FIRST EDITION

NIRO NUCLEAR INNOVATION AND RESEARCH OFFICE

Department for Business, Energy & Industrial Strategy

BEIS Nuclear Innovation Programme Summary Brochure

This brochure is optimised for online viewing, where each page contains links to websites and publications providing more information to that presented on the following pages.

It is recommended you access the online version which can be found at https://www.nirab.org.uk/useful-links or via the QR code below.

Ministerial Foreword

To achieve our clean growth ambitions by 2050 we need to facilitate delivery of the UK's net zero commitments. No single technology will accomplish this, but we can succeed in this endeavour by backing innovation. Innovation is a key driver for reducing the cost of clean technologies and crucial to transforming the UK energy system.

A range of technologies is important in tackling climate change and diversifying our supply, contributing to the UK's energy security and growth. This is why we're embracing the safe, clean, affordable new generation of nuclear reactors. Nuclear power is, and will continue to be, a key part of our low-carbon energy mix.

The Ten Point Plan for a Green Industrial Revolution set out how we are pursuing large-scale nuclear, whilst also looking to the future of nuclear power in the UK through further investment in Small Modular Reactors and Advanced Modular Reactors.

The Government's support for Nuclear Innovation has contributed to substantial successes.

We made our commitment to the UK nuclear sector absolutely clear in the British Energy Security Strategy and are seeking to deploy up to 24GW of nuclear power by 2050, three times more than now. Investing in the future generation of nuclear technology is paramount to making this happen. The trailblazing innovation programmes represented in this brochure highlight the incredible achievements we have made to date and will spearhead a British nuclear renaissance.

Greg Hands

Minister of State
Department for Business, Energy and Industrial Strategy

Nuclear Innovation Programme Background and Overview

In 2015 the UK Government committed to invest up to £505 million in an ambitious research and development programme named the Energy Innovation Programme (EIP) to bring technologies towards commercialisation. The Programme aimed to support innovation that would deliver cost-effective solutions contributing to a decarbonised energy supply, economic growth, and jobs in the UK energy sector and its supply chain.

The Nuclear Innovation Programme (NIP) formed part of EIP, running from 2016 to 2021 the NIP set out to further the UK's civil nuclear energy objectives. This brochure brings together all the projects funded through the NIP providing an insight into the areas of work undertaken and how technology and innovation in the nuclear sector has been enhanced by the programme.

The NIP programme was designed to align with the recommendations made by the Nuclear Innovation and Research Advisory Board (NIRAB), a board established by the Government in 2014 to advise on nuclear innovation and research. The high level objectives of the NIP were:

1. To deliver an ambitious nuclear R&D programme, including a process to identify and support modular reactor technology options that could offer significant value to the UK.
2. To reinvigorate the capability, capacity, and credibility of the UK Nuclear R&D landscape, focusing on key areas of historical strength and future opportunity.
3. To explore and develop the potential for innovation to reduce the cost of nuclear deployment and operation for both near and long-term technologies.

Launched in 2016, the NIP was due to complete at the end of the 2020-2021 Financial Year (FY) however the impact of COVID-19 throughout 2020 and 2021 led to several of the active contracts having extensions granted into the 2021-2022 financial year to allow completion of their projects. Over the course of the programme there has been a greater emphasis on the delivery of facilities and demonstrators that can make a meaningful impact on Net Zero.

The brochure is prepared so that each sub programme is introduced and then a page is presented on each project within the sub-programme. These pages have been produced by the lead organisation of each project and are designed to provide an overview of the project including project outcomes and next steps. Each page also has links embedded within to publications, organisations websites and other additional information shared by the projects.

The following infographics highlight the geographical reach of the programme, organisations engaged and publications resulting from this programme. Selected highlights provide some examples of the research and innovation undertaken and the impact of this.

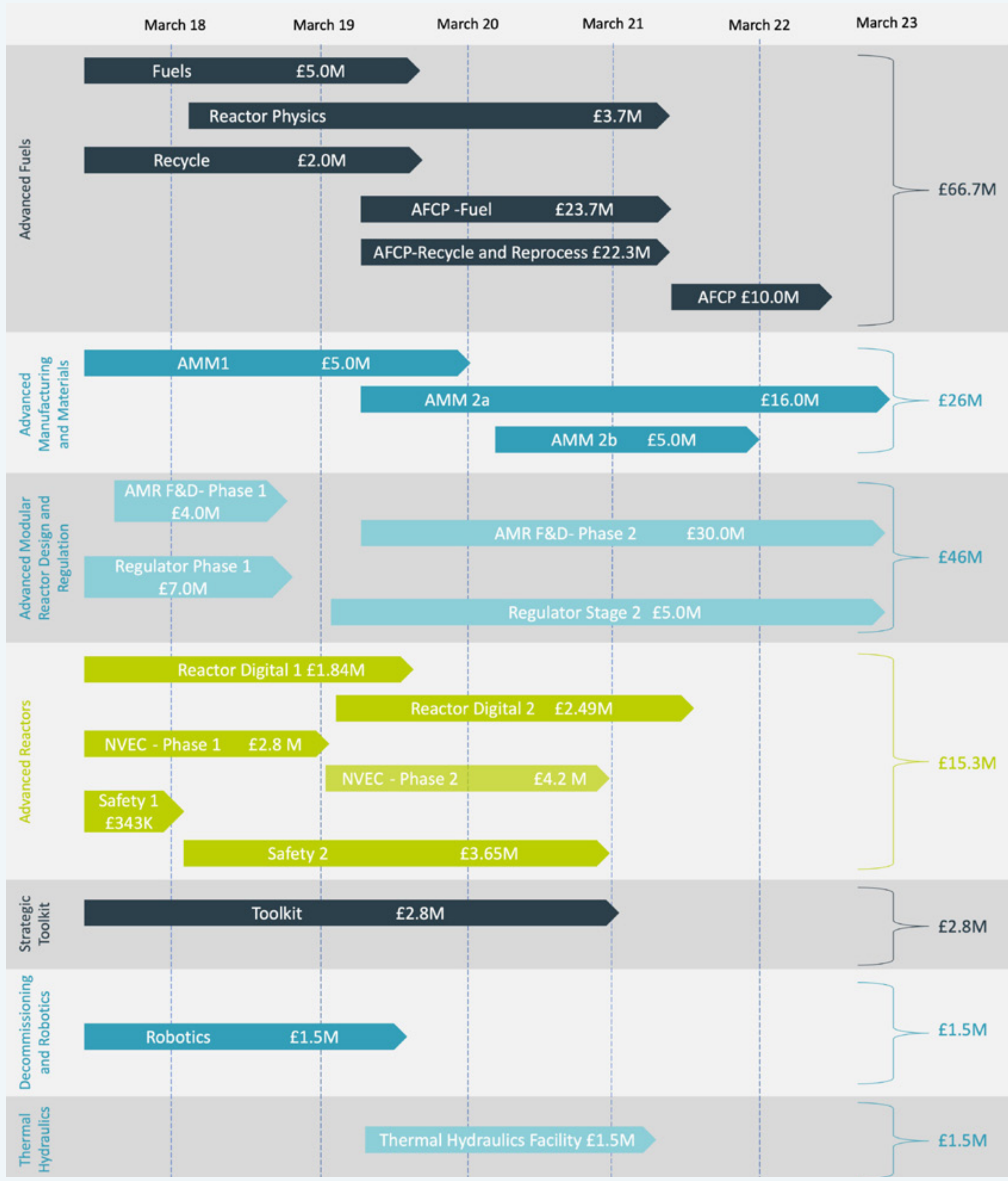
Dan Mathers

Executive Director
Nuclear Innovation and Research Office (NIRO)

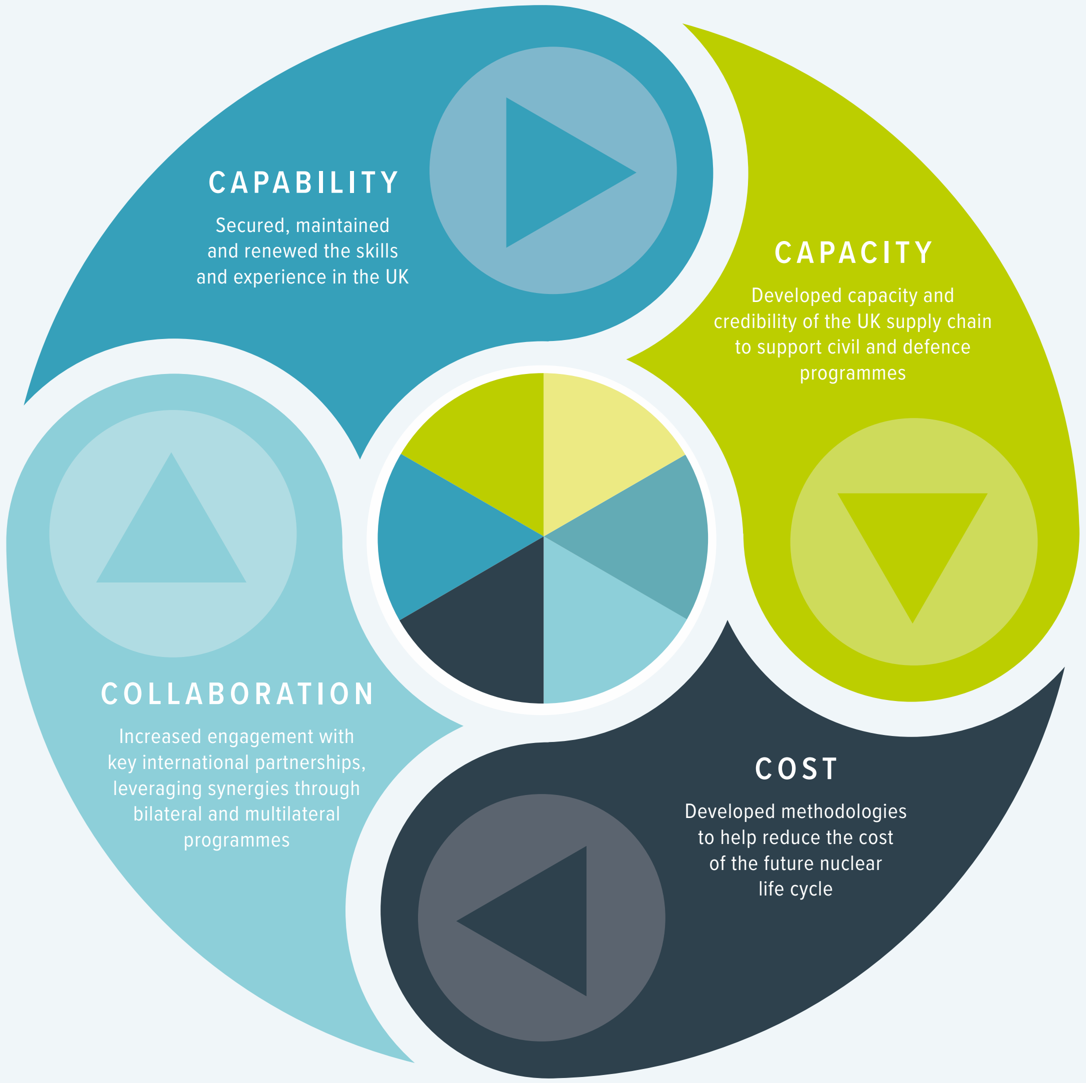
The Nuclear Innovation Programme is made up of the following sub-programmes:

1) Advanced Fuels, 2) Advanced Manufacturing and Materials, 3) Advanced Modular Reactor Design and Regulation, 4) Advanced Reactors, 5) Strategic Toolkits, 6) Decommissioning & Robotics, 7) Thermal Hydraulics.

The graphic below provides an overview of these sub-programmes within the Nuclear Innovation Programme alongside their durations and funding.



NIP Impact



118	27	3	4	156
Organisations	Universities (20 UK Universities)	UK National Laboratories	International Laboratories	Publications

This map provides an overview of the spread of UK organisations involved in the Nuclear Innovation Programme, demonstrating the involvement of organisations across the length and breadth of our shores.

Selected highlights of the Nuclear Innovation Programme

Coordinated a UK group with input to international irradiation programmes including Halden and Jules Horowitz Reactor along with UK engagement in Nuclear Energy Agency Working Groups.

Enabled a small SME new to the sector, to create a unique large scale (m^3 volume) metal additive manufacturing system, including ultra-modern UK developed power ultrasonics (making very challenging materials more workable) and real-time (layer by layer) quality assurance capability.

Defined and clarified a path through safety case and security case production and licensing for vendors of new nuclear plant.

Delivered an Advanced Modular Reactor mock-up in a short period from initial concept, through to design, manufacture and assembly demonstrating the nuclear sectors ability to deliver critical projects on time and budget.

Demonstrated that new nanostructured steels (NSSs) can mitigate material degradation and enhance operation under combined high temperature, corrosive and high irradiation environments.

Developed eight state of the art test facilities to support Lead Fast Reactor development, including a state-of-the-art facility for materials corrosion testing capable of reaching 800°C in flowing liquid lead enabling collection of valuable experimental data on prototypical materials and components/systems.

Established through the National Nuclear Laboratory, the UK's first International Atomic Energy Agency (IAEA) Collaborating Centre, creating a global hub of expertise in the nuclear fuel cycle.

Identified the developments required in Nuclear Power Plant Design Codes and Standards, for new Small Modular Reactor and Advanced Modular Reactor designs to satisfy UK regulation.

Progressed technologies enabling significant time and cost savings when manufacturing key nuclear components, such as Electron Beam Welding, which can drastically reduce the time over traditional welding techniques of pressure vessels from months to weeks.

Influenced new guidance on the early integration of security objectives of skills development within the design of nuclear facilities.

Transformed the UK's Nuclear Thermal Hydraulics Computational Fluid Dynamic modelling capability for Advanced Modular Reactors, particularly for liquid metals and molten salts technologies.

Through the Advanced Fuel Cycle Programme alone, supported 95 PHD's and PostDocs with more than £10.3M investment in UK academic institutions and 60% of supply chain investment supporting SMEs, while using 20 facilities and generating 10 new capabilities in the UK, including 4 new capabilities with the Nuclear Fuel Centre of Excellence, extending advanced fuel expertise.

Funded the development of a Nuclear Virtual Engineering Capability (NVEC) and developed tools for facilities to be 'Secure by Design', defined and accepted by World Institute of Nuclear Security.

Contents

Page 13

FUELS AND RECYCLE OVERVIEW

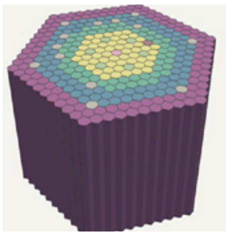
Page 14

Advanced Fuel Cycle Programme (AFCP)
Advanced Nuclear Fuels
Lead: National Nuclear Laboratory

Page 15

Advanced Fuel Cycle Programme (AFCP)
Advanced Recycling and Sustainability
Lead: National Nuclear Laboratory

Page 16

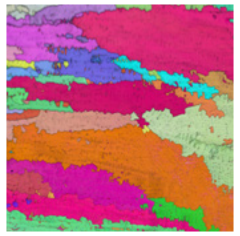


Reactor Physics
Lead: National Nuclear Laboratory

Page 17

ADVANCED MANUFACTURING AND MATERIALS OVERVIEW

Page 18



Project FORCE Advanced Manufacturing and Materials
Lead: Frazer-Nash Consultancy

Page 19

Single Manufacturing Platform Environment (SIMPLE)
Lead: Nuclear AMRC

Page 20

Intelligent Fixtures for Optimised and Radical Manufacture (InFORM)
Lead: Nuclear AMRC

Page 21

NPP Design Codes and Standards for the UK
Lead: Jacobs

Page 22

Materials/Manufacturing Technology Evaluation for Advanced Reactors (MATTEAR)
Lead: Jacobs

Page 23

NanoStructured Steels to Extend Operational Performance for Nuclear Reactors
Lead: The University of Sheffield

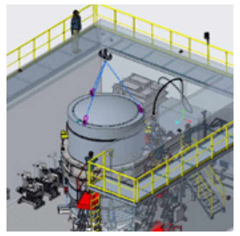
Page 24

Project Faith
(Fuel Assembly Incorporating Thermal Hydraulics)
Lead: Cammell Laird

Page 25

Future Advanced Structural Technologies
Lead: Rolls-Royce PLC

Page 26

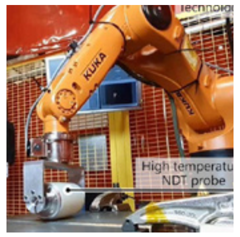


The Industrialisation of Thick Section Electron Beam Welding for the Nuclear Industry
Lead: Sheffield Forgemasters

Page 27

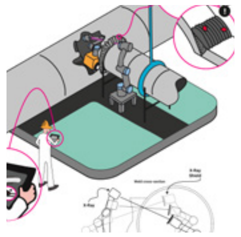
Establishing AMR Structural Integrity Codes and Standards for UK GDA (EASICS) Project
Lead: EDF Nuclear Generation Ltd.

Page 28



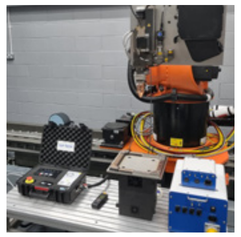
AWESIM Automated Welding Equipment
System Inspection and Monitoring
Lead: Cavendish Nuclear

Page 29



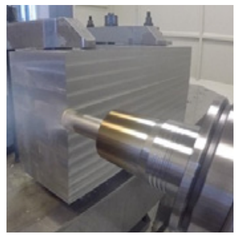
Mobile Weld radiography using Computed Tomography (MW-CT)
Lead: Createc

Page 30



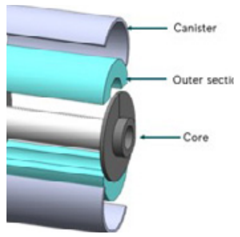
SonicSMR – Ultrasonic enabled Laser Additive Manufacturing with in-line Inspection
Lead: Laser Additive Solutions

Page 31



Process Improvement Through CO2 Cooling - PITCO2C
Evaluating the combined coolant and lubrication characteristics of supercritical CO2 (scCO2) + Minimal Quantity Lubricant (MQL) Lead: Nuclear Energy Components

Page 32



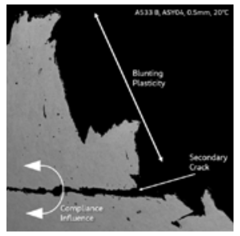
Sensing Advanced Structures
Lead: Rolls-Royce PLC

Contents

Page 33

Advanced Manufacture & Materials (AMM) U-Battery Advanced Modular Reactor HTGR:Full Scale Demonstrator.
Lead: Urenco

Page 34



Evaluation Technologies for Advanced Manufacturing Qualification (ETAMQ)
Lead: Jacobs

Page 35

ADVANCED MODULAR REACTOR (FEASIBILITY AND DEVELOPMENT AND REGULATOR CAPACITY) OVERVIEW

Page 36

AMR - Feasibility and Development Studies (Phase 1)

Page 37

Advanced Modular Reactor Phase 2
U-Battery High Temperature Gas Reactor
Lead: Urenco

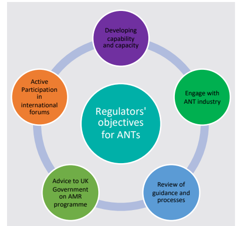
Page 38

Lead: Westinghouse Fast Reactor

Page 39

Tokamak Energy- Advanced Modular Reactor Fusion Project

Page 40

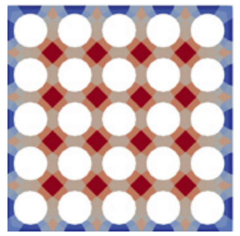


Preparing for Regulating Advanced Nuclear Technologies (ANTs). The Office for Nuclear Regulation (ONR) and Environment Agency (EA)

Page 41

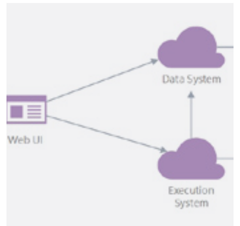
ADVANCED REACTORS OVERVIEW

Page 42



Advanced reactor thermal hydraulics
model development
Lead: Frazer-Nash Consultancy

Page 43



Nuclear Virtual Engineering Capability
Lead: Jacobs

Page 44

Reactor Design: Safety & Security Research and Development Programme
Lead: Frazer-Nash Consultancy

Page 45

STRATEGIC TOOLKITS OVERVIEW

Page 46

Strategic Toolkit and Nuclear Facilities
Lead: National Nuclear Laboratory

Page 47

DECOMMISSIONING ROBOTICS OVERVIEW

Page 48

Integrated Innovation in Nuclear Decommissioning (IINDe)
Lead: Innovate UK and Nuclear Decommissioning Authority (NDA)

Page 49

THERMAL HYDRAULICS FACILITY OVERVIEW

Page 50

Thermal Hydraulics Test Facility Concept Design
Lead Company: UKAEA

Fuels and Recycle Overview

Advanced Fuels Programme - £8.7m

The Advanced Fuels Programme aimed to develop advanced nuclear fuels in the UK that are more efficient and safer for current and future reactors, and that retains an indigenous fuel manufacturing capacity in the UK. Phase 1 (£5.0m, April 2017 to September 2019) covered accident tolerant fuels (ATF), coated particle fuels (CPF), plutonium-based fuels, reactor physics modelling and nuclear data.

Phase 2 (£3.7m, April 18-Septemer 21) focused on CPF and reactor physics.

Both Phases of work were delivered by the National Nuclear Laboratory.

Recycle and Reprocess Programme - £2.0m

The Recycle and Reprocess Programme was a one phase programme focused on Light Water Reactor fuels with fast reactor dual recycling and waste management. This Phase was delivered by the National Nuclear Laboratory from April 2017 to September 2019.

Advanced Fuel Cycle Programme (AFCP) - £56m

The AFCP combined Advanced Fuels (£23.7m) and Recycle and Reprocess (£22.3m) were a follow on to the two previous programmes. Its objectives were to develop skills, knowledge, and capabilities in the areas of advanced fuels and recycle and waste management, through development of new technologies, processes and intellectual property, that can contribute towards a reduction in the whole lifecycle costs of nuclear energy.

Building on previous programme phases, 11 projects have been funded across three fuels and several reprocessing and waste areas, including accident tolerant fuels, aqueous reprocessing, coated particle fuel, fast recycle, nuclear data, and core facilities and personnel required to support advanced fuel cycle.

A further £10M phase focused on nearer term advanced fuels as well as continuing the wider work from earlier in the programme.

Advanced Fuel Cycle Programme (AFCP)
Advanced Nuclear Fuels
Lead: National Nuclear Laboratory

Project background

AFCP is the largest UK public sector investment in future fuel cycle R&D for a generation. AFCP was established to support Net Zero through integrated fuels and recycle innovation. By developing capability and capacity, AFCP aims to deliver significant economic, environmental and international impact for the UK. For the advanced fuels element of the programme, the technical mission is to develop fuels for current and future reactors to secure long-term indigenous fuel manufacture in the UK. AFCP has incorporated work on near-term advanced technology fuels (ATF) for light water reactors (LWR), coated particle fuels (CPF) for high temperature reactors (HTR) and fast reactor fuels (FRF). AFCP has focused on developing near-term, commercially viable ATF products alongside advanced fuels for future reactors that could be deployed in the UK and internationally.

AFCP worked with more than 90 UK organisations

AFCP covered eleven technical themes, with the advanced fuel covering four areas

AFCP has enabled NNL and the UK to re-establish the capability to produce uranium active kernels for coated particle fuels using casting technology and process.

Investment in AFCP has enabled technology development across all areas of the programme. Where a TRL level has not increased we have seen significant UK capability enhancement.

Organisations involved (Click on logo to view website)

National Nuclear Laboratory, Imperial College London, NPL National Physical Laboratory, JAEA, University of Birmingham, Sheffield Hallam University, Prifysgol Bangor University, Wissen Technology, Manchester 1824 The University of Manchester, Catapult Energy Systems, Lucid Catalyst, Westinghouse, Teer Coatings, Henry Royce Institute, Lucideon, National Composites Centre, Lancaster University, University of Cambridge, University of Bristol, Jacobs, The University of Sheffield, Sellafield Ltd, Manchester Metropolitan University

Technology next steps

Deliver an accelerated pathway to a UK manufacturing capability for CPF in time for the deployment of a high temperature AMR demonstrator.
Produce UK-developed ATF coated cladding lead test rods (LTRs) available for irradiation in a commercial LWR. This will be done using the full-scale coating capability developed under AFCP by a UK SME. The testing and characterisation of coated cladding will support licensing of ATF technology in future UK reactors.
Develop advanced high density (e.g. uranium nitride) fuel manufacturing capability in the UK with applicability across reactor types, including large and small modular Light Water Reactor (LWR) and fast spectrum Advanced Modular Reactor (AMR). Enable future manufacturing capability for FRF in the UK, which will demonstrate an integrated approach by recycling used fuel to produce new AMR fuel.

Key outcomes from project

Impactful innovation: Developing options that promote sustainability and de-risk deployment of advanced nuclear technology. First irradiation testing of a UK-developed ATF concept in the Massachusetts Institute of Technology (MIT) reactor.

Capability and skills: Designed, installed, and commissioned a UK facility to manufacture the first fast reactor MOx pellet in a generation. Developed people, expertise, and equipment, to manufacture and characterise active CPF fuel kernels in the UK for future High Temperature Gas Reactors (HTGRs)

International influence: UK contribution to Generation IV International Forum (GIF) in fast reactor fuels for the first time in over a decade. Establishment of NNL as the UK's first International Atomic Energy Agency (IAEA) Collaborating Centre, marking the first worldwide IAEA centre dedicated to advanced fuel cycles. Building on international co-operations in ATF (e.g. Westinghouse), CPF (e.g. Japan Atomic Energy Agency), FRF (e.g. (GIF) and nuclear data development (e.g. OECD-Nuclear Energy Agency (NEA)).

Commercial potential: UK Small to Medium Enterprise (SME) Teer Coatings developed full-scale coating system that is being taken forward by fuel vendor.

Other key project information

Phase 1 Investment BEIS: £5,000,000 Match Funding: N/A	**Phase 1** Project Start Date: April 2017 Completion Date: September 2019
Phase 2 Investment BEIS: £23,700,000 Match Funding: N/A	**Phase 2** Project Start Date: August 2019 Completion Date: September 2021
Phase 3 Investment BEIS: £9,000,000 Match Funding: N/A	**Phase 3** Project Start Date: October 2021 Completion Date: September 2022

Interaction with other NIP projects and more broader links to R&D programmes/collaboration:
- Engaged with all other NIP projects.
- Leveraged over £130 million in international programmes
- Working with more than 25 organisations across 11 countries. Significant influence in multi-lateral programmes with IAEA, OECD-NEA, GIF and EU Horizon projects.

AFCP as a whole has:
- Worked with more than 90 UK organisations
- Supported over 90 PhDs and post-docs
- Delivered work in more than 20 UK facilities and delivered 10 new UK capabilities
- Over 100 publications, presentations and peer reviewed journal papers
- Supported significant TRL increase across advanced fuels and fuel cycle

Key reports / presentations

Programme website

Advanced nuclear fuel cycle roadmaps

Key websites

Programme website: afcp.nnl.co.uk/

Key project contact:

Name: Paul Nevitt
Email: paul.nevitt@uknnl.com
Tel: +44 (0) 1925 933 705

Advanced Fuel Cycle Programme (AFCP) Advanced Recycling and Sustainability Lead: National Nuclear Laboratory

Project background

AFCP is the largest UK public sector investment in future nuclear fuel cycle R&D for a generation. AFCP was established to support Net Zero through integrated fuels and recycle innovation. By developing capability and capacity, AFCP aims to deliver significant economic, environmental and international impact for the UK. For the recycle element of the programme, the technical mission is to provide credible technical options for advanced reprocessing of spent fuels (including elements of aqueous and pyro-processing). By 2030, these advanced options aim to be competitive with the other fuel cycle options available to decision makers. AFCP has proposed that this can be achieved by developing a "21st Century" separation process to reach Technology Readiness Level (TRL) 6 (marking the completion of technology demonstration at an appropriate scale under realistic conditions with realistic materials).

Organisations involved (Click on logo to view website)

National Nuclear Laboratory, Lucideon, GRI, Frazer-Nash Consultancy, University of Bristol, University of Cambridge, Lancaster University, Northumbria University Newcastle, University of Leeds, Manchester 1824 The University of Manchester, University of Strathclyde, orano, Sellafield Ltd, C-Tech Innovation, Britest, University of Birmingham, The University of Edinburgh, University of Liverpool, The University of Sheffield, Sheffield Hallam University

Key outcomes from project

Impactful innovation: Developing options that promote sustainability and de-risk deployment of advanced nuclear technology. Flexible, advanced processes that reduce costs, wastes and add proliferation barriers.

Capability and skills: Maintaining unique, internationally-recognised UK fuel cycle skills and building new capabilities and wider UK networks. Capturing valuable UK historic fuel cycle experience, including information capture from the UK's historic fuel reprocessing programmes.

International influence: Delivering on international collaborations and extending UK influence. Enabling UK to be a 'top table' nuclear fuel cycle nation. Establishment of NNL as the UK's first International Atomic Energy Agency (IAEA) Collaborating Centre, marking the first worldwide IAEA centre dedicated to advanced fuel cycles.

Future planning: World-leading and unique experimental data generated in active laboratories. Using existing and new tools (e.g. Sim Plant, ORION, Life Cycle Analysis (LCA)) to evaluate fuel cycle options. Understanding benefits & costs of different nuclear pathways & fuel cycle options.

Key reports / presentations

Programme website

Advanced nuclear fuel cycle roadmaps

Key websites

Programme website: afcp.nnl.co.uk/

AFCP worked with more than 90 UK organisations

AFCP covered eleven technical themes, with the recycle and sustainability areas covering seven areas

Overview of technical fuel recycle process

Series of flowsheet rig trials in unique facility raising TRL of advanced aqueous separations to TRL 4

Investment in AFCP has enabled technology development across all areas of the programme. Where a TRL level has not increased we have seen significant UK capability enhancement.

Technology next steps

Develop advanced fuel recycle processes to support the long-term sustainability of Light Water Reactor (LWR) and Advanced Modular Reactor (AMR) fuel cycles. This will be done by using insight gained from Sim Plant, the modelling tool that AFCP has developed for digitally simulating a future fuel recycle factory.

Further reduce future recycle plant size with a focus on sustainability, proliferation resistance and economics. This will be supported by the development of process flowsheets and testing capabilities.

Develop the framework for the strategic assessment of future fuel cycle options. This will be done through economic and environmental (life cycle) modelling with the aim to demonstrate critical stages of the UK's development of advanced fuel recycle and production process for LWR and AMR.

Other key project information

Phase 1 Investment BEIS: £2,000,000 Match Funding: N/A	**Phase 1** Project Start Date: April 2017 Completion Date: September 2019
Phase 2 Investment BEIS: £22,300,000 Match Funding: N/A	**Phase 2** Project Start Date: August 2019 Completion Date: September 2021
Phase 3 Investment BEIS: £1,000,000 Match Funding: N/A	**Phase 3** Project Start Date: October 2021 Completion Date: September 2022

Interaction with other NIP projects and more broader links to R&D programmes/collaboration:
- Engaged with all other NIP projects.
- Leveraged over £130 million in international programmes
- Working with more than 25 organisations across 11 countries. Significant influence in multi-lateral programmes with IAEA, OECD-Nuclear Energy Agency (NEA), Generation IV International Forum (GIF) and EU Horizon projects.

AFCP as a whole has:
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- Supported over 90 PhDs and post-docs
- Delivered work in more than 20 UK facilities and delivered 10 new UK capabilities
- Over 100 publications, presentations and peer reviewed journal papers
- Supported significant TRL increase across advanced fuels and fuel cycle

Key project contact:

Name: Paul Nevitt
Email: paul.nevitt@uknnl.com
Tel: +44 (0) 1925 933 705

Reactor Physics Lead: National Nuclear Laboratory

Project background

The primary aim of the Reactor Physics project was to develop the UK neutronics, fuel performance and thermal-hydraulics modelling capability (validated computer codes, developers and users). The focus was on Light Water Reactor (LWR), High-Temperature Gas-cooled Reactor (HTGR) and Lead-Metal-cooled Fast Reactor (LMFR) applications. Such a capability is needed to design UK advanced fuels, to determine their behaviour in current and future reactors, and to qualify them for commercial use. This is part of a broader vision to develop an independent and authoritative UK capability for integrated modelling of the reactor physics of any existing or future UK reactor type.

The research activities included coupling fuel performance and reactor physics codes; modelling advanced fuels under normal operation and accident conditions, including coupling fuel performance and whole plant performance via a multi-physics approach; higher fidelity neutronic calculations; augmenting existing UK codes to accurately model heat transfer in HTGRs; and understanding the work required to adapt the UK code system for reactor physics analysis of LMFRs.

Organisations involved (Click on logo to view website)

Project partners:

National Nuclear Laboratory, Jacobs, University of Liverpool, Manchester 1824 The University of Manchester, University of Cambridge, Imperial College London, EDF

Supporting organisations:

UPC, NC State, N.IN.E.

Key outcomes from project

Innovation: Novel Fortran-C-Python interface used to facilitate code coupling between UK WIMS reactor physics codes and UK fuel performance codes ENIGMA (for LWRs) and TRAFIC (for LMFRs). New advanced fuel performance capability developed in ENIGMA, which was introduced into a new LWR multi-physics calculation scheme for accident analysis. Novel multi-scale thermal-hydraulics approach adopted for HTGR temperature and coolant flow calculations. Two whole-core high-fidelity neutronics methods introduced into the WIMS code.

Capability and skills: Developed people, expertise and software for LWR, HTGR and LMFR reactor physics modelling. Facilitated by access to international code repositories, cross-organisation code usage, and training and support from international experts (UPC, N.IN.E. and NCSU).

International collaborations: The Reactor Physics project supported or leveraged a number of international research projects, including the OECD Halden Reactor Project and the EU Horizon 2020 projects ESFR-SMART and GEMINI+. In addition, project partners participated in international benchmarking exercises under the framework of the OECD Nuclear Energy Agency (NEA).

Key reports / presentations


Development of an equilibrium loading pattern and whole-core fuel performance assessment in the Advanced Boiling Water Reactor (ABWR) with UO2 and U3Si2 fuels (Progress in Nuclear Energy)

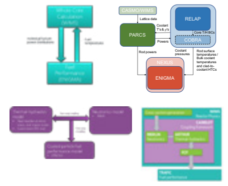

Whole core coupling methodologies within WIMS (PHYSOR2020)


Multi-physics framework for whole-core analysis of transient fuel performance after load following in a pressurised water reactor

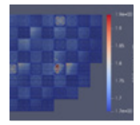
Key websites

Programme website: afcp.nnl.co.uk/

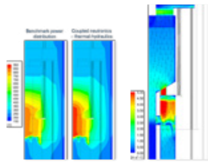
A number of different computer code systems were developed in the Reactor Physics project for LWR (top), HTGR (bottom left) and LMFR (bottom right) applications



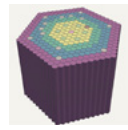
The new LWR capability has been demonstrated by simulating an uncontrolled rod withdrawal accident in the Zion PWR; predictions of stress-corrosion cracking (SCC) clad crack lengths (% of clad wall thickness) are illustrated



The new HTGR capability has been demonstrated by simulating the Chinese HTR-10; predictions of reactor temperatures and coolant flow during normal operation are illustrated



The new LMFR capability has been demonstrated by simulating the Phénix LMFR; the core nodalisation scheme is illustrated



Technology next steps

Underpin design and licensing for LWR advanced technology fuels (ATFs) being developed in the UK.
Support development of UK advanced nuclear technology (ANT) fuels, with a focus on coated particle fuel for HTGR applications (in particular for the AMR demonstrator) and pin designs for lead-cooled fast reactor (LFR) applications.
Work with academia to incorporate advanced modelling techniques (e.g. peridynamics) into UK reactor modelling capability.
Extend reactor physics modelling to non-fuel applications (e.g. radioisotope production) to support UK development of these applications.
Support post-irradiation storage and disposal of UK spent fuel by extending fuel performance modelling to the full lifecycle of the fuel.
Provide validated tools (stand-alone or coupled computer codes) for the UK Nuclear Virtual Engineering Capability (NVEC).
Calibrate and validate advanced fuel modelling using experimental data on advanced fuel material properties and behaviour under irradiation; align with both UK (including AFCP) and overseas research programmes. Align modelling development with industry goals and regulatory requirements.

Other key project information

Phase 1 (as part of Advanced Fuels project) Investment BEIS: £300,000 Match Funding: N/A	**Phase 1** (as part of Advanced Fuels project) Project Start Date: April 2017 Completion Date: March 2018
Phase 2 (stand-alone project) Investment BEIS: £3,700,000 Match Funding: N/A	**Phase 2** (stand-alone project) Project Start Date: April 2018 Completion Date: September 2021

Engaged with NIP projects on Advanced Fuels, Digital Reactor Design, Strategic Toolkit and Nuclear Facilities, and Reactor Thermal-Hydraulics Helped steer international activities via UK representation on the Generation-IV International Forum (GIF), the International Atomic Energy Agency (IAEA) Collaborating Centre on the Advanced Fuel Cycle, the IAEA Technical Working Groups on Fuel Performance and Technology, Fast Reactors and Gas-Cooled Reactors (TWGFPT, TWG-FR and TWG-GCR), and the NEA Expert Group on Reactor Fuel Performance (EGRFP)

The Reactor Physics project has:
- produced over 10 external publications and over 20 internal reports
- facilitated collaborative working between the 7 UK partner organisations (NNL, Jacobs, University of Liverpool, University of Manchester, University of Cambridge, Imperial College London, EDF Energy)
- supported the development of 16 early career staff and 6 PDRAs while utilising the expertise of 20 SMEs and 4 senior academics

Key project contact:

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Advanced Manufacturing and Materials Overview

The Advanced Manufacturing and Materials (AMM) programme holds the promise of a significant potential decrease in the capital costs and risks of new nuclear power stations by offering a number of benefits including off-site fabrication. Innovation in this area can also facilitate the sector in meeting the wider overarching cost reduction targets set out in the Nuclear Sector Deal (NSD).

The programme was delivered over two phases, with Phase 2 further split between Phase 2a and 2b. Phase 1 (£5m, April 2017 to April 2019) funded seven projects which encompassed a range of technologies and processes aimed at reducing the cost of nuclear build. Phase 2a (£16m) funded four projects to build on the work of Phase 1 by developing technologies from laboratory scale and concept work towards technology demonstration, scale up and commercialisation. Phase 2b (£5m) funded seven projects and focused on increasing the manufacturing or technology readiness levels used in the manufacturing and construction of nuclear power stations deployable in the near, medium and/or long term.

Projects

Phase 1 - £5,000,000

- Frazer-Nash Consultancy - Project Force
- Nuclear AMRC - Advanced Manufacturing Research Centre - Single Manufacturing Platform Environment (SIMPLE)
- Nuclear AMRC- Intelligent Fixtures for Optimised and Radical Manufacture (InFORM)
- Jacobs - NPP - Nuclear Power Plant Design Codes and Standards for the UK
- Jacobs- Materials / Manufacturing Technology Evaluation for Advanced Reactors (MATTEAR)
- Cammell Laird- Pre Fabricated Module Design (Fit for Modules) (Captured within Project Faith Phase 2a page)
- Sheffield University Nano- Structured Steels to Extend Operational Performance for Nuclear Reactors

Phase 2a - £16,000,000

- Cammell Laird- Project FAITH - Fuel Assembly Incorporating Thermal Hydraulics
- Rolls- Royce - Project FAST - Future Advanced Structural Technologies
- Sheffield Forgemasters - The industrialisation of thick section electron beam welding for the nuclear industry
- EDF Nuclear Generation - Establishing AMR Structural Integrity Codes and Standards for UK GDA (EASICS)

Phase 2b - £5,000,000

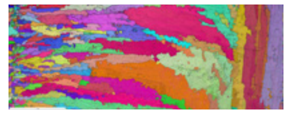
- Cavendish Nuclear- AWESIM Automated Welding Equipment System Inspection and Monitoring
- Createc - Mobile Weld radiography using Computed Tomography (MW- CT)
- Laser Additive Solutions Sonic SMR - Ultrasonic enabled Laser Additive Manufacturing with in - line Inspection
- Nuclear Energy Components- Process Improvement Through CO_2 Cooling - PITCO$_2$C Evaluating the combined coolant and lubrication characteristics of supercritical CO_2 (scCO_2)+ Minimal Quantity Lubricant (MQL)
- Rolls-Royce - SAS- Sensing Advanced Structures
- Urenco- Advanced Manufacture & Materials (AMM) U-Battery Advanced Modular Reactor HTGR: Full Scale Demonstrator.
- Jacobs Evaluation Technologies for Advanced Manufacturing Qualification (ETAMQ)

Project FORCE Advanced Manufacturing and Materials Lead: Frazer-Nash Consultancy

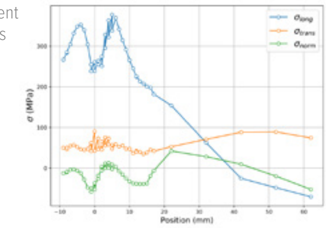
Project background

The overall aim of Project FORCE was to "Improve understanding of advanced joining methods with a view to enhancing the procedures in assessment codes such as R5 and R6". The objectives for the three work packages were:
1) Provide validated residual stress profiles which reduces the cost of implementing these welding technologies limiting the need for further residual stress measurement;
2) Apply innovations in probabilistic assessment methods from other industries to the nuclear industry to improve component design and structural integrity assessment approaches;
3) Increase understanding of the failure of power beam welds and demonstrate that the technique and material combination are a good candidate for future reactor designs and to reduce complexity and conservatism of current assessment methods.
The candidate material was thin section 316L austenitic steel, which is likely to be used in SMR, AMR and fusion components.

Electron backscatter diffraction micrograph showing grain size and crystallographic orientation in the weld and heat affected zone.



Diffraction-based measurement of residual stress state across a weld.



Macrograph showing narrow gap autogenous EB weld in thin section 316L.

Organisations involved (Click on logo to view website)

FRAZER-NASH CONSULTANCY · CAMMELL LAIRD · NUCLEAR AMRC · University of BRISTOL · VEQTER Residual Stress Experts

Technology next steps

A significant dataset of weld residual stress measurements in 316L austenitic stainless steel thin-section plates and pipes with electron and laser beam welds has been produced and its dissemination is ongoing.

An efficient modelling technique has been developed and used to propose parametrised residual stress profiles. The (ductile-dominated) failure of thin-section 316L components is now better understood, including in the presence of welds.

A numerical approach has been developed to predict the influence of constraint on fracture, which has applications across all thin-section components. The probabilistic framework developed in this project is being developed further in the EDF led, Phase 2 project EASICS.

Key outcomes from project

Through our programme of R&D, we have developed a portfolio of information that, when combined with other information in the publicly available literature, helps to unlock some of the blockers to the adoption of power beam welding so that it is significantly closer to realisation for nuclear components. The project has driven forward UK based technological capability in advanced joining within the UK supply chain. This will lead to opportunities for manufacturers and consultancies both to supply UK nuclear constructors and operators and to export into the global nuclear market.
Specifically, the main outcomes from the three work packages are:

- Weld Residual Stress
  - Manufactured and characterised a range of electron beam and laser beam weld geometries, including extensive residual stress measurements. Project also developed a crystal plasticity modelling framework, a modelling approach for predicting residual stresses and a framework for parameterised residual stress profiles.
- Probabilistic methods
  - Undertook measurements of variability in weld residual stress and developed guidance on design of response surfaces and a means to account for limited data and tools to specify scale of Monte Carlo analysis. The framework was applied to a structural integrity case study.
- Fracture modelling
  - Investigated effect of thermal exposure on fracture toughness and characterised fracture in 316L weldments and developed mechanistic understanding of 316L weld failure. Project also developed a parameterised modelling approach incorporating novel damage models.

Other key project information

Investment by BEIS in stage 1: £24,980
Investment by BEIS in stage 2: £1,372,061
Matched funding: N/A

Stage 1: June to August 2017
Stage 2: January 2018 to November 2020

Interaction with other NIP projects and more broader links to R&D:
- NNUMAN community
- EDF's R6 Panel Weld Residual Stress Subgroup
- Collaborated with other NIP projects to maximise value within the programme (in particular the Phase 1 AMM project MATTEAR)

Project Dissemination included:
- UK SIMULIA Symposium
- 26th International Conference on Nuclear Engineering
- ASME PVP 2019 (5 papers) and 2022 (2 papers) Conferences
- IMechE webinar 2019 "Optimising Structural Integrity: Addressing Reliability Challenges for Industry Adoption of New Testing Methods"

Knowledge exploited in several areas including:
- ATLAS+ Horizon 2020
- SINDRI Prosperity Partnership
- Undergraduate Projects at the University of Bristol

- NAFEMS Seminar 2020 "Welding Simulation – How Much Validation is Enough?"
- 15th International Conference on Engineering Structural Integrity and 2019 International Symposium on Structural Integrity (ESIA15-ISSI2019)

Key reports / presentations

Numerous papers presented at ASME Pressure Vessels and Piping Conference (PVP) in 2019 and 2022 alongside tailored dissemination events to specific audiences upon request. These presentations are available upon request.

The reports are not publicly available however we will be pleased to collaborate and discuss access to them or provide further information upon request.

Key websites

Project website: www.innovationfornuclear.co.uk/

Key project contact:

Name: Graeme Horne
Email: g.horne@fnc.co.uk
Tel: 01306 870381

Single Manufacturing Platform Environment (SIMPLE)
Lead: Nuclear AMRC

Project background

The SIMPLE project laid the groundwork for the integration of a range of fabrication, machining and inspection operations onto a single manufacturing platform. To prove the SIMPLE concept, we demonstrated these digital techniques by developing an integrated welding and monitoring tool. Combining a range of sensors and analytical tools with a mechanised arc welding head, this tool can allow automated in-process inspection of welds, improving quality and production efficiency.

(SIMPLE and InFORM looked at the two extremes of large scale manufacturing. SIMPLE focussed on all operations being undertaken on one machine/platform whereas InFORM looked at minimising non-value-added operations when moving between machines/platforms.)

Welding operation with video, acoustic, laser and power monitoring sensors

Organisations involved (Click on logo to view website)

Technology next steps

AWESIM (Automated Welding System Inspection and Monitoring) is an industry match-funded project that followed on from SIMPLE and was undertaken as part of the NIP where it developed the welding inspection concept to TRL 5.

Key outcomes from project

- Successfully demonstrated the synchronous gathering of data from 4 sensor technologies during a narrow groove tungsten gas arc welding operation - a significantly data-rich environment.
- Successfully deployed acoustic sensor technology in a working shop floor environment by using dual microphones and machine learning.
- Developed an emerging sensor technology - Electronic Speckle Pattern Interferometry (ESPI) - to justify further deployment to operate in a manufacturing environment.
- Defined an Open Source communications protocol to enable faster development of additional sensor technologies.

Other key project information

Investment BEIS: £1,300,000
Match funding: N/A

Project Start Date: May 2018
February 2018 was start of Phase 2
Completion Date: August 2019

SIMPLE enabled the NIP project AWESIM as well as leveraging £600,000+ of 6 industry-funded Nuclear AMRC Research Board projects.

On the 2nd and 3rd July 2019, Nuclear AMRC hosted a 2-day Nuclear Innovations Conference with over 200 attendees and presentations from all the current NIP projects at the time

The 8 work packages had widely varying TRL start and finish points – three of them starting at 2 and three finishing near 4. All work packages increased the TRL levels starting at and average of 2 and ending at an average of 3.

Key reports / presentations

Summary report

Full report

Key websites

namrc.co.uk/services/crd/simple/
www.youtu.be/LUI2ayu6qhA

Key project contact:

Name: David Anson
Email: David.anson@namrc.co.uk
Tel: 0114 215 8047

MANUFACTURING & MATERIALS

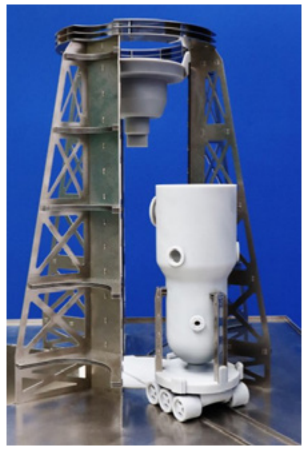
Intelligent Fixtures for Optimised and Radical Manufacture (InFORM)
Lead: Nuclear AMRC

Project background

InFORM (Intelligent Fixtures for Optimised and Radical Manufacture) focuses on technologies which can save time and money throughout the manufacturing process for large-scale nuclear components. The focus was both on reducing/eliminating non-added-value tasks as well as reducing added value operations.

(SIMPLE and InFORM looked at the two extremes of large scale manufacturing. SIMPLE focussed on all operations being undertaken on one machine/platform whereas InFORM looked at minimising non-value-added operations when moving between machines/platforms.)

Concept model for a pressure vessel assembly platform combining all the InFORM technologies



Organisations involved (Click on logo to view website)

Technology next steps

- Further research to improve productivity and capability in UK supply chain.
- Develop use of super critical CO_2 coolants, advanced computer aided manufacturing & scan-based measurement techniques, hollow ingot forging & modular press tooling, materials & intelligent fixtures for large pressure vessels, local vacuum electron beam welding technology.
- Exploration of opportunities for commercial deployment of the higher TRL technologies.

Key outcomes from project

- Demonstrated 220% improvement in tool life when machining with super critical CO_2 coolant.
- Demonstrated elimination of one stage in a three-stage process in preparing to machine large scale forgings.
- Demonstrated innovative assembly process for welded reactor pressure vessels which could significantly reduce cost and lead time for a new generation of small modular reactor (SMR).
- Developed a 4IR technology demonstrator of intelligent fixturing sensors to provide continuous process monitoring in nuclear manufacturing.
- Identified a range of measuring technologies to meet the project's specific requirements in forging, machining, assembly and welding.

Other key project information

Investment BEIS: £1,100,000
Match funding: N/A

Project Start Date: May 2018
February 2018 was start of Phase 2
Completion Date: August 2019

InFORM enabled the NIP project PIT CO_2C as well as leveraged £500,000+ of 6 Nuclear AMRC Research Board projects and £300K+ from 2 Nuclear AMRC commercial projects.

On the 2nd and 3rd July 2019, Nuclear AMRC hosted a 2-day Nuclear Innovations Conference with over 200 attendees and presentations from all the current NIP projects at the time

The 6 work packages had widely varying TRL start and finish points – one starting as low as 1 and another finishing at 4. All work packages increased the TRL levels starting at an average of 2 and ending at an average of 3.

Key reports / presentations

Summary report

Technical Report

Key websites

namrc.co.uk/services/crd/inform/
www.youtube.com/watch?v=hdTKKVOeK30

Key project contact:

Name: David Anson
Email: David.anson@namrc.co.uk
Tel: 0114 215 8047

NPP Design Codes and Standards for the UK
Lead: Jacobs

Project background

The objective of the Nuclear Power Plant (NPP) Codes and Standards project was to identify what advances in codes & standards will be required to enable various developments to be fit for purpose to Small Modular Reactor (SMR) / Generation IV (Gen IV) / Advanced Modular Reactor (AMR) reactor types, with the aim of ensuring acceptance by both UK and international regulators:

- What developments are required for new SMR / Gen IV / AMR designs to satisfy UK regulation.
- Support all the materials, manufacturing developments, and the advanced modular reactor development programmes.
- Promote UK expertise.

Without considering codes and standards (and procedures), the advances proposed in other projects will hit regulatory obstacles from the design codes and regulatory bodies. Therefore, the impact on codes and standards is important to the materials and manufacturing programme to ensure deployment of the developed technology.

Organisations involved (Click on logo to view website)

Advisory Group:

TWI, Manchester 1824 The University of Manchester, Rolls-Royce, World Nuclear Association, ONR Office for Nuclear Regulation, EDF, University of Bristol, University of Strathclyde, Imperial College London, AREVA

Department for Business, Energy & Industrial Strategy → Jacobs, National Nuclear Laboratory

External Discussions:

GE Hitachi, U-Battery Local Modular Energy, EDF, Westinghouse

Other Themes:

The University Of Sheffield, Nuclear AMRC, Cammell Laird, Frazer-Nash Consultancy

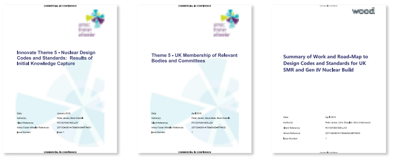
Key outcomes from project

The project has undertaken an exercise to identify what developments are required for new SMR (both near- and longer-term) / Gen IV / AMR designs (for different generic reactor types) to satisfy UK regulation, namely:

- Supporting all the materials and manufacturing developments and the advanced modular reactor development programmes.
- Looking to promote UK expertise to the wider community with a number of potential recommendations made.
- High-level road map for areas to consider and activities to enhance links to code bodies developed.

A plan has been developed through extensive engagement with industry, consultants and academia, within the UK and overseas. This has led to the grouping of approximately 45 items, which have then been reviewed to identify the most pressing design codes, and standard's needs (repeated for a range of reactor types). This ranking was performed through understanding the relative importance of an identified gap and a measure of the effort (informed by cost and duration). This, along with suggestions on how to enhance the UK engagement with the different code bodies, forms the basis of the road map suggested for future work.

Key reports / presentations



Theme 5 Deliverables: Initial Knowledge Capture (D1); International Bodies & Committees (D2); and Summary & Road-Map (D3)

ASME PVP (PVP2018-85075 & PVP2019-93861) and Nuclear Future Papers

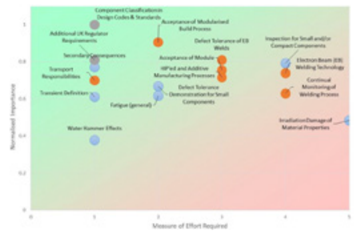
None of these documents are freely available online

Key websites

Project website: www.innovationfornuclear.co.uk/
ASME PVP: event.asme.org **and** www.asme.org
ASTM: www.astm.org
Project website: www.afcen.com

Illustration of gaps and how these were reviewed. Shown are the highest 15 ranked items identified by the gap ranking exercise for a short-term SMR showing perceived normalised importance against qualitative effort.

Technical barriers (blue, potential design acceptance challenges), cost barriers (orange, potential affordability challenges) and regulatory items (grey, which may support/challenge regulatory acceptance) for a longer-term SMR.



Technology next steps

Some of the key recommendations for future work from this review include:

- A UK forum for codes and standards should be established. This should enhance the UK position to better link to the design codes and standards, with focused UK International Working Groups (IWG) to these codes established. (Note the ASME III UK IWG has since been established).
- A UK Generic Design Assessment (GDA) interpretation document should be developed. (Note that this has been developed as part of a follow-on project, EASICS)
- Roadmap identified key technical areas that should be suitably addressed.

Other key project information

Investment BEIS: £300,000 excluding VAT
Match Funding: N/A

Project Start Date: June 2017
Completion Date: June 2019

Interaction with Themes 1, 2, 3 & 4 (e.g. AM Processes, Welding Techniques, Manufacturing Requirements, & Module Requirements). Engagement with the UK Nuclear Industry, and the International Design Codes & Standard Committees (ASME, ASTM & AFCEN).

Road map produced to support SMR and Gen IV reactors in the UK:

- Reducing the time and cost associated with modifying design codes and standards to help meet the 2030 SMR aspiration.
- High-level guidance to reduce the burden of the GDA process.
- Prioritising ongoing development activities.

Project key facts:

- Over 20 collaborators with extensive industrial engagement.
- Worldwide dissemination through ASME PVP conference presentations and papers in 2018 and 2019, as well as through Nuclear Future paper.
- Key items identified and projects to address some of these established.

Key project contact:

Name: Dr Peter James
Email: peter.james2@jacobs.com
Tel: 01925 696921

Materials/Manufacturing Technology Evaluation for Advanced Reactors (MATTEAR)
Lead: Jacobs

Project background

There is a significant requirement to reduce the capital cost of future nuclear plants, for example, using innovations in manufacturing technologies. Four key manufacturing technologies were selected by a consortium of reactor vendors, developers and operators to determine their development status. An advanced evaluation capability in a novel advanced reactor coolant was also undertaken.

The project was aimed at both lightwater reactor and high temperature concepts. Clearly the appropriate evaluations differ across the systems. Four manufacturing technologies – electron beam welding, dissimilar metal joints, hot isostatic pressing (HIPing) of metal powder, and additive manufacturing – were down-selected, along with appropriate structural materials. Project partners Nuclear AMRC and TWI performed the manufacturing to generate test material for subsequent evaluation.

Fracture toughness, creep and fatigue performance were measured over a range of temperatures and in various reactor environments. A review of novel materials that could be applied to future reactor concepts was also performed.

Organisations involved (Click on logo to view website)

Jacobs, TWI, Nuclear AMRC, Manchester 1824 The University of Manchester, U-Battery Local Modular Energy, Rolls-Royce, moltex clean energy, AREVA, Westinghouse, EDF, GE Hitachi

Key outcomes from project

Material produced by four novel manufacturing techniques to enable high quality mechanical evaluation data to be measured. 11 reports detailing the production of the test materials, evaluation of the manufacturing technologies, materials development requirements and the exploitation route.

The electron beam welding and powder metallurgy + HIPing processes were identified to offer high performance opportunities in the short term and appeared to have good commercial potential for structurally important applications. On the other hand, the additive manufacturing and the dissimilar metal joining approaches will require further developments for key structural applications and may need a new approach to qualification of the material for nuclear application.

An initial demonstration of a molten salt corrosion protection method was demonstrated with austenitic stainless steel at 600 °C, providing an encouraging first step for this reactor technology.

A fatigue test capability in a liquid lead environment was developed and successfully demonstrated.

Key reports / presentations

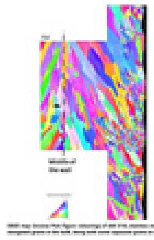
None of these documents are freely available online

Key websites

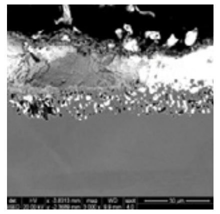
Project website: www.innovationfornuclear.co.uk
ASME PVP: event.asme.org **and** ttps://www.asme.org

Electron beam welding of 75 mm low alloy steel plate. Post-weld heat treated and then fracture toughness tested.

Microstructural cross-section of additively manufactured austenitic stainless steel. Elongated grain structure, following the thermal gradients during deposition.



Lead (Pb) ingress (white regions) into the surface of an austenitic stainless steel test piece, after fatigue testing at 600 °C in a liquid lead environment.



Technology next steps

It is expected that further commercial opportunities for the manufacturing technologies evaluated in this programme will emerge as clarity on future reactor developments is achieved, with those noted to have the potential in the short term – electron beam welding and powder metallurgy + HIPing – likely to be industrially applied first. However, even with these technologies there remains development hurdles in terms of demonstrating process repeatability and ensuring design code acceptance (although both technologies now have some level of recognition in the US and European design codes).

For the dissimilar metal joints and additively manufactured materials there is a need to undertake further mechanical performance studies of key properties. Whilst for the additive manufacturing processes the specific limitations of each process needs to be recognised and the process developments for them performed, for example controlling the metal powder oxygen content for those processes using metal powder.

Other key project information

Investment BEIS: £1,190,000
Match funding: N/A

Project Start Date: January 2018
Completion Date: August 2019

Interacted with the following NIP projects – "NPP Design Codes and Standards for the UK", "Establishing AMR Structural Integrity Codes & Standards for UK GDA", Sheffield Forgemasters EB Welding Development & Westinghouse LFR Development. Also working with Manchester University, NAMRC and EPRI to develop technologies initiated under this current programme.

Review of future reactor types and materials research and development requirements, covering:

- Gen III+ and Gen IV reactor types
- Key environmental interaction issues
- Novel material developments required

Project key facts:

- Two UK project specific dissemination events attended by >80
- World-wide dissemination through ASME PVP Conference presentations
- Supplied materials into subsequent projects

Key project contact:

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Tel: +44 (0)75110 92784

NanoStructured Steels to Extend Operational Performance for Nuclear Reactors
Lead: The University of Sheffield

Project background

The major innovation in the project is adaptation of the state of the art laboratory conceptualised nanostructured steels towards industrial scale production.

The main objectives of the project were:

1. Developing new nanostructured steels (NSSs) that mitigate materials degradation and enhance operation under combined high temperature, corrosive and high irradiation environments, which are relevant to all energy sectors but particularly Generation IV and small modular nuclear reactors. The ultimate aim of the work is to develop a material with 30,000 hours creep lifetime at 650°C and 200 MPa and a 100,000 hours lifetime at 650°C and 150 MPa, which is twice the life in comparison with the same steel matrix without a strengthening nanostructure.
2. Developing and optimising manufacturing routes using advanced thermodynamic and thermomechanical processing modelling combined with stateoftheart laboratory experimentation, enabling industrial production of NSSs using existing industrial infrastructure.
3. Utilising advanced microstructure and mechanical property testing to develop a mechanistic understanding of the role of nanostructures in the material behaviour during manufacturing, and under simulated severe environments (high temperature, radiation, corrosion).

Organisations involved (Click on logo to view website)

The University Of Sheffield. Materials Processing Institute. Sheffield Forgemasters. National Nuclear Laboratory. UK Atomic Energy Authority

Technology next steps

There is more fundamental work to be done, relating to compositional changes as well as Thermomechanical processing to fully optimise the microstructure and associated performance. This will involve much characterisation in terms of microscopy, corrosion behaviour, not to mention the potential changes due to fabrication such as welding. All of this work will require a similar team, taking expertise from universities, government laboratories, catapult centres and commercial metal producers.

There are still many unanswered questions. However the project feels we have an opportunity to develop a commercially viable alloy, thus enhancing existing capabilities in the nuclear sector for both fission and fusion reactors.

Key outcomes from project

This project developed a new heat treatment strategy for a commercial alloy which resulted in superior mechanical properties with no difference in corrosion behaviour. Additionally, a new reduced activation alloy was developed with very good mechanical properties and corrosion behaviour, making it a likely possible candidate, with small changes to the existing chemistry, for use in fusion reactors.

The work has successfully demonstrated that the ferritic steel compositions (Alloys 693 and 666) are viable competitors to the existing commercial grade P91, exhibiting higher levels of strength at room and elevated temperatures, albeit with a lower degree of tensile ductility and impact fracture energy. The lower fracture energy, specifically the upper shelf energy is further complicated from a high amount of data scatter. This scatter in turn is directly related to the inhomogeneity associated with the alloy steels. This inhomogeneity has originated in the casting process, resulting in some alloy segregation which further elongate during the forging process. Additionally, this lower fracture energy is also associated with a higher level of internal porosity, which often difficult to control in smaller castings. It is anticipated that improvements in fracture behaviour will result in these, or similar alloy compositions with larger scale castings and better steel cleanliness practices.

Other key project information

Investment BEIS: £267,630
Match funding: N/A

Project Start Date: January 2018
Completion Date: March 2020

This project started at TRL level 2 and is predicted to have reached TRL5 on completion.

This grand challenge required detailed understanding of chemical and thermophysical pathway management at the cutting edge of steel production. This could only be realised utilising advanced thermodynamic, mechanistic and experimental analysis supported by modelling combined with industrial know how, which is uniquely combined in this consortium.

This project led to a PhD studentship (EPSRC) with additional funding from UKAEA and further production of the 666 alloy was included within the subsequent Phase 2 project with Sheffield Forgemasters shown later in this section of the brochure.

Key reports / presentations

No public documents released from this work

Key websites

Programme website:

Key project contact:

Name: For further information of this project please contact NIRO
Email: info@niro.org.uk

Project Faith
(Fuel Assembly Incorporating Thermal Hydraulics)
Lead: Cammell Laird

Rig delivered to NNL Workington W/C 8th March

Project background

Project FAITH (Fuel Assembly Incorporating Thermal Hydraulics) builds on the Fit For Modules project. This created a roadmap for developing "plug and play" modules for nuclear plant in the UK. The aim for project FAITH is to show how modular builds can deliver solutions for new nuclear and utilises the roadmap developed during Fit for Modules.

In the development phase of the new nuclear reactor designs, the design of fuel assemblies must be optimised. With limited facilities capable of testing fuel assemblies in the UK, project FAITH will deliver a solution capable for both water and sodium cooled reactors using modular designs.

The production of the rig will be a baseline for future projects and applications, with its strong transport integrity plan reducing cost of onsite commissioning and the use of cutting-edge technologies to monitor the health of rig in transportation and through-life.

Organisations involved (Click on logo to view website)

Cammell Laird. GE. Hitachi. National Nuclear Laboratory. Eleven-I. Jacobs. Frazer-Nash Consultancy. University of Liverpool. SeaKing group. IPS Marine Fabrications Limited

Technology next steps

The design of Rig 2 a sodium rig, will be ready to go into a safety case and ultimately production in future work.

The process and technology outputs of this project should be applied to larger production projects and tested with repeatability. A larger rig or similar would be a suitable next step and test.

Key outcomes from project

Demonstrating, using the build of a thermal hydraulics rig, the effectiveness of offsite modular manufacture.

The capturing and exploration of the technologies that are best applied to the nuclear industry.

Core Completed:

Shipbuilding Process Capture, Rig 1 design, Rig 1 production, Rig 1 Commissioning at Cammell Laird, Rig 1 Delivery, Rig 1 Commissioning at NNL.

Auxiliary Completed:

Transport Integrity plan and analysis, laser scanning, VR training

Outstanding: Rig 2 design, lessons learnt, final process capture

Other key project information

Phase 1	Phase 2
Investment BEIS: £198,972 Match Funding: N/A	Investment BEIS: £ 5,150,000 (70%) Match funding: £ 2,250,000 Total: £7,400,000

Phase 1	Phase 2
Project Start Date: March 17 Completion Date: September 18	Project Start Date: June 19 Completion Date: January 22

Multiple collaboration events with NVEC through NNL.

- Upskilled employees in different software's such as: 3D Inventor, Artec Studio (Laser scanning) & Pixyz review (Virtual reality)
- 3 journal papers
- Used shipbuilders experience in structures & mechanical engineering to build rig.

Key reports / presentations

Cammell Laird Collaborates with University of Liverpool to Keep Nuclear Energy Project On Track | Cammell Laird (clbh.co.uk)

Key websites

News article: Virtual Engineering Centre

Cammell Laird Collaborates with University of Liverpool to Keep Nuclear Energy Project On Track | Cammell Laird (clbh.co.uk)

Key project contact:

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Future Advanced Structural Technologies
Lead: Rolls-Royce PLC

Project background

The aim of Project FAST (Future Advanced Structural Technology) is to develop a novel method of manufacturing nuclear pressure vessels. Key technologies being developed for this specific application are: Hot Isostatic Pressing (HIP) of SA508 low alloy steel vessel sections; Thick Section Electron Beam (EB) welding of vessel sections; process modelling and physical process development. A number of physical demonstrators have been produced, starting with small material test pieces, then escalating in size and complexity to push the boundaries of current capability. This resulted in the manufacturing of the Small Vessel Demonstrator (SVD), which is believed to be the World's first HIP & TSEBW pressure vessel, as well one section of the Large Vessel Demonstrator (LVD), a sub-component of a much larger vessel.

Small Vessel Demonstrator

Large Vessel Demonstrator

Ring Section Demonstrator

Material Test Blocks

Organisations involved (Click on logo to view website)

Technology next steps

Over the last two years, several key areas for further development have been identified. Rolls-Royce is currently funding the programme to further understand the material properties of SA508, the HIP of FV520 material and furthering HIP canister filling methods, and EB welding of HIPed material. Rolls-Royce is working with multiple powder companies to develop the material over the next year before we will look to develop a cross-industry ASME code case.

Key outcomes from project

The BEIS funding allowed Project FAST to produce the world's first HIPed SA508 pressure vessel with the SVD. The SVD weighs ~2 tonnes, measures 2.4m high and 1.4m in diameter (including nozzles). It has an EB weld within the structure of the component and one joining the two halves together. The LVD1 section weighs 4.2 tonnes, measures 1.5m tall and 1.6m in diameter. The method of manufacture for this component included new and improved processes that ensures the quality of large HIP components and de-risks many of the stages. Improvements were made in canister design, powder supply, the canister filling method, and outgassing operations. The demonstrator's sister component (LVD2), completed to canister manufacturing stage and paused prior to filling to allow for further lessons learnt to be embedded.

Other key outputs from FAST have been:

- An increase in material toughness of the HIPed material through manufacturing controls.
- Development of EB welding parameters and techniques.
- Thermal cycling of the ring section demonstrator.

Other key project information

Investment BEIS: £1,400,136 (63%)
Match funding: £800,000
Total: £2,200,136

Project Start Date: November 2019
Completion Date: August 2021

No interaction with other NIP projects but did present project intent and progress to ONR and Environment Agency.
There was some initial links with the MATTEAR project but not progressed further.

The world's first HIPed SA508 pressure vessel.

- Skills development
  Handling of oxygen-sensitive metallic powder (particularly wrt filling large canisters)
  Fabrication of complex HIP canisters
  Modelling of HIP consolidation for HIP canisters with complex geometries.
- Number of Journal papers
  ASME Pressure Vessel & Piping conference 1x technical paper (PVP2020-21044)
  ASME International Conference on Nuclear Engineering 2x technical papers (ICON27-1021 & ICONE28/Power2020-16035)
  International Institute of Welding 1x technical paper (IIW2020 IV-1457-20, published in Welding in the World journal)
  International Electron Beam Welding conference 1x technical paper (Abstract #6870)
  European Powder Metallurgy Association 2x presentations (EuroHIP2020 & EuroPM2020)

Key reports / presentations

ASME ICONE28-Power2020 Paper

Rolls-Royce's Introduction of HIP Nuclear Components

Key websites

BEIS Advanced Manufacturing Materials Successful Projects announcement
EB WELDING OF HOT ISOSTATICALLY PRESSED LOW ALLOY STEEL

Key project contact:

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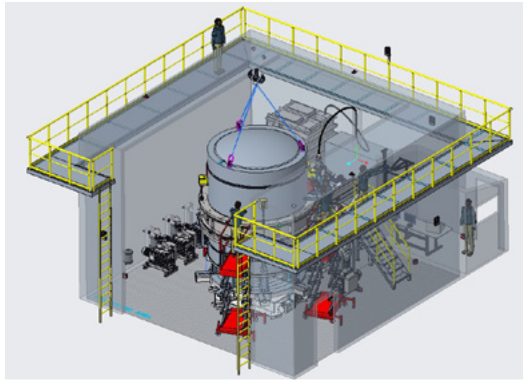
The Industrialisation of Thick Section Electron Beam Welding for the Nuclear Industry
Lead: Sheffield Forgemasters

Project background

Sheffield Forgemasters has led a consortium of partners in its largest ever research and development project, with an overall project value of £10.3 million. The company has explored the industrialisation of Electron Beam Welding (EBW) in civil nuclear pressure vessel (PV) fabrication, with the potential to integrate welding into the manufacturing process, offering material improvements and substantial reductions in manufacturing time and cost.

The project will demonstrate production rate ready techniques using a full-sized (ø3 x 4.3 m) small modular reactor (SMR) pressure vessel and also produce several grades of steel alloys suitable for both civil fission and fusion nuclear applications. This will advance manufacturing process that have not yet been brought to industrialisation in this sector.

Local vacuum EB welder housed in a custom designed X-Ray enclosure



Organisations involved (Click on logo to view website)

Technology next steps

EBW of thick section steel is at currently Technology Readiness Level (TRL) level 5. This project aims to progress to TRL and Manufacturing Capability Readiness Level (MCRL) 6. If the process and equipment are demonstrated to be robust enough, and sufficient markets identified, further commercialisation of the EBW process will be pursued.
Key challenges;

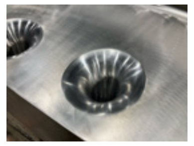
- EBW parameter development for defect free circumferential weld in 200mm nuclear grade steel
- Machine tool and local vacuum seal durability and repeatability
- Large scale X-ray enclosure supply and manufacture
- Fabricated vessel handling, heat treatment and machining
- Code and regulator acceptance of EBW

Key outcomes from project

This project explores the industrialisation of EBW in civil nuclear fabrication, with the potential to integrate welding into the manufacturing process and removing welded structure through heat treatment. Sheffield Forgemasters are installing an electron-beam welder capable of welding 3m diameter cylinders under localised vacuum and without traditional welding preparation, offering faster and narrower welds than traditional methods, plus the ability to weld as part of the manufacturing process, prior to quality heat treatment. Mechanical properties and thus pressure vessel integrity will be vastly improved over traditional weldments.

200mm thick section circumferential weld

EBW is commonly used in other engineering sectors, however on a much smaller scale. This project has demonstrated how EBW can improve mechanical properties over traditional welding and show how the technology can be integrated into the manufacturing route to remove component welded microstructures.



Complex cladding achieved inside nozzle and finish machined

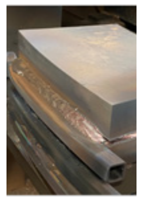
Other key project information

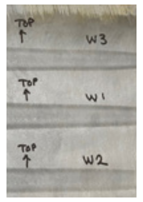
Investment BEIS: £7,700,000 (75%)
Match funding: £2,600,000
Total: £10,300,000

Project Start Date: August 2019
Completion Date: August 2022

Using EBW over traditional welding techniques, circumferential welding of pressure vessels can be reduced from approximately 150 days to 10 days. Through the science that we have already refined, we will be able to produce safer, higher integrity components for the next generation of nuclear power generation, with lower costs and vastly reduced production times.

EBW trials conducted and associated macros





The project has also collaborated alongside an invited steering committee of; Rolls Royce (Civil Nuclear), Rolls Royce (Submarines), Cavendish Nuclear, the Ministry of Defence and the UK Atomic Energy Authority.

Key reports / presentations

wwwsheffieldforgemasters.com

wwwsheffieldforgemasters.com

Key websites

Home - Sheffield Forgemasters
Research, Design & Technology - Sheffield Forgemasters

Key project contact:

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Establishing AMR Structural Integrity Codes and Standards for UK GDA (EASICS) Project
Lead: EDF Nuclear Generation Ltd.

Project background

Advanced Modular Reactors (AMRs) may be integral to the UK achieving the committed "Net-Zero" carbon emissions by 2050, providing flexibility between electricity production, process heat for decarbonisation of heavy industry and efficient production of "red" hydrogen (using thermal energy directly). The key benefits of AMRs arise from operating at high temperatures. However, operation at high temperature significantly increases the structural integrity challenges, notably regarding creep, thermal aging and environmentally assisted mechanisms.

It has previously been identified (AMM Phase 1) that there is currently no clear route to demonstrate the structural integrity of high temperature reactors to the UK regulator and there are known limitations in the available codes and standards. This project provided guidance on how existing design codes (i.e. AFCEN RCC-MRx and ASME Section III Division 5) and assessment methodologies (e.g. UK based R5 and R6 Assessment Procedures) can be used for design substantiation within a UK regulatory framework and identify what further work may be required for an AMR to be licenced in the UK.

Organisations involved (Click on logo to view website)

Project partners:

EDF, National Nuclear Laboratory, Rolls Royce

Key Contract Partners:

Jacobs, Frazer-Nash Consultancy, University of Bristol

Other Contract Partners and Organisations Providing Input/Review:

TWI, Manchester 1824 The University of Manchester, Stress Engineering Services Inc., cea, ONR Office for Nuclear Regulation

Key outcomes from project

The intended outcome was to develop assessment methodology in several key areas (WP1-3) as well as provide guidance on the use of codes and standards within the UK regulatory environment (WP4). Key outcomes include:

WP1: Structural Reliability Approaches

- Series of published case studies demonstrating the application of reliability/probabilistic structural integrity assessment methods.
- A Probabilistic Guidance document was produced, setting out a hierarchy of reliability methods suitable for application during design and through life.

WP2: Thin Section Defect Tolerance

- Defect tolerance demonstration is not required in other regulatory regimes and is therefore a unique UK challenge.
- Fracture and creep crack growth testing demonstrated that current advice may be overly conservative for thin section geometries.

WP3: Creep-Fatigue Behaviour

- Focussing on cyclic stress-strain behaviour of relevant materials, it was shown how accounting for cyclic evolution and impact of creep on cyclic behaviour could dramatically improve lifetime assessments.
- The testing of HIP Alloy 617 also showed the dramatic impact that the manufacturing route can have on lifetime performance.

WP4: Codes and Standard Guidance

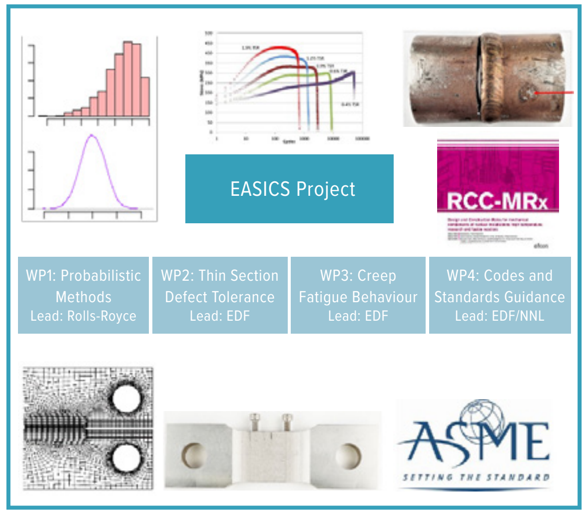
- The headline guidance document details expectations of the regulator, status of and comparison of available codes and a review of operational experience from existing high temperature nuclear plant, notably UK AGRs.
- A review and discussion of this information by an international independent panel resulted in 26 recommendations being identified.

Key reports / presentations

The guidance documents produced are not yet available online. Please contact M Chevalier for access to the following documents.

- Probabilistic Structural Integrity Assessment Guidance for AMR Codes and Standards, Version 2.0, February 2022
- Guidance for the Structural Integrity Demonstration of Advanced Modular Reactors in the UK, Revision 001, February 2022.

A number of papers have also been published, a subset include:
https://doi.org/10.1115/PVP2020-21721
https://doi.org/10.1115/PVP2021-62845
https://doi.org/10.1111/ffe.13572
https://doi.org/10.1115/PVP2020-21717
Note a summary of the headline guidance document is being published at ASME PVP2022 (paper PVP2022-84897), but is not yet available online.



Technology next steps

- With probabilistic methods well established under the EASICS project, future work is expected to work towards inclusion of these methods in the R5/R6 assessment procedures and ASME design code.
- The WP4 Guidance document sets out 26 recommendations for the attention of Government, BEIS, the regulator, AMR vendors and developers, and the wider nuclear industry.
- Recommendations range from identifying the value of GDA (undertaken by a regulator with experience of high temperature reactors), ensuring lessons are learnt from AGR operational experience, and to the need to protect niche skills and facilities in the UK with the ongoing closure of AGRs.
- It is concluded that no single design code is adequate to substantiate design in the UK regulatory environment. Procedures are available for most requirements, but notable gaps remain. This gives rise to clear technical priorities that need to be addressed, notably regarding material properties and environmental interactions.
- A High Temperature Structural Integrity Forum is to be established (being set up by P James, Jacobs), to coordinate and/or share development in this area, bringing together relevant UK activities on ASME, AFCEN and R5/R6 assessment methods.

Other key project information

Investment BEIS:	£1,373,000 (60%)
Match Funding:	£890,000
Total:	£2,263,000

Project Start Date:	September 2019
Completion Date:	December 2021

The EASICS Project was built upon 3 projects undertaken in the AMM Phase 1:

- Nuclear Design Codes and Standards: Considering a strategy for development in the UK and international engagement, led by Jacobs.
- Material/Manufacturing Technology Evaluation for Advanced Reactors (MATTEAR): Considering testing of novel materials, led by Jacobs.
- Advanced Materials- considering welding residual stress modelling, probabilistic modelling and fracture modelling- led by FNC.
  This EASICS collaboration was built on the existing SIAP (Structural Integrity Assessment Procedures) collaboration, which oversee the development of the R5/R6 Assessment Procedures, and the High Temperature Centre, which is an EDF funded network of University partners.

Across the work packs, a significant amount of work has been delivered:

- 33 reports and memos
- 15 papers (some are pending publication or under review)

An extensive amount of testing has been undertaken, at both EDF, Jacobs and University of Bristol facilities including:

- 4 tensile tests and 9 fracture tests
- 5 creep crack growth tests
- 34 fatigue tests
- 36 creep-fatigue tests
- 4 feature tests on a welded pipe.

Key project contact:

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MANUFACTURING & MATERIALS

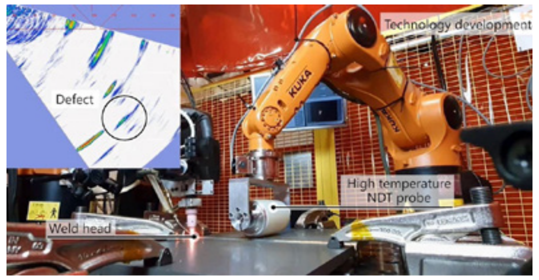
AWESIM Automated Welding Equipment System Inspection and Monitoring
Lead: Cavendish Nuclear

Project background

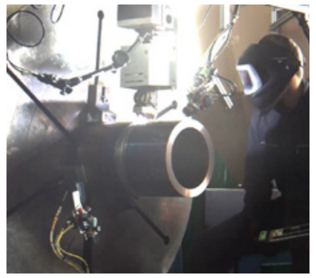
The Non Destructive Evaluation (NDE) inspection and verification of high integrity welds is predominantly a manual process, performed by skilled engineers when welds are fully finished and cold. As defects are only detected when the welds are complete, this limits productivity and throughput, increases re-work and creates schedule uncertainty.

Cavendish Nuclear led a consortium of industrial and academic partners, supported by subject matter experts (SMEs), with the aim of reducing high integrity manufacturing costs by optimising the welding and inspection processes by using innovative technologies. AWESIM introduced high-temperature in-process weld condition monitoring and ultrasonic inspection directly at the point of welding, detecting flaws as they occur, reducing rework and repair, removing inspections of flaw-free components, so saving significant time and reducing costs. AWESIM's ultimate aim is to deliver high-quality welds right, first time.

Temperature compensated phased array ultrasound sensor from ANRC, University of Strathclyde



AWESIM project test rig at NAMRC, University of Sheffield



Organisations involved (Click on logo to view website)

Industrial partners:

Cavendish Nuclear part of Babcock International Group, Doosan Babcock

Academic partners:

University of Strathclyde Advanced Nuclear Research Centre, Nuclear AMRC

Supporting SMEs:

babcock, Frazer-Nash Consultancy, Peak NDT

Technology next steps

AWESIM phase II aspires to develop the technology elements and deliver them at TRL6. Prototype applications are already planned on complex-shaped penetration welds typically found in saddles, penetrations and liner inserts commonly found in the defence sector on submarine hulls and weapon launch system structures which feature thick-section intersecting curved plates. Application to thick walled components, such as reactor primary circuit components and vessels is also under development. Current work that is in progress will aim to progress miniaturisation and ruggedisation of the sensors and to develop a hand held phased array roller probe for instantaneous local NDE.

Key outcomes from project

The purpose of AWESIM phase I was to develop real time welding process condition monitoring and simultaneous non-destructive testing, taking technical readiness (TRL) through to TRL 5 / 6. This has been achieved by focusing on a large bore, thick walled pipe weld of a form typically seen in the nuclear industry. Technical demonstrations to showcase the detection of typical weld defects such as porosity, sidewall lack of fusion, incomplete root penetration and flux/slag inclusions took place. All measurements were undertaken at high-temperature (up to 350 °C) in real time, without the use of acoustic couplant and using industrially representative welding equipment. In addition to the significant technical advances made by AWESIM phase I, the project has ably demonstrated the power of collaboration in innovation between academic and industrial partners, making a real tangible impact on bringing new, potentially disruptive technology to the fore.

Other key project information

Investment BEIS: £1,347,738 (65%)
Match funding: £725,705
Total: £2,073,433

Project Start Date: May 2020
Completion Date: December 2021

The UK's new Nuclear Build programmes will provide significant potential for the deployment of AWESIM technology. For example, primary circuit welded assemblies are have the requirement for thick section high integrity multi pass welds; an application to which AWESIM would be ideally placed to facilitate reduced manufacturing costs and increasing schedule certainty.

- AWESIM is a shining example of collaboration between industrial and academic partners, co-funded by the UK Government, to facilitate development of new technology with tangible, real world manufacturing benefits.
- AWESIM has proven real time welding process condition monitoring and simultaneous non-destructive testing is a reality.

- AWESIM Phase I has increased the TRL level from 3 / 4 to 5 / 6.
- AWESIM has shown that prolonged non-destructive testing can now be carried out at high-temperature (up to 350 °C) without the use of acoustic couplant.
- AWESIM promises manufacturing schedule certainty and reduced manufacturing cost for high integrity components.

Key reports / presentations

AWESIM

Key websites

www.cavendishnuclear.com/

Key project contact:

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Mobile Weld Radiography using Computed Tomography (MW-CT)
Lead: Createc

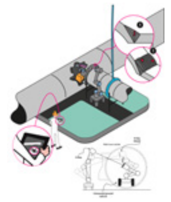
Project background

Weld inspection is an essential component of many high value manufacturing and maintenance activities e.g. ships, aircraft, nuclear reactors etc. Weld radiography is a mainstay of weld inspection but has two considerable drawbacks when deployed in-situ: it is potentially hazardous, making its use obstructive and dangerous, and it does not reliably detect certain types of defect.

Createc has developed a concept, MW-CT, that will combine 3D position sensing techniques, with autonomous robotics to make an in-situ radiography system which is safer, less obstructive and has higher performance by using in-situ Computed Tomography (CT) for generic welds or other industrial inspection.

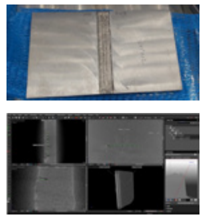
This system provides the advantages of weld CT scans with the convenience of mobile in-situ measurement. MW-CT uses independent robotic arms either side of the weld to build up the images for a Computed Tomography (CT) scan.

Tomography (CT) scan of a pipe weld



Independent robotic arms either side of the weld building up images for a Computed Tomography (CT) scan

(Top) Example of sample test with knowns flaws manufactured by NAMRC and (bottom) its associated CT scan



Organisations involved (Click on logo to view website)

createc TSP ENGINEERING NUCLEAR AMRC Department for Business, Energy & Industrial Strategy

Technology next steps

One of the key future innovations is the ability to achieve the accuracy required for CT with independent robotic systems either side of the weld. This would allow the system to be used in a wide range of applications, not limited by having to physically co-locate the two robotic systems.
The consortium is aiming to further the development of the project to take the technology to TRL7 and demonstrate a mobile robotic platform that can perform weld tomography in an active environment.
The technology will be demonstrated in an advanced manufacturing cell at the Nuclear AMRC. The next stage towards commercialisation will be a pilot scheme installing demonstrator cells in customer facilities working with our Advisory Group, and the wider Nuclear AMRC membership group.

Key outcomes from project

The consortium has built a novel robotic solution for Computed Tomography (CT) where the X-Ray is moved around the workpiece automatically. This has the potential to rethink the way in-situ Non Destructive Testing (NDT) is done for objects with difficult size, shape and access.
Createc developed a suite of software packages throughout the project that are and will remain useful to other robotics projects.
These include the following functionalities:
- Robot dual arm synchronised motion
- 3D environment scanning
- Collision avoidance
- Automated scan path
- User Interface (UI) to remotely operate robots and visualise scan results
- Computed Tomography using cobots

In addition, NAMRC have produced a set of Weld test pieces that have been tested through most conventional NDT method (e.g. Ultrasound, Phased array, CT, etc), these provide a test bench to enable the development of a new NDT methods.

Other key project information

Investment BEIS: £314,596 (78%)
Match funding: £88,707
Total: £403,303

Project Start Date: April 2020
Completion Date: September 2021

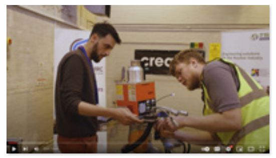
Subsequent work NIP projects and broader links to R&D programmes/collaboration inc. leverage into this project and leverage this project has had on any subsequent work.
- Supported the US / UK action plan and presented internationally
- Production of test samples available from NAMRC to support development of new DT technologies
- Future collaboration within the consortium to exploit value from this programme

- New radiography capability within Createc.
- TRL level increase from a technology concept to a demonstration on representative environment.

Key reports / presentations

RAIN Hub project webinar

NAMRC newsletter



Project demonstration video

Key websites

Project lead website: www.createc.co.uk
NAMRC: www.namrc.co.uk/
TSP Engineering: www.tsp-engineering.co.uk/

Key project contact:

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SonicSMR – Ultrasonic enabled Laser Additive Manufacturing with in-line Inspection
Lead: Laser Additive Solutions

Project background

The SonicSMR project used a multidisciplinary approach, combining a laser-based metal Additive Manufacturing process with power ultrasonics, real-time optical process monitoring and AI-based automated defects recognition to achieve zero-distortion, zero-defect metal Additively Manufactured components, suitable for use in Small Modular Reactors (SMRs).
Objectives of the highly innovative project included: critical/complex part manufacturing cost reduction, real-time quality assurance, high material utilisation, product customisation and reduced lead times, all enabled using metal Additive Manufacturing. The project targeted high-integrity components typically found in a wide range of nuclear power plants, such as SMRs, as well as nuclear waste associated equipment.
The key target of the project was to produce a Technology Demonstrator – "Something Real"

The SonicSMR Laser Processing Cell

The SonicSMR Laser Cell Control Room

Organisations involved (Click on logo to view website)

LAS LASER ADDITIVE SOLUTIONS NUCLEAR AMRC Brunel University London TARAZ metrology IVY TECH

Technology next steps

The as-built SonicSMR system is already being used by two UK based organisations who are focussed on nuclear fusion system parts and their ongoing maintenance and repair.

LAS and the other project partners though are keen to seek additonal funding to further industrialise the SonicSMR technology so that SMR/AMR supply chains are provided with a further optimised alternative manufacturing process when making complex, expensive and safety critical parts.

Other Net Zero technologies that require high-spec but difficult to process materials, such as Hydrogen production, could also benefit from SonicSMR additive manufacturing/coating/joining technology.

Key outcomes from project

A nuclear-industry relevant Additive Manufacturing cell was designed and built at Laser Additive Solutions (LAS) premises in Doncaster, South Yorkshire. The facility includes a 3kW TRUMPF Laser, a 9-axis KUKA Robot system, and build volume capacity of 5m x 3m x 2m. Ancillary equipment includes both consumable metal wire and powder delivery systems.

Project partners developed and installed innovative power ultrasonic and AI-based defect recognition capability:
- Brunel University London, Cambridge: Sonication system used to create beneficial microstructures (grain refinement) and AI-based in-process/layer-by layer defect recognition capability
- Ivy-Tech, Derby: Transducer holder system which maintained finely controlled surface contact, measured via load-cells, between AM manufactured parts and the ultrasonic transducers
- Taraz-Metrology, Nottingham: 3D Optical Vision system used to confirm geometry of the AM built parts and real-time QA (layer-by-layer scans to confirm no defects present e.g. cracking, lack of fusion etc.)
- NAMRC, Sheffield: Brought together the SonicSMR technologies and proved, using real nuclear-industry components, the effectiveness of the system

Other key project information

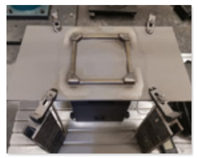
Investment BEIS: £876,800 (78%)
Match funding: £246,709
Total: £1,123,509

Project Start Date: May 2020
Completion Date: July 2021

Links to Net Zero R&D programmes/collaboration including subsequent commercial follow-on work:
- Currently supporting two nuclear fusion organisations (UKAEA and Tokamak Energy) applying our R&D to their development projects
- Valves used in non-civil power generating systems have already been manufactured using SonicSMR derived technology at LAS, Doncaster
- Project results achieved have been presented to several SMR supply chain vendors with the aim of encouraging the use of AM in future power generation plants

Project key facts:
- World-leading metal Additive Manufacturing Cell installed in Doncaster, South Yorkshire
- Technology developed in the 14-month long project already being used for Net Zero related commercial customers on high-end applications
- Pre and Post-Project meetings with the ONR highlighted a substantive change in attitudes regarding how Metal-AM can be a real advantageous manufacturing technology once mis-placed risk-related concerns are overcome

Key reports / presentations



Video of SonicSMR AM process

Nuclear Engineering International magazine article

Key websites

Project website www.laseradditivesolutions.co.uk/

Key project contact:

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Process Improvement Through CO_2 Cooling - PITCO$_2$C Evaluating the combined coolant and lubrication characteristics of supercritical CO_2 (scCO_2) + Minimal Quantity Lubricant (MQL) Lead: Nuclear Energy Components

Project background

Evaluating the combined coolant and lubrication characteristics of supercritical CO_2 (scCO_2) together with Minimal Quantity Lubricant (MQL) on legacy machine tools and as both a coolant and an assisting lubricant in the manufacture of high value nuclear components.

scCO_2 is becoming commonly used in modern non-nuclear manufacturing, due to its advantages of low critical pressure and temperature, stability, non-toxic, abundant reserves and low cost. Introducing scCO_2 + MQL to replace soluble oil coolant can advance the machining processes due to consequent improvements in material removal rates, cost savings and reduction in environmental impact. This project quantified those savings in the nuclear supply chain while developing a rotary coolant adaptor to allow widespread deployment of the technology on legacy machine tools.

Organisations involved (Click on logo to view website)

Key outcomes from project

The project was to develop the PITCO$_2$C technology to take it closer to production for 321L stainless steel and demonstrate its benefits for the production of fuel assembly components. This was done by developing a rotary gas connector for retrofitting a scCO_2 + MQL unit to legacy machine tools, removing barriers to adoption for the supply chain. The prototype connector was tested on one of NEC's fully enclosed CNC milling machines, and at TSP Engineering in Workington, Cumbria on larger open architecture machine tools.
The production of a cost model and carbon footprint model based on this real-life industrial data provided a robust financial and environmental justification for the nuclear supply chain and wider UK manufacturing sector.
Project successes included:
Increased tool life
The project was able to build on work previously done at the NAMRC and show a measurable increase of over 150% in the tool life on milling applications. Further work will be done to see if we can increase cutting parameters to reduce cycle time. This will be a case of balancing tool life and cycle time reductions to maximise productivity. To take advantage of the benefits offered by scCO_2 we need to complete design and manufacture of a robust rotary coolant adaptor.

- Greater knowledge of requirements of scCO_2+MQL as a cutting coolant/lubricant and what is needed to deliver this to the cutting edge. NEC have gained valuable knowledge regarding sealing and bearing technologies through the work done on this project.
- Progress towards having a working rotary coolant adaptor which, when completed, should enable production of an adaptor which can be utilised in the manufacturing sector to increase competitiveness, reduce waste and reduce negative health effects by removing traditional flood coolant

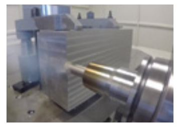
Key reports / presentations

Nuclear AMRC News article

Production Engineering Solutions article

Key websites

Machining trial with scCO_2 at NEC



NEC design Rotary Adaptor for scCO_2

Technology next steps

This machining technology is at TRL (Technology Readiness Level) 6 as the benefits in milling are well understood. However further research is still required before the significant gains demonstrated in milling can also be achieved on turning machines. The key next steps planned for this work are to test on combined milling and turning (mill-turn), and to continue development of the scCO_2 rotary cooling adaptor, which is only currently at TRL3, to allow this technology to be utilised on older legacy machine tools, of which there are many still in use.

Other key project information

Investment BEIS: £376,000 (68%)
NEC Match funding: £174,000
Total: £550,000

Project Start Date: May 2020
Completion Date: August 2021

Two journal papers have been produced as a result of this project – The first on developing turning using scCO_2 and the second on the development of the cost and carbon footprint model.

Nuclear Energy Components Ltd has developed its skills in 2D and 3D design by developing a Rotary Coolant Adaptor and also it's knowledge of seal technology for use in this adaptor.

Key project contact:

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Sensing Advanced Structures Lead: Rolls-Royce PLC

Project background

The aim of Project SAS (Sensing Advanced Structures) is to develop novel methods of joining sensing fibres, both internally and externally. These methods would remove the need for traditional penetrations and pressure, temperature, and strain transducers on nuclear power plants & components. The key technologies being developed specific for this application are: fibre bragg gratings; externally mounting fibre solutions; internal fibre embedment solutions and signal interrogation.

Physical demonstrators were manufactured to show internal & external sensing technologies. Incorporating optical fibre sensing technology into nuclear components such as pressure vessels and pipework, has the possibility of reducing the amount of equipment required for plant control, the potential to provide condition monitoring of nuclear plant components, and plant layout simplification. The technologies developed here could be utilised on new products, or retrofitted to in-service components.

Organisations involved (Click on logo to view website)

Key outcomes from project

The project down selected different methods for connecting the optical fibres to the internal and external demonstrators. Diffusion bonding (DB) and Hot Isostatic Pressing (HIP) were used to internally embed the optical fibre. Diffusion bonding was the down selected method of manufacture for the internal demonstrator. Adhesives, glass brazing and blown powder additive manufacture were used to externally attach optical fibres. The adhesive route was down selected for the external demonstrator. The external demonstrator successfully showed temperature response tracking during trials, with the adhesive-coated FBG providing a more rapid signal response compared to a traditional outlet thermocouple in the same position on the trial rig. The internal demonstrator however had no signal response during trials, route cause identified as cracks in the ferrule and fibre itself. In addition, the multi mode nature of Sapphire fibre and the low reflectivity of the fibre bragg gratings (FBGs) meant it was not possible to interrogate a signal. Thus, moving forward, Silica fibre must be used.

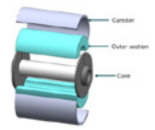
Key reports / presentations

BEIS Closure Report produced detailing key outcomes and lessons learnt during the project.

Key websites

BEIS Advanced Manufacturing Materials Successful Projects announcement

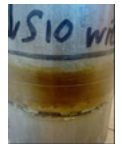
Central core



Internal DB design concept

DB HIP canister

The externally attached fibre using adhesives



Technology next steps

To improve the fibre robustness the fibre coating requires development with regards to material & thickness. These can be developed at the labscale. Experiments with high cooling rates, high temperature connectors may produce more repeatable results. Finally identifying NDT techniques to assess embedded fibre post manufacturing will be required to simplify the development process and prove out the technology.

Other key project information

Investment BEIS: £259,989 (65%)
Match funding: £140,000
Total: £399,989

Project Start Date: July 2020
Completion Date: April 2021

No interaction with other NIP projects but did present project intent and progress to ONR and Environment Agency.

- Skills development
Understanding of processing silica fibres above extant specification limits (e.g. temperature and pressure) and impact on optical performance when applying various attachment methods.
Manufacturing considerations for incorporation of fibres into/onto pressure retaining parts

Key project contact:

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Advanced Manufacture & Materials (AMM) U-Battery Advanced Modular Reactor HTGR:Full Scale Demonstrator. Lead: Urenco

Project background

U-Battery is an Advanced Modular Reactor (AMR) 4MW electric or 10MW thermal High Temperature Gas Reactor (HTGR), capable of providing a low-carbon source of heat or power for energy intensive industry and remote locations. The U-Battery's design is based on well developed technology and processes that have evolved in a series of HTGRs starting with the DRAGON at Winfrith from the 1960's. The U-Battery will be delivered to the site as a series of fully outfitted and tested modules that will maximise safety and quality by minimising on site operations programme and cost risks. The demonstrator provides a full scale mock-up of the U-Battery Reactor Cavity created by the coupling of two modules that contain the principal vessels, comprising: Reactor Pressure Vessel, Intermediate Heat Exchanger, and interconnecting Cross Vessel Duct.

U-Battery full scale mock-up

Organisations involved (Click on logo to view website)

Technology next steps

The AMM mock-up has proved a valuable asset for the development of the U-Battery approach to offsite module construction.

Proposed technology next steps to enable design underpinning of key details installation and outage operations include; remote Installation of a simulated graphite core and TRISO fuel blocks; demonstration of control rods and secondary shutdown systems; and thermal performance of the Reactor Cavity Control System.

Key outcomes from project

The full scale U-Battery Demonstrator was delivered and installed at the Cavendish Nuclear Whetstone Facility near Leicester in August 2021.
Key outputs include confirmation of details of the U-Battery Reactor Cavity module installation and decommissioning processes; midlife replacement of potential life limiting components such as the Cross Vessel Duct; application of remotely operated inspection vehicles for statutory vessel inspection. As well as demonstrating proof of concept, the Project also demonstrated constructability, on-time delivery in UK and transportation compatibility with UK road transport network.
The project included delivery of a comprehensive 3D model and other underpinning documents/drawings. The mock has provided the first tangible output of an AMR to be assessed by the regulators, investors, nuclear industry, insurers, media, supply chain and other key stakeholders.

Other key project information

Investment BEIS: £1,100,892 (65%)
Match Funding: £592,788 industry
Total: £1,693,680

Project Start Date: July 2020
Completion Date: September 2021

As well as the AMM programme, U-Battery is participating in Phase 2 of the UK Government's AMR Competition. In July 2020, it was one of 3 vendors to progress from Phase 1 to 2 of the competition and was awarded £10m of funding to initiate design and development work.

Aim is to take advantage of the economies of scale used in advanced manufacturing, modularisation settings and production line assembly techniques to produce this new generation of AMR technology, which will make a valuable contribution to the UK's decarbonisation. efforts. and, in turn, help deliver net-zero. We are now working to form new partnerships to support the next phase of U-Battery's design and development.

Building a full-scale model gives a real sense of what an AMR looks like as well as how it can be built. It also enabled us to determine the requirements for the preliminary concept design and justify the nuclear power plant's operational safety case.

Key reports / presentations

www.u-battery.com

www.u-battery.com

Key websites

www.u-battery.com

Key project contact:

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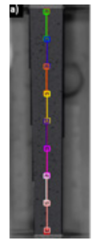
MANUFACTURING & MATERIALS

Evaluation Technologies for Advanced Manufacturing Qualification (ETAMQ) Lead: Jacobs

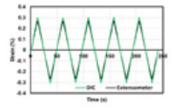
Project background

New manufacturing technologies and proposed advanced reactors require significant mechanical characterisation prior to their commercial adoption. Currently, there is limited UK capacity for such high-quality mechanical testing and these evaluations can be time consuming and costly to perform.
Three mechanical test types were the focus of this project: elevated temperature creep, strain controlled fatigue and fracture toughness. Two of these made use of the non-contacting strain measurement system – digital image correlation (DIC). DIC tracks a painted speckle pattern and the quality of this pattern is a key requirement for reliable strain measurement. This project used this technology in both the creep and fatigue testing to increase the amount of useable information from a single test.
Historically, the standard fracture toughness test methodology for high ductility materials has occasionally been found to be inoperable, requiring re-work, extra cost and lost time. In this work, a mechanistic understanding for the test procedure failure was studied to enable such problems to be avoided in future developments.

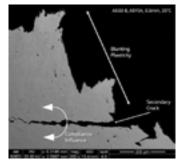
Location of the DIC virtual extensometers that measure strain along multiple points of one single tapered specimen.



Strain vs time for the first five cycles of the DIC controlled trial where good correlation between the real and virtual extensometers is apparent.



Secondary electron microscopy image highlighting blunting plasticity and secondary crack formation during fracture



Organisations involved (Click on logo to view website)

Technology next steps

Creep Testing - Further trials to include lower stress, smaller strain regimes, and to determine the sensitivity and stability of DIC. However, the technology could be deployed in the next few months for some applications. The development of the technology across further test stations is being investigated. A presentation to the British Standards committee is proposed.
Fatigue Testing - Further demonstration of the reliability of long term fatigue cycling at room temperature and the ability to produce similar fatigue endurances to those obtained from conventional extensometry.
For elevated temperature fatigue cycling, the elimination of the noise inducing thermal eddies are key and the use of vacuum conditions are being investigated.
Fracture Testing - The implications of the findings from this study will require presenting to the test standards committee, suggesting that modifications to the test standard may be required for some high ductility materials.

Key outcomes from project

Creep Testing - Two tapered test specimen geometries were developed, which enabled a range of test stresses to be achieved in a single test. DIC was successfully used to measure the strain development in the different regions of the test specimens and showed good correlation with conventional creep testing. This has the potential to multiply the number of datasets generated from a single test, enhancing UK capacity and reducing testing time.
Strain-Controlled Fatigue Testing - A non-contacting, local strain control method for low cycle fatigue testing employing DIC was developed. This was demonstrated both at room temperature and elevated temperature (550 °C), although the elevated temperature control requires further development to be reliable. An improved furnace design for DIC was manufactured. The surface speckle pattern used by the DIC for strain tracking was also developed in this project.
Fracture - Two materials identified and evaluated – one of which exhibited good test standard characteristics and a second which showed anomalous behaviour. An alternative crack monitoring system was installed alongside the conventional clip gauge and this showed similar behaviour suggesting that secondary crack formation is contributing to the compliance measurement. Detailed microscopy showed distinct features for the anomalous tests and suggested a potential cause.

Other key project information

Investment BEIS: £181,431 (65%)
Match funding: £97,694
Total: £279,126

Project Start Date: April 2020
Completion Date: March 2022

This project has linked with the MATTEAR BEIS project, using materials and extending property measurements. Discussions around the use of DIC with UKAEA were held. In addition, findings from the fracture work were also discussed with Rolls-Royce and EDF, highlighting potential alternative routes for the work.

Key project facts:

- UK first for DIC controlled room temperature fatigue testing.
- Successfully demonstrated DIC measurements across tapered creep specimen. Such tests effectively multiply the testing capabilities for the lab by >50 %.
- Successful implementation of a secondary crack extension monitoring system (DCPD), which highlighted the anomalous crack extension behaviour of the specimen during fracture.

Key reports / presentations

Final_Report

Creep_Report

Fatigue_Report

Fracture_Report

None of these documents are freely available online

Key websites

www.innovationfornuclear.co.uk/

Key project contact:

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Advanced Modular Reactor (Feasibility and Development and Regulator Capacity) Overview

The Advanced Modular Reactor (AMR) programme aimed to develop AMR technologies towards commercialisation and build UK supply chain & regulatory capability to support this development. The programme consisted of two strands, each with two Phases.

1. **The AMR Feasibility and Development (F&D) Project (£34m)**

- Phase 1 (£4m, November 2017 - October 2018): Eight projects undertaking a feasibility study on a specific AMR design to build and provide evidence base for future policy decisions.
- Phase 2 (£30m, July 2019 - March 2023): Awarded to three Phase 1 projects (U-Battery, Westinghouse, Tokamak) to undertake further Research & Development activities on their AMR design.

2. **The Regulatory Capability (RC) for Modular Reactors Project (£12m)**

- Phase 1 (£7m, September 2017 - October 2018) for Office for Nuclear Regulation and Environmental Agency to develop further capability and capacity to regulate modular reactor designs.
- Phase 2 (£5m, April 2019 - March 2023) to engage with specific designs involved in the AMR Feasibility & development projects and continued capability and capacity building to regulate a range of modular designs.

AMR - Feasibility and Development Studies (Phase 1)

Project background

Of the £34M BEIS invested in the Advanced Modular Reactor (AMR) feasibility and development (F&D) project, phase 1 provided funding of up to £4 million to undertake a series of feasibility studies for AMR designs, with contracts worth up to £300,000.

The overall aim of the programme was to maximise the amount of off-site factory fabrication targeting, generating low cost electricity, increased flexibility in delivering electricity to the grid and increased functionality, such as the provision of heat output for domestic or industrial purposes, or facilitating the production of hydrogen alternative applications, that may generate additional revenue or economic growth.

8 organisations were awarded contracts to produce feasibility studies as part of phase 1 of the AMR F&D project these being, Advanced Reactor Concepts LLC, DBD Limited, Blykalla Reaktorer Stockholm AB (LeadCold), Moltex Energy Limited, Tokamak Energy Ltd, U-Battery Developments Ltd, Ultra Safe Nuclear Corporation, Westinghouse Electric Company UK.

Organisations involved (Click on logo to view website)

ARC DBD LeadCold tokamak energy
U-BATTERY Local Modular Energy moltex clean energy USNC ULTRA SAFE NUCLEAR Westinghouse

Technology next steps

Following on from demonstrating clear value for money and government approval, a share of up to £30 million was available for selected projects from phase 1 to undertake development activities. The successful organisations whose pages follow in this brochure were Tokamak Energy, Westinghouse, and U-Battery.

Key outcomes from project

Funding provided to eight contractors to undertake a feasibility study on a specific AMR design to provide an evidence base. These feasibility studies were submitted by January 2019, and have now been reviewed. As part of this study, there were a number of support contracts that facilitated the studies.

Key Outcomes: 8 consistently formatted feasibility studies providing a detailed evidence base on various AMR designs.

Each organisation provided an abstract summarising their proposal which is shared below. The claims and opinions expressed in the abstracts are those of the applicant organisation and don't necessarily reflect the official policy or position of BEIS.

Other key project information

Investment BEIS: £4,000,000
Match funding: NA

Project Start Date: November 2017
Completion Date: October 2018

Key reports / presentations

Link to Project

Key websites

www.gov.uk/government/publications/advanced-modular-reactor-amr-feasibility-and-development-project

Key project contact:

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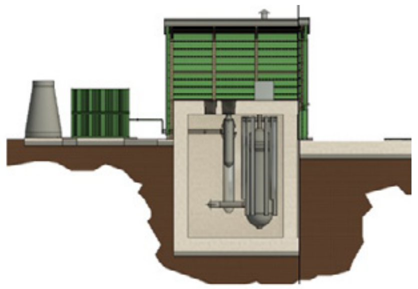
Tel:

Advanced Modular Reactor Phase 2
U-Battery High Temperature Gas Reactor
Lead: Urenco

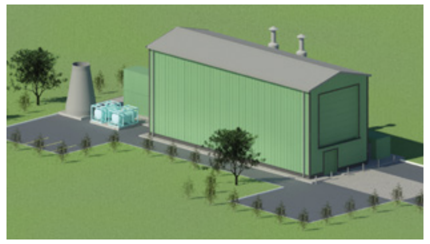
Project background

U-Battery is an Advanced Modular Reactor (AMR) 4MW electric or 10MW thermal High Temperature Gas Reactor (HTGR), capable of providing a low-carbon, cost-effective, locally embedded and reliable source of heat or power for energy intensive industry and remote locations. U-Battery aligns with the Ten Point Plan for the Green Industrial Revolution in the ambition to develop an Advanced Modular Reactor (AMR) demonstrator by the early 2030s at the latest. The U-Battery's design is based on well developed technology and processes that have evolved in a series of HTGRs starting with the DRAGON at Winfrith from the 1960's. The U-Battery has a Helium cooled, prismatic graphite core loaded with high accident tolerant TRISO fuel (TRi-structural ISOtropic). The U-Battery will be delivered to the site as a series of fully outfitted and tested modules that will maximise safety and quality by minimising on site operations, programme and cost risks.

Cross section of the U-Battery reactor cavity



3D image of the U-Battery HTGR



Organisations involved (Click on logo to view website)

urenco, Kinectrics, Jacobs, Nuclear AMRC, National Nuclear Laboratory, Cavendish Nuclear, The University of Manchester, Rolls-Royce, Costain

Technology next steps

The key technical objective is to ensure the U-Battery is economically viable and that will requires all systems and components to be simple, reliable and delivered in a form that maximises commercial off the shelf (COTS), off site module build and minimises onsite activities

Key outcomes from project

With funding from the BEIS AMR Phase 2 competition U-Battery Developments Ltd is delivering the Conceptual design of the first of a kind (FOAK) deployment of the AMR HTGR, known as the U-Battery. The U-Battery AMR Phase2 is due to be completed September 2022 and a FOAK is anticipated to be completed before the end of the decade.

Key outcomes from project include confirmation of design of key U-Battery Reactor systems comprising; fuel, coated particles and fuel blocks; core and primary cooling circuit, Reactor Pressure Vessel structures and components; safety and auxiliary systems; control instrumentation and autonomous operations; power conversion systems including heat and electrical power options; refuelling and core component replacement; and building and civil structures. Other outputs include decommissioning spent fuel and waste management; safety and environmental impact; advanced manufacturing including module design; transportation of modules and fuel import/export; and human factors with respect to operations and maintenance.

Other key project information

Investment BEIS: £10,000,000
Match funding: N/A
U-Battery is participating in Phase 2 of the UK Government's AMR Competition. In July 2020, it was one of 3 vendors to progress from Phase 1 to 2 of the competition and was awarded £10m of funding to initiate design and development work.

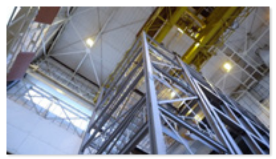
Project Start Date: Summer 2020
Completion Date: Summer 2022

U-Battery presents a great opportunity to help deep decarbonisation of the hard to abate sections of the economy and support the UK Government's commitment to reach net zero by 2050, levelling-up, as well as support energy security and energy independence.

U-Battery is a cogeneration unit (10MW thermal and 4MW electric) capable of providing electricity for energy intensive industries and contribute to the decarbonisation of heat and hydrogen/synthetic fuel production.

We have also successfully delivered the AMM U-Battery mock-up in a short period from initial concept, through to design, manufacture and assembly has been a real success for the nuclear industry and demonstrated its ability to deliver critical projects on time and budget.

Key reports / presentations



YouTube

Key websites

www.u-battery.com/

Key project contact:

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FEASIBILITY AND DEVELOPMENT

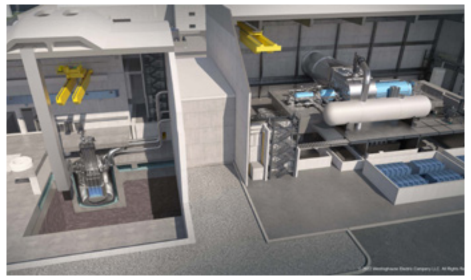
Westinghouse Lead-cooled Fast Reactor

Project background

Westinghouse is developing its Next Generation of high-capacity nuclear power plants based on Lead Fast Reactor (LFR) technology. With a net power output of approximately 450 MWe, the Westinghouse LFR's primary mission is to reduce front-end capital cost and generate flexible and cost-competitive electricity even in the most challenging global energy markets, while offering mission versatility and satisfying the highest safety and sustainability standards. LFR technology is supportive of this goal, and was selected by Westinghouse after realistic and unbiased consideration of all competing nuclear technologies, accounting for multiple evaluation criteria encompassing safety, economics, market versatility including non-electricity missions (e.g., process heat, hydrogen), technology readiness, fuel cycle flexibility, etc. LFR development, which leverages collaboration with global partners, is being accelerated through the setup and operation of eight state-of-the-art test facilities in the UK, aimed at demonstrating key materials, systems, components and phenomena of the Westinghouse LFR. In this context, a key role is played by Westinghouse-Springfields, which is envisioned to become a Centre of Excellence for LFR technology development.

Westinghouse LFR two-unit site (artistic rendering)

Cut-out of Westinghouse LFR Nuclear Island and Turbine Building



Organisations involved (Click on logo to view website)

Westinghouse, Ansaldo Nucleare, ENEA, Fauske & Associates, Argonne National Laboratory, Frazer-Nash Consultancy, National Nuclear Laboratory, Nuclear AMRC, Los Alamos National Laboratory, Jacobs, INL Idaho National Laboratory, Bangor University, Oak Ridge National Laboratory, The University of Manchester, University of Pittsburgh, UNM, Texas A&M, PennState, Wisconsin, BYU

Technology next steps

Westinghouse continues development of LFR using experimental and analytical results obtained during Phase 2 of the AMR programme. This includes advancing design maturity at component, system and plant layout level, which will consistently feed into updates of cost and business case models. In addition, test facilities set up as part of Phase 2 of the AMR Programme will continue to be used based on priorities, and their use will be complemented by integral effect testing in a properly-scaled, larger size facility reproducing key components/systems of the Westinghouse LFR. In parallel, down-selected materials will be further assessed for longer testing time and, when applicable, in operating conditions that will include the effect of irradiation. The resulting increase in TRL, together with ongoing customer interaction, will allow to proceed into licensing and LFR demonstration.

Key outcomes from project

The Westinghouse LFR will be developed through a staged approach commencing with a lower-power demonstration LFR which, through adoption of reduced duty conditions, maximises the use of high readiness materials thus allowing demonstration of LFR's overall safety and performance characteristics in the 2030 timeframe. Experimental data and operating experience accumulated with the demonstration LFR will be used to support the development of the 450 MWe-class plant, which is currently being designed by Westinghouse and its partners for commercialisation purposes and is envisioned to operate at more demanding conditions to further enhance economic performance. Phase 2 of the Advanced Modular Reactor programme plays a key role in the development of both the near-term LFR demonstrator and its subsequent, higher performance evolution. Key outcomes of the AMR project are:

- Setup and operation of eight state-of-the-art test facilities in the UK, which will bring the UK at the forefront of LFR technology development globally
- Collection of experimental data to accelerate LFR design and licensing
- Engagement with the UK Regulators to discuss key aspects of LFR technology in preparation to future GDA efforts
- Development of an LFR modular delivery strategy to selected UK sites
- Training and familiarisation of UK professionals on LFR technology development

Key reports / presentations

The Westinghouse Lead Fast Reactor: design overview and update on development activities (International conference on fast reactors and related fuel cycles, FR22, April 2022).

Progress in the Westinghouse LFR Safety Analysis in Support of the UK Advanced Modular Reactor Programme (19th International Topical Meeting on Nuclear Reactor Thermal Hydraulics, NURETH-19, March 2022).

Development of phenomena identification and ranking table for Westinghouse lead fast reactor's safety (Progress in Nuclear Energy, Vol. 131, Jan 2021).

Other key project information

Investment BEIS: £300,000 (AMR Phase 1); £10,000,000 (AMR Phase 2)
Match funding: Westinghouse and its key partners Ansaldo Nucleare and ENEA invest in LFR development both inside and outside of the AMR programme.

The Westinghouse LFR project started in 2015. In the frame of this project, the AMR programme took place during these time periods:
AMR Programme - Phase 1: July 2018 - March 2019
AMR Programme - Phase 2: July 2020 - March 2023

Interaction with other NIP projects and more broader links to R&D programmes/collaboration:
- Advanced Fuel Cycle Programme, through development activities on Uranium Nitride fuel and advanced fuel rod cladding
- Digital Reactor Design, through development activities aimed at enhancing thermal hydraulic modelling capabilities for liquid metal-cooled reactors
- Generation IV International Forum, supporting UK contribution to international collaboration on Generation IV nuclear technologies

Key facts of AMR Phase 2 programme:
- Nine international organisations
- Eight state-of-the-art test facilities supporting LFR development erected at various UK institutions (Westinghouse-Springfields; Ansaldo Nuclear – Wolverhampton; Jacobs – Warrington; University of Bangor)
- Advances in Uranium Nitride fuel manufacture and testing at the National Nuclear Laboratory and University of Manchester
- Training on LFR technology R&D and on design/operation of associated experimental infrastructure offered to approximately 50 UK professionals by ENEA, a world leader in LFR technology R&D

Key websites

www.westinghousenuclear.com/new-plants/lead-cooled-fast-reactor

Key project contact:

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Tokamak Energy- Advanced Modular Reactor Fusion Project

Project background

The aim of the Advanced Modular Reactor programme at Tokamak Energy is to advance technology required for a commercial nuclear fusion device. Tokamak Energy develops spherical tokamaks and associated technology with the goal of developing the fusion power plant of tomorrow, while commercialising the technological applications today.

For plasma facing components (PFCs), advances are needed to ensure the components survive the heat loads and erosion from energetic particles from the plasma. The technologies and the associated analysis required for design are key for the development of any nuclear fusion device.

For a Spherical Tokamak (ST), high-temperature superconductors (HTS) are an enabling technology. Under AMR, a cryogenic power supply for high-current magnets, error field correction coil designs, manufacturing tooling for large scale HTS magnets, a cryogenic rig for applying high compressive stress to energised HTS coils and quench protection system methodology are being developed.

Organisations involved (Click on logo to view website)

University of Huddersfield – Inspiring global professionals
Cambridge Vacuum Engineering
mtc
TWI
Jülich Forschungszentrum
Qdot Technology
University of Illinois Urbana-Champaign
LAS Laser Additive Solutions
HSSMI

Key outcomes from project

PFC technology development

An in-depth review into existing PFC materials, joining techniques and cooling strategies was carried out to understand the technology landscape and see where development could be carried out. This review has enabled Tokamak Energy to develop functional requirements for a commercial nuclear fusion reactor and allow a much more focused approach toward technologies that are relevant to the application. The broad areas of development included solid PFCs, liquid metal PFCs, cooling systems, pumping systems, and high heat flux testing facilities.

HTS Magnet technology development

Development of the cryogenic power supply and the demonstration that it has less than 30% of the dissipation of the conventional high-current leads from room temperature. Development of code for the design and analysis of tokamak error field correction coils (EFCC). Design, construction, and use of a rig to apply compressive stresses up to 500 MPa to cold and energised HTS test coils to measure degradation in real time. Development of quench protection methodology for large-scale HTS magnets. Feasibility study to review and develop manufacturing processes and the associated tooling for fabricating large-scale HTS TF magnets.

Key reports / presentations

Tokamak Energy HTS article

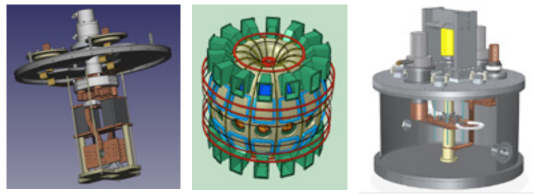
AMR Divertor Lab opened

Key websites

Company website: www.tokamakenergy.co.uk
Consultant website: www.littlebeastengineering.com/
Consultant website: www.hssmi.org/

PREFACE cooling rig at Tokamak Energy

CryoPSU (left), EFCC's on an ST concept (centre), Cryo compression rig (right)



Technology next steps

Tokamak Energy is committed to developing a commercial nuclear fusion demonstration reactor. In progressing towards this goal, the PFC technology must be upscaled and developed to a commercial quality, reliability, and durability for deployment.

The test facilities and skills developed through the AMR programme will be used for progressing the Technology Readiness Level (TRL) of solid and liquid PFC's. The divertor and PFC solutions will eventually be deployed as reactor-relevant solutions on ST-HTS.

The next Toroidal Field (TF) HTS magnets to be designed and built by Tokamak Energy will utilise the manufacturing processes and tooling proposed under AMR. The coil designs will use the stress data from the AMR funded test rig and the quench protection system will be based on the schemes developed. These coils will be fundamental to the ST-HTS medium scale tokamak which will consolidate the technology developed by Tokamak Energy.

Other key project information

Investment BEIS: £10,000,000
Match funding: N/A

Project Start Date: July 2020
Completion Date: December 2022

PFC Technology Development project chosen key facts:

- PFC Cooling Technologies TRL increase from 2 to 5
- Particle Erosion TRL increase from 2 to 5
- Divertor System Level Integrated Engineering Design
- High Heat Flux (E-Beam), Evaporation Rig & Gettering Experiment Development
- Computational forward modelling (SOLPS, HEAT, FreeGS) upskilling
- ST40 Plasma Exhaust Data Analysis Deployment
- Supply Chain and Collaboration network extended
- Multiple journal articles published
- Increased Intellectual Property portfolio and journal outreach.

HTS Magnet Development project chosen key facts:

- Cryogenic PSU TRL increase from 2 to 5
- Cryogenic stress loading TRL increase from 2 to 5
- EFCC design and analysis codes developed
- Partial Insulation TRL increase from 3 to 4

Key project contact:

Name: Marion Hudson, AMR Programme Manager
Email: marion.hudson@tokamakenergy.co.uk
Tel: +44 (0)1235 617936

Preparing for Regulating Advanced Nuclear Technologies (ANTs). The Office for Nuclear Regulation (ONR) and Environment Agency (EA)

Project background

ANTs encompass a wide range of innovative nuclear reactor technologies, including Small Modular Reactors (SMRs) and Advanced Modular Reactors (AMRs).

In October 2017, as part of the Clean Growth Strategy, the government announced that it will invest up to £12 million to further develop the capability and capacity of the nuclear regulators (ONR and EA) to support and regulate the development of ANTs.

Since 2017, the nuclear regulators (ONR and EA) have developed and implemented programmes of work with the following objectives (see figure 1):

- Develop capability and capacity to regulate ANTs
- Modernise our GDA process
- Provide regulatory advice to the Department for Business, Energy and Industrial Strategy (BEIS)
- Engage with international regulatory bodies
- Engage with ANT industry and supply chain

Organisations involved (Click on logo to view website)

ONR Office for Nuclear Regulation
Environment Agency

Key outcomes from project

Develop capability and capacity to regulate ANTs

We have developed world class expert technical capability to assess and regulate innovative ANT ensuring ONR and EA are ready to regulate these technologies now. We've trained over 30 inspectors on ANT technologies, attended over 20 international conferences and organised cross-regulator knowledge management workshops.

Modernised Generic Design Assessment (GDA)

The modernised GDA provides greater flexibility and options for licensing and design assessment in the UK. It is already being utilised for the assessment of the Rolls-Royce SMR in accordance with its specific objectives and technical readiness, but the modernised process could be applied in alternative ways to different technologies whilst still providing the regulatory assurance to vendors, investors, government and the public that has become its hallmark.

Regulatory Advice to UK Government (BEIS)

We completed a multi-disciplinary evaluation of seven AMR designs selected by BEIS as part of its AMR Feasibility and Development Project. We produced regulatory criteria based on our existing regulatory guidance and applied this to the AMR F&D project to provide our expert advice on if an AMR design could meet UK regulatory requirements in the future.

Maintained global leadership on international regulatory cooperation

We actively participated in several ANT international forums, such as the IAEA SMR Forum. We shared good practices with overseas regulators and research organisations to further develop our capability and influence ANT international standards. We participated in a technical consultancy meeting on the applicability of IAEA standards to AMRs, providing technical expertise to support the production of IAEA guidance.

Engage with ANT industry and supply chain

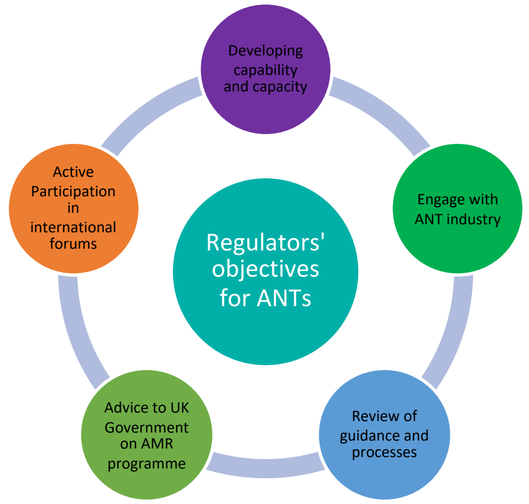
We held over 50 seminars and 1-to-1 workshops with ANT vendors and supply chain organisations. The phased approach allowed early sight of design developments and an opportunity to communicate our regulatory expectations to support entry into GDA.

Key reports / presentations

Key websites

www.onr.org.uk/advanced-nuclear-technologies/index.htm
www.gov.uk/government/publications/advanced-nuclear-technologies/advanced-nuclear-technologies

Nuclear regulators' (ONR and EA) objectives for ANTs



Technology next steps

Rolls-Royce SMR Ltd's 470 MW Small Modular Reactor design has started the modernised GDA process.

The nuclear regulators (ONR and EA) will provide regulatory advice to BEIS on its AMR Research, Development & Demonstration Programme. This utilises our knowledge on High Temperature Gas Reactors (HTGRs), with BEIS aiming to lead to a HTGR demonstration by the early 2030s at the latest.

Other key project information

Investment BEIS: £12,000,000
Match funding: N/A
Project Start Date: September 2017
Completion Date: March 2023

Interaction with other NIP projects and more broader links to R&D programmes/collaboration inc. leverage into this project and leverage includes:

- Engaged with 10 UK based Advanced Manufacturing companies
- Collaborated with international regulatory bodies discussing cross-cutting topics and sharing of good practices

Highlights of the ONR and EA engagement with ANT vendors:

- Three phase engagement with eight AMR vendors on regulatory expectations
- Series of engagements with SMR vendors on regulatory expectations

Highlights of the ONR Advanced Manufacturing and Materials Project

ONR engaged with 10 UK based Advanced Manufacturing companies Objectives included engaging with vendors to provide advice on UK nuclear regulation; develop our knowledge; and review our guidance for compatibility with advanced manufacturing technologies.

Key project contact:

Email: ant@environment-agency.gov.uk
Email: ANTs@onr.gov.uk

Advanced Reactors Overview

Advanced Reactors was a two-phase programme that applied digital engineering techniques to the design and development of reactor systems and components. The programme combined two streams of work: Thermal Hydraulics Modelling; and Nuclear Virtual Design. Phase 1 funded three projects (with one split between two Phases of work).

Phase 2 built on the work of Phase 1 and continued with thermal hydraulic model development, including identification of any necessary supporting R&D. The Phase also supported further developments in Nuclear Virtual Engineering Capability (NVEC), and developed innovative methods for verification and the management of data to support NVEC.

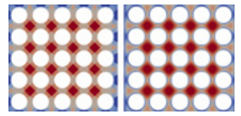
Advanced reactor thermal hydraulics model development
Lead: Frazer-Nash Consultancy

Project background

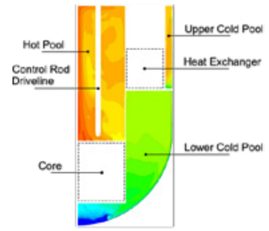
The aim of the Thermal Hydraulic Model Development programme is to develop a digital reactor design capability within the UK for Advanced Nuclear Technologies (ANTs), which includes Small Modular Reactors (SMRs) and Advanced Modular Reactors (AMRs). The goals of the programme include establishing a world leading UK capability in thermal hydraulics; becoming a preferred partner for engagement in international collaborative design projects for new reactors; and reducing the cost of nuclear reactor design and build.

Nuclear Thermal Hydraulics (NTH) is a key element of Nuclear Power Plant (NPP) design and safety. It is the study of engineering systems where energy from nuclear fuel is transferred by a coolant to a power generation turbine or to the environment by heat transfer, flow processes or phase change.

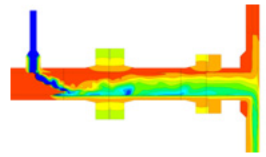
Novel Coarse Grid CFD method to model whole fuel assembly



Primary circuit temperature predictions to support Lead Fast Reactor (LFR) design



CFD analysis validation of emergency core cooling system for an SMR



Organisations involved (Click on logo to view website)

Core Team - Building Knowledge Base

Additional Phase 2 Partners - Upskilling Wider Industry and Routes to Exploitation

Technology next steps

This project has transformed the UK's NTH CFD modelling capability for AMRs, particularly for liquid metal and molten salt, but there remain a large number of challenges in modelling NTH phenomena.

There is a growing potential and interest in high fidelity CFD tools for nuclear reactor design with live international collaboration opportunities.

In order to support a UK AMR Demonstrator programme, it is necessary to develop an AMR system modelling capability, backed up by the industrialisation of our novel Coarse Grid CFD method.

Key outcomes from project

Phase 1: A critical review was conducted of thermal hydraulic modelling capability and worldwide test facilities, together with a detailed user requirements exercise. This was used to develop modelling and facility specifications, together with a recommendation for the focus of the proposed £40m NTH test facility in North Wales. Innovative models have been developed that are relevant to both SMR and AMR reactor programs to increase UK understanding and improve UK capability. This facility project was subsequently progressed in later phases by the UKAEA.

Phase 2: A set of 6 Technical Volumes and 4 Case Studies have been published summarising good practice for NTH analysis of single phase heat transfer and natural convection to improve the UK's Computational Fluid Dynamic (CFD) predictive capability for passive safety arguments in ANTs. This project has significantly enhanced the visibility and reputation of the UK nuclear industry on the international stage. Dissemination: The outputs from the programme are hosted on the IMechE website and were disseminated to UK and international thermal hydraulics community. We are exploiting this work through collaboration with SMR and AMR vendors.

Other key project information

Phase 1	Phase 2
Investment BEIS: £1,844,715 Match Funding: N/A	Investment BEIS: £2,490,000 Match Funding: N/A

Phase 1	Phase 2
Project Start Date: March 2017 Completion Date: September 2019	Project Start Date: April 2019 Completion Date: December 2021

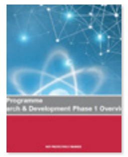
Interaction with other NIP projects and more broader links to R&D programmes/collaboration inc. leverage.
- Supported the US / UK action plan and presented internationally
- Supported multiple vendors applying our R&D to their development projects
- Collaborated with other NIP projects to maximise value within the programme

Project chosen key fact such as
- Over 50 collaborators
- Over 40 project deliverables with 1000+ pages
- Dissemination to over 15 countries

R&D undertaken for these nuclear technologies and referenced as best practice by leading international bodies:
- Gen III+ (Light Water)
- Gen IV (Molten Salts, Liquid Metals & High Temperature Gas Reactors)

Key reports / presentations

Link to Project webpage



Phase 1 summary

Modelling review

Facility review

Technical Volumes

Case Studies

Key websites

Project website: www.innovationfornuclear.co.uk/

Technical Volumes and Case Studies: www.imeche.org/digital-thermal-hydraulics

Key project contact:

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Tel: +44 (0)1179 226242

BACK TO CONTENTS

Nuclear Virtual Engineering Capability
Lead: Jacobs

Project background

Modern nuclear design, construction, commissioning, operation and decommissioning requires collaboration of multiple organisations.

The Nuclear Virtual Engineering Capability (NVEC) at its core is a way of working to improve the flow of data inside an organisation and between organisations. The primary challenges addressed by NVEC are: overcoming siloed working, improving information handover, enhancing innovation and improving cost management.

As a key element of NVEC, a prototype software framework for collaboration was developed, and its use and benefits demonstrated in a range of commercially oriented applications. Combined with the software framework, NVEC comprises standards and guidance and ultimately an NVEC community spanning the nuclear sector and adopting a more collaborative and digitally aware working culture.

Organisations involved (Click on logo to view website)

Phase I partners:

wood. | VIRTUAL ENGINEERING CENTRE | ROLLS ROYCE | EDF | NATIONAL NUCLEAR LABORATORY | UNIVERSITY OF LIVERPOOL | Imperial College London | UNIVERSITY OF CAMBRIDGE

Phase II partners:

Jacobs | VIRTUAL ENGINEERING CENTRE | ROLLS ROYCE | EDF | NATIONAL NUCLEAR LABORATORY | NUCLEAR AMRC

*Wood logo is now Jacobs

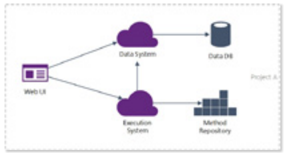
Key outcomes from project

- The software framework developed can serve as a common data and modelling environment. By enabling a 'single source of truth' and integration of data management with physics simulations it forms the basis to develop and operate digital twins. Several case studies have been developed demonstrating the benefits of the framework, including:
  - Integration of tools to assess the ageing of graphite in nuclear reactors
  - System level modelling of a molten salt reactor
  - Integration of software toolkit to enable an agile robot-based approach to decommission of nuclear sites
  - Digital twin for manufacturing of nuclear reactor component
  - Integration of coupled multi-physics simulations for nuclear reactors
  - Operation of models based on live sensor data (thermal/hydraulic)
- The project has succeeded in creating a community of users and has facilitated collaboration. Various dissemination activities have been carried out including presentations, workshops and demonstration events.
- A benefits analysis has shown that NVEC will enable significant efficiency improvements throughout the life cycle of a nuclear facility.
- A roadmap has been developed focussing on both the development of the core NVEC elements and opportunities for the application of NVEC.
- Phase 1 of the NVEC project included the evaluation of industry demands and capacities and the development of a proof-of-concept software framework. Building on this initial work, Phase 2 has laid the foundations for the establishment of NVEC across the sector and its use for commercial project.

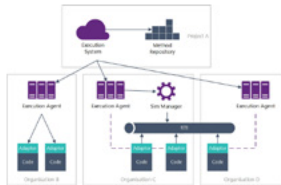
Key reports / presentations

NVEC digital environment

Prototype NVEC software architecture



Integrated simulation within prototype NVEC architecture



Technology next steps

Key future activities of importance for the sustainable establishment of NVEC in the nuclear sector are:

- Further development of the software framework to be tailored to the evolving needs of the users.
- Further refinement and implementation of a governance model to facilitate continuous development and of a commercial model to enable organisations to benefit from NVEC.
- The application of the NVEC approach and software architecture to real world problems to build up the capability in the UK, to demonstrate the use of new tools/methods developed and to inform the requirements for further software developments.

Other key project information

Phase I:	Phase II:
Investment BEIS: £2,800,000	Investment BEIS: £4,200,000
Match funding: N/A	Match funding: N/A

Phase I	Phase II
Project Start Date: 2017	Project Start Date: 2019
Completion Date: 2019	Completion Date: 2021

Interaction with other NIP projects and broader links to R&D programmes/collaboration:

- Close collaboration with other NIP projects maximising value of NIP programme.
- Links developed with R&D programmes in partner organisations (companies and universities)

Project key facts:
- Development of software framework over 6 TRLs
- Over 40 collaborators
- Several early career researchers engaged

Key websites

Project website: www.n-vec.co.uk

Key project contact:

Name: Dr Albrecht Kyrieleis | Zoe Pawezowski
Email: albrecht.kyrieleis1@jacobs.com | zoe.pawezowski@jacobs.com
Tel:

Reactor Design: Safety & Security Research and Development Programme
Lead: Frazer-Nash Consultancy

Project background

The 2017 NIRAB Reactor Design Recommendation Report advised the UK that, "Developing digital tools and fundamental scientific understanding needed to design and build future generations of reactors in an accelerated and cost-effective way, with emphasis on ever increasing safety". The Safety and Security programme was commissioned to research new techniques and methods that provide engineers with a greater insight into their reactor technology's safety and security performance, empowering them to make risk informed decisions that drive cost reduction. The programme includes 20 Research and Development projects focused in four key areas of both safety and security:

- Advanced Safety Case Methodologies
- Security Modelling and Simulation Assessment Methodologies
- Reactor Design for Safety, Security and Safeguards
- Control and Instrumentation Safety and Secure Design Capability

The programme encompasses targeted engagement with end users from industry and the regulator to ensure the outputs of the programme are put into practical use to realise benefits for the UK nuclear sector.

Organisations involved (Click on logo to view website)

FRAZER-NASH CONSULTANCY | NATIONAL NUCLEAR LABORATORY | Jacobsen analytics | Lancaster University | UNIVERSITY of York | University of BRISTOL | EDF | context | ROLLS ROYCE

Key outcomes from project

- A path through safety/security case production and licensing for vendors of new nuclear plant defined and clarified.
- Key principles and tools for facilities to be 'Secure by Design' defined and accepted by World Institute of Nuclear Security.
- Novel options for security architectures for a fleet of SMRs assessed and guidance produced.
- Application of MBSE in safety cases has attracted wide interest from industry.
- Integration between safety & security disciplines has been improved (e.g. ALARP for security).
- Improved understanding of impact of new technologies (information displays and automation) on AMR operators.
- Test facility for qualification and assessment of smart electrical power system components for UK nuclear applications, in partnership with Nuclear AMRC in Derby.
- Enduring dissemination and exploitation activities are ongoing in 2021, to continue upskilling people across the industry.

Key reports / presentations

Alternative Programming Approaches for Nuclear Software

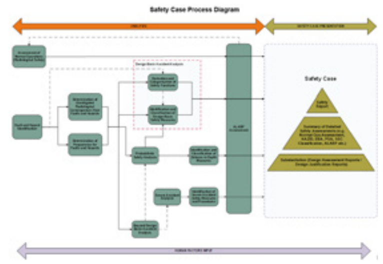
Application of MBSE

Secure by Design - Guidance document - Principles and Methods

Advances in Common Cause Failure Analysis and a Roadmap for Future Probabilistic Safety Analysis

C&I Test Facility – Smart power device test bed showing the testing of a relay. Installed capability at NAMRC.

The safety case toolkit provides a single source repository of safety case guidance and best practice tools and techniques.



Technology next steps

As outlined in the UK Government's Ten Point Plan and Energy White Paper, advanced nuclear technologies have a key role to play in meeting net zero targets. Safety & Security (S&S) remains an R&D priority.

The challenges for SMR and AMR technologies will be even greater, with considerable differences from current plant and the requirement to integrate with novel heat and hydrogen energy systems. This is an issue the industry must tackle to successfully deploy SMRs & AMRs in the 2030s, with targeted R&D and enabling activity at the heart of that effort.

Other key project information

Phase I:	Phase II:
Investment BEIS: £343,883	Investment BEIS: £3,649,456
Match funding: N/A	Match funding: N/A

Phase I	Phase II
Project Start Date: March 2017	Project Start Date: April 2018
Completion Date: March 2018	Completion Date: March 2021

Follow-on work has been secured with SMR and AMR vendors, to exploit and apply the outputs of the Safety & Security programme to their reactor designs. The outputs and reports have also been made freely and publicly available via our website to best support exploitation and onward application by our sector.

Secure by Design:
- Development of new guidance on the early integration of security objectives of skills development within the design of nuclear facilities.
- International engagement through WINS (World Institute for Nuclear Security)
- Methodology adopted by leading advanced nuclear technology vendors

Cyber incident response and recovery framework
- An interactive framework, collating good practice from 31 international standards
- Provides support to operators of nuclear facilities acting as a working guide for cyber security duty holders.

Key websites

Project summaries and outputs will be made available:
www.innovationfornuclear.co.uk/safetyandsecurity.html

Safety Case toolkit is available: www.innovationfornuclear.co.uk/toolkit/toolkit.html

Key project contact:

Name: Tom Purnell, Business Manager
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Tel: +44 (0) 1179 226242

Strategic Toolkits Overview

The Strategic Toolkits programme was an integrated programme on nuclear facilities and development of a strategic toolkit covering the following areas:

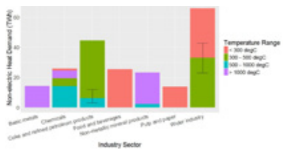
1. Strategic Assessment – development of nuclear energy-futures modelling tools, and identifying and developing solutions to assess potential nuclear fuel scenarios.
2. Fast Reactor Knowledge Capture – a targeted knowledge capture exercise on UK fast reactor programmes, and the assessment, organisation and dissemination of results as appropriate.
3. Regulatory Engagement – facilitate engagement and input from UK nuclear regulators with wider nuclear R&D programme.
4. Access to irradiation facilities – membership of the Halden Reactor/Jules Horowitz Reactor.
5. NEA Membership and Data bank – improved coordination and optimal use of facilities available to the UK nuclear sector.

Strategic Toolkit and Nuclear Facilities
Lead: National Nuclear Laboratory

Project background

The strategic toolkit and nuclear facilities project was established to inform Government decision making on the implementation of nuclear technologies within its energy policies. Through creating a suite of tools and underpinning data, the project aims to support Government's ability to make evidence-based policy decision on nuclear technologies. The work also aimed to improve the coordination and optimal use of the facilities available to the UK nuclear sector. This includes ensuring the UK's continued representation at international collaboration networks (Halden Reactor Project, Jules Horowitz Reactor) in order to influence the direction of research and development (R&D) programmes for the benefit of the UK. The project includes the UK's membership of the OECD Nuclear Energy Agency (NEA) and NEA Databank, which is crucial for UK influence and operations

Matrix of reactor technologies and outlet temperatures, this enables a consideration of possible role in future industrial decarbonisation.



Mapping of non-electric heat demand for industry to enable an assessment of possible roles for future nuclear technologies in industrial decarbonisation

Significant work under this programme was focussed on capturing the significant UK fast reactor programme. This has been captured and archived for future UK benefit using experts from the UK fast reactor programme.

Temperature range	Light Water Reactor (LWR)	Liquid Metal Fast Reactors (LMFR)	High Temperature Reactor (HTR)	Very High Temperature Reactor (VHTR)	Molten Salt Reactor (MSR)	Supercritical Water Reactor (SCWR)	Gas-cooled Fast Reactor (GFR)
<300 °C	✓	✓	✓	✓	✓	✓	✓
300-500 °C		✓	✓	✓	✓	✓	✓
500-1000 °C			✓1	✓	✓		✓
>1000 °C							

Organisations involved (Click on logo to view website)

National Nuclear Laboratory · IDM integrated decision management · Jacobs · EDF · Grallator · NEA Nuclear Energy Agency · RJH

Technology next steps

Apply tools and capabilities to assessments in support of decision making on nuclear technology and energy policy.

Enhance and supplement existing tools to meet future assessment requirements.

Ensure UK participation in post-Halden programmes such as the NEA Framework for Irradiation Experiments (FIDES).

Broaden knowledge capture activities to support future reactor development and deployment.

Key outcomes from project

Tools and models: Creation of a high-level model framework that brings together existing models and techniques used to assess emerging technologies, fuel cycles and future energy scenarios. Development of fuel cycle models to provide enhanced capability. Generic Feasibility Assessment reactor tool developed with further underpinning data.

Knowledge capture: Knowledge of historical UK programmes, including the UK Fast Reactor Programme, has been captured for future use.

International influence: Coordination of a UK group on and influence to international irradiation facility programmes including Halden and Jules Horowitz Reactor. UK influence in key OECD-NEA working groups.

Future planning: Assessment of future scenarios and technologies, and recommendations in relation to industry future fuels and materials irradiation needs.

Other key project information

Investment BEIS: £2,800,000
Match funding: N/A

Project Start Date: April 2017
Completion Date: March 2021

Interaction with other NIP projects and more broader links to R&D programmes/collaboration:
- Engaged with all other NIP projects.
- Enabled UK membership of the Halden Reactor Project
- UK membership of the OECD Nuclear Energy Agency (NEA) and the NEA Databank.

Project chosen key facts:
- Significant journal papers on strategic assessment of nuclear
- Extensive UK fast reactor programme information captured

Key reports / presentations

The Role of Nuclear Power in Meeting Current and Future Industrial Process Heat Demands

The Potential of Pressurised Water Reactors to Provide Flexible Response in Future Electricity Grids

The Fuel Cycle Implications of Nuclear Process Heat

Assessment of High-Electrification UK Scenarios with Varying Levels of Nuclear Power and Associated Post-Fault Behaviour

Key websites

Programme website: www.nnl.co.uk/innovation-science-and-technology/strategic-toolkit/

Key project contact:

Name: Paul Nevitt
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Decommissioning/Robotics Overview

The Decommissioning/Robotics programme was delivered jointly with Innovate UK and aimed to develop and demonstrate innovative and integrated nuclear decommissioning systems.

It comprised of just one project a £1.5M investment from BEIS with the majority (£7M) being Innovate UK and NDA funding.

This project, as the following page shows, delivered a number of extremely innovative technologies which will hopefully be deployed across the nuclear over the coming years.

Integrated Innovation in Nuclear Decommissioning (IINDe) Lead: Innovate UK and Nuclear Decommissioning Authority (NDA)

Project background

An £8.5 million competition was launched in 2017 to find technologies that could be combined into a single, seamless process to help dismantle some of the most radioactive facilities at Sellafield and other nuclear sites through fostering collaborative innovation within the supply chain.
The Integrated Innovation in Nuclear Decommissioning (IINDe) competition was collaboratively funded by the Nuclear Decommissioning Authority (NDA), Innovate UK and BEIS. Full funding was offered for collaborative projects to devise technologies that would access highly contaminated structures, efficiently manage waste, reduce risks to workers, increase productivity, reduce timescales and cut costs to taxpayers.
The challenge was to combine standalone technologies and integrate them into a single remotely operated system with smooth interaction between the different component parts. Robotics, artificial intelligence, virtual reality, autonomous navigation, and conventional engineering equipment all featured in the projects.
The objective was to develop a decommissioning toolkit of scalable, transferable and integrated solutions which would drive safer, faster and cheaper decommissioning.

Organisations involved (Click on logo to view website)

Almost 30 organisations were involved in a range of consortia from micro SMEs to academic institutions to large international organisations. This included organisations new to the nuclear sector including gaming, sea fishing, medical imaging, fume extraction, space, oil & gas and defence industries.

NDA | UK Research and Innovation | Sellafield Ltd

Key outcomes from project

The first stage of the competition identified 15 submissions with potential with five subsequently shortlisted. Each shortlisted demonstration project received up to £1.5 million and teams spent 2 years taking conceptual ideas from the drawing board to reality by building prototype demonstrators for testing in a simulated radioactive environment.
In 2019, following inactive demonstrations, 2 of the 5 (Barrnon and Wood) were selected with a view to demonstrating their solutions in one of Sellafield's radioactive facilities. The winning projects were highly innovative, integrating a range of technologies and capabilities that have the potential to enable a step change for nuclear decommissioning. As well as robots, all the solutions featured virtual reality, 3-dimensional imaging and autonomous navigation.
The blog posts shown on the right and video below, provide an insight to the diverse range of Organisations involved (Click on logo to view website) and the innovative solutions devised.

Key reports / presentations

assets.publishing.service.gov.uk/government/uploads/system/uploads

www.youtube.com

nda.blog.gov.uk

Key websites

Project website: assets.publishing.service.gov.uk/government
nda.blog.gov.uk/2019

Technology next steps

After testing integrated working models in a realistic non-radioactive environment, the projects will now progress to demonstrating their solutions in one of Sellafield's radioactive facilities.
Potentially the work from IINDe can be scaled up for larger challenges and transferred to different facilities at Sellafield, as well as other nuclear sites and non-nuclear hazardous environments.
For the whole sector but specifically NDA, the success of this and previous programmes has reaffirmed the importance of innovation and ensuring everyone plays their part in leading the drive for innovation to deliver decommissioning safer, faster, cheaper.

Other key project information

Investment BEIS: £ 1,499,900
Innovate UK and NDA funding: £7,000,000

Project Start Date: March 17
Completion Date: January 20

Note this work was only 17% funded through NIP with the majority of the investment coming from NDA and Innovate UK.
The NIP funding was primarily to support research into managing wider hazardous environments in the nuclear industry along with technology transfer for offshore decommissioning and mining decommissioning.

Blog posts from each collaborating consortia to learn more about their project and experience:

Barrnon - The Barrnon Integrated Decommissioning System (BIDS), "A tracked platform hosting a pair of hydraulic arms, each with a robot at the end"

Cavendish - The In Cell Decommissioning System (IDS) "Combining established technologies in spatial and radiometric scanning, remote deployment and virtual reality (VR) control."

Createc - Elephants to Ants "Integrate a number of smaller robots in a flexible, dynamic way"

Nuvia -Nu-Decom "A new, integrated approach to safe, remote decommissioning that's repeatable and predictable"

Wood - Anchored in reality but pushing innovation into under-developed areas "Integrate new data and control technologies into an end-to-end system"

Key project contact:

Melanie Brownridge (NDA) melanie.brownridge@nda.gov.uk
Roger Townsend (Innovate UK) roger.townsend@innovateuk.ukri.org
Chris Hope (SL) christopher.x.hope@sellafieldsites.com

Thermal Hydraulics Facility Overview

UK Atomic Energy Authority were tasked with a budget of £1.5m by BEIS [and the Welsh Government, who contributed further co-funding] with the production of an outline design, plan and cost estimate to inform future decisions on any design, construction and operation of a potential facility.

Thermal Hydraulics Test Facility
Concept Design
Lead Company: UKAEA

Project background

Whilst the UK has a capability (skills and infrastructure) in thermal hydraulics there are currently no large scale test facilities. A Nuclear Innovation and Research Advisory Board (NIRAB) recommendation identified the need for a large scale national thermal hydraulic test facility.

A project was commenced with BEIS investing £1.5m as part of the Nuclear Innovation Programme and co-funding from Welsh Government.

Organisations involved (Click on logo to view website)

Concept Design Lead

UK Atomic Energy Authority

Support

ATKINS
Member of the SNC-Lavalin Group

McBains

Key outcomes from project

A Royal Institute of British Architects (RIBA) stage 2 cost (concept design for the facility and housed lightwater reactor loop) was developed, accompanied by a high level delivery programme.

Key reports / presentations

A concept design has been completed.

Key websites

www.gov.uk/government/publications/nuclear-sector-deal
www.innovationfornuclear.co.uk/

Figure 1 - Concept Design of Site Layout

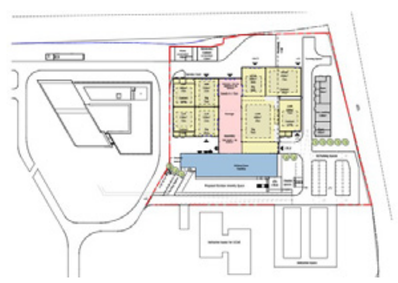

Figure 2 - Concept Design Side Elevation

Technology next steps

The concept design has been assessed with subsequent work carried out by the National Nuclear Laboratory (with central and Welsh Government support) to;

- Further develop facility, loop and utility costs and timelines,
- Down select potential facility site locations,
- Work with Anglesey Council on local planning and wider stakeholder matters,
- Engage a number of potential industry users,
- Develop a case for further investment on the back of the above.

Other key project information

BEIS investment (excluding Welsh Government co-funding): £1,500,000
Match funding: N/A

Concept Design
Start Date: September 2019
Completion Date: April 2021

Prior to the commencement of the UKAEA concept design, a separate package of work was placed to Frazer-Nash Consulting. This package looked at the feasibility for the facility and initial market assessment for thermal hydraulic testing need.

Key project contact:

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BACK TO CONTENTS

Any enquiries about this brochure, please contact the named individual on each page or for more general enquires
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