Molten Salts Technology R&D Capability and Infrastructure Map for the UK

DESNZ Molten Salts Advisory Group

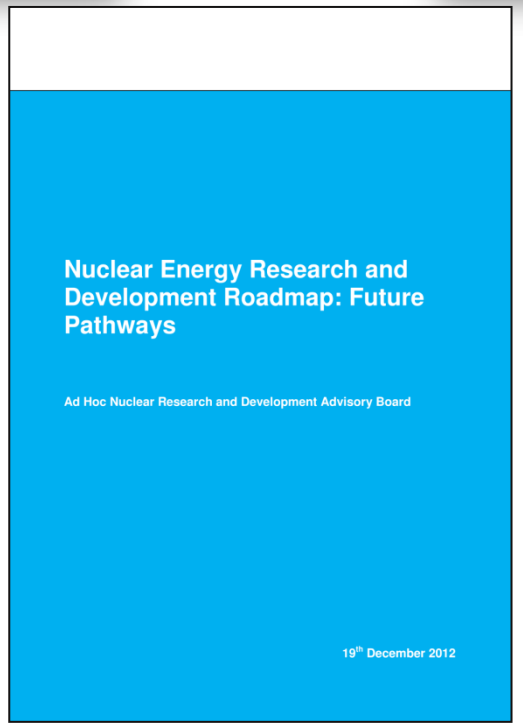
Molten Salts Technology R&D Capability Overview – Early 2000s

- The majority of the UK's current expertise and infrastructure in molten salts technologies has evolved from long-standing interests in the pyroprocessing of spent nuclear fuel (mainly to support the possible deployment of fast reactors) and established industrial technologies for materials purification and production (e.g. FFC Cambridge process) .
- Generally this was supported by:
  - BNFL (Now UKNNL) through the BNFL Molten Salts Programme (up to 2005).
  - UK universities through research council funding but typically with non-coordinated approaches.
  - RSC, through the Molten Salts Discussion Group, now known as MSILDG (Molten Salts and Ionic Liquids Discussion Group).
  - Activities with industry.
- Links between pyroprocessing R&D and other molten salts technologies such as MSRs, nuclear fusion, and energy transfer and storage has been historically poor.
- The lack of definitive future energy policies, particularly for nuclear energy, made it difficult to find support for molten salts activities.
- Many molten salts activities had to transfer or merge with interests in ionic liquids (e.g. RSC MSDG became the MSILDG, EUCHEM Molten Salts conference became the EUCHEM Molten Salts and Ionic Liquids conference).

Molten Salts Technology R&D Capability

Overview *2010-onwards*

- Release of UK energy policy and the implementation of NIRO/NIRAB with the nuclear energy R&D roadmap has:
  - Identified molten salts technologies as a key component of the advancing energy landscape.
  - Proposed fast reactor systems and supporting recycle within the closed fuel cycle pathway option in the nuclear roadmap.
  - Renewed interest in molten salt reactors in next generation reactor systems in the UK (e.g. the emergence of Moltex Energy).
  - Led to a more cohesive molten salts R&D community providing linkages across various molten salts technology platforms.



Molten Salts Technology R&D Overview
2010-onwards

- The formation of the REFINE (A coordinated materials programme for the sustainable REduction of spent Fuel vital In a closed loop Nuclear Energy cycle using molten salts) consortium brought together the vast majority of the molten salts expertise throughout the UK.
- Supported by EPSRC (£1.5 M); led by the University of Edinburgh; from 2011 to 2015.
- Provided a coordinated approach for molten salts R&D activities in the UK for the first time.
- Ensured the retention and expansion of molten salts capability in the UK.
- Research areas in direct electrochemical reduction, electrorefining, speciation and analysis.
- Provided a platform for engagement in molten salts R&D in EU programmes (e.g. SACSESS; ASGARD) and has led to further molten salts activities and expanded infrastructure.

Project Partners

THE UNIVERSITY of EDINBURGH

NATIONAL NUCLEAR LABORATORY

MANCHESTER 1824

The University of Nottingham

UCL

UNIVERSITY OF CAMBRIDGE

Molten Salts Technology R&D Overview
Emerging interests in Molten Salt Technologies

- The application of molten salts has been recognised across many new and emerging energy generation and storage technologies.
  - Many of these applications have recently emerged and expanded with the need for low-carbon technologies and enhanced energy/heat efficiency and sustainability.
- Key applications are:
  - heat-transfer fluids across various operations in the chemical process industry, especially high quality heat.
  - Thermal energy storage to support solar power stations, most commonly as nitrate salts.
  - Both as a fuel and coolant in various molten salt reactor designs.

An aerial view of the 100-megawatt molten salt tower solar thermal power plant in Dunhuang, Northwest China's Gansu province, on Dec 25, 2018. (Obtained from https://www.chinadaily.com.cn/a/201901/08/WS5c3408aba31068606745f714.html; Copyright - Yang yanmin – Imaginechina)

Current Molten Salts R&D Infrastructure in the UK

Specific for Molten Salts R&D

User facilities for Molten Salts Technology R&D

- Pyrochemical Research Laboratory (PRL) established since 2016
- Molten Salts in Nuclear Technology Laboratory (MSNTL) – awarded in 2019 and to be fully operational by 2023
- National Nuclear Laboratory: Central Laboratory – Plutonium Active Pyroprocessing Apparatus (PAPA) Facility to be deployed in Central Laboratory to allow molten salts R&D with high specific activity radionuclides (via BEIS Advanced Fuel Cycle Programme).

Pyrochemical Research Laboratory (PRL)
National Nuclear User Facility

- Established in 2016 through funding (£0.9 M) from DECC (now BEIS).
- Facility was designed to primarily support the development and demonstration of integrated pyrochemical reprocessing of nuclear fuel
- Can readily be used to support molten salts R&D in other technology areas.
- Use of fuel relevant non-radioactive compositional salt mixtures at laboratory scale, along with process monitoring techniques.

- Located at the University of Edinburgh

Equipment includes:

- 4 interconnected dry atmosphere gloveboxes, each tailored to a specific type of research activity listed below:
  - Salt preparation
  - Large scale salt measurements
  - Medium scale salt measurements
  - Salt analysis and optical/spectro-electrochemical measurements
- Associated supporting equipment includes:
  - Various furnaces and oven of differing sizes and orientations
  - High current potentiostats
  - Imaging bay
  - TGA/DSC
  - Raman/IR and UV-visible spectrometers with specially designed spectroscopic furnace for in-situ measurements.
  - Salt flow loop for dynamic studies

Spectroscopic furnace

Imaging bay within the salt analysis glovebox

Contact: Dr Justin Elliott; Email: Justin.Elliott@ed.ac.uk

Website: www.prl.chem.ed.ac.uk

Molten Salts in Nuclear Technology Laboratory (MSNTL)
National Nuclear User Facility

- Awarded £2.3M in 2019 as part of BEIS funded NNUF Phase 2 (for completion by 2023).
- Aims to provide a molten salt R&D facility capable of studying fluoride salts in nuclear systems within the UK for the first time:
- Enabling the UK's expertise in chloride salts from pyroprocessing studies to study alternative salt systems in order to explore expanding research areas such as molten salt reactor technologies.
- Providing an interdisciplinary hub for molten salts research across multiple technology areas with radioactive materials.

Np(IV) in molten LiCl-KCl eutectic

Equipment to include:

- Numerous materials corrosion test rigs
- Gravity fed molten salts flow loop
- Molten salts irradiation test rig
- High temperature column for dynamic ion exchange studies with molten salts
- Bespoke gloveboxes and supporting infrastructure for handling molten salts with radioactive material
- Supporting furnaces of various types
- TGA/DSC coupled with GC-MS
- High temperature rheometers
- Potentiostats
- Various existing spectroscopic and electrochemical kit

Dalton Cumbrian Facility
(image courtesy of Dalton Nuclear Institute)

Network of locations

- Prime hub in the Centre for Radiochemistry Research (UoManchester) for medium active to "hot" work
- UoEdinburgh for low active work, also linking with Pyrochemical Research Laboratory
- Dalton Cumbrian Facility for radiation studies
- Input from UCL and UoSheffield

Contact: Dr Clint Sharrad, The University of Manchester

Email: clint.a.sharrad@manchester.ac.uk

United Kingdom National Nuclear Laboratory

World-leading facilities

£1.5bn

of nuclear facilities:

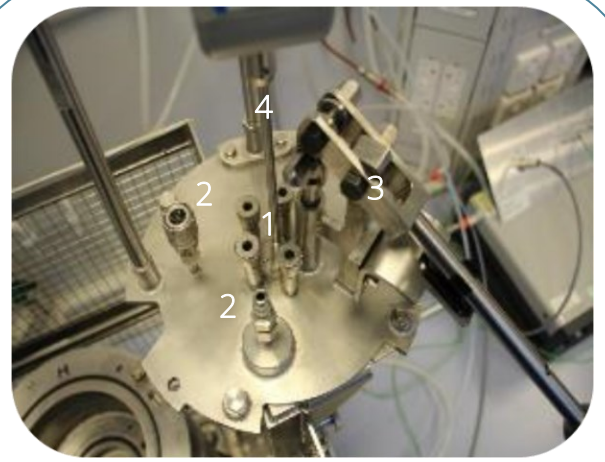
- Routine Laboratories
- Active Laboratories
- Glovebox Facilities
- Nuclear Fuel Labs
- High Active Cells
- Large Rig Halls

Pyrochemical Alpha-active Processing Apparatus (PAPA)

A plutonium capable molten salt electrochemical apparatus with atmospheric control

United Kingdom National Nuclear Laboratory

Mechanical bellows-
Lowers and raises electrodes in and out of the salt without breaking seals.
Includes a safety lock system



Top plate:
[1] electrodes, [2] gas inlet/outlet,
[3] sampling system,
[4] motorised mixer

Faraday cage with stowage for simple crucible manipulation and electrode adjustment

Front and rear heat guards

Manual wheel to control bellows

Movable frame allows repositioning when not in use
Top plate stowage system – provides stability and safety to set up electrodes and a standard position for electrodes

UK Universities – Molten Salts R&D Capability and Infrastructure

- The vast majority of the capability and infrastructure for molten salts R&D is arguably located in universities within academic groups and departments.
- Training of the next generation of molten salts subject matter experts is undertaken within these research entities, and supplemented by access to UK user facilities and international links.
- Key examples of such academic groups in the UK who directly engage in molten salts R&D are listed below with key equipment and capability identified.
- Note: This is not comprehensive as there are likely to be other molten salts capability within larger infrastructure that either has been or in the midst of being developed with UK universities and other research facilities.

UNIVERSITY OF BIRMINGHAM

Birmingham Centre for Energy Storage (BCES)

- **Facilities for thermal, physical, structural, optical and chemical properties characterisation and measurements** – these include density, viscosity (rheological properties), thermal conductivity, diffusivity, electrical and ion conductivity, phase transition, heat capacity, surface and interfacial tension, dilatometer (expansion/contraction), crystallinity, composition, thermal cycling, and optical properties (e.g. absorption, diffraction, transmittance) … for up to 1800^{o}C.
- **High Flux Accelerator-Driven Neutron Irradiation facility** – this can be used for understanding neutron interactions with molten salts as well as container materials. There is a need to study radiation assisted corrosion of containment materials.
- **MC40 Cyclotron facility** – this can deliver a flexible range of ions for doping and irradiating molten salts and understanding the properties of the doped and irradiated molten salts and containment materials.
- **Various lab scale testing rigs** – these are for flow and heat transfer behavior, which can be adapted for molten salts research e.g. thermal cycling of molten salt flow, freeze-thaw cycling of salts in pipes, valves, bends, pumps, etc.
- **Over 1000m^2 lab space, very well-equipped, with 3 dedicated technicians for the labs** – funded mainly by two initiatives: EPSRC Great Eight Initiatives with two projects of ~13M; and Energy Research Accelerator (ERA for Midland universities and BGS) with a £60M government funding and £190M industry and partner funding.

MC40 Cyclotron facility

Neutron irradiation facility at Birmingham

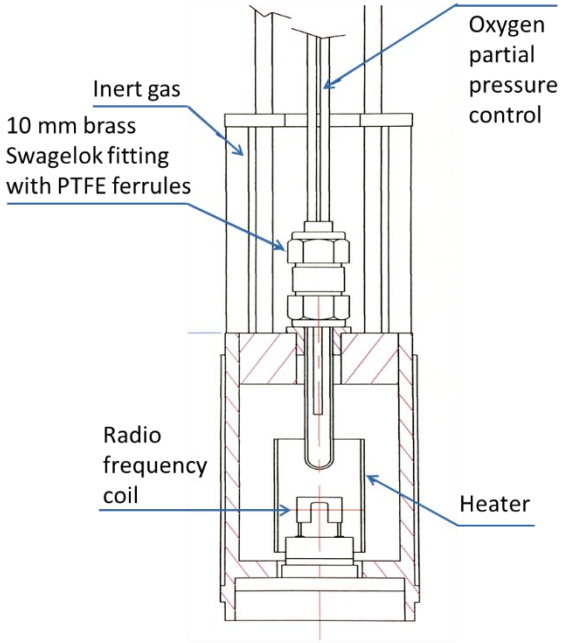
Contact: Prof. Yulong Ding

Email: Y.Ding@bham.ac.uk

UNIVERSITY OF CAMBRIDGE

Speciation and Characterisation in Molten Salts

- **In situ molten salt nuclear magnetic resonance probe**
  - Working temperature up to 1273 K (1000˚C)
  - Oxygen partial pressure control
  - X-Resonant frequency range: 39.3 - 188.6 MHz; enabling $^{35/37}$Cl, $^{6/7}$Li, ^{23}Na, ^{133}Cs, ^{17}O, ^{139}La, ^{2}H and ^{9}Be NMR measurements.
  - Y-Resonant frequency range: 400 - 500MHz; enabling ^{19}F, ^{1}H and ^{3}H NMR measurements.
  - Measurement of isotope specific dynamics (self-diffusion) of both anions (Cl, F) and cations (Li, Na, Be) also in the presence of additives/impurities (Cs, Sr, O, ^{1}H & ^{2}H - to simulate ^{3}H)
- **Two high specification anoxic glove boxes**
  - 0.1 ppm H_2O, 0.1 ppm O_2 ; for salt drying and refining.
  - In situ furnace for refining and sample loading without atmospheric contact
- **Pyro-processing**
  - 8 Molten salt rigs for pyro-processing, direct reduction applications
- **Modelling and measurement of melt dynamics**
  - molten salt properties from both empirical and ab initio methods
  - Thermal & electrical conductivity, heat capacity, viscosity
- **Computational reactor modelling of MSR capabilities**
  - A comprehensive set of tools for multi-physics (neutronics, thermal-hydraulics, isotopic depletion) modelling of salt-fuelled and salt-cooled reactors through deterministic and Monte-Carlo routes.



Contact: Profs Ian Farnan and Eugene Shwageraus

Email: if203@cam.ac.uk; es607@cam.ac.uk

Electrochemical Innovation Lab

- University College London (UCL) hosts the Electrochemical Innovation Lab (EIL), which has a dedicated nuclear fuel processing lab, with depleted uranium and thorium capabilities.
- Since being formed in 2010, the EIL has attracted more than £25 million of funding and is currently home to over 60 researchers in electrochemical science and technology, including molten salts for nuclear applications.
- The EIL is well equipped with gloveboxes, furnaces and electrochemical cells, to conduct molten salts experiments at high standards.
- It hosts the UCL Centre for Correlative X-ray Microscopy, a world-leading suite of X-ray CT instruments, which produce non-destructive high-quality 3D images, with resolution ranging from 10s nm to 10s μm, and sample size from 10s μm to 10s cm.
- It also has its own XRD diffractometer and SEM/EDS microscope, in addition to other high-end facilities.
- EIL researchers have access to equipment at the London Centre for Nanotechnology (LCN) to use other analytical tools, such as FIB. They also have access to other facilities at UCL at the Department of Chemical Engineering, Department of Chemistry and Department of Physics.
- EIL researchers are often granted beam-time at national and international synchrotron and neutron facilities, to carry out a range of work in imaging, diffraction and spectroscopy.





Website:
https://www.ucl.ac.uk/eil
Contact: Prof. Dan Brett
Email: D.Brett@ucl.ac.uk

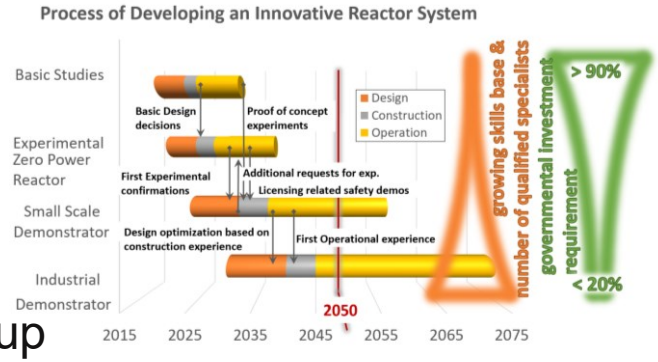
Molten Salt Reactor Physics Modelling and Simulation Hub

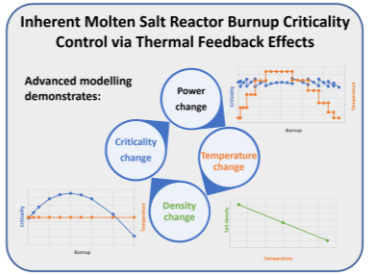
UNIVERSITY OF LIVERPOOL

Science and Technology Facilities Council | Daresbury Laboratory

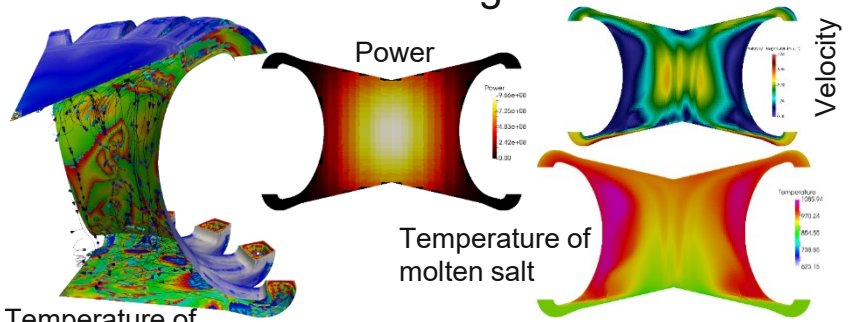
Collaboration of a variety of experts for multi-disciplinary modelling and simulation of molten salt reactors

- **Innovative reactor process development** – identification of key process steps and development demand for future nuclear systems
- **Neutron physics and power** – determination of power distributions in molten salt systems including feeding, salt cleaning and fuel burnup
- **System design and operational cycle development** – multi-disciplinary design optimization including interaction with salt chemistry
- **Fluid dynamics and heat transfer** – reactor cooling dependent on the required fidelity using different tools from system studies to detailed CFD
- **High and low fidelity coupled multi-physics modelling** – multi-phase CFD, Monte-Carlo & deterministic neutron transport, fuel burnup…
- **Multi-disciplinary interaction – physics, chemistry, engineering** – operation and control of nuclear systems and collaborative optimization of the whole nuclear system from cradle to grave – mining to final disposal
- **Management of multi-disciplinary M&S proposals and projects** – iMAGINE, Frozen wall, Zero power, invited IAEA collaboration partner
- **Optional: Quantum Mechanics and Molecular Dynamics for M&S of material properties**





> 15 journal publications specializing on MSR technologies



Contact: Dr Bruno Merk

Email: B.Merk@liverpool.ac.uk

Cross-cutting R&D infrastructure

Interdisciplinary nuclear user facilities that can provide further support to molten salts technology R&D

Sir Henry Royce Institute

Key selected aims

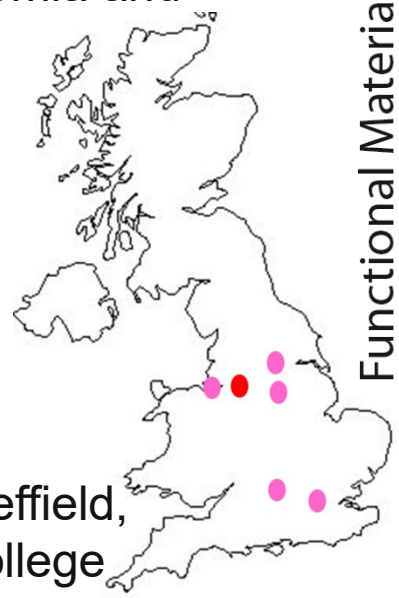
- Accelerate safely and with confidence the use of advanced materials in existing and emerging industrial sectors within the UK
- Invent and innovate new materials in various sectors covering fabricating, testing, analysing and demonstration.
- Provide an international beacon for UK expertise and deliver national leadership and critical mass to allow identification of expertise within the UK.
- Attract inward national and international investment from industry, academia and Government

Value

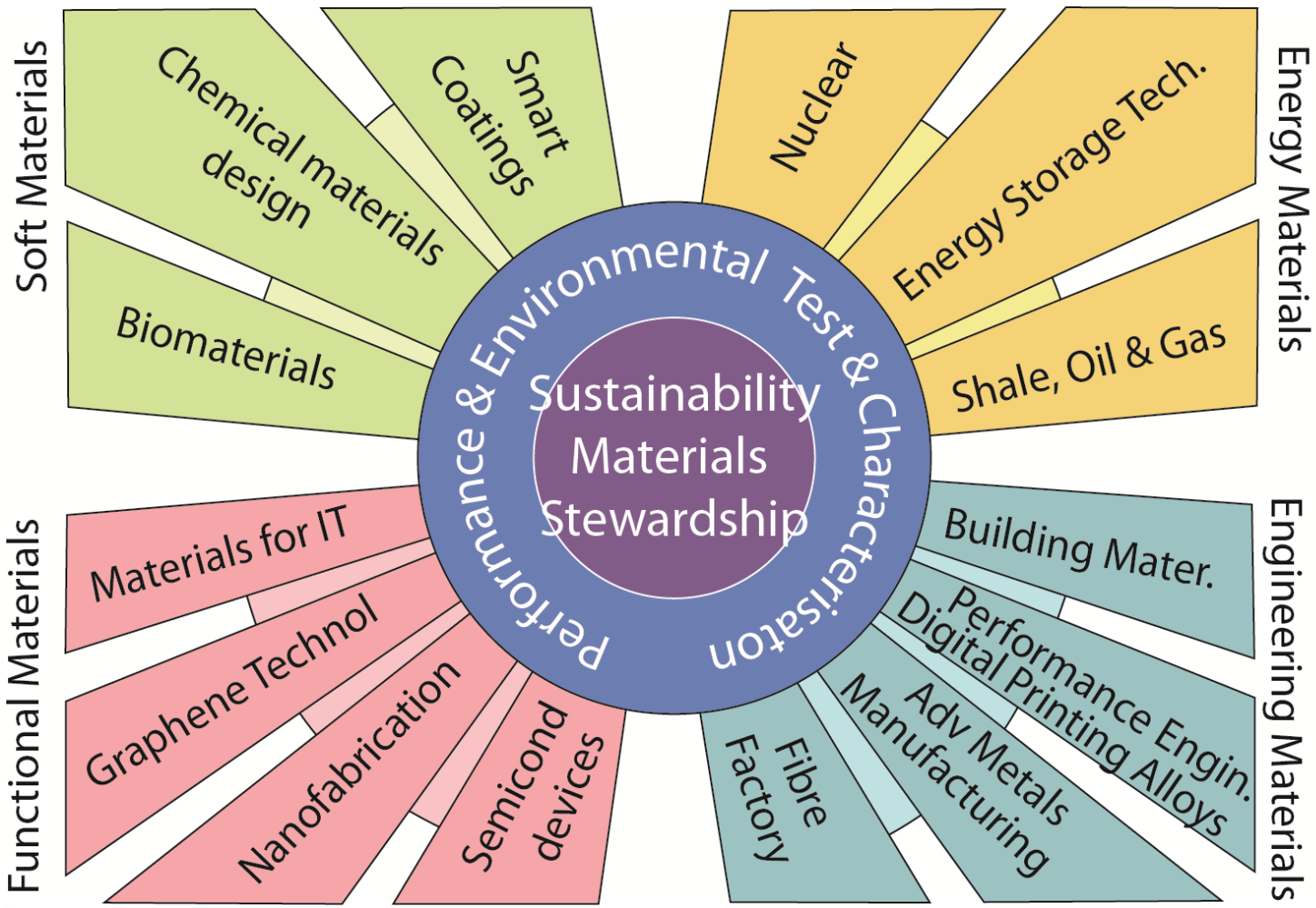
- £ 303 M total
  - £ 235 M capital
  - £ 68 M project funding

Location

- Centre at Manchester
- Spokes in Liverpool, Leeds, Sheffield, Oxford, Cambridge, Imperial College



Scope



- ***Contact: Prof. Francis Livens (as Royce nuclear champion) The University of Manchester***
- ***Email: francis.livens@manchester.ac.uk***

Advanced Manufacturing Research Centre

The Advanced Manufacturing Research Centre (AMRC) is a collaboration of academic and industrial partners from across the nuclear supply chain, with the mission of helping UK manufacturers win work at home and worldwide. The two key areas of focus including manufacturing and digital innovation and supply chain development services.

Manufacturing innovation:
The AMRC works with companies to overcome their manufacturing problems, and help them develop the technical capability to compete on cost, quality and delivery.
Resources and capabilities have been determined by industry partners, with the aim of helping suppliers reduce cost, improve quality, reduce lead time and cycle time, and reduce risk in manufacturing.
The AMRC's core R&D capabilities cover:

- Machining
- Welding & cladding
- Metrology & inspection
- Modularisation
- Visualisation
- Digital systems and senor technology

Supply chain development services:

- Targeted support services to manufacturers, from free advice and expertise service; to demand model modelling to map future contract opportunities and help match manufacturers with relevant work packages.
- For example, the flagship Fit For Nuclear programme is a unique service to help UK manufacturers get ready to bid for work in civil nuclear, allowing companies to measure their operations against industry standards and take the necessary steps to close any gaps.

Website: www.amrc.co.uk; **Email:** enquiries@namrc.co.uk

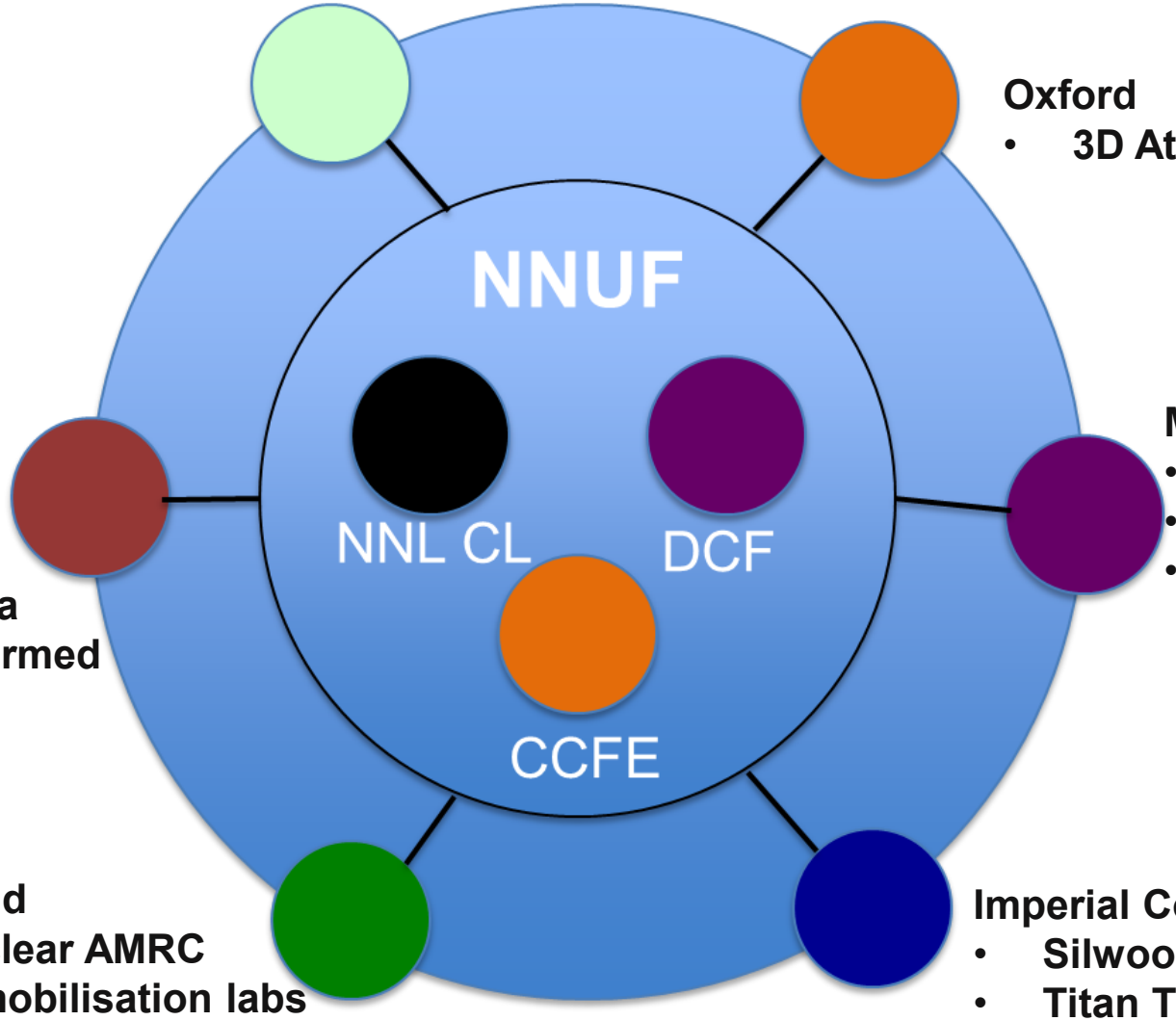
National Nuclear User Facility

- NNUF is part of the HM Government's Nuclear Industrial Strategy announced in 2013.
- Initial investment of £15M across 3 major hubs.
- Aims to provide greater accessibility to world leading technologies as a collaborative effort from four complimentary hubs within the UK.
- Has expanded with further investment (~£75 M), including PRL and MSNTL.

- *Other interdisciplinary NNUF hubs can provide support to molten salts technology R&D*

***Website**.:* www.nnuf.ac.uk

NNUF Phase 2
- **Various facilities**
- **Multiple locations**



Oxford
- **3D Atom Probe**

Manchester
- **Reactor testing**
- **Titan TEM**
- **Radiochemistry lab**

NNUF Phase 2a
- **To be confirmed**

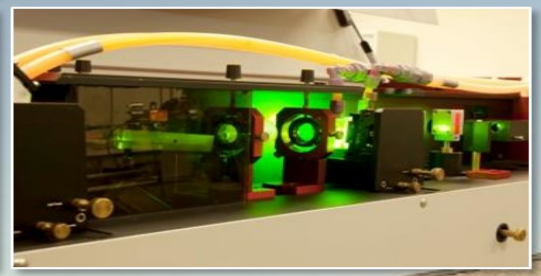
Sheffield
- **Nuclear AMRC**
- **Immobilisation labs**

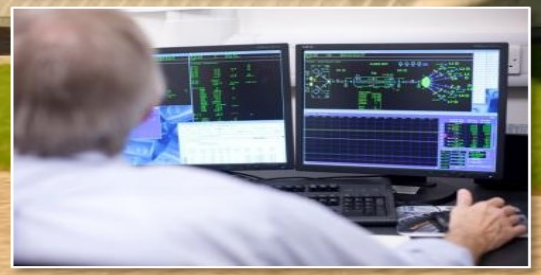
Imperial College
- **Silwood Park**
- **Titan TEM**

MANCHESTER 1824
The University of Manchester
Dalton Nuclear Institute

Dalton Cumbrian Facility (DCF)

- Radiation science (materials and chemistry)
  - 5MV tandem ion accelerator
  - 2.5MV light ion accelerator to be added
  - Self-contained high dose rate ^{60}Co gamma irradiator
  - Supporting laboratory facilities for materials and solution characterisation.
- Also part of the Henry Royce Institute and the EPSRC UK National Ion Beam Centre.
- Hub for the MSNTL NNUF





- Engineering decommissioning including materials decontamination and waste treatment.
- Active facilities access

Location: Westlakes Science Park, West Cumbria

Website: www.dalton.manchester.ac.uk/research/facilities/cumbria-facilities/

Culham Centre for Fusion Energy

Materials Research Facility (MRF)

Various equipment available for:

- Sample preparation (e.g. Precision ion-beam polishing, sputter coater)
- Microstructural analysis (e.g. microscopy, FIB, diffraction)
- Mechanical testing (e.g. chambers for high T testing)
- Thermo-physical characterisation (e.g. thermal desoprtion spectroscopy)

Capable of handling non-active to high-active materials

Website: https://mrf.ukaea.uk/

Location: Culham Science Centre, Abingdon

Advanced Digital Radiometric Instrumentation for Applied Nuclear Activities (ADRIANA)

- Development of real time detection for radiometric sensing using:
  - Ultra low background γ-ray spectroscopy
  - Neutron imaging
  - γ-ray imaging

Website: https://www.nnuf.ac.uk/adriana

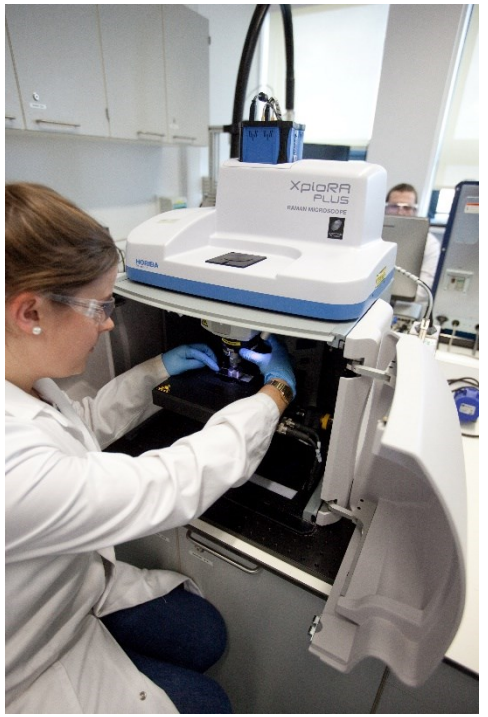
High Temperature Facility (HTF) Alliance

- High temperature testing of materials up to 1000 °C.
- Exposure environments include pressurised gas for VHTR/HTR, liquid metal for SFR/LFR and inert atmospheres
- Draws together the high temperature materials community in the UK.
- Materials testing techniques and equipment include:
  - Tensile and fracture testing.
  - Creep strain/rupture and creep crack grain growth
  - Acoustic emission monitoring equipment for monitoring crack initiation and propagation
  - Potential difference monitoring equipment for monitoring crack initiation and crack growth

- ***Website***: https://www.htfalliance.com/; **Location**: Warrington

HADES / MIDAS Facility

- Supports internationally competitive research and development in the management and disposal of radioactive wastes from the nuclear fuel cycle.
- £3M MIDAS facility co-funded by DECC; opened in 2015.
- Expanded as HADES facility with £1M support from UKRI in 2020
- Multiple techniques for the synthesis of wasteforms and subsequent probing of wasteform behaviour and performance, such as:
  - Glove box handling of ^{99}Tc, ^{60}Co, transuranics, nat. U/Th
  - High temperature materials processing
  - Thermal analysis
  - Diffraction and spectroscopy
  - Chemical and radiochemical analysis
  - Electron microscopy



Location: The University of Sheffield

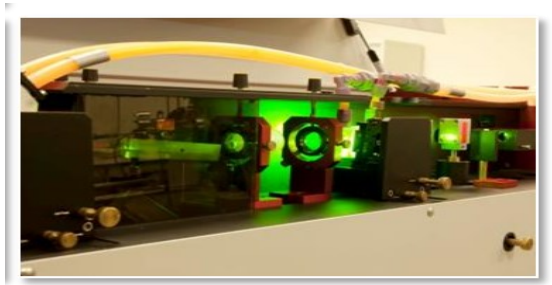
Website:
www.sheffield.ac.uk/materials/research/facilities/midas

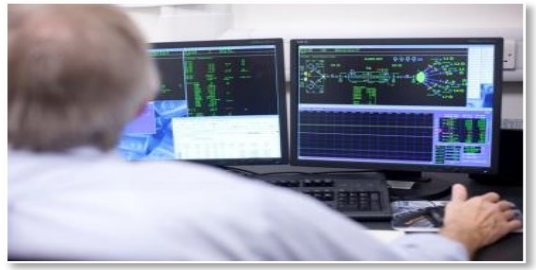
Cross-cutting R&D infrastructure

Interdisciplinary university based facilities that can provide further support to molten salts technology R&D

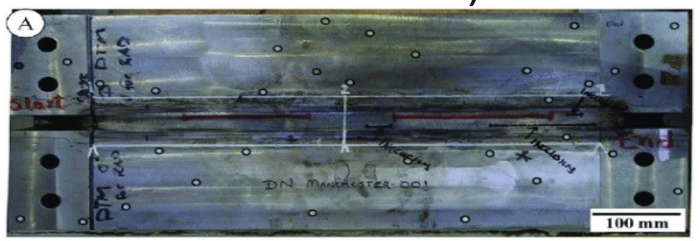
MANCHESTER 1824
The University of Manchester
Dalton Nuclear Institute

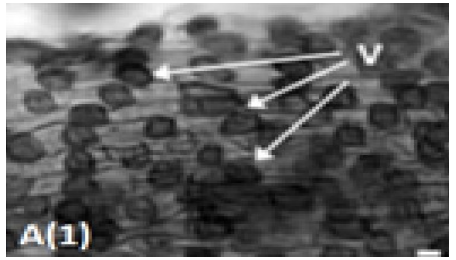
Dalton Nuclear Institute Specialist Research and Training Facilities





- Nuclear fuels laboratory (including plutonium capability)
- Nuclear graphite laboratory
- Radiochemistry laboratories (including plutonium work)
- Nuclear manufacturing (NNUMAN)
- Materials Performance Centre (including Electron Microscopy Centre)
- Fuel cladding research (Zr, coatings, joining)
- Manchester X-ray Imaging Facility
- Thermal hydraulics
- Nuclear separations laboratories (IX, SX, electrorefining, flocculation, contam/decontam)





Website: www.dalton.manchester.ac.uk

School of Chemical and Process Engineering
FACULTY OF ENGINEERING

UNIVERSITY OF LEEDS

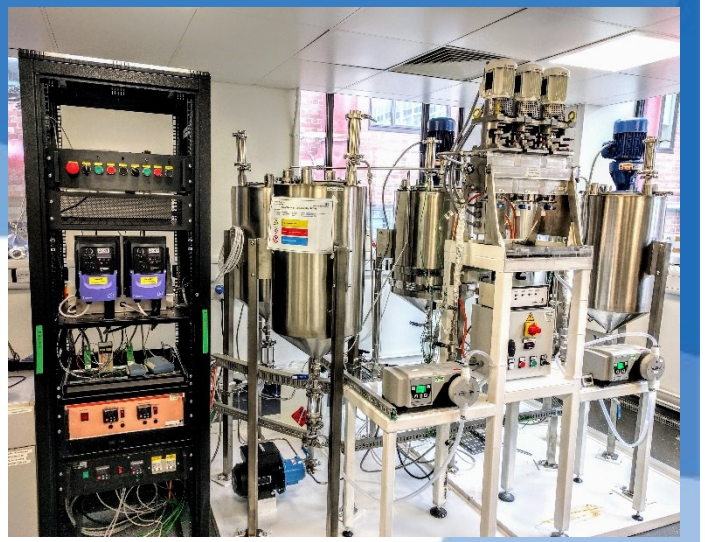
Nuclear.Leeds

160m^2 of specialist laboratory space for nuclear science and engineering

- Dedicated fume cabinets
- Anaerobic glovebox
- Pilot scale rigs for solvent extraction research
- Gamma spectroscopy
- LIBS (laser induced breakdown spectroscopy)

Capability to work with radioactive materials:

- 1.2GBq alpha emitters
- 120GBq others except alpha emitters
- 20kg uranium and thorium
- dose constraints:
  1mSv / year whole body dose
  10mSv / year extremity dose



Core Challenges in Molten Salts Technology Development

Key development areas for the progression along TRLs and ultimately successful deployment of molten salt technologies are identified as follows:

- **Chemistry**
  - E.g. Long term salt behaviour and performance, Salt clean-up methods, Sensing and analysis
- **Engineering**
  - E.g. Scale-up, dynamic vs batchwise operations, thermal hydraulics
- **Materials**
  - E.g. Containment materials development, Long-term corrosion behaviour
- **Safety**
  - E.g. Safety monitoring systems, Criticality assessment in nuclear operations
- **Sustainability**
  - E.g. Efficient methods for treating and disposing of salt residues and other waste streams; integrated closed fuel cycle operation
- **Regulation**
  - E.g. Predictive understanding of maloperation scenarios, On-line monitoring

Rarely will specific development requirements sit within one discipline area.