key analytical methods for characterisation of plutonium and MOX powder samples. The installed equipment includes:

- A scanning electron microscope (SEM) with an energy dispersive X-ray (EDX) analyser: The SEM-EDX is a bench top instrument wholly contained within the glove box. Examples of SEM images taken of PuO_2 are shown in Figure 6. The images show PuO_2 (a) calcined from plutonium (IV) oxalate in the laboratory at a low temperature (350-450 °C in air) to give a high surface area powder (~40 m^2/g); (b) Magnox PuO_2 re-calcined in the laboratory at 950 °C in air to give a low surface area powder (~3 m^2/g); and (c) and (d) different morphologies found in a sample of legacy high chloride PuO_2 retrieved from storage that was originally manufactured in 1974. These samples can be compared to previously published images of Thorp and Magnox PuO_2 [20] and it can be seen that, despite all the powders being produced from thermal decomposition of plutonium (IV) oxalate, there are clear differences in morphologies reflecting different conditions during oxalate precipitation, calcination, thermal treatments and probably ageing in the storage environment.
- A thermobalance for thermogravimetric analysis (TGA) under various atmospheres (N_2; Ar; air; 2.5% H_2/Ar mix; CO_2; humidity): the thermobalance will primarily be used for studies of gas adsorption-desorption onto PuO_2; thermal decomposition of plutonium compounds; LOH analysis; and determining metal/oxygen ratios of mixed oxides.
- Powder X-ray diffraction (XRD): Plutonium and MOX samples are mixed with an epoxy resin and the puck formed is held within a bespoke sample holder. After rigorous decontamination, following approved procedures, these samples can be moved to the XRD instrument that is situated in one of the laboratories. Figure 7 illustrates various stages of the XRD analysis and an example PuO_2 diffraction pattern. Current work is investigating the influence of sample age and annealing/storage temperature on the lattice parameter due to radiation induced defects. Figure 8 illustrates the variations in lattice parameters we have measured from aged PuO_2 heat-treated at different temperatures.
- Brunauer-Emmett-Teller (BET) specific surface area (SSA) analyser: Specific surface area is a key measurement for ensuring PuO_2 powders in storage meet acceptable levels for water content and also remain suitable for future fuel manufacturing if that is selected as the eventual disposition route. SSA is an important physical property for powder characterisation and the method is currently undergoing a series of validation exercises prior to routine use on PuO_2 powders.

Figure 9: The ceramography glove box line in NNL's High Alpha Labs facility

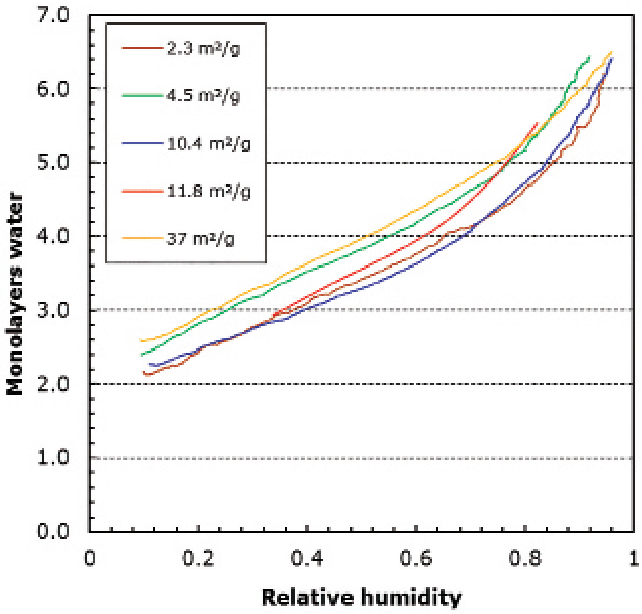
There are also ceramography and metallography glove boxes for preparing ceramic and metal samples for optical microscopy and SEM; a glove box with tooling for opening non-standard plutonium packages and a second batch furnace for heat treating so-called residues, ie, plutonium containing materials that are not classed as high purity reprocessing plant products. The ceramography process line is illustrated in Figure 9. Future installations to support the ultimate disposition of UK plutonium, such as a MOX fuel line for preparing test pellets and a hot isostatic press (HIP) for immobilisation in a ceramic matrix [4], are also under consideration.

In summary, the High Alpha Labs Facility represents a step change in UK capability to underpin the long term safe storage and ultimate disposition of the UK plutonium stockpile. It is a world class R&D facility for characterisation of plutonium materials and packages, fully compliant with all modern safety and security standards, and, while the current focus is on ramping up to full operational capability, even at this early stage it is delivering some unique data on UK plutonium.

Opportunities for collaboration

While the situation and materials in the UK are rather unique, it was discussed earlier how other countries, such as the USA and France, either have similar issues or common interests in understanding the basic chemistry of PuO_2. We have, therefore, where appropriate, engaged in information exchanges. Those with US national laboratories are facilitated by an agreement between the Nuclear Decommissioning Authority (NDA) and US Department of Energy (US-DOE) Environmental Management Office. Also, international conferences such as the Plutonium Futures series provide excellent opportunities for sharing progress. The 2012 conference was held for the first time in the UK at the University

Figure 10: Baskerville Reactor (top left) used for pressure-temperature measurements of PuO_2 water adsorption-desorption experiments and the associated glove box furnace for heating the reactor (top right). Also shown are examples of the measured variation of water sorption with relative humidity for a range of specific surface areas (bottom)



of Cambridge, co-hosted by NNL, the UK's Atomic Weapons Establishment (AWE), the French Atomic Energy Commission (CEA) and the EU's Joint Research Centre (JRC), which is based in Karlsruhe, Germany. Papers from the conference were reported in the Actinide Research Quarterly journal published by Los Alamos National Laboratory [34].

Since 2012, follow-on conferences have been held in Las Vegas (2014) and Karlsruhe (2016), and the next meeting is scheduled for September 2018 in San Diego.

Nationally, UK universities are being supported by NNL, Sellafield and the NDA to develop new research interests and build expertise related to plutonium storage and disposition. The most notable example is through the *DISTINCTIVE* project (http://distinctiveconsortium.org/)—an academia-industry collaboration funded by the EPSRC (Engineering and Physical Sciences Research Council) and led by the University of Leeds—that was set up to provide academic research and innovation into key challenges across the UK's nuclear clean up and decommissioning programme.

One of the four major themes in *DISTINCTIVE* is PuO_2 and fuel residues. This covers behaviour in interim storage, novel measurement methods and immobilisation in wasteforms by research teams at the universities of Lancaster, Manchester, Birmingham and Sheffield.

Some highlights from the *DISTINCTIVE* research on plutonium storage chemistry include the use of quantum modelling to probe the different layers of water that adsorb to the PuO_2 surface [35] and the development of a quartz crystal microbalance for gravimetric measurements of water adsorption onto actinide oxide surfaces [36]. Both of these approaches complement the P-T measurements made at NNL (described in Box 1), providing a more fundamental understanding of the interactions between water and the PuO_2 surface.

Other highlights have been the opportunities for university researchers at both PhD and post-doctoral levels to get 'hands-on' experience working with plutonium oxide powders in the PuMA Lab and have their samples analysed by the new equipment available in the High Alpha Labs.

Conclusions

Sellafield has a mission to ensure the safe and secure storage of the UK's civil plutonium inventory until a disposition programme is eventually implemented. There is consequently a recognised need for research on the behaviour of plutonium during long-term storage, particularly the mechanisms that can lead to generation of gases within the containers and the effects of ageing on the powder properties.

To support this objective, there has been substantial investment in new R&D facilities for characterisation of plutonium-containing oxide powders and ceramic pellets. As a consequence, the new High Alpha Labs facility has recently been commissioned with the capability to receive PuO_2 packages from Sellafield and perform the full suite of surveillance needs from analysis of head space gases extracted from the can to can materials inspections and powder characterisation.

The Can Surveillance programme adds to existing plutonium R&D programmes that are exploring the underlying science of gas generation and developing the basis for stabilisation of legacy PuO_2 that is highly contaminated with chloride species

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adsorbed onto the oxide surface. In parallel, growing academic expertise and research programmes are providing complementary approaches, developing innovative techniques and probing the fundamental chemistry.

In the longer term, these capabilities will also enable us to experimentally underpin the technical basis behind other future industrial scale plutonium operations in the UK, whether that is recycling plutonium as new fuel or disposal after immobilisation in a ceramic wasteform.

As a final note, these R&D facilities and projects are enabling the rejuvenation of key skills—from UK subject matter experts in plutonium science to 'hands-on' glove box operators—as well as training the next generation both in industry and at universities.

Box 1: Water adsorption and desorption on PuO_2

Small quantities of water and other atmospheric gases, typically <0.5 wt.%, are unavoidably adsorbed on to hygroscopic PuO_2 during the production and packaging processes in the reprocessing plants. As PuO_2 is self-heating due to radioactive decay, when stored in cans this water can desorb and raise steam pressure in the welded can.

Also, as there is a temperature gradient across a PuO_2 can, water may migrate to the cooler regions. If condensation then occurs in cooler parts of the can it would increase the risk of water radiolysis generating hydrogen gas. Plant operating envelopes can be defined based on models of water desorption adapted from literature data under vacuum [16, 37] and in a sealed container [38].

However, there remains a significant opportunity to reduce some of the conservative assumptions made in these models. Therefore, a series of experiments has recently been completed, similar in style to those made at Los Alamos National Laboratory in the US, in which PuO_2 is heated to ~230°C in a sealed isothermal container (a customised design labelled the Baskerville Reactor) in the presence of known masses of water and the resulting pressure change measured with a heat tolerant pressure transducer (see images in Figure 10).

The P-T relationship during cooling is used for data analysis as the heating cycle is too rapid to establish pseudo-isothermal conditions inside the vessel. Comparing pressure differences between the experiment and the pressure expected from the known total amount of water in the vessel enables calculation of the amount of water residing on the PuO_2 surface. Provided the specific surface area of the PuO_2 is known, the mass of adsorbed water can be converted to the equivalent number of water ML on the PuO_2 surface and plotted against the relative humidity (RH) in the vessel during each experimental run. Example data are illustrated in Figure 10.

An important finding has been that there are only small deviations between curves obtained for a range of UK PuO_2 products. Materials studied included PuO_2 from both Thorp and Magnox reprocessing plants and PuO_2 with varying physical properties, for example, surface area, carbon content, age.

One sample was temperature cycled in the vessel five times over consecutive days to probe the reversibility of the adsorption-desorption process and longer runs with hold points in the cooling curve have also been made to check for any kinetic effects (only minor).

The broad agreement obtained across these different experimental campaigns provides confidence that the data generated by our methods accurately describe the physi-sorbed water layers on UK PuO_2.

While these data fit established theory (BET adsorption) at RH < 60 %, there are deviations from both theory and the results reported by Los Alamos on US PuO_2 [38] at high RH, with less water adsorbed in our experiments than would be predicted. However, our data agree rather well with a wide range of data compiled from the published literature for other meso-porous metal oxides [39].

The deviation from the behaviour reported by Los Alamos (and BET theory) at high RH may be due to differences in the morphology of the PuO_2 used (Los Alamos researchers used weapons grade plutonium dioxide from Hanford, with a surface area of 0.8m2/g ,whereas we used civil grade, oxalate-derived PuO_2 with surface area from 3–40m2/g).

A final point is that extrapolations of the curves towards 0% RH provides an indication of the number of chemi-sorbed H_2O layers, which is found to be around 2ML. This is higher than expected because the first layer of water is thought to chemi-sorb by association with the plutonium sites at the surface forming hydroxyl groups but the bonding mode for a second strongly bound layer is not well understood.

However, other researchers have also suggested multiple layers of strongly bound water can exist on PuO_2 [16, 37].

The amount of strongly bound water that forms is important because it behaves differently under alpha radiolysis. For now, the relationship between weakly bound (physi-sorbed) and strongly bound (chemi-sorbed) water remains an open question and new approaches to probing the nature of the chemi-sorbed water on the PuO_2 are needed.

One promising method is quantum modelling of the PuO_2 surface and how it interacts with water molecules [35]. Such fundamental studies are being made as part of an academia-industry collaboration funded by the Engineering and Physical Sciences Research Council: the DISTINCTIVE programme in which one of the four key themes is PuO_2 and Fuel Residues.

Species	Concentration
Helium	27 %
Nitrogen	56 %
Argon	17 %
Nitrous oxide	246 ppm

Table 1: Results from gas chromatographic analysis of the first can punctured in the High Alpha Labs

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Acronyms

AWE: UK's Atomic Weapons Establishment
BET: Brunauer-Emmett-Teller
CEA: French Atomic Energy Commission
CFA: Conditions for acceptance
EDX: Energy dispersive X-ray
GC: Gas chromatography
HIP: Hot isostatic press
JRC: EU's Joint Research Centre (JRC)
LOH: Loss-on-heating
NDA: Nuclear Decommissioning Authority
NNL: National Nuclear Laboratory
PCP: Plutonium can processing
P-T: Pressure-temperature
PuMA Lab: Plutonium and Minor Actinides Laboratory
RH: Relative humidity
SEM: Scanning electron microscope (SEM)
SSA: Specific surface area
TGA: Thermogravimetric analysis
US-DOE: US Department of Energy
XRD: X-ray diffraction

Dr Jeff Hobbs is a technical manager in the PuO_2 production and storage area at Sellafield. He has worked on the Sellafield site for the last 24 years, initially in R&D, then technical plant support within Magnox reprocessing. For the last 10 years he has been working in the PuO_2 storage area coordinating R&D work programmes to underpin long term storage.

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Designed potential

The authors discuss the conceptual design of an unshielded intermediate level waste handling facility

The UK has accumulated a legacy of radioactive waste and continues to produce radioactive wastes from various industries and programmes. UK government policy for management of this waste is safe and secure interim storage, followed by geological disposal, as set out in the 2014 Implementing Geological Disposal White Paper [1]. Radioactive Waste Management (RWM), a wholly owned subsidiary of the Nuclear Decommissioning Authority (NDA), is responsible for delivering a geological disposal facility (GDF) and managing the UK's higher activity radioactive waste inventory.

Waste disposal units (DUs) containing unshielded intermediate level waste (UILW) are currently planned to be transported to a GDF and transferred underground in standard waste transport containers (SWTC). Waste DUs would be removed from SWTCs in part of a GDF called an 'inlet cell. The inlet cell, a key part of the GDF, is assumed by RWM to be located underground and would be a shielded facility which would allow the remote unpacking and handling of waste DUs* from SWTCs. From the inlet cell, the waste DUs would then be transferred to disposal areas for emplacement.

During 2016, RWM prepared an updated generic design for the GDF [2]. The design was bounded to a range of geological environments (higher strength rock, lower strength sedimentary rock and evaporite rock) suitable for UILW disposal in the UK.

The generic GDF inlet cell design has a planned receipt capacity (2,500 SWTCs per annum), which will remain for the UILW emplacement period of the GDF programme. The throughput for some periods will be modified to match the SWTC receipt rate by changing the operational shift pattern, for example, going from three-shift (24 hour) working pattern to two-shift operations. The GDF generic design waste receipt schedule has a planned capacity of 2,300 SWTCs per annum for approximately 24 years, followed by 1,500 per year for about 44 years.

The generic design was classified by RWM using the NDA's Technology Readiness Level (TRL) methodology. This methodology comprises three components:

- Technology: Refers to a technological process, method, or technique such as machinery, equipment or software needed for the plant, facility or process to achieve its purpose.
- Readiness; Refers to time. Specifically it means ready for operations at the present time.
- Level: Refers to the level of maturity of equipment. Equipment that is already being used for the same function in the same environment has a higher level of maturity than equipment that is still being developed. The levels are a nine-point scale based on a qualitative assessment of maturity.

The generic design [2] was estimated to have a TRL of two, at the 'invention and research' stage. The aim of this phase of the design development work was to enhance this TRL to three, 'proof of concept' or 'demonstration, in principle, with the potential to work'. This would provide confidence that an inlet cell could be constructed, operated to meet the throughput target for UILW waste packages and be decommissioned in the range of geological environments suitable for hosting a GDF in the UK.

This paper describes the techniques that supported the development of a conceptual design for the UK (GDF) UILW inlet cell. The approach to the design utilised existing proven

Category	Objective
1 - Throughput	To meet the necessary UILW DUs receipt rate of 2,500 per year.
	To identify the optimum realistic throughput rate.
2 - Availability, reliability and maintainability (ARM)	To maximise inlet cell availability, reliability and maintainability.
	Availability to process 2,500 DUs per year.
3 - Safety	To demonstrate that SWTCs can be safely unloaded and processed in an underground environment.
	To ensure the doses and potential risks from the inlet cell operations are as low as reasonably practicable (ALARP).
4 - Technical feasibility	To enhance the TRL for an inlet cell from 2 to 3.

Table 1: Summary of objectives

*A 'disposal unit' or 'DU' is a waste package or group of waste packages that can be handled, stacked and transported together as a single unit for disposal purposes. For example, a UILW DU could consist of one 3 metre cubic box, one 3 metre cubic drum, or four 500 litre drum waste packages contained within a steel stillage. A 'stillage' is a metal frame designed to hold four 500 litre drum waste packages so that they can be handled, stacked and transported as a single DU.

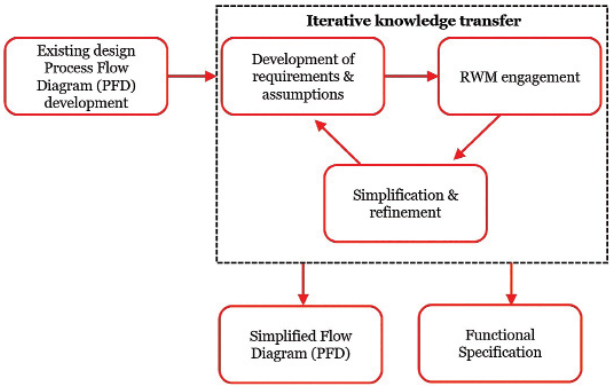

Figure 1: Iterative knowledge transfer used in the development of both the functional specification and the process flow diagram

engineering, knowledge sharing and systems engineering all fully integrated with building information modelling (BIM) technology. A summary of the objectives is shown in Table 1.

Initial review and simplification

An initial process flow diagram (PFD) was produced, which baselined the sequential steps of the generic design process: importing the SWTC (and DU) into the inlet cell, removing the DU from the SWTC, sentencing the DU to the disposal areas for emplacement and finally exporting the SWTC for reuse. The team used the PFD as a basis for knowledge sharing of best practice, legislative and guidance requirements and design/operations experience to propose some initial simplifications.

The proposed simplifications included:

- Relocating the off-gas pressure equalisation of the SWTC to the surface and incorporating off-gas monitoring. This gave the benefit of registering any significantly different radiation readings from SWTCs prior to the SWTCs being sentenced underground. This provides a means of identifying any potential defects while the SWTCs are at surface level, avoiding potential contamination while underground and on the return to the surface.
- By placing the emphasis on best practice, legislation and guidance, which had underpinned the design of existing UK facilities the team were able to simplify the generic design by removing 14 individual functional process steps.

These initial proposals reduced the complexity of the inlet cell by reducing the number of process stages required.

Systems engineering and optioneering

A systems engineering approach was then applied to produce a functional specification [3] for the inlet cell, which consisted of a hierarchy of fully integrated set of functional, safety, throughput and maintenance requirements.

The functional specification comprises two hierarchical levels of requirements at increasing levels of detail. The first level covers 'user requirements (where the 'user' is deemed to be the operator of the inlet cell) level. The second level includes 'system requirements, which are structured by functionality and interfaces. The third level of associated sub-system requirements will not be derived until during a subsequent detailed design phase.

The functional specification provided a constant reference baseline to ensure the options derived during the optioneering study and subsequent design development remained completely aligned to the overall project aims and objectives. This proved to be a significant advantage, providing the design team with a point of focus throughout the design process and a basis for simplification and refinement, as illustrated in Figure 1.

The next phase of the design requirements was the selection of the most appropriate design options the selection of the most appropriate design options using the simplified PFD and functional specification as a basis. This phase of the design was supported by extensive knowledge sharing.

The design team was fortunate to have a considerable amount of design and operations experience from the Sellafield encapsulation suite of facilities. In addition to this, Sellafield, shared their experience of automated and manual unbolting equipment, and further, generously supported the design by providing the team with an opportunity to visit the Magnox encapsulation facility and associated product stores. This gave the team a fascinating insight into the operation of a facility, which in principle was very similar to what the GDF inlet could look like in reality. Street Crane Express of Sheffield also offered guidance on various mechanical lifting options and associated costings. The

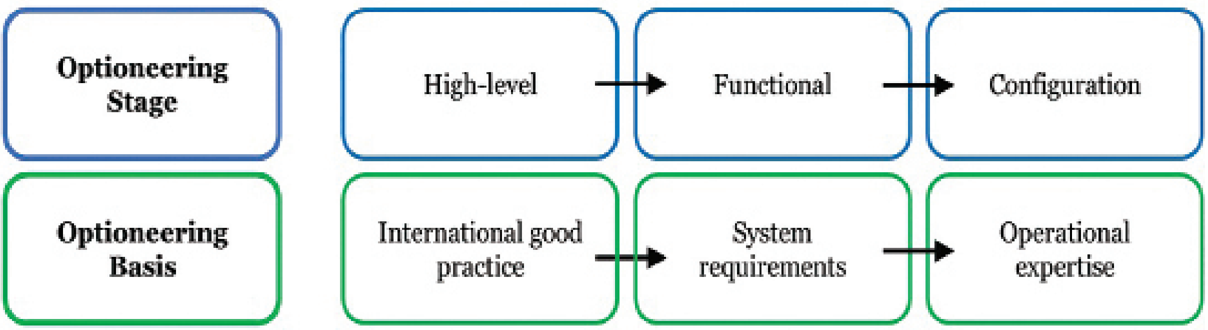

Figure 2: Optioneering stages and associated basis

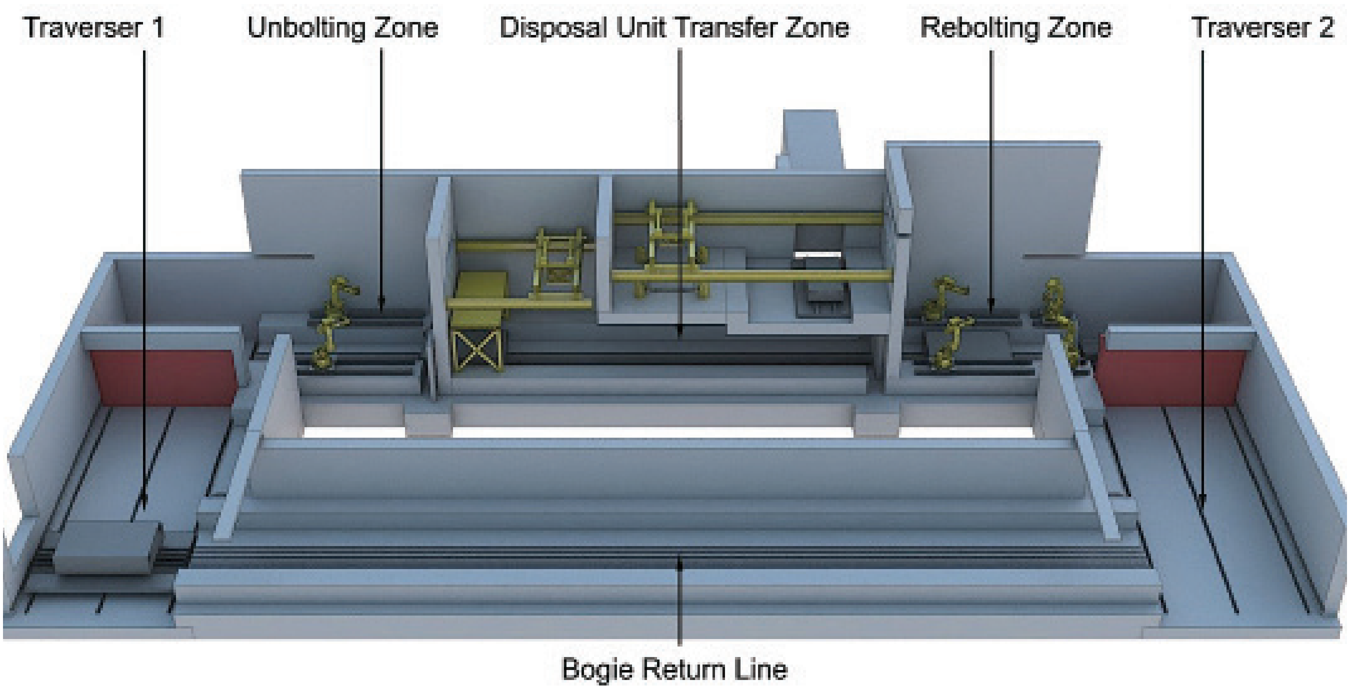

Figure 3: The UILW inlet cell facility design developed in during this design phase

optioneering study was conducted over three distinct stages; 'high-level', 'functional' and 'configuration', as illustrated in Figure 2.

High-level optioneering considered both above and below ground options, based on international good practice. This included examination of the Swiss (Nagra) Conceptual Facility Design for receipt and transfer of UILW as a surface-located alternative example. At the functional-stage options were considered against the system requirements. An example of the functional optioneering included considering how the SWTC would be transported through the process steps. The options included an endless chain drive, a conveyor system and a bogie. The configuration stage, supported by operational experience and the visit to Sellafield considered two top-level options:

- The SWTC entering and exiting the inlet cell from the same location.
- The SWTC, utilising a production line principle would enter the inlet cell from one location, pass through a series of process steps and be returned to the start location via an independent route.

Design Development

The option chosen to be carried forward was based on a series of processing steps at different locations, using the production line principle. A simple configuration for achieving a production line facility was developed. This consisted of tunnels connecting orthogonally which achieved the return of the bogies to a location where the SWTCs could be loaded and off-loaded and reduced the cycle time of an SWTC as it travelled through the facility. This is illustrated in Figure 3.

The operational sequence of the inlet cell facility is as follows. The SWTC is posted into the facility in the bottom left hand corner utilising an 80Te Electric Overhead Travelling Crane (EOTC). The SWTC is placed on a waiting bogie, which in turn is located on one of two traversers. The SWTC is transported from the start point through the roller shutter door to the start of the processing tunnel by one of the traversers. On reaching the start of the processing tunnel the bogie is driven off traverser number 1 to the unbolting zone.

The SWTC is unbolted in the unbolting zone and driven through a shield door into the disposal unit transfer zone where the lid is removed by a 12Te EOTC fitted with a dedicated grapple. The lid is placed on a seismically qualified steel stand. The SWTC is then moved forward to a dedicated location where a second 12Te package removal crane, fitted with a dedicated grapple engages with the disposal unit. The disposal unit is raised to the upper level of the disposal unit transfer zone and placed on a bogie for transport to final disposal. The SWTC lid is replaced and the SWTC is driven through a second set of shield doors to the rebolting zone. On completion of the rebolting the SWTC is then remotely monitored and, once cleared driven onto a second traverser to start of the return tunnel. On reaching the return tunnel the SWTC disembarks the second traverser and returns to the start point via the return tunnel (refer to Figure 4). On reaching the start point the SWTC is removed from the Inlet Cell and returned to the surface.

There were two means chosen to move the SWTC within the facility, a bogie and traversers. The primary engineering

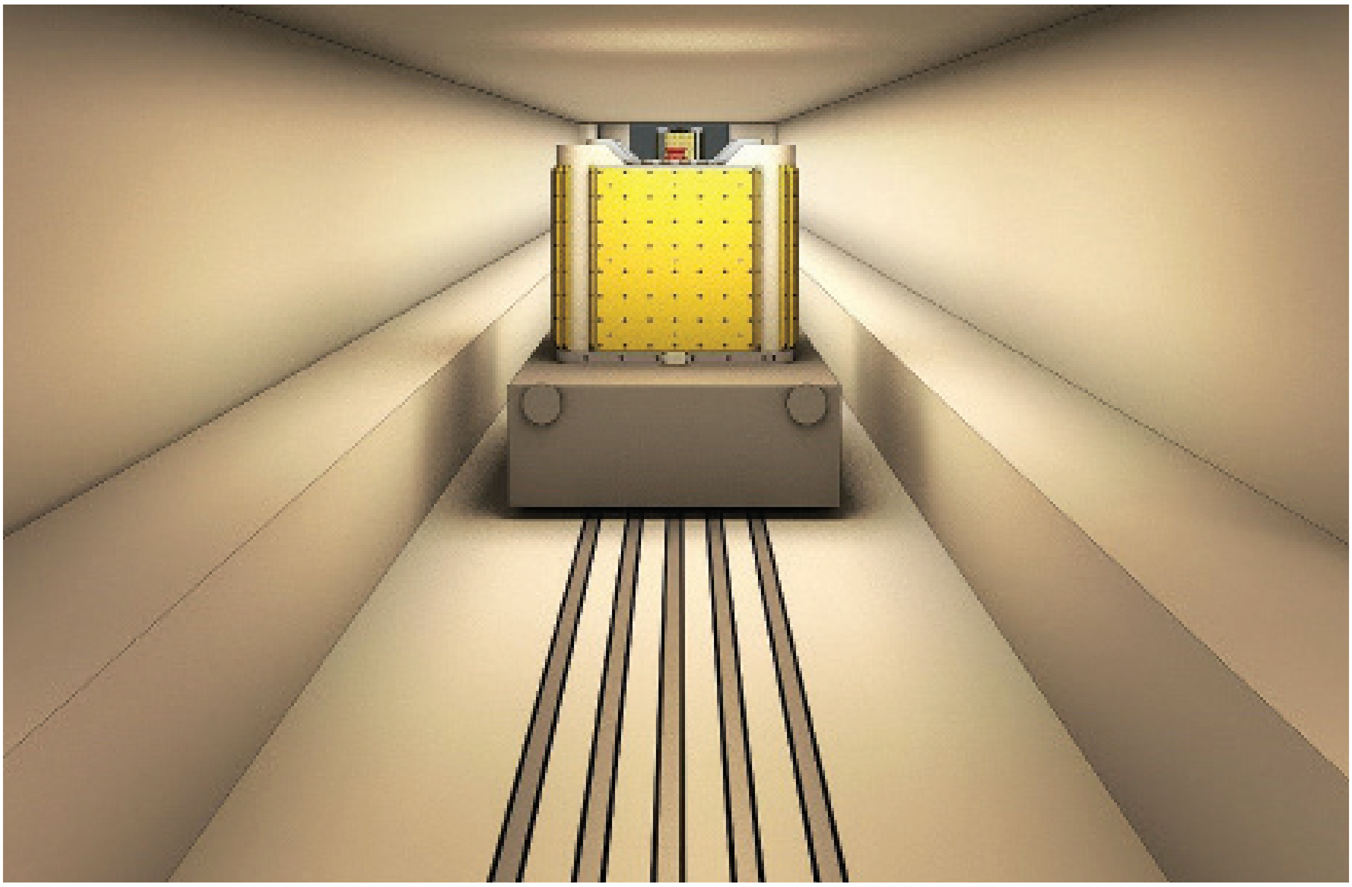

Figure 4: Bogie and SWTC in the return tunnel

consideration for the bogie was the bogie length to rail wear/ wheel stress. The team was able to overcome this challenge by utilising a three-axle design, which with subsequent modification to the suspension, ensured the load was equally distributed across all the three axles. By optimising the length, this supported the throughput as the structural size of the cell, and subsequently the distance between processing stages, could be reduced.

The traversers proved a simple means of accommodating the orthogonal interfaces of the proposed configuration. A traverser is shown in Figure 3 at the start point (bottom left hand corner) with a bogie ready to receive collection of a SWTC.

The traversers consist of a wide platform bogie, with the bogie and SWTC load distributed across a number of rails and axles. Busbars have been chosen as a means of distributing power to the transporters. The busbar distribution integrates well with the third, fourth and fifth power rail power philosophy and enables on-board control devices to be utilised reducing the amount of electrical cabling and necessary penetrations into the inlet cell.

The integrated use of a bogie and traversers underpinned what may be regarded as a relatively novel step for nuclear design. The design team proposed an operating philosophy utilising multiple bogies (a total of four) in operation simultaneously under PLC control. Since there no operators, under normal operations would be permitted into the inlet cell this enabled an optimum solution to powering the bogies though the zones and in the return tunnel. The chosen solution consisted of a third, fourth and fifth set of electrical power rails.

Kuka Systems provided robotic equipment expertise in support of the remote bolting and rebolting of the SWTC lid. The solution is based on proven technology, meets the system requirements and was dimensionally integrated into the inlet cell design (refer to Figure 5).

The structure of the UILW inlet cell facility fully incorporates the shielding requirements as specified by RWM. However, the design only utilises the required shielding thickness in the area where the DU is exposed within the process. The rest of the facility civil structural design complies with UK and ISO standards to ensure the necessary strength and structural stability.

Designing for effective maintenance is a critical part of modern design. The UILW inlet cell facility has dedicated, shielded crane maintenance areas. In support of this there are dedicated maintenance cranes along with designed transfer routes and equipment for the export and import of crane components. The design incorporates an outline breakdown recovery strategy implemented from outside of the cell, enabling the package to be safely manipulated in the event of component failure on the package handling crane.

Building information modelling

BIM played a large part of the design, ensuring the design

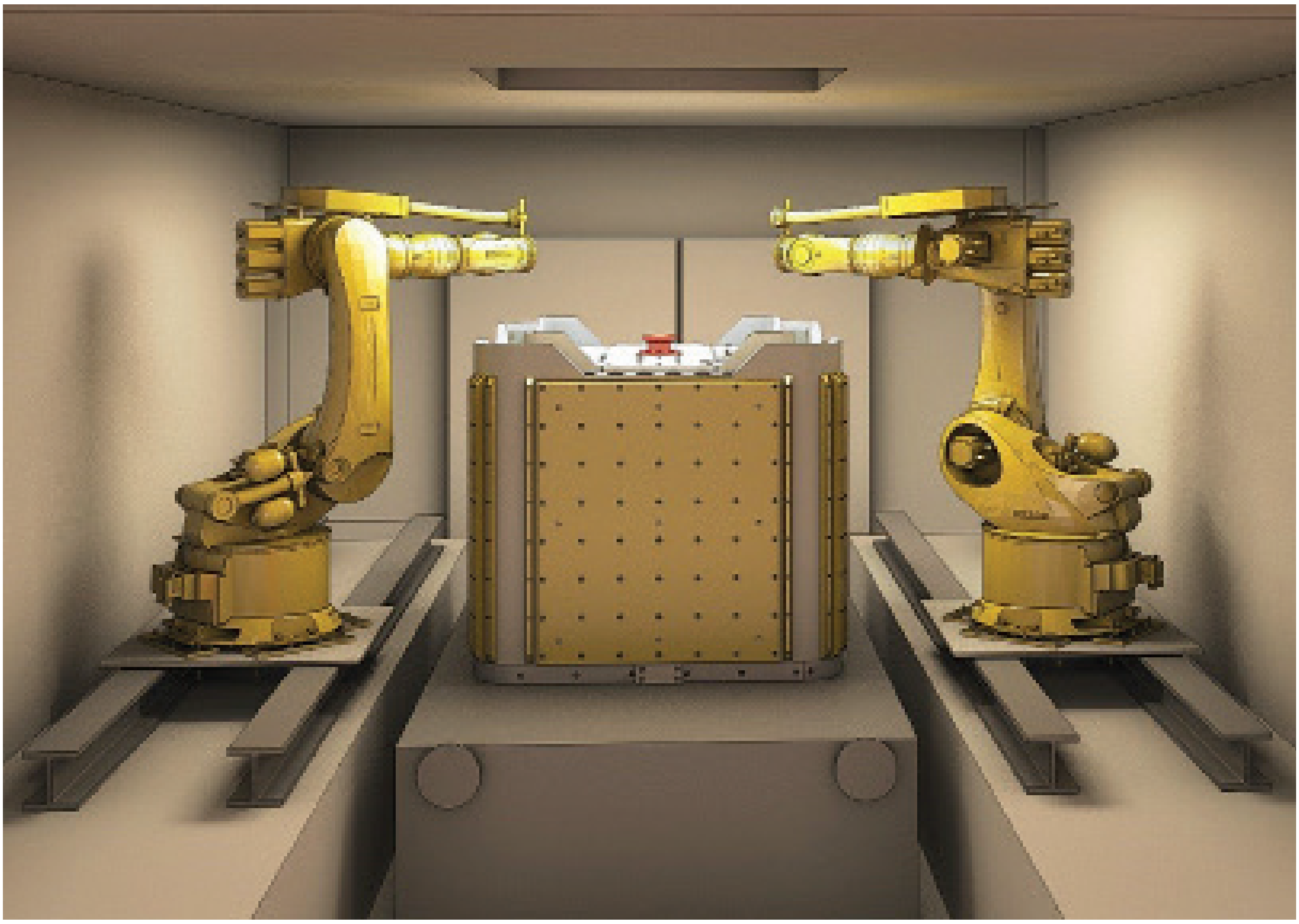

Figure 5: Robotic unbolting/bolting of the SWTC

remained aligned to the requirements. The data input into the BIM system originated from the technical specification. The technical specification contained significant amounts of technical data on all of the equipment within the UILW inlet cell facility. By default, since the technical specification was fully aligned to the requirements, the BIM data was therefore also completely aligned. This ensured that all the visual representations, the 3D model, drawings and animation then in turn fully integrated with the systems engineering approach.

As the design is developed in the future the BIM model has the capability to integrate the sub-system requirements, all new components, interface details, materials and dimensions/ fits and tolerances. These can be integrated into the BIM model and continually reviewed, managed and aligned to the original requirements forming a complete integrated management system.

Another significant advantage in utilising BIM is the ability of the system to interface with similar software packages in the wider UK industry. Examples include crane manufactures who could export their detailed design, in response to a project specification directly into the overall BIM system.

Looking forward, BIM has the capability to store all the necessary information (calculations / design standards/sub-models) supporting design substantiation reports and the nuclear safety case. The benefit of utilising BIM in this role is the system's ability to control and manage individual access to the entire portfolio of stored design information.

This represents enormous potential to help support the entire GDF design. During the detailed design phase there will be a requirement to rationalise, refine and develop ideas, and control and manage supply chain data and information. BIM provides an opportunity to support the management control of the design in the detailed development phase.

Conclusions

Throughout the project, the use of systems engineering and BIM facilitated effective and efficient communication of a 'single source of the truth' during multiple iterations and across a project team, which was dispersed widely across the UK.
3D modelling and animations were used to ensure the design aligned to requirements, enabled identification of safety and throughput enhancements during technical review and effective communication of design progress to the client.
This provided a platform to assimilate and transfer knowledge of nuclear design and operational experience from a range of experts to ensure design efficiency and effectiveness. In doing so, this resulted in:

- The potential to process UILW at a GDF at an increased rate by using an automated operation to enable the use of multiple bogies within a production-line type configuration. This enhancement provides a maximum annual throughput of 9,882 SWTCs assuming a 50-week, 24-hour continuous working pattern. Based on this assumption, an availability figure of 25% is required in order to meet a plant throughput of 2,500 units per year. This offers the potential benefit of removing DUs from waste producer sites at a faster rate, which could potentially accelerate decommissioning.
- Demonstration of UILW inlet cell technical feasibility by basing the design on standard industrial equipment and remote operations proven in a nuclear environment.
- The foundation for an asset management approach during maintenance and decommissioning in order to manage, maintain and replace equipment components over the lifetime of a GDF. Such a strategy would potentially provide a further opportunity for financial saving, by increasing equipment effectiveness and utilisation across the entire GDF project.

References

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Acronyms

ALARP: As low as reasonably practicable
DU: Disposal unit
EOTC: Electric Overhead Travelling Crane
GDF: Geological disposal facility
NDA: Nuclear Decommissioning Authority
PFD: Process flow diagram
RWM: Radioactive Waste Management
SWTC: Standard waste transport containers
TRL: Technology readiness level
UILW: Unshielded intermediate level waste

Richard Hardy is an engineering manager for RWM with more than 10 years of experience in the nuclear industry. He has a MEng in mechanical engineering from the University of Leeds, and is a chartered engineer and a member of IMechE. He manages GDF design studies for waste package transfer, handling and operations.

Alastair Clark is a geologist and technical integrator, specialising in radioactive waste management with 15 years of experience working worldwide projects. He has a unique mix of technical understanding and management skills tailored to radioactive waste management. His experience covers strategy, programme development, siting, site characterisation, waste packaging, design and post-closure performance.

Mike Farrer has more than 20 years of experience in the nuclear industry. He was technical lead and lead mechanical engineer on the design. He is a fellow of the Nuclear Institute, IMechE and Safety & Reliability Society, as well as a chartered engineer and a senior engineer for Arup.

Neil Robertson has more than 25 years of experience, spanning oil and gas to construction. Working in engineering design, strategy and deliverables and has a detailed understanding of design across all engineering disciplines. He is a technician member of the IStructE and has a PG diploma in BIM and Integrated Design.

Stine Norskov is a member of fib ECG. She received her MSc in structural engineering from Aarhus University in 2014 with special focus on theory of plasticity in relation to concrete. She was first author of the lead paper of the analysis and design session in the 2015 fib Symposium.

Ken Cowell has more than 40 years of industrial experience and a track record of leading successful designs, commissioning programmes and supporting early operations. He utilised his EC&I experience on the GDF project to design the underlying philosophy in support of the remote and simultaneous operating philosophy.

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