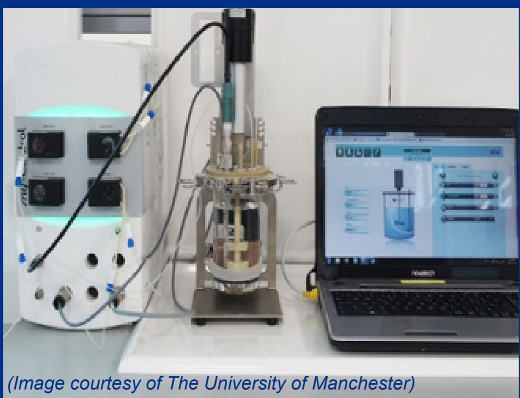
Sellafield Ltd

Sellafield medium to long term research needs

Supporting the mission at Sellafield





(Image courtesy of The University of Manchester)

Executive summary

Covering six square kilometres, Sellafield is home to more than two hundred nuclear facilities and the largest inventory of untreated nuclear waste in the world, with a diverse portfolio covering the management of special nuclear material, spent fuel management, reprocessing, decommissioning and waste management. As a company, Sellafield Ltd is preparing for the end of reprocessing and delivering its mission as efficiently as possible while providing value for money. The future for the Sellafield site is the:

- continuing hazard reduction programme of legacy facilities;
- management of the closure, and decommissioning, of the current spent fuel reprocessing plants, and associated facilities;
- continuation of waste management operations together with the implementation of new ones;
- management of the land and
- safe storage of waste forms pending final disposal.

Government policy and the Nuclear Decommissioning Authority (NDA) strategy defines the mission for Sellafield Ltd which is to remediate the Sellafield site to an agreed end state. As a wholly owned subsidiary of the NDA, the company has recently published a set of documents which together define the direction for the business together with the transformation it needs for success. The company has defined the organisation it needs to become as the mission evolves in the Corporate Strategy [1]. The detail on how the company will achieve its mission is presented in Transforming Sellafield [2] and the Corporate Plan [3] which details the timeline of key activities that will take place between now and 2036.

Sellafield Ltd is required to define a “Technical Baseline”, this sets out all of the processes and technologies used or planned to be used to deliver the mission. These processes and technologies need to be sufficiently underpinned by Research and Development (R&D) and as the mission evolves, it is essential that the science and technology areas requiring R&D investment are aligned to the changing needs of the business. A review has been undertaken to identify key areas, where R&D will be focussed, in the medium to longer term, to ensure that the mission continues to be underpinned and to manage future risks.

The purpose of this document is to present the details of the review. Five science themes and six technology areas have been identified, which when combined form the science and technology Work Breakdown Structure (WBS) against which medium to longer term research needs have been captured. The document does not cover the shorter-term challenges that the business is facing i.e. where direct technical support to project and programmes is needed.

Critical to success is greater integration and coordination of the various R&D programmes that are delivering science and technologies and therefore programmes will be managed by research teams with end-user input. Key to delivery of the work to address these needs is the supply chain, academia and the potential for collaboration with funding opportunities from other organisations such as Research Councils UK (RCUK), these are presented and explained in this document.

This is the first publication of this document and it is underpinned by science and technology research needs sheets that have been articulated in a consistent manner, these are stored centrally within the Sellafield management system and they will be used as a basis for dialogue with interested parties who wish to engage with Sellafield Ltd. For more information please contact: ***technical.innovation@sellafieldsites.com***

This document identifies the research needs for technology development and underpinning science areas that will be addressed over a period of ca four years. The research needs sheets will be live documents to allow the value streams to flexibly influence the medium to long term research programmes but these will be reviewed at least annually to ensure continuous alignment and that any emerging needs are captured.

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(Image courtesy of The University of Manchester)

Section 1 Background

1.1 The mission at Sellafield

Sellafield is the largest UK nuclear site with a unique and diverse range of complex challenges arising from 60 years of varied nuclear operations. As a company, Sellafield Ltd is faced with the challenge of preparing for the end of reprocessing and delivering its decommissioning mission as efficiently as possible whilst providing value for money. Over the next few years the Sellafield site will transform from an operational reprocessing site to a site dedicated to waste management and clean-up. Thorp reprocessing will be completed by 2018 and Magnox reprocessing complete by 2020, Post Operational Clean-Out (POCO) of facilities will start and in parallel with this, is the continuing hazard reduction programme to remove waste from legacy ponds and silos on the site. As the mission changes the company has defined a transformation plan which sets out how it will transform the business to deliver value by accelerating hazard reduction and increasing value for taxpayer’s money through improved efficiency [2].

Sellafield is transforming…….

“We are preparing for the mission change and have defined the organisation we want to be in ten years’ time – how we operate internally, our size and shape, the way we work with the supply chain, and our ability to maximise wider opportunities in the future.”

“We are developing a high-performance, value-led organisation that reduces high hazard faster, costs the taxpayer less, and responds more quickly to potential funding changes. At the same time, we are looking for ways to maximise the socio-economic benefit from our funding and supply chain spend.”

1.2 Nuclear Decommissioning Authority strategy and alignment with the Sellafield value streams

Since April 2016 Sellafield Ltd has been a wholly-owned subsidiary of the NDA, the organisation established to ensure the UK's nuclear legacy sites are decommissioned and cleaned up safely, securely, cost-effectively and in ways that protect people and the environment. The NDA strategy [4] describes the high-level approach to delivering this mission and this is structured around themes which include:

Strategic theme	Description
Spent fuel management	Safe, secure and cost-effective lifecycle management of spent fuels.
Nuclear materials	Safe, secure and cost-effective lifecycle management of nuclear materials.
Site decommissioning and remediation	Decommissioning and remediation of designated sites, and release of them for other uses. The theme comprises four topic areas, namely decommissioning, land quality management, site interim and end states and land use.
Integrated waste management	Waste management in a manner that protects people and the environment, now and in the future, and in ways that comply with government policies and provide value for money.

The NDA manages seventeen sites across the UK with Sellafield being the largest site and home to the most challenging legacy facilities. Indeed, all of the objectives within the NDA strategic themes are relevant to Sellafield. In line with Site Licence Conditions [5], Sellafield Ltd is responsible for keeping the site safe and secure, cleaning it up to a defined end state to the satisfaction of the NDA, and to facilitate this, the company works in four value streams [6]. Working in value streams enables the company to focus effort and resources on work that will have the biggest impact on the mission in ways that will add value and reduce waste. Value can be defined in many ways for example cost efficiency, risk or hazard reduction or acceleration of the programme, Sellafield Ltd's approach to defining value is consistent with the NDA value framework [7].

The four Sellafield value streams are consistent with the NDA strategic themes, with the exception of integrated waste management. Wastes are a key component of all of the value streams arising from current operations, retrievals and decommissioning. Successful delivery of the Sellafield mission relies on the availability of a sustainable waste management infrastructure to support all of the value streams.

	Strategic theme	Description	Value delivered
Waste management	Retrievals	Reduction of high hazard risks from legacy facilities	By retrieval of nuclear waste, fuel and sludge that is stored inside legacy ponds and silos as fast as possible.
	Remediation	The clean-up of the Sellafield site	Through schedule effectiveness and cost efficiency. Several cost-saving opportunities are being explored, including work schedules, waste segregation, storage and process improvement.
	Spent fuel management	The receipt, reprocessing and storage of spent nuclear fuel	By doing this as cost efficiently as possible.
	Special nuclear materials	The safe, secure and appropriate storage of special nuclear materials	Through cost efficiency.

1.3 Purpose and scope

Why scientific underpinning and technology development?

In order to deliver its mission to safely and securely remediate the Sellafield site, the company is required to ensure that all processes and technologies used or planned to be used (known as the "Technical Baseline") are sufficiently underpinned by R&D. This is captured in the Technical Baseline and underpinning Research and Development (TBuRD) document and is reviewed on an annual cycle. One of the cornerstones of Sellafield Ltd's business is a reliance on scientific underpinning of its processes. Sellafield has been at the forefront of science and technology since the beginning of the nuclear age. These decades of activities have yielded an enormous volume of scientific information on which Sellafield Ltd bases its processes. The importance of this underpinning is embodied in the Office for Nuclear Regulation's (ONRs) Safety Assessment Principles for Nuclear Facilities [8]:

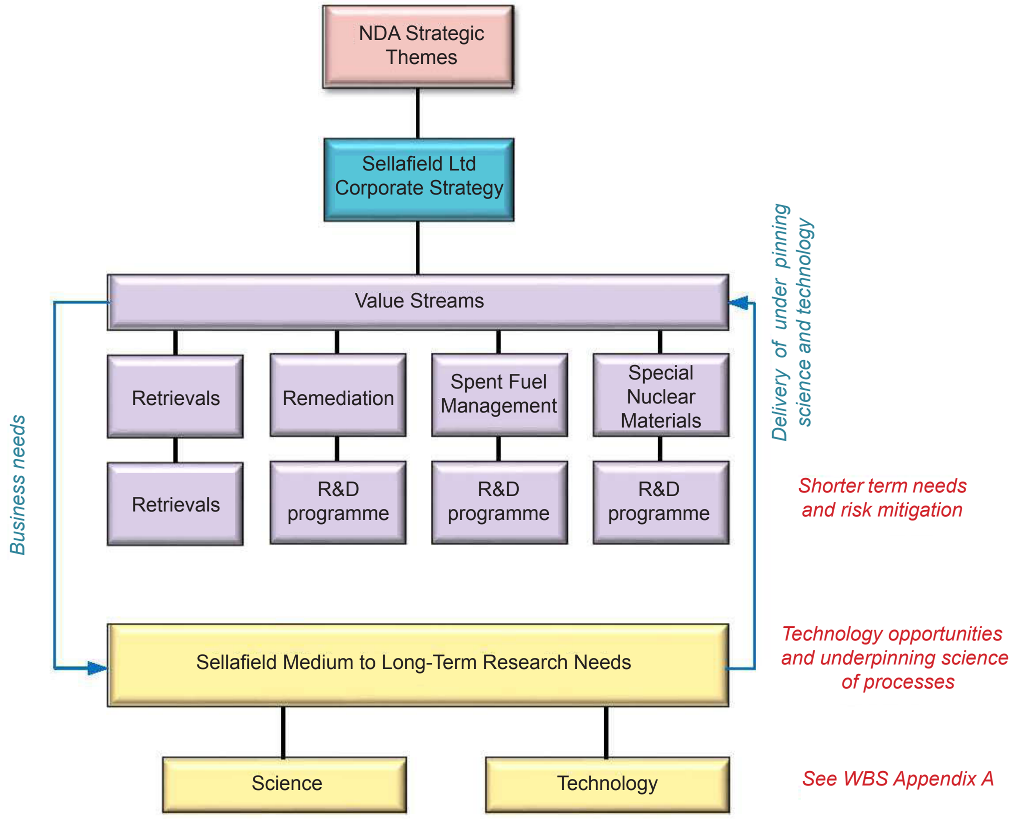
Engineering Principle EMC2

The safety case and its assessment should include a comprehensive examination of relevant scientific and technical issues taking account of precedent when available.

The relevant science applicable to operations is captured in either Sellafield's internal management systems or published in scientific literature and the four value streams discussed in Section 1.2 have technical programmes that focus on the shorter-term needs and risks associated with their operations. There are however, areas where Sellafield needs to develop more detailed scientific understanding of processes particularly where more knowledge and understanding is required or where the mission is changing.

Sellafield is the largest UK nuclear site undergoing decommissioning with a diverse range of complex technical challenges. This is an expensive process, lasting more than 100 years, with the current estimate calculated to be £90 billion (undiscounted) [9] to cover the decommissioning of facilities, managing and disposing of all waste and the remediation of land. This figure is based on assumptions, decisions and technologies that are currently available and scientific underpinning provides the necessary underpinning of this baseline. As the mission evolves there is an opportunity to adopt more modern techniques and invest in innovative technologies to meet the challenges of the future mission. There are areas where new and emerging technologies can be progressed through the Technology Readiness Levels (TRL) scale (Section 3) to a point where they can be integrated into the business by the value streams.

It is essential that through the transformation process the company understands where investment is needed for scientific underpinning and to introduce new technologies that can assist the complex job of cleaning up Sellafield. To complement the R&D programmes delivered via the value streams, a corporate function of Sellafield Ltd manages the R&D programmes required to deliver underpinning science of processes and new innovative technologies aligned to the needs of the business. This R&D forms the subject matter of this document "Sellafield medium to long-term research needs". The figure below illustrates how the research needs fit into the hierarchy stemming from the NDA Strategy.



How the medium to long term research needs are aligned to the value streams

The purpose of this document is to:

- Clearly articulate the medium to long term science and technology research needs requiring R&D investment aligned to the Sellafield mission.
- Provide the company with the information it needs to make informed decisions on work prioritisation.
- Encourage opportunities for dialogue and involvement in R&D from academia, the supply chain and stakeholders.
- Set out the medium to long term research needs where work needs to be initiated in the next four years for the benefits of this work to be realised by the value streams. The research needs captured on the template in Appendix B provide an indication of the timeframe for when a particular piece of research or a technology is required.
- Ensure efficient use of resources. There is an opportunity to maximise the use of available funding routes such as the RCUK and Innovate UK.

The research needs will be reviewed annually to ensure that they remain focussed and robust.

The benefits gained from collating the medium to long-term research needs are:

- Clarity between research needs and the work being (or that will be) undertaken.
- Structure and consistency in the presentation of research needs across the business.
- Visibility of research needs across the business will ensure duplication and overlaps are avoided leading to improved efficiency.
- Identification of priorities so that resources can be used in an effective manner.
- A facilitation tool for engagement with the supply chain and academia that will focus research, making efficient use of programmes from external sources such as Research Councils and Innovate UK.

Section 2 Analysis of scientific needs

2.1 Underpinning science

Why scientific underpinning and technology development?

The Sellafield mission is technically complex and requires programmes of underpinning science to support it. Whilst ongoing programmes are aligned to the current mission, it is critical that the needs of the changing mission are periodically reviewed to ensure that resources are invested in the areas of most importance to the business. As Sellafield is undergoing transformation this further supports the need for a high-level review of the needs of the business. A review was carried out with input from both senior technical managers and specialist technical leads from across the business which identified five key science themes that cut across the value streams. A detailed exploration of each of the scientific themes was then undertaken to develop the topic areas in the work breakdown structure (Appendix A) and to clearly articulate the research needs on the template presented in Appendix B.

A summary describing the subject matter of each of the science themes is presented in Section 2.2 of this document.

The five science themes are:

- *Materials science*
- *Process chemistry*
- *Particulate behaviour*
- *Data science*
- *Environmental science*

Operator working with a radiochemical glovebox (*Image courtesy of the National Nuclear Laboratory)*

2.2 The five science themes

2.2.1 Materials science

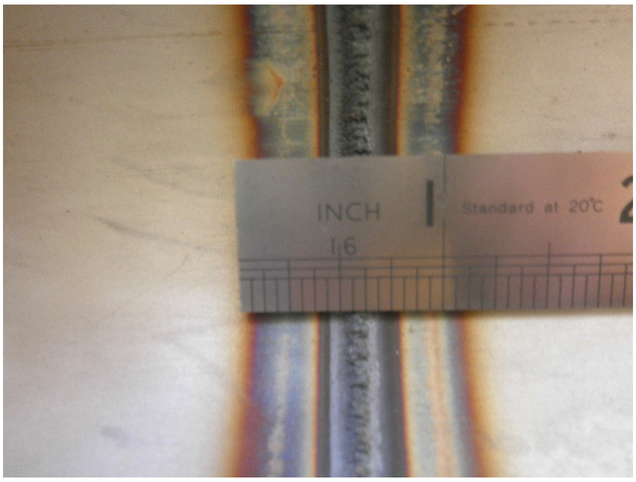
A wide range of materials are used on the Sellafield site, often for unique and challenging applications. These materials are typically used in equipment for highly radioactive processes, providing reliable shielding and containment of hazardous solids, liquids and gases. A common feature of these operating environments is the requirement to maintain performance under beta, gamma, alpha and/or neutron irradiation. Depending on the application, the materials can also be required to perform in environments which are demanding in other respects, including high temperatures, pressures, acidity and abrasion.

The unique challenges of industrial operations in a nuclear environment make replacement of installed equipment extremely difficult and so the materials are often expected to have long service lifetimes, often for several decades and occasionally for more than a century. For example, waste containers are being held in storage prior to geological disposal. A further consequence of the nuclear environment is that access for monitoring or inspection can be difficult. It is therefore important that material properties in the relevant environment are well understood, so that performance throughout the operating life can be confidently predicted. Nevertheless, there is still a requirement to monitor the materials performance of key equipment using remotely deployed instrumentation.

A fundamental understanding of the chemical, physical and engineering properties of materials in their relevant operational environment, backed up with appropriate monitoring and inspection, therefore allows appropriate decisions in support of existing operations and design of new plants.

The materials used on the Sellafield site include:

- Steels and other ferrous and non-ferrous alloys are used in a range of applications, including spent fuel cladding, process vessels and pipework, shielded cell liners, waste containers and process equipment.
- Spent fuel as metals, oxides or other compounds.
- Polymers used in, for example, seals and hoses.
- Glass, ceramics and cement grouts as encapsulating or immobilising matrices for radioactive waste.
- Concretes and other construction materials.
- Electronic components in control, monitoring and inspection systems.
- Novel materials which may have the potential for future uses or to replace existing materials.



Scientific research provides an understanding of how oxidation (heat tint) affects corrosion resistance on stainless steel fabrications used in the manufacture of storage containers


A key nuclear safety requirement for product storage is containment, it is important to understand the effect of surface finish on performance, including the bar code identifiers

The key areas for scientific underpinning in this theme are:

i. Improved inspection – There is a need to understand the current plant condition and have confidence that life limiting degradation will be detectable before failure and therefore underpin long-term storage and operation. This addresses the condition of plant/infrastructure, process plant and materials. Information is required to underpin strategy and operations and meet regulatory requirements.

ii. Material performance and degradation – Underpinning science of metallic, cement-based and fuel materials performance in both current and future applications to enable assessment of ageing plant structures, new build plants, as well as performance of stored spent fuel.

iii. Polymeric and non-metallic materials – Degradation mechanisms and long-term performance, impact of material changes on performance, inspection of polymers *in situ*, assessment of new materials and technologies (including 3D printing), management of ageing plant through use of modern repair technology.

iv. Container materials performance – There is a range of package configurations on the Sellafield site for special nuclear material, raw waste and encapsulated waste packages. There is a requirement to predict performance of these over 100 years or more with respect to the store environment during service, including for example, the integrity of welds and lifting and closure mechanisms. This will also require novel *in situ* inspection capability.

v. Waste product evolution and interactions – Understanding of the way in which the wastes interact with immobilisation matrices to predict performance. This includes cement based wasteforms, thermally treated wastes and stored raw wastes (for future encapsulation within various potential finishing plants).

vi. Improved/new materials and manufacture – Assessment of novel materials and manufacturing processes so that advantage can be taken of features that may improve performance, for example in high radiation environments.

vii. Spent fuel storage – Condition and degradation in both wet and dry storage of fuel and cladding including short term nuclide release, environmental conditions (such as temperature over time) and condition monitoring.

viii. Graphite disposal - Effective method to deal with the graphite waste stream, storage and disposal, *in-situ* characterisation.

ix. Effects of radiation on materials – Understanding and quantifying the impact and long-term effects on materials in storage, degradation of materials e.g. polymers and processes already occurring e.g. corrosion, with emphasis on Sellafield specific experiments with irradiated material.

x. Infrastructure – Behaviour of materials used in building structures, pipe bridges and stores such as steel reinforced concrete over long timescales especially corrosion.

2.2.2 Process chemistry

Historically, spent fuel is reprocessed by separating the spent fuel into its components, uranium, plutonium, waste streams and authorised discharges. The Sellafield site will continue to reprocess fuel until 2018 in Thorp and 2020 for Magnox fuel supported by an infrastructure of treatment facilities such as the Enhanced Actinide Removal Plant (EARP), the Site Ion Exchange Plant (SIXEP) and the Waste Vitrification Plant (WVP) to manage and process the waste streams from reprocessing operations. As the site moves from reprocessing, some of these plants will be decommissioned and others may be used to process wastes from the clean out of redundant facilities. In addition, since there is no longer a requirement to reprocess fuel, an alternative approach is to store spent fuel in purpose-built facilities prior to a future decision on final disposal.

There are more than 100 tonnes of plutonium dioxide that need to be consolidated at Sellafield in a safe, secure environment with planned storage for up to 100 years or more. This drives the need for minimum repackaging prior to plutonium disposition being fully implemented.

The underpinning science behind these processes needs to be understood so that:

- Control of operational processes can be maintained at all times, understanding the acceptable process parameters and the consequences of deviation from those parameters, and by monitoring these parameters on plant.
- Plant efficiency can be improved, for instance by increasing plant throughput, maximising separation factors in an effluent treatment process, increasing waste loadings in an encapsulation process to reduce the number of waste packages requiring storage, or to improve product quality.
- Existing processes can be adapted to accept changing feeds, for example to deal with changing effluent composition.
- New processes can be developed to assist in the delivery of the changing mission, including for example, alternative reagents for post-operative clean out of redundant plant.

This understanding will also be incorporated in process models to aid in predicting the performance of existing processes and the design of new processes. The key areas for scientific underpinning in this theme are:

i. Chemistry and modelling of highly active liquor systems - Defining the operating envelope of existing highly active liquor systems for handling POCO liquors for example foaming in evaporators, kinetics of ammonium nitrate decomposition and the generation of droplets in boiling evaporators.

ii. Spent fuel pond chemistry – See materials science, spent fuel storage (Section 2.2.1).

iii. Grout/encapsulation chemistry – Supports the re-purposing of existing processes and the development of novel systems, including novel mixing technologies, immobilisation of new wastes by existing processes (primarily in drum mixing), higher waste loadings and new encapsulant formulations (see particulate behaviour).

iv. Understanding of site-wide off-gases – Off-gas treatment and abatement for volatiles and reactive gases, aerial production mechanisms for new and existing operations, understanding potential mechanisms for unexpected reactions leading to aerial discharges (including organics). This topic area has related subject matter with other areas of process chemistry and with particulate behaviour.

v. Stored plutonium – For a range of solid plutonium chemical types and physical forms; an understanding of surface speciation and chemistry, bulk behaviour evolution, bevaviour of chloride contaminated plutonium in heat treatment processes and storage and developing new characterisation techniques where required.

vi. Effluents – Improved understanding of the composition and behaviour of effluents during retrieval, POCO and remediation. Optimisation of abatement processes to process changing feeds.

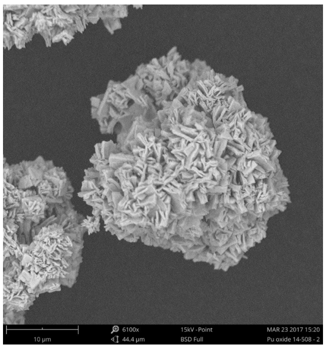
vii. Behaviour of POCO solids and residues – To underpin decisions on retrieval and treatment of solids/residues, including their compatibility with downstream processes, physical and chemical characterisation of residual solids and organic residues is required.

viii. Chemistry of vitrification – Definition of the operating envelope for the vitrification process. Behaviour in long term storage and abatement of process volatiles.

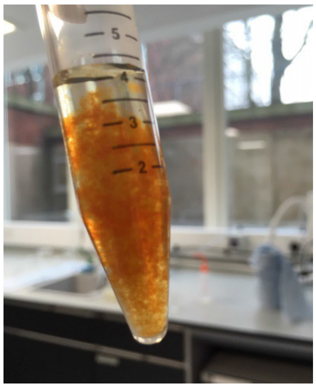
ix. Radiolysis – Radiolysis of a range of materials including water in contact with radiogenic surfaces (e.g. POCO slurries; plutonium dioxide (PuO_2); spent fuel; exotics; metals) leading to gas generation (including hydrogen) and degradation of the surface, organics and cementitious phases.

x. Microbiology – Understanding their impact on, for example processes, storage and infrastructure such as pipe lines.

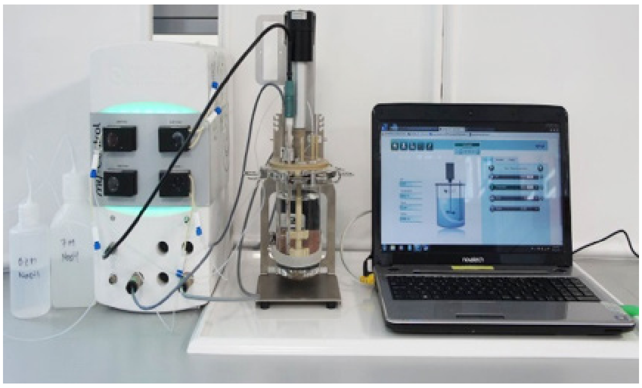
xi. Contamination and decontamination – Improved understanding of contaminants including chemical composition, concentration and binding mechanisms for the development of tailored or improved decontamination technologies that could remove contamination through a targeted approached whilst minimising wastes.



A catalogue of PuO_2 SEM images provides the information needed to understand the changes that have occurred as a result of long-term storage of PuO_2 on the Sellafield site

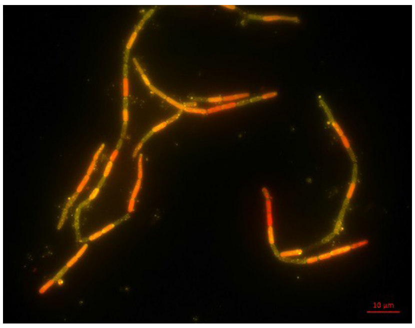


Radionuclides are removed from the aqueous phase in the EARP process into the ferric floc precipitate *(Image courtesy of the National Nuclear laboratory)*



Research has used a novel, bench-scale rig to mimic the EARP process in the laboratory
(Image courtesy of The University of Manchester)

Research on glass formulations so that new feeds arising from wash-out operations during POCO may be successfully solidified by vitrification



A number of legacy ponds have exhibited seasonal microbial activity, often referred to as "algal blooms" during which visibility within the ponds is impaired, potentially hindering waste retrieval efforts. DNA sequencing of samples from a pond at Sellafield has indicated the presence of a photosynthesising cyanobacterial species that displays tolerance to radiation and alkaline pH. This knowledge will be crucial in developing approaches for controlling the blooms *(Image courtesy of The University of Manchester)*

2.2.3 Particulate behaviour

This science theme covers the properties and behaviour of particulate materials on the Sellafield site. These include sludges and slurries found in legacy facilities or that may be generated during POCO operations and solid particulate or liquid droplets in gas streams.

A large proportion of the radioactive sludge at Sellafield is a by-product from the storage of nuclear fuel and other debris found in historic ponds and silos on the Sellafield site. However, there is also a significant inventory of other sludges generated as a result of effluent treatment processes e.g. spent ion exchange media, precipitated flocculent masses and insoluble solids arising as a result of evaporator concentration and fuel dissolution.
To enable safe retrieval, processing and packaging of these materials for long term storage and disposal it is important to understand their composition and behaviour throughout the lifecycle of their formation, evolution, transport and disposition.

Research requirements include, for example, understanding of the composition and behaviour of sludges generated as a result of POCO operations; or residual solids that have formed in tank heels with little existing characterisation. There is a need to understand the impact of these on the decommissioning programmes and explore treatment options.

Suspended solid particulates or liquid droplets in gases can be generated in a number of ways including high pressure water jetting of radioactive surfaces, and as a result of retrieval activities from open air ponds. These source terms will become increasingly significant during decommissioning operations. There is a requirement to reduce uncertainty in and to fill knowledge gaps in radioactive airborne particulate generation and evolution behaviour. This will underpin design of future plants, abatement techniques, aerial effluent flowsheets, area classifications and personnel protection needs.

Plutonium dioxide is stored at Sellafield as dry powder and is also recognised as a particulate material, this area of research is captured in process chemistry (Section 2.2.2 – stored plutonium).

The key areas for scientific underpinning in this theme are:

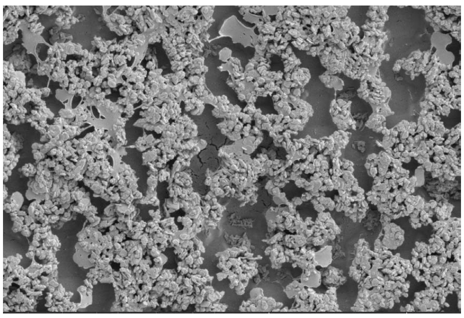
i. Properties of POCO sludges and slurries – Understanding the sources and behaviours of residual solids that exist as mixtures, potential benefits of separating components and effects of additives/cleaning agents on behaviour.

ii. Properties of radioactive sludges and slurries - For example, bulk uranium corrosion product sludges, colloid formation, predicting and monitoring gas production (including hydrogen), settling behaviour and the effect of solid surfaces on radiolysis of sludges and *in-situ* measurement.

iii. Grout systems for encapsulation – Processing and product properties for both inorganic cement systems and organic polymer encapsulants (see process chemistry).

iv. Release of airborne particles - Understanding of liquid aerosol generation from processes such as high-pressure water jetting, splashing and bubble bursts and solid particulate generation and disposition generated, for example, as result of cutting and grinding operations.

v. Abatement of aerial effluents – Effectiveness of abatement techniques such as filters and scrubbers as a function of particle size, distribution and air velocity (see process chemistry – understanding of site wide off-gases).



SEM images of sludges are obtained to understand their composition as part of a research programme to underpin the safe retrieval, processing and packaging of these materials

2.2.4 Data science

Large volumes of data have been collected and used daily on the Sellafield site throughout its operational history. With the development of more rapid and *in-situ* methods to characterise the data, this volume will grow exponentially. These data are required to support decision-making; decisions that maintain efficient and safe routine plant operations and increasingly, that support the planning of future decommissioning and waste management programmes.

In order that the best decisions are made, appropriate data of appropriate quality are required. This needs to be readily accessible in a form that aids interpretation, using models where appropriate and allows prediction of future states depending on what actions are taken, or not taken in response to the available information.

The data science theme addresses all aspects of data collection, storage, processing, access and use to support decision-making at both operational and strategic levels. The key areas for scientific underpinning in this theme are:

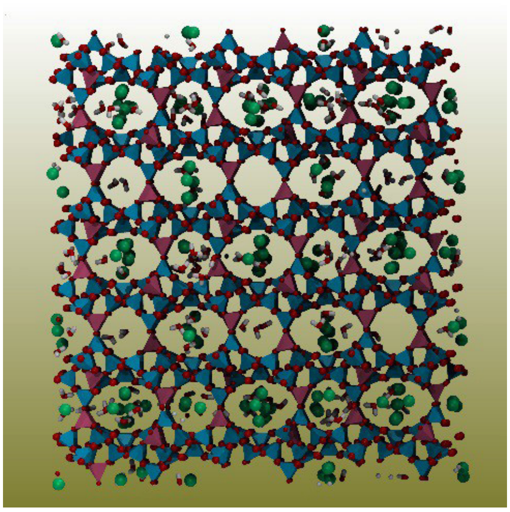
i. Sources of data - Technologies are required to extract data from a number of sources in cost-effective way, for example from obsolete systems. This is an enabling task that will support the data science theme but R&D is not anticipated.

ii. Measurement science - Novel techniques with site-wide applications to generate improved data in harsh environments, calibration free systems and reduced sampling uncertainty.

iii. Data quality – Statistical modelling to complete datasets and trawling software to fill gaps where information exists but where it is an incompatible or inaccessible format.

iv. Data processing – Bayesian statistics or process based models applied to Sellafield needs. Machine learning, artificial intelligence and data mining.

v. Data use – Validation and verification using visualisation techniques such as virtual and augmented reality.



The image shows the molecular structure of clinoptilolite which is the material used as the ion exchanger on the SIXEP plant. Applying data analytics to plant data and coupling it with machine learning and mechanistic understanding develops new methods for quantifying uncertainties with respect to plant performance

2.2.5 Environmental science

During an evolving decommissioning programme over many decades, particular attention will be paid to the remediation of ageing structures and land quality management. In particular, Sellafield's Separation Area includes a number of legacy plants associated with radioactive waste reprocessing. A relatively small amount of radioactive liquor is known to have leaked to ground from certain of these plants. The site therefore operates a programme of groundwater monitoring and will carry out appropriate remediation as part of the clean-up programme. There is a good scientific understanding of the behaviour of radioactivity in the environment that has been developed to support current reprocessing operations at Sellafield, however the coming years will see a change in focus to environmental remediation. Understanding of the long-term fate of radioactivity in the environment and its potential impact on a changing natural and man-made environment is required to aid decision making for remediation.

The key areas for scientific underpinning are:

i. Re-use and recycling of materials – To ensure that the waste management hierarchy is optimised there are opportunities to re-use materials such as uncontaminated building materials, for example, as aggregates on other parts of the site.

ii. Contamination in facilities maintained in a long-term quiescent state - The current strategy is to take buildings through decommissioning and demolition to the base slab.

iii. Behaviour of contamination in the subsurface - Understanding the chemical and biochemical processes in a range of materials such as concrete, soils, underground pipes and near surface hydrogeological environments. Evolution of the Sellafield site through climate change scenarios. Methods to improve understanding of hydrogeology of the site and surrounding area. Modelling and the biosphere.

iv. Locating and quantifying contamination in the environment – *In-situ* or in-field groundwater monitoring technologies, laboratory techniques for environmental samples, *in-situ* measurements from higher activity zones, *ex-situ* for characterisation of ground and subsurface. Changes in distribution over time.

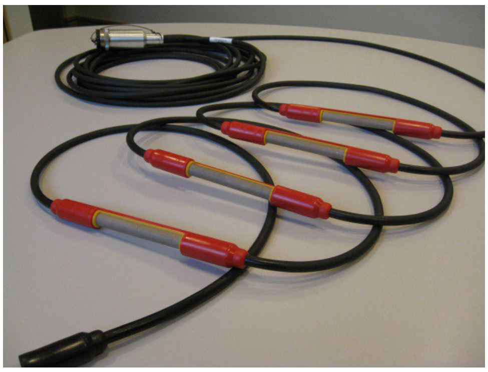
v. Impact of contamination in the environment – Development of an integrated environmental model using modern techniques and computing.

vi. Soil and groundwater remediation – Development of site material balance and a model for evaluation of remedial end points, development of methods for the removal and packaging of ILW soils, alpha contaminated soils and trench wastes. Methods for fixing contamination in source zones and methods to limit intrusion for example barriers or capping. Contingency planning.

vii. Disposal of wastes – Mechanisms for the mobilisation and transport of key radioactive and non-radioactive species from managed disposal of wastes on the site or from buried structures which may be left *in-situ*.

viii. Socio-economic modelling – Social value of the site and its associated infrastructure to the linked community. This knowledge can be used to address remedial end points, influence land use and redevelopment plans.


Column experiments at the University of Manchester to research techniques to control the spread of groundwater contamination


Development of sensor arrays with novel electrode materials by the British Geological Survey, to measure long-term electrical property changes in radioactively contaminated soils using geoelectrical monitoring technology

Section 3 Technology development

3.1 Identification of technology opportunities

A review of the value streams was undertaken with the technical leaders from these areas. This was an iterative process focussing on the process steps needed to achieve the clean-up of the Sellafield site, including characterisation, POCO, dismantling, waste treatment and storage. Six key themes emerged where opportunities for employment of innovative technologies, tools and techniques, to reduce costs, improve safety and reduce timescales were identified.

As with underpinning science, a work breakdown structure has been developed for the six technology themes (Appendix A) and a series of Science and Technology Needs Sheets for each topic have been articulated.

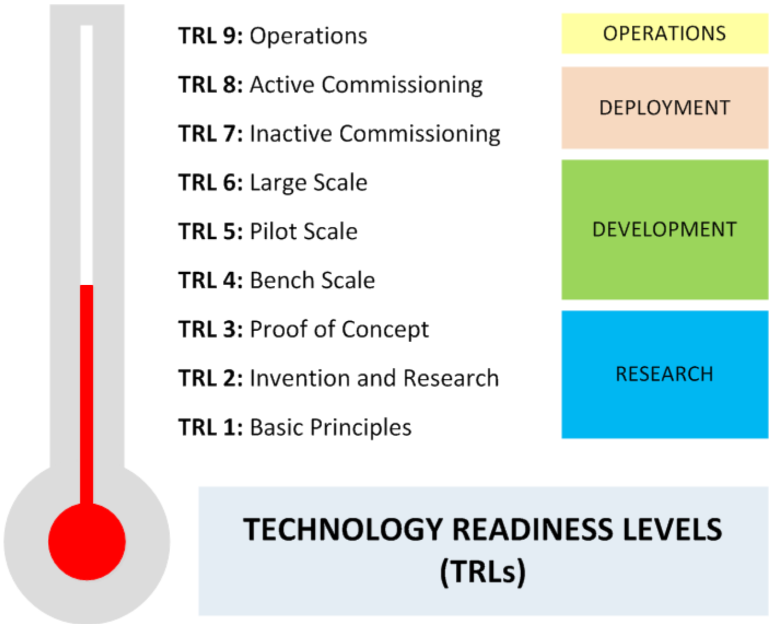
The areas identified for R&D investment to develop technologies:

- ***Waste treatment and conditioning and packages***
- ***Condition monitoring and inspection of interim stored wastes and products***
- ***Novel analytical techniques***
- ***Post operational clean-out***
- ***Decommissioning***
- ***Robotics and artificial intelligence***

Each of the areas identified for R&D investment is discussed in Section 3.3. These are expected to change as the decommissioning and clean-up mission evolves.

3.2 Assessment of technical maturity

Development programmes addressing the needs of the business aim to bring forward technologies through the Technology Readiness Level scale from fundamental research and early development, lab and pilot scale through to active demonstration.



Sellafield Ltd has adopted the TRL scale that is used widely across the NDA estate and there is detailed guidance on this in EGG 10 [10].

The MIRRAX remote inspection vehicle has been developed, with The University of Manchester, to explore and characterise enclosed legacy facilities which have limited access ports. Its reconfigurable design means that it can be deployed through a 150mm port before changing its footprint shape to provide a stable platform for mobile characterisation

3.3 The six technology development themes

3.3.1 Waste treatment, conditioning and packages

There is a requirement for radioactive waste producers to convert waste into a passive and safe form as soon as reasonably practicable for intermediate level wastes. This has usually been achieved by encapsulation in a cement based matrix. Cement based encapsulants offer many advantages such as robust products with well understood properties at a reasonable cost and continue to be the baseline technology for a number of waste streams. However, developments in cement powder supply in response to a range of sustainability challenges present a threat to the long-term availability of current materials. Furthermore, cements have a number of disadvantages and are unlikely to be the optimal solution for all future waste immobilisation requirements. Consequently, R&D is essential to deliver credible alternatives for encapsulation of all higher activity wastes.

There are various insertion points for alternative treatment technologies into the technical baseline, depending on the retrievals timescale of each waste stream, and these generally fall between 2022 and 2040. To underpin decisions on waste immobilisation strategies over this timescale, research is required on a range of options which have potential benefits over Portland cement based processes, including:

- Thermal technologies
- Alternative low temperature processes, including geopolymers, polymers and novel inorganic cements

Waste containers used for disposal of waste are expensive, with current projections suggesting that over the lifetime of the Sellafield mission up to £4 billion will be spent on waste containers alone. There is therefore an opportunity to benefit from new manufacturing techniques in order to reduce the baseline costs. An R&D programme is required to provide an improved range of cost-effective waste container options that have been designed to facilitate decommissioning.

Research is ongoing into the feasibility of thermal treatment as a technique to immobilise wastes at Sellafield, this is a test facility in the NNL Workington facility. Cameras inside the melter provide the ability to monitor progress *(Both mages courtesy of the National Nuclear laboratory)*

Example of products generated from alternative treatment processes thermal (left) and geopolymers (right)
(Both images courtesy of the National Nuclear laboratory)

The key areas where technology development opportunities have been identified are:

i. Thermal treatment – Understanding and treatment of plutonium contaminated material (PCM) feeds, smaller volumes and problematic wastes, application of hot iso-static pressing to higher active and intermediate level wastes including feeds containing plutonium, sludges and clinoptilolite. Storage of wastes ready for later vitrification and long-term evolution of products (this is linked to underpinning science of the chemistry of vitrification in Section 2).

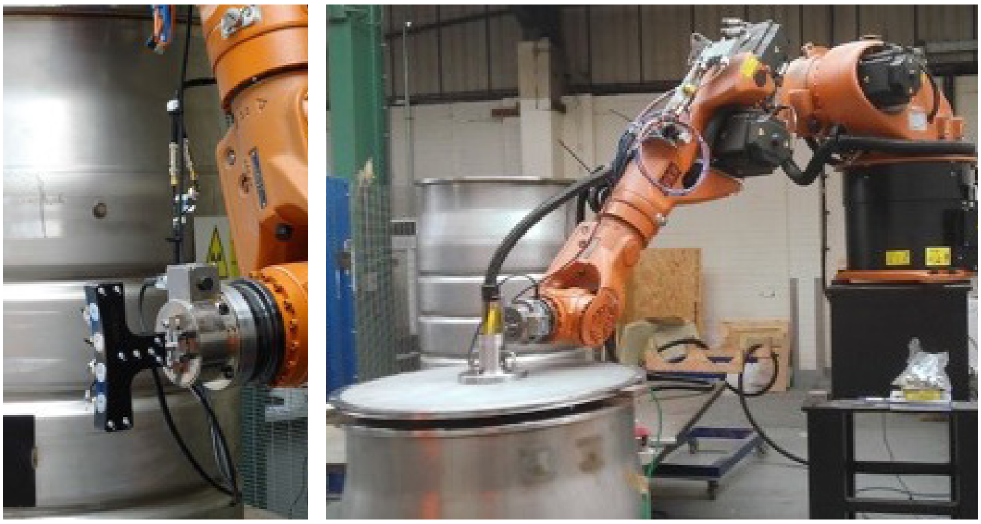
ii. Encapsulants – See underpinning science themes; materials science, process chemistry and particulate behaviour.

iii. Other waste treatment – treatment or pre-treatment of wastes that are incompatible with current treatment options.

iv. Package and store innovation – feasible alternative container and package design, flexible adaptable designs, alternative disposal concepts, entombment media and product marking/identification.

3.3.2 Condition monitoring and inspection of interim stored wastes and products

For many years encapsulated waste products have been stored on the Sellafield site and over the next decade, retrievals from legacy ponds and silos will generate many more. As Sellafield evolves into a waste management and remediation site, the range of waste products is also expected to increase. A programme of inspection of key properties of waste packages will ensure safe storage. With many thousands of packages located in engineered stores, it would be impractical to extract and inspect all packages, so *in-situ* measurements will be required. To address the site wide challenge of package and stores inspection there is a need to provide a range of measurement and deployment techniques to demonstrate control, take appropriate mitigating action where required and reduce dose to workers who currently provide an *ad-hoc* measurement capability. There is an additional driver to aggregate the many Condition Monitoring and Inspection (CM&I) measurement techniques and deployment requirements to increase benefit and improve efficiency across Sellafield.



A range of tools and techniques are required to inspect packages and manage storage

The key areas where technology development opportunities have been identified are:

i. Waste and product behaviour – Understanding the evolution of nuclear materials stored and how it impacts on long term safe storage. Measuring materials properties *in-situ* will underpin the storage strategy, for example, how much heat is being generated by the material and what does the storage system need to tolerate.

ii. Waste and product package – Inspection/measurement tools or techniques to enable the detection of signs of unexpected degradation and *in-situ* technologies requiring robotic or automated deployment in dark store environments where traditional communication channels or power sources are absent.

iii. Store conditions – For existing stores, obtain a better understanding of how store environments can change under a range of likely scenarios for different waste packages, to increase predictability of the environment and thus help infer waste behaviour. Tools for monitoring the environment to provide an early indication of deviation from the predicted environment including temperature, humidity and chloride. Understanding long term optimum storage conditions for a range of products to provide information that could be used to influence new store design and build and to improve existing stores.

3.3.3 Novel analytical techniques

As the Sellafield mission evolves there will be a fundamental change in the analytical demand from Sellafield customers resulting in a switch from mainly process analysis of confirmatory samples to a greater proportion of characterisation of material with less understood precedents – the nature of the latter means that the measurement requirement will need to be determined on a case by case basis. The analytical capability must therefore be agile enough to meet a constantly changing demand. The focus in this area is therefore to deliver technologies that will provide innovative means to meet the future challenge in a safe, effective and efficient manner.

Sellafield Ltd has been looking for ways to improve efficiency in the collection and analysis of concrete samples in a safe manner. ViridiScan uses a laser to remove a small sample for *in-situ* analysis

The key areas where technology development opportunities have been identified are:

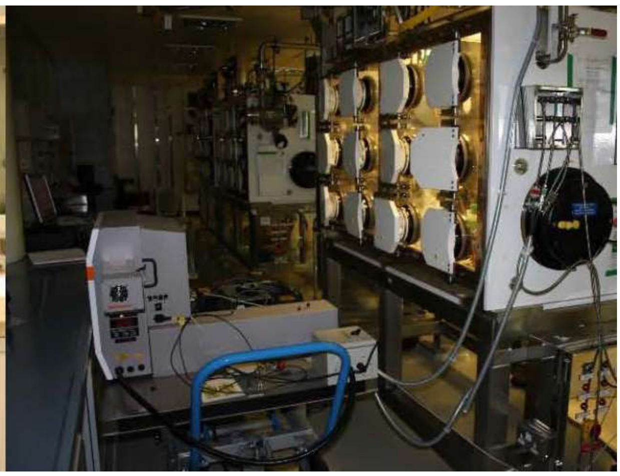
i. Tool and technique evolution - Focussing on the improvement of existing tools and techniques, this might be through the ability to deploy *in-situ* techniques, improved sampling (including automation of sampling), minimisation of waste generation, non-destructive analysis and improved accuracy, precision and limits of detection.

ii. Tool and technique revolution - Development of tools and techniques that might change the way analysis is carried out, for example process modelling, control and safety case demonstration to remove the need for analysis, direct analysis on primary samples and techniques that require smaller samples with less waste generation. Examples include, autonomous and automated analysis and linked multi-analytical equipment.

iii. Engineering - Development of engineering techniques or processes that increase safety and will allow a greater degree of agility and/or efficiency in the operation of Analytical Services for example, miniaturisation of instruments making them small and light enough to take to the plant or field.

iv. Information technology – Robust information/data management systems are required to underpin the techniques developed in (i) to (iii) above. The need will be defined by the technology theme but the solution(s) will need to be integrated into the innovations delivered via the data science theme.

Sample preparation for laboratory analysis *(Both images courtesy of the National Nuclear laboratory)*



Raman spectroscopy linked to a glovebox to analyse plutonium containing solids

3.3.4 Post operational clean-out

The normal approach to POCO is the clean down of a facility using the tools and processes that are readily available. Sellafield Ltd is exploring opportunities to investigate and consider the potential for additional activities that go beyond the traditional approach to POCO. An alternative approach has been termed “Enhanced POCO” and could provide a step change in the lifetime costs through reduced surveillance & maintenance and future decommissioning burden. In addition, there are significant potential savings through increased decontamination, using for example more effective reagents, which could provide dose reduction (and hence greater options for decommissioning) and waste declassification (facilitating a reduction in storage and disposal costs and/or alternative storage arrangements).

Complex networks of pipes and vessels present a significant decontamination challenge at Sellafield

Electrochemical enhancement of nuclear decontamination solutions is being developed as a potential technology that can provide decontamination using aggressive reagents *(Image courtesy of the National Nuclear laboratory)*

The key areas where technology development opportunities have been identified are:

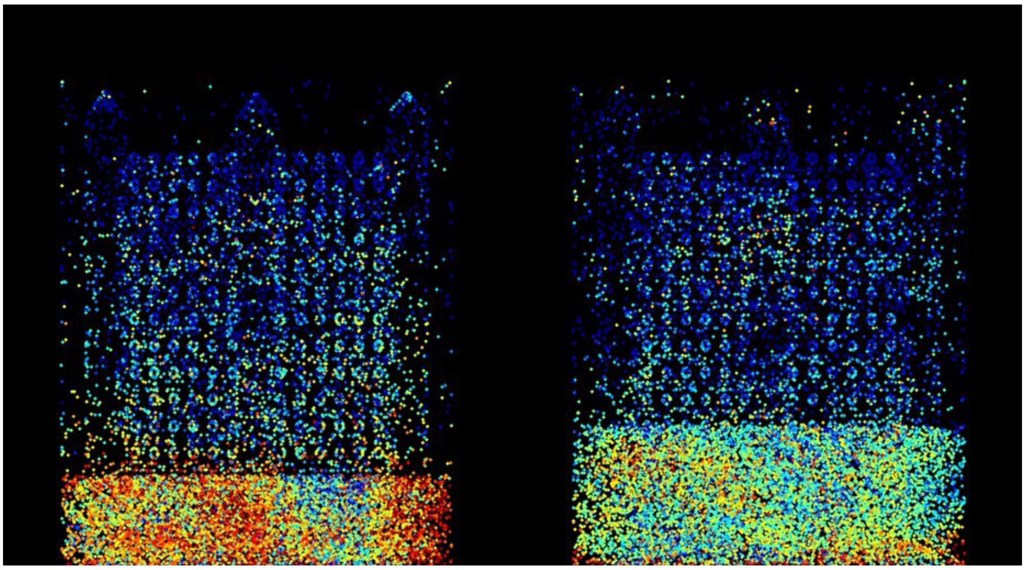
i. Characterisation of the system – Tools and techniques to establish location, quantity and form of the material to identify appropriate treatment processes (develop both existing and new techniques); methods to determine the materials of construction of pipework and vessels; methods to ascertain the configuration of cells, pipework and vessels.

ii. Access into the system – For information gathering (physical, visible, radiological, chemotoxic); deployment of reagents, chemicals and monitoring probes using existing penetrations and pipework; application of Commercial Off-The-Shelf (COTS) equipment.

iii. Treating the system – Methods to deploy monitoring and sampling equipment and decontamination tools and reagents; methods to remove solids, sludges and effluents; methods to maintain ventilation and containment during POCO operations.

iv. Effluent and waste disposal – Processes for treating contaminated liquid effluents; computer modelling of effluents to understand their compatibility with site treatment plants and optimise use of those treatment plants.

As part of the preparations for POCO, there is a requirement to develop tools to provide information about the distribution of activity in highly active facilities. This device is a tungsten collimated detector and it has been used to provide the activity distribution (pictured below) before the removal of highly active liquor (left) and after replacement (right) with weaker washings



3.3.5 Decommissioning

The decommissioning challenge can be summarised as access to and characterisation of facilities and their content followed by optimised processing of the waste and infrastructure for reuse or disposal. The aim is to provide technologies or techniques that can make this process safer, cost effective and cost efficient.

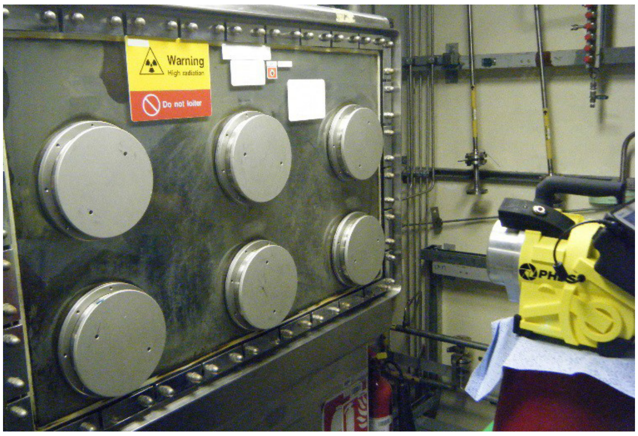
The key areas where technology development opportunities have been identified are:

i. Plant characterisation – Information is required to determine the method, scheme and/or options for decommissioning from a range of relevant parameters which need to be determined. For example, rapid generation of dose maps overlaid onto models of cells with complex networks of pipes and vessels; location and quantity of heels and residues; depth profiles in porous substances in order to generate models for planning.

ii. Infrastructure and enabling activities - Such as access to and from facilities, means to protecting and increasing the productivity of operators and methods for preventing/reducing the spread of contamination.

iii. Plant dismantling - Including techniques for structures, vessels and pipework plus heels and residues for example cleaner cutting methods, reliable deployment platforms that can overcome cluttered environments and interchangeable tooling.

iv. Waste characterisation and conditioning - Sampling techniques for a wide range of wastes with rapid assessment for waste sentencing; local fit-for-purpose treatment and methods for segregation and sentencing.



A range of tools and techniques are needed to obtain information about the inventory in and around facilities, often in challenging areas

3.3.6 Robotics and artificial intelligence

Microelectronics, data processing and robotic technologies, including autonomously operated systems have undergone rapid development over the last 10 years, driven by productivity and safety benefits across a range of industrial sectors, including agricultural, warehouse distribution centres, food and transport and by mass consumer markets in mobile phone, video gaming and the internet sectors.

The government, academia and some industries have recognised that robotics are game changers in the way we live and work in our environment today. Increased utilisation of robotic technology has the potential to significantly increase productivity of UK industry with resulting growth in the UK economy. This has provided national and international funding opportunities.

With the end of reprocessing approaching and as Sellafield Ltd prepares for a programme of decommissioning there is an opportunity to take advantage of this funding to broaden its use of Robotics and Artificial Intelligence (RAI) to increase safety, productivity and reduce financial risk.

The benefits gained from increased use of RAI

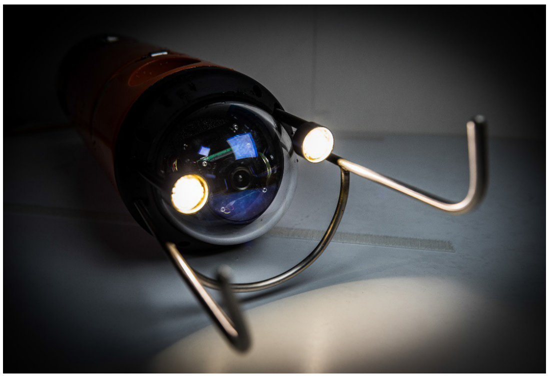
Improved safety - Move the operative away from the hazardous part of the task. Reduce both radiological incidents (e.g. worker contamination) and conventional accidents (e.g. falls).

Increased productivity – Reduce the time associated with decommissioning tasks resulting in cost and schedule improvements.

Job enrichment – Remove dull and repetitive tasks allowing workers to carry out more value adding tasks.

Reduced uncertainty in the nuclear provision – The current nuclear provision includes significant uncertainty associated with the cost of developing required remote technologies. Development of RAI technologies against opportunities should have the additional benefit of reducing the cost uncertainties associated with the required technologies.

Economic growth – Develop technology that UK companies can sell either directly or through the provision of services to the wider UK and international nuclear decommissioning markets as well as other sectors (e.g. Oil & Gas).



Developed with The University of Manchester, the Avexis robot can ‘see’ inside a silo via cameras attached to its body. Recently deployed at Sellafield, the device also has the ability to help dislodge small amounts of waste clinging to the silo wall

Off the shelf robots can be adapted to Sellafield processes, they can be used for a variety of tasks such as waste packaging, size reduction, and sorting and segregation. In scenarios such as this, operators can be removed from the workface which increases safety

The key areas where technology development opportunities have been identified are:

i. Waste processing - Autonomous size reduction capability and 24 per hour/7 day per week sort and segregation with robotically enhanced waste packing to increase productivity, reduce waste packages and stores.

ii. Restricted access decommissioning – Robotic capability for high hazard environments such as high radiation, for example remote devices for small tasks and fully autonomous glove box operations.

iii. Assisted manual operations – Robotically enhanced operatives using wearable technology, robotic assistants to carry out the hazardous part of the task and technologies that can enable an operator to reach the workface quickly, for example robotic scaffolding.

iv. Reduction of deployment risk - Standardised equipment with a single set of spare parts that can be configured in a short space of time. Modular systems that can be adapted to suit, task by task.

v. Interim states enhancements – Robotic techniques for autonomous management of facilities in a long-term phase known as "dry and dark" or stores that can maintain their own systems and manage nuclear waste without operator intervention over the life-time of the stores.

vi. Increasing pond productivity – Techniques that can operate in low visibility to retrieve material from a pond such as heavy items without disturbing visibility or residual sludge. Tether-less underwater systems for inspection in areas that are difficult to access.

vii. Enabling technologies - Complete characterisation coverage of facilities, investigation of the benefits of virtual reality for everyday use to enhance operations and autonomous sampling.

Section 4 Delivery

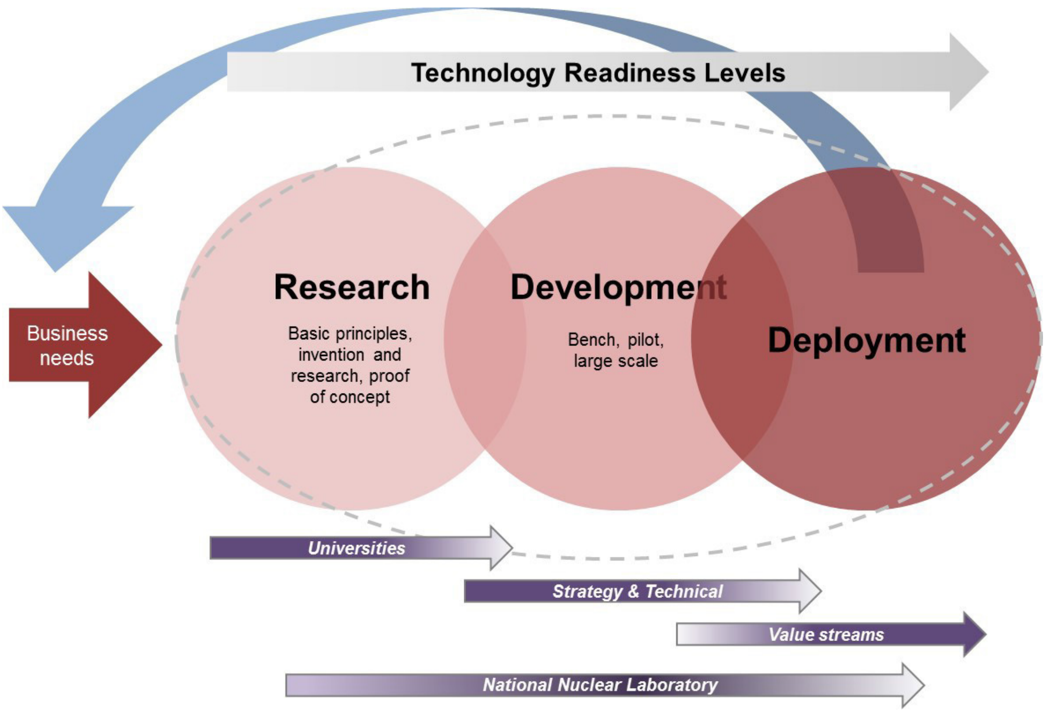
4.1 Introduction to delivery

R&D programmes and projects financially supporting technology development and underpinning science at Sellafield are supported by both Sellafield Ltd and by a broad range of organisations, external to Sellafield Ltd, including the National Nuclear Laboratory (NNL), NDA, Small and Medium Enterprises (SMEs) and the academic sector. Sellafield Ltd has a long history with NNL and in October 2016 a unique agreement was formalised between the two companies who pledged to work together to deliver value for UK taxpayer. As the site drives forward its decommissioning programme which spans 100 years, it is in the public interest for the companies to work more closely together to ensure hazard reduction on the Sellafield site is done safer, quicker and cheaper, as more innovative solutions are developed.

Critical to the success rate for the delivery of the R&D needs is the greater integration and coordination of programmes to maximise efficiency, identify gaps and opportunities and deliver value for money to the UK tax payer. This section describes the resources available to manage and deliver coordinated R&D programmes through research teams drawn from the technical expertise, strengths and experience available in the technical community. By clearly articulating the science and technology areas requiring research and development investment, aligned to the needs of the business, this document aims to encourage opportunities for dialogue and involvement in R&D from academia, the supply chain and stakeholders.

4.2 Delivery of underpinning science and technology

Each science and technology programme area, described in Sections 2 and 3, are to be managed by an Integrated Research Team (IRT) which will provide a multi-disciplinary approach with input from the end user. A number of IRTs have been established already with a delivery programme in place and are demonstrating this successful approach. The IRTs aim to consist of a Sellafield Ltd lead from the Strategy and Technical (S&T) function, expertise from Sellafield Ltd and, where appropriate, NNL, external organisations such as academia, supply chain and regulators. It should be noted that some of the subject matter within the scope of a particular IRT has common elements featuring within other IRTs which will be managed as appropriate, two of the IRTs will support most of the others; data science and robotics & artificial intelligence. This approach draws on the technical expertise, strengths and experience from a variety of sources to provide a coordinated and well-balanced team to deliver an optimised programme. Another benefit of this approach is the potential to maximise funding opportunities and this is discussed in more detail later in this section. Techniques that progress through the TRL scale successfully will be demonstrated in a suitable active environment at Sellafield with the expectation that delivery teams on plant will assess final suitability and undertake selection. The figure shown below illustrates the TRL scale with the varying roles that key functions play as technologies are developed (this is generally a linear process, however research can directly support existing plants and processes that have been adapted to meet new challenges).



4.3 Interfaces and stakeholder engagement

There are a number of existing groups that are relevant to the research needs for Sellafield, for example the Nuclear Waste and Decommissioning Research Forum (NWDRF) and its various working groups, which promotes a common understanding and collaboration between relevant bodies across the UK about respective R&D needs and a process will be developed for engaging with these groups in a coordinated manner across the portfolio of research.

4.4 Funding opportunities

Funding for R&D is available from multiple sources for example Sellafield Ltd, NNL, NDA Direct Research Portfolio, RCUK such as the Engineering and Physical Sciences Research Council (EPSRC) and Innovate UK. Sellafield Ltd has been involved in coordinated research programmes involving multiple universities such as Decommissioning, Immobilisation and Storage soluTIons for NuClear wasTe InVEntories (DISTINCTIVE) and Autonomous and Intelligent Systems (AIS) that have attracted funding from, for example, other parts of the nuclear industry and the EPSRC. Improving the clarity and timing of research needs will lead to improved focus, better use of grant funding and can open up opportunities for co-funded research.

4.5 Additional enabling functions

There are a number of enabling functions:

- This document identifies the research needs for technology development and underpinning science areas that will be addressed over a period of ca four years. The research needs sheets will be live documents to allow the value streams to flexibly influence the medium to long term research programmes, reviewed annually to ensure continuous alignment and that any emerging needs are captured.
- Management of the research programmes are to be managed by an IRT as described above, systems and processes are in place to enable IRTs to function efficiently with governance procedures established to ensure that end users from the value streams are engaged.The science and technology needs sheets are stored centrally within the Sellafield management system and they will be used as a basis for dialogue with interested parties who wish to engage with Sellafield Ltd. For more information please contact: *technical.innovation@sellafieldsites.com*
- Task sheets prepared in response to the research needs which document the work that is underway (or will be undertaken).
- It is a Site Licence requirement to demonstrate visibility and transparency of their Technical Baseline to the NDA and a number of key pieces of information are required including R&D tables which detail plans to resolve technical issues underpinning delivery. The software system used for this will also capture the detailed science and technology needs sheets so that R&D tasks can be directly linked to the research needs.
- Knowledge, skills and learning from experience play a vital role in the efficient delivery of R&D. As part of the transformation process Sellafield Ltd has a project in place to ensure that resources and capabilities are in place to respond to the changing site requirements and a further initiative is addressing the site wide information and knowledge management requirement [2].
- The work breakdown structure in this document also includes horizon scanning which seeks to gain early insight into new science and technologies that could have very substantial benefits to the Sellafield mission. This extends to trends in new areas such as digital, automation and new materials. A process for registering new ideas, and progressing them, in a coordinated manner across the business is under development.
- Engagement of the engineering and design capability in the development of technologies.
- Whilst R&D in social sciences[1] is not addressed within the scope of this document at this present time, Sellafield Ltd recognises the impact of the evolving mission on the local community and supply chain and has identified potential opportunities for the future such as the export of nuclear expertise in the wider nuclear community. The business aims to continue to be an integral part of the community by providing employment, undertaking pioneering research, developing skills and encouraging investment.

[1] With the exception of socio-economic modelling which has been defined as a topic area within the scope of radioactivity and contamination in the environment.

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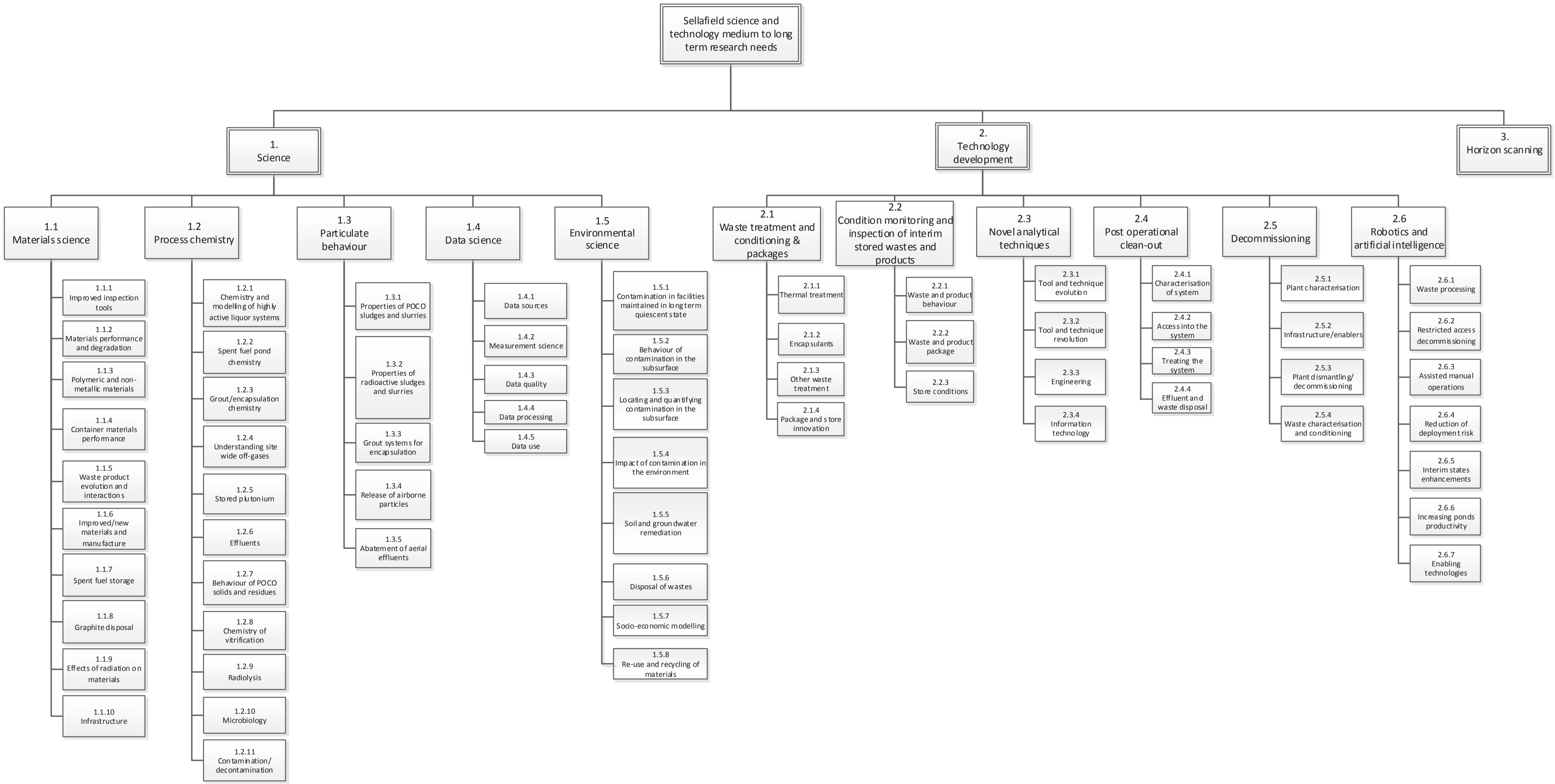
Acronyms and abbreviations

AIS	autonomous intelligent systems
COTS	commercial off-the-shelf
CM&I	condition monitoring and inspection
DISTINCTIVE	Decommissioning, Immobilisation and Storage soluTIons for NuClear wasTe InVEntories
EARP	Enhanced Actinide Removal Plant
ELENDES	Electrochemical enhancement of nuclear decontamination solutions
EPSRC	Engineering and Physical Sciences Research Council
IRT	Integrated Research Team
MIRRAX	Miniature Inspection Robot for Restricted Access eXploration
NAMRC	Nuclear Advanced Manufacturing Research Centre
NDA	Nuclear Decommissioning Authority
NNL	National Nuclear Laboratory
NWDRF	Nuclear Waste and Decommissioning Research Forum
ONR	Office for Nuclear Regulation
PCM	plutonium contaminated material
POCO	post operational clean out
RAI	robotics and artificial intelligence
RCUK	Research Councils UK
R&D	research and development
SIXEP	Site Ion Exchange Plant
SME	small to medium enterprise
S&T	Strategy and Technical
TBuRD	Technical Baseline and underpinning Research and Development
TRL	technology readiness level
WBS	work breakdown structure
WVP	Waste Vitrification Plant

Appendix A - Work Breakdown Structure



Appendix B - Science and Technology Needs Sheet

Science/Technology theme *(WBS e.g. radioactivity in the environment/ decommissioning)*	
Science & Technology WBS reference (e.g. 2.5.1 plant characterisation)	
Accolade reference	
Is there sufficient R&D in place to address the research need? *(Yes/No/Add a comment if necessary)*	

Research need *(A clear link to the knowledge or technology gap)*

Background and context *(Any background information explaining what has led to needing to do this work, why is it required? What is the issue? What is the baseline methodology?)*

What is the desired outcome? (e.g. Closure of knowledge gap, technology integrated into the baseline)

Value drivers (what will the benefits be? e.g. reduction in lifetime cost, accelerates schedule)

Reduce environmental footprint	☐	Increase in workforce safety	☐
Reduction in lifetime cost	☐	Accelerates schedule	☐
Reduction in technical risk/uncertainty	☐	Improves certainty for overall baseline plan	☐
Improvement in nuclear safety	☐	Reduction of in year cost	☐
Legislative compliance	☐	Increase in regulatory confidence	☐
Socio economic	☐	Reduced risk of interconnections /decouples downstream requirements	☐

Timeframe *(When is the answer/research/technology needed? Where does it link into a key insertion point in the business)*	
Target TRL *(for technology development)*	**Choose an item.**
End user (s)	

Further information *(References, other relevant text)*

Prepared by