The North West Nuclear Arc Science and Innovation Audit

2018

A Science and Innovation Audit Report sponsored by the Department for Business, Energy & Industrial Strategy.

Department for Business, Energy & Industrial Strategy

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FOREWORD

Dame Sue Ion

Dame Sue Ion has over 30 years' experience in the nuclear sector in a wide variety of roles, and has acted as an expert advisor to Government on all aspects of nuclear energy. She is a Fellow of the Royal Academy of Engineering and a Fellow of the Royal Society. She resides in the North West Nuclear Arc.

The nuclear sector in the UK faces a period of unprecedented change. While Government still sees nuclear energy as part of a balanced energy mix, and the new build project at Hinkley is proceeding, the recent developments at Wylfa Newydd and Moorside illustrate the huge challenges still faced by the sector. There is no intrinsic reason why nuclear projects should be late and over budget, but they often are and, as renewables become increasingly competitive and tough questions about the cost of dealing with our nuclear legacy are asked, the sector needs to respond. There is an appetite for change among all nuclear stakeholders, but it is not yet clear what form this change might take, or how radical this change could be.

In these circumstances this Science and Innovation Audit of the Northwest Nuclear Arc is very timely. It highlights the globally significant science and innovation assets in the area, with world-class research facilities and internationally renowned organisations, and identifies the major economic contribution the nuclear industry makes. It also shows how the whole could be so much more than the present sum of the parts, with particular positive impact in disadvantaged, predominantly rural areas, if we can integrate the individual elements more effectively, drive cultural and organisational changes across the sector, and find new ways to develop the skills we need. These are unique challenges, but the Northwest Nuclear Arc, with its emphasis on innovation and cross sector leverage across all aspects of the nuclear landscape, is uniquely placed to meet them.

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A Science and Innovation Audit Report sponsored by the Department for Business

These Science and Innovation Audits are a BEIS-sponsored initiative but the reports and recommendations are those of the Consortia.

LIST OF ABBREVIATIONS

ADRIANA	Advanced Digital Radiometric Instrumentation for Applied Nuclear Activities, Lancaster University
ABWR	Advanced Boiling Water Reactor
AGR	Advanced Gas-cooled Reactor
AGT	European Working Group
AMR	Advanced Modular Reactor
AP1000	Type of Nuclear Reactor, pressurised water reactor
APR	Advanced Pressurised Reactor
AWE	Atomic Weapons Establishment
BECBC	Britain's Energy Coast Business Cluster
BEIS	Business Energy and Industrial Strategy, Government Department
BNFL	British Nuclear Fuels Ltd
CEA	Commission for Atomic Energy and Alternative Energies
CEGB	Central Electricity Generating Board
CDT	Centre for Doctoral Training
CNNC	China National Nuclear Corporation
CoNE	Centre of Nuclear Expertise
CPD	Continuous Professional Development
CRR	Centre for Radiochemistry Research, University of Manchester
DECC	Department for Energy and Climate Change
DCF	Dalton Cumbrian Facility, University of Manchester
DCU	Decommissioning and Clean Up
EA	Environmental Agency
EFR	European Fast Reactor
ENSREG	European Nuclear Safety Regulators Association
ENSTTI	European Nuclear Safety Training and Tutoring Institute
EPR	European Pressurised Water Reactor
EPSRC	Engineering and Physical Sciences Research Council
ESNII	European Sustainable Nuclear Industrial Initiative
EURATOM	European Atomic Energy Community
FOAK	First-Of-A-Kind
FE	Further Education
FID	Final Investment Decision
FRCG	Fast Reactor Consultants Group
FTEs	Full Time Equivalents
GDA	Generic Design Assessment
GDF	Geological Disposal Facility
GIF	Generation IV International Forum
GVA	Generic Value Added
GW	GigaWatt
HE	Higher Education
HEIs	Higher Education Institutions
HERCA	Heads of the European Radiological Protection Competence Authorities
HLS	High Level Skills
IAEA	International Atomic Energy Agency
IFNEC	International Framework for Nuclear Energy Cooperation
ITU	Institute for Transuranium Elements, Karlsruhe (now Joint Research Centre)
LEP	Local Enterprise Partnership
LLW	Low Level Waste
LLWR	Low Level Waste Repository
LWR	Light Water Reactor
MIAMI	Microscopes and Ion Accelerators for Materials Investigation, University of Huddersfield
MIDAS	Materials for Innovative Disposition from Advanced Separations, University of Sheffield
MRL	Manufacturing Readiness Level
MTRL	Manufacturing Technology Research Laboratory
MW	MegaWatt
NAMRC	Nuclear Advanced Manufacturing Research Centre
NAO	National Audit Office
NERC	Natural Environment Research Council
NCfN	National College for Nuclear
NDA	Nuclear Decommissioning Authority
NIBC	National Ion Beam Centre
NIC	Nuclear Industry Council
NIP	Nuclear Innovation Programme
NIRAB	Nuclear Innovation and Research Advisory Board
NIRO	Nuclear Innovation and Research Office
NNC	National Nuclear Corporation
NNL	National Nuclear Laboratory
NNUF	National Nuclear Users Facility
NNUMAN	New Nuclear MANufacturing (EPSRC Programme Grant)
NTEC	Nuclear Technology Education Consortium
NSAN	National Skills Academy for Nuclear
NSSG	Nuclear Skills Strategy Group
NWNF	North West Nuclear Forum
NWNA	North West Nuclear Arc
OECD	Organisation for Economic Cooperation and Development
ONR	Office of Nuclear Regulation
PWR	Pressurised Water Reactor
R&D	Research and Development
RD&I	Research, Development and Innovation
SETC	Skills and Education Task Force
SIA	Science and Innovation Audit
SME	Small to Medium Enterprise
SMR	Small Modular Reactor
STFC	Science and Technology Facilities Council
TRL	Technology Readiness Level
TW	TeraWatt
UKAEA	United Kingdom Atomic Energy Authority
UKRI	UK Research and Innovation
UTC	University Technical College
UTGARD	Uranium/Thorium beta/Gamma Active R&D Lab (at Lancaster University)
WEO	World Energy Outlook
WENRA	Western European Nuclear Regulators Association
WNF	Wales Nuclear Forum

EXECUTIVE SUMMARY

Overview & Context

In Autumn 2015 the UK Government announced regional Science and Innovation Audits (SIAs) to catalyse a new approach to regional economic development. SIAs enable local consortia to focus on analysing regional strengths and identify mechanisms to realise their potential. In the North West of England and North Wales, a consortium was formed in 2017 to focus on our strength in the Nuclear Sector. This report presents the results which includes broad-ranging analysis of the North West Nuclear Arc's (NWNA) capabilities, the challenges and the substantial opportunities for future economic growth.

> *The future success of the [nuclear] industry is central to achieving the Clean Growth Grand Challenge set out in the Industrial Strategy; to maximise the advantages for UK industries of the global shift to cleaner forms of economic growth. The UK nuclear sector, with its historical strength and skilled workforce across the country, is well-placed to capture that opportunity.*
>
> *June 2018, the Nuclear Sector Deal.*

The World Energy Outlook[1] projects that global energy demand will rise by 30% between today and 2040. Based on the 'Sustainable Development Scenario', with power generation all but decarbonised, nuclear power use is predicted to grow up to 15%, an increase of nearly 5%. Nuclear power will continue to be a key part of the Government's commitment to Clean Growth, one of four Grand Challenges in the Industrial Strategy. The Government seeks to enhance the UK's nuclear commercial base and global market share.

The NWNA consortium comprises Bangor University, Welsh Government, the Dalton Institute (University of Manchester) and the National Nuclear Laboratory (NNL). The focus of the SIA is on the strengths and capabilities of civil nuclear energy, in NW England and North Wales, with an easterly extension to take in Sheffield and Leeds. The vision is that it is possible to re-engineer the nuclear sector, driving 30% reductions in cost and time, without compromising safety and security,[2] and that the NWNA is uniquely positioned to maximise the opportunity for the UK.

The view in the NWNA is that it can bring about lasting economic benefits and prosperity through innovation in the sector, working in partnership with Industry, academia, regional government and local communities to transform the UK's nuclear industrial capability and enhance its global presence.

[1]http://www.iea.org/Textbase/npsum/weo2017SUM.pdf

[2]https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/665473/The_Nuclear_Sector_Deal_171206.pdf

The Audit

The results of the SIA show that nowhere else in Europe is so much nuclear expertise so concentrated, with unparalleled access to a world-renowned skills base and pioneering expertise in nuclear research and development. The NWNA is one of few regions in the world with a nuclear industry covering the full life-cycle.

Physical Assets

There is a wide range of physical and innovation assets within the region, with over 20 facilities providing research support to academic and industrial activity in the region including university laboratories, the National Nuclear Users Facilities (NNUF), National Nuclear Laboratory (NNL), private facilities and public-private partnerships. The process and ease of accessing these facilities is generally limited due to the safety and security requirements. However, with the inclusion of some of these facilities in the NNUF programme, access has improved and continues to be a focus for improvement.

There are the science and innovation sites, that include Westlakes, Birchwood, Trawsfynydd and the Menai Science Parc, where there are hubs of activity related to nuclear and innovation. Trawsfynydd has been identified as an ideal site, already licensed for nuclear, for deploying a First of a Kind (FOAK) modular reactors.

There are various industry networks set up, including the Centre for Nuclear Excellence (CoNE) based in Cumbria. CoNE is supporting the nuclear sector to capitalise on the nuclear opportunities in the UK and globally. A key initiative that CoNE has been developing with partners is establishing an Innovation Partnership to create a vibrant marketplace for innovation, a key recommendation of this SIA.

People & Skills

Nowhere else in Europe is so much nuclear expertise so concentrated, with unparalleled access to a world-renowned skills base and pioneering expertise in nuclear research and development. However, the workforce is ageing, and the Nuclear Workforce Assessment predicts there could be shortage of up to 40,000 workers by 2036. Maintaining the population of nuclear Subject Matter Experts is an explicit priority in the Nuclear Sector Deal, and availability of High Level Skills (HLS) and subject matter experts, is identified as 'of particular concern' by the Nuclear Skills Strategy Group (NSSG).

The North West Nuclear Arc

uniquely houses 15 nuclear skills providers, both Higher Education (HE) and Further Education (FE), which can provide specialist training across the full range of skill levels 1-8, and already has Centre for Doctoral Training (CDT) programmes which can support the development of the subject matter experts. Refreshing the workforce also provides the opportunity for diversification, in particular in addressing the gender balance.

Knowledge Base

The evidence illustrates the significance of the NWNA's knowledge base. The NWNA universities account for 46% of the EPSRC Nuclear fission spend (£46.5m), and the Nuclear Innovation and Research Advisory Board (NIRAB) report on the UK Civil Nuclear Research & Development (R&D) Landscape estimated that 44% of university researchers are within the NWNA. Analysis of grants and publications demonstrates that research in the NWNA spans the whole spectrum of nuclear related activities, with an impressive track record of working internationally, crucial in establishing global markets for new products, and securing the UK's position in global markets. This is overwhelming evidence that the NWNA is the single most 'nuclear' research intensive region in the UK, and a sound basis on which to foster innovation.

An analysis in InnovateUK grants related to nuclear since 2004, shows that the NWNA organisations occupy three of the top five spots, which demonstrates not only the expertise, but also the organisations' ability and interest in commercialisation. This is fundamental to creating an innovative environment, and meeting the aspirations set out in the UK's industrial strategy.

Business Environment

There are >235 companies in the nuclear industry in the NWNA, contributing over £5bn to the UK economy. These companies provide 1 in every 64 jobs in NWNA totalling an estimated 30,000 jobs, accounting for nearly 40% of the 78,000 people directly employed in nuclear in the UK.

A number of potential growth opportunities have been identified, which are:

- increasing the UK's share of global Decommissioning and Clean Up (DCU) related services,
- developing and building capability for some, or all of the components for Small Modular Reactors (SMRs),
- developing and building capability for Advanced Modular Reactors (AMRs),
- providing an attractive regulatory regime and environment for innovation in nuclear.

Conclusions

The NWNA is the only area in the UK with full fuel cycle capabilities and the organisations and expertise to address many of the challenges identified in securing secure clean energy.

The NWNA has:

- excellent facilities, however some gaps have been identified and access could be improved,
- sites suitable for development and new build,
- a strong research and knowledge base, with the largest share of EPSRC funding in nuclear science, and organisations attracting the most InnovateUK funding,
- a solid business environment with >235 companies and >30,000 employees,
- world class expertise and industry in decommissioning and site remediation,
- training providers to provide training to meet the expected increase in demand and skill shortages.

Growth opportunities include:

- expanding the export market in decommissioning and clean up, and supporting local companies to innovate,
- Government and industry working together to accelerate the deployment of SMRs, to take an international lead producing SMRs, or their components,
- Remedial action needed includes:
- investment in infrastructure,
- better integration of the assets and activities through initiatives such as the proposed Innovation Partnerships. Setting up a national network based on regional strengths could foster collaboration rather than competition, and help deliver the Nuclear Industry Council (NIC) Mission,
- intervention and civil nuclear initiatives which can deliver a trained workforce, including more and continuous investment in the CDTs, and cultivating a more diverse workforce,
- inducing technical change, such as fully exploiting digitisation, and emulating practices in other sectors, such as aviation, oil & gas, pharmaceuticals, and off-shore wind,
- change in organisational and individual culture and behaviour.

Recommendations

Physical Assets (Infrastructure)

1. Invest in new test facilities: further analysis is required, but these may include a reactor for research and experimental purposes, a thermal hydraulics facility, and a site for deploying FOAK SMRs.
2. Continue to improve the ease of access to existing facilities.
3. Consider an 'accredited access' system issued on the basis of training and competence and incentivise industry to make their facilities more open for collaboration.
   Innovation Assets (Ideas)
4. Create two Innovation Partnerships in Cumbria and North Wales.

People & Skills

5. Design and deliver a coherent skills pathway bringing together all providers and fostering skills development for the nuclear sector.
6. Ensure that the nuclear labour market becomes more diverse, attracting more women, and people from different cultural and ethnic backgrounds.

Knowledge Base

7. In line with the Industrial Strategy, ensure that an appropriate share of the proposed increase in investment in R&D to 2.4% of GDP is achieved and targeted at nuclear related research.
8. Use the Industrial Strategy Challenge Fund as a mechanism to attract investment in nuclear related innovation targeted at high growth potential Small to Medium Enterprises (SMEs).
9. Create an environment in which non-nuclear and smaller companies can learn from the Tier 1 companies.

Business Environment

10. Provide industry with confidence by supporting investment in long term projects.
11. Assess the global market and the opportunities for the UK for SMRs and AMRs. Determine the modular reactor technologies to support long term and create an environment that will support their development.
12. Standardise and modularise components to speed up delivery times and lower direct costs.
13. Ensure that technologies and techniques used for new nuclear build draw on best practices deployed in mainstream major construction projects, such as London 2012.[3]
14. Focus on accelerating commercialisation of new products, at scale, within rapid timescales.
15. De-nuclearise elements and remove the 'specialness' of nuclear, where possible such as in other high hazard, highly regulated, high profile industries.
16. Review the scope to further promote the UK's proposition internationally.

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[3]http://learninglegacy.independent.gov.uk/themes/design-and-engineering-innovation/index.php

INTRODUCTION 1.

The Government's Industrial Strategy[4] recognises the role science, research and innovation plays in driving productivity and growth and identifies 'place' as one of the five key foundations. In order to build on areas of greatest potential in every region, the Government initiated the Science and Innovation Audits (SIAs), to map local research and innovation strengths and infrastructure. The SIAs aim to build the evidence base of where key strengths are, and bring together local consortia of business, universities, research and innovation organisations, Local Enterprise Partnerships (LEPs) and their equivalents in the Devolved Administrations.

In the 3rd wave of SIAs, Bangor University (with the support of the Welsh Government) joined with The University of Manchester's Dalton Institute and the National Nuclear Laboratory (NNL) to examine the North West Nuclear Arc (NWNA).[5] This aligns with clean growth, one of the Government's Grand Challenges: (published May 2018)[6], in which the civil nuclear sector will have a significant role to play in producing low carbon energy. More information on innovation in clean growth can be found in the North West Costal Arc Clean Growth Partnership SIA led by Lancaster University.

The NWNA SIA focuses on the assets, capabilities and expertise that are available in the defined geographic area in the civil nuclear energy sector. The Nuclear Sector Deal which was published in June 2018 sets out some key sector targets and the North West Nuclear arc with its inherent capability across the entire fuel cycle will be key in the delivery of those targets.[7]

- "Sector will achieve savings of 20 % in the cost of decommissioning by 2030" – the bulk of those costs and facilities are in the NW and the innovations required will be developed and delivered from there.
- "Target 30 % reduction in the cost of new build projects by 2030" – there's a link to the SMR/AMR programme and the first of a kind sites available across the arc. The research and innovation capability in the North West Nuclear arc can drive the TRL programme for the chosen AMR developers.
- "Improve diversity across the sector to achieve 40 % female participation in nuclear by 2030" – a national nuclear target, but given the largest 5 companies of nuclear workforce is in the North West, the arc will be essential in this and are currently leading with a very strong WiN presence and regional groups.
- "Maximise UK content in projects including by publishing Supply Chain Plans" – data shows the supply chain is heavily based in the North West Nuclear Arc.
- "To generate good jobs and greater earning power for all"– the North West Nuclear Arc is the largest contributor to UK nuclear skills and education development, with education providers spanning across all education levels.
- "To be the world's most innovative economy" – there is a huge range of research and innovation capability in the North West Nuclear Arc through our universities and NNL. The new Thermal Hydraulics facility to be built on Anglesey will also contribute significantly to this.

The Hypothesis is that it is possible to re-engineer the nuclear sector, driving 30% reductions in cost and time, without compromising safety and security,[7] and that the NWNA is uniquely positioned to maximise the opportunity for the UK. The vision for the NWNA is that it can bring about lasting economic benefits and prosperity through innovation in the sector, working in partnership with Industry, academia, regional government and local communities to transform the UK's nuclear industrial capability and enhance its global presence.

There is an opportunity to maximise the advantages for UK industry from the global shift to clean growth – through leading the world in the development, manufacture and use of low carbon technologies, systems and services that cost less than high carbon alternatives.

The move to cleaner economic growth – through low carbon technologies and the efficient use of resources – is one of the greatest industrial opportunities of our time. Whole new industries will be created and existing industries transformed as we move towards a low carbon, more resource-efficient economy.[2]

[4]https://www.gov.uk/government/topical-events/the-uks-industrial-strategy

[5]The project development and working group for this SIA can be found in Appendix 1.

[6]https://www.gov.uk/government/publications/industrial-strategy-the-grand-challenges/industrial-strategy-the-grand-challenges

[7]https://www.gov.uk/government/publications/nuclear-sector-deal/nuclear-sector-deal

The UK is one of the few countries in the world with a nuclear industry covering the full life-cycle. From enrichment to decommissioning - through fuel production, power generation, manufacturing, engineering, legal, financial and advisory services, spent fuel recycling and research & development. All these major components of civil nuclear Research, Development & Innovation (RD&I) and operational capability are to be found in the NWNA, representing a large proportion of the UK's nuclear industry and R&D capability. The region has two potential new build development sites at Moorside and Wylfa Newydd. Hence the area can support the full spectrum of nuclear activities.

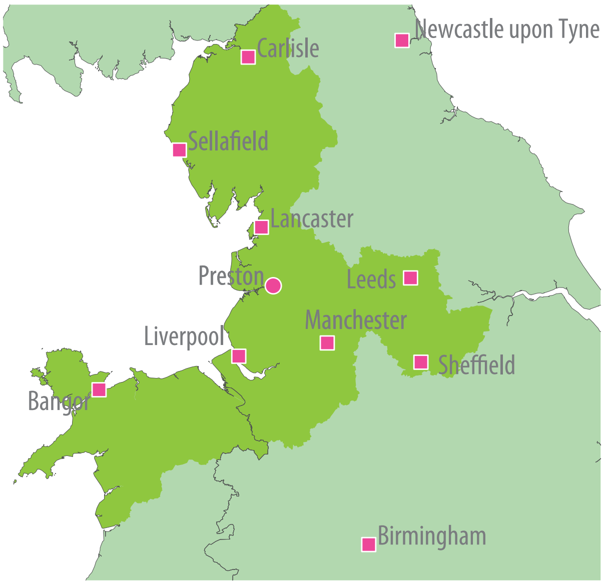

Figure 1: The audit region (dark green)

The NW Nuclear Arc (NWNA) is defined by the area shown in Figure 1 below. The NWNA sweeps down from Carlisle through Lancaster and Preston, then continues to Manchester where it turns westwards to Warrington and Liverpool, and crosses the border into North Wales, finishing in North West Wales. The shaded area in figure 1 shows that the audit's geography, which includes an eastern corridor that crosses the Pennines to include the world class experimental facilities, universities and companies operating in South Yorkshire, and embrace the Northern Powerhouse. In terms of Local Enterprise Partnerships (LEPs), the area includes the North Wales Economic Ambition Board, Liverpool and Sheffield City region, Cheshire and Warrington, Cumbria, Greater Manchester and Lancashire (Figure 2).

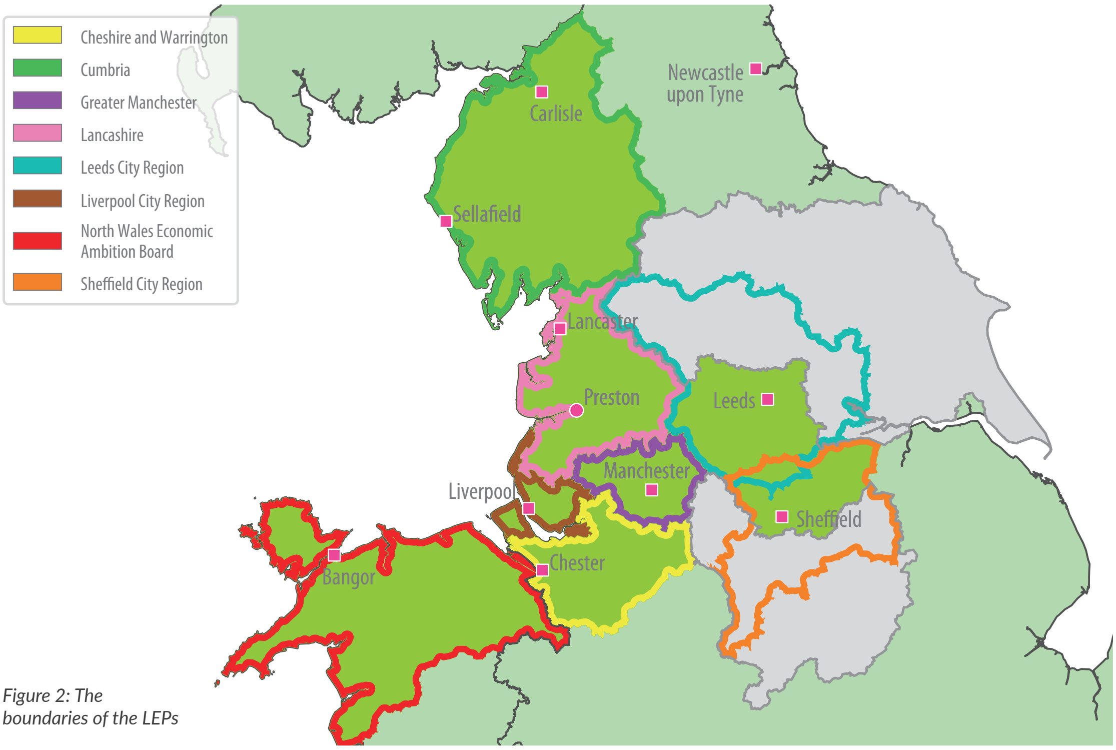

Figure 2: The boundaries of the LEPs

The area encompasses a significant proportion of the UK's existing civil nuclear RD&I, (e.g. university, NNL and Wood Group facilities, as will be demonstrated in the knowledge section of this audit) and operational capability and there are sites available for large new nuclear deployments (Wylfa Newydd and Moorside). The current capability and mix in the NWNA is unique in the UK in terms of Higher Education Institutes (HEIs), Tier 1 and 2 companies, and their supply chains, regulators, decommissioning and new build, as well as specialist facilities providing an arena for technical innovation, and technology transfer.

Hundreds of companies and investors in the nuclear industry already benefit from the geographic proximity and easy connectivity to build more efficient and reliable supply chains, readily access customers across the UK, and access a pool of highly-skilled people attuned to the specific needs of the nuclear industry.[8] Key strengths and assets include:

- RD&I: both facilities and research expertise with depth and breadth, which includes the universities of Lancaster, Liverpool, Manchester, Leeds, Sheffield and Bangor.
- Decommissioning and Clean up expertise at Sellafield.
- Waste disposal at the Low Level Waste Repository (LLWR).
- Major facilities including the National Nuclear Laboratory, Wood Group High Temperature Facility, Science and Technology Facilities Council (STFC), Nuclear Advanced Manufacturing Research Centre (NAMRC), Cammell Laird.
- National agencies:
  - o Office of Nuclear Regulation (ONR),
  - o National Decommissioning Authority (NDA),
  - o Environment Agency (EA) & Natural Resources Wales.
- People – expertise and skills, covering a range of education levels across HE and FE.
- Good mix of industry organisations and an established supply chain.

Details of the audit are presented in Section 3 below, following the section (2) on the global, national and regional context, which includes an overview of the global market for Small Modular Reactors (SMRs) and Advanced Modular Reactors (AMRs), and the outlook for the future, and an overview of the UK/NWNA's overall position in that context.

The audit follows the guidelines, with sections on:

- physical facilities • innovation assets • talent and skills
- knowledge base • business environment.

The gaps and related opportunities are highlighted in the conclusions (section 4), and whilst there is an impressive range of facilities, there are some gaps. Currently some significant pieces of work (e.g. helium measurements in plutonium materials) have to take place overseas, and already this is becoming increasingly difficult in the light of Brexit. Further work is required to review facilities required, but ideally the mix will support a range of technologies, including the development of modular reactors, which could be an excellent opportunity for UK industry. (See NNL Feasibility Study.[9])

For the purposes of the SIA, in line with Government's description, innovation is taken to be: 'activity that is new in its context, such as implementation of a new or significantly improved product, service or process, a new marketing method or new organisational methods' - at the local and regional level (BIS, 2014b).

In these discussions, three distinct types of innovation were identified, one predominantly around organisations and the way they work and two around technical change:

- Organisational change. Changes in the structures of organisations; changes in relationships within and between organisations; contractual and other mechanisms to encourage and adopt technical innovations.

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[8]https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/595853/Nuclear_in_the_Northern_Powerhouse_LR.pdf

[9]http://www.nnl.co.uk/media/1627/smr-feasibility-study-december-2014.pdf

- Technology transfer. The adoption in the nuclear sector of well-developed technologies which are established in non-nuclear industries.
- New knowledge. This can lead to better understanding of an existing system, or to development of new technologies from low Technology Readiness Level (TRL) R&D through to practical deployment in the nuclear sector.

The conclusions (Section 4) are that the current capability and mix in the NWNA is unique in the UK in terms of HEIs, Tiers 1 and 2 companies, regulators, decommissioning and new build, as well as specialist facilities providing an arena for technical innovation, and technology transfer. Gaps have been identified, and remedial actions recommended (section 5), for example to create Innovation Partnerships and an environment that will support the development of A/SMRs.

Furthermore, given the mix of high level skills required going forward provides an opportunity for the NWNA to develop a single training pathway with enhanced CDTs, Level 8 Degree Apprenticeships, Accelerated Speed to Competence and refreshed Nuclear Technology Education Consortium (NTEC).

THE GLOBAL NUCLEAR ENERGY MARKET

2.

Globally, nuclear generated power has remained stable over the past few years, (around 10.6 % in 2016 as seen in Figure 3) after declining steadily from a historic peak of 17.5 % in 1996, shown in Figure 4. In 2016 nuclear plants supplied 2477 TWh of electricity, up from 2441 TWh in 2015. This is the fourth consecutive year that global nuclear generation has risen, with output 130 TWh higher than in 2012[10].

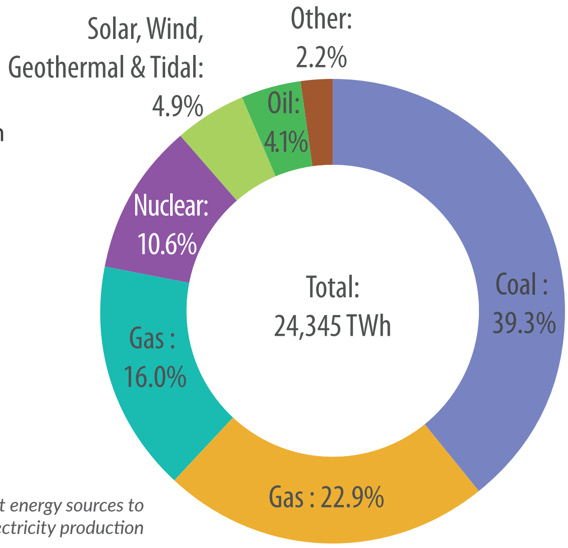


Figure 3: Contributions from different energy sources to the overall global electricity production

The trends in nuclear production are shown in the diagram below, taken from BP's "Statistical Review of World Energy", 2017.[11]

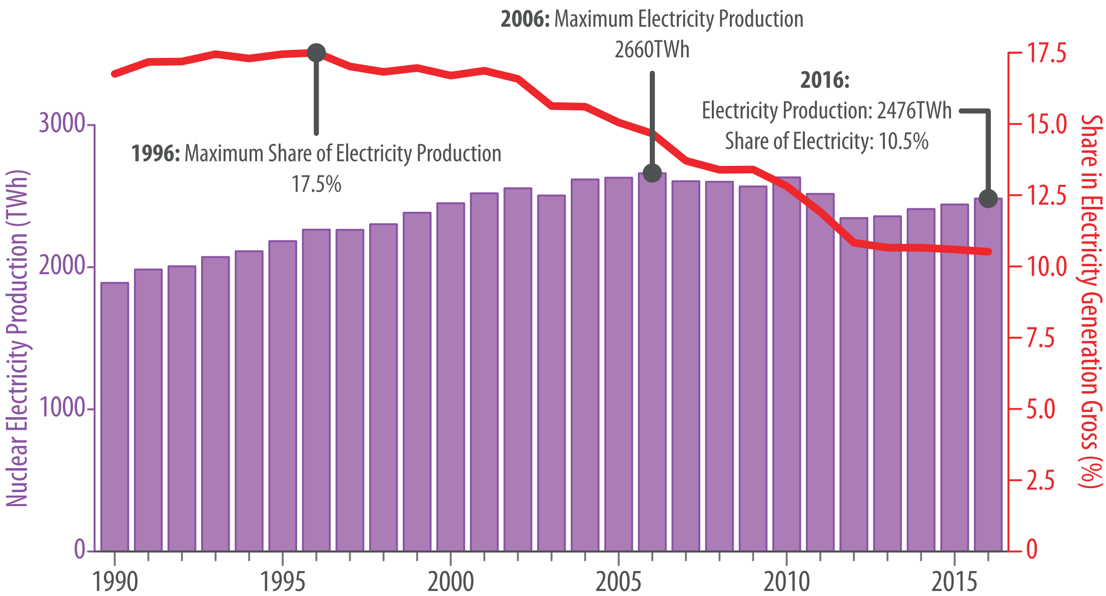


Figure 4: Trends in Nuclear Electricity Production in the World 1990-2016.[11]

Most nuclear electricity is generated using reactors which were developed in the 1950s and 1960s. The average age of the world's operating nuclear reactor fleet continues to rise, and by mid-2017 stood at 29.3 years. However, there are between 50 and 60 more reactors under construction in thirteen countries, equivalent to 16 % of existing capacity, while an additional 150-160 are planned, equivalent to nearly half of existing capacity. Almost 80 % of all new-build units (42) are in Asia and Eastern Europe, with 20 in China alone.[12]

[10] http://www.world-nuclear.org/information-library/current-and-future-generation/nuclear-power-in-the-world-today.aspx
[11] BP, "Statistical Review of World Energy", 2017
[12] http://www.iea.org/Textbase/npsum/weo2017SUM.pdf

With regards to the future, The World Energy Outlook based on the 'New Policies Scenario', projects that global energy needs rise more slowly than in the past but still expand by 30 % between today and 2040. This is the equivalent of adding another China and India to today's global demand. Based on the 'Sustainable Development Scenario', with power generation all but decarbonised, the generation mix could comprise renewables (over 60 %), nuclear power (15 %) as well as a contribution from carbon capture and storage (6 %). Solar is expected to be the cheapest form of clean energy for many regions, including Asia & Africa.

2.1 UK Nuclear Industry

The UK was an early adopter of nuclear power, and the first station to be connected to the grid, Calder Hall, which came on stream in 1956, is located in Cumbria, in the NWNA. This means that the UK was also one of the first places to embark on decommissioning and clean up. This is discussed in more detail below. The timeline for UK power plants is shown in the figure below.

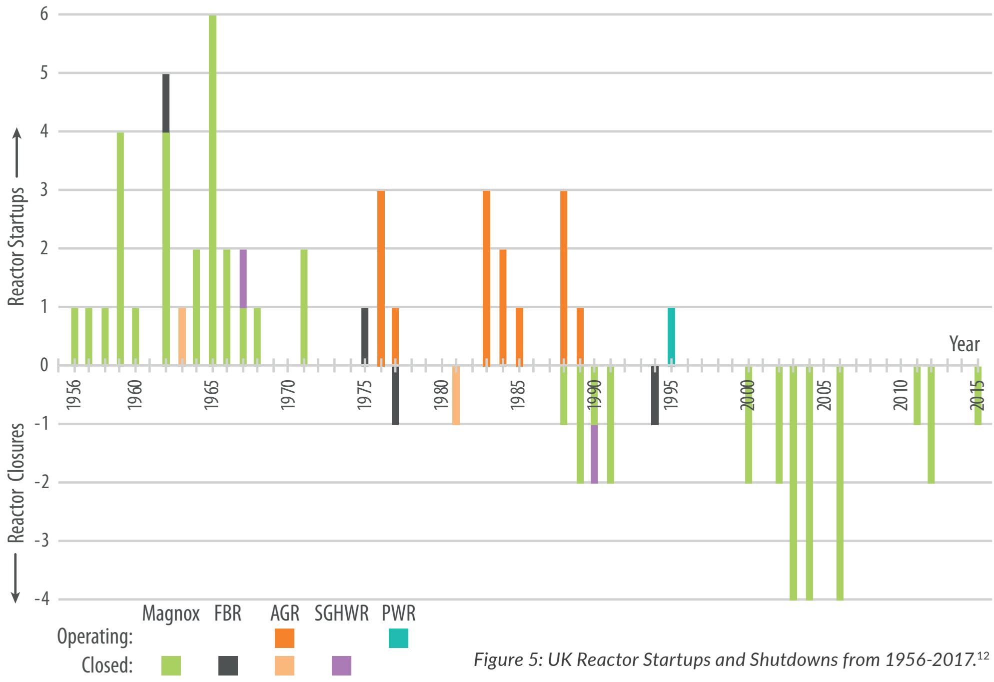


Figure 5: UK Reactor Startups and Shutdowns from 1956-2017.[12]

By 2016, the 12 first-generation Magnox plants, with 26 reactors, had all been retired. The UK still operated 15 reactors: seven second-generation nuclear stations, each with two Advanced Gas-cooled Reactors (AGR), together with the newest reactor, Sizewell-B, the only pressurised water reactor (PWR) in the UK which was completed in 1995. These reactors provided 65.1 TWh or 20.4 % of the country's electricity, down from a high of 26.9 % in 1997. The average age of the UK fleet stands at 33.4 years and a significant number of these reactors are also at, or near the end of, their design lives. However, owner EDF Energy is planning to extend the lifetimes of all the AGRs, and announced between December 2012 and February 2016 that it planned to seek:

- 7-year extension to 2023 for Hinkley Point B and Hunterston B,
- 5-year extension to 2024 for Heysham-1 and Hartlepool, and
- 10-year extension to 2030 for Dungeness, Heysham-2 and Torness.

The UK government set out its policy in its March 2013 publications Long Term Nuclear Energy Strategy[13] and The UK's Nuclear Future.[14] In the latter, the Government proposed the construction of 12 new reactors at five sites, producing 16 GW annually.

The government aims to improve decommissioning and to sustain and improve the nuclear skills base. (There is a section on the decommissioning sector at the end of this chapter, and skills are covered in the audit Section 3.) Furthermore, it intends to build an integrated nuclear industry through a nuclear industry strategy. The strategy includes the goal of using research and development, so that the UK becomes a 'top-table' nuclear nation through innovating in nuclear design a key partner of choice in commercialising Generation III+, IV and SMR technologies worldwide.[8]

As part of this policy, the UK government wishes to see the development of SMRs in the UK. Small modular reactors are so far unproven, but they remain an option worth exploring[15]. The Welsh Affairs Committee supports this policy, and recommended that the Government supports their development by creating the appropriate regulatory and business environment in which they can succeed. Furthermore, if SMRs are developed, the Committee went on to say that in their view Trawsfynydd in North Wales would be an ideal location for a first-of-its-kind model[16]. This aligns with the North Wales Economic ambition board proposition, which, amongst other projects, highlights the Trawsfynydd Power Station Project which aims to help develop the site further for SMR deployment. SMRs are discussed in the section below on reactor technologies.

[13] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/168047/bis-13-630-long-term-nuclear-energy-strategy.pdf
[14] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/168048/bis-13-627-nuclear-industrial-strategy-the-uks-nuclear-future.pdf [15] http://www.nnl.co.uk/media/1627/smr-feasibility-study-december-2014.pdf
[15] http://www.nnl.co.uk/media/1627/smr-feasibility-study-december-2014.pdf
[16] https://publications.parliament.uk/pa/cm201617/cmselect/cmwelaf/129/129.pdf

2.2 The National Importance of the North West Nuclear Arc

The region is of vital importance to the UK nuclear industry. Activity within the nuclear arc touches the entire nuclear fuel cycle from enrichment and fuel manufacture, through reactor operation and maintenance into decommissioning, site restoration and reuse (e.g. Wylfa, Wylfa Newydd and potential future use of Trawsfynydd). Furthermore it encompasses the majority of the UK's existing civil nuclear R&D and operational capability, as demonstrated in this audit.

The potential for major new nuclear deployments in the area, together with the potential to expand the region's existing capabilities could, if properly exploited, prompt huge economic growth. Given the type of skills and the nature of the industry this would be expected to lead to the creation of enduring high-value jobs in R&D and operational deployment. This benefit would be distributed throughout the indigenous supply chain for both specialist nuclear and more general companies from Small to Medium Enterprises (SMEs) all the way up to major contractors and suppliers. Much of this expansion would be expected to come as a result of major inward investments. For instance, should the projects progress, the proposed Wylfa Newydd and Moorside projects could result in £30bn+ of investment.

Whilst nuclear new build is of national importance, it should not be allowed to overshadow the world class work that is taking place within the region on decommissioning and site remediation. Although there is innovative work to be done in the supply chain and on the periphery of the reactor system, new-build reactors are turnkey products where the development work on their tightly regulated designs has been conducted many years previously. As a result, there could be much more scope to innovate within the field of decommissioning rather than new-build. Furthermore, the vendors of the GigaWatt (GW) scale reactors headed for the UK are from countries such as France (EPR), Japan (ABWR) and Korea (APR). Whilst their inward investment and confidence in the UK market is positively regarded, much of the R&D and associated intellectual property resides elsewhere. By comparison many of the companies associated with decommissioning are homegrown. As a result there are considerable opportunities to expand the export market for the innovative products and services developed and proven during the clean-up of the UK's domestic nuclear legacy. The Nuclear Decommissioning Authority (NDA) has an important role to play in this which will be discussed later in this report.

The market for the purposes of this SIA has been classified into 4 key segments:

- New build
- (Small) Modular reactors
- Advanced Nuclear Reactors and Technologies

Decommissioning and clean up.

2.3 Civil Nuclear Reactor Technologies

The nuclear power industry has been developing and improving reactor technology for more than five decades and is starting to build the next generation of nuclear power reactors. Several generations of reactors are commonly distinguished:

- Generation I - developed in 1950-60s, (last one shut down in the UK in 2015)
- Generation II - typified by the present US and French fleets and the most in operation
- Generation III (and III+) - the advanced reactors (distinction from Gen II is arbitrary) in operation in Japan and under construction in several countries.
- Generation IV - designs still on the drawing board which will not be operational before the 2020s.
- So-called third-generation reactors have:
- more standardised design for each type to expedite licensing, reduce capital cost and reduce construction time,
- a more robust design, making them easier to operate and less vulnerable to operational upsets,
- higher availability and longer operating life – typically 60 years,
- further reduced possibility of core melt accidents,

[17] The development of small modular reactors may change this significantly opening up the possibility of an export market for a UK reactor design. This will be discussed later in the SMR section of this report.

- substantial grace period, so that following shutdown the plant requires no active intervention for (typically) 72 hours,
- stronger reinforcement against aircraft impact than earlier designs, to resist radiological release,
- higher burn-up to use fuel more fully and efficiently, and reduce the volume of waste,
- greater use of burnable absorbers ('poisons') to extend fuel life.

Since nuclear power generation has become established, the size of individual reactor units has grown from 60 MWe to more than 1600 MWe, with corresponding economies of scale in operation. However, a strong interest in small and simpler units for generating electricity from nuclear power, and for process heat has developed, driven both by a desire to reduce the impact on viability of high capital costs and to provide power away from large grid systems[18]. The International Atomic Energy Authority (IAEA) defines 'small' as under 300 MWe, and up to about 700 MWe as 'medium'. Together they are now referred to by IAEA as small and medium reactors (SMRs). However, 'SMR' is used more commonly as an acronym for 'small modular reactor', designed for serial construction and collectively to comprise a large nuclear power plant. The technologies involved are numerous and very diverse. For the purposes of this report SMR refers to the latter, and a section on these is presented below, under Advanced Nuclear Technologies. The main reactor types and development of travel are shown in the diagram below.

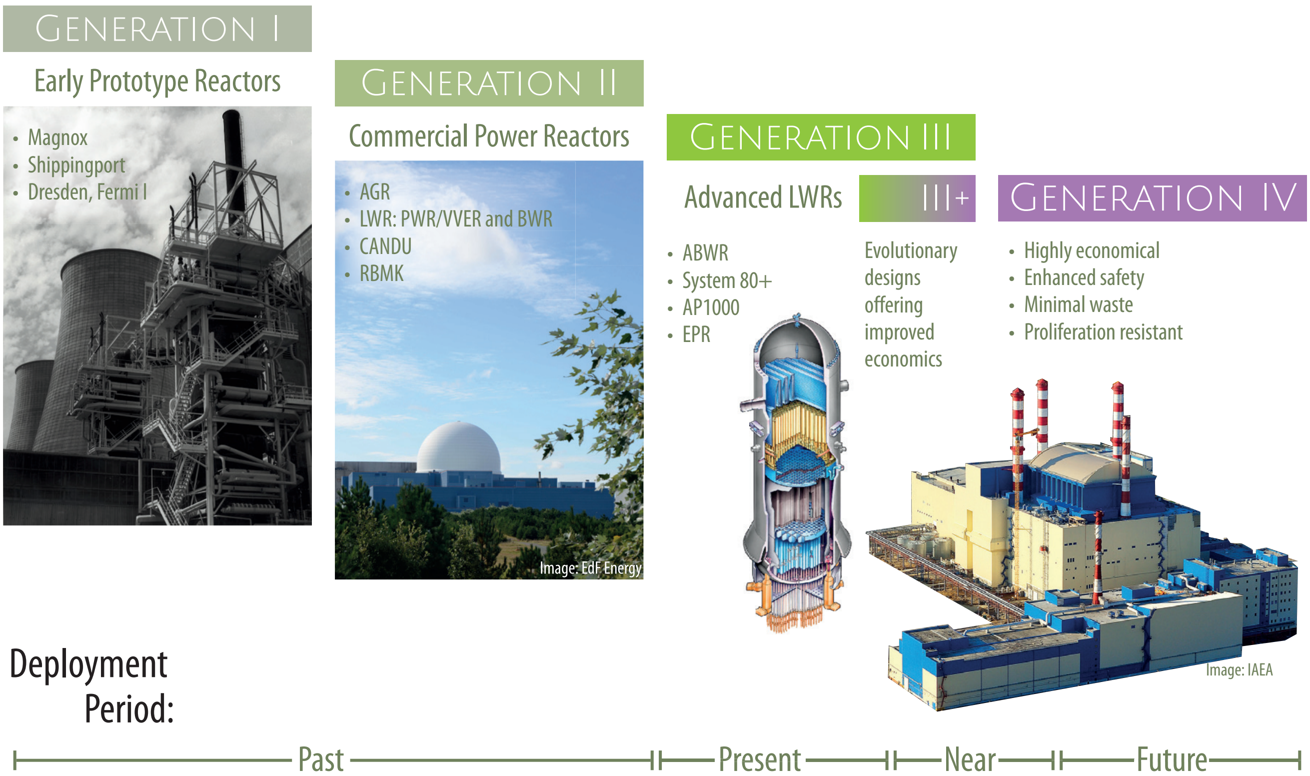


Figure 6: Timeline showing the development of Nuclear Reactors from Generation 1 in the 1950s to Generation IV in the 2030s and beyond.

Reactor suppliers in North America, Japan, Europe, Russia, China and elsewhere have a dozen new nuclear reactor designs at advanced stages of planning or under construction, while others are at a research and development stage.

Fourth-generation reactors are at the R&D or concept stage, and, together with SMRs are discussed in the next section.

[18] http://www.world-nuclear.org/information-library/nuclear-fuel-cycle/nuclear-power-reactors/small-nuclear-power-reactors.aspx

2.4 New Build

EDF Energy's Hinkley Point C project is the first of the UK new build stations under construction. It will house two European Pressurised Water (EPR) reactors. The Final Investment Decision (FID) was made in July 2016 and construction of the first reactor is planned to be complete by 2025.[19]

Wylfa Newydd in Anglesey, to be operated by Horizon Nuclear Power, is intended to host two Hitachi-GE Advanced Boiling Water Reactors (ABWRs)..[20] However, Hitachi-GE have paused work on the Wylfa Newydd project indefinitely. The UKABWR design completed Generic Design Assessment (GDA) in December 2017 and work towards obtaining the Development Consent Order (DCO) is still ongoing.

NuGeneration originally planned to build three Westinghouse AP1000 PWRs at the Moorside site in Cumbria but, following Westinghouse's USA Chapter 11 bankruptcy in March 2017, Nugen's sole remaining owner, Toshiba sought a buyer for the company. Although advanced discussions with the Korea Electric Power Company were actively pursued as a nominated potential new owner following a competitive process, those commercial discussions could not be brought to a successful completion. As a result Toshiba decided in November 2018 to wrap up Nugen as an operating entity, and this was subsequently completed in January 2019. Ownership of the Moorside development site has therefore reverted back to its original owner, the NDA.

The Moorside site remains a nominated nuclear development site as a part of the relevant National Policy Statement, and along with Wylfa and Trawsfynydd are the currently nominated sites within the NWNA for future nuclear generation development for either large scale or small modular reactors.[21]

2.5 Small Modular Reactors

As mentioned above, SMRs are defined by the IAEA as reactors producing up to 300 MW of electric power that can be largely built in factories as modules to minimise costly on-site construction and take advantage of advanced construction and manufacturing techniques. By adopting factory build techniques it is hoped that fleets of such reactors can be deployed and economies of number realised that will make them cost competitive with traditional GW reactors. An initial SMR power station would be a fraction of the cost of a large GW-scale new build, and avoid the huge upfront costs and decade-long development times of current reactors. However, the economics of SMRs have yet to be proven.

Economies of scale are envisaged for SMRs due to the factory design and assembly and numbers produced. SMRs are seen as a much more manageable investment than large traditional nuclear power plants and their smaller scale and modular design can overcome the cost-overruns and construction delays that have plagued conventional nuclear projects.

While the financing of nuclear power plants has become more challenging in the last three decades, new financial products and processes have been developed over this period that can be used to finance the production and operation of SMRs. The size and production process of SMRs allows access to a new pool of investors and financing options; from corporate loans, capital markets instruments (both debt and equity), venture capital, private equity, hedge funds, pension funds and insurance companies. A mixture of these options can be used to attract investors to specific projects, such as phased financing to mitigate risk across the different phases of the project, from construction to adding additional units. The ability to re-cycle capital over a shorter time frame means that SMRs have a real advantage over large nuclear power plants when it comes to financing.

SMRs provide an opportunity to look beyond the basics of traditional financing of new nuclear power plants construction and operation, and adopt new approaches to fund energy production in the UK and help create a multibillion-pound export market.

Interest in SMRs was rekindled post Fukushima as the decay heat that led to reactor meltdown can

[19] https://www.edfenergy.com/energy/nuclear-new-build-projects/hinkley-point-c
[20] https://www.horizonnuclearpower.com/our-sites/wylfa-newydd
[21] https://www.theguardian.com/business/2017/dec/06/korean-energy-firm-kepco-rescue-moorside-nuclear-power-project
[22] http://www.nnl.co.uk/media/1627/smr-feasibility-study-december-2014.pdf

be more easily prevented in a small reactor. The potential global SMR market is estimated to be between 65–85 GWe by 2035, valued at £250–400 billion; and a UK market of around 7 GWe.[22] While SMRs may solve the size issues (capacity and investment) of large nuclear plants, they are affected by the general decline in interest in nuclear new-build. The creation of a market for SMRs will first require successful deployment of First-of-a-kind (FOAK) reactors in the vendor's country before other countries will consider deploying the technology. Unless governments and industry work together in the next decade to accelerate the deployment of the first SMR prototypes that can demonstrate the benefits of modular design and construction, the market potential of SMRs may not be realised in the short to medium term.[23] (See earlier reference to Welsh Affairs Committee recommendation to build a FOAK at Trawsfynydd in Wales.)

The UK government has recognised that SMRs may offer significant opportunities to manufacturers, and if the UK can take an international lead in SMR technology development, the UK could produce SMRs, or their components, for the global market.[24] This could have a significant impact on the UK supply chain, and hence the economy.

A 2014 SMR feasibility study led by NNL gave a best estimate of around £80/MWh for capital cost per megawatt output. This is below the strike price agreed for Hinkley Point C.. Rolls-Royce is now targeting a price of £60/MWh for its SMR design, similar to the cost of offshore wind. The following SMR developers have publicly expressed interest in UK development, and are working with the NAMRC.

- Rolls-Royce is developing a modular reactor capable of providing 220-440 MWe, it has been designed to be compact enough to be transported by truck, train or barge. The reactor will use proven technology with a high degree of commercial or standardised components, and is designed specifically for factory manufacture and commissioning. Over three quarters of the design by cost is modular, opening up opportunities for UK supply chain companies to enter into volume manufacturing. The Nuclear AMRC is working with Rolls-Royce at its consortia to support development.
- Westinghouse is developing a 225 MWe pressurised water reactor, largely based on technologies deployed in its AP1000 design. An NAMRC study determined that Westinghouse's use of UK advanced manufacturing techniques offers a potential 50% reduction in delivery lead times and offers substantial cost savings to SMR manufacturing.
- NuScale Power is developing the Power Module, a 50 MWe pressurised water reactor and generator, designed to be deployed in clusters of up to 12 per site. NuScale is actively seeking potential UK suppliers and has a supplier registration page at suppliers.nuscalepower.com
- Urenco is working with Wood and Atkins on an ultra-small design called U-Battery. Based on pebble bed technology, each reactor will produce just 4 MWe plus 10 MWt. Target markets include back-up power, desalination plants and smart cities.
- China National Nuclear Corporation (CNNC) is also adapting Westinghouse AP1000 technology for its ACP100 SMR, with an output of 100 MWe plus 310 MW thermal power which can be used in district heating schemes.
- Moltex Energy, a privately-held UK company, is developing a 150 MWe stable molten salt reactor, designed for modular deployment in clusters of up to 10 units per site.
- GF Nuclear is an independent power generation company which aims to develop the South Korean 100 MWe Smart reactor in the UK.

Generation IV SMRs

For completeness, this section provides an overview of the main Generation IV technologies being developed. The Generation IV International Forum (GIF)[25] involves governments of 14 countries (the UK is currently a non-active member) where nuclear energy is significant now

[23]http://www.iea.org/publications/freepublications/publication/Nuclear_RM_2015_FINAL_WEB_Sept_2015_V3.pdf
[24]http://namrc.co.uk/intelligence/smr/
[25]https://www.gen-4.org/gif/jcms/c_9260/public

and seen as vital for the future. In 2014, the Forum produced the GIF Technology Roadmap Update, which confirmed the selection of six technologies to focus effort on.[26]

They were selected on the basis of being 'clean, safe and cost-effective means of meeting increased energy demands on a sustainable basis, while being resistant to diversion of materials for weapons proliferation and secure from terrorist attacks'. Those most likely to be deployed first are the sodium-cooled fast reactor, the lead-cooled fast reactor and the very high temperature reactor technologies. The molten salt reactor and the gas-cooled fast reactor were shown as furthest from a demonstration phase.

The start of the deployment of Gen IV reactors is not foreseen before 2030, and they are consequently are considered outside the scope of this SIA. However, in December 2017 Innovate UK launched the Small Business Research Initiative (SBRI): nuclear advanced modular reactors, feasibility and development competition, with a budget of £4m. The evaluation stage is due to be completed by March 2019, with the outcomes announced thereafter.

2.6 Decommissioning and Clean Up

Under the Energy Act, 2004, the NDA is responsible for the management of the UK's nuclear legacy, including decommissioning of 17 nuclear sites across the UK (of which 6 are in the NWNA), immobilisation of wastes in passively safe forms, interim storage and, ultimately, disposal.[28]

Low Level Wastes (LLW) are disposed in the Low Level Waste Repository (LLWR) in Cumbria, while Higher Activity Wastes, plus some LLW unsuitable for the LLWR, will be disposed underground in a Geological Disposal Facility (GDF). Government will shortly invite potential volunteer host communities to express interest in hosting the GDF and, since an operational GDF is likely to be some decades in the future, packaged wastes will need to be stored for many years prior to transport to the GDF and final disposal.[29]

The NDA programme is estimated to cost £115 billion overall and last around 120 years. Sellafield is by far the most complex site in the NDA Estate, with over 70% of the cost of the NDA mission being incurred at Sellafield and over 75% within the NWNA. Some materials, notably separated plutonium, have not yet been formally designated as wastes, and hence may or may not be included in the inventory for disposal. In the interim, they are held in safe and secure storage.[23 30]

As noted above, the AGRs, operated by EDF Energy, are coming to the end of their working lives, after which they will also be decommissioned and the resulting wastes disposed of. The cost of AGR decommissioning will be met by the dedicated Nuclear Liabilities Fund while part of the approval process for future reactors, including the new build fleet, is the establishment of a Funded Decommissioning Programme.

[26] https://www.gen-4.org/gif/upload/docs/application/pdf/2014-03/gif-tru2014.pdf
[27] https://apply-for-innovation-funding.service.gov.uk/competition/80/overview
[28] NDA Strategy
[29] The Nuclear Provision; Geological Disposal White Paper
[30] NDA Business Plan

THE NORTH WEST NUCLEAR AUDIT

3.

The aim of this section is to capture the nuclear activity that is present within the NWNA region. This audit is presented in 5 main categories: physical assets, innovation assets, skills base, knowledge base and business environment. These categories have enabled all the research assets and facilities in the NWNA, the large range of skills providers in the region, the nuclear research that is conducted in the region, in both academia and industry, and information on the large range of nuclear companies that are present within the region to be captured. This audit demonstrates that the NWNA is a unique region containing major components of the UK's nuclear RD&I and operational capability and well over half of all the UK's civil nuclear industry and R&D capability.

3.1 Physical Assets

This section is focused on the facilities and physical assets available for carrying out research and innovation activities related to the nuclear sector in the NWNA area. A list of facilities identified to date has been drawn up, including university laboratories, the National Nuclear Users Facilities (NNUF), National Nuclear Laboratory, private facilities and public-private partnerships. The list of facilities shown in the map and table below, have been classified into 3 groups based on the type of access:

- University Facilities: housed and funded by the host University.
- User Facility: those which can be accessed by any user, each facility will have its own application process for access, for example the National Nuclear User Facility (NNUF) Scheme. The NNUF scheme was launched in 2013 when the Government announced the Nuclear Industrial Strategy. The investment from EPSRC provides capital costs for facilities with the aim of providing equipment for experiments on materials that are too radioactive for conventional university laboratories.[31]
- Private Facilities: exclusively reserved for use by the host company due to the workload from the facility owner's programme and/or the sensitive nature of the work that is carried out there.

User access options, training requirements, access requirements, usage statistics, where reported, capabilities and equipment and any relevant outputs in the form of patents and papers are available in the appendix.

As can be seen in Figure 7 and Table 1 there are a large range of University research laboratories and facilities within the NWNA. These Universities

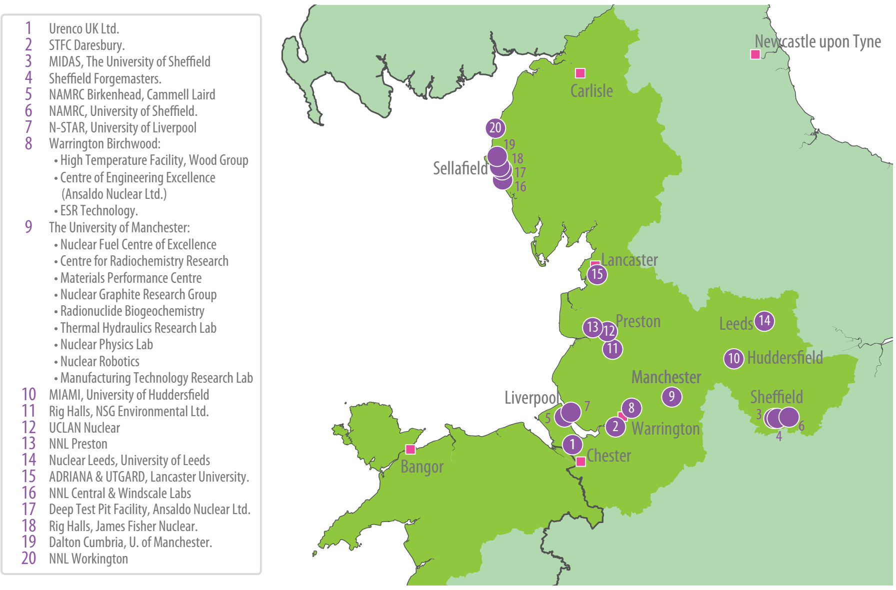


Figure 7: Map of the research facilities within the North West Nuclear Arc.

[31]http://www.nnuf.ac.uk

not only provide excellent research facilities but make an important contribution to nuclear skills provision within the region and also generate world class research, evidenced through publications in the nuclear research area. These are presented in more detail in the 'Skills' and 'Knowledge Base' sections of this audit.

There is also a large range of user facilities within the region, some are supported through the NNUF programme and some are funded through other funding sources such as the Science and Technology Funding Council (STFC). These facilities support research which is being carried out at various sites across the UK and provide specialist facilities to support a wide range of research within the nuclear industry.

Table 1: Table of Physical Assets within the North West Nuclear Arc.

Facility	Access
The University of Manchester: Nuclear Fuel Centre of Excellence • Centre for Radiochemistry Research • Materials Performance Centre • Nuclear Graphite Research Group • Radionuclide Biogeochemistry • Thermal Hydraulics Research Laboratory • Nuclear Physics Laboratory Nuclear Robotics • Manufacturing Technology Research Laboratory	University
N-STAR Facilities, University of Liverpool	University
Nuclear Leeds Facilities, University of Leeds	University
UCLAN Nuclear, University of Central Lancashire	University
MIAMI facility, University of Huddersfield	User Facility
STFC Daresbury	User Facility
Dalton Cumbrian Facility, The University of Manchester.	User Facility, NNUF
Lancaster University: • ADRIANA facility • UTGARD facility	User Facility, NNUF
MIDAS facility, The University of Sheffield	User Facility, NNUF
Warrington Birchwood High Temperature Facility, Wood Group	User Facility, NNUF
National Thermal Hydraulics Facility (TBC)	User Facility
Henry Royce Institute (Under Construction)	User Facility
Warrington Birchwood Centre of Engineering Excellence, Ansaldo Nuclear Ltd.	Private
ESR Technology	Private
Deep Test Pit Facility, Ansaldo Nuclear Ltd. (North West Division).	Private
Nuclear AMRC Birkenhead facility, Cammell Laird Rig	Private
Preston Laboratory, National Nuclear Laboratory • Active Rig Hall for batch processing • Analytical laboratories (low and intermediate level activity material) UKAS • Waste processing and analytical technique development • Fuel development and testing capability	Private
Rig Halls, Laboratory, NSG Environmental Ltd.	Private

Facility	Access
Sellafield Central Laboratory, National Nuclear Laboratory • Non-active and active laboratories • High-active alpha laboratory • Beta and gamma cells • Pu and MOX facilities • Graphite laboratories • Full scale (active) test facilities	Private/User Facility NNUF
Sheffield Forgemasters	Private
Windscale Laboratory, National Nuclear Laboratory • Active Handling and Inspection • Large shielded cells • Remote operations capability • Core capabilities are: Post Irradiation Examination (PIE); Source Handling; Waste segregation, packing and dispatch.	Private
Workington Rig Halls and Inactive demonstration Facilities, including Robotics and Remote Engineering, National Nuclear Laboratory.	Private
Urenco UK Ltd.	Private

Also in the region is the Nuclear Advanced Manufacturing Research Centre (NAMRC) which contains a range of facilities that specifically underpin moving scientific discoveries up Technology Readiness Levels (TRLs) and Manufacturing Readiness Levels (MRLs). This research is essential for the advancement of the nuclear engineering field. The NAMRC was created in 2011 through the High Value Manufacturing Catapult and, while it has its main facility in Rotherham, it has expanded recently with the 2017 opening of an outpost in Birkenhead, in partnership with Cammell Laird.

The aim of NAMRC is to help UK manufacturers to progress up the MRL and TRL scales, with a specific focus on levels 3-5 and 2-4 respectively, in order to help bridge the gap between proof of concept work which is traditionally carried out at Universities through to production readiness which is traditionally industry focused.

The NAMRC has extensive capabilities and expertise in 10 core technology themes; Advanced Machining, Large-volume metrology, Mechanised arc welding, Electron beam manufacturing, Laser beam manufacturing, Hot isostatic pressing, Bulk additive manufacturing, Non-destructive testing, Visualisation and Integrated manufacturing.[32]

The National Nuclear Laboratory (NNL) is a government owned and operated nuclear services technology provider covering the whole of the nuclear fuel cycle. With various sites located in the NWNA, NNL provides many unique facilities for high level radioactive work that cannot be carried out at Universities. The role of NNL within the industry is needs base research testing which helps convert science to technology, establish the practicality of fundamental research coming out of Universities, to scale up experiments and to use actual materials in the specialist licensed facilities that lie within the NWNA. This role is unique in the UK and results in the NNL taking on a role of Technical Challenge Translator & Facilitator within the UK nuclear industry.

Private companies have much to add and many different capabilities in the region. Certain unique facilities exist, such as Urenco Ltd. at Capenhurst which provides a significant part of the European capabilities for uranium enrichment. The new High Temperature Facility, run by Wood Group on behalf of a private-public partnership called the High Temperature Alliance, provides a specialised and unique environment for high temperature mechanical testing. The large metallurgical facilities of Sheffield Forgemaster's nuclear branch provide large scale forging and steel working capabilities for use in the nuclear field.

[32](http://namrc.co.uk/download/about/Nuclear-AMRC-capabilities.pdf)

Furthermore, there is a large network of rig halls and testing facilities in the region that supports the various nuclear stakeholders such as Sellafield, NNL and Rolls-Royce Nuclear.

Access Requirements

The process and ease of accessing these facilities varies. Access to these facilities is generally limited due to the safety and security requirements associated with radioactive materials and this has reduced the number of external collaborators that have been able to work within these labs. However, with the inclusion of some of these facilities in the NNUF programme, access has improved and continues to be a focus for improvement within the region.

The impact of Brexit is resulting in access to foreign labs becoming more restricted to UK researchers, so a stronger focus on improving the ease of access to the many unique UK facilities that are present within this region is important.

In 2016, a PhD student was permitted to access NNL Central Labs to conduct research that was not possible in their home institution. A lot of paperwork and security clearance work over several months was needed ahead of the 2 week visit, and the student was not permitted to carry out any hands-on work themselves. 2 members of NNL staff were required to carry out the work under the student's guidance. Due to limitations of the equipment available and restrictions on the range of chemicals which could be used, the results were inconclusive, and questions were raised in NNL regarding the time of the 2 supervising staff who were pulled from commercial work for 2 weeks. The difficulties in gaining access and the supervision requirements once access is granted makes these experiments very difficult to justify during the relatively short research period of a PhD, and therefore raises questions on the practical accessibility of these facilities.

UK's Fast Reactor Knowledge Capture Project

As well as physical assets, the nuclear industry has been involved in capturing the vast knowledge that is held within the industry. In 2014-2015, NNL, NIRO/NIRAB, DECC(BEIS) and NDA were all independently approached by a group of consultants, the Fast Reactor Consultants Group (FRCG) with a proposal to consolidate the UK's fast reactor knowledge into a single searchable database.

The project is now a BEIS Nuclear Innovation Programme (NIP) work package (work package 2 of the Strategic Toolkit Programme) running until December 2018. It is believed that the fast reactor database is likely to contain upwards of 50,000 documents.

Trawsfynydd

Another physical asset within the region is the Trawsfynydd site which lies in the Snowdonia Enterprise Zone in North Wales. This site was highlighted in a House of Lords Science and Technology Select Committee Report as a potential site for SMR deployment as "it is [in] public ownership, it has the right infrastructure (cooling capacity; grid connectivity; road connections; routes to transport large loads to site), local support, support at a North Wales and Wales level [and] proximity to centres of excellence for manufacturing."[33] It was also noted in the IMechE report in 2014 that the UK Government and Welsh Government should support Trawsfynydd as the location for the building and demonstration of an SMR.[34] Utilising this site for First-Of-A-Kind (FOAK) SMR deployment would provide the region with high value jobs and help boost the local economy.[35]

Future Physical Asset Development

Two future developments in the region which may significantly contribute to the NWNA's physical assets are the development of the UK National Thermal Hydraulic Facility, and the Henry Royce Institute.

The planned UK National Thermal Hydraulic Facility would provide a unique international capability that would greatly benefit the nuclear thermal hydraulic research in the UK and may provide the spine for future Light Water Reactor (LWR) research in the UK. Current proposals include locating this facility on the Menai Science Park (M-SParc) on Anglesey.

The Henry Royce Materials for Nuclear Energy area brings together expertise from the Universities of Manchester and Sheffield, NNL

[33]House of Lords Science and Technology Select Committee 'Nuclear research and technology: Breaking the cycle of indecision' 2017
[34]IMechE Report 2014, https://www.imeche.org/policy-and-press/reports/detail/annual-review-2014
[35]House of Commons Welsh Affairs Committee 'The future of nuclear power in Wales' 2016-2017

and United Kingdom Atomic Energy Authority (UKAEA). The aim is to establish capability for researchers across academia and industry to prepare, test and analyse radioactive materials for fission and fusion applications. Proposed facilities within the NWNA include expanded capabilities for research into nuclear fuels, wasteforms and irradiated materials.

3.2 Innovation Assets and Initiatives

In addition to the physical assets where research can be conducted within the region, there are clusters of nuclear companies on two science parks, at Birchwood Park in Warrington and Westlakes Science and Technology Park in Cumbria, with a third under development in North Wales, the Menai Science Parc. These sites house a large number of nuclear related companies who can benefit from working together in close proximity, and could be considered and further developed to become "Areas of innovation"[36]:

> "places designed and curated to attract entrepreneurial minded people, skilled talent, knowledge-intensive businesses and investments, by developing and combining a set of infrastructural, institutional, scientific, technological, educational and social assets, together with value added services, thus enhancing sustainable economic development and prosperity with and for the community."
> Luis Sanz, IASP Director General

As well as these physical clusters, the region boasts a number of Nuclear Forums and Cluster groups which bring together all parties with an interest in nuclear within the regions they represent. Britain's Energy Coats Business Cluster (BECBC) in Cumbria, the North West Nuclear Forum (NWNF) in Warrington, and the Wales Nuclear Forum (WNF) conduct regular meetings providing their members with invaluable networking and learning opportunities within the nuclear sector and aim to promote the services offered by members to the nuclear industry. The table below summarises the different committees and groups that are active within the region.

Table 2: Summary of committees, groups and fora active within the NWNA.

Britain's Energy Coast Business Cluster	In operation for more than 15 years, BECBC is a mature 320+ member cluster group of companies from nuclear tier 1s to small energy and non-energy related SMEs working in Cumbria but centred around the nuclear sector in Cumbria. Their goal is to be a "Cumbrian Collaboration with Global Reach" and in addition to a range of member services, sharing of best practice and learning, coaching, and regular networking, they reach out to similar cluster groups across the UK and internationally.
North West Nuclear Forum	A platform for like-minded nuclear companies and SMEs that have a footprint in the Birchwood / Cheshire / North West area, with an interest in sharing information and working together to generate business in the nuclear sector, from New Build to Nuclear Decommissioning. The Forum: • Acts as a conduit for dissemination of useful information to the regional supply chain. • Promotes the strength, diversity, professionalism and depth of services offered in the region This Forum organises quarterly lunchtime meetings with relevant invited speakers and networking opportunities. ***This Forum has strong links with the Wales Nuclear Forum with mutual objectives.***
Wales Nuclear Forum	Established in 2017, the WNF is the central information point for anyone located in Wales wanting to be kept up to date on Nuclear industry news, projects and events. Members also benefit from access and participation at regular forum meetings, compliance reports and essential training support. Currently 107 members signed up with a further 3 partner memberships

NDA's Regional SME Steering Groups (Cumbria; North; Scotland; South/ Central; Wales)	Providing a forum to discuss improving the attractiveness and the health of the market that supports the NDA sites, with specific focus on SMEs. Enables direct and public voice to the NDA in order to more effectively support its decommissioning and Site restoration mission.
The Boiling Water Reactor Research Hub	This is a joint project between Bangor University and Imperial College London with support from Hitachi-GE and Welsh Government. The aim is to promote research into Boiling Water Reactors across the UK by supporting Hitachi-GE and Hitachi Research in developing working groups into BWR Technology.
NDA Estate SME Mentoring Scheme	To promote and encourage participation of SMEs. An annual scheme that interested SMEs can apply for via the NAMRC website.
Nuclear AMRC Fit4Nuclear (F4N)	Bespoke service to help UK manufacturing companies get ready to bid for work in the civil nuclear supply chain. Areas of focus are: Strategy & Leadership; Design & Project Management; People Excellence; Process Excellence; Health & Safety Culture; Quality Management & Systems.
Sellafield's Game Changers	Sellafield Ltd actively seek to engage businesses, academia and individuals who can bring their innovative, smart technologies and digital solutions into the nuclear arena and help accelerate the decommissioning programme whilst also reducing costs and upholding Sellafield's commitment to human and environmental safety. This programme is run by Sellafield and supported by the University of Manchester Dalton Institute and the National Nuclear Laboratory.

Other innovation assets that can be found in the region include the Centre of Nuclear Excellence (CoNE) which is based in Cumbria. CoNE is partnership of nuclear Tier 1s (BAE Systems, LLWR, Sellafield Ltd, NDA, NNL, NuGen), communities represented by Copeland, Allerdale and Barrow Borough Councils and the Cumbria LEP, and also the nuclear supply chain represented by BECBC. CoNE is focused on support of the nuclear sector in Cumbria and the UK and aims to help position Cumbria to fully capitalise on the nuclear opportunities in the UK.

CoNE undertakes work on a number of cross cutting themes including Skills, Supply Chain and Innovation and has developed an Innovation Partnership which will:

- understand, map and segment the market for nuclear innovation, identifying strengths and capabilities,
- create visibility of immediate and long-term innovation problems,
- work with Tier 1s to put in place effective structures and practices that facilitate rapid delivery of initial ideas, prototypes and the effective partnerships needed for the delivery of selected solutions,
- speed up the flow of ideas and solutions and create a culture of innovation by putting problem holders and innovators together, through formal and informal means, to stimulate conversation and the sharing of ideas, increasing serendipity and creative collisions,
- build on and promote existing regional and national innovation programmes.

In so doing the Innovation Partnership aims to create a "Vibrant Marketplace for Innovation in Cumbria" in and around the nuclear sector.

3.3 Skills

In order to support current programmes in decommissioning and clean up, geological disposal, and new build, as well as future fission and fusion programmes, a large range of nuclear skilled workers are needed in the UK. However a >75% decline in high level (levels 6-8) nuclear skills has been occurring over the last 25 years.[37] Figure 8 shows the projected demand of the UK nuclear workforce from 2016-2036 alongside the current workforce projected and clearly shows a discrepancy between the projected demand and the projection of the current workforce. Without a clear skills intervention, there could be shortage of up to 40,000 workers by 2036.

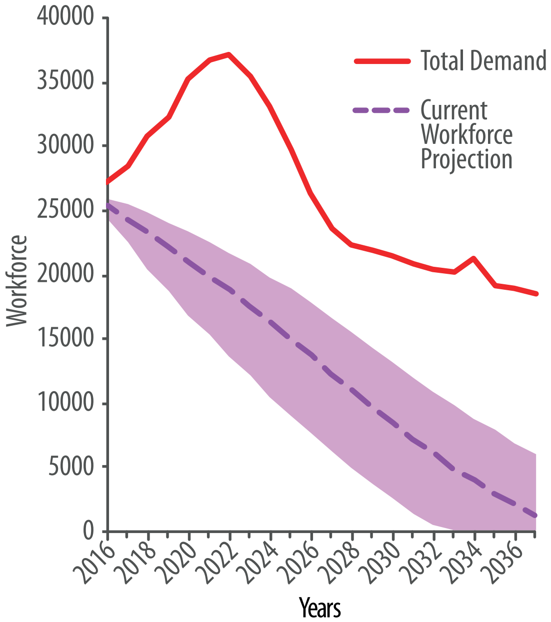
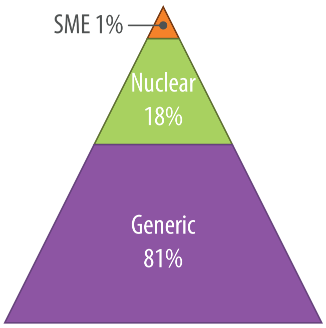


Figure 8: Demand and Projection of current workforce, the current workforce projected (dotted line) on the basis of retirement at 65 and an additional 4% general attrition.[38]

The Nuclear Workforce Assessment shows a required net inflow of 7,000 Full Time Equivalents (FTEs) per annum for the next 5 years.[38] Since the current inflow is approximately 3,000 FTEs per annum[39] the UK falls short of its skills requirement levels by a large margin hence the UK's long term civil nuclear initiatives require over 1000 new entrants per year, with ca 70% in technical or professional grades.[40]

The Nuclear Skills Strategic Group (NSSG) categorised skills within the nuclear industry into 3 main groups; subject matter experts (a small number of experts with specialist skills that take years to acquire), nuclear skills (specialist skills that are only required in the nuclear industry e.g. safety case engineers) and generic skills (those that can be found outside the nuclear industry).[37] The current proportions are shown in the pyramid in Figure 9, showing that nuclear specific and subject matter experts skills make up only 19% of the skills required. This demonstrates that sector jumpers could play an important role in the nuclear skills shortage as there is a large need for generic skills within the nuclear industry.

Figure 9: Skills pyramid where segment area is proportional to fractional occupancy[37]



The CoNE Skills and Education Task Force (SETC) has conducted some analysis on the nuclear workforce in Cumbria. They have identified eight pinch point groups which satisfy at least 2 of the following criteria; significant volumetric growth, limited local supply, and current industry shortage. These are areas in which the nuclear workforce could suffer the most without a clear skills programme. These identified pinch point groups are:

- civil engineering,
- construction & construction management,
- project management & controls,
- operations & commissioning,
- plant design & engineering,
- business functions,
- quality management,
- nuclear safety case & safety assessors, and
- chemistry & chemical engineering.[41]

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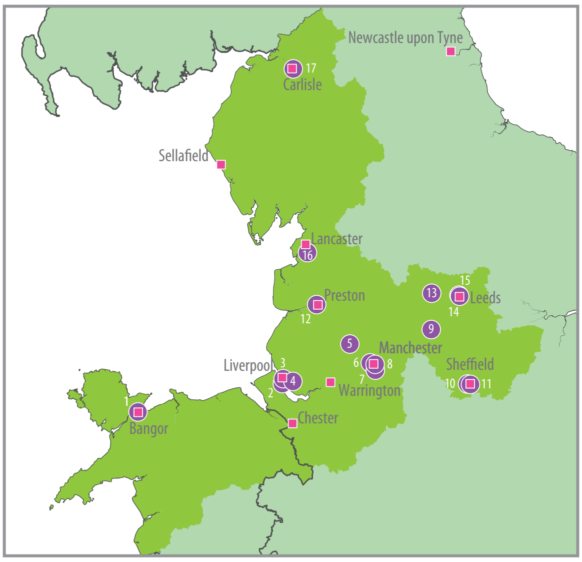
[37]Coverdale (2002) Nuclear and radiological skills study
[38]NSSG: Nuclear Workforce Assessment 2017
[39]http://www.cogentskills.com/nssg/nssg-news/121217-nuclear-skills-strategy-group-welcomes-nuclear-industry-council-proposals-to-government-for-a-sector-deal/
[40]COGENT Sector Skills Power People: The Civil Nuclear Workforce 2009-2025
[41]Cumbria Nuclear Statistics Briefing Document, November 2017.

As well as the need for generic nuclear skills and due to an ageing workforce within the nuclear industry, maintenance of the UK population of nuclear subject matter experts is an explicit priority in the forthcoming Nuclear Sector Deal, and availability of High Level Skills (HLS) and subject matter experts, where doctoral level training is frequently the first step on the career path, is identified as "of particular concern" in the Nuclear Skills Strategy.[42] As well as the civil sector, there will be additional demand from defence, safeguards and security activities.

Table 3: Institutions and nuclear skill levels that are located in the NWNA.

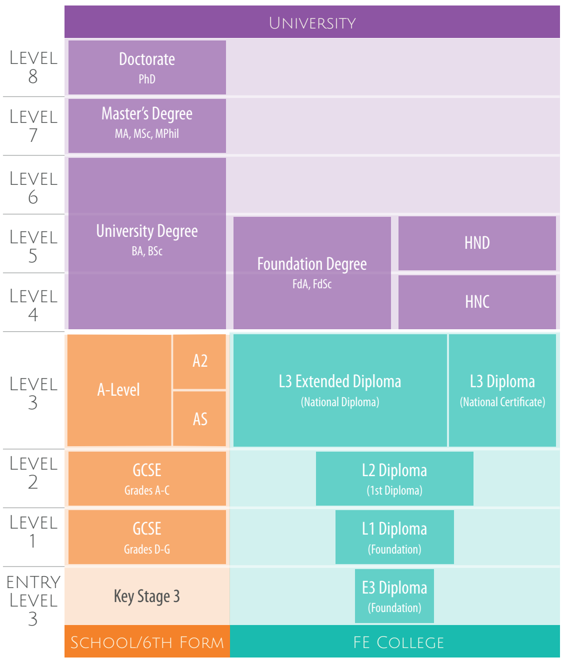
Institution	Level (nuclear)
University of Cumbria	5
UCLAN	5 6
Blackpool and The Fylde College	2 6
Furness College	1 6
Lancaster University	5 8
Bury College	2 6
University of Manchester	5 8
University of Liverpool	5 8
Coleg Llandrillo Menai	3 6
University of Bangor	5 8
Coleg Cambria	2 6
University of Sheffield	5 8
University of Leeds	3 6
Warrington UTC	1 3
Energy Coast UTC	1 3

The North West Nuclear Arc uniquely houses a large range of nuclear skills providers which can provide specialist training across the full range of skill levels. Table 3 and Figure 10 shows the location of the skills providers on a map, showing a clear cluster in the NWNA, and a depiction of the levels these institutions are able to provide in nuclear specific training.



1 Bangor University
2 University of Liverpool
3 Liverpool John Moores University
4 Liverpool Hope University
5 University of Bolton
6 University of Salford
7 Manchester Metropolitan University
8 University of Manchester
9 University of Huddersfield
10 University of Sheffield
11 Sheffield Hallam University
12 UCLAN
13 University of Bradford
14 University of Leeds
15 Leeds Beckett University
16 Lancaster University
17 University of Cumbria

Figure 10: Map of the range of Skills providers, and a skills ladder demonstrating the qualifications that the skill levels relate to.



[42]NSSG (2017) Nuclear Skills Strategic Plan

The range of nuclear skills provision across a large range of institutions within the NWNA region results in an ability to train a large range of nuclear skilled workers to meet the projected shortages. One specific area where the NWNA is uniquely placed is the HLS/ subject matter expert aspects of the skills agenda. This is because the NWNA houses the entire gamut of the UK's nuclear programme as will be discussed in the 'organisations' section of this audit, as well as a large range of institutions which can deliver training up to level 8.

One method to deliver the high level skills training is through Centres for Doctoral Training (CDTs) which provide PhDs to students in a specific area (nuclear in this case) but across a wide range of subject areas (e.g. chemistry, engineering, physics, etc).

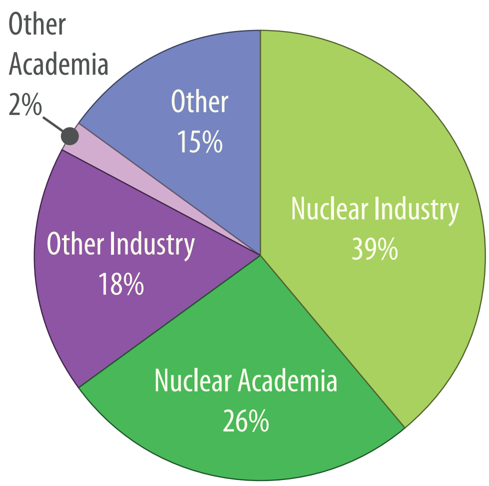


Figure 11: Pie Chart of employment area of students who completed the Nuclear First DTC scheme, categorised as nuclear industry, nuclear academia, other industry, other academia or other. Information provided by the Centre for Doctoral Training Office at Manchester University.

The first nuclear CDT in the UK, named the Nuclear First DTC (Doctoral Training Centre) was run between The University of Manchester and The University of Sheffield, both of which lie in the NWNA. This scheme ran from 2009-2017 and figure 11 shows the employment figures from this PhD scheme. Over 60% of those who completed the scheme now work within the nuclear sector, either in industry (39%) or academia (26%), demonstrating the effectiveness of CDTs as a way to develop highly skilled personnel for the sector. Currently there are 2 nuclear CDTs in the UK; one centred in the NWNA which is run by The University of Manchester in partnership with Lancaster University, The University of Leeds, The University of Liverpool and the University of Sheffield as well as key partners including AmecFW (now Wood Group), Areva, AWE, EDF, the NDA the NNL, Rolls-Royce, and Sellafield Ltd. The second CDT is run out of Imperial College London with The University of Cambridge and Open University. Both have recently been successful in securing funding from EPSRC for a third round of CDTs with Bangor and Bristol joining the Imperial led programme.

3.4 Knowledge Base

The level of funding for nuclear R&D in the established nuclear countries has diminished to a worrying degree. This is demonstrated in Figure 12 which shows a large investment through the 1970s and early 80s which dropped to a steady level from about 1990 until the Fukushima incident of 2011 when nuclear R&D investment fell dramatically. Considering the data solely for the UK, the situation appears even bleaker. After around 1996 the section of the chart representing the UK has shrunk to be almost unidentifiable, a situation which persists until the data ends in 2013. It should be noted that the situation in the UK has improved somewhat in response to the very low level of investment, NIRAB was founded in 2013 and programmes such as NNUF, the nuclear CDTs were joined by investment from DECC and now BEIS.

[43] https://thebreakthrough.org/images/pdfs/How_to_Make_Nuclear_Innovative.pdf

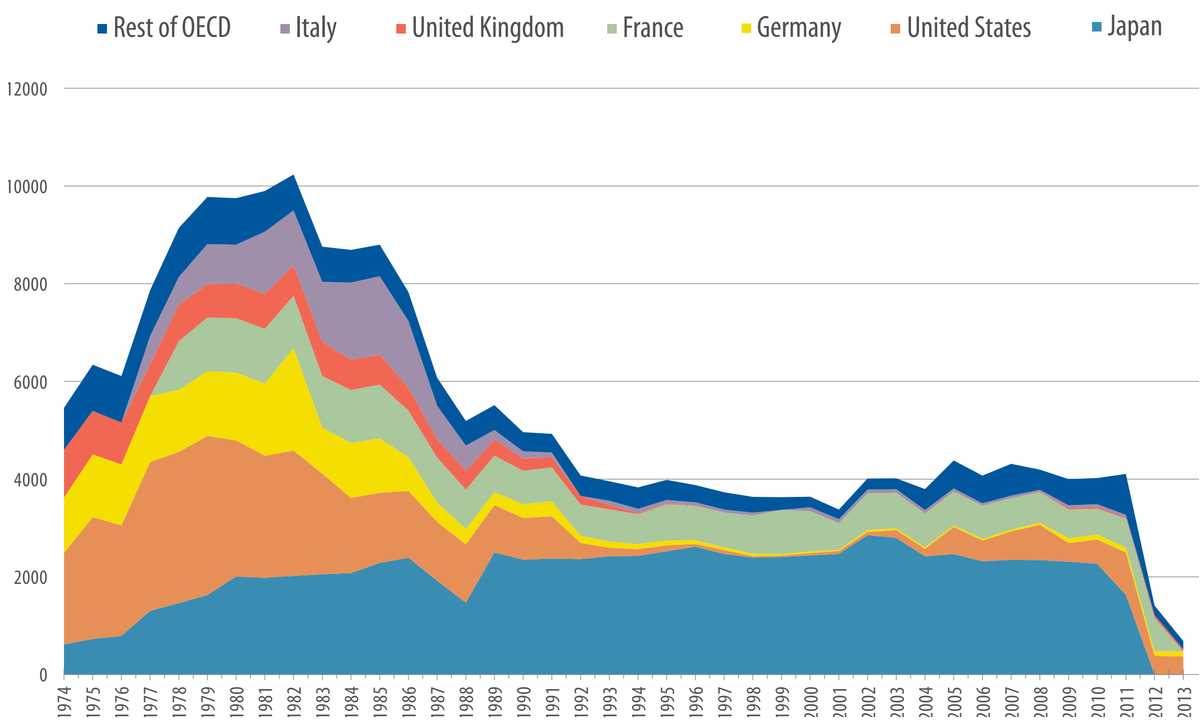


Figure 12: Total R&D spending on nuclear fission in OECD countries (millions of USD at 2013 value). Data taken from OECD statistics library, figure is based on that found in "How to Make Nuclear Innovative Report" from the Breakthrough Institute.[43]

A strong nuclear research base is important for developing the new technologies and methods on which the industry may depend in the future. In this section the research that is conducted in the NWNA is captured through analysis of publications and successful grant applications.

Journal and conference papers, technical reports and books are key outputs from academic research. A review of these publications provides an overview on what is being done and by whom. As part of the 2017 report, "The UK Civil Nuclear R&D Landscape Survey" NIRAB also analysed publications in nuclear.[44] Given its recent publication, it has been used as the starting point for this audit.

NIRAB and its secretariat Nuclear Innovation and Research Office (NIRO) provide independent advice on nuclear research and innovation to the Government. In their 2017 report data was collected by questionnaire from universities, companies and national labs. As a result, it provides a considerable level of detail regarding the UK's nuclear R&D capability and knowledgebase. Given that this data is still relevant, the analyses presented in this audit aims to complement rather than repeat those in the NIRAB survey. Despite this, some of its findings are directly relevant to the Northwest Arc and will now be highlighted.

In the context of innovation, having an appreciation of the number of people engaged in fission and fusion R&D, both in universities and private companies is useful. This is because people engaged in such work often provide the new thinking that should provide a conduit to process improvement, new technologies, industries and hence economic growth. In their report NIRAB provide data on the number of full time equivalent (FTE) workers engaged in this work.

[44]The UK Civil Nuclear R&D Landscape Survey, Feb 2017, http://www.nirab.org.uk/media/10671/nirab-123-4.pdf

Figure 13 which shows the academic researcher data in aggregate: the number of academic researchers working inside the Nuclear Arc and in the rest of the UK. From this it can be seen that around 44% of university researchers are within the Nuclear Arc – this is significantly above what may be expected given that the audit region contains only 18% of the UK's population[45] and contains only 9 of the 31 universities reported by NIRAB. When the "Staff" segments are compared the difference between the Nuclear Arc and the rest of the UK is marginal meaning they are effectively the same. Similarly the numbers of postdoctoral researchers in the region's universities are comparable to those in the rest of the UK combined (45% of the total).

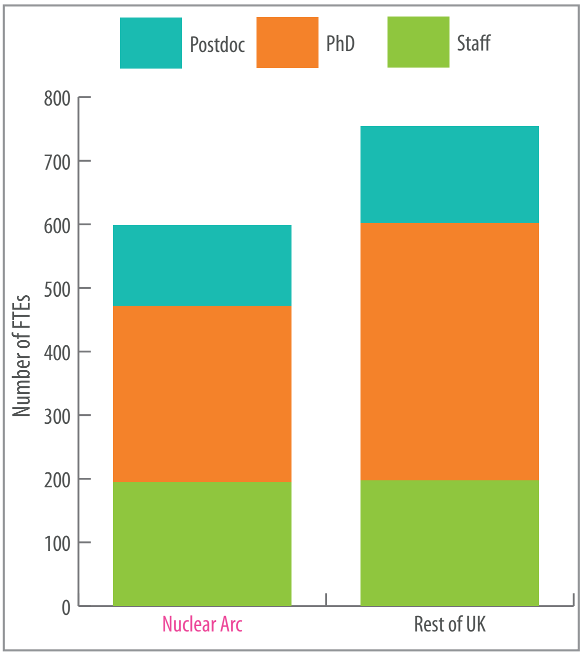


Figure 13: Aggregation of NIRAB data for 2015-2015 showing the number of FTEs inside and outside the Nuclear Arc.

Additional data were collected from the Scopus abstract database for nuclear publications from the United Kingdom for the period 2006-2018.[46 47]

University	Publication Count
University of Manchester	442
University of Sheffield	266
University of Leeds	113
Lancaster University	83
University of Liverpool	52
University of Huddersfield	30
University of Salford	27
Sheffield Hallam University	16
University of Central Lancashire	14
Bangor University	5
Liverpool John Moores University	4
Manchester Metropolitan University	4
University of Cumbria	4
University of Bolton	2
Leeds Beckett University	1
Liverpool Hope University	1
University of Bradford	1

Table 4: Nuclear publication counts (fission and fusion) for universities within the North West Nuclear Arc 2006-2018.

Table 4 gives the publication data for all the universities within the Nuclear Arc that have contributed least one paper. There are 11 universities listed and the diversity is encouraging and indicates the depth of experience spread throughout the region.

[45] NWNA population estimate of 11,308,428 is based on 2011 census data. This was calculated by summing over the population weighted centroids contained within region of Northwest Nuclear Arc. Data provided by ESRC Consumer Data Research Centre, which was derived from National Statistics, Scottish Government and Ordnance Survey data which are all © Crown copyright and database right 2015.
[46] The search was conducted on the 18th April 2018, therefore only part of 2018 is represented in the search results. In not all papers from 2017 may have made it into the database at the time of data collection.
[47] The exact methodology employed is given in Appendix: Methodology for bibliometric study.

Rank	University	Publication Count
1	University of Manchester	442
2	Imperial College London	309
3	University of Sheffield	266
4	University of Cambridge	159
5	University of Bristol	149
6	University of Oxford	138
7	University of Leeds	113
8	Lancaster University	83
9	University of Strathclyde	78
10	UCL	75
11	University of Birmingham	69
12	University of Surrey	59
13	University of Liverpool	52
14	Cardiff University	52
15	Loughborough University	48

Table 5: The top 15 nuclear universities in the UK by publication count 2006-2018. Highlighted rows are in the NWNA.

Widening the scope to United Kingdom, Table 5 lists the top fifteen universities by paper count.

Institutions within the Arc are highlighted and the significance of their output is apparent, occupying 5 of the top 15 spots with Manchester and Sheffield, 1st and 3rd respectively.

Modern research fosters collaboration between multiple authors, and by examining the author list of each publication the links can be identified.[48] By counting the number of papers co-authored by these organisations the socio-technical collaboration network underpinning nuclear research in the region has been identified. The truly global scope of the collaboration between organisations in the NWNA is illustrated graphically in Figure 14 (n.b. this also includes industrial, government and other research partners), which shows where the strongest research links exist with other regions. The bibliometric study shows that shared European facilities are critical to UK nuclear research and collaboration – consequently maintaining access for researchers through the Brexit/Euratom transition is crucial.

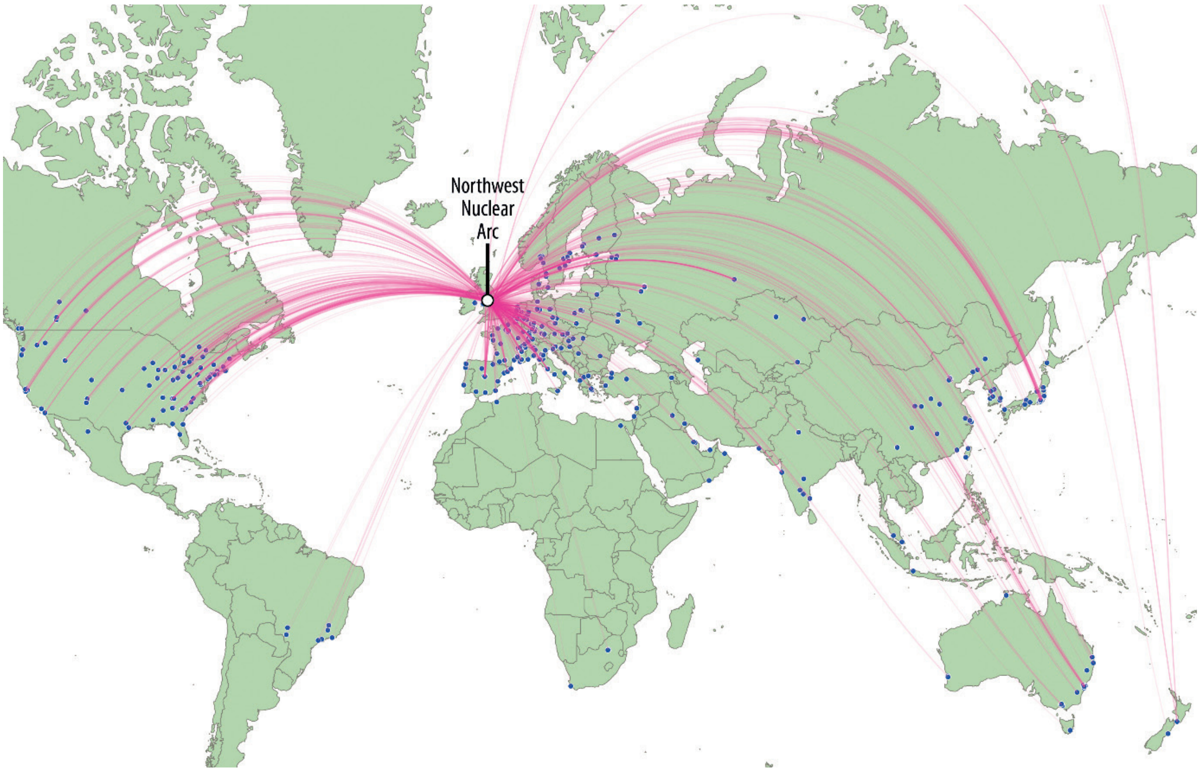


Figure 14: Map showing collaborative links between organisations within the Nuclear Arc and the rest of the World.

One of the main funding bodies in the UK is EPSRC and, at the time of writing, the EPSRC Nuclear Fission portfolio contained 77 grants worth £65.4m.[49] Of this, £46.5m of the portfolio can be attributed to the 37 grants led by Nuclear Arc universities. When it is remembered that the region contains 21 of the UK's 135 higher education institutions or roughly 16%, this reinforces the importance of the Arc's universities in nuclear research.

In order to provide a better understanding provided by the EPSRC in nuclear fission, the complete portfolio is represented in schematic form in Figure 15, the EPSRC project titles can be found in appendix 4. The inner ring shows circles representing the institutions which investigators and co-investigators belong.

The diameter of these shows the number of grants an organisation is part of. This is also apparent by the number of links made to the central, green, ring of nodes which represent individual grants. Again the diameter is proportional to the number of links the grant makes with investigators and partners.

The red edges show who is principal investigator for a grant. The grants are further connected to an outer ring of "partners"; these are entities that provide financial, technical or research services but may not be at the coal-face, conducting the everyday research associated with a grant. Typically industry partners are found in this category.

[49]Engineering and Physical Research Council, Visualise Our Portfolio, Nuclear Portfolio: https://epsrc.ukri.org/research/ourportfolio/vop/grantlist/RESEARCHAREA/73/THEME/Energy/9999/ (accessed 24th May 2018).

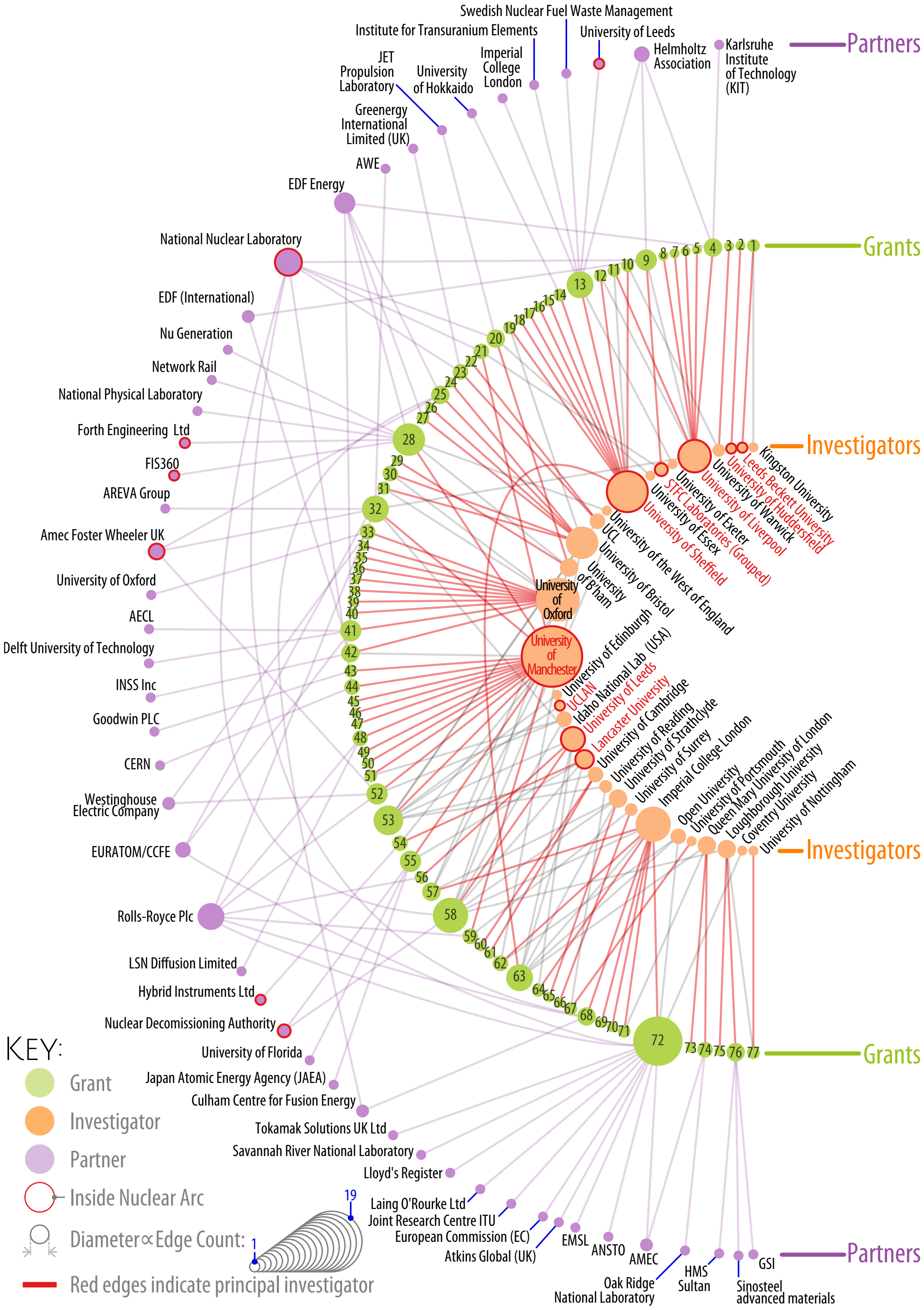


Figure 15: Visualisation of the EPSRC's fission portfolio. This shows how the organisations that investigator and co-investigators belong to are related to grants and outside research partners. This helps to give an impression of who leads, collaborates and supports research in the UK. Note: the titles for the grant IDs in the figure are given in Appendix 4.

Figure 15 makes certain features of the Portfolio apparent – most universities are involved in only one or two grants with a handful of 'hub' universities commanding a much larger number of grants. In this respect the Nuclear Arc is a success story: the University of Manchester leads the way being involved with 19 for which it is principal investigator on most (16 grants). Overall, when ranked by the number of grants held, the Nuclear Arc holds three of the top five places (see Table 6).

Rank	University	Number of EPSRC Grants	Number as Principal Investigator
1	University of Manchester	19	16
2	University of Oxford	13	10
3	University of Sheffield	12	10
4	Imperial College London	10	8
5	University of Liverpool	9	6

Table 6: Top 5 Universities ranked by number of EPSRC nuclear research grants held. Nuclear Arc universities are highlighted.

The range of research topics covered under these grants is varied which reflects the depth of talent in the region's universities. Notably, there have been important developments taking place in nuclear robotics: in 2017, the University of Manchester was awarded almost £6 M across the "Robotics for Nuclear Environments"[50] and "TORONE - TOtal characterisation for Remote Observation in Nuclear Environments"[51] grants (28 and 55 in Figure 15). This represents the largest investment in nuclear robotics within the Portfolio, reflecting the University of Manchester's and therefore the North West Nuclear Arc's status as a leader in this field.

Figure 15 can provide further information on larger consortium projects. Most grants tend to involve investigators from only one or two research organisations (this holds for 69 of the 77 grants). Projects that bring together a larger consortium of universities are therefore of particular note. Two of the largest, by value and number of collaborators are DISTINCTIVE and PACIFIC (58 and 53 in Figure 15) and each include researchers from eight universities. DISTINCTIVE is related to nuclear waste whilst PACIFIC targets fuel research and significantly both are led by universities in the NWNA (DISTINCTIVE by Leeds and PACIFIC by Manchester). Although both are reaching their conclusion, they are in the process of being renewed and it is likely that the NWNA will maintain its central role in the follow on projects. Another important research network is represented by the JUNO grant (labelled 63), this names co-investigators from seven universities and aims to facilitate and encourage UK-Japan nuclear research collaboration. Importantly it is led by the University of Sheffield, clearly adding more weight to the assertion that the Nuclear Arc's universities are essential to the UK's domestic and international research networks.

The other large collaborative grants obvious in Figure 15, are the two current CDTs, one based in the NWNA (32: Next Generation Nuclear) and the other in the South (72: ICO CDT), and the NUCLEAR consortium (label 57). Although the NUCLEAR consortium is run by Imperial College, it is interesting to note that as of 2019, its annual flagship event, the Nuclear Academics Discussion Meeting, which brings together the UK's nuclear research community, will have been hosted by a Nuclear Arc university on five out of eight occasions.

It should also be noted that the National Nuclear Laboratory plays an important supporting role to university led research. Of the research partners shown in Figure 15, only Rolls-Royce can match NNL for the number grants it has supported.

To better understand the strengths of the region's universities, the subject areas in which they published have been analysed. To allow comparison with NIRAB's survey data their classification scheme has been adopted here. This defines the following eight categories:

- Fuel Fabrication: Uranium conversion and enrichment, fuel development, fuel manufacture, fuel cycle assessment.
- Reactors: Reactor technology/design, reactor component manufacture, reactor operation including materials degradation and structural integrity, activation and structural integrity.

[50] EPSRC grant reference EP/P01366X/1.
[51] EPSRC grant reference EP/P018505/1.

- Advanced Reactors: Advanced reactor systems (Gen IV), fuel recycle / reprocessing for advanced systems.
  Spent Fuel Handling: Spent fuel storage, fuel recycle / reprocessing for current operations, nuclear materials management.
  Waste: Waste retrieval, legacy clean-up, effluent management, geo-science, earth science.

- Decommissioning: Decontamination, structure demolition, asset management, post operation clean out.
  Fusion: Plasma, advanced materials for fusion, tritium handling in fusion, activation studies for fusion, nuclear data for fusion, remote handling for fusion.
  Cross-cutting technologies: Advanced computational methods, neutronics, safety, security, social studies, public engagement, regulatory, economic.

A radar plot is shown in Figure 16 which compares the research outputs in the NWNA with those outside according to the NIRAB classes. Each axis represents the percentage of publications representing that class. It should be noted that fusion has been excluded here, as fusion research is dominated Culham Centre for Fusion Energy that its inclusion does not allow a representative view of the nuclear research mix either in the NWNA or across the rest of the UK. As can be seen in the radar plot, the NWNA publications have an emphasis on the back-end of the fuel-cycle with waste, spent-fuel handling and decommissioning representing a greater fraction of the region's academic output.

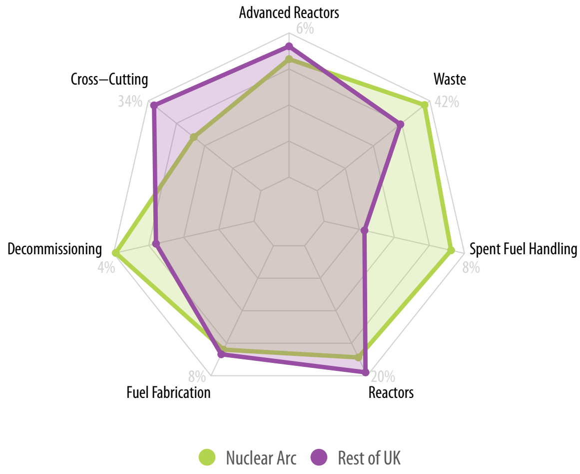


Figure 16: Radar plot showing the research mix for academic publications inside the NWNA and the rest of the UK.

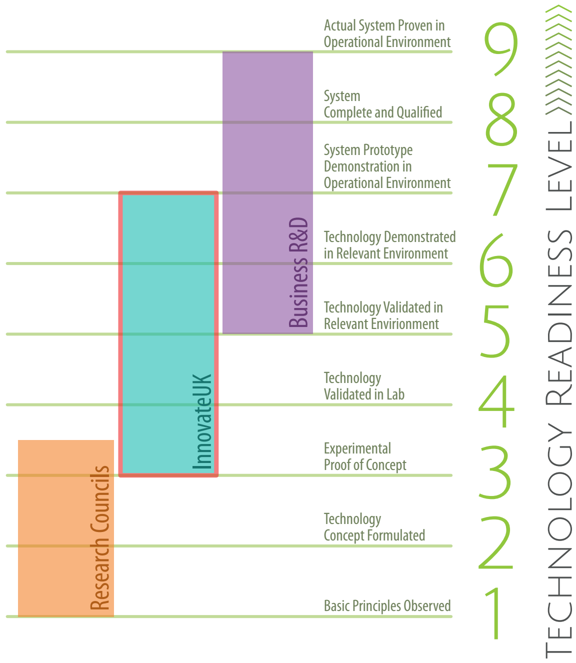


Figure 17: The position of InnovateUK in relation to technology readiness levels.

InnovateUK describes itself as the "UK's innovation agency", and provides funding to aid the development and realisation of potential of new ideas. Figure 17 shows where InnovateUK sits in the context of Research Councils funding and industrial R&D. Typically Research Councils such as EPSRC and NERC support fundamental research at TRL 1-3, largely in universities. Beyond this point InnovateUK funding kicks in to provide an interface to private industrial R&D at the higher TRLs. By examining the type of work funded by InnovateUK and looking at which companies and universities are working with each other it is possible to gain a better understanding of nuclear innovation and its commercialisation. In the coming years the funding landscape that is about to be described may see a significant change as, since May 2017, the seven Research Councils, Research England and InnovateUK have now been integrated within a new organisation named UK Research and Innovation (UKRI).

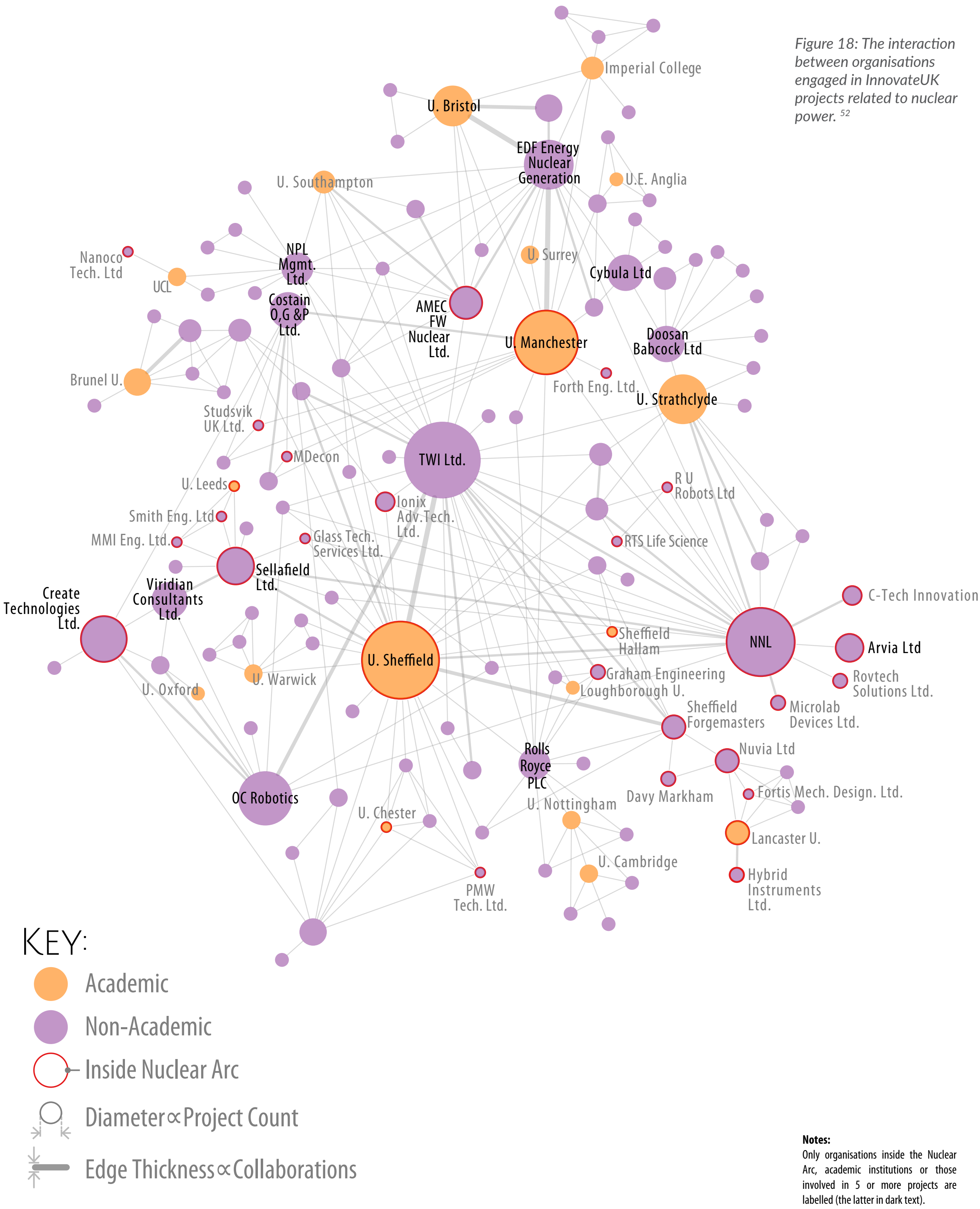


Figure 18: The interaction between organisations engaged in InnovateUK projects related to nuclear power. [52]

Notes:
Only organisations inside the Nuclear Arc, academic institutions or those involved in 5 or more projects are labelled (the latter in dark text).

[52]EData extracted from "Innovate UK funded projects between 2004 and 1st April 2018 Spreadsheet" – published 13th April 2018 (https://www.gov.uk/government/publications/innovate-uk-funded-projects accessed 2nd May 2018).

InnovateUK's list of funded projects[52] was mined for nuclear projects conducted since 2004. This data is presented graphically in Figure 18 for the entire UK. Organisations are represented as circles, sized by the number of projects conducted. These are then linked by edges showing collaboration between a pair of organisations (with heavier edges showing more than one collaboration). Academic entities are clearly highlighted in orange and organisations from the Arc are highlighted with red outlines. The intention of this figure is to show the structure and nature of collaboration embodied by this research portfolio, consequently, to avoid clutter, only companies involved in five or more projects, universities or any entity inside the Arc have been labelled.

A striking feature of the network in Figure 18, is its level of interconnectivity: the diagram is dominated by a large cluster of interlinked companies in its top half (entities not linked into this cluster are arranged in the bottom left of the figure for NWNA companies, middle bottom for companies outside the Arc and bottom right for academic institutions). The presence of the super-cluster shows that a significant proportion of the organisations receiving InnovateUK funding have contributed to multiple projects and often collaborate with different sets of partners depending on the project. This level of interconnection also shows that InnovateUK is achieving success in its stated aim to connect organisations with one another.

Within the super-cluster there are a number of hub organisations that have extensive connections in the collaborative web. These are the companies and universities that have been involved in the largest number of projects. When ranked by this metric, the NWNA performs very well occupying three of the top five spots with 1st place going to the University of Sheffield (16 projects) and 3rd to the National Nuclear laboratory (14 projects). The entire top 20 is given in Table 7 and shows that the NWNA is well represented.

Table 7: Organisations involved in InnovateUK projects ranked by the number of projects conducted. Highlighted rows indicate organisations from inside the Nuclear Arc. The table also includes information on the number of InnovateUK projects led by each institution.

Rank	Name	Projects as Lead	Project Count
1	University of Sheffield	3	16
2	TWI Ltd.	1	15
3	National Nuclear Laboratory Ltd.	3	14
4	University of Manchester	5	13
5	Oliver Crispin Robotics Ltd.	9	10
6	Create Technologies Ltd.	7	9
7	EDF Energy Nuclear Generation Ltd.	3	9
8	University of Strathclyde	2	9
9	Sellafield Limited	2	7
10	University of Bristol	0	7
11	Cybula Limited	6	6
12	Viridian Consultants Ltd.	5	6
13	Costain Oil, Gas & Process Ltd.	3	6
14	AMEC Foster Wheeler Nuclear UK Ltd.	3	6
15	Doosan Babcock Ltd.	0	6
16	Arvia Technology Ltd.	5	5
17	Symetrica Security Ltd.	5	5
18	Rolls-Royce PLC	1	5
19	NPL Management Ltd.	0	5
20	Beran Instruments Ltd.	4	4

The very strong performance shown by the University of Sheffield and University of Manchester in this list is worthy of comment. Earlier in this report, it was shown that both publish extensively indicating that involvement in InnovateUK projects is not at the expense of their fundamental research. Remarkably, with the exception of Bristol, the universities close to Sheffield and Manchester by number of publications, namely Imperial, Cambridge and Oxford have much lower involvement in InnovateUK projects having been involved in only 3, 2 and 1 awards respectively. Although by no means a general pattern across the audited region, the particularly strong showing of Manchester and Sheffield, points to a willingness to reach up into the higher TRLs. It may be that there may be lessons that can be learned from them on how to engender this kind of entrepreneurial spirit, allowing more of the UK's World class university based research to be translated into economic growth in the form of new products, services and perhaps entirely new industries.

Of the 247 nuclear related awards from the InnovateUK database, 111 had the involvement of at least one Nuclear Arc organisation (45%). In terms of grants awarded, £19.3m of funding has been offered for work in the audited region. This represents 34% of the £56.2m offered in nuclear overall. This headline figure does not tell the whole story however: when ranked by the total amount offered, the top organisations in the NWNA perform well. As shown in Table 8, Sheffield Forgemasters and the University of Manchester have both been awarded £2.5m since 2004 and 6 out of the top 10 cumulative award totals reside inside the NWNA.

Rank	Name	Project Count	Total Grants Offered £	Avg. Grant Per Project £
1	Oliver Crispin Robotics Ltd.	10	4,878,397	487,840
2	TWI Ltd.	15	2,887,808	192,521
3	Sheffield Forgemasters RD26 Ltd.	4	2,683,306	670,827
4	University of Manchester	13	2,593,102	199,469
5	Create Technologies Ltd.	9	1,996,841	221,871
6	Viridian Consultants Ltd.	6	1,612,087	268,681
7	Lynkeos Technology Ltd	2	1,589,357	794,679
8	AMEC Foster Wheeler Nuclear UK Ltd.	6	1,563,925	260,654
9	University of Sheffield	16	1,440,042	90,003
10	National Nuclear Laboratory Ltd.	14	1,192,182	85,156
11	University of Strathclyde	9	1,082,088	120,232
12	Vulcan SFM Ltd.	1	1,020,000	1,020,000
13	Symetrica Security Ltd.	5	990,947	198,189
14	Tetronics (International) Ltd.	2	880,517	440,259
15	Cybula Ltd.	6	758,606	126,434
16	Beran Instruments Ltd.	4	755,355	188,839
17	Caunton Engineering Ltd.	2	740,628	370,314
18	Glass Technology Services Ltd	1	716,190	716,190
19	Costain Oil, Gas & Process Ltd.	6	671,981	111,997
20	Brunel University London	4	632,302	158,076

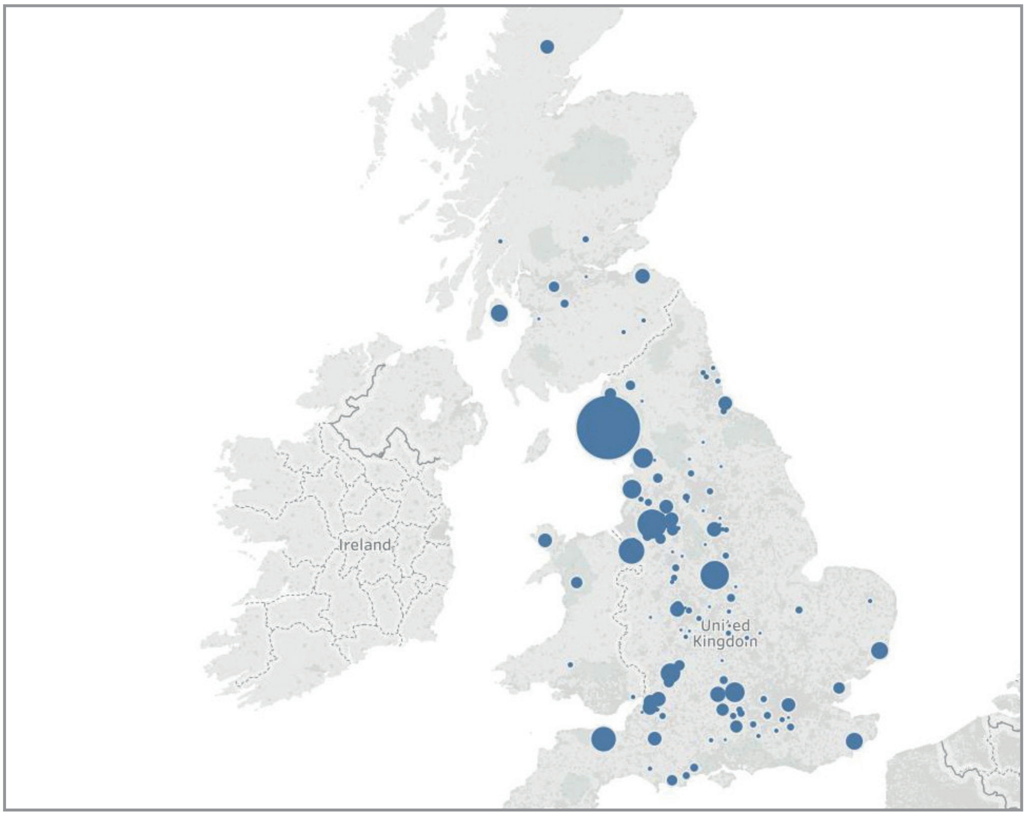
Table 8: InnovateUK nuclear project funding. Highlighted rows show organisations within the Nuclear Arc.

3.5 Business Environment

Within the North West Nuclear Arc, there are many organisations that span across the different tier levels. Tier 1 contractors refers to the parent body organisation or site license company on an NDA site, Tier 2 contractors provide the main interface with the Tier 1 companies. They hold direct contracts with the Tier 1 organisations to deliver a supply of services on the licensed site. Tier 3&4 organisations are usually SMEs who generally contract with Tier 2 contractors. Examples of Tier 1 organisations in the NWNA include Sellafield Ltd, Westinghouse, LLWR, Urenco, Magnox, EDF and Horizon Nuclear Power. Tier 2 organisations in the region include Jacobs, Wood plc, Atkins and NNL. This large variety of Tier 1 and Tier 2 organisations within the region shows the importance of this region in the UK's nuclear industry.

This is highlighted with the fact that the NWNA comprises 235 companies that specifically work in the nuclear sector, with a combined turnover of £58.8bn.[53] These companies provide 1 in every 64 jobs in Northwest England totalling roughly 30,000 jobs. The region accounts for well over a third of the 78,000 people directly employed in nuclear in the UK, this is demonstrated in Figure 19.[54] The map clearly shows a high proportion of nuclear employees within the NWNA, with other obvious clusters in the UK due to Rolls-Royce in Derby and the EDF New Build in the South West of England.

Figure 19: Map of employees in the nuclear industry categorised by county as described in the NIA UK Jobs Map.[53]



[53] The Nuclear Industry Association: Nuclear Activity 2016 (published 2017).
[54] The Nuclear Industry Association Jobs Map, Summer 2017.

This cluster of nuclear organisations provide a regional contribution to the UK's economy of >£5bn Gross Value Added (GVA), see Figure 20.[55 56 57] The NWNA is therefore crucial to the UK nuclear industry, and is the most extensive cluster of nuclear activities in the UK, providing a vital contribution to the UK economy.

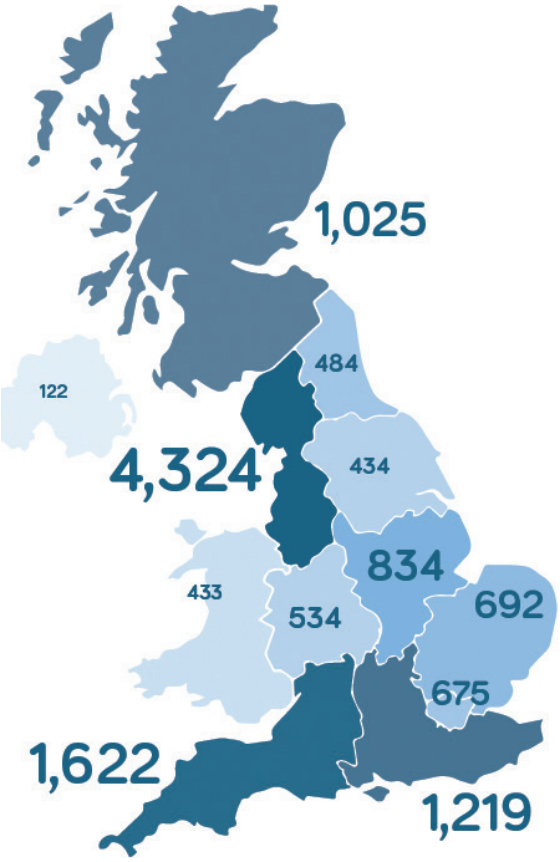


Figure 20: Illustration of the Regional Gross Value Added in £M (GVA; a measure of impact on UK's GDP or Gross Domestic Product) from the Nuclear Sector across the UK. This shows the considerable impact of the North West region and pushing the GVA value over £5bn.

Uniquely in the UK, the Northwest Nuclear Arc has a strong presence from all actors in the civil nuclear sector, including the statutory regulators (ONR, headquartered in Bootle; and the EA nuclear regulatory activity, with foci in Penrith and Warrington). ONR is the UK regulator for nuclear safety, security and safeguards, for radioactive materials transport on road and rail and for non-nuclear safety on nuclear sites.

ONR enforces a range of legislation including the Nuclear Installations Act 1965, the Health and Safety at Work etc Act 1974 and the Nuclear Industries Security Regulations 2003. Nuclear Licensed Sites in the Northwest Nuclear Arc include Sellafield; BAE Systems, Barrow; Capenhurst; Springfields; Wylfa; and Trawsfynydd, as well as the potential new build sites at Moorside and Wylfa Newydd. EA is the regulatory body responsible for environmental protection on nuclear sites and in respect of radioactive material more generally across England. The Environment Agency enforces legislation including the Environmental Permitting (England and Wales) Regulations 2010 and the High-activity Sealed Radioactive Sources and Orphan Sources Regulations 2005. While environmental regulation of nuclear activity in Wales is the responsibility of Natural Resources Wales, it is actually carried out under contract by the EA. ONR and EA have a Memorandum of Understanding which covers matters of mutual interest.

[55] Fit for Nuclear Companies Database, Nuclear AMRC: http://namrc.co.uk/services/f4n/companies/ (accessed Spring 2018).
[56] Companies House: https://www.gov.uk/government/organisations/companies-house (accessed Spring 2018).
[57] Office for National Statistics, Newport, Wales.

4. CONCLUSION

Context & Overview

"Nuclear power is, and will continue to be, a key part of our low-carbon energy mix." The Government sees the domestic new build and wider nuclear market as an essential platform to further enhance the UK nuclear commercial base and grow global market share.[58] Nuclear energy is part of the Government's commitment to Clean Growth, one of the four Grand Challenges set out in the Industrial Strategy. The overriding conclusion from the SIA is that the NWNA has, within its region, the organisations and expertise to address many of the key challenges, which are[59]:

- continuous improvements in safety,
- successfully delivering the first wave of new nuclear power stations,
- ensuring effective waste management and decommissioning plans are in place,
- driving down the costs of nuclear power,
- establishing effective collaborations at home and overseas on R&D and innovation.

It is the only area in the UK with full fuel cycle capabilities, with all elements of the civil nuclear fuel cycle, including decommissioning & clean up, uranium enrichment, fuel fabrication, operating reactors and is a major area for potential large new nuclear deployments (Wylfa Newydd and Moorside) and, potentially, advanced future reactors.

Whilst the new build developments are of national importance and there may be some scope for innovation in the supply chain, there is limited innovation in the development work as it is likely that large nuclear new builds in the UK will have designs that were completed years ago, and not in the UK. There is world class work that is taking place within the region on decommissioning and site remediation, and there could be much more scope to innovate than for new build. Many of the companies associated with decommissioning are homegrown, and there are considerable opportunities to expand the export market, developed and proven during the clean-up of the UK's nuclear legacy.

There is strong interest in SMRs, and the potential global SMR market is estimated to be between 65–85 GWe by 2035, valued at £250–400 billion, and a UK market of around 7 GWe. However, successful deployment is dependent on having a FOAK, therefore government and industry need to work together to accelerate the deployment if the UK is to take an international lead produce SMRs, or their components. The Welsh Affairs Committee have recommended that a FOAK be built in Wales.

Physical Assets

There is a wide range of physical and innovation assets within the region, with over 20 facilities, many unique, that provide research support to academic and industrial activity in the region. NNL occupy a unique role within the industry as a 'Technical Challenge Translator & Facilitator' and contribute to the range of specialist research facilities within the NWNA.

The process and ease of access to facilities can be limited due to the safety and security requirements, reducing the scope for collaboration. However, with the inclusion of some in the NNUF programme, access has improved and continues to be a focus for improvement. There are still some issues that need to be addressed in terms of access and the business models deployed.

There are some gaps in provision, and access to facilities in Europe may become more difficult in future. To fully realise the benefits of an innovative nuclear sector, some investment in infrastructure will be necessary.

Innovation Assets

There are clusters of nuclear companies at Birchwood and Westlakes Science and Technology Park, and a growing number in Menai Science Parc, which provide a solid foundation for establishing for the NWNA a sense of 'Place', and creating a vibrant business environment in which innovation can be nurtured.

[58] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/168047/bis-13-630-long-term-nuclear-energy-strategy.pdf
[59] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/665473/The_Nuclear_Sector_Deal_171206.pdf

There have been initiatives to stimulate innovation, and where there have been funded programmes, the UK has typically developed world class solutions, such as in the DCU arena. The overriding conclusion being that the existence of a sustained major programme is a necessary and sufficient condition for the UK to have capability. A more substantial and stable programme supporting innovation is required.

Although most of the components needed to drive change in the nuclear sector exist in the NWNA, more integration is required. This could help stimulate innovation, develop localised supply chains and retain talent. It is an ideal 'test-bed' site for new and innovative ideas. The concept of Innovation Partnerships, being explored by the Centre of Nuclear Excellence (CoNE), could deliver a vibrant marketplace for innovation.

Innovation Partnerships would be ideal test-beds for innovation in the nuclear industry, and locations for the trialling of innovative new nuclear programmes. There are three distinct types of innovation that could be implemented within the nuclear industry: organisational change, technology transfer and new knowledge, all of which could be explored in the safety of an Innovation Partnership. Setting up a national network based on regional strengths could foster collaboration rather than competition, and help deliver the Nuclear Industry Council Mission.

The NWNA provides an ideal location for two Innovation Partnerships: in Cumbria and in North Wales. Cumbria, as the location for a well established, large, long term nuclear programme, should be used as a model for the development of an innovation ecosystem locally, and as a model to support the development of the innovation ecosystem in North Wales, centred on the re-purposing of Trawsfynydd and the potential new build at Wylfa Newydd, and complementing the Welsh Government's investment in Menai Science Parc.

People & Skills

Nowhere else in Europe is so much nuclear expertise so concentrated, with unparalleled access to a world-renowned skills base and pioneering expertise in nuclear research and development. However, the workforce is aging, and the Nuclear Workforce Assessment predicts there could be shortage of up to 40,000 workers by 2036. There needs to be intervention and civil nuclear initiatives which can deliver a trained workforce.

The areas within the NWNA where the major nuclear programmes are focused are relatively isolated and rural. There is a need to retain young people in these locations by providing high value employment.

Currently, there is little diversity in terms of gender, ethnicity, social background, culture and region. The shortfall identified could present an excellent opportunity to address the lack of diversity, and attract wider groups who can contribute to creativity and innovation in the sector.

The fact that there is a concentration of skills providers and they can deliver training across all the levels from 1-8 means that the NWNA is well placed to rise to the challenge, right through to the highest level skills and subject matter experts.

The availability of High Level Skills and Subject Matter Experts, is identified as "of particular concern" in the Nuclear Skills Strategy. The nuclear CDTs have proved to be successful way to develop highly skilled personnel, with over 60 % of graduating PhDs now working in the nuclear sector, either in industry (39%) or academia (26%). There are currently 2 nuclear CDTs in the UK, one of which is in the NWNA run by The University of Manchester in partnership with four NWNA university partners, and industry. More and continuous investment in the CDTs will be required.

Knowledge Base

The evidence illustrates the significance of the NWNA's knowledge base. The NWNA universities (17) account for 46% of the EPSRC Nuclear fission spend (£46.5m), and the NIRAB report on the UK Civil Nuclear R&D Landscape estimated that 44% of university researchers are within the NWNA. This is overwhelming conclusive evidence that the NWNA is the single most 'nuclear' research intensive region in the UK, and that focusing on nuclear in the NWNA is playing to a major strength, a necessary requirement to foster innovation.

The evidence on publications reinforces that the NWNA encompasses the whole spectrum of nuclear related activities, and the research illustrates the spread of expertise across the spectrum of nuclear related topics. Furthermore, when looking at the international perspective, the collaboration between the NWNA and the rest of the world is very impressive. Having the international links is crucial in establishing global markets for new products, and capitalising on the strengths of the region, and the UK's position in global nuclear markets going forward.

An analysis in InnovateUK grants related to nuclear since 2004, shows that NWNA organisations occupy three of the top five spots with 1st place is the University of Sheffield (16), 3rd NNL (14) and 4th University of Manchester (13). This further demonstrates, not only the expertise, as measured by publications, but also the organisations' ability and interest in commercialisation. This is fundamental to creating an innovative environment, and meeting the aspirations set out in the UK's industrial strategy.

Business Environment

There are at least 235 companies in the nuclear industry in the NWNA, including major Tier 1 and Tier 2 contractors, as well as the supporting supply chains, which dominate the nuclear contribution to UK GVA, with this cluster of nuclear organisations contributing over £5bn to the UK economy, a solid foundation for innovation programmes. These companies provide 1 in every 64 jobs in NWNA totalling an estimated 30,000 jobs, accounting for nearly 40% of the 78,000 people directly employed in nuclear in the UK, making the NWNA the most crucial 'nuclear' region.

A number of potential growth opportunities have been identified, which are:

- increasing the UK's share of global DCU related services,
- developing and building capability for some, or all of the components for SMRs,
- developing and building capability for AMRs,
- providing an attractive regulatory regime and environment for innovation in nuclear.

To bring about gains through innovation and reduction in costs will require change in organisational and individual culture and behaviours. The sector has been slow to adapt to technical change, such as fully exploiting digitisation, and there is scope to build on the experiences in other sectors, such as aviation, oil & gas, pharmaceuticals, and off-shore wind.

Given the strong presence of nuclear companies, there are active nuclear fora such as the North West Nuclear Forum and the Wales Nuclear Forum, as well as the Centre of Nuclear Excellence (CoNE), which means that there are a number of networking mechanisms already in place.

The importance of the region is further evidenced by the presence of other civil nuclear sector players, including the statutory regulators ONR and the EAs nuclear regulatory activity.

RECOMMENDATIONS 5.

The recommendations are targeted at all the participants in the nuclear sector, and are presented in terms of the 5 pillars identified in the Industrial Strategy.

Physical Assets (Infrastructure)

1. Invest in new test facilities: a more detailed review of the facilities available and analysis of the gaps is required. However, based on the audit and comments, there needs to be a mix of facilities in the region that will support a range of activities. Suggestions include:
   - research reactor for research and experimental purposes,
   - thermal hydraulics facility,
   - a microscopy facility for materials characterising and testing, crucial for the new build programme in North Wales,
   - Trawsfynydd as a FOAK site for deploying SMRs.
2. Continue to improve the ease of access to existing facilities:
   - review the business models at national facilities.
3. Consider a more universal approach to access through the use of an 'accredited access' system issued on the basis of training and competence
   - incentivise industry to make their facilities more open for collaboration.

Innovation Assets (Ideas)

4. Create two Innovation Partnerships in Cumbria and North Wales, which can:
   - create visibility of immediate and long-term innovation challenges,
   - foster more collaboration and build effective partnerships,
   - address barriers to innovation,
   - deploy innovation from other sectors and enabling technologies such as robotics and digital,
   - support the development of AMRs,
   - provide a business environment where innovation, entrepreneurship, investment and economic growth are driven by visible and diverse opportunities,
   - work with business and community stakeholders to create a market for technical, business and social innovation, supporting innovators and problem holders to solve problems,
   - speed up the flow of ideas and solutions and create a culture of innovation, increasing serendipity and creative collisions, and
   - build on and promote existing regional and national innovation programmes.

People & Skills

5. Design and deliver a coherent skills pathway bringing together all providers and fostering skills development for the nuclear sector. This includes:
   - introducing an Accelerated Speed to Competence and refreshed NTEC, which has a short, fat structure and Continuous Personal Development (CPD) focus, supported by further educational vocational courses and the National College for Nuclear (NCfN)
   - increase the number of graduate apprenticeships
   - expand the CDT initiative for Level 7 and Level 8 skills.
   - accelerate development of next generation subject matter experts
6. Ensure that the nuclear labour market becomes more diverse, attracting more women, and people from different cultural and ethnic backgrounds. The skills gap that is emerging and the shortage of new entrants offers a tremendous opportunity to redress the current situation.

Knowledge Base

7. In line with the Industrial Strategy, ensure that an appropriate share of the proposed increase in investment in R & D to 2.4% of GDP is achieved and targeted at nuclear related research.
8. Similarly, with regard to the proposed Industrial Strategy Challenge Fund, invest in nuclear related innovation targeted at high growth potential SMEs.
9. Create an environment in which non-nuclear and smaller companies can learn from the Tier 1 companies.
10. Develop new, collaborative programmes to meet the skills challenges.

Business Environment

11. Provide industry with confidence by supporting investment in long term projects.
12. Assess the global market and the opportunities for the UK for both SMRs and AMRs. Decide on which modular reactor technology to support and create an environment that will support their development (at the time of writing the results of the SBRI competition to carry out feasibility studies into AMRs have not been published).
13. Standardise and modularise components to speed up delivery times and lower direct costs.
14. Ensure that technologies and techniques used for new nuclear build draw on best practices deployed in mainstream major construction projects, such as London 2012.[60]
15. Focus on accelerating commercialisation of new products, at scale, within rapid timescales.
16. De-nuclearise elements and remove the 'specialness' of nuclear, where possible such as in other high hazard, highly regulated, high profile industries.
17. Review the scope to further promote the UK's proposition internationally.
18. Expand the regional content in Nuclear New Build and map the supply chain, as well as potential suppliers.

[60] http://learninglegacy.independent.gov.uk/themes/design-and-engineering-innovation/index.php

APPENDIX 1

The NWNA SIA is led by Bangor University (BU) with the University of Manchester (UoM) and National Nuclear Laboratory (NNL) as partners with support from Welsh Government (WG).
The project development and working group is explained below.

Project Lead – Sian Hope (BU)
Project Manager – Debbie Jones (BU)
SMEs – Francis Livens (UoM), Andrew Sherry (NNL), Robert Hoyle (WG), Bill Lee (BU), John Idris Jones
Project Consultant – Karen Padmore

Audit Programme Manager – Michael Rushton (BU)
Audit Workstream Leads
Physical Assets – Dimitri Pletser (Imperial College London on behalf of BU)
Skills – Sarah Heath (UoM)
Knowledge Base – Michael Rushton (BU)
Business Environment – Manon Higgins-Bos (NNL)

Additional Support from – Adam Wadding (WG), Ken McEwan (Centre of Nuclear Excellence CoNE), Conor Galvin (Imperial College London on behalf of BU), Luci Collinwood (WG), Ed Jones (BU), Viola Davies (KTN), David Brown (Technopolis)
Administrative Support – Annwen Hughes (BU)

APPENDIX 2

User access options, training requirements, access requirements, usage statistics, if reported, capabilities and equipment and any relevant outputs in the form of patents and papers are available for the physical assets included in the audit.

Advanced Digital Radiometric Instrumentation for Applied Nuclear Activities (ADRIANA)
Host: Lancaster University, Lancaster, LA1 4YW
LEP: Lancashire
PI: Professor Malcolm Joyce
Classification: Public
Ownership type: University
Access model: NNUF
Payment model: NNUF, industrial pay-to-play possible
Training requirements: Two online modules for university - level dosimeter distribution, followed by specific on-site training provided by facility staff
Recent usage statistics: (October 2017-March 2018) 10% maintenance, 5% out of service, 5% UKAEA active work, 60% University of Lancaster, 20% industry/external organisations
Capabilities: Sealed source activity lab for sophisticated neutron detection. High-order neutron multiplicity analysis of actinide materials. Contains a 32-detector neutron calorimeter.

- High-multiplicity analysis of actinide-containing materials
- Instantaneous characterisation for safeguards / real-time fuel assay
- Related output:
- Jones, A. R., M. D. Aspinall, and M. J. Joyce. "A remotely triggered fast neutron detection instrument based on a plastic organic scintillator." Review of Scientific Instruments 89.2 (2018): 023115.
- ‘Concealed nuclear material identification via combined fast neutron / gamma-ray computed tomography (FNGCT): a Monte-Carlo study’, M. Licata and M. J. Joyce, J Inst. 2018.
- Astromskas, Vytautas, and Malcolm Joyce. "Time-dependent characterisation of stability performance of EJ-309 detector systems." EPJ Web of Conferences. Vol. 170. EDP Sciences, 2018.
- ‘Investigating artefacts associated with α particle interactions in charge coupled devices’, paper #1381, N-23-163, R. Newton, M. J. Scott and M. J. Joyce, IEEE NSS 2017, Atlanta.
- ‘Real-time determination of Rossi-α distribution, active fast neutron multiplicity, neutron angular distribution and neutron spectrum using organic liquid scintillators’, paper #2434, N-09-2, R. Sarwar, V. Astromskas, C. H. Zimmerman, S. Croft and M. J. Joyce, IEEE NSS 2017, Atlanta.
- ‘Shielded nuclear material identification via combined fast neutron/gamma-ray computed tomography (FNGCT)’, paper #2918, N-03-098, M. Licata and M. J. Joyce, IEEE NSS 2017, Atlanta.
- ‘Stabilization of EJ-309 liquid scintillation detectors’, paper #3049, N-03-162, V. Astromskas and M. J. Joyce, IEEE NSS 2017, Atlanta.
- Beaumont, J. S., Shippen, B. A., Mellor, M. P., & Joyce, M. J. "Imaging of fast neutrons and gamma rays from 252Cf in a heavily shielded environment." Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 847 (2017): 77-85.
- Jones, A.R., and Joyce, M. J. "The angular dependence of pulse shape discrimination and detection sensitivity in cylindrical and cubic EJ-309 organic liquid scintillators." Journal of Instrumentation 12.01 (2017): T01005.

Patents:

- “Neutron Assay”, M. Joyce, O.R.R. Chris - US Patent App. 15/428,769, 2017

Ansaldo Centre of Engineering Excellence

Host: Ansaldo Nuclear Ltd., Chadwick House, Birchwood Park, Warrington, WA3 6AE
LEP: Cheshire and Warrington
Classification: Private Company
Ownership type: Private
Access model: N/A
Payment model: Consultancy
Most recent reported usage statistics: None reported

Ansaldo Deep Test Pit Facility

Host: Ansaldo Nuclear Ltd. (North West Division), Energy Coast Business Park, Egremont, Beckermet, CA22 2NH
LEP: Cumbria
Classification: Private company
Ownership type: Private
Access model: None
Payment model: Consulting
Training requirements: None
Most recent reported usage statistics: None reported

Central Laboratory

Host: National Nuclear Laboratory, Sellafield, Seascale CA20 1PG
LEP: Cumbria
PI: Dr Dominic Rhodes
Classification: Public
Ownership type: National Nuclear Laboratory
Access model: NNUF
Payment model: NNUF, pay-to-play options available

Access/Training requirements: Security clearance (BPSS) required, followed by thorough on-site training. Significant barriers, as BPSS is required and in most cases SC vetting is required for hands-on work. Shortest minimum lead time for short work is 4 weeks. Longest minimum lead time, for active glovebox work is 14 weeks.
Most recent reported usage statistics:

- FIB-SEM (October 2017 – March 2018) 53.2% out of service, 23.9% NNL use, 2.3% maintenance, 20.6% not in use
- XCT (October 2017 – March 2018) 89.9% not in use, 3.8% external university use, 6.3% NNL use

Capabilities: National Nuclear User Facility run by the National Nuclear Laboratory. Currently two of three planned facilities are in use. A unique combined Focused Ion Beam – Scanning Electron Microscope (FIB-SEM) facility for active samples and an advanced X-Ray Microtomography (XCT) system for active materials. A final Field Emission Gun – Transmission Electron Microscope is planned, but not in use yet.

- FIB-SEM consists of a FEI Helios for use with trace active samples. Active samples can be processed for external use
- Access to NNL active TEM (JEOL 2100, fitted with 80mm2 Oxford Instruments EDX detector, with EELS upgrade (Gatan Quantum 965ER) planned)
- XCT facility contains a Bruker Skyscan 1172 X-Ray Microtomography system capable of ~1µm voxel resolution, up to 8000X8000 pixel images for each slice and resolution limit of ~0.8µm. Samples up to 27mm (or 50mm using multiple scans) can be accommodated.

Recent output:

- "The Processing and Product Characteristics of a Blended Cement Grout incorporating a Polycarboxylate Ether Superplasticiser" – Matthew Isaacs, Martin Hayes, Steven Rawlinson, Michael Angus, Adam Qaisar, Steven Christie, Steven Edmondson, David Read, Advances in Cement Research, Volume 30 Issue 4, April, 2018, pp. 148-158
- "Depth profiling of lanthanide contaminated corroded stainless steel under nuclear process conditions" – In review, NPJ Materials Degradation (FIB data)

Centre for Radiochemistry Research

Host: Dalton Institute, The University of Manchester, Oxford Road, Manchester, UK, M13 9PL
LEP: Greater Manchester Region
PI: Prof. Nik Kaltsoyannis/ Prof Steve Liddle
Classification: Public
Ownership type: University
Access model: EPSRC
Payment model: EPSRC
Most recent reported usage statistics: None reported

Capabilities: The Centre for Radiochemistry Research (CRR) work on a spectrum from blue skies investigations to industry ready development work. Activities range from fundamental coordination and organometallic chemistry to the study of colloids, immobilised glasses and concrete materials, and to challenges in nuclear waste management and its environmental impact. The centre houses 23 fume hoods in ~4,300 sq. ft. of space behind a radiological barrier. Glove box facilities are complemented by a full range of in-house structural, spectroscopic, magnetic, radiometric and computational characterisation techniques. In addition to uranium and thorium, the CRR works with neptunium, plutonium, americium and technetium. List of collaborators include: Los Alamos, Grenoble and Diamond Light source beamlines, HZDR Dresden, Regensburg

University, University of Toulouse, University of Lancaster, University of Minnesota, University of South Dakota, National Nuclear Laboratory, Pacific Northwest National Laboratory, Sellafield LtD, Nuclear Decommissioning Authority, Kyushu University Japan, Clemson University, Savannah River Research Site, Lawrence Livermore Nuclear Laboratories, Karlsruhe Institute for Technology, Leibniz University

- NMR,
- Raman,
- UV-vis-NIR,
- IR,
- Fluorimeter,
- Gamma Spectrometry,
- Alpha spectrometry,
- Liquid scintillation Analysis (α/β discrimination),
- Autoradiography,
- Glovebox facilities
- With further access to: SQUID, LIBS, ICP-MS and AEs, XRD, XRF

Recent output:

- Surface speciation and interactions between adsorbed chloride and water on cerium dioxide, Sutherland-Harper, S., Taylor, R., Hobbs, J., Pimblott, S., Pattrick, R., Sarsfield, M., Denecke, M. A., Livens, F., Kaltsoyannis, N., Arey, B., Kovarik, L., Engelhard, . M., Waters, J. & Pearce, C. 2018 Journal of Solid State Chemistry. 262, p. 16-25

- Characterisation, coverage, and orientation of functionalised graphene using sum-frequency generation spectroscopy, AlSalem, H. S., Holroyd, C., Danial Iswan, M., Horn, A. B., Denecke, M. A. & Koehler, S. P. K. 2018 Phys. Chem. Chem. Phys.. 20, p. 8962-8967
- Sources and Behaviour of Actinide Elements in the Environment, Denecke, M. A., Bryan, N., S, K., Morris, K. & Quinto, F. 2018 Experimental and Theoretical Approaches to Actinide Chemistry. John Wiley & Sons Ltd, p. 378-444
- Phase retrieval of coherent diffractive images with global optimization algorithms, Truong, N. X., Whittaker, E. & Denecke, M. A. 1 Dec 2017 In : Journal of Applied Crystallography.50, 6, p. 1637-1645
- Confinement of iodine molecules into triple-helical chains within robust metal–organic frameworks, Zhang, X., Da Silva, I., Godfrey, H., Callear, S. K., Sapchenko, S., Cheng, Y., Vitorica-Yrezabal, I., Frogley, M. D., Cinque, G., Tang, C. C., Giacobbe, C., Dejoie, C., Rudić, S., Ramirez-Cuesta, A. J., Denecke, M. A., Yang, S. & Schroder, M. 15 Nov 2017 Journal of the American Chemical Society. 139, 45, p. 16289–16296
- High Spin Ground States in Matryoshka Actinide Nanoclusters: A Computational Study, Hu, H-S. & Kaltsoyannis, N. Jan 2018 Chemistry: A European Journal. 24, p. 347–350
- Oxygen Vacancy Formation and Water Adsorption on Reduced AnO2 {111}, {110} and {100} Surfaces (An = U, Pu); A Computational Study, Wellington, J. P. W., Tegner, B., Collard, J., Kerridge, A. & Kaltsoyannis, N. 2018 Journal of Physical Chemistry C. 122, p. 7149–7165
- The performance of density functional theory for the description of ground and excited state properties of inorganic and organometallic uranium compounds, Reta, D., Ortu, F., Randall, S., Mills, D., Chilton, N., Winpenny, R., Natrajan, L., Edwards, B. & Kaltsoyannis, N. 2018 Journal of Organometallic Chemistry. 857, p. 58-74
- Transuranic computational chemistry, Kaltsoyannis, N. 2018 Chemistry: A European Journal. 24, p. 2815–2825
- Uncovering the Origin of Divergence in the CsM(CrO4)2 (M = La, Pr, Nd, Sm, Eu; Am) Family through Examination of the Chemical Bonding in a Molecular Cluster and by Band Structure Analysis, Galley, S. S., Arico, A. A., Lee, T-H., Deng, X., Yao, Y-X., Sperling, J. M., Proust, V., Storbeck, J. S., Dobrosavljevic, V., Neu, J. N., Siegrist, T., Baumbach, R. E., Albrecht-Schmitt, T. E., Kaltsoyannis, N. & Lanatà, N. 2018 Journal of the American Chemical Society. 140, p. 1674–1685
- Deposition of artificial radionuclides in sediments of Loch Etive, Scotland, Al-Qasmi, H., Law, G., Fifield, L. K., Howe, J. A., Brand, T., Cowie, G. L., Law, K. & Livens, F. 2018, Journal of Environmental Radioactivity.
- Uranium dioxides and debris fragments released to the environment with cesium-rich microparticles from the Fukushima Daiichi Nuclear Power Plant, Ochiai, A., Imoto, J., Suetake, M., Komiya, T., Furuki, G., Ikehara, R., Yamasaki, S., Law, G., Ohnuki, T., Grambow, B., Ewing, R. C. & Utsunomiya, S. 2018

Environmental Science and Technology.

- Impacts of Repeated Redox Cycling on Technetium Mobility in the Environment, Masters-Waage, N., Morris, K., Lloyd, J., Shaw, S., Mosselmans, J. F. W., Boothman, C., Bots, P., Rizoulis, A., Livens, F. & Law, G. 2017 Environmental Science and Technology. 51.
- Isotopic signature and nano-texture of cesium-rich micro-particles: Release of uranium and fission products from the Fukushima Daiichi Nuclear Power Plant, Imoto, J., Ochiai, A., Furuki, G., Suetake, M., Ikehara, R., Horie, K., Takehara, M., Yamasaki, S., Nanba, K., Ohnuki, T., Law, G. T. W., Grambow, B., Ewing, R. C. & Utsunomiya, S. 2017 Scientific Reports. 7, 1, 5409
- Quantifying technetium and strontium bioremediation potential in flowing sediment columns, Thorpe, C., Law, G., Lloyd, J., Williams, H., Atherton, N. & Morris, K. 2017 Environmental Science and Technology.
- Uranium(V) incorporation mechanisms and stability in Fe(II)/Fe(III) (oxyhydr)oxides, Roberts, H., Morris, K., Law, G., Mosselmans, J. F. W., Kvashnina, K., Bots, P. & Shaw, S. 2017 Environmental Science & Technology Letters .
- Evidence for Single-Metal Two-Electron Oxidative Addition and Reductive Elimination at Uranium, B. M. Gardner, C. E. Kefalidis, E. Lu, D. Patel, E. J. L. McInnes, F. Tuna, A. J. Wooles, L. Maron, and S. T. Liddle, Nat. Commun., 2017, 8, s41467-017-01363-0.
- The inverse-trans-influence in tetravalent lanthanide and actinide bis(carbene) complexes, M. Gregson, E. Lu, D. P. Mills, F. Tuna, E. J. L. McInnes, C. Hennig, A. C. Scheinost, J. McMaster, W. Lewis, A. J. Blake, A. Kerridge, and S. T. Liddle, Nat. Commun., 2017, 8, 14137.
- Molecular and Electronic Structure of Terminal and Alkali Metal-Capped Uranium(V)-Nitride Complexes, D. M. King, P. A. Cleaves, A. J. Wooles, B. M. Gardner, N. F. Chilton, F. Tuna, W. Lewis, E. J. L. McInnes, and S. T. Liddle, Nat. Commun., 2016, 7, 13773.
- Thorium-Phosphorus Triamidoamine Complexes Containing Th-P Single- and Multiple-Bond Interactions, E. P. Wildman, G. Balázs, A. J. Wooles, M. Scheer, and S. T. Liddle, Nat. Commun., 2016, 7, 12884.
- Triamidoamine Uranium(IV)-Arsenic Complexes Containing One-, Two-, and Three-fold U-As Bonding Interactions, B. M. Gardner, G. Balázs, M. Scheer, F. Tuna, E. J. L. McInnes, J. McMaster, W. Lewis, A. J. Blake, and S. T. Liddle, Nat. Chem., 2015, 7, 582-590.
- Salt metathesis routes to homoleptic near-linear Mg(II) and Ca(II) bulky bis(silyl)amide complexes, Leng, J-D., Goodwin, C. A. P., Vitorica-Yrezabal, I. & Mills, D. 9 Apr 2018 (Accepted/In press) Dalton Transactions.
- Chromium Chains as Polydentate Fluoride Ligands for Actinides and Group IV Metals, Leng, J-D., Kostopoulos, A., Isherwood, L., Ariciu, A-M., Tuna, F., Vitorica-Yrezabal, I., Pritchard, R., Whitehead, G., Timco, G., Mills, D. & Winpenny, R. 28 Mar 2018 (Accepted/In press) Dalton Transactions.
- Exploring Synthetic Routes to Heteroleptic UIII, UIV and ThIVBulky Bis(silyl)amide Complexes, Goodwin, C., Tuna, F., Mcinnes, E. & Mills, D. 2018 European Journal of Inorganic Chemistry.
- Molecular magnetic hysteresis at 60 K in dysprosocenium, Goodwin, C., Ortu, F., Reta, D., Chilton, N. & Mills, D. 2017 Nature. 548, p. 439-442
- End-on cyanate or end-to-end thiocyanate bridged dinuclear copper(II) complexes with a tridentate Schiff base blocking ligand: Synthesis, structure and magnetic studies, Khan, S., Sproules, S., Natrajan, L., Harms, K. & Chattopadhyaya, S. 2018 New Journal of Chemistry.
- Expanding the scope of biomolecule monitoring with ratiometric signaling from rare-earth upconverting phosphors, Natrajan, L., Hay, S., Jones, A., Harvey, P., Oakland, C., Burgess, L. & Andrews, M. 3 Aug 2017 European Journal of Inorganic Chemistry.
- Investigation into the Effects of a Trigonal Planar Ligand Field on the Electronic Properties of Lanthanide(II) Tris(silylamide) Complexes (Ln = Sm, Eu, Tm, Yb), Goodwin, C., Chilton, N., Natrajan, L., Boulon, M-E., Ziller, J. W., Evans, W. J. & Mills, D. 1 May 2017 Inorganic Chemistry.
- A polynuclear and two dinuclear copper(II) Schiff base complexes: Synthesis, characterization, self-assembly, magnetic property and DFT study, Bhattacharyya, A., Bauzá, A., Sproules, S., Natrajan, L., Frontera, A. & Chattopadhyaya, S. 2017 Polyhedron.

- Optical Properties of Heavily Fluorinated Lanthanide Tris β-Diketonate Phosphine Oxide Adducts, Swinburne, A., Langford Paden, M., Chan, T. L., Randall, S., Ortu, F., Kenwright, A. & Natrajan, L. 2016 Inorganics.
- Inner-sphere vs. outer-sphere reduction of uranyl supported by a redox-active, donor-expanded dipyrrin, Pankhurst, J. R., Bell, . N. L., Zegke, M., Platts , L. N., Lamfsus, . C. A., Maron, L., Natrajan, L., Sproules, S., Arnold, P. L. & Love, J. B. 2016 Chemical Science.

Dalton Cumbria Facility (DCF)

Host: Manchester University, Westlakes Science & Technology Park, Moor Row, Cumbria, CA24 3HA
LEP: Cumbria
PI: Professor Francis Livens
Classification: Public
Ownership type: University
Access model: NNUF
Payment model: NNUF, NIBC, pay-to-play options available
Training requirements: Training provided on-site
Most recent reported usage statistics:

1. DCF Material preparation/heat treatment facility (October 2017 – March) 46.5% not in use, 47.3% University of Manchester, 5.2% maintenance, 1% external universities (not-specified)
2. DCF Material Characterisation (October 2017 – March) 35.5% not in use, 5.4% industry/external organisation, 54.5% University of Manchester, 4.6% maintenance
3. DCF Material Damage - Accelerator (October 2017 – March) 26.7% not in use, 9.3% industry/external organisation 24% external universities (not-specified), 28% University of Manchester, 12.0% maintenance,
4. Capabilities: National Nuclear User Facility with irradiation facilities for the analysis of nuclear materials. Facilities include materials preparation and heat treatment capabilities, advanced characterisation techniques and accelarators for radiation damage studies. Also supports studies through the NIBC framework.

- 5 MV Tandem ion accelerator producing Mz+ ions with energy 5(Z+1) MeV:
- High current TORVIS source providing 10MeV 1H+ at 100µamps, 15MeV 4He2+ at 15µamps
- Low current SNICS source providing partially and fully stripped heavy ions e.g. 35MeV 12C6+ at 150namps
- Six beamlines with three high precision raster scanners
- 2.5 MV single-ended accelerator (NEC Model 7.5SH)
- High current RF source for:
- Up to 100µA of 1H+ (up to 2.5 MeV ions)
- Up to 50µA of 4He+ (up to 2.5 MeV ions)
- Lower currents of heavier gas elements.
- Two beamlines meeting with 2 of the existing 5 MV tandem Pelletron allowing for dual beam irradiations.
- Beam line “hot cell” to allow higher penetration & higher damage rate studies
- In-situ experimental equipment (Rutherford Backscattering Spectrometry & high temperature autoclave)
- Equipment for the handling, storage & onward transport to CCFE & NNL Central Lab of activated samples
- Foss Therapy Model 812 60Co self-contained high dose rate gamma irradiator:
- Sample chamber absorbed dose rates from <100Gy/hr up to >10 kGy/hr
- Analytical Laboratory: High Performance Liquid Chromatography, Ion Chromatography, Gas Chromatography, Surface Area & Porosity Analyser (BET Method), Fluorescence Spectrophotometer, UV-Vis Spectrometer, Total Organic Carbon & Nitrogen Analyser and a Karl Fischer Titrator.
- Characterisation Laboratory: Field Emission Gun, Environmental Scanning Electron Microscope incorporating EDS, EBSD & WDS, heating/cooling stage and tensile rig, a range of optical microscopes, micro hardness testing, FT-IR Spectrometer/FT-Raman Spectrometer/Raman Microscopy, 2D XRD and Time-domain thermoreflectance
- Heat Treat Laboratory: Equipment includes a tube furnace, high temperature vacuum furnace and Spark Plasma Sintering (SPS) system
- Surface Science Laboratory: UHV controlled atmosphere chamber with low energy electron gun (2 – 50eV) and laser-induced fluorescence for surface science studies

Recent output:

- J Ward, S Middleburgh, M Topping, A Garner, D Stewart, MW Barsoum, M Preuss, P Frankel. Crystallographic evolution of MAX phases in proton irradiating environments. Journal of Nuclear Materials, (2018).

- Garner, A., Baxter, F., Frankel, P., Topping, M., Harte, A., Slater, T., Tejland, P., Romero, J. E., Darby, E. C., Cole-Baker, A., Gass, M., and Preuss, M., Investigating the Effect of Zirconium Oxide Microstructure on Corrosion Performance: A Comparison between Neutron, Proton, and Non-irradiated Oxides. Zirconium in the Nuclear Industry: 18th International Symposium, ASTM STP1597, R. J. Comstock and A. T. Motta, Eds., ASTM International, West Conshohocken, PA, pp. 491–523, (2018).
- Impagnatiello, S.M. Shubeita, P.T. Wady, I. Ipatova, H. Dawson, C. Barcellini, E. Jiminez-Melero. Monolayer-thick TiO precipitation in V-4Cr-4Ti alloy induced by proton irradiation. Scripta Materialia, 130 174-177, (2017).
- Ipatova, P.T. Wady, S.M. Shubeita, C. Barcellini, A. Impagnatiello, E. Jiminez-Melero. Radiation-induced void formation and order in in Ta-W alloys. Journal of Nuclear Materials, 495 343-350, (2017).
- Ipatova, P. T. Wady, S. M. Shubeita, C. Barcellini, A. Impagnatiello, E. Jimenez-Melero. Characterization of lattice damage formation in tantalum irradiated at variable temperatures. Journal of Microscopy (2017).
- Ipatova, S. Donnelly, P. T. Wady, R. Harrison, D. Terentyev, S. M. Shubeita, E. Jimenez-Melero. Structural defect accumulation in tungsten and tungsten-5wt.% tantalum under incremental proton damage. (2017).
- Liam H. Isherwood, Robyn E. Worsley, Cinzia Casiraghi and Aliaksandr Baidak. Alpha Particle Irradiation of Bulk and Exfoliated MoS2 and WS2 Membranes. Nucl. Instr. Meth. Phys. Res., Sect. B (2017).
- Donoclift, D. Radiation Tolerance Studies of Commercial Strippable Coatings and Fixatives used for Decontamination, peer-reviewed conference paper for International Waste Management Symposium 2018
- T. Carey et al. (2018). ''Removal of Cs, Sr, U and Pu Species from Simulated Nuclear Waste Effluent using Graphene Oxide'' submitted to Journal of Radioanalytical and Nuclear Chemistry in March 2018.

Daresbury Science Park

Host: Science and Technology Facilities Council (STFC), Daresbury, Keswick Lane, Daresbury, WA4 4FS
LEP: Cheshire and Warrington
PI: Professor Susan Smith
Classification: Public
Ownership type: Public, STFC/RCUK
Access model: RCUK for Daresbury Lab/Hartree Centre/Cockcroft Institute/Virtual Engineering Centre, pay-to-play for Sci-Tech Campus
Payment model: RCUK, pay-to-play options available
Training requirements: On-site training provided
Most recent reported usage statistics: None reported.
Capabilities: Science park containing four national STFC funded facilities, the Daresbury Laboratory, the Hartree Centre, the Cockcroft Institute, the Virtual Engineering Centre and Sci-Tech campus which contains a set of facilities open to industry and start-ups. Daresbury Laboratory is a multi-disciplinary laboratory, which houses the nuclear physics group and engineering and detector technology capabilities. The Cockcroft Institute houses particle accelerator research and development centre Accelerator Science and Technology Centre (ASTeC), which collaborates with Lancaster, Liverpool and Manchester University. The Hartree Centre is a computational facility focusing on big data and computational techniques. The Virtual Engineering Centre works on immersive visualisation, modelling and simulation of engineering systems, there is much collaboration with the Hartree Centre.

Recent output:

- S Acharya, J Adam, et al. "The ALICE Transition Radiation Detector: construction, operation, and performance." Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 881 (2018): 88-127.
- Atar, Leyla, et al. "Quasifree (p, 2 p) Reactions on Oxygen Isotopes: Observation of Isospin Independence of the Reduced Single-Particle Strength." Physical review letters 120.5 (2018): 052501.
- Acharya, S., et al. "Constraining the magnitude of the Chiral Magnetic Effect with Event Shape Engineering in Pb–Pb collisions at sNN= 2.76 TeV." Physics Letters B 777 (2018): 151-162.
- Acharya, S., et al. "Systematic studies of correlations between different order flow harmonics in Pb-Pb collisions at s NN= 2.76 TeV." Physical Review C 97.2 (2018): 024906.

- Adamova, Dagmar, et al. "J/ψ production as a function of charged-particle pseudorapidity density in p–Pb collisions at sNN= 5.02 TeV." Physics Letters B 776 (2018): 91-104.
- Acharya, Shreyasi, et al. "First measurement of jet mass in Pb–Pb and p–Pb collisions at the LHC." Physics Letters B 776 (2018): 249-264.

Nuclear sector/supply chain companies fostered by Sci-Tech facilities:
Analytech, Asset Handling, Booth Welsh, Chester Simplex, Decision Analysis Services, SGM Projects

ESR technologies facility (Formerly National Centre for Tribology)
Location: 202 Cavendish Place, Birchwood Park, Warrington, Cheshire WA3 6WU
LEP: Cheshire and Warrington
Nuclear Lead: Hugues Renondeau
Classification: Private company
Ownership type: Private
Access model: None
Payment model: Consultancy
Training requirements: N/A
Most recent reported usage statistics: None reported
Capabilities: Research and consultancy company borne from the old UKAEA and its National Centre for Tribology. Company does much work on materials and applications, with branches focusing on space and vacuum applications, oil and gas, safety management and nuclear materials. In nuclear specifically work continues with test rig design and development, corrosion, fretting and metrology.
Recent projects

- NCT have recently developed a 2-axis impact fretting test rig, which is currently being used to investigate a range of AGR coolant chemistry on the reactor tribology, and specifically the wear of the fuel element tie-bars and the fuel pin-brace interaction (PBI). The wear produced on the specimens is assessed in-house using our extensive metallurgical (optical microscopy, SEM-EDX, etc.) and metrological (CMM, WLI profilometry) facilities.
- Another recent project involves the construction of a rig to investigate the running-in/early life failure of jacking oil pumps (JOP) used on the bearing systems of nuclear reactors. The rig exercises the JOPs over a significant portion of their operational range for a short period of their projected operational life whilst monitoring them for any signs of degradation (predominantly wear). Their flow, pressure generated, and debris particle counts are monitored and logged in order to establish if they are operating in an acceptable manner, prior to installation on the reactor.
- Finally, NCT has (within the last 20 years) supplied a working high temperature and high water pressure test tribometer. This was a general-purpose piece of equipment, which was fitted with a range of test contacts and kinematics. The test environment was controlled in the high temperature and pressure autoclave where the water could be pressurised to levels of up to 170 bar and could be heated to a maximum level of 350°C.

High Temperature Facility (HTF)
Host: Wood group, Walton House, 404 Faraday Street, Birchwood Park, Warrington, WA3 6GA
LEP: Cheshire and Warrington
PI/Contact: Dr. Andrew Wisbey
Classification: Public
Ownership type: Private (Wood group)
Access model: NNUF
Payment model: NNUF, pay-to-play options available
Training requirements: Training provided on-site
Most recent reported usage statistics:
HT Fatigue: (October 2017 – March 2018) 20% system upgrade, 30% Wood use, 40% maintenance, 10% industry/external use
HT Creep: (October 2017 – March 2018) 40% Wood use, 60% maintenance
Capabilities: National Nuclear User Facility for the high temperature analysis of materials. High Temperature Facility is run by the High Temperature Facility Alliance and hosted by the Wood group. Two facilities are available for use. The HT Fatigue and HT Creep facility are used to determine materials properties at high temperature (up to 1000°C).

- Tensile Testing (loads up to 100 kN in tension and compression)
- Fracture Testing (loads up to 250 kN and in the temperature range -196 to 1000°C)
- Creep strain / rupture (loads up to 30 kN)
- Creep crack growth (loads up to 30 kN)
- Strain and load-controlled low cycle fatigue initiation (loads up to 100 kN in tension and compression)

- Fatigue crack growth (loads up to 100 kN in tension
- and compression)
- Creep-fatigue initiation / growth (loads up to 100 kN
- in tension and compression)
- Thermo-mechanical fatigue initiation / growth (loads up to 100 kN in tension and compression)
- Miniaturised tensile / creep / fatigue testing (loads up to 10 kN)
- High cycle fatigue endurance / crack growth (up to 100 Hz test frequency and loads up to 10 kN)

Recent output:
"The Next Nuclear Model", A.Wisbey, Materials World, Sept 2017

Manufacturing Technology Research Laboratory

Host: The University of Manchester, Pariser Building, Floor G, Sackville Street, Manchester, UK, M13 9PL
LEP: Greater Manchester Region
PI: Dr Neil Irvine
Classification: Public
Ownership type: University
Access model: EPSRC, NNUMAN
Payment model: EPSRC, NNUMAN, commercial pay-to-play options available
Training requirements: Local SQEP does work, but occasionally for long projects will train locally.
Most recent reported usage statistics: None reported
Capabilities: Research facility with a main focus on improving manufacturing technologies. Postgrad only laboratory that collaborates with industry a lot, Rolls-Royce, Hitachi-GE, etc. Aims to work at TRL 2-4 and improve implementation and uptake of basic science. Has many different cutting, welding and testing facilities, with welding externally tested to ASME standards. Shares facilities with the Materials Performance Centre and collaborates a lot with NAMRC.

- Submerged-arc cladder: Submerged-arc and electroslag cladding system with cladding and welding heads.
- Narrow gap gas tungsten arc welding (GTAW) system, with NG300 welding torch capable of reaching 250mm into narrow gaps.
- IPG/Kuka 16kW fibre laser robotic welding system, highest-powered fibre laser system in the UK, coupled to a 6-axis Kuka robot and a 2-axis turn/tilt table, Precitec welding head capable of welding metallic materials up to 25mm thickness in a single pass and 45mm thickness in two passes from both sides, without filler materials
- IPG/Kuka 16kW fibre laser robotic remote cladding system
- Multi-axis Edgewave 400W picosecond laser cold machining system, Ultra-short pulse (10 picosecond pulse length) Nd:YVO4 laser, Coupled with a 7-axis Aerotech CNC motion control system with an x-y beam scanning (Scanlab) speed up to 10m/s (600m/min)
- Multi-axis Agie Charmilles Form 20 EDM die sinker
- Multi-axis Agie Charmilles Fi400CCS wire cutting machine
- Recent output:
- Measurement and Modelling of the Residual Stresses in Autogenous and Narrow Gap Laser Welded AISI Grade 316L Stainless Steel Plates. AS Elmesalamy, H Abdolvand, JN Walsh, JA Francis, W Suder, S Williams and L Li, International Journal of Pressure Vessels and Piping
- Residual stresses in thick-section electron beam welds in RPV steels. Smith MC, Gandy D, Ferhati A, Romac, Paddea S. Proceedings of 2016 ASME Pressure Vessels & Piping Conference, 17-21 July 2016, Vancouver BC, Canada
- Design and manufacture of industrially representative weld mock-ups for the quantification of residual stresses in a nuclear pressure vessel steel. Francis J, Smith MC, Jeyaganesh, B, Vasileiou A, Rathod D, Roy MJ, Irvine NM. Proc 10th International Conference on Residual Stresses, Sydney, Australia, July 3-7, 2016.
- Process simulation integrated tool axis selection for 5-axis toolpath generation. LT Tunc, E Budak, S Bilgen, M Zatarain. CIRP Annals - Manufacturing Technology 64(1):1 · June 2016. DOI: 10.1016/j.cirp.2016.04.113
- Positional capability of a hexapod robot for machining applications. Barnfather JD, Goodfellow MJ and Abram T. Int J Adv Manuf Technol. DOI: 10.1007/s00170-016-9051-0
- Effects of MQL on surface integrity in robotic milling of austentic stainless steel. Tunc LT, Gu Y, Burke MG, Procedia CIRP PROCIR-D-15-00549R2. DOI: 10.1016/j.procir.2016.02.337

- Mechanistic Studies on Type 300 Stainless Steels Manufactured by Hot Isostatic Pressing: The Impact of Oxygen Involvement on Fracture Behaviour. Cooper A, Dhers J, Sherry AH. Proceedings of ASME PVP 2016, Vancouver. PVP2016-63033
- Nature of Ga focused ion beam induced phase transformation in 316L austenitic stainless steel. Babu P, Irukuvarghula S, Harte A, Preuss M. Acta Materialia 120 (2016) 391e402. DOI: 10.1016/j.actamat.2016.08.008

Materials for Innovative Disposition from Advanced Separations (MIDAS)

Host: University of Sheffield, Western Bank, Sheffield, S10 2TN
LEP: Sheffield City Region
PI: Professor Neil Hyatt
Classification: Public
Ownership type: University
Access model: NNUF
Payment model: NNUF, pay-to-play options available
Training requirements: On-site training offered.
Most recent reported usage statistics: (October 2017 – March 2018) 5% out of service, 8.7% industry/external organisation, 14.2% international usage, 8.3% maintenance, 63.8% University of Sheffield

Capabilities: National user facility for the analysis of nuclear materials, with a special aim to investigate nuclear waste. MIDAS collaborates and overlaps with University of Sheffield's Immobilisation Science Laboratory.

- Extensive sample and materials processing facilities including a range high temperature furnaces (up to 1850oC), glove boxes, Hot Isostatic Pressing (AIP 6-30H), powder milling/grind/mixing facilities, grinding/cutting/polishing
- Extensive analysis suite, with thermal analysis, electron microscopes, diffraction, surface area analysis, compositional analysis and radiological analysis methods
- Thermal analysis suite, with DSC/DTA/TGA (Netzsch TG 449 Jupiter and Mettler Toledo TGA/DSC) and high temperature viscometry (Theta Rheotronic II)
- Diffraction suite consists of XRF (Panalytical Zetium), multiple XRD (Bruker D2 Phaser and Panalytical Xpert 3)
- Mossbauer (Wissel MRG-500) and Raman (Horiba Xplora Plus) spectrometry
- Pycnometry (Micromeritics Accupyc II) and BET adsorption apparatus (Beckman Coulter SA-3100) available
- High resolution Gamma spectroscopy (Canberra BEGe) and liquid scintillation counter (Hidex 300SL)
- Chemical analysis possible with ICP-OES (Thermo-Fisher 6000iCAP) and ion chromatography (ICS1100)
- SEM/EDX (Hitachi TM3030) with sample prep (C-coater, ion polishing) and possible further access to UoS Sorby Centre of Electron Microscopy
- Specialist equipment and laboratory for waste form performance, durability and leaching studies available.
- Recent output:
- Multi-scale investigation of uranium attenuation by arsenic at an abandoned uranium mine, South Terras, C.L. Corkhill, D.E. Crean, D.J. Bailey, C. Makepeace, M.C. Stennett, R. Tappero, D. Grolimund, N.C. Hyatt, npj Materials Degradation, 1 (2017), 19.
- Reactive spark plasma synthesis of CaZrTi2O7 zirconolite ceramics for plutonium disposition, S.K. Sun, M.C. Stennett, C.L. Corkhill, N.C. Hyatt, Journal of Nuclear Materials, 500 (2018) 11-14.
- Phase Formation and Evolution in Mg(OH)2-Zeolite Cements, S.A. Walling, S.A. Bernal, L.J. Gardner, H. Kinoshita, J.L. Provis, Industrial & Engineering Chemistry Research, 57 (2018) 2105-2113
- Hot-isostatically pressed wasteforms for Magnox sludge immobilisation, P.G. Heath, M.W.A. Stewart, S. Moricca, N.C. Hyatt, Journal of Nuclear Materials, 2018 (499) 233-241.
- Characterisation of a high pH cement backfill for the geological disposal of nuclear waste: The Nirex Reference Vault Backfill, R.G.W. Vasconcelos, N. Beaudoin, A. Hamilton, N.C. Hyatt, J.L. Provis, C.L. Corkhill, Applied Geochemistry, 89 (2018) 180-189.
- Response to the discussion by Hongyan Ma and Ying Li of the paper "Characterization of magnesium potassium phosphate cement blended with fly ash and ground granulated blast furnace slag", L.J. Gardner, S.A. Bernal, S.A. Walling, C.L. Corkhill, J.L. Provis, N.C. Hyatt, Cement and Concrete Research 103 (2018) 249-253.

- Synthesis and characterisation of brannerite compositions (U0.9Ce0.1)1-xMxTi2O6 (M = Gd^{3+}, Ca^{2+}) for the immobilisation of MOX residues, D.J. Bailey M.C. Stennett, B. Ravel, D. Grolimund, N.C. Hyatt, RSC Advances, 8 (2018) 2092-2099.
- Transformation of Cs-IONSIV (R) into a ceramic wasteform by hot isostatic pressing, T.Y. Chen, E.R. Maddrell, N.C. Hyatt, A.S. Gandy, M.C. Stennett, J.A. Hriljac, Journal of Nuclear Materials, 498 (2018) 33-43.
- On the existence of AgM9(VO4)6I (M = Ba, Pb), E.V. Johnstone, D.J. Bailey, M.C. Stennett, J. Heo, N.C. Hyatt, RSC Advances, 7 (2017) 49004 – 49009.
- Chloride binding and mobility in sodium carbonate-activated slag pastes and mortars, X.Y. Ke, S.A. Bernal, O.H. Hussein, J.L. Provis, Materials and Structures, 50 (2017) 252.
- Uptake of chloride and carbonate by Mg-Al and Ca-Al layered double hydroxides in simulated pore solutions of alkali-activated slag cement, X.Y. Ke, S.A. Bernal, J.L. Provis, Cement and Concrete Research, 100 (2017) 1-13

Materials Performance Centre (MPC)

Host: The School of Materials, University of Manchester, Oxford Road, Manchester, M13 9PL
LEP: Greater Manchester Region
PI: Professor Grace Burke
Classification: Public
Ownership type: University
Access model: EPSRC
Payment model: EPSRC collaboration, however pay-to-play to be introduced with Henry Royce, industry fees for use of characterisation suite
Training requirements: Local H&S training and other training
Most recent reported usage statistics: none reported
Capabilities: Largest nuclear materials research facility in the UK. Work is focused mainly on the performance of materials for use in nuclear. A wide spectrum of materials examined, within four themes: Plant Materials, Core Materials, Waste Management Materials and Fuel Materials, with research focused on Irradiation Damage of Materials, Zirconium Technology, Environmental Degradation and Nuclear Waste and Spent Fuel. Has close links with DCF and Wood's HTF and Manchester's MTRL.

- Six advanced autoclaves, with two unique large recirculating autoclaves and a set of imaging autoclaves for degradation work
- Special hydrogenated steam/CO2 autoclave for accelerated testing
- Advanced characterisation facilities with FEI Titan G2 S/TEM with Super X and EELS, FEI Talos F200 with Super X with FEG ESEM and FEI Magellan, Zeiss Merlin and Zeiss Sigma FEG-SEMs
- 5 TEM for nuclear use, with a FIB sample holder for active samples.

13 SEM for inactive nuclear use.
Recent output:

- (2017) Crump T, Ferté G, Jivkov AP, Mummery P, Tran V-X. Dynamic fracture analysis by explicit solid dynamics and implicit crack propagation. International Journal of Solids and Structures, 110-111, 113-126.
- (2017) Oernek, C, et al.: Characterization of 475°C Embrittlement of Duplex Stainless Steel Microstructure via Scanning Kelvin Probe Force Microscopy and Magnetic Force Microscopy. Journal of the Electrochemical Society, 164, 6, C207-C217.
- (2017) H. Dawson, M. Serrano, S. Cater, N. Iqbal, L. Almásy, Q. Tian, E. Jimenez-Melero. Impact of Friction Stir Welding on the microstructure of ODS steel. J. Nucl. Mater. 486 129.
- Impagnatiello, S. de Moraes Shubeita, P. Wady, I. Ipatova, H. Dawson, C. Barcellini, E. Jimenez-Melero. Monolayer-thick TiO precipitation in V-4Cr-4Ti alloy induced by proton irradiation. Scripta Mater. 130 (2017) 174.
- (2017) Al-Shater A., Engelberg D., Lyon, S.B., Donohoe C., Walters S., Whillock G., Sherry A.H.: Characterization of the Stress Corrosion Cracking behavior of Thermally Sensitized 20Cr-25Ni Stainless Steel in a Simulated Cooling Pond Environment. Journal of Nuclear Science & Technology

Microscopes and Ion Accelerators for Materials Investigations (MIAMI)

Host: CP/02 Cockroft Building, University of Huddersfield, Queensgate, Huddersfield, HD1 3DH
LEP: Lancashire
PI: Professor Stephen Donnelly
Classification: Public
Ownership type: University

Access model: EPSRC, through UK National Ion Beam Centre (NIBC) framework, new EPSRC grant, retroactive EPSRC grant, EPSRC students, pump priming (10% time allocation) and commercial
Payment model: EPSRC through UKNIBC, limited commercial pay-to-play accessibility
Training requirements: No training required – access to the facility includes 2 x operators for operation of the ion beam(s) and transmission electron microscopes
Recent usage statistics: (April 2017-March 2018) 25% maintenance, 63% University of Huddersfield, 12% UKNIBC.
Capabilities: MIAMI is a world-class electron microscopy and ion irradiation facility at Huddersfield University that consists of two custom built instruments with in-situ ion beam for irradiation and ion implantation.

- MIAMI-1 consists of a JEOL JEM-2000FX TEM (80-200 kV accelerating voltage) coupled with a 100 kV ion accelerator. The TEM is equipped;
    - Single and double tilt holders
    - Double tilt heating (up to 1000°C) and double tilt heating (up to 1300°C) holders allowing in-situ irradiation at elevated temperature or post irradiation annealing
    - Liquid nitrogen cryogenic cooling holder
    - Straining holder
    - 4 megapixel Gatan Orius digital camera
  - o The ion accelerator couple to MIAMI-1 is capable of;
    - 2-100 keV ion accelerator
    - Most ion species from H-W
    - Fluxes: 1010-1014 ions/cm2/s

- MIAMI-2 is a new simultaneous dual ion beam coupled with a Hitachi H-9500 TEM. The microscope comprises;
    - 60-300 kV accelerating voltage
    - Double tilt heating (up to 1000°C) and double tilt heating (up to 1300°C) holders allowing in-situ irradiation at elevated temperature or post irradiation annealing
    - Liquid nitrogen cryogenic cooling holder
    - Straining holder
    - Tomography holder
    - 16 megapixel Gatan OneView digital camera and 300 fps video capability
    - Gatan EELS system (GIF Quantum SE) for EFTEM mapping and spectrum imaging
    - Bruker EDX system (Quantax 400 with XFlash 6T 60 detector)
    - Environmental capability, up to 1 Pa with up to 4 gases
  - o In-situ ion beams
    - 1 – 20 keV Colutron ion source for running low mass gases (H, He, etc)
    - 20 – 350 keV NEC ion source capable of running most species up to Pb
    - Ion beams can be mixed and incident on the sample at an angle of 18.7° to the electron beam

Recent output:

- R.W. Harrison, J.A. Hinks, S.E. Donnelly, Influence of pre-implanted helium on dislocation nucleation and growth in self-ion irradiated tungsten, Scripta Materialia, 150, (2018), 61-65.
- Ipatova, I., Harrison, R. W., Wady, P. T., Shubeita, S. M., Terentyev, D., Donnelly, S. E., & Jimenez-Melero, E., "Structural defect accumulation in tungsten and tungsten-5wt.% tantalum under incremental proton damage." Journal of Nuclear Materials (2017)
- Ipatova, I., Harrison, R. W., Terentyev, D., Donnelly, S. E., & Jimenez-Melero, E., et al. "Thermal Evolution of the Proton Irradiated Structure in Tungsten–5 wt% Tantalum." Journal of Fusion Energy 36.6 (2017): 234-239.
- R.W. Harrison, G. Greaves, J.A. Hinks, S.E. Donnelly, Engineering self-ordering helium bubble lattices in tungsten, Scientific reports, 7 (2017), 7724
- Harrison, R. W., Greaves, G., Hinks, J. A., & Donnelly, S. E. "A study of the effect of helium concentration and displacement damage on the microstructure of helium ion irradiated tungsten." Journal of Nuclear Materials 495 (2017): 492-503.
- Tunes, M. A., Harrison, R. W., Greaves, G., Hinks, J. A., & Donnelly, S. E. "Effect of He implantation on the microstructure of zircaloy-4 studied using in situ TEM." Journal of Nuclear Materials 493 (2017): 230-238.

Nuclear Advanced Manufacturing Research Centre (NAMRC)

Host: University of Sheffield, Advanced Manufacturing Park, Brunel Way, Catcliffe,

Rotherham S60 5WG
LEP: Sheffield City Region
CEO: Andrew Storer
Classification: Public
Ownership type: University
Access model: Individual cases-by-case
Payment model: Case-by-case, EPSRC access possible, NNUMAN
Training requirements: None, work is done by local SQEP
Most recent reported usage statistics: Not reported/confidential
Capabilities: The NAMRC was created in 2011 through the High Value Manufacturing Catapult and this research and manufacturing facility is essential for the advancement of the nuclear engineering field. Manufacturing research is required to provide the tools necessary to take findings from the basic science to higher Technology Readiness Levels (TRL) and Manufacturing Readiness Levels (MRF), works at at higher TRL and MRL (3-6 and 2-6 respectively). Collaborates through NNUMAN with NNL and MTRL at Manchester. Also runs the Fit4Nuclear programme to integrate SME in nuclear supply chain.
Machining:

- Dörries Contumat VTL: Very large vertical turning/milling lathe, capable of working on parts up to 5 metres diameter and 3 metres height.
- Soraluce FX12000: Very large floor-type horizontal boring machine, capable of working on pieces up to 12 metres length and 5 metres diameter.
- Heckert HEC1800: Large high-precision horizontal boring machine, with turning, milling and deep-drilling capabilities.
- Heckert HEC800: Heavy-duty machining centre for milling, turning, drilling and multi-diameter turn-face capabilities.
- Mori Seiki NT6600: Large multi-axis mill-turn machine
- TBT ML700: Large deep-hole boring centre, capable of drilling 5-110mm diameter and 8 metres depth.
- Welding
- Pro-Beam K2000 EBW chamber: Largest, in the UK, electron beam welding chamber with range of advanced features, for joining and additive manufacturing of vessels and components

- Pro-Beam K25 EBW chamber: Electron beam welding chamber for pilot research into innovative joining techniques for large components.
- Diode laser cell: High-speed, high-quality, low-waste cladding of large components with stainless steel, nickel alloys and wear-resistant alloys.
- Disk laser cell High-speed, high-quality welding of large components.
- ITW Miller SAW cell: Flexible submerged arc welding cell for conventional narrow-groove, circumferential and longitudinal welding.
- Polysoude GTAW cell: Multi-function gas tungsten arc welding cell offering choice of heads for wide range of applications.
- K-TIG 1000 keyhole welding: High-speed single-pass full-penetration GTAW system for tubes, pipes and other fabrications.
- ESAB planetary: SAW ESAB A6-MHW submerged arc welding system designed for joining nozzles and access hatches to cylindrical vessels or flat plates.
- AMI tubesheet welding cell: Specialised GTAW cell for autogenous welding of tubes and tubesheets.
- AMI narrow groove welding cell: Orbital welding cell for large and small diameter narrow groove weld preparations.
- Lincoln Electric multi-wire SAW: Lincoln Electric welding head feeding up to five wires, mounted on 6 x 6 metres Pema column and boom.
- Bulk additive manufacturing cell: Robotic cell capable of building high-integrity parts from the ground up, and adding metal features to large forgings such as pressure vessels.
- Quintus hot isostatic pressing facility Densification of cast or additive parts, and consolidation of metallic powders to produce near-net shape components.
- Metrology & inspection
- Range of Coordinate measuring machines (CMM) housed in temperature-controlled and vibration-isolated facilities.
- Hexagon DEA Delta capable of taking parts up to 6 x 3 x 2 metres – the largest CMM capability in the High Value Manufacturing Catapult.
- Leitz PMM-C capable of sub-micron resolution on parts up to 1.2 metres length – the most accurate CMM capability in the High

Value Manufacturing Catapult.

- Leica AT901 laser tracker and T-Probe for inspection and assembly tracking of very large components.
- Nikon Metrology laser radar, offering remote operation for restricted access areas
- GOM ATOS III structured light and Cognitens WLS400M photogrammetry systems to rapidly capture surface coordinates of components, for comparison with CAD data or for distortion analysis
- Range of on-machine tools – including Renishaw's Sprint system – to inspect and measure components while mounted in machining centres.
- Vibration analysis for identifying sources of machining chatter and precautionary maintenance.
- Ultrasonic probes for in-process tracking and monitoring of tool position, and automated inspection of bores and deep holes.
- Non-destructive testing (NDT) Visual, dye penetrant and magnetic particle inspection to identify material surface flaws.
- Visualisation
- Virtalis ActiveWall, 4.5-metre-wide single-screen system with 3D back projection and 4K resolution
- Wearable technology
- Hands-free technology for virtual reality and augmented reality.
- Current equipment includes Oculus Rift and HTC Vive

Recent output:

- Tunc, Lutfi Taner. "Prediction of tool tip dynamics for generalized milling cutters using the 3D model of the tool body." The International Journal of Advanced Manufacturing Technology 95.5-8 (2018): 1891-1909.
- Swarnakar, Akhilesh Kumar, Omer Van der Biest, and Bernd Baufeld. "Young's modulus and damping in dependence on temperature of Ti–6Al–4V components fabricated by shaped metal deposition." Journal of materials science 46.11 (2011): 3802-3811.
- Wunderlich, Wilfried, et al. "SPS-Sintering of NaTaO3-Fe2O3 Composites." J. Aust. Ceram. Soc 47.2 (2011): 57-60.
- Swarnakar, Akhilesh Kumar, Omer Van der Biest, and Bernd Baufeld. "Thermal expansion and lattice parameters of shaped metal deposited Ti–6Al–4V." Journal of Alloys and Compounds 509.6 (2011): 2723-2728.
- Baufeld, B. "Effect of deposition parameters on mechanical properties of shaped metal deposition parts." Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture 226.1 (2012): 126-136.
- Baufeld, Bernd. "Mechanical properties of Inconel 718 parts manufactured by shaped metal deposition (SMD)." Journal of materials engineering and performance 21.7 (2012): 1416-1421.
- Tunc, Lutfi Taner, and Jay Shaw. "Experimental study on investigation of dynamics of hexapod robot for mobile machining." The International Journal of Advanced Manufacturing Technology 84.5-8 (2016): 817-830.
- Maurotto, A., and C. T. Wickramarachchi. "Experimental investigations on effects of frequency in ultrasonically-assisted end-milling of AISI 316L: A feasibility study." Ultrasonics 65 (2016): 113-120.
- Tunc, L. T., and Jay Shaw. "Investigation of the effects of Stewart platform-type industrial robot on stability of robotic milling." The International Journal of Advanced Manufacturing Technology 87.1-4 (2016): 189-199.
- Tunc, Lutfi Taner, et al. "Process simulation integrated tool axis selection for 5-axis tool path generation." CIRP Annals65.1 (2016): 381-384.
- Baufeld, B., et al. "Electron Beam Additive Manufacturing at the Nuclear AMRC."
- Dutilleul, T., J. Priest, and B. Baufeld. "Electron beam characterisation."
- Alcock, J. A., and B. Baufeld. "Diode laser welding of stainless steel 304L." Journal of Materials Processing Technology 240 (2017): 138-144.
- Zhang, B., and S. A. Billings. "Volterra series truncation and kernel estimation of nonlinear systems in the frequency domain." Mechanical Systems and Signal Processing 84 (2017): 39-57.
- Tunc, L. T., and Dave Stoddart. "Tool path pattern and feed direction selection in robotic milling for increased chatter-free material removal rate." The International Journal of Advanced Manufacturing Technology 89.9-12 (2017): 2907-2918.
- Li, Feng, Carl Hitchens, and David Stoddart. "A performance evaluation method to compare

the multi-view point cloud data registration based on ICP algorithm and reference marker." Journal of Modern Optics 65.1 (2018): 30-37.

Selection of companies in NWNA integrated with F4N and other programmes:
GA Engineering (North West) Ltd, Fairham Mouldings Ltd, TPG Engineering Ltd- Dukinfield, Laker Vent Engineering Ltd, NIS Ltd, TSP Engineering Ltd., Barrnon Ltd, Hargreaves Ductwork Ltd, James Fisher Nuclear, Hosokawa-Micron Ltd, Endress+Hauser Ltd

Nuclear Advanced Manufacturing Research Centre (NAMRC) Birkenhead

Host: Cammel Llaird, Campbeltown Road, Birkenhead, Merseyside CH41 9BP
LEP: Liverpool City Region
PI:
Classification: Public
Ownership type: Private company
Access model: NNUMAN
Payment model: Case-by-case, EPSRC access possible, NNUMAN
Training requirements: None, work is done by local SQEP
Most recent reported usage statistics: None reported/confidential
Capabilities: NAMRC Birkenhead opened July 2017, is still in infancy and still slowly filling with equipment, not fully operational yet. It is hosted by Camel Llaird and will use Camel Llaird ship building and modular manufacturing expertise. It will focus on modularisation and modelling with AR/VR and simulation suits. 1000m2 of workshop space and will host specialised machining, joining and assembly equipment to develop and prove modular manufacturing techniques for nuclear applications. It will look at validation of components and construction with a view to infrastructural improvements within nuclear, not just core nuclear.
Current equipment list:

- Virtalis ActiveWall
- 7-metre-wide single-screen system with 3D short-throw projection and 4K resolution.
- Can be viewed by up to 12 people.
- Can be linked to off-site VR facilities for collaborative working.
- Wearable VR/AR technology
- Hands-free technology for virtual reality and augmented reality.
- Current equipment includes HTC Vive and Microsoft HoloLens.
- Applications in collaborative design, training, guided assembly, repair and maintenance.
- Stratasys F270 3D printer
- Rapid prototyping to support the design process for modular assemblies.
- 305 x 254 x 305 mm build volume.
- Four material spool bays – three for model (ABS-M30, PLA, ASA) and one for support (QSR).
- GrabCAD Print software.
- Capabilities under development include:
- Virtual sandbox
- Virtual environment to allow people to naturally and collaboratively explore large complex designs.
- Develop low-cost virtual tools and demonstrators to support modularisation.
- Create a low-cost alignment/metrology demonstrator for modules and ultimately support the development of a model-based systems engineering (MBSE) / VR tool.
- Equipped using low-cost off-the-shelf technology, allowing cost-effective adoption by SMEs.
- Flow line assembly for modular manufacturing
- Flexible production line to develop and prove modular manufacturing techniques for nuclear applications.
- Selection of specialised machining, joining and assembly equipment.

Nuclear Fuel Centre of Excellence

Host: Dalton Nuclear Institute, The University of Manchester, Pariser Building, Floor G, Sackville Street, Manchester, UK, M13 9PL
LEP: Greater Manchester Region
PI: Prof. Tim Abram
Classification: Public
Ownership type: University
Access model: EPSRC
Payment model: EPSRC, no pay-to-play options.
Training requirements: Thorough training provided locally. For short projects work done by local SQEP. For longer projects, visitors will have to complete RW-1 training (8-12 weeks) to become SQEP. Other barriers include BPSS vetting where work is done on NNL premises of Preston or Sellafield laboratories.
Most recent reported usage statistics: No detailed reports, but approximately 90% University of Manchester and 10% external researchers (Surrey and Sheffield recently)
Capabilities: NFCE is a research facility that

focuses on the manufacture and deposition of coatings and other protective layers on components of nuclear power fuel rods and reactor cores. In the NFCE laboratories fuel pellets can be manufactured in a suite of atmosphere-controlled glove boxes, and a wide range of microstructural, thermo-physical, and mechanical testing can be undertaken in the active characterisation laboratories. The Centre has several kg of uranium metal and UO2 powder, as well as smaller quantities of U-bearing materials that have been fabricated in the NFCE, such as U3Si2 and (U,Zr) alloys. It collaborates with other facilities such as DCF, NNL and facilities at Sellafield.

- All equipment (apart from the laser joining/bonding rig) is located in (U,Th) active laboratories.

EQUIPMENT LOCATED IN INERT ATMOSPHERE GLOVE BOXES

Five glove boxes are available: typically run with an argon atmosphere and moisture and oxygen controlled to < 5 ppm.

The following equipment is normally available in the boxes, although additional equipment can be introduced as necessary.

- Range of balances (Sartorius, 0.01 mg)
- In-box materials storage safe.
- Mixer Mill (Retsch MM400)
- Sieve shaker (Retsch)
- Jaw Crusher (Retsch)
- Pelleting press (NNL proprietary design, supplied by Fort Vale)
- Slow speed diamond saw
- Automatic grinder/polisher (Struers Tegra Hot Cell System)
- Arc Melter
- Induction Melter
- Mould Pre-Heater
- Particle Size Analyser (Malvern Mastersizer)

FUEL MANUFACTURING EQUIPMENT

- Planetary Ball Mill (Retsch PM100)
- Spark Plasma Sintering Furnace with glovebox system (Thermal Technologies SPS 10-4)
- High-Temperature Reducing-Atmosphere Sintering Furnace (Carbolite HTRH-1800 with hydrogen gas system and off-gas burner)
- Chamber furnace (Lenton)
- Drying Oven (Carbolite A-Series)

Vacuum Furnace (RD Webb Red Devil

CERAMIC CLADDING JOINING/BONDING EQUIPMENT

- 1 kW fibre laser joining system with translating and rotating stages (DeBe Lasers/IPG YLR-1000-WC)

CHARACETRISATION EQUIPMENT

- S/T-EM (FEI Nova NanoSEM 450 with Oxford Instruments EDS/EDX and EBSD systems)
- XRD (Panalytical Empyrian)
- X-ray tomograph (Nikon XT H 225ST)
- 3D Measurement Confocal Microscope (Olympus LEXT 4100)
- Micro Raman Spectrometer (Horiba XploRA+)
- Scanning Probe Microscope (Agilent/Keysight 5500)
- STA Pt-Furnace (Netzsch STA 449 Jupiter F1)
- STA Steam-Furnace (Netzsch STA 449 Jupiter F1)
- Laser Flash Analyser (Netzsch LFA 457/2/G)
- Dilatometer (Netzsch DIL 402 C/4/G)
- Dynamic Mechanical Analyser (Netzsch DMA 242E)
- ICP Mass Spectrometer (Agilent 7700) with Laser Ablation unit
- Gas Chromatograph (Agilent 7890A)
- Helium pycnometer (Micromeritics AccuPyc II 1340)
- BET Surface Area Analyser (Micromeritics Gemini VII)

ENVIRONMENTAL TESTING EQUIPMENT

- Two static autoclaves (400 °C / 200 bar)
- SAFETY AND STORAGE EQUIPMENT
- Two Hand/Foot Contamination Monitors (Canberra Sirius-5)
- Two Continuous Air Monitors (Canberra iCAM)
- Recirculating Fume Hood
- Radioactive Materials Storage Safe

Recent output:

Paul JI, Schmidt MJJ & Abram TJ (2016) Selective Area Laser Deposition of FCC Beta Silicon Carbide, Crystal Research and Technology, 51: 441–445. doi:10.1002/crat.201600089

Turner J, Lambert H, Abram TJ, & Scott I (2015). Thermodynamic Modelling of Corrosion of Structural Metals by Molten Salts - Effect of Sacrificial Metals. Proc. Int. Conf. on Thorium Energy, Bhabha Atomic Research Centre, India.

Gentile M, Xiao P, & Abram TJ (2015), Palladium Interaction with Silicon Carbide, Journal of Nuclear

Materials 462 100-107
Gentile M & Abram T J (2015) Properties of Al2O3–CaO Glass Joints of Silicon Carbide Tubes, Ceramic Materials for Energy Applications: Proc. 39th International Conference on Advanced Ceramics and Composites, American Ceramic Society, DOI: 10.1002/9781119211709.ch2
Bari K, Osarinmwian C, López-Honorato E & Abram TJ (2013), Characterization of the Porosity in TRISO Coated Fuel Particles and its Effect on the Relative Thermal Diffusivity, Nuclear Engineering and Design 265, 668-674.
Gentile M, Xiao, P & Abram TJ (2013) XRD and TG-DSC Analysis of the Silicon Carbide-Palladium Reaction, Developments in Strategic Materials and Computational Design, American Ceramic Society, DOI: 10.1002/9781118807743.ch24
Hamodi NH, Abram TJ, Lowe T, Cernik R J, & López-Honorato E (2013) The Chemical Durability of Glass and Graphite–Glass Composite Doped with Cesium Oxide, Journal of Nuclear Materials, 432, 529-538
Hamodi NH, Lowe T & Abram TJ (2012) Interaction of Embedded Tri-Isotropic Fuel Particles with Melt of Alkaline Borosilicate Glass, Int J Appl Glass Science 3 254-262, DOI: 10.1111/j.2041-1294.2012.00084.x
Hamodi NH, Papadopoulou K, Lowe T & Abram TJ (2012) Thermal Analysis and Immobilisation of Spent Ion Exchange Resin in Borosilicate Glass, Journal of Glass and Ceramics 2 111-120, DOI:10.4236/njgc.2012.23016
Hamodi, NH & Abram TJ (2011) Microstructure Characterization of Simulated Tri-Isotropic (TRISO) Particles Embedded in Alkaline Borosilicate Glass. Int J Appl Glass Sci. 2 334–342. doi:10.1111/j.2041-1294.2011.00064.x
López-Honorato E, Meadows PJ, Xiao P, Marsh G & Abram TJ (2008) Structure and Mechanical Properties of Pyrolytic Carbon Produced by Fluidized Bed Chemical Vapor Deposition, Nuclear Engineering and Design 238 3121-3128.
López-Honorato E, Chiritescu C, Xiao P, Cahill DG, Marsh G & Abram TJ (2008), Thermal Conductivity Mapping of Pyrolytic Carbon and Silicon Carbide Coatings on Simulated Fuel Particles by Time-Domain Thermoreflectance. Journal of Nuclear Materials 378 35-39.
PhD Theses:
Joel Turner (2012) The Performance of a Nuclear Fuel-Matrix Material in a Sealed CO2 System
Klaudio Bari (2013) Assessing the Feasibility of Encapsulating Spent Fuel Particles (TRISO) and Ion Exchange Resins in Borosilicate Glass
James Buckley (2017) The Manufacture and Characterisation of Composite Nuclear Fuel for Improved In-Reactor Performance
Kris James (2017) The Design and Performance of a Civil Marine Reactor with Regard to the Thermal Performance of the Fuel
James Paul (2017) Laser Induced Chemical Vapour Deposition Of 3C-SiC Applied to Silicon Carbide Joining for Novel PWR Fuel

Nuclear Graphite Research Group (NGRG)

Host: The School of Materials, University of Manchester, Oxford Road, Manchester, M13 9PL
LEP: Greater Manchester Region
PI: Dr Abbie Jones
Classification: Public
Ownership type: University
Access model: EPSRC
Payment model: EPSRC, no pay-to-play options, but group does consultancy for industry on radiometrics
Training requirements: Strict. Every new radiation worker retested by Dr Jones. RW-1 training required before lab access. If work is less than 3 months, local SQEP staff/technicians will do work, if 3months+ then buddy system training after RW-1 and test by Dr Jones.
Most recent reported usage statistics: None reported
Capabilities: Research facility focusing on work with radioactive graphite of AGR and Magnox stock. Shares laserflash facilities with the NFCE and overlaps with Rahman spectroscopy and uses the Henry Moseley Tomography suite. 5 active laboratories with the following equipment.

- Thermal Treatment Analyser
- Liquid beta scintillation counter
- Na (TI) detector for gamma spectroscopy
- Scanning electron microscope with EDX
- Polarised optical microscope
- Laser confocal microscope
- Dynamic Young's modulus apparatus
- Micromerics Tristar II 3020 surface area analyser
- Helium pycnometry
- Isotope modelling – Fispact
- High temperature induction furnace (2100°C)
- Low temperature ovens – long term leaching behaviour at 70°C
- Low temperature furnace – for creep experiments
- Recent output:

- (2017) An understanding of lattice strain, defects and disorder in nuclear graphite, R Krishna, J Wade, AN Jones, M Lasithiotakis, PM Mummery, BJ Marsden, Carbon 124, 314-333
- (2017) Thermal oxidation of nuclear graphite: A large scale waste treatment option A Theodosiou, AN Jones, BJ Marsden, PloS one 12 (8), e0182860
- (2017) Simultaneous heating and compression of irradiated graphite during synchrotron microtomographic imaging, AJ Bodey, Z Mileeva, T Lowe, E Williamson-Brown, DS Eastwood, et al. Journal of Physics: Conference Series 849 (1), 012021
- (2017) Crump, Timothy, et al. "Dynamic fracture effects on remote stress amplification in AGR graphite bricks." Nuclear Engineering and Design 323 (2017): 280-289.

Nuclear Physics Group, University of Manchester
Host: School of Physics and Astronomy, University of Manchester, Schuster Laboratory, Brunswick Street, Manchester, M13 9PL
LEP: Greater Manchester Region
PI: Professor John Billowes
Classification: Public
Ownership type: University
Access model: STFC
Payment model: EPRSC/STFC, no pay to play
Training requirements: Local H&S training
Most recent reported usage statistics: None reported
Capabilities: Nuclear physics group focusing on work done at CERN and other accelerators. Physical facilities in NWNA include, machining workshop, teaching lab and detector laboratory in support of CERN work. HPC computing facilities available with variety of software packages.

- Detector laboratory, with much expertise in production and testing of state-of-art multi-wire proportional counters
- Machining workshop for production of CERN compatible gear
- Teaching laboratory for students and externals, includes Ge detectors and neutron tanks
- HPC facilities (RED QUEEN) with 800 cores
- ANSWERS code suit, with additional licenses for MCNP, GEANT4, FLUKA and FISPIN

Recent output:

- Physical Review Letters (2017) A. Welker, N. A. S. Althubiti, D. Atanasov, K. Blaum, T. E. Cocolios, F. Herfurth, S. Kreim, D. Lunney, V. Manea, M. Mougeot, D. Neidherr, F. Nowacki, A. Poves, M. Rosenbusch, L. Schweikhard, F. Wienholtz, R. N. Wolf, and K. Zuber, Binding Energy of 79Cu: Probing the Structure of the Doubly Magic 78Ni from Only One Proton Away, doi: 10.1103/PhysRevLett.119.192502
- Physical Review C (2017), W. Urban, M. Czerwiński, J. Kurpeta, T. Rząca-Urban, J. Wiśniewski, T. Materna, Ł. W. Iskra, A. G. Smith, I. Ahmad, A. Blanc, H. Faust, U. Köster, M. Jentschel, P. Mutti, T. Soldner, G. S. Simpson, J. A. Pinston, G. de France, C. A. Ur, V.-V. Elomaa, T. Eronen, J. Hakala, A. Jokinen, A. Kankainen, I. D. Moore, J. Rissanen, A. Saastamoinen, J. Szerypo, C. Weber, and J. Äystö, Shape coexistence in the odd-odd nucleus 98Y: The role of the g9/2 neutron extruder doi: 10.1103/PhysRevC.96.044333
- Physical Review C (2017) M. Sabaté-Gilarte, M. Barbagallo, N Colonna, F. Gunsing, P. Žugec, V. Vlachoudis, Y. H. Chen, A. Stamatopoulos, J. Lerendegui-Marco, M. A. Cortés-Giraldo, A. Villacorta, C. Guerrero, L. Damone, L. Audouin, E. Berthoumieux, L. Cosentino, M. Diakaki, P. Finocchiaro, A. Musumarra, T. Papaevangelou, M. Piscopo, L. Tassan-Got, O. Aberle, J. Andrzejewski, V. Bécares, M. Bacak, R. Baccomi, J. Balibrea, S. Barros, F. Bečvář. C. Beinrucker, F. Belloni, J. Billowes, D. Bosnar, M. Brugger, M. Caamaño, F. Calviño, M. Calviani, D. Cano-Ott, R. Cardella, A. Casanovas, D. M. Castelluccio, F. Cerutti, E. Chiaveri, G. Cortés, K. Deo, C. Domingo-Pardo, R. Dressler, E. Dupont, I. Durán, B. Fernández-Domínguez, A. Ferrari, P. Ferreira, R. J. W. Frost, V. Furman, K. Göbel, A. R. García, A. Gawlik, I. Gheorghe, T. Glodariu, I. F. Gonçalves, E. González, A. Goverdovski, E. Griesmayer, H. Harada, T. Heftrich, S. Heinitz, A. Hernández-Prieto, J. Heyse, D. G. Jenkins, E. Jericha, F. Käppeler, Y. Kadi, T. Katabuchi, P. Kavrigin, V. Ketlerov, V. Khryachkov, A. Kimura, N. Kivel, M. Kokkoris, M. Krtička, E. Leal-Cidoncha, C. Lederer, H. Leeb, M. Licata, S. Lo Meo, S. J. Lonsdale, R. Losito, D. Macina, J. Marganiec, T. Martínez, C. Massimi, P. Mastinu, M. Mastromarco, F. Matteucci, E. A. Maugeri, E. Mendoza, A. Mengoni, P. M. Milazzo, F. Mingrone, M. Mirea, S. Montesano, R. Nolte, A. Oprea, F. R. Palomo-Pinto, C. Paradela, N. Patronis, A. Pavlik, J. Perkowski,

J. I. Porras, J. Praena, J. M. Quesada, K. Rajeev, T. Rauscher, R. Reifarth, A. Riego-Perez, M. S. Robles, P. C. Rout, C. Rubbia, J. A. Ryan, A. Saxena, P. Schillebeeckx, S. Schmidt, D. Schumann, P. Sedyshev, A. G. Smith, S. V. Suryanarayana, G. Tagliente, J. L. Tain, A. Tarifeño-Saldivia, A. Tsinganis, S. Valenta, G. Vannini, V. Variale, P. Vaz, A. Ventura, R. Vlastou, A. Wallner, S. Warren, M. Weigand, C. Wolf, P. J. Woods, C. Weiss, and T. Wright, High-accuracy determination of the neutron flux in the new experimental area n_TOF-EAR2 at CERN, doi: 10.1140/epja/i2017-12392-4

- Physical Review C (2017), G. J. Farooq-Smith, A. R. Vernon, J. Billowes, C. L. Binnersley, M. L. Bissell, T. E. Cocolios,T. Day Goodacre, R. P. de Groote, K. T. Flanagan, S. Franchoo, R. F. Garcia Ruiz, W. Gins, K. M. Lynch, B. A. Marsh, G. Neyens, S. Rothe, H. H. Stroke, S. G. Wilkins, and X. F. Yang, Probing the 31Ga ground-state properties in the region near Z=28 with high-resolution laser spectroscopy, doi: 10.1103/PhysRevC.96.044324
- Physical Review C (2017), G. L. Wilson, M. Takeyama, A. N. Andreyev, B. Andel, S. Antalic, W. N. Catford, L. Ghys, H. Haba, F. P. Heßberger, M. Huang, D. Kaji, Z. Kalaninova, K. Morimoto, K. Morita, M. Murakami, K. Nishio, R. Orlandi, A. G. Smith, K. Tanaka, Y. Wakabayashi, and S. Yamaki, Beta-delayed fission of 230Am, doi: 10.1103/PhysRevC.96.044315

NSG Environment Ltd. – Rig Halls and Laboratory

Host: Scientia House, Western Avenue, Matrix Park, Chorley, Lancashire, PR7 7NB
LEP: Lancashire
Business development manager: James Rudd
Classification: Private
Ownership type: Private Company
Access model: N/A
Payment model: Consultation
Training requirements: N/A
Most recent reported usage statistics: None reported
Capabilities: Facility to support client development work with scaled down, inactive work before moving to active work on scientist in labsite. Dedicated 30- man team of scientists, has a range of capabilities, including test material and simulant preparation and analysis, cement and polymer testing; small scale encapsulation mixes; compressive strength measurement; gas generation measurement; and chemical analysis

- Inactive wet chemistry
- trace active work and decontamination
- cement chemistry
- polymeric sciences for encapsulation
- evaporation and drying trials
- lab development of test materials to replicate active waste
- sample preparation facilities
- fume cupboards
- thermal cycling trials
- particle size analysis
- conditioned storage areas for samples
- Workshop, 3 workshops larger scale for projects waste retrieval, waste treatment and tech solutions, largest has 20m high ceiling with 20t crane

Clients supported:

- National Decommissioning Authority assets: Magnox, Sellafield, Dounreay
- NDA direct research portfolio
- Aldermaston
- Site support at LLWR at Drigg

N-Star Liverpool

Host: University of Liverpool, 765 Brownlow Hill, Liverpool L69 7ZX
LEP: Liverpool City Region
PI: Prof Eann Patterson
Classification: Public
Ownership type: University
Access model: EPSRC
Payment model: EPSRC, commercial pay-to-play available
Training requirements: Local H&S provided
Most recent reported usage statistics: None reported
Capabilities: University of Liverpool's N-STAR nuclear research are split between three departments, with each specialising in different topics, the Physics department works mainly on developing gamma ray spectroscopy techniques, the Electrical Engineering & Electronics department studies the applications of plasma and its impact on materials and the School of Engineering works on materials research, with the Imaging Centre at Liverpool supporting the work with a range of different microscopes. The School of Engineering also houses the Institute of Risk and Uncertainty that examines and quantifies how risks impact reactor systems. N-STAR has extensive industry links and partners with NNL, Wood, STFC

Daresbury, CCFE and Mirion.

- Low background systems (4 available) with gammy ray detectors for analysis of samples ~1-2g. The system has excellent performance in 210Pb dating of environmental samples, and for detailed measurements of gamma ray emitters in the U & Th decay chains.
- Germanium detectors (6-8) suitable for high energy gamma ray spectroscopy, which can be used for all gamma ray environmental emitters, such as 137Cs and 214Am, as well as medical isotopes.
- Low pressure He plasma irradiation facility for the irradiation of surfaces
- Magnetron sputtering devices (3) that can be used for thin film coating production
- JEOL 2100FCs TEM/STEM installed Aug. 2008 (Quantum GIF 963 July 2010, EDAX T-Optima Windowless EDX system), with 200 kV Schottky FEG with 80, 100, 120, 160kV operation also available, with an STEM resolution of <100 pm demonstrated. HAADF, MAADF, BF, EDX, EELS, SI capabilities.
- JEOL 2000 FXII, 200kV instrument with Analytical Pole Piece, Tungsten Filament electron source, Analytical Scanning Attachment, EDAX Genesis 4000 Si(Li) EDX System with mapping capability.
- JEOL JSM 7001F Schottky FEG SEM with super-hybrid objective optics and through-the-lens detector, standard detector and retractable Backscatter Electron detector, Oxford Inca X-Act SDD (Si Drift) EDX system.
- JEOL JSM 6610 Tunsgten Filament SEM with large area sample handling capability, standard and backscatter detectors, Oxford Inca X-Act SDD (Si Drift) EDX system and WebSEM full internet control capability.
- FEI Helios 600i dual beam system with Omniprobe Manipulator installed Oct. 2012. The FIB instrument is equipped with gas injection systems, EDAX EBSD and Optima EDX analysis capabilities.

Nuclear Leeds

Host: University of Leeds, Leeds LS2 9JT
LEP: Leeds City Region
PI: Prof. Bruce Hanson
Classification: Public
Ownership type: University
Access model: EPSRC, no pay-to-play options available, but two ad-hoc commercial collaborations being set-up.
Payment model: EPSRC
Training requirements: Local H&S induction and for active lab, Leeds University Radiological Awareness training, with further training at facility.
Most recent reported usage statistics: None reported
Capabilities: Nuclear Leeds has two laboratories for nuclear work, a recently built uranics lab and a rig hall. The DECC-funded uranics lab is currently used for inactive wet chemistry, but will be commissioned for active work at the end of 2018 and will be used for wet radiochemistry of uranics. Second facility is a rig hall with flow loop experiments and space for other rigs.

- 160m2 of active laboratory space, once commissioned will have, limits:
- 1.2GBq alpha emitters
- 120GBq others except alpha emitters
- 20kg uranium and thorium
- 3-stage Robotel BXP040 centrifugal contactors
- Active Mbraun glovebox with atmospheric control
- 3 fumehoods and wet chemistry facilities available
- Analysis: Cobra II auto Gamma Counter, Applied Photonics LIBS
- Lab dose constraints:
- 1mSv / year whole body dose
- 10mSv / year extremity dose
- 110m2 of rig hall space
- Flow loop experiments incorporates a laser-based particle image velocimetry (PIV) measurement system and will be used to investigate the near-wall flow behaviour in multiphase flows

Recent output:
Mathematical model of the oxidation of a uranium carbide fuel pellet including an adherent product layer, J.S. Shepherd, M. Fairweather, B.C. Hanson and P.J. Heggs, Applied Mathematical Modelling, Volume 45, May 2017, Pages 784-801
Gas Retention and Release from Nuclear Legacy Waste, Johnson, M, Peakall, J, Fairweather, M; Biggs, S; Harbottle, D; Hunter, T (2016) Gas Retention and Release from Nuclear Legacy Waste. Proceedings of Waste Management Conference 2016, 06-10 Mar 2016, Phoenix, Arizona, USA. WM Symposia. ISBN 9781510826335
Aqueous hydroxylation mediated synthesis of crystalline calcium uranate particles, Weixuan Ding, Johannes A. Botha, Bruce C. Hanson and

Ian T. Burke, Journal of Alloys and Compounds, Volume 688, Part B, 15 December 2016, Pages 260-269
Influence of shape and surface charge on the sedimentation of spheroidal, cubic and rectangular cuboid particles, Neepa Paul, Simon Biggs, Jessica Shiels, Robert B. Hammond, Michael Edmondson, Lisa Maxwell, David Harbottle and Timothy N. Hunter, Powder Technology, Volume 322, December 2017, Pages 75-83
Enhanced adsorption capacity and selectivity towards strontium ions in aqueous systems by sulfonation of CO2 derived porous carbon, S. Baika, H. Zhang, Y. K. Kima, D. Harbottle and J. W. Lee, RSC Advances, 2017, 7, 54546-54553, DOI: 10.1039/C7RA09541D
Cementitious Grouts for ILW Encapsulation - Hydration & Continuity of Supply within the UK, Hawthorne, J, Cann, G and Black, L (2016) Cementitious Grouts for ILW Encapsulation - Hydration & Continuity of Supply within the UK. Proceedings of Waste Management Conference 2016. Waste Management Conference 2016, 06-10 Mar 2016, Phoenix, AZ, USA. WM Symposia. ISBN 978-0-9828171-5-5

Preston Laboratory

Host: National Nuclear Laboratory, Building A709, Springfields, Preston, Lancashire, PR4 0XJ
LEP: Lancashire
PI: Dave Goddard
Classification: Public
Ownership type: NNL
Access model: EPSRC
Payment model: EPSRC, commercial pay-to-play available.
Training requirements: Strict. Significant barriers present. Visitors need to be BPSS vetted and minimum lead time will be 8-10 weeks.
Most recent reported usage statistics: None reported
Capabilities: Research facility focusing on work with uranium. Two main uranium-based streams:

- Uranium active chemistry, Process instrumentation, Radiometrics, LLW/ILW physical and radiochemical characterisation, Rig hall, Pilot Plant
- Uranium active oxide product development, Powder processing laboratories, Total enclosures for hazardous powder work, pellet pressing

Active capabilities include:

- XRD, FTIR,
- XRF, TGA-MS, GC, ICP-OES, ICP-MS
- α-, β- and γ-spectrometers ; calorimeters ; gas analysis ;
- PSD, SSA ; rheometers ;
- Thermal diffusivity.
- Recovery or removal of uranium from waste residues :
- Machining, centrifuges, dissolvers, SABRE dissolver, acid /oil processing.
- TGA-MS, PSD, SSA, laser flash analysis
- Sintering, spark plasma sintering, arc melting, milling
- Pellet press, furnaces, rattler, enclosures.
- Engineering developments (U-active).
- SEM/EDX, ESEM, SPM, SIMS, Confocal POM ; fluorine chemistry

Radionuclide Biogeochemistry Suite

Host: Williamson Research Centre for Molecular Environmental Science, School of Earth and Environmental Sciences, The University of Manchester, Oxford Road, Manchester, M13 9PL
LEP: Greater Manchester Region
PI: Dr Katherine Morris
Classification: Public
Ownership type: University
Access model: EPSRC
Payment model: EPSRC,
Training requirements: RW-1 training required before lab access.
Most recent reported usage statistics: None reported
Capabilities: The Radionuclide Biogeochemistry Suite was opened in 2011 after the development of the Research Centre for Radwaste Disposal and the associated appointments of Prof. Katherine Morris, Dr Dirk Engelberg and Prof. Andrey Jivkov. In 2013, there was an allied appointment of Prof Sam Shaw, and an additional laboratory, the Environmental Mineralogy suite was also developed as part of the Radionuclide Biogeochemistry Suite. The labs were funded via investment from The University of Manchester and an endowment from BNFL.

The lab suite is focussed on handling radionuclides in a range of complex materials from the engineered and natural environment. It has the licenses and experience to handle beta / gamma and alpha emitting radionuclides at the levels required for X-ray absorption spectroscopy. Radioisotopes handled within the laboratory include Pu, Np, Am, Ra, 137Cs, 90Sr, 99Tc and it can receipt active materials from nuclear facilities under the appropriate authorisations. An additional unique capability in the lab is the combined capability to examine radionuclide behaviour, mineralogy and microbiology of complex, radioactive environmental samples. Current search includes work on nuclear decommissioning, radioactive waste disposal, analysis of environmental radioactivity, naturally occurring radiological material and radioactively contaminated land.

- 1 controlled area designated zone
- 3 supervised areas
- anaerobic cabinets
- fume hoods
- controlled atmosphere glove boxes
- laminar flow hoods
- DNA extraction facilities and clean room
- 10°C cold room
- ovens
- -80°C freezers
- Incubators
- light cabinets and normal ancillary equipment for a wet chemistry laboratory
- ICPAES
- ICPMS
- XRD
- FEG-SEM
- TEM
- surface area
- XRF

Recent publications:
Impacts of Repeated Redox Cycling on Technetium Mobility in the Environment, Nicholas K Masters-Waage, Katherine Morris, Jonathan R Lloyd, Samuel Shaw, J Frederick W Mosselmans, Christopher Boothman, Pieter Bots, Athanasios Rizoulis, Francis R Livens, Gareth TW Law, Environmental science & technology, 51, 24, 14301-14310
Quantifying Technetium and Strontium Bioremediation Potential in Flowing Sediment Columns, Clare L Thorpe, Gareth TW Law, Jonathan R Lloyd, Heather A Williams, Nick Atherton, Katherine Morris, Environmental science & technology, 51, 21, 12104-12113
Uranium (V) incorporation mechanisms and stability in Fe (II)/Fe (III)(oxyhydr) oxides, Hannah E Roberts, Katherine Morris, Gareth TW Law, J Frederick W Mosselmans, Pieter Bots, Kristina Kvashnina, Samuel Shaw, Environmental Science & Technology Letters, 4, 10, 421-426
Long-term immobilization of technetium via bioremediation with slow-release substrates, Laura Newsome, Adrian Cleary, Katherine Morris, Jonathan R Lloyd, Environmental Science & Technology, 51, 3, 1595-1604

Robotics for Extreme Environments Group

Host: School of Electrical and Electronic Engineering, The University of Manchester, Sackville Street Building, Manchester, M13 9PL
LEP: Greater Manchester Region
PI: Prof. Barry Lennox
Classification: Public
Ownership type: University
Access model: EPSRC
Payment model: EPSRC
Training requirements: None required.
Most recent reported usage statistics: None reported
Capabilities: Manchester's Robotics for Extreme Environments work on robotic systems for decommissioning and work in highly active environments. The group works with Sellafield, Rolls Royce, EDF Energy, AWE and Nuvia. It has facilities for use at DCF and NNL's Workington laboratory.

- MIRRAX robot: ground based platform able to be deployed through 150 mm ports and able to generate 3D topographical and radiological maps.
- CARMA robot: ground based platform, based on Clearpath Jackal robot and able to generate 3D topographical and radiological maps.
- AVEXIS: submersible robot able to be deployed through a 150 mm port and measure neutron and gamma dose (using Lancaster University detectors)
- MALLARD: Floating platform able to navigate autonomously in pond environments.
- CORIN: Hexapod robot (about 500 mm x 500 mm)
- MONA: Small (6cm diameter) robots for use in swarm robotics experiments (able to self-charge and so can operate for weeks or even months if necessary)
- Vicon indoor positioning system
- Clearpath Husky robot with Universal Robots UR-5 manipulator
- 2 x Universal Robots UR-5 manipulators and haptic glove

Recent output:
Okumura, K, Sapta Riyana, E, Sato, W, Maeda, H, Katakura, J, Kamada, S, Joyce, MJ and Lennox, B,

(2018), 'A Method for the Prediction of the Dose Rate Distribution in a Primary Containment Vessel of the Fukushima Daiichi Nuclear Power Station', accepted for publication in, Progress in Nuclear Science and Technology

Kamada, S, Kato, M, Nishimura, K, Nancekievill, M, Watson, S, Lennox, B, Jones, A, Joyce, M, Okumura, K and Katakura, J, (2018), 'Development of ROV system to explore fuel debris in the Fukushima Daiichi nuclear power plant', accepted for publication in Progress in Nuclear Science and Technology

Nancekievill, M, Jones, A, Joyce, M, Lennox, B and Watson, S, (2018) 'Development of a Radiological Characterization Submersible ROV for use at Fukushima Daiichi', IEEE Transactions on Nuclear Science

Arvin, F, Watson, S, Turgut, A.E., Espinosa, J, Lennox, B, (2017), 'Perpetual robot swarm: long-term autonomy of mobile robots using on-the-fly inductive charging', Journal of Intelligent & Robotic Systems

Groves, K and Lennox, B, (2017), 'Directional wave separation in tubular acoustic systems - the development and evaluation of two industrially applicable techniques', Applied Acoustics, 116, 249-259

Sheffield Forgemasters International Ltd.

Location: Sheffield Forgemasters International, Brightside Lane, Sheffield, S9 2RW
LEP: Sheffield City Region
Nuclear business manager: Brian Rice
Classification: Private
Ownership type: Private
Access model: N/a
Payment model: Consultancy
Training requirements: N/A
Most recent reported usage statistics: None reported
Capabilities: Sheffield Forgemasters International Ltd. is a company with a long tradition of smelting, forging and casting metal. It has a two relevant specialised sub-units, Sheffield Forgemasters Engineering and Sheffield Forgemasters RD26. Sheffield Forgemasters Engineering is the specialised nuclear forging company, which has the ISO 9001 approved quality assurance system for steel castings and forgings with ASME NCA 3800 accreditation for nuclear forgings and castings. It is capable of forging, casting and heat treating very large single pieces.

- Manufacture of nuclear cask components
- 4000 tonne and 10000 tonne presses produce forgings up to 200 tonnes
- Steel castings from 1 to 350 tonnes single piece weight and maximum size of 16.5 x 7.5x 4.6 metres
- Comprehensive range of heat treatment facilities centrally controlled and monitored for horizontal and vertical processing up to 22 metres long
- Proven capability for components in 12% Cr steels for super critical applications
- Continuing alloy developments to meet higher service temperatures
- Approved to ASME NCA 3800 and has a long history of manufacture of components for civil and military applications
- Typical products include nuclear island components for the UK nuclear submarine programme, transition cones, shell strakes and tube sheets for steam generators and finish-machined pump components for safety systems
- The company is a significant supplier of nuclear cask forgings whether for the TN designs or designs for the UK nuclear programme
- RD26 is the research and development arm of Sheffield Forgemasters and is geared mainly towards materials science and metallurgy. It has many different techniques at its disposal, including surface analysis, chemical analysis, material properties and modelling capabilities.
- CNC lathes for machining standard tensile test pieces
- Milling machines for machining Charpy impact test pieces to ASTM E23 and
- BS EN ISO 148/1 standards
- Carbolite muffle furnace with chart and digital recorders for heat treatment of test piece blanks to 1200°C
- Semi-automatic horizontal and vertical band saws with an ability to saw up to
- 1.2 x 1.4 x 0.5 metres with a maximum capacity of 1.5 tonnes
- Broaching machines for 2mm 'V' and 2mm 'U' notch
- Tensile testing machine – ZWICK/ROELL 250kN
- Charpy impact testing – Two ZWICK/ ROELL high strength 450 Joule Charpy
- impact testing machines
- Micro and macro Vickers hardness testing – INDENTEC ZHV 30

- Rockwell hardness testing – INDENTEC 4150 AK
- Brinell hardness testing – NEWAGE
- Measuring projector for measuring 'V' and 'U' notch Charpys – MITUTOYO
- SARMIEKE fume cabinet
- Grinding and polishing machines
- Mounting press for micro and macro samples
- LEICA X500 microscope with a Clemex optical microscope camera and software
- NIKON stereo scan microscope
- CANON 10 megapixel digital 35mm camera for macro photographs
- JEOL Scanning Electron Microscope and Oxford Instruments 80mm2 EDX detector

Thermal Hydraulics Research Laboratory

Host: Dalton Nuclear Institute, The University of Manchester, Pariser Building, Floor G, Sackville Street, Manchester, UK, M13 9PL
LEP: Greater Manchester Region
PI: Prof. Hector Iacovides
Classification: Public
Ownership type: University
Access model: EPSRC
Payment model: EPSRC
Training requirements: Local
Most recent reported usage statistics: None reported
Capabilities: Research facility for nuclear thermal hydraulics with many specialised rigs pertaining to heat and mass transfer, fluid flow and associated phenomena. Experimental research into complex heating, cooling and fluid flow systems. Also used for validation of test cases and simulation validation.

- Rotating flow water rig, used to visualise and determine fluid flow under many different situations
- EDF High Pressure and Temperature Test Facility, heat transfer research equipment for experiments at AGR operating pressures and temperatures.
- CNET Thermal Hydraulics Loop, multi-purpose facility for convection research, currently used to simulate PWR reactor vibrations.
- Natural Convection Cavity, slanted and heated test rig designed to research convection and fluid flow of air
- Internal Air flow facility, used to investigate forced convection and recently used for reactor fuel cooling flow passages.

- Recent output:
- D Cooper, M A. Cotton, H Iacovides and S Zhang", The effects of natural and mixed
- convection on heat transfer across adjacent micro-channels, in extreme pressure and
- temperature conditions. ", Journal of Applied Thermal Engineering, 106, 640-650, 2016
- L. Santini, A Cioncolini, M.T. Butel, M.E. Ricotti, Flow boiling heat transfer in a helical coil steam generator for nuclear power applications, International Journal of Heat and Mass Transfer 92 (2016) 91-99.
- F Abdulsattar, D Cooper, H Iacovides, S Zhang" Turbulent Flow Development inside a
- Rotating Two-Pass Square Duct with Porous Blocks.", ISABE-2017-21382, International
- Symposium on Air-Breathing Engines, Manchester, 2017
- C. Liu, A. Cioncolini, J. Silva, D. Cooper, H. Iacovides, Experimental study of a flexible
- cantilever rod subjected to axial water flow, 2017 MACE PGR Conference, 3 April 2017,
- Manchester, UK.
- Cioncolini, S. Cassineri, J. Duff, M. Curioni, F. Scenini, Micro-orifice single-phase flow at very high Reynolds number, Experimental Thermal and Fluid Science 91 (2018) 35-40.
- A Cioncolini, J Silva, M Quinn, D Cooper, H Iacovides "Axial flow-induced vibration in
- cantilevered rods: and experimental benchmark study for nuclear reactor applications".

UCLan Nuclear chemistry laboratory

Host: University of Central Lancashire, Preston, Lancashire, PR1 2HE
LEP: Lancashire
PI: Prof. Harry Eccles
Classification: Public
Ownership type: University
Access model: EPSRC
Payment model: EPSRC, commercial pay-to-play
Training requirements: Local H&S
Most recent reported usage statistics: None reported
Capabilities: Former radiochemistry lab that has now reverted to non-active work due to licensing arrangements. Uses non-active surrogates such as Nd and Ce for U and Pu respectively and inactive Cs and Co for inactive surrogate cation chemistry. Analysis methods include ICP-MS (10 ppb sensitivity).

Recent output

- Rout, S. P., Payne, L., Walker, Stephen, Scott, T, Heard, P., Eccles, Harry, Bond, Gary , Shah, P., Bills, P. et al (2018) The Impact of Alkaliphilic Biofilm Formation on the Release and Retention of Carbon Isotopes from Nuclear Reactor Graphite. Scientific Reports, 8 (4455). ISSN 2045-2322
- Eccles, Harry, Bond, Gary, Kavi, Parthiv , Holdsworth, Alistair and Rowbotham, Dan (2018) Highly Active Waste Elimination (HAWE): A New Concept in Nuclear Reprocessing. Dalton Transactions. ISSN 1477-9226 (Submitted)
- Holdsworth, A. F., Eccles, Harry, Mao, Runjie, Halman, A.M. and Bond, Gary (2017) Comparing the Batch and Flow Syntheses of Metal Ammonium Phosphates: A Green Chemistry Approach. Green Chemistry. ISSN 1463-9262
- Eccles, Harry, Bond, Gary and Emmott, John David (2017) Advanced Reprocessing – The Potential for Continuous Chromatographic Separations. Journal of Chromatography and Separation Technologies, 8 (348).
- Harry , Heard, P.J., Scott, T.B. and Williams, S.J. (2016) Synthesis of carbon-13 labelled carbonaceous deposits and their evaluation for potential use as surrogates to better understand the behaviour of the carbon-14-containing deposit present in irradiated PGA graphite. Journal of Nuclear Materials, 470. pp. 268-277. ISSN 00223115

Urenco UK Ltd.

Location: Capenhurst Lane, Capenhurst, Chester CH1 6ER
LEP: Cheshire and Warrington
Managing Director Urenco UK Ltd.: Martin Pearson
Classification: Private
Ownership type: Private Company
Access model: N/A
Payment model: None, restricted.
Training requirements: N/A.
Most recent reported usage statistics: None reported
Capabilities: Urenco UK ltd. has a facility at Capenhurst that is used for uranium refinement. Uranium hexafluoride is refined to usable U-235 content for fuel production. On-site presence of Q&A facility and lab. On-site are also Urenco Chemplants to deal with tails of the refinement process and Urenco Nuclear Stewardship which works with NDA and MOD for decommissioning and recycling of civil and military uranics.

- Three enrichment plants at Capenhurst: E23 (80% of production), E22 and A3,
- Capenhurst facility accounts for 4,700 tSWA (tonnes of separative work per annum), which is approximately 25% of Urenco's global output
- Urenco Chemplants capabilities
- Urenco Nuclear stewardship capabilities

Uranium/Thorium beta/Gamma Active R&D Lab (UTGARD)

Host: Lancaster University, Lancaster, LA1 4YW
LEP: Lancashire
PI: Professor Colin Boxall
Classification: Public
Ownership type: University
Access model: National Nuclear User Facility (NNUF)
Payment model: NNUF
Training requirements: Two online modules for university - level dosimeter distribution, followed by specific on-site training provided by facility staff
Most recent reported usage statistics: (October 2017 – March 2018) 1.4% maintenance, 43.6% Lancaster University, 54.6% other universities (unspecified)
Capabilities: Process chemistry laboratory for work on beta and gamma active fission products, U, Th and alpha tracers. Funded by the UK Government Department of Energy & Climate Change in 2015, UTGARD is a national facility for the study of nuclear process chemistry, offered to external users on an open access basis through the UK National Nuclear Users' Facility.

- Alpha, beta, gamma counting facility with access to ADRIANA
- Two sets of twin 1.2 cm diameter annular centrifugal contactors;
- Positive and negative pressure glove box for inert atmosphere/dry studies and powder/alpha work respectively – with Karl Fisher titration system
- Spectroscopy capabilities include UV-vis, Raman (two instruments with hot stage and laser wavelengths of 532 and 785 nm), FT-nIR and fluorimetry
- Chromatographic capabilities include HPLC and ion chromatography
- Electrochemistry systems include, low current potentiostats, impedance spectroscopy and

electrochemical quartz crystal nanogravimetry

- Materials characterisation techniques accessible, include TGA/DTA with couple MS, SEM with EDS, XRF and AFM
- Viscometry and rotary mixers

Recent output:

- "The DISTINCTIVE University Consortium: An Overview" M. Fairweather, L. Tovey, C. Boxall, J.A. Hriljac, N.C. Hyatt, N. Kaltsoyannis, W.E. Lee, R.J. Lunn, S.M. Pimblott, D. Read, T.B. Scott in Waste Management 2018 Conference Proceedings, WM Symposia, Temple, Arizona, 2018, Paper No. 18102
- Tzagkaroulakis, Ioannis, Colin Boxall, and Divyesh Trivedi. "Real-Time Nanogravimetric Monitoring of Corrosion in Radioactive Decontamination Systems." MRS Advances 2.10 (2017): 577-582.
- Bromley, Michael A., and Colin Boxall. "The Effects of Nitric Acid on Extraction Properties of TODGA during Fission Product Management." MRS Advances 2.10 (2017): 563-568.
- Howett, Elizabeth, Colin Boxall, and David Hambley. "AGR Cladding Corrosion: Investigation of the Effect of Temperature on Unsensitized Stainless Steel." MRS Advances 2.11 (2017): 615-620.
- Laventine, D., Wilbraham, R., Boxall, C., Taylor, R., & Orr, R. "Direct mass analysis of water absorption onto ceria thin films." MRS Advances 2.12 (2017): 649-654.
- Parker, Andrew J., Malcolm J. Joyce, and Colin Boxall. "Remediation of 137Cs contaminated concrete using electrokinetic phenomena and ionic salt washes in nuclear energy contexts." Journal of hazardous materials 340 (2017): 454-462.
- "Photocatalytically driven dissolution of macroscopic nickel surfaces", R.J.Wilbraham, C.Boxall, R.J.Taylor, Corrosion Science, 131, 137-146 (2017). DOI: 10.1016/j.corsci.2017.11.018 IF = 5.3

Patents:

- "Method for Formation of Porous Metal Coatings" C. Boxall, M.A. Bromley, UK patent no. GB249483, 4-10-2017

Workington Rig Halls and Inactive demonstration Facilities

Host: National Nuclear Laboratory, Havelock Road, Workington CA14 3YQ
LEP: Cumbria
PI: Andrew Shimmin
Classification: Public
Ownership type: NNL
Access model: EPSRC
Payment model: EPSRC, Commercial pay-to-play options
Training requirements: Strict. Significant barriers present. Visitor needs to be BPSS vetted and minimum lead time on access is 10 weeks.
Most recent reported usage statistics: None reported
Capabilities: Research facility on large non-radioactive test rigs. A large, 6000m2, rig hall, with 60 tonne rated cranes, supported by engineering workshops. A further 6.4m x 6.4m x 6.0m deep pit facility with 246 m3 wet or dry pit for underwater testing or housing tall rigs up to 14m tall and is used to simulate pond or silo access. Work is done on cement encapsulation development and testing. Further work includes robotics work by the ROMANS (Robotic Manipulation for Nuclear Sort and Segregation) consortium.
Current rigs include:

- Jet Ballast: Scaled mock-up of HAST tank-pilot scale experimental test results which feed into existing HAST operational strategies
- Slurry Transport Rig: Full scale effluent transport and settling experimental work
- Sand Bed Filter Rig: Small fluid beds used to carry out experimental filtration studies on SIXEP sand bed and clinoptilolite filters
- Pu Ceramics: HIP & Plutonium Ceramics Rigs. Experimental heat treatment using small scale furnace
- Hales Coil Inspection: Testing/demonstration of inspection devices
- HOTSpot: Full liquor depth HAST replication, investigate liquor chemistry and associated corrosion rates
- Thermosyphon: Full liquor depth evaporator replication, investigate liquor chemistry and associated corrosions rates
- Small boiling rig: Design to justify CFD model for evaporator C remnant life
- Draft tube rig: Design to justify CFD model for evaporator C remnant life, but full liquor depth conditions
- Cure Cells: Ventilated heated chambers (WxDxH 3m x 3m x 3m) ; up to 50°C
- Mixers Capacities (L): 100, 250, 500, 500, 500 (in-drum mixing), 2000

APPENDIX 3

The bibliometric study appearing in this audit was conducted using the following method:

1. Searches for nuclear related publications were conducted against the Elsevier Scopus database. Only papers including at least one author from the United Kingdom were included.
2. The search query used with Scopus was:

(TITLE-ABS-KEY(nuclear) OR TITLE-ABS-KEY(fission) OR TITLE-ABS-KEY(uranium) OR TITLE-ABS-KEY(plutonium) OR TITLE-ABS-KEY(actinide) OR TITLE-ABS-KEY(radioactive)) AND AFFILCOUNTRY("United Kingdom") AND PUBYEAR = {YEAR} AND NOT (SUBJAREA(AGRI) OR SUBJAREA(ARTS) OR SUBJAREA(BIOC) OR SUBJAREA(IMMU) OR SUBJAREA(MEDI) OR SUBJAREA(NEUR) OR SUBJAREA(NURS) OR SUBJAREA(PHAR) OR SUBJAREA(HEAL))

- In the "PUBYEAR = {YEAR}" clause, the {YEAR} placeholder was replaced with years from 2006-2018. Allowing a search for each year in this range to be performed. The first year is 2006, as before this, the number of papers returned was found to be too low to be statistically significant.

- The "TITLE-ABS-KEY" search terms were used to search for the following in the title, abstract or keywords belonging to a publication:
  - o nuclear
  - o fission
  - o uranium
  - o plutonium
  - o actinide
  - o radioactive

- Results were excluded from the following subject areas (SUBJAREA) as the nuclear keyword in particular leads to an excessively large number of irrelevant search results:
  - o AGRI: Agricultural and biological sciences
  - o ARTS: Arts and humanities
  - o BIOC: Biochemistry and genetics
  - o IMMU: Immunology
  - o MEDI: Medicine
  - o NEUR: Neuroscience
  - o NURS: Nursing
  - o PHAR: Pharmacology, toxicology and pharmaceuticals
  - o HEAL: Health professions.

3. The search results from these queries were then hand checked for false positive matches which were removed from the dataset.
4. The papers were then hand-classified according to the NIRAB classifications defined earlier.
5. The location (latitude and longitude) of each unique author affiliation was determined and checked.
6. A number of affiliations were found to have been mis-classified as being in the UK in the Scopus database (particularly a number from the Ukraine). Every affiliation was re-assigned to a country by checking against all the World's country boundaries (including coastal boundaries)[1], any papers that then didn't have any UK authors were removed at this point.
7. UK author locations were further categorised as being inside or outside the audited region. The audited region was defined as the intersection of several enterprise partnerships (see introduction for more information) and the North Wales Economic Ambition Board. For this purpose shapefiles from the Office for National Statistics Open Geography Portal were used[2].

[1]Country outlines from the following database were used: "Marine and land zones: the union of world country boundaries and EEZ's – version 2, 2014" downloaded from http://www.marineregions.org on 29th April 2018. This contains data provided by the Flanders Marine Institute.
[2]Contains National Statistics data © Crown copyright and database right 2014 and Contains OS data © Crown copyright and database right 2014.

APPENDIX 4

Table of EPSRC project titles that are represented in Figure 15 in the audit.

Key	ESPRC Grant Reference	Title
1	EP/M018709/1	Smart on-line monitoring for nuclear power plants (SMART)
2	EP/M01858X/1	Radiation Damage in Nanoporous Nuclear Materials
3	EP/R012474/1	Reducing Risk through Uncertainty Quantification for Past, Present and Future Generations of Nuclear Power Plant
4	EP/R005850/1	Innovative LWR Simulation Tool for the Nuclear Renaissance in the UK
5	EP/M018105/1	From Processing to Simulated In-Reactor Performance of Zr Cladding.
6	EP/P027962/1	Radiation effects and differential damage in binary carbide hybrids
7	EP/M018415/1	SMART
8	EP/R013136/1	MAINTAiN - Multi-scAle INTegrity assessment for Advanced high-temperature Nuclear systems
9	EP/R001618/1	Feasibility of the use of frozen walls in molten salt fast reactors (MSFR-FW)
10	EP/N017870/1	Glass-Ceramic Wasteforms for High Level Wastes from Advanced Nuclear Fuel Reprocessing
11	EP/M018792/1	Glass-Ceramics: Damaging Bubble Formation
12	EP/M026558/1	Silicate Nanoparticles for Extraction of Radionuclides (SINNER)
13	EP/N017374/1	Critical Analysis of Spent Fuel Structure in Radionuclide Release
14	EP/P013171/1	Predicting long-term performance of cement disposal systems for radionuclide-loaded zeolite and titanate ion exchangers
15	EP/N017684/1	Development of solidification techniques with minimised water content for safe storage of secondary radioactive aqueous wastes in Fukushima
16	EP/R006075/1	Simulated Used Nuclear Fuel Dissolution as a Function of Fuel Chemistry and Near Field Conditions
17	EP/N508494/1	Innovative Forging and Fabrication Solutions for the Energy Sector
18	EP/M026566/1	Advanced Waste Management Strategies for Technetium and Iodine in the Nuclear Fuel Cycle
19	EP/R01924X/1	CHaracterisation, Imaging and MaPping of fuel debris for safe retrieval (CHIMP)
20	EP/P017487/1	Robust remote sensing for multi-modal characterisation in nuclear and other extreme environments
21	EP/R001499/1	Three Dimensional Optical Imaging of Neptunium Redox Speciation-A Feasibility Study
22	EP/R019223/1	Developing Innovative Radiation Measurement Technologies for Decommissioning
23	EP/P034101/1	Novel intensified liquid-liquid contactors for mass transfer in sustainable energy generation.
24	EP/N017641/1	An ultrasonic measurement system and its robotic deployment into vessels for the combined assessment of debris condition and water leakage
25	EP/R013136/1	MAINTAiN - Multi-scAle INTegrity assessment for Advanced high-temperature Nuclear systems
26	EP/R012423/1	Reducing risk through uncertainty quantification for past, present and future generations of nuclear power plants

27	EP/M019446/1	Advanced structural analysis for the UK nuclear renaissance
28	EP/P01366X/1	Robotics for Nuclear Environments
29	EP/N016351/1	Creep and Creep-Fatigue Crack Growth Mechanisms in Alloy 709
30	EP/P034446/1	Structural integrity characterisation of nuclear materials via nano additive manufacturing
31	EP/M018598/1	UNIGRAF: Understanding and improving graphite for nuclear fission
32	EP/L015390/1	EPSRC Centre for Doctoral Training (CDT) in Nuclear Fission- Next Generation Nuclear
33	EP/M018237/1	Corrosion and hydrogen pick-up mechanisms in zirconium nuclear fuel cladding alloys in active environments
34	EP/R006245/1	RADIATION RESISTANT HIGH ENTROPY ALLOYS FOR FAST REACTOR CLADDING APPLICATIONS
35	EP/P003591/1	Linking Microstructure to Neutron Irradiation Defects in Advanced Manufacture of Steels
36	EP/N017110/1	SiC fuel cladding: Macroscopic effects of radiation on mechanical and thermal properties from microstructural-scale characterisation and modelling
37	EP/M018679/1	UNIGRAF: Understanding and Improving Graphite for Advanced nuclear Fission
38	EP/P004458/1	The UK National Nuclear User Facilites Working Group
39	EP/R013136/1	MAINTAiN - Multi-scAle INTegrity assessment for Advanced high-temperature Nuclear systems
40	EP/M017540/1	Effect of Zr on the microstructure of corrosion resistant ODS steels
41	EP/N004493/1	An innovative, multi-scale, real-time approach to the understanding of deformation and fracture in irradiated nuclear reactor core graphites
42	EP/R009392/1	Understanding the mechanisms controlling low potential stress corrosion cracking in nuclear reactors
43	EP/N017854/1	Modeling and Validation of Irradiation Damage in Ni-based Alloys for Long-Term LWR Applications (US/UK)
44	EP/N00700X/1	Research on Nuclear Data measurements and evaluations for nuclear fission energy.
45	EP/R005745/1	Mechanisms of Retention and Transport of Fission Products in Virgin and Irradiated Nuclear Graphite
46	EP/P003591/1	Linking Microstructure to Neutron Irradiation Defects in Advanced Manufacture of Steels
47	EP/R012423/1	Reducing risk through uncertainty quantification for past, present and future generations of nuclear power plants
48	EP/R000956/1	Silicide-Strengthened Steel - A New Method of Wear Protection within Nuclear Environments
49	EP/R005729/1	Generalised high-order Eulerian Smoothed Particle Hydrodynamics for internal flows applied to flow-induced vibration and nuclear tube banks
50	EP/R010269/1	Multi-scAle INTegrity assessment for Advanced high-temperature Nuclear systems
51	EP/M018482/1	Carbides for Future Fission Environments (CAFFE)
52	EP/M018105/1	From Processing to Simulated In-Reactor Performance of Zr Cladding.

53	EP/L018616/1	PACIFIC - Providing a Nuclear Fuel Cycle in the UK for Implementing Carbon Reductions
54	EP/N017749/1	Technology development to evaluate dose rate distribution in PCV and to search for fuel debris submerged in water
55	EP/P018505/1	TORONE - TOtal characterisation for Remote Observation in Nuclear Environments
56	EP/R005974/1	Defect dynamics in energy materials
57	EP/I037644/1	Nuclear Universities Consortium for Learning, Engagement And Research: NUCLEAR
58	EP/L014041/1	Decommissioning, Immobilisation and Storage soluTIons for NuClear wasTe InVEntories (DISTINCTIVE)
59	EP/M018814/1	Understanding the In-Reactor Performance of Advanced Ceramic Cladding Materials
60	EP/M018482/1	Carbides for Future Fission Environments (CAFFE)
61	EP/R029113/1	AGR Technologies for Enabling Molten Salt-cooled Reactor Designs
62	EP/M018296/1	Indo-UK Civil Nuclear Network
63	EP/P013600/1	JUNO: A Network for Japan - UK Nuclear Opportunities
64	EP/M018733/1	Grace Time
65	EP/R001138/1	Development of Novel Treatments for Carbon-based radioactive wastes
66	EP/M01858X/1	Radiation Damage in Nanoporous Nuclear Materials
67	EP/M018709/1	Smart on-line monitoring for nuclear power plants (SMART)
68	EP/P003591/1	Linking Microstructure to Neutron Irradiation Defects in Advanced Manufacture of Steels
69	EP/M018261/1	Indo - UK: Premature, Oscillation-Induced Critical Heat Flux ("Premature OICHF")
70	EP/M018482/1	Carbides for Future Fission Environments (CAFFE)
71	EP/P013198/1	Investigation of the safe removal of fuel debris: multi-physics simulation
72	EP/L015900/1	EPSRC Centre for Doctoral Training in Nuclear Energy: Building UK Civil Nuclear Skills for Global Markets.
73	EP/R004870/1	Modelling of glasses as nuclear waste forms
74	EP/M022684/2	Predictive Modelling for Nuclear Engineering
75	EP/R005745/1	Mechanisms of Retention and Transport of Fission Products in Virgin and Irradiated Nuclear Graphite
76	EP/M018598/1	UNIGRAF: Understanding and improving graphite for nuclear fission
77	EP/M018210/1	Design and Maintenance of Nuclear Safety Systems for Life Extension (DaMSSLE)