Proceedings Paper:
Fairweather, M, Biggs, SR, Ward, AME et al. (2016) Collaborative Research Programme in Decommissioning, Immobilisation and Storage Solutions for Nuclear Waste Inventories (DISTINCTIVE). In: Proceedings of the Annual Waste Management Conference (WM2016): Education & Opportunity in Waste Management. Waste Management Conference WM2016, 06-10 Mar 2016, Phoenix, Arizona. ISBN: 9781510826335.

Collaborative Research Programme in Decommissioning, Immobilisation and Storage Solutions for Nuclear Waste Inventories (DISTINCTIVE)

M. Fairweather[a, *], S.R. Biggs[a, †], A.M.E. Ward[a], C. Boxall[b], N.D.M. Evans[c], J.A. Hriljac[d], N.C. Hyatt[e], N. Kaltsoyannis[f, ‡], W.E. Lee[g], R.J. Lunn[h], S.M. Pimblott[i], T.B. Scott[j]

[a]School of Chemical & Process Engineering, University of Leeds, Leeds LS2 9JT, UK
[b]Dept. of Engineering, Lancaster University, Lancaster LA1 4YR, UK
[c]Dept. of Chemistry, Loughborough University, Loughborough LE11 3TU, UK
[d]School of Chemistry, University of Birmingham, Birmingham B15 2TT, UK
[e]Dept. of Materials Science & Engineering, University of Sheffield, Sheffield S1 3JD, UK
[f]Dept. of Chemistry, University College London, London WC1H 0AJ, UK
[g]Dept. of Materials, Imperial College London, London SW7 2AZ, UK
[h]Dept. of Civil & Environmental Engineering, University of Strathclyde, Glasgow G1 1XQ, UK
[i]School of Chemistry, University of Manchester, Manchester M13 9PL, UK
[j]School of Physics, University of Bristol, Bristol BS8 1TL, UK

ABSTRACT

The UK government remains committed to nuclear power as an important part of the energy generation capacity over the next 30-50 years and possibly beyond, with aspirations for both new-build power stations and lifetime extension of the existing fleet. A central component of public acceptance for any new-build programme is the need to demonstrate our ability to safely manage and dispose of high- and intermediate-level wastes from legacy nuclear operations. Clear milestones associated with the needs of waste management and decommissioning have been provided by the UK government, and most rely on further research and technical developments being delivered over the next 10-20 years. The DISTINCTIVE (Decommissioning, Immobilisation and Storage Solutions for Nuclear Waste Inventories) consortium is carrying out research that addresses the broad area of nuclear waste and decommissioning, bringing together key industry partners and leading academic researchers from 10 of the UK's leading research intensive universities. The research being carried out is multi-disciplinary and covers both fundamental and applied topics, with research projects clustered in four major themes: AGR, Magnox and exotic spent fuels; PuO_2 and fuel residues; legacy ponds and silo wastes; and structural integrity. The consortium builds upon and consolidates the work of previous Research Councils' UK Energy Programme-funded projects in the same field although, importantly, this new project draws in researchers from a larger group of universities and increases the multi-disciplinary nature of the group. All participating research groups have a strong track-record of supporting the nuclear industry through basic and applied research as well as consultancy activities. Key aims of the consortium are to extend and develop a relevant academic skill base in the UK associated with the needs of the nuclear waste management industry, to train the next generation of UK researchers, equipping them with skills and experiences relevant to nuclear waste management and decommissioning issues, and to carry out cutting-edge research that has the potential to provide new and innovative pathways to better management of both legacy and future nuclear wastes.

* Corresponding author, e-mail: m.fairweather@leeds.ac.uk
† Current address: Faculty of Engineering, Architecture and Information Technology, University of Queensland, Brisbane Qld 4072, Australia
‡ Current address: School of Chemistry, University of Manchester, Manchester M13 9PL, UK

INTRODUCTION

The UK government remains committed to nuclear power as an important part of the UK's energy generation capacity over the next 30-50 years, and possibly beyond [1]. The recently published "Nuclear Industrial Strategy" describes the government's aspirations for both new-build power stations and life extension of the existing fleet [2]. A central component of public acceptance for this new-build programme, however, remains a demonstrable ability to manage and dispose of high- and intermediate-level wastes from legacy nuclear operations safely. This links to on-going studies of public attitudes towards nuclear power which repeatedly show that acceptance is directly linked to having scientifically robust routes for the safe clean-up and disposal of any wastes [3, 4].

Within the 2013 "Nuclear Industrial Strategy" [2], clear milestones associated with the needs of nuclear waste management and decommissioning are provided and these rely upon further research and technical developments being delivered over the next 10-20 years. Indeed, central objectives for the strategy are [2] "to have a joined up approach to nuclear R&D across government, industry and academia which serves to benefit the UK economy and ensures the security of supply" and "to establish the UK industry as a global leader in waste management and decommissioning...". It is clear, therefore, that there is a substantial and current need for further research in the broad area of nuclear wastes supporting this strategy. UK government policy associated with nuclear waste management was updated and extended through the 2008 White Paper "Managing Radioactive Waste Safely" [5] which was based on the 2006 recommendations of the Committee for Radioactive Waste Management (CoWRM) [6]. The Nuclear Decommissioning Authority (NDA), through its strategy, is responsible for the delivery of the policy aims with respect to legacy wastes [7]. Through both the policy documents and the associated strategy for delivery, it is understood that the ultimate goal within the UK is for the management of nuclear waste through a geological disposal facility (GDF). Despite a programme of consultation over more than 5 years, however, public attitudes to hosting a GDF remain sceptical and there is, as yet, no defined host site. This attitude is undoubtedly linked to a lack of confidence in the proposed waste management approaches and highlights a continuing need to improve fundamental understanding and technology in this area. It must also be underpinned by a credible programme of safe interim storage options at various sites across the UK. The waste management and disposal strategy is additionally relevant to wastes arising from new-build, with any disposal facility requiring the capability to house wastes from both these sources [2].

There is, therefore, a clear imperative, given the needs of both new-build reactors and legacy wastes, to develop innovative approaches to waste management and decommissioning to deliver safe and cost effective answers to storage and disposal issues. The need for a strong and vibrant R&D community focussed on the issues of safe storage for spent nuclear fuels and other wastes has also been highlighted in the "Nuclear Industrial Strategy" [2] where the need for a strong R&D community is unequivocally recognised. Indeed, the report states that a key aim is for "... the UK to have a clear competitive edge in waste management and decommissioning technologies ... through innovation and experience...".

The work of the DISTINCTIVE consortium is part of the response to these needs, providing support to a strong and internationally leading group of researchers in this key technology area. The existence of the collaborative programme also sends a powerful signal to the international community about the UK's commitment in the field. The project came about following a workshop on Nuclear Decommissioning, Immobilisation and Waste organised by the Engineering and Physical Sciences Research Council (EPSRC) on behalf of the Research

Councils UK Energy Programme in May 2013, with a call for proposals subsequently being issued. The project follows on from earlier, highly successful consortia which also addressed research challenges associated with nuclear waste management and decommissioning, also supported by the EPSRC, namely the KNOO (Keeping the Nuclear Option Open) and DIAMOND (Decommissioning, Immobilisation and Management of Nuclear Wastes for Disposal) projects. The DISTINCTIVE consortium learned from these previous activities in formulating the new project, and widened and deepened the pool of talent within academia with direct experience of nuclear-related R&D involved in the project. When allied to the strong links of the partners with the industry R&D community, the project provides an excellent route for building a greater capacity for R&D within the UK, underpinning the strategic needs of the country. The research being undertaken also addresses key strategic priorities in EPSRC's portfolio, not least in the training of a significant number of PDRA (post-doctoral research assistants) and PhD student researchers with high level skills of direct relevance to issues in nuclear waste and decommissioning. The large cohort of research staff and students directly addresses the skills agenda, a major issue for the industry, with consortium members having a proven track record in providing employees to site licensees, supply chain companies, the NDA and the National Nuclear Laboratory (NNL). The research being undertaken also directly addresses the EPSRC's Energy theme and the associated sub-theme of Nuclear Power. The construction of the consortium as a close partnership between academics and key industry partners from across the UK is also aligned with the stated EPSRC strategy for this sub-theme of "...support (for) a balanced portfolio of research, to support the supply of skilled people and to maximise impact through close links with users and international partners".

The project is led by the University of Leeds, with the world-class university network made up from academics at Imperial College London, Lancaster University, Loughborough University, University College London and the universities of Birmingham, Bristol, Leeds, Manchester, Sheffield and Strathclyde. Key project partners are the NNL, the NDA and Sellafield Ltd. They played a central role at the original workshop in 2013, and in providing strategic guidance, challenge definition, academic-industrial links, and access to people and facilities. They also had significant input in reviewing the content of the programme of work, and in providing advice to improve the relevance of individual projects and theme areas.

Core funding is provided by the EPSRC which, together with the Universities' own contribution, covers the cost of 10 PDRAs, investigator and technician time, as well as costs associated with active research projects, minor pieces of equipment, impact and dissemination activities, and general meeting and conference attendance. Additionally, 22 PhD researchers, who have been funded jointly by the universities and key industry partners, are undertaking work aligned with the various theme areas being covered, as outlined in the following section. Details of the projects being undertaken by all these researchers are given below. This brings the total funding for the project to approximately £8.4M. In order to maximise the benefit of the project to other PhD students undertaking work in related areas, through support for attendance at various consortium events, the project has also recognised 16 associated PhD researchers from the 10 universities that make up the project, as well as 2 researchers from Queen's University Belfast. Details of these projects may be found on the consortium website (http://distinctiveconsortium.org/). This large cohort of researchers directly addresses the skills agenda noted above.

The project runs from February 2014 to November 2018, and its strategic aims are:

- To carry out internationally leading science and engineering research in the area of decommissioning and nuclear waste management.

- To support research that provides routes to innovative technology developments that can be applied to decommissioning and nuclear waste management.
- To foster and develop new multi-disciplinary research partnerships between academic and industry researchers.
- To train the next generation of UK researchers, equipping them with skills and experiences relevant to nuclear waste management and decommissioning issues.
- To provide a focal point for government, industry and academics through which current and future R&D issues associated with nuclear waste and decommissioning can be discussed.
- To provide a route for public understanding of the underlying research and development needs, opportunities and solutions to nuclear waste and decommissioning.

Overall, therefore, the DISTINCTIVE project aims to provide a world-class programme of relevant research into nuclear waste management and decommissioning with a special focus on UK needs. Through our impact strategy we aim to bridge the credibility gap in public perception of radioactive waste management, through improved public understanding of the supporting scientific evidence and genuine two-way dialogue concerning socio-economic and ethical impacts of waste management practice. The consortium does not directly address geological disposal or radionuclide leakage/mobility, although many of the research packages will link directly to this, as this is currently covered within complementary research activity supported by the Natural Environment Research Council.

The consortium brings together leading researchers in the field from a diverse array of backgrounds and experience with a track-record of innovation and problem solving of relevance in the nuclear field. The leadership group of the consortium are all distinguished researchers with a significant track-record of working on topics of direct relevance to the major aims of the consortium. The research programme builds upon the collected expertise of this core academic group.

In what follows, the major research themes covered by the project are described, together with details of the specific projects being undertaken by the core team of PDRAs and PhD students. Cross-cutting themes are then covered, namely active research projects and outreach and public engagement, finally followed by details of how the project is being managed and subsequent conclusions.

RESEARCH THEMES

The current UK waste inventory is large and complex. It presents multiple challenges that are not fully understood, with research needed to find viable technologies for its ultimate treatment, storage and disposal. New knowledge and technology is still needed in areas such as waste recovery from storage facilities, conditions for interim safe storage, and stable wasteforms for different wastes over different geological timescales. These needs cut across all stages of waste management and disposal, and require a range of skills and knowledge to be brought to bear.

Our approach for clustering the research uses the strategic R&D themes in the 2011 NDA Strategy [7]. The latter's themes of "site restoration", "spent fuels", "nuclear materials" and "integrated waste management" therefore map directly onto our themes of "structural integrity", "AGR, Magnox and exotic spent fuels", "PuO_2 and fuel residues" and "legacy ponds and silo wastes", respectively. This ensures excellent strategic alignment with the needs of UK industry.

The consortium involves staff from a range of science and engineering disciplines, including radiochemists, radiation chemists, physicists, environmental scientists, process engineers, materials scientists and civil engineers. Each project has a team of supervisors and we encourage and foster interactions across the themes.

AGR, Magnox and Exotic Spent Fuels

The current declared lifetime for advanced gas-cooled reactor (AGR) power stations from EDF Energy will result in the generation of approximately 8800t of AGR fuel across the whole fleet. Of this inventory over 2,300t has been reprocessed to date, meaning there is estimated to be approximately 6,600t which still needs to be managed [8]. The NDA has reported that their preferred option for AGR spent fuel, excluding current reprocessing contracts in THORP, is to keep the fuel in interim storage prior to packaging for disposal in the UK GDF in circa 2075 [9]. Risks exist with longer-term wet storage of AGR spent fuel and so a transition to dry storage may be a preferred option. A similar argument has also been made for Magnox uranium spent fuel stored in the Sellafield ponds, where retrieval and repackaging is needed. For both types of spent fuels this transition, as well as the dry store environment, may carry unknown risks, e.g. to AGR cladding integrity or hydride formation on U metal, and so better understanding is required before this can be implemented.

The goal of this spent nuclear fuels (SNF) theme is to increase knowledge and mechanistic understanding of the processes involved, and to quantify the physiochemical evolution of SNF and wasteforms of different types in storage environments, with specific emphasis on aqueous (pond) as well as dry storage. A concurrent aim of the theme is to develop an internationally renowned and integrated team of experimentalists, theoreticians and modellers with significant expertise and capability in tackling waste management problems for SNF of different types in numerous storage scenarios.

The aim of this theme is to provide technical underpinning to the options for the management of the UK's AGR, Magnox and exotic spent fuels. The objectives are:

- To understand the evolution of Magnox and exotic SNF during recovery from aqueous storage, drying and repackaging.
- To develop spectroscopic methods for improved determination of SNF dissolution and corrosion rates in water.
- To determine the optimum drying conditions for AGR fuels and the subsequent surface reactivity and alteration of unclad UO_2 in dry storage.
- To determine the consequences of radiation damage in SNF, cladding and other wasteforms for safe long term storage.
- To determine suitable waste management options for spent carbide fuels.

These objectives are being met by several linked projects in three work packages –

Wet Fuel Storage Issues which includes a project on:

- Use of time resolved laser fluorescence spectroscopy (TRLFS) to investigate dissolution rates – Investigation of the dissolution and corrosion rates of SNF in water using TRLFS, focussing on the solid-solution interface.

Transitions to Dry Fuel Storage with projects on:

- An investigation of wasteform evolution during wet-recovery and drying of SNF – Considering physiochemical changes occurring in SNF during recovery from aqueous storage, forced drying and repackaging in an 'open' but nominally dry engineered containment system.
- UO_2 surface reactivity and alteration – Studying the reactions occurring at the surface of uranium oxides, in particular dissolution and photocatalysis, to model the long-term behaviour of SNF.
- Determination of optimum drying conditions for AGR fuels – Experimental study and development of a process model to predict optimum conditions for drying.

Long-term Storage Effects and Exotic Fuels:

- Grain boundary damage mechanisms in strained AGR cladding under irradiation – Aims to elucidate the principal radiation damage mechanisms, and link radiation-induced atomic scale changes in AGR cladding material to its mechanical integrity and susceptibility to localised corrosion.
- Options for exotic carbide fuels – Aims to understand the oxidation mechanism of carbide fuels, develop a suitable oxide wasteform, and identify the best encapsulation and immobilisation form for these oxides.
- A life cycle approach as a decision tool for nuclear waste management and decommissioning of existing and future plants – Development of a life cycle assessment tool to help decision-making processes within the nuclear field and improve public perception of nuclear energy.

PuO_2 and Fuel Residues

The safe and secure management of Pu is a matter of serious international concern, with ~250t of separated Pu currently stockpiled worldwide [10]. Nearly 50% of this material is in long-term storage in the UK whilst the British government develops its options for final treatment and disposition. Options for this are [11]: (i) reuse as a fuel in modern reactors (e.g. as MOX fuel or within a fast reactor – e.g. PRISM, Power Reactor Innovative Small Module) prior to disposal; (ii) prompt immobilisation for disposal as soon as is practicable; or, (iii) continued long term storage (prior to disposition).

Option (i) is best considered in the context of Pu fuel cycle research. Thus, the focus of this theme is on options (ii) and (iii). The R&D needs of both are now pressing: in option (iii) due to it being the current default; in option (ii) because of a comparative lack of R&D on Pu conditioning and packaging due to policy uncertainty as to whether it would be disposed of in a GDF. Addressing these needs is complicated by Pu's high radioactivity, decay heat and radiotoxicity, nuclear safeguard requirements and, for some UK Pu contaminated materials targeted for disposal, poor inventory. Thus, there is also a critical requirement for research on characterisation methods for Pu-bearing materials.

Therefore the main aim of this theme is to provide technical underpinning to the options for the UK's civil plutonium inventory. The objectives are:

- To understand how the structure and properties of PuO_2 change with time in the presence of H_2O.
- To understand the roles these processes play in gaseous product evolution from PuO_2 in storage.
- To understand radiation induced amorphisation and dissolution kinetics of Pu wasteforms.
- To develop novel, fast neutron based radiometric methods for the quantification, isotopic composition assessment and remote imaging of Pu-bearing materials.

These objectives are being met by several linked projects in three work packages –

The Behaviour of PuO_2 During Interim Storage:

- Understanding the interfacial interactions of plutonium dioxide with water – Experimental study of the surface chemistry of water adsorbed on PuO_2 to help predict conditions that may lead to gas generation during long-term storage.
- Understanding the interfacial interactions of plutonium dioxide with water – Complementary modelling study to understand the behaviour of adsorbed surface water on PuO_2 and its role in radiolytic H_2 generation.
- Modelling the surface chemistry of PuO_2 at the molecular level – Using computational models to study the behaviour of water on plutonium oxide surfaces to investigate if hydrogen is produced.
- Computational modelling of PuO_2 ageing and fuel residues – Combining a number of modelling techniques to provide further understanding of ageing mechanisms associated with PuO_2 at the atomic scale.

The Behaviour of Pu-Bearing Wasteforms and Encapsulants:

- Ceramic materials for actinide disposition – Investigation of betafite pyrochlore as a potential host phase for actinide disposition in ceramic and glass-ceramic wasteforms.
- Current glass-ceramic formulations for Pu disposition – Development and understanding of glass-ceramic wasteforms for actinide immobilisation, and the application of hot isotopic pressing to reduce total wasteform volume and cost.
- Understanding actinide sorption and binding to cement materials for radioactive waste management – Investigation of the sorption and incorporation mechanisms of Pu and Am onto engineered barrier cement materials, and the subsequent transport processes under groundwater flow.

Methods for the Characterisation of Stored Pu, Plutonium Contaminated Materials and Pu Contaminated Facilities:

- Real-time fast neutron plutonium assay for Pu storage and ageing applications – Investigation of the use of fast-neutron multiplicity analysis to infer isotopic composition, in situ, for applications including Pu accountancy in storage, criticality assurance and proliferation prevention in Pu management.
- In-situ characterisation of heavily-contaminated Pu finishing environments – Development of a technique based on the collimation and detection of fast-neutrons with which to assess the distribution of Pu.

Legacy Ponds and Silo Wastes

The legacy ponds and silos (LP&S) at Sellafield are currently the biggest safety and security threat facing the UK, costing £70M/annum just to maintain their basic condition and prevent leakages [7]. They represent 22% of all Sellafield site programmes, 35% of total site costs and 77% of major project costs during the next 4 years, and greater than 90% of the nuclear hazard potential. LP&S decommissioning and clean-up has to be the UK's top priority engineering programme. The objectives of the NDA's LP&S Strategy include: acceleration of high hazard/high risk reduction; reduction or mitigation of the impact of the risk of a loss of containment of nuclear materials; preparation of the facilities for retrieval operations; retrieval of the waste; and immobilisation of the waste. The projects in this theme will provide fundamental understanding of key aspects of the Sellafield programme including characterisation, mobilisation and transport, multi-phase sludge transport, immobilisation and conditioning, and effluent clean-up and monitoring of the effluent prior to discharge.

The main aim of this theme is therefore to develop innovative technical approaches to clean up UK legacy wastes. The objectives are:

- To understand the durability of heterogeneous intermediate level waste glass/ceramic wasteforms from LP&S wastestreams.
- To develop improved ways to remove radionuclides from solution, using both novel inorganic ion exchange solids and tailored binding superparamagnetic nanoparticles, to treat complex and variable effluents.
- To develop new micro- and ultra-filtration methods for use with sludges.
- To provide three-dimensional modelling and simulation for sludge disturbance, mobilisation and transport, with supportive experimental studies, and manipulation planning for removing corroding nuclear materials.
- To develop a better understanding of gas hold-up in sludges.
- To develop improved techniques for remote monitoring of sludges and heterogeneous wastes.

These objectives are being met by several linked projects in three work packages –

Wasteform Durability

- Durability of heterogeneous ILW glass/ceramic wasteforms from complex wastestreams – Understanding the corrosion mechanisms in heterogeneous wasteforms resulting from thermal methods such as plasma vitrification and Joule-heated in-can vitrification.

Effluent Treatment and Analysis

- Novel ion exchange materials – Development of a new ion exchange material based on known and stable minerals such as zirconium or tin silicates for effluent clean-up, especially for Sr and Cs.
- Enhanced shear micro- and ultra-filtration without recycle pumping – Investigation of enhanced sheer micro-filtration to increase the rate of liquid flow across a membrane to enable small, portable filtration units for waste treatment.
- One step extraction and quantification of radionuclides using superparamagnetic bead and nanopore technologies – Investigation of the use ligands immobilised onto silica-coated paramagnet beads to selectively bind trace radioactive contaminants from solutions.
- Magnetic nanoparticles for waste separation or sequestration – Assessing the potential for core-shell magnetic-sorbent structures to be used in wasteform separation, or in the removal of radionuclides from liquid streams.

Pond and Silo Sludges

- Measurement and modelling of sludge mobilisation and transport – Characterisation of the physical and flow properties of nuclear waste slurries using ultrasonic methods, and development of a validated predictive model for complex particle-laden flows in closed pipes.
- Gas retention and release from nuclear legacy waste – Understanding the mechanisms for retention and release of gas in corroded Magnox sludge to prescribe a safe waste management strategy.
- Characterisation of flocculated waste suspensions with acoustic backscatter – Fundamental analysis to quantitatively understand the flocculation of fine Magnox and settling sludge systems using an acoustic backscatter array.

- Development of Raman spectroscopy techniques for the remote analysis of nuclear wastes in storage – To demonstrate the potential and possibility of performing stand-off Raman spectroscopy for corroded Magnox sludge analysis.
- Autonomous systems for nuclear decommissioning in extreme radiation environments – Investigation of the limitations of various techniques and sampling procedures used to monitor particle size distribution of sludge in ponds, and understanding how radiation sources in ponds can be mapped.
- Computational simulations of storage pond sludge disturbance – Use of computational methods to investigate the composition of sludge and particulates in storage pond water to refine reprocessing methods.

Structural Integrity

Monitoring, preserving and improving the integrity of on-site structures is a significant issue for site decommissioning and management. This theme focuses on complex technical challenges ranging from site-scale infrastructure preservation and restoration, to characterisation and handling of individual waste packages. Legacy plants contain buildings, chimneys, storage ponds, silos and waste packages that have deteriorated over several decades. The nature of site operations has also led, in some areas, to the creation of extreme radiation environments. Access to infrastructure, for characterisation and preservation, may be limited by high radiological hazard and/or by the proximity of other fragile or hazardous structures. These uniquely challenging conditions can result in an increased financial cost and a severe reduction in the availability of engineering solutions.

Therefore, the main aim of this theme is to develop reliable systems for infrastructure characterisation, restoration and preservation, that minimise current, and future, radiation exposure of the workforce whilst providing economically viable technological solutions. The objectives are:

- To develop in-situ ground barriers that could act as a ‘second skin’ surrounding on-site structures, such as silos and ponds, for prevention of subsurface radionuclide migration.
- To develop smart solutions for remote crack detection, infrastructure health prediction and building preservation that can be retrofitted to existing sites.
- To develop autonomous systems with increased functionality and to coordinate them through a CAD-based real-time management system, to facilitate planning and execution of decommissioning works.

These objectives are being met by several linked projects in three work packages –

Physical Ground Barriers for In Situ Contaminant Containment

- In-situ ground contaminant containment – Investigation of use of colloidal silica as a new grouting material for the creation of a hydraulic ground barrier for use on contaminated sites to control pollutant migration.

Remote Crack Detection, Infrastructure Health Prediction and Building Preservation

- Crack sealing and water transport – Investigation of novel materials, such as nano-silica, silica fume and metakaolin, as crack-healing agents.
- Nano-cracking of cement phases: reactivity and dissolution – Development of a model for understanding the development of the strain induced in cement/concrete by chemical alteration through time.

Development and Real-time Management of Autonomous Systems for Decommissioning

- Production of real-time segmented as-built CAD models for the planning and execution of remote and human intervention tasks – Developing methods for instant CAD modelling of a nuclear plant to facilitate planning and execution of remote handling and decommissioning operations.

CROSS-CUTTING ACTIVITIES

Active Research Projects

A key component of the research programme is the use of world-class active research facilities at the NNL and elsewhere. By its very nature, active research is costly, time consuming and needs careful planning. Two major projects were planned at the start of the project which required the embedding of two PDRA staff within the NNL for the duration of the programme. Additionally, a number of other projects have indicated a potential need for active research facilities, and the consortium holds funds in support of such activities. Recently, following a call for proposals, three further projects were awarded funds to pursue active work, and a second call for proposals is currently open. One academic member is acting for the consortium as the cross-cutting champion in this area with responsibility for promoting the use of active facilities and to ensure that we receive excellent advice and support, especially in relation to technical needs and duration of work.

Outreach and Public Engagement

The outreach activities are again being led by a member of academic staff as a cross-cutting champion. Full details of the outreach and impact strategy and plan are given in the following section. This theme has overall responsibility for promoting the work of the consortium through delivery of this plan. Central to this is the development of outreach materials and activities that underpin a core message about the importance to the economy and society of our research programme. The cross-cutting theme leader is also responsible for supporting the promotion of the consortium to stakeholders, policy makers and the general public, engaging other researchers in the consortium, as needed, to deliver the plan.

IMPACT STRATEGY

The project identifies three distinct groups of non-academic beneficiaries from consortium activities: site licence companies and the associate industrial supply chain; government, regulators and implementation authorities; and society and stakeholder groups. Our strategy will potentially impact in four key domains:

- *Knowledge* – through the creation of new fundamental understanding and technology, leading to long term economic, social, environmental, safety, health and security benefits associated with improved radioactive waste management and disposal practice.
- *People* – through the provision of highly skilled employees to the nuclear and allied sectors in support of the national nuclear skills pipeline, trained through excellent research.
- *Economy* – through knowledge exchange and commercialisation, leading to uptake or implementation of research, to reduce the cost of nuclear decommissioning and geological disposal, by bringing new products and processes to market.
- *Society* – through knowledge exchange with key stakeholders to enhance the legitimacy of radioactive waste management policy and regulation, and improve public confidence.

In so doing, the project aims to address a key objective of the recently published UK Nuclear Industry Strategy [2]: “To establish the UK industry as a global leader in waste management and decommissioning”, through exchange of knowledge, capability, people and public engagement.

Five critical enablers are identified as forming the core of the impact strategy:

- *Building and maintaining relationships and networks* – several mechanisms will be used to ensure strong engagement with potential beneficiaries of the work undertaken in support of uptake of the research, delivering impact across all four impact domains. An annual research conference forms the core of our networking and knowledge transfer activities. This meeting provides an opportunity for academic, industry and other partners to share research advances, supporting collaboration and knowledge exchange. At the first meeting, held on 15th-16th April 2015, more than 100 delegates were in attendance, with approximately 50% from industry. Theme meetings are being held approximately 6 months after the annual conference, and provide an opportunity for focused discussion of research findings and emerging collaborative opportunities, assisting integration of knowledge and capability across distinct projects. Challenge-led theme meetings are also planned. These will be organised in a responsive fashion by our industrial partners to harness the broad collective experience and capability of the consortium in meeting specific industry needs-led research challenges, providing a rapid and effective impact mechanism. Lastly, we have established links with world-leading research groups and have invited key personnel from these groups to be on our International Advisory Group to bring international perspective and challenge, as well as presenting keynote lectures at our annual conference and theme meetings.
- *Communication and dissemination* – two key mechanisms are being used to support impact delivery in the knowledge and economy domains. The consortium website (http://distinctiveconsortium.org/) is now established and regularly maintained, providing a repository and showcase for key information and outcomes of the research. A biannual newsletter also summarises consortium progress as an accessible digest, with the first newsletter now available to download from the website. Also, in addition to publishing relevant research results in high impact journals and at international conferences, publication in industry magazines has also been targeted to connect directly with end users.
- *Public, media and government engagement* – the project is proactively engaging key stakeholders including the media, contractors, nuclear ‘host’ communities, and active non-governmental organisations to deliver impact through knowledge exchange in the social domain. Informal and formal mechanisms for public engagement are being used to give members of the public the opportunity to discuss relevant issues of concern with researchers and amongst themselves. These will take the form of a World Cafe and deliberative workshops, where discussion of the socio-economic and ethical impacts of the consortium research agenda, and present public perspectives on decommissioning and waste management policy, can be discussed, with written/photographic reports recorded. We are also supporting a proposal for a major radio documentary which will explore the story of past and future radioactive waste management challenges to be informed by, and showcase, the research contribution of the consortium. Engagement with government is also planned through an evening lecture and panel discussion in London, and via a focused event at Westminster to showcase the work of the consortium to government and policy makers.
- *Knowledge transfer and commercialisation* – existing institutional arrangements are being used to support spin-out and commercialisation of research, to achieve impact in the economy domain. All partners in the project have well established enterprise/knowledge transfer offices with the resources and experience needed for protecting IP and designing exploitation strategies.

- *Training and development* – Researchers on the project are being developed as agents for change, and to facilitate the skills pipeline through experiential activities to achieve impact in the people domain. Our core industry partners have agreed that all researchers within the consortium will have an industry mentor who meets with the researcher and their supervisors on a regular basis to discuss research progress and facilitate links to industry for adoption of outcomes. Building on this partnership, it is also our intention to ensure that all researchers have at least one placement within industry during their research time. External engagement also forms a key part of this activity and it is recognised that researchers need to be equipped with the required skills. A three-day engagement summer school is therefore planned for all researchers, which will deliver practical training activities combined with instructional seminars, as well as considering associated ethical and inter-generational issues.

LEADERSHIP AND MANAGEMENT

Michael Fairweather is the principal investigator and director of the consortium, supported by Abby Ward as consortium manager who provides general support to the director and to all consortium members across all of the noted areas of activity.

A Management Board, responsible for the day-to-day running of the project, is made up of Fairweather, Colin Boxall, Nick Evans, Joe Hriljac, Neil Hyatt, Nik Kaltsoyannis, Bill Lee, Rebecca Lunn, Simon Pimblott and Tom Scott as academic members, and Ward as consortium manager, with representatives of NNL, NDA and Sellafield Ltd. (Mike Angus, Rick Short and Debbie Keighley, respectively) representing the key industry partners. A representative from EPSRC has an ex officio position on the Management Board. All the leading academics have extensive records of research leadership, collaborative projects in the nuclear industry, and training of PDRA staff. The Board meets at 6 monthly intervals, and has oversight of the budget and allocation of resources, and reviews progress against targets. It also controls the allocation of strategic research funds to facilitate active research, international research secondments, and small equipment purchases which are allocated against bids from individual projects, taking account of the strategic aims of the consortium.

Strategic leadership is provided by an International Advisory Group which consists of members of the Management Board, and additionally includes representatives from partner organisations involved in supporting the research objectives, as well as leading academics from complementary international research activities. At present, these include representatives from Amec Foster Wheeler, Atkins, AWE, BAM Ritchies, Costain, Doosan Babcock, EPSRC, Environment Agency, Escubed Ltd., European Commission, Jacobs, Low Level Waste Repository Ltd., MMI Engineering Ltd., Nuclear Technologies, Nuvia Ltd., NuVision Engineering, Pacific Northwest National Laboratory, Savannah River National Laboratory and the U.S. Department of Energy. The Group is chaired by Prof. Ian Pegg from the Catholic University of America, Washington, D.C., U.S.A, and meets annually and advises on the scientific programme to ensure continued relevance and focus within the consortium.

CONCLUSIONS

New technologies must be developed to facilitate the safe and timely decommissioning of existing nuclear plant, and to address the diverse challenges that lie ahead. This inevitably requires a multi-disciplinary approach, and expertise spanning traditional engineering and science boundaries. The DISTINCTIVE project achieves this though a team approach which utilises complementary academic expertise, new links made between members at different academic institutions, and by industry playing a major role in project delivery. In doing so the consortium is facilitating new networks across the industry-academic interface and broadening the experience of our academic members, increasing their awareness of the potential for knowledge transfer into the sector. The consortium also wishes to be inclusive in terms of industry engagement, with other partners encouraged to give input and support, either through the joint supervision of researchers on individual projects, and/or membership of the International Advisory Group.

As the UK moves forward, decommissioning numerous nuclear sites, planning and constructing a nuclear waste repository, and building new nuclear power generation plant, it is essential for the higher education sector to also deliver sufficient skilled personnel into the industry. Due to the resurgence of the industry and the workforce demographic, there will be an ongoing requirement for graduate professionals to fill job vacancies in the nuclear sector over the next 15 years. The DISTINCTIVE consortium is helping to meet this need by training the next generation of researchers, equipping them with skills and experiences relevant to nuclear waste management and decommissioning issues.

Lastly, the main aim of the project is to carry out internationally leading science and engineering research in the area of decommissioning and nuclear waste management that has the potential to provide new and innovative pathways to better management of both legacy and future nuclear wastes. We believe that continued support for research programmes such as DISTINCTIVE will prove critical to the industry in addressing the complex challenges that lie ahead.

REFERENCES

1. Department of Energy and Climate Change, *National Policy Statement for Nuclear Power Generation (EN-6)*, URN 11D/716, HM Government (2011).
2. Department for Business, Innovation and Skills, *Nuclear Industrial Strategy – The UK's Nuclear Future*, BIS/13/627, HM Government (2013).
3. Unattributed, A Nuclear Divide, *International Atomic Energy Agency Bulletin*, 50-1, 34 (2008).
4. M. Greenberg, K. Lowrie, J. Burger, C. Powers, M. Gochfeld and H. Mayer, Nuclear Waste and Public Worries: Public Perceptions of the United States' Major Nuclear Weapons Legacy Sites, *Human Ecology Review*, 14, 1 (2007).
5. Department for Environment, Food and Rural Affairs, Department for Business, Enterprise and Regulatory Reform, and Devolved Administrations for Wales and Northern Ireland, *Managing Radioactive Waste Safely: A Framework for Implementing Geological Disposal*, Command 7386, HM Government (2008).
6. Committee for Radioactive Waste Management, *Managing our Radioactive Waste Safely – CoRWM's Recommendation's to Government*, CoRWM Doc. 700 (2006).
7. Nuclear Decommissioning Authority, *Strategy*, NDA (2011).
8. Nuclear Decommissioning Authority, *Topic Strategy: Oxide Fuel*, NDA Doc. SMS/TS/C2/G0/001 (2010).
9. Nuclear Decommissioning Authority, *Oxide Fuels: Preferred Options*, NDA Doc. SMS/TS/C2-OF/001/Preferred Option (2012).
10. www.world-nuclear.org/info/Nuclear-Fuel-Cycle/Fuel-Recycling/Plutonium/
11. Department of Energy and Climate Change, *Management of the UK's Plutonium Stocks – A Consultation Response on the Long-Term Management of UK-Owned Separated Civil Plutonium*, URN 11D/819, HM Government (2011).

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the financial support of the Research Councils' UK Energy Programme under grant EP/L014041/1, "Decommissioning, Immobilisation and Storage Solutions for Nuclear Waste Inventories (DISTINCTIVE)", and for the additional support provided by our key industry partners, NDA, NNL and Sellafield Ltd. We also acknowledge the support from all members of our International Advisory Group and all industrial project supervisors.