UK Atomic
Energy
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UK Fusion Materials Roadmap
2021-2040

HENRY ROYCE INSTITUTE

UKRI Engineering and Physical Sciences Research Council

About roadmapping and landscaping

This report is partly sponsored by the Henry Royce Institute for advanced materials as part of its role around convening and supporting the UK advanced materials community to help promote and develop new research activity.

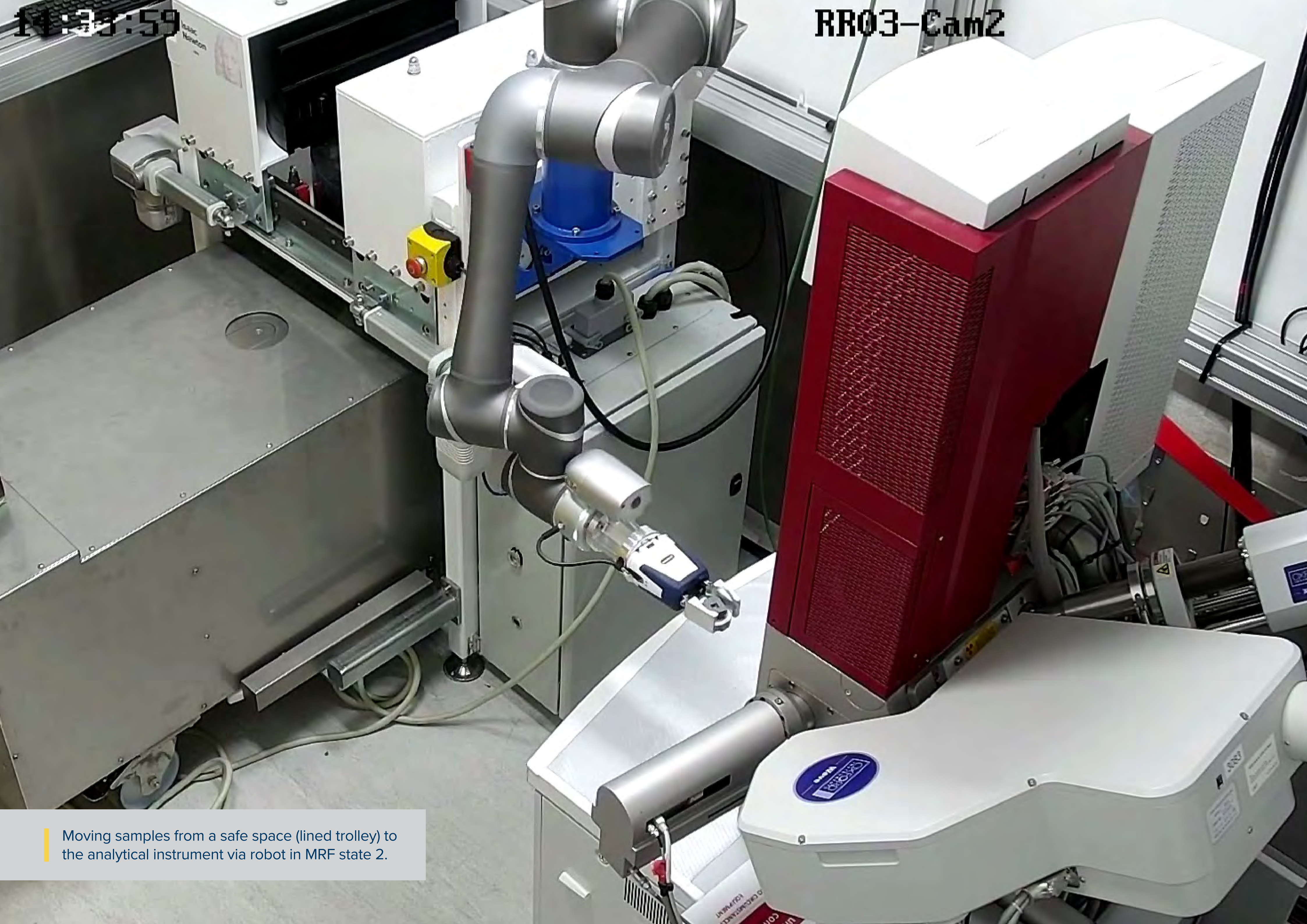
The overriding objective is to bring together the advanced materials community to discuss, analyse and assimilate opportunities for emerging materials research for economic and societal benefit. Such research is ultimately linked to both national and global drivers, namely Transition to Zero Carbon, Sustainable Manufacture, Digital & Communications, Circular Economy as well as Health & Wellbeing.

CONTENTS

SUMMARY

Key waypoints in fusion landscape	2020	2024	2028	2032	2036	2040
	• STEP concept design starts	• ITER first plasma • STEP concept design review	• DEMO Conceptual Design Consolidation	• STEP build starts	• ITER high power operation	• STEP first plasma • DEMO build starts

Fusion Roadmap driver	Materials Roadmap	Near Term	Stretch Targets / Disruptors
New regulatory framework for fusion without high level waste	**Enable low activation waste predominance in fusion**	▪ Weldable, cost-effective Reduced Activation Ferritic Martensitic (RAFM) structural materials ▪ High purity raws for armour, structure, divertor baseline materials ▪ Full tritium inventory model across plant material interfaces (first wall, cooling circuit, detritiation plant)	▪ 'Dust'-free armour materials for safe recycling
Breeding ratio >1; fuel self sustainability	**Boost breeding ratio, block tritium losses**	▪ New breeder materials beyond orthosilicates and titanates, developed via UK compact neutron source facility ▪ Mitigate segregation of non-multiplying zones in $BeTi_{12}$ amplifier ▪ Tritium permeation barriers for balance of plant	▪ Additive manufactured Li ceramic as continuous blanket ▪ Feasible alternative multipliers ($LaPb_3$, Zr_5Pb_4, YPb_2) ▪ Optimised tritium extraction microstructures
High fusion energy through effective confinement at high magnetic fields (>8T)	**Define the possible in irradiation resilient magnets, insulation at cryogenic temperatures**	▪ Irradiation tests on REBCO to E>0.1MeV / ~0.001 dpa (current limit) at operating T, spectrum, B ▪ Improved insulation e.g. novel amorphous ceramics or imides ▪ Understanding of annealing path in irradiated cryogenically-cooled resistive aluminium	▪ Cryogenic irradiation tests on REBCO beyond ~0.001 dpa (aiming for overtest to 0.1dpa)
Plant efficiency (100 MWe)	**Develop higher temperature structural materials (>550°C)**	▪ Fabrication-scale microstructural tuning of castable complex nanostructured alloys (carbide / nitride / more inert precipitates) to reach >600°C ▪ Optimised SiC-SiC composites (nanostructured SiC fibre for enhanced irradiation resilience; pyrolysis free interphases; transmutation gas routine architecture)	▪ Weldable and lower cost ODS / HiP'd powermetallurgy variants to reach 700°C ▪ Additive manufactured divertor materials with integrated cooling structures ▪ Thermo electric first wall /divertor material for direct plant output contribution
Plant availability (50%) and cost (£10bn)	**Deliver engineering assurance for materials under powerplant conditions**	▪ Synergistic dual ion beam irradiation campaigns (proton + load; proton + corrosion; proton + cryo) on baseline materials for low dpa mechanical property degradation ▪ First Finite Element based failure prediction models *across* microstructures ▪ Simulated in situ (dose-temperature conditions) material response via 'whole problem approach' utilising physics-derived atomistic response laws	▪ Synergistic irradiation campaigns (neutron + load; neutron + corrosion; neutron + cryo) on baseline and novel materials with emphasis on high dpa impact quantification on mechanical properties (especially creep-fatigue) ▪ Stitched length- and time-scale failure prediction models ▪ Modelled transmutation gas impact on mechanical degradation



Moving samples from a safe space (lined trolley) to the analytical instrument via robot in MRF state 2.

INTRODUCTION & METHODOLOGY

OVERVIEW

Dear reader,

In the year in which this Roadmap is published, the UK will down-select the site for its very first fusion powerplant, the Spherical Tokamak for Energy Production (STEP). Delivery of this prototype is scoped for 2040 - a timeframe in which the USA has announced plans to trial its first demonstration fusion plant. By 2050, Europe hopes to bring into operation its DEMO fusion powerplant. **An age of fusion engineering and delivery has begun.**

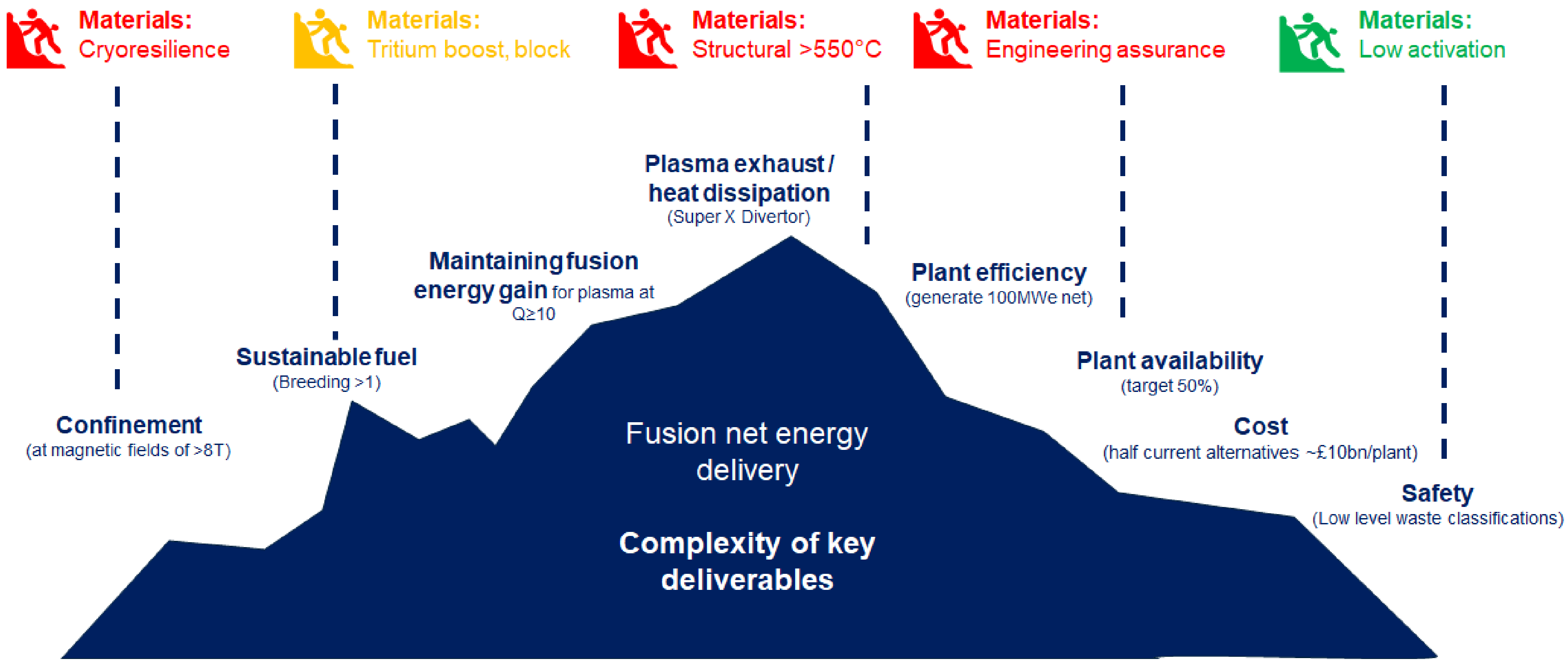


Fig. 1: Materials as enabler across the Fusion Roadmap

Fusion is challenging in many senses but the key components of the fusion roadmap are well defined (Figure 1). Materials will be part of the build challenge, but also **an enabler** in terms of safety, fuel sustainability and cost control. Baseline materials have already been identified for the world's soon-to-be-largest tokamak ITER, but there is plenty of scope for the development of new and novel materials in the decades towards STEP and DEMO.

The fusion reactor environment is possibly the **most extreme environment any material will face,** with the combination of irradiation and thermal, magnetic, electric and mechanical loads. While high energy neutrons displace atoms, creating short term damage, lower energy neutrons trigger transmutation (the modification of atoms to other elements), releasing a slow burning onslaught of compositional damage and gas build-up that may cripple reactor components over operation periods. Tritium – the fuel of fusion – will inevitably seep through materials close to the plasma but it must not pass into the balance of plant if safety and fuel budgets are to be maintained. Thus our triple whammy in fusion materials: Tritium, transmutation and displacement.

Ordinary test opportunities for materials qualification and development do not apply to this application: No neutron source globally, currently operates at high enough energies and fluxes to mimic STEP and DEMO operating conditions. Fusion materials scientists must seek creative new ways to demonstrate materials' viability and to offer **engineering assurance,** and will do so through proxy irradiation experiments, a panoply of modelling approaches and simulators, and compensatory engineering design. With time, surveillance programmes in operating plants will deliver the fuller picture of material evolution under 14 MeV neutron doses at fluxes of 10^{14} n/cm2/s. International partnerships to access Materials Test Reactors will be important for interim irradiation campaigns.

At the start of 2021, UKAEA hosted, with the support and sponsorship of The Henry Royce Institute, a series of Roadmap workshops with UK academia, industry and various parastatal enterprises (NAMRC, AWE, NNL). Interest in fusion was high, but working knowledge of fusion reactors low, and the learning has been that **UKAEA has a key role to play in disseminating fusion technical data** more widely, as well as providing access to predictive software to calculate material activation and decay, and to test facilities for active materials.

Subsequent to the early canvassing workshops, UKAEA also convened a number of consultations on irradiation and modelling, and distributed a questionnaire to the nuclear materials supply chain in 2021. **Aggregated inputs are presented in this Roadmap.** They range from clear ideas for immediate R&D to close those materials performance gaps already defined, to broader and more generic long terms materials improvements which may in turn steer future engineering design in fusion tokamaks.

If there is a **sequential path to fusion, for materials,** it must be defined functionally: shortlist candidates –> irradiate to understand neutron response in the form of material damage –> model to extrapolate that damage to full impact for operating conditions and lifetime –> mitigate via microstructural enhancements based on the damage observation and modelling. Acceleration through this sequence requires integrated experiment and modelling, with intelligent definition and quantification of the uncertainties which will attach to extrapolations from these experiments and models. Some voice the opinion that modelling may be capable of replacing irradiation altogether. **Most agree that engineering assurance/qualification is the central issue and failure mode prediction will be the most critical activity.**

In the various materials families (metals, ceramics, composites) application context drives specific requirements:

- Structural materials must be capable of greater creep resilience at higher temperatures than those currently confirmed for irradiated metals
- Superconducting magnet materials will need to be demonstrated as viable at low displacement per atom damage levels, in cryogenic tests
- Tritium breeding compounds – mostly lithium based – should be optimised for breeding ratios and tuned for maximum efficiency of detriation
- Across the piece, low activation should add value to, but not exclude, otherwise optimal candidates

Hence a broad scheme of five major areas of work has been identified as requisite to engineering progress in the upcoming design and build of STEP and then DEMO:

- Enable low activation waste predominance in fusion
- Deliver high breeding ratio compounds
- Define the possible in irradiation resilient magnets and associated insulation
- Develop higher temperature structural materials (>550°C)
- Deliver engineering assurance for materials under powerplant conditions

Ideally, fusion will see a programmatic approach from government, to funding support for the considerable body of research required in materials and technology, in years to come. This Roadmap aims to place before the UK materials community **a starting point –** there should be iterations of the narrative in the future, as familiarity grows. Although the ideas have been shaped locally, where there are opportunities to collaborate internationally, national and overseas capabilities should be linked to support the ambition. It is also hoped that this information will start to inform the UK materials supply chain so vital to delivering commercial fusion.

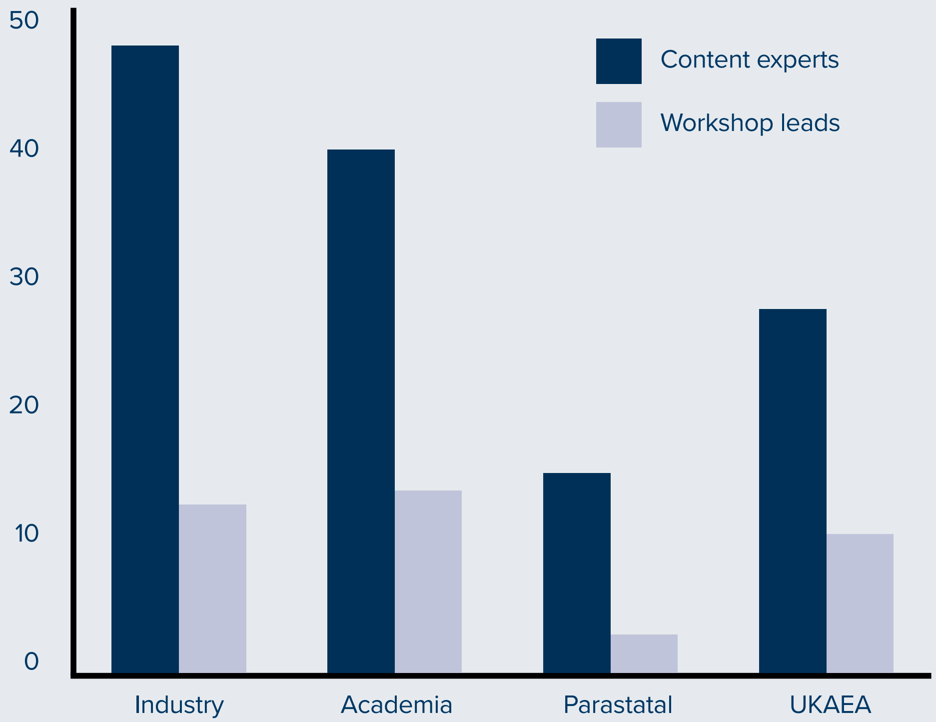
The aim is to gather stakeholders around common themes and **generate momentum** in the testing, mechanistic understanding, and surmounting, of irradiation damage. This Roadmap is released by way of a 'tender' (ie specification for work) document: where challenges are generic, there is an implied invitation to get involved to shape experimental investment and planning in more depth; where next steps are already outlined in detail, there is an implied invitation to action (create a consortium, seek funding, deliver solutions to the outlined challenge). This is a call to arms. I look forward to working with you on the very worthwhile goal of enabling low carbon electricity generation for this century.

Dr Amanda Quadling, Director of Materials, UKAEA

ROADMAPPING APPROACH & METHODOLOGY

The UK Fusion Materials Roadmap exercise was initiated via a series of on-line collaborative workshops, funded by Royce and facilitated by IfM (University of Cambridge) in early 2021. These aimed at a first share and review of current information on potential materials for fusion energy. Ahead of each workshop, 120 experts from industry, academia, parastatals like NNL and NAMRC, and UKAEA submitted viewpoints. These were consolidated and debated by 30 leads across the 4 workshop sessions to collate a narrative on Drivers for Fusion Materials, Attributes of Materials Required, Materials Available, and Innovation Paths to Close the Gap (why / what / how).

In a second phase of work, UKAEA hosted two subject-specific consultations with experts, on the topics of materials irradiation and modelling respectively. A survey was also distributed to affiliates in the nuclear materials supply chain. Aggregating the workshop deliberations, consultations contents and survey responses, a working Roadmap draft was created and distributed to an editorial team of UK experts and UKAEA professionals to tighten content delivered here.

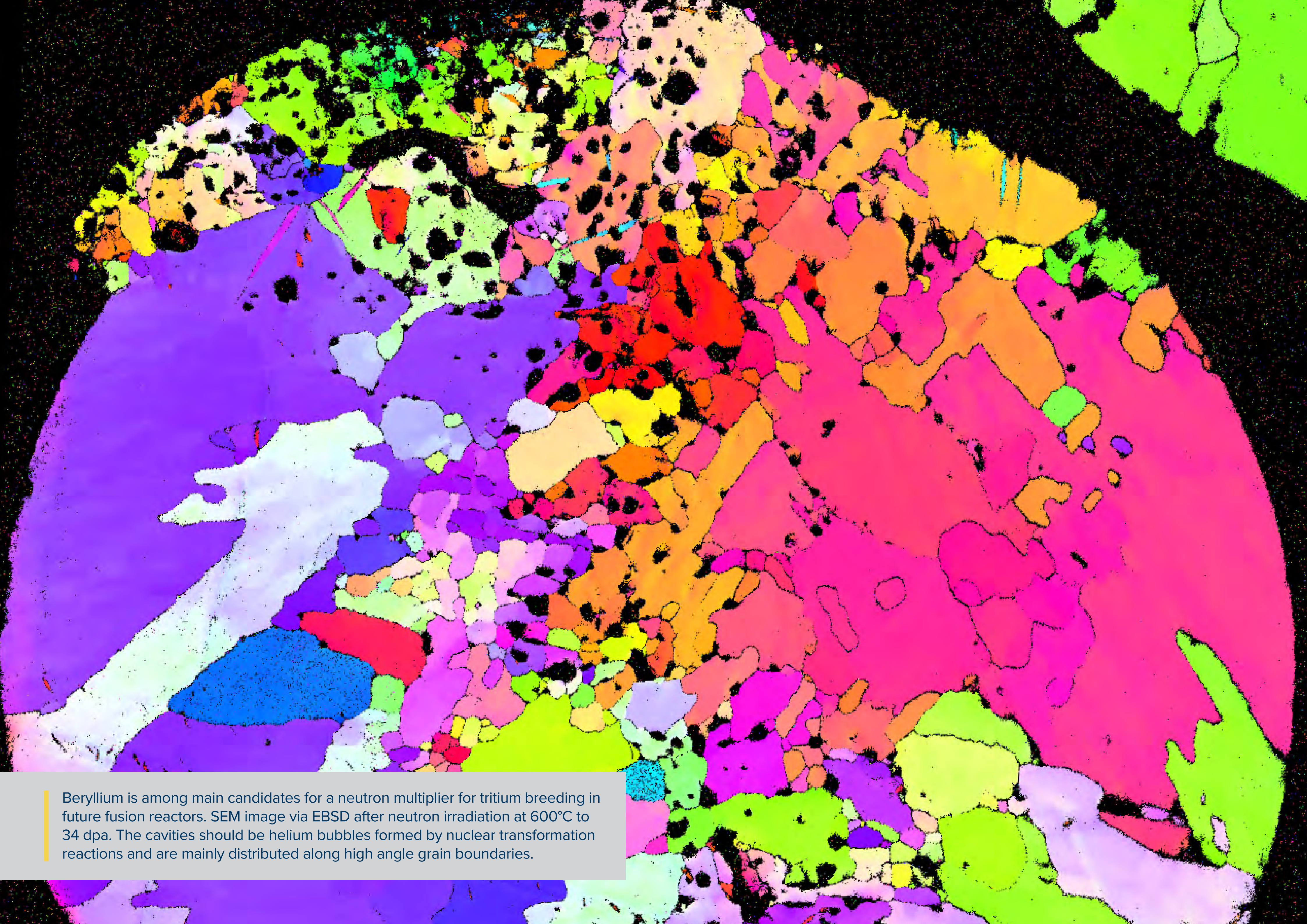


In scope:

- Materials irradiation
- Materials modelling
- Materials development
- Brief aspects of process innovation for bulk materials, raw materials supply, materials qualification
- *Structural, armour, heat sink, magnet, insulation materials*

Out of scope:

- Materials manufacture, joining (both part of a separate Fusion Technology Roadmap to come. However, aspects that are covered in this document include i) materials that enable better joining, and ii) the impact of manufacturing on microstructures)
- Engineered materials design, testing, qualification
- *Liquids, organic materials, diagnostic / electronics / monitoring materials, civil/ construction materials*



Beryllium is among main candidates for a neutron multiplier for tritium breeding in future fusion reactors. SEM image via EBSD after neutron irradiation at 600°C to 34 dpa. The cavities should be helium bubbles formed by nuclear transformation reactions and are mainly distributed along high angle grain boundaries.

CONTEXT - INDUSTRY & APPLICATION

DRIVERS

Driver	From 2020	From 2025
POLITICAL	Reduction in reliance on fossil fuels, greater utilisation of the national grid and progress towards zero carbon in UK	
POLITICAL	Development of strategic partnerships to access specialist facilities (manufacturing, irradiation, etc.)	Access arrangements established for strategic materials (e.g. Be and 6Li)
ECONOMIC	Current know how and materials requirements captured for fusion and related industries	Development of supply chain to support requirements. Establish supplier network
ECONOMIC	Strategic partnerships across UK nuclear to enable innovation and access to global nuclear funding. Establish strong links with Gen-IV fission community	
SOCIOLOGICAL	Establish fusion materials community and steering committee. Identify key research themes and research niches	ITER operations and lessons learnt
SOCIOLOGICAL	Education and training for next-generation of nuclear materials scientists. Establish strategic university	
TECHNOLOGICAL	Advancements in fission (primarily Gen-IV) and aerospace technology driving new material development	
TECHNOLOGICAL	Development and exploitation of novel manufacturing and joining technologies	
LEGAL	Mapping of design and regulatory codes to enable harmonisation	Formulation of regulatory framework prior to STEP construction
ENVIRONMENTAL	Development of materials and clean manufacture processes to enable production of reduced activation fusion materials	
ENVIRONMENTAL		Identification and establishment of waste (such as molten salt and lead), tritiated

2020 2025

Zero carbon electricity production in UK (demonstrate 80% reduction in UK carbon output)

Route to net zero carbon by 2050

Enabling access to ITER, materials testing, extract useful materials data

initial nuclear materials

Long-term development of supply chain to support commercial fusion and GenIV fission. Working with zero-carbon supply chain initiatives

Demonstration of suitable material selection to build prototype fusion plants. Viability of fusion

links, cross-cutting academic linkages across technological sectors, and provide suitable sponsorship for research and training programmes

Focus and enhancement of UK expertise in niche areas, such as breeder blanket design (with major progress from STEP) and tritium analysis/handling

Standardisation of small-scale and novel methods to support materials qualification with significant uncertainty

Identification and investment in technologies to enable waste reprocessing and circular economy

management streams for hazardous materials such as beryllium, coolants components etc.

Route to net zero carbon by 2050

2030 | 2035 | 2040

POLITICAL

The UK has developed a low-carbon roadmap from climate change committee, pledging to reach a zero-carbon economy by 2050. From 2035, the UK will need to demonstrate a 78% reduction in sources of electricity from high-carbon sources[1]. This will necessitate a shift from oil and gas plants, towards a greater use of renewables and nuclear energy to provide a sustainable baseload. This will be a key moment for fusion and Advanced Nuclear Technologies in fission, to demonstrate viability both from a technical and economic perspective. The STEP plant becoming operational in the 2040's will be a transformative moment as the UK enters the final decade to a zero-carbon economy. UK has an opportunity to capitalise on its current world-leading position in fusion - both with facilities and skilled people – most recently demonstrated in the announcement by General Fusion to build their demonstration facility at Culham, Oxfordshire[2]. With consistent, long term, dedicated funding from UKRI / BEIS / ARIA, strategic partnerships can be built and a programmatic approach enacted to ensure robust and coherent R&D delivery. Fusion has already leveraged £1.4bn from £347m invested[3].

ECONOMIC

It is essential, as we advance through the 2020's, that a strong and diverse fusion materials supply chain is established. The UK has a wealth of knowledge available from fission plant design and operation (AGR, PWR, SMR), along with experience of the challenges and solutions to materials sourcing and management. It is an important moment for the UK to be well-aligned with global nuclear energy developments, as £930bn is planned for global investment into new build nuclear through to the 2030's[4]. Therefore, an effective network with nuclear material operators and suppliers should be established, with UKAEA bridging the gap into the fusion materials domain. Here we should work collaboratively to define materials requirements as an output from the design community, to the material supply chain. This should be developed in unison with the Gen-IV design community, as many material performance demands are shared with fusion materials. It is important that in parallel with this, the supply chain is developed carefully to ensure that we don't inadvertently drive a problem upstream by purchasing materials from highly polluting or carbon intensive sources.

1 - https://www.gov.uk/government/news/uk-enshrines-new-target-in-law-to-slash-emissions-by-78-by-2035
2 - https://www.gov.uk/government/publications/nuclear-industrial-strategy-the-uks-nuclear-future
3 - https://www.gov.uk/government/news/government-investment-in-fusion-energy-boosts-british-economy-by-14-billion
4 - Nuclear energy: Fusion plant backed by Jeff Bezos to be built in UK - BBC News

SOCIOLOGICAL

It is important that the benefits of shared knowledge and efforts across a range of research areas are identified and realized. As a demonstration, this roadmapping exercise has identified a key community of individuals who are well-placed to advise and shape a materials research agenda with strong links to parallel industries such as fission, oil and gas and aerospace. A fusion materials steering group would be beneficial to serve as a sounding board for research proposals, but also to advise on overall direction and appropriate cross-cutting linkages. As ITER moves into an operational phase in 2025[5], it is crucial that the UK remains closely aligned to this programme, capturing lessons learnt and operational experiences to further define materials limitations and requirements for the next-generation commercial fusion fleet. From 2030, there will be an important emphasis to demonstrate the viability of commercial fusion power. At this point, STEP detailed design will be nearing completion, along with final materials selection for the prototype plant. A rigorous and effective process for materials selection, and clear action plans for further materials developmental requirements must be well-established from this point.

TECHNOLOGICAL

Advancements in Gen-IV fission, particularly around materials for irradiation-tolerance, high-temperature operation and good corrosion resistance will be key requirements for plants such as the molten-salt reactor (MSR) design[6]. From aerospace, developments for high strength to weight ratio materials such as composites are important to consider for fusion, alongside high-temperature coatings and other materials designed to endure extreme environments. A fusion materials steering group would be ideally placed to enable wider access and interaction to these sectors. As global demand in sustainable energies increases and the benefits that fusion power offers are realised, breeding blanket design and tritium handling will be central technological themes in the coming decades. The UK has established expertise in these areas, through national involvement on STEP and DEMO design programmes, as well as tritium handling for JET.

5 - https://www.iter.org/proj/ITERMilestones
6 - https://world-nuclear.org/information-library/current-and-future-generation/molten-salt-reactors.aspx

LEGAL

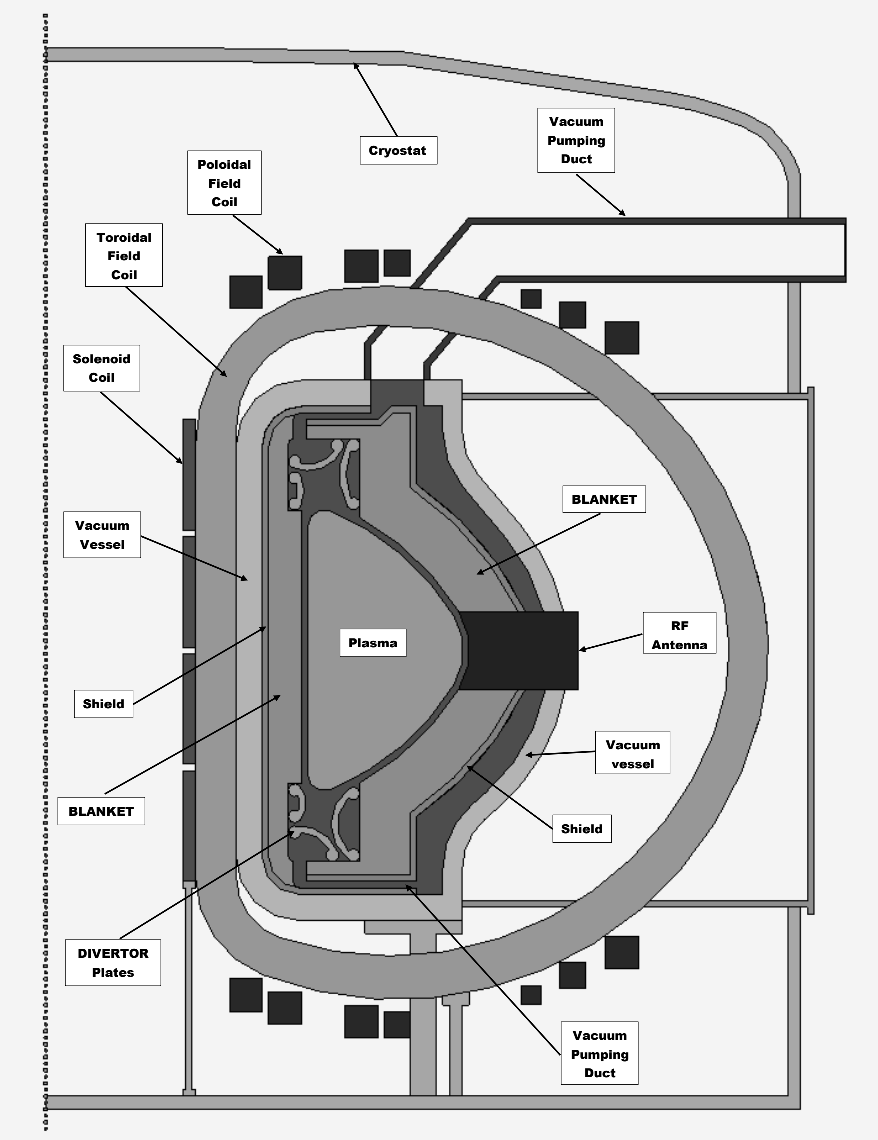
Within the UK, design codes, regulations and standards for fusion power plants do not yet exist. It is therefore important that at this early stage, to map and where possible, unify various materials design codes in order to ease compliance in the future and ensure that innovation in the fusion sector is not stifled. Already, in Europe, the RCC-MRx code includes fusion-specific design rules which can be mapped across and assessed. It follows that in 2025-2030, as the STEP concept enters detailed design, the regulatory framework is being established. As part of the regulatory space, standardisation for non-standard materials testing will be crucial as test volumes are constrained due to limited amounts of material irradiated to sufficient damage levels. This includes standardisation of small scale test techniques, such as micro tensile and small punch (recently published standard as BS EN 10371:2021), and non-contact techniques such as digital image correlation (DIC), which may be necessitated due to challenging material testing setups and sub-size sample geometries.

ENVIRONMENTAL

As the UK drives towards a zero-carbon economy, it is important that the fusion sector supports development of a clean supply chain in parallel with the UK governments clean growth strategy[7]. Low carbon manufacture of materials such as steel, must also be coupled with manufacturing advancements to enable production of reduced activation materials. Such materials include steels with reduced, Ni, Nb, Co and Mo contents and are essential to ensuring that fusion plant materials can be disposed of as low-level waste (LLW) after 100 years. (The development of these high-performance low-activated materials should not be stifled by the limitation of today's upstream and downstream processing technology. In fact, materials development will drive evolution within the manufacturing community, capable of returning advancements in materials processing capability.) As part of a circular economy, it is important that as STEP enters detailed design, investigation into routes for effective waste segregation and reprocessing are conducted, and viability assessments into preferred routes are completed and subsequently developed further. It is important that a clear route for waste reprocessing is established and that component designs best enable separation of hazardous wastes from conventional waste.

7 - https://www.gov.uk/government/publications/clean-growth-strategy

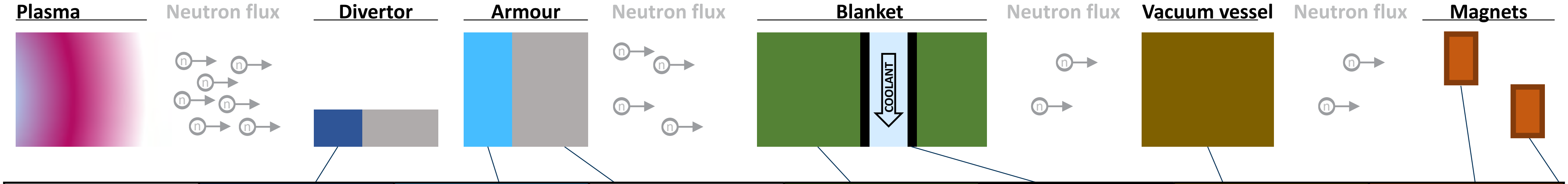
APPLICATION - MATERIALS IN SITU



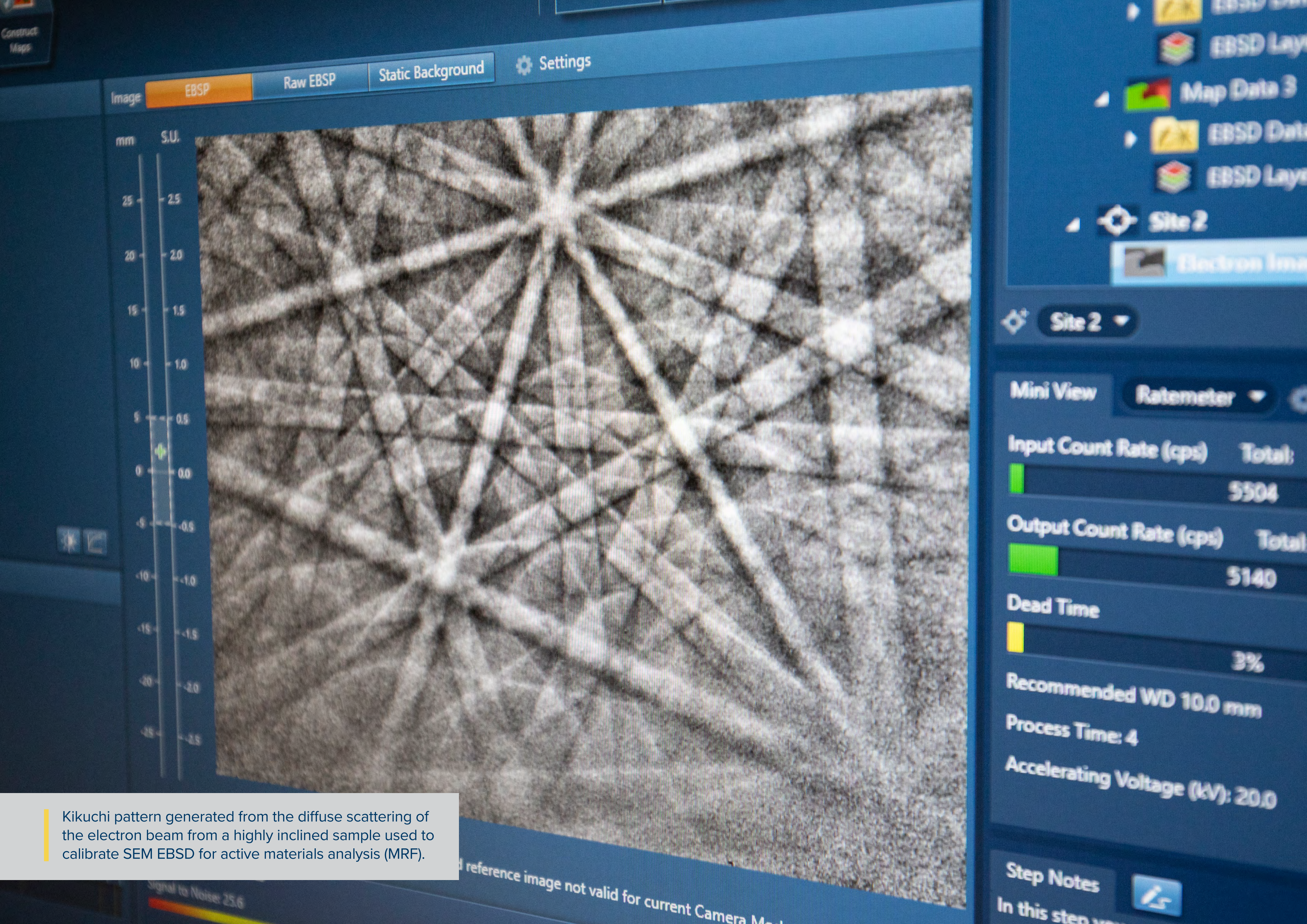
Adapted from an unknown source

		Temperature (°C)	Neutron flux at 14 MeV (n/cm²/s)	Peak steady state Heat flux (MW/m²)
Divertor				
	Plasma facing	<1300	1.5×10^{14}	STEP : 20-25, DEMO : 10
	Heat sink	<600	1.5×10^{14}	STEP : 20-25, DEMO : 10
First wall				
	Plasma facing	<900	5×10^{14}	<7
	Heat sink	<900	3×10^{14}	<7
Shield		<850	3×10^{14}	Volumetric heat flux to the shield <10MW/m²
Blanket				
	Front (first wall heat sink)	<900	3×10^{14}	<7
	Back	<700 (with water cooling, higher if metal cooling)	5×10^{13}	<2

APPLICATION ENVIRONMENT



Challenge	Divertor strike plate (detached divertors)	Armour surface	Armour substrate	Blanket breeder, multiplier and casing	Blanket cooling pipes	Vacuum vessel	Magnets
Neutron radiation	HIGH	VERY HIGH	HIGH	MEDIUM	MEDIUM	LOW	LOW
Temperature	VERY HIGH	YES	YES	MEDIUM	MEDIUM	NO	NO
Heat flux	HIGH	YES	YES	NO	NO	NO	NO
Magnetic stresses from coils	SOME	YES	YES	YES	YES	YES	YES
Corrosion	(IF ACTIVE COOLING)	NO	YES	YES	YES	(IF ACTIVE COOLING)	NO
Mechanical load	SOME	YES	YES	YES	YES	YES	YES
Helium generation	HIGH	HIGH	HIGH	MEDIUM	MEDIUM	LOW	NO
Cooling fluid pressure	NO	NO	YES	NO	YES	NO	NO
Plasma erosion	MEDIUM	YES	NO	NO	NO	NO	NO
Tritium absorption	YES	YES	LOW	YES	YES	LOW	NO



Kikuchi pattern generated from the diffuse scattering of the electron beam from a highly inclined sample used to calibrate SEM EBSD for active materials analysis (MRF).

MATERIALS DEVELOPMENT

The primary aim of fusion materials development is to modify existing, or design and build new, materials that maintain their functionality when exposed to high neutron doses under the extreme operating conditions (thermal, magnetic, electrical and mechanical) anticipated for future powerplants such as STEP and DEMO.

In the first instance, some **fusion impact can be anticipated** - with materials development occurring prior to irradiation experiments. Scope exists to balance some properties (strength, creep, toughness, thermal conductivity, oxidation/ corrosion resistance) in novel unirradiated microstructures, based on what is already known about neutron displacement and transmutation, and from years of fission experience. Development options envisaged here include metal foams to accommodate differential thermal strains; controlled porosity and void arrangements to act as isotope catchment systems 'wells' to reduce embrittlement; nano particles to improve conductivity; and printed integrated electrical circuits. Process innovation may provide volumetric doping to tailor preferential property orientations via nanoprecipitates.

In the second instance, **fusion materials development will be driven by experimental research.** This is an arduous undertaking in the context of irradiation because of highly variable experimental conditions intrinsic to test reactor operation and the long time frames that sometimes apply. Conventional full-scale testing may not always be relevant (single parameter variation over large homogenous volume) for fusion's complex loading conditions and high gradient fields, and planned experiments will generally be some orders of magnitude off true application conditions on several aspects at any one time (fluence, flux, energy spectrum, heat flux). Nevertheless, well constrained experiments with self-ion implantation, proton-based dual beam set ups, compact medium-flux neutron sources, and Materials Test Reactors will all contribute materials damage information. Applied to specific material microstructures and properly qualified for experimental conditions, such information will underpin interative efforts to tune new microstructures – and qualify likely operating behaviour for existing microstructures.

In the third instance, a thorough mechanistic understanding of the phenomena that drive materials degradation under fusion irradiation is required in order to improve and alter existing materials and microstructures and to design new material systems with greater promise: Experiments will enable better models, and **modelling itself will become the driver in fusion materials development**. As skill and knowledge grow in the industry, particular emphasis is required (in experiments and modelling) on the *synergistic* impact of the various damage phenomena from neutron exposure: hardening, embrittlement (due to atomic displacements) embrittlement (due to He and other transmutation gases), creep, creep-fatigue, compositional segregation, swelling, and irradiation-exacerbated corrosion.

While irradiation-induced damage is highly specific for some materials - burnup of ^{6}Li in tritium breeders, for example, and reduced Jc (critical current density) and increased Tc (critical temperature) in superconducting magnet materials – hardening, segregation, creep and embrittlement are common impacts for most material systems. Hence a generic set of experiments is outlined for fusion material development below (see also the irradiation section) and then beyond these generic requirements, the next few pages outline key material-specific requirements for progression.

A MODERN MATERIALS APPROACH:

1. Can we design materials that develop to enhanced performance *under* irradiation conditions?

2. Should we design materials for in situ replacement by robotics (*sacrificial* phases)?

3. How do we make fusion materials *sustainable* / recyclable?

4. Can we design SMART materials for future powerplant operation to deliver in situ monitoring and maintenance/ failure prediction? (Some examples are already envisaged: self-diagnostic heat exchanger modules using lamination techniques to provide integrated tritium barrier signal systems; topology-controlled materials / auxetics as promising candidates for strain sensing.)

TO DEVELOP EACH NEW FUSION MATERIAL (OR MATERIAL FAMILY), WE NEED TO:

Determine performance under irradiation	Characterise the impact of neutron dose on prioritised mechanical properties (creep, toughness, and particularly DBTT in bcc options). Qualify the impact due to displacement damage (typically short timescale experiments) vs that due to transmutation / compositional effects (longer timescale experiments or experiments with gas implantation and varying starter compositions). Where proxies are used for neutrons, qualify outcomes accordingly.
	Determine the synergistic effect of other loads applied simultaneous with irradiation (mechanical, thermal, magnetic, electrical, cryogenic)? Stress combinations and stress cycling data adds value.
Demonstrate microstructural and chemical link/s to irradiation resilience	Determine how crystallography – as well as the interfaces / grain size/ distribution/ density and size of precipitates (ODS, nanostructured steels) - impact defect structure, scaling and propagation.
	Evaluate the dependency between chemical bond energies and defect structure and propagation (density functional theory has indicated the latter is dependent to some extent, on the former).
Explore likely temporal evolution of bulk properties under operating conditions	Establish whether there is a hysteresis characteristic over multiple irradiations or potential for new degradation mechanisms over time (for example, in fission there is concern about late blooming phases or late onset embrittlement)
	Describe and understand evidence for damage recovery / annealing / saturation relative to time, dose and temperature. Qualify for irradiation source. Do some microstructural elements improve resilience over time, under dose? Does dose over time obviate optimised microstructures?
Understand the fuel interface	Determine whether, and to what extent, the material – post irradiation – retains deuterium and tritium. Establish the trapping mechanism or link to degradation phenomenon.
	Determine the route to, and rate of, permeation of fuel (useful for safety and fuel budget perspectives).
Develop safer variants	Evaluate the potential to 'swop out' elements within the compositional space, for those less prone to long half lives, while maintaining microstructural benefits established to this point, especially for mechanical properties (ie. develop low activation variants).
	Evaluate impact of microstructure on spallation and delamination under plasma conditions to improve waste control / safety.

DIRECTION OF TRAVEL

METALS AND ALLOYS (STRUCTURAL / HEAT SINK / ARMOUR)

Castable variants - Complex Nanostructured Alloys (CNAs)	Optimise high temperature mechanical properties (especially creep) through novel thermomechanical treatments on RAFM variants at fabrication scale (new quench, temper sequences).	Explore alternative size, density, location and chemistry of precipitate phases (carbides, nitrides, aluminides) to optimise for inertness in operation but to allow casting in first instance.		
Powder metallurgy variants - Oxide Dispersion Strengthened (ODS) Alloys	Tune yttrium oxide content to reach acceptable balance between formability and irradiation resilience /high-temperature performance.	Improve consistency in powder metallurgy methods (superior powder sizes/ morphologies) to optimise stoichiometry to reduce O, N and C contaminants and decrease activation in service.	Optimise homogeneity and reproducibility at scale. May be assisted by mechanical alloying such as the Surface Treatment of gas Atomised powder followed by Reactive Synthesis (STARS) process.	Near net shape (NNS) process innovation, to alleviate joining issues (e.g. FAST, HIP, AM) and to minimise welds.
Grade 91/92, RAFM and austenitic (316SS) steels	Priority is to find a high temperature (>550°C) ferritic martensitic variant - pushing past current ductile to brittle transition temperature challenges.	Austenitic improvements in irradiation resilience should focus on ability to accommodate transmutation He (including high Ni variant viability).		
Boron-strengthened steels (e.g. MARBN)	Can we replace Co in these?	Control rods contain Ni which needs lower activation alternative.		
CuCrZr	Priority is to find a high temperature (>300°C) variant for heat sinks.	Self passivating surfaces needed for plasma facing variants in the event of oxygen exposure – focus on recrystallisation.	Address coolant corrosion issues.	

Chronology based on priority or building complexity →

DIRECTION OF TRAVEL

METALS AND ALLOYS (STRUCTURAL / HEAT SINK / ARMOUR)

Zr, V, Cr alloys	Higher temperature Zr variants required, beyond current 300-400°C.	Can fusion adopt and adapt accident tolerant fuel cladding developments re Zr, particularly AXIOM alloys (Westinghouse) and quaternary ultra-low tin alloys (AREVA).	Mitigation strategies for hydriding (and associated embrittlement) and tritium uptake.	Exploit neutron transparency of V and Cr variants – newer alloys?
Ti alloys	Evaluate decomposition and absorption of Ti oxide layer into base metal above 600°C and how this may influence tritium uptake.	Assess optimal alloy phase types (near α, metastable β or stabilised β) for fusion.		
High entropy (HEA), Multi Component (MCA) and Compositionally Complex Alloys (CCA)	Understand touted irradiation damage tolerance and confirm base properties are attractive (temp strength and ductility).	Particular focus on thermal conductivity properties after irradiation due to known drop-off trends.	Low activation variants required.	May be possible to precipitate strengthen medium entropy variants.
Tungsten	Understand effect of plasma exposure and melting on thermal and mechanical properties; enhance plasma erosion resilience.	Validate binderless sintering or low activation binders.	Understand impact of anisotropy arising from traditional fabrication and relative benefits from additive manufacturing options, on mechanical performance.	Assess technology for Mo isotope separation as most likely alternative material in armour / first walls.
Beryllium	Understand effect of plasma exposure and melting on thermal and mechanical properties; enhance plasma erosion resilience.	Understand impact of water exposure (dust formation, oxidation) on mechanical properties in situ in tokamak.	Explain and quantify different fuel retention mechanisms of D and T.	

Chronology based on priority or building complexity →

DIRECTION OF TRAVEL

CERAMICS AND COATINGS (BLANKET WALLS, CIRCUIT COATINGS, FLOW SEPARATORS)

CERAMIC MONOLITHS

- Compare impact of manufacturing routes (e.g. SITE, NITE, CVI, PiP, polymeric precursor 3D printing) and architectures on relative irradiation resilience of resulting microstructure.
- Develop Transient Phase Liquid Bonding compatible with fusion-relevant materials. Evaluate joinability with metals.
- Consider thermo electric ceramic elements for heat-electrical conversion direct to plant.

CERAMIC COMPOSITES:

SiCf-SiC
TiC, ZrC, HfC variants
Tungsten carbide
Mullite-mullite

- Compare known benefit of neutron transparency of SiC with sparse data on irradiation breakdown of C in this composite at 14 MeV in context of breeder front wall or continuous (non welded) breeder structure.
- Understand relative impact of SiC fibre nano-crystallinity vs strength of fibre-matrix interface on irradiation resilience.
- Find alternative, lower activation and non-pyrolysing interphase materials, relative to graphite.
- Explore alternative weave architectures and impregnation styles to modify electrical and radiation reflection at phase interfaces.
- Understand role of macroscale porosity vs microscale atomic lattice layers for helium permeation and release under transmutation.

COATINGS:

AlO_x, Er_2O_3, nitrides (CrN, BN)

- Establish compatibility with coolant environments (aqueous, liquid metal, molten salt, gas) up to 650°C.
- Corrosion trials utilising static and flowing conditions, with oxygen content monitoring.
- Tritium permeation trials up to temperatures of 650°C.
- Evaluation of additive manufacture (AM) to apply coatings to complex geometries.
- Stacking trials to optimise thickness vs delamination.

CERAMICS (BREEDERS AND AMPLIFIERS)

CERAMIC SYSTEMS:

Li orthosilicate
Li metatitanate
Li zirconate
Alternatives with lead

- Improve crush resistance in pebble breeder ceramics and explore alternative physiologies to pebbles.
- Define required ^6Li enrichment.
- Establish compatibility with coolant environments (aqueous, liquid metal, molten salt, gas) up to 650°C.

- Mitigate segregation of non-multiplying zones in $BeTi_{12}$ as amplifier.
- Mitigate U impurity in Be amplifier compounds.
- Identify and investigate alternative Li multiplier composites as well as broader suite of multipliers: $LaPb_3$, Zr_5Pb_4, YPb_2.
- Establish compatibility with coolant environments (aqueous, liquid metal, molten salt, gas) up to 650°C.

Chronology based on priority or building complexity →

DIRECTION OF TRAVEL

MAGNETS AND INSULATORS

RESISTIVE MAGNET MATERIALS

- Determine degree of annealing of aluminium (and copper coils) in thermal cycling regime of fusion.
- Evaluate feasibility of higher purity electroplated Cu as feedstock or applied directly in magnets.
- Improved solder materials required for large magnets (high conductivity and strength).
- Development of low-activation solder variants.

SUPERCONDUCTING MAGNET MATERIALS

- Establish feasibility of sustained operation of REBCO type tapes at ~10^{22} n/m^2 (E>0.1MeV; ~0.001 dpa) and property recovery in cyclic pulse regime.
- Tailor REBCO type tapes for fusion (taking into account, effects on secondary particle equilibrium into the REBCO layer)- no Ag/ low -activation, non-magnetic substrates – would need to retest and requalify.
- For cryogenic sealing of large magnets, investigate performance of thermoplastic/ elastomer solutions for LHe, gHe and alternatives.
- For large, high-field magnets, high strength structural support required at cryogenic temperatures.
- Identify alternative coolants (e.g. LH_2, LNe) for 20-30 K operation (based on thermohydraulics).

INSULATORS / SHIELDING

- RADHARD organic potting compounds required for tokamak coils: tailor organic chemistry to generate G10 variant.
- Develop inorganic alternatives to resins for high temperature insulation: eg amorphous dense ceramics via reactive alkali metals and boron compounds (expand on those with good thermal conduction properties in fission related tests).
- Develop RADHARD inorganic insulators for cryogenic operation.

Chronology based on priority or building complexity →

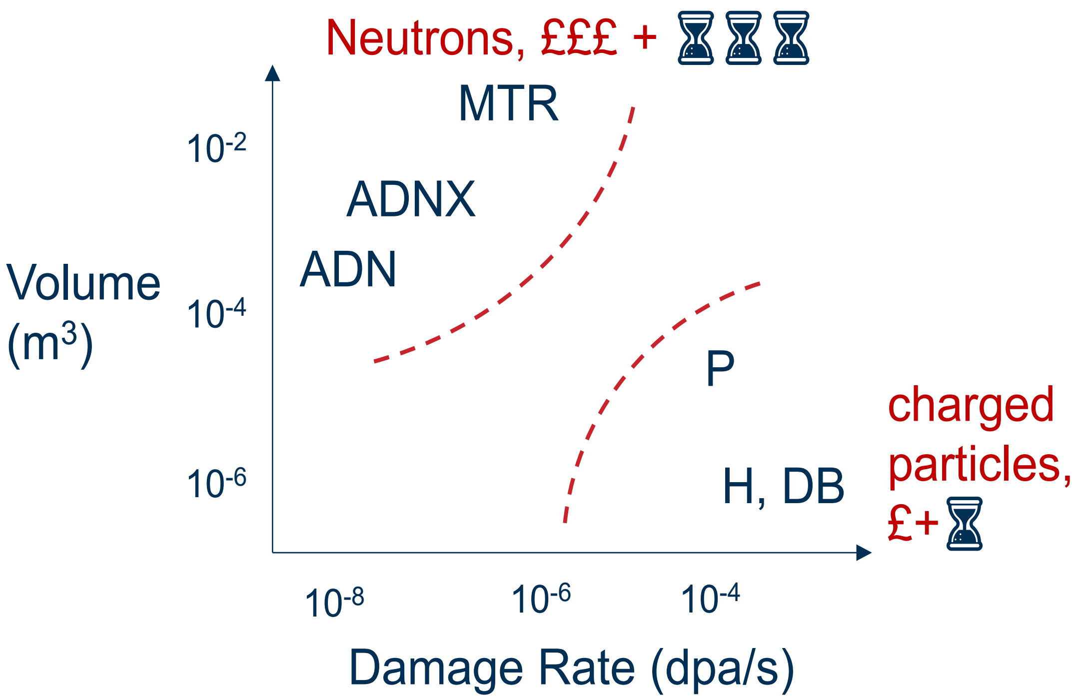
The Quantum Design Dynacool Physical Property Measurement System (PPMS) is a 14T superconducting solenoid magnet with an active sample operating from room temperature up to 1000K or down to 1.8K.

IRRADIATION

IRRADIATION - A PROGRAMMATIC VIEW

Experiments for nuclear data	More and better, datasets are required on neutron cross-sections, decay heat, uncertainty quantification and neutronics benchmarks. These ultimately deliver component lifetime estimates, enable predicted shielding requirements, underpin waste management strategies and support diagnostics development and validation.
Experiments to enhance breeder materials	Development of improved breeder and amplifier materials requires experimental configurations that address both efficiency of tritium creation in the substrate materials as well as subsequent release / removal of the entrained tritium from the breeder (and any amplifiers). These experiments lend themselves to compact neutron source options. A pre-requisite is good understanding of the impact of accuracy of the breeding ratio determination.
Experiments to underpin and validate damage modelling and to down select materials	In the first few hours of fusion powerplant operation, it is anticipated that significant reduction of thermo-mechanical integrity will occur in armour / first wall materials and areas of high thermal and neutron flux. Modelling of fusion damage in materials currently looks to cover two arcs: first, the development of fundamental laws governing material behaviour at the atomistic level (leading to an understanding of how stress and strain might evolve in dose-temperature regimes and affect defect propagation); second, the use of finite element based techniques to model microstructure-wide phenomena in response to irradiation, to understand and predict failure. Both initiatives require well controlled irradiation experiments on well constrained samples to feed and validate the models. In parallel, first powerplant builds start ~2030 and design engineers will rely on a candidate list of existing materials to work with: *relative* prioritisation among these candidate materials requires evaluation of their irradiation responses, even if full irradiation doses are not available this decade. Surveillance programmes to validate micro/meso/macro models and nuclear data in real operating environments will inevitably fall to a mid century timeframe.
Experiments to provide engineering assurance on components and joins	For the development of enhanced neutron irradiation resilient materials, improved performance is sought first against degradation from atomic displacements (leading to dislocation loop structures and cavities, and the potential for solute precipitation, segregation to grain boundaries etc.; second against declining integrity due to transmutation's compositional impact and third, against the considerable damage wrought by gases that evolve in various neutron capture and decay reactions. Experiments to understand the evolution of materials damage must address surface and bulk microstructural effects, the interfaces between solid and gaseous phases and the temporal aspect of transmutation (which creates considerable microstructural damage over months / years). Industry concensus is currently that, with the absence of 14 MeV neutron test facilities operating to fluxes in excess of 10^{12} n/cm^2/s to simulate powerplant fusion, materials engineering assurance cannot rely on the traditional approach of applying materials handbook properties to standard failure threshold calculations, and instead, will need to rely heavily on modelling. Modellers in fusion will increasingly look to link reactor environment to materials behaviour, simulating materials responses in situ and taking account of local stress loading (heat, magnetic and electric field etc). This approach requires materials experiments linking loads, temperature and irradiation dose to provide data to underpin and validate the simulations.

USE OF IRRADIATION SOURCES



PHENOMENA

1 - Displacement Damage
2.1 - Transmutation Gases
2.2 - Transmutation Solids

RATE

L - Low (sub dpa)
H - High (10 dpa)
D - Dynamic

VOLUME

S - Small (µm - mm)
B.1 - Big (10s - 100s µm)
B.2 - Big (mm)

	Radiation Source	Damage Phenomena	Damage Rate	Volume
H	Charged particles (Heavy Ions)	1	H	S
DB	Dual Beam	1, 2.1	H	S
P	Protons	1	H, D	S, B.1
ADN	Accelerator Driven Neutrons	1, 2.1*, 2.2*	L	S, B.1, B.2
ADNX	Future Facilities	1, 2.1*, 2.2*	L	S, B.1, B.2
MTR	Materials Test Reactors	1, 2.1**	H, D***	S, B.1, B.2

* Neutron energy spectra not DT fusion
** Transmutation gas production by doping can cause artifacts
*** Extremely high cost

LOCAL IRRADIATION SOURCES

HIGHER FLUXES (10^{12} N/CM^2/S)

Inertial electrostatic confinement neutron source (fusor style) being explored at **University of Bristol**, taking account of Japanese studies – may use ASTRAL* or microNOVA* type source.

ASP at AWE (neutron).

Compact neutron source facility (10^{12} n/cm^2/s) being scoped for Sellafield for 2025 **(Project STELLAR)** – may use Phoenix* type source.

*Phoenix, ASTRAL, microNOVA are commercial systems

USEFUL UK BEAMS AND SOURCES

Birmingham cyclotron (proton beam) – Additional in-situ corrosion+proton setup imminent: 650°C H_2O, molten salt, 1000°C with loading vacuum or O_2 atmosphere; stress rig installation Oct 2021.

Birmingham high flux accelerator driven neutron source – coming onstream 2022.

Dalton Cumbrian Facility – Dual beam capability coming onstream late, 2021 (ion and protons)
For irradiation + Stress: DCF are developing a rig to support the irradiation of thin ~20 µm samples under load, with in-situ DIC to measure creep strains as a function of the irradiation.

LOWER FLUXES (10^4 N/CM^2/S)

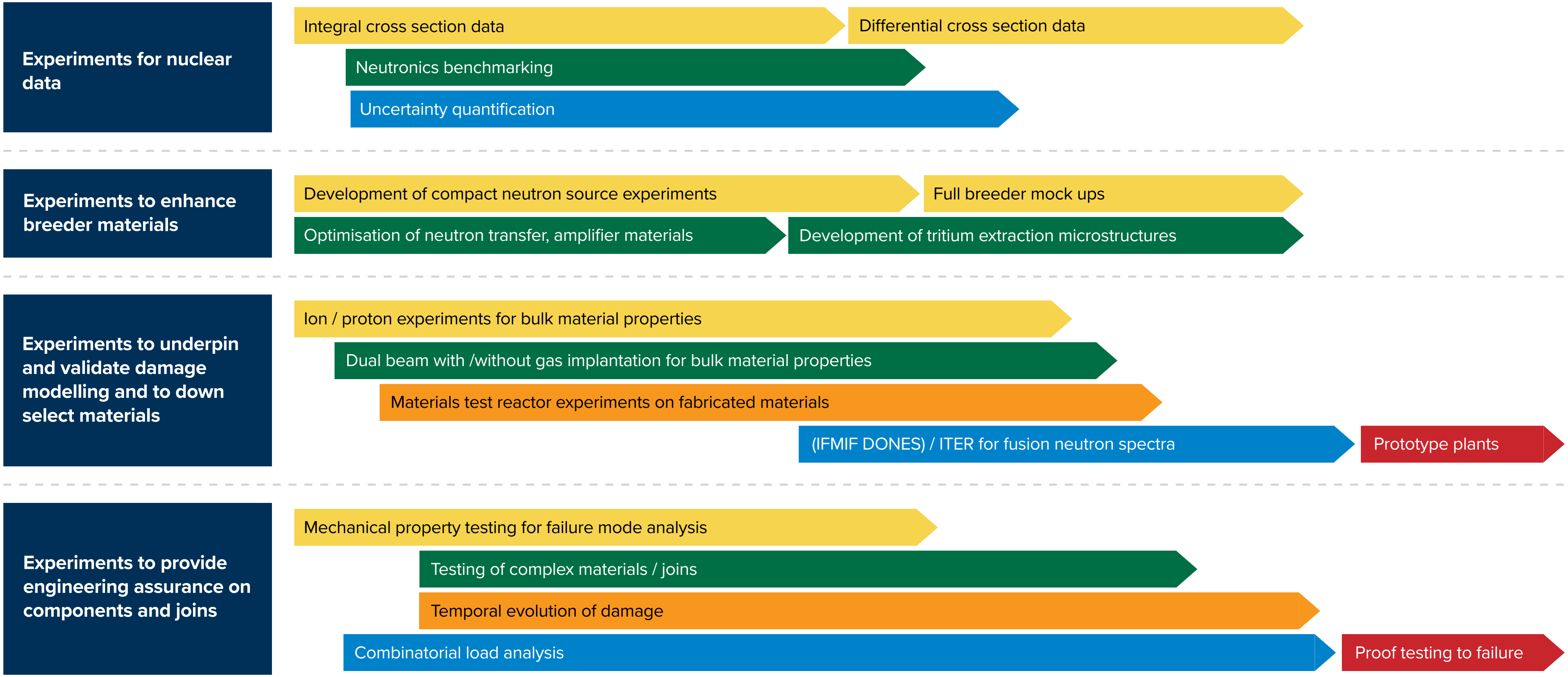
MIAMI - **University of Huddersfield.**

2020 2022 2024 2026 2028

INTERNATIONAL MATERIALS TEST REACTORS include: HFIR (USA), BOR60 (Russia), ANSTO (Australia), NRG (Netherlands), NCBJ (Poland), BR2 (Belgium), LVR-5 (Czech Republic), KURRI (Japan) etc.
FUSION NEUTRON GENERATORS include: Frascati (Italy), NG TUD (Germany) and HINEG (China).

DIRECTION OF TRAVEL

IRRADIATION – SUMMARY



Left to right = broad increasing availability of sources and/or increasing build in complexity of work

DIRECTION OF TRAVEL

IRRADIATION – NUCLEAR DATA

Experiments for nuclear data

- Integral cross section data
- Differential cross section data
- Neutronics benchmarking
- Uncertainty quantification

Experiments to enhance breeder materials

Experiments to underpin and validate damage modelling and to down select materials

Experiments to provide engineering assurance on components and joins

Integral cross section data

- DT cross sections required for a wide range of pure materials, with uncertainties well constrained in terms of fluence rate, energy spectrum, angular distribution and time profile (inverse relationship between sample size and flux)
- Start with spectra around 14 MeV, to achieve “integral” cross section measurements only
- Decay heat measurements on milligrams of materials possible, pending detection limits, and best accomplished with whole energy absorption spectrometry (WEAS)

Differential cross section data

With tighter spectrum control and achievement of peak source at 14.1 MeV, collection of “differential” cross section data will be possible.

Neutronics benchmarking

- Mono- and multi-material test data are required, against well defined geometries and well characterised sources, using rigs of the order of one cubic metre (representing several neutron mean free paths) or at least one metre thick to represent reactor wall thickness, in shielded box to prevent neutrons scattering within laboratory
- Need 14 MeV neutrons and at least 10^8 n/cm²/s, for several days

Uncertainty quantification

- Experiments required to quantify uncertainties, evaluate the distribution of isotope mixes arising and monitor the rate of Li burn up
- With 14 MeV and mixed fusion spectra $>10^{13}$ n/cm²/s, uncertainty reduction and code qualification in/of transmutation prediction offers an alternative to cross section measurements (requires DONES type source?)

DIRECTION OF TRAVEL

IRRADIATION – BREEDER MATERIALS DEVELOPMENT

Experiments for nuclear data

Compact neutron sources

- Commercial option SHINE/Phoenix (USA) are aiming to reach 10^{12} - 10^{13} n/cm²/s via R&D on windows in coming ~2 years, with DoE investment; possible installation of Phoenix source at Sellafield, UK under STELLAR proposal
- Commercial options microNOVA / ASTRAL (Japan currently using) with inertial electrostatic confinement (IEC) experimental rig proposed at University of Bristol targeting 10^{12} n/cm²/s with deuterium-deuterium capability in first instance (capable of running for >10,000 hrs)

Experiments to enhance breeder materials

- Development of compact neutron source experiments → Full breeder mock ups
- Optimisation of neutron transfer, amplifier materials → Development of tritium extraction microstructures

Experiments to underpin and validate damage modelling and to down select materials

Experiments to provide engineering assurance on components and joins

Full breeder mock ups

- Utilise graphite (^{13}C) to modify thermal to fast flux neutrons in IEC set ups
- Enhance installations with tritium containment and extraction infrastructure (at reactor temperatures) and tritium handling protocols (limiting possible localities to NNL, Culham in the UK) to enable measurement of tritium breeding ratios, validate breeding models and to confirm reactor fuel-cycle (ideally with 14 MeV to qualify moderation path)
- Build experimental rigs of suitable size (cubic metre) for experiments on component scale materials

Optimisation of materials

- Neutron transfer materials (e.g. zirconia) tests are required to optimise energy spectrum moderation / tuning
- Li compounds in ceramic form are currently prone to crushing under mechanical load and newer compounds must be identified and tested for breeding ratios
- Use of liquid Li as both source and test bed is contemplated

Extraction microstructures

- Micro / nano crystalline microstructure development required for optimised tritium extraction (potentially using Li deuterides) –testing in situ with tritium extraction infrastructure
- Higher temperature experiments (700°C) for optimal extraction

DIRECTION OF TRAVEL

IRRADIATION – DAMAGE STUDIES

Experiments for nuclear data

Experiments to enhance breeder materials

Materials test reactors

- Achieving 10 dpa would get the community to a basic understanding of new equilibrium / steady state conditions in irradiated candidates
- The FIDES consortium (~17 nations) under Nuclear Energy Agency started Jan/Feb 2021 with an open invitation to UK fusion to achieve some interim data until DONES comes online

IFMIF - DONES

- This source will be DEMO oriented with a 40 MeV energy primary deuteron beam; the neutron energy after the deuterons will hit the Li screen at around 14 MeV

STEP (UK), DEMO (EU) etc.

- First prototype powerplants will provide in situ testing under real conditions of fusion net energy operation, with in surveillance monitoring to provide real time evidence of material modification / damage

Experiments to underpin and validate damage modelling and to down select materials

Ion / proton experiments for bulk material properties

Dual beam with /without gas implantation for bulk material properties

Materials test reactor experiments on fabricated materials

(IFMIF DONES) / ITER for fusion neutron spectra

Prototype plants

Experiments to provide engineering assurance on components and joins

Ion / Proton experiments (intermediate energy (10-30 MeV) is relevant as a neutron proxy)

- Simple materials are required for first models
- A representative suite of basic materials types (steel, ceramic, Zr alloys) should be irradiated to underpin a range of modelling initiatives to understand and validate basic degradation in different crystallographies
- Experiments to downselect first candidate materials should aim for rapid screening at low dpa's and look for relative performance
- In situ monitoring would enhance outcomes (e.g. ion irradiation under TEM analysis at MIAMI; radiolysis experiments under ion and proton irradiation at MIBL; XFEM to evaluate interaction of damage structures with pre-existing microstructure under loading, using Harwell / synchrotron)

Dual beam with/ out gas

- Dalton Cumbria Facility (2021) and University of Birmingham (2022) both soon capable of proton-neutron combinations
- UK fusion community to define fusion relevant irradiation protocols for these installations – ideally to at least 600°C or even 1000°C
- He generation is a priority requirement, to test damage resilience, first in down selections / candidate screenings and subsequently, for engineering assurance
- It should be possible to undertake neutron irradiation subsequent to He-implantation. Relatively large/ thick samples (several 100g) required for gas damage evaluations

DIRECTION OF TRAVEL

IRRADIATION – ENGINEERING ASSURANCE

Experiments for nuclear data

Experiments to enhance breeder materials

Experiments to underpin and validate damage modelling and to down select materials

Experiments to provide engineering assurance on components and joins

Mechanical property testing for failure mode analysis

Single variable material experiments should be designed to investigate one particular mechanical property at a time (e.g. fracture toughness) modifying under irradiation and gas production towards failure mode modelling.

Testing of complex materials / joints

Testing of complex materials and joints is required, utilising methodologies built off simpler material test results but will be constrained by sample volumes in reactors.

Temporal evolution of damage

- High temperature tests (600°C -1000°C) are required to several dpa, to understand creep and temporal evolution of damage over several weeks, months
- There may be potential in using quantum heat sources to simulate and accelerate high-heat flux intensity to test for extended operating period performance - e.g. high heat flow testing up to $20MWm^2$

Combinatorial loads

Enhanced installations with experimental rigs are needed, to study response to cryogenic (4.5K, 77K), corrosion, magnetic and mechanical loading conditions under irradiation conditions. Proton facilities for investigation of synergistic effects of irradiation + are of primary interest to STEP: rigs are required for i) irradiation + stress, ii) irradiation + corrosive media and iii) irradiation + cryo cooling (for magnets). Rigs will also be possible for compact neutron source installations; cold finger capabilities will be available in dual beam installations in the UK.

Proof testing

Successful design of experiments to drive materials / joins to failure under irradiation would enable a proof-testing route to engineering assurance (ie irradiation damage assessment across welds and under operating stress conditions) – only possible in operating tokamak/ plant mid century.

POST IRRADIATION EXAMINATION FACILITIES IN THE UK

MRF IN 2021

Mechanical:
nanoindenter, small scale tensile tester, ultrasonic fatigue rig, impedance spectroscopy

Microstructural:
FIB, SEM

MRF IN 2023

Mechanical:
- dynamic (standard scale) tensile / compression testing

Thermophysical:
- DSC, TGA, laser flash, dilatometer

Microstructural:
- Plasma FIB, TEM

MRF IN 2025

+ sample archive

NNL IN 2021

Highly Active:
Visual Inspection, measurements, Fuel analysis (fission gas, isotopics), density measurements, thermal properties, LOM, SEM, sample fabrication/ size reduction, electrical resistivity, fracture properties, strength testing, elastic properties, Pycnometry, Gas Diffusivity/Permeability

Medium & Low active:
Low + medium load strength testing, micro/macro hardness, LOM, SEM (+WD, EBSD), (FEG) TEM (+EELS), FIB (+cryostage), PFIB (+SIMS), Laser flash, Raman, DSC, TGA, elastic properties, Pycnometry, Gas Diffusivity/Permeability, Machining

NNL IN 2023

Highly Active:
- laser Raman (3 ƛ)
- micro indenter, profilometry
- hydrogen charging
- electrochemistry
- small scale tensile testing
- H analysis

Medium & Low active:
- ultramicrotome
- XRD

NNL IN 2025

Highly Active:
- small scale punch testing
- sample archive
- laser flash
- LIBS

Medium & Low active:
- sample archive

POST IRRADIATION EXAMINATION FACILITIES IN THE UK

DCF IN 2021

Irradiation:

Ion beam accelerators (x2), gamma & X-ray irradiators.

In-situ/ex-situ PIE, corrosion studies:

SEM, XRD, IBA (PiXE etc.), High Temp Loop, EPR, FT-IR/FT Raman/ Raman Microscopy

DCF IN 2023

Irradiation:

+ dual ion beam capability.

In-situ/ex-situ PIE, corrosion studies:

+ in-situ EELS & SIMS, high temp (1,000°C+) irradiations, ion pulse radiolysis

+ implanted light gas detection - D,3He, 4He - (subject to funding)

Low-flux variable energy neutrons (1 - 20 MeV)

DCF IN 2025

Irradiation:

+ triple ion beam (subject to funding)

In-situ/ex-situ PIE, corrosion studies:

+ bespoke in-situ mechanical testing

HARWELL IN 2021

UoMaH:
Sample Environments:

- Toxic cell (for compression testing)

DLS:

- Delivery of Imperial University Active Handling cells for 112 (Tomography, diffraction and SAXS under stress, temperature & atmosphere)
- Start of Highly active sample remote handling

HARWELL IN 2023

UoMaH:
Sample environments development:

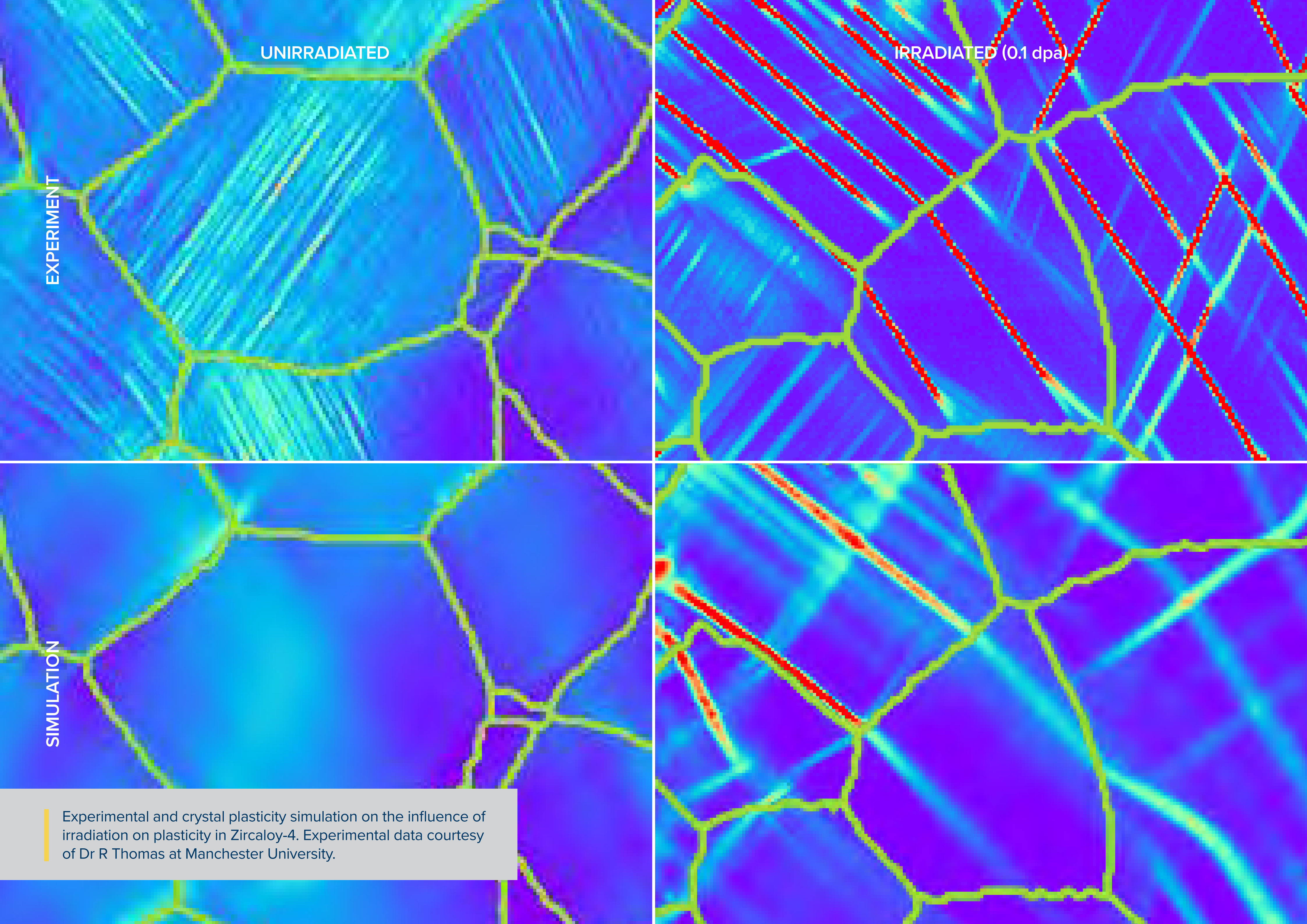
- Toxic Cells (for tension & Electro Thermal mechanical testing)
- Grazing incidence X-ray diffraction cell, Reaction cell, X-ray absorption spectroscopy cell

DLS:

- Imperial University Active Handling cells for 112 (Tomography, diffraction and SAXS under stress, temperature & atmosphere)
- Highly active sample remote handling

HARWELL IN 2025

DLS:
Highly active sample remote handling



Experimental and crystal plasticity simulation on the influence of irradiation on plasticity in Zircaloy-4. Experimental data courtesy of Dr R Thomas at Manchester University.

MODELLING

MODELLING – Multiple levels of activity required from understanding damage mechanisms to predicting materials failure

To predict onset of failure in components during operation.

MULTI PHASE/MULTI GRAIN/WELDS (MICROSTRUCTURAL APPROACH)

Direction and approximate magnitudes/ rates of change for selected properties based on key failure modes, is required, on down-selected materials, in the **SHORT** term.
It will be vital to account for environmental conditions in the models (e.g. coolant).
The link between damage and changes to thermal conductivity and other bulk properties should form part of this work.
MOOSE framework (multi-physics C++ outputting directly to FEA) is available for Crystal Plasticity Finite Element Modelling to undertake such predictions but other platforms (and isogeometric algorithms) should also be considered. Can we use peridynamic modelling?
Refined and more accurate predictions with mechanistic understanding are required in the **MEDIUM** term for improved science on microstructural evolution.
Predictive models continuously validated with surveillance testing during operation, are envisaged **LONG TERM.**

To predict macroscopic stress and strain in materials during operation.

STITCHING LENGTHSCALE AND TIMESCALE

A whole problem approach is advocated, to simulate materials responses in situ, applying tokamak operating conditions (especially dose-temperature of immediate environment).
Use of an elastic dipole tensor in Density Functional Theory – as well as Crystal Plasticity approaches -will enable moving from atoms to continuum modelling.
Evolution of materials at doses >0.1dpa is non linear and requires priority efforts in the **SHORT term.**
Quantitative models for deformation, including transmutation effects, should be possible in the **MEDIUM term.**

SINGLE PHASE – SINGLE GRAIN (ATOMISTIC APPROACH)

Density functional theory and molecular dynamics have been used to deliver extensive understanding of DEFECTS in some *structural materials* moving to thermal equilibrium:
Size and saturation (power law pertains moving from point defects to dislocations)
Structure (is determined by local chemical bonds rather than elastic energy)
Density (brings high stress, triggering avalanches, leading to dislocation networks and defect clusters)
Non linearity (occurs as volume strain may be high where lattice strain is not; latter is lower due to pseudo planar effect of aggregated defects)
Mobility (determined by a critical threshold density of lattice obstacles)
Volume (increase is high for interstitial defects but not equal-and-opposite for dimensional changes brought about by void defects)
TRANSMUTATION triggered embrittlement lifetimes have been calculated for elements in mainstream DEMO materials.
More work is needed on a *wider range of materials (breeders, magnets, shields, insulators etc).*
Work on impact of nanoparticles (within grain / at grain boundary) is required.

2018 | 2020 | 2022 | 2024 | 2026 >>>

MATERIALS MODELLING AT UKAEA FOR IRRADIATED MATERIALS – State of play at 2021 demonstrates areas of focus

Baseline materials for STEP and DEMO, and some nearest alternatives	**Physical Properties**					
	Chemistry (DFT)	**Irradiated microstructure, transmutation**	**Static properties**	**Dynamic evolution**	**Experimental validation of model**	**Finite element modelling, failure modes**
Structural materials • EUROFER • Castable RAFM complex nanostructured alloy • ODS	Alloys Defects Ferromagnetism	Neutronics	Swelling Elastic moduli	Spin lattice dynamics Dislocations	Neutron diffraction	Defect swelling FEM
Armour materials • Tungsten • SMART W-Cr-Y	Alloys Defects	Atomic microstructure Neutronics	H retention Conductivity Swelling Void decoration Y segregation Oxidation	Object kinetic Monte Carlo Non-adiabatic Molecular Dynamics	Transmission Electron Microscopy Atom probe tomography Transient grating spectroscopy Thermal desorption spectroscopy	
High heat flow materials • CuCrZr	Defects, Cu	Neutronics		Non-adiabatic Molecular Dynamics, Cu	Nanoindentation	Crystal plasticity,Cu
Breeder materials (substrate / breeder / amplifier) • SiCf-SiC composite • Li orthosilicate / titanate etc. • $BeTi_{12}$	Some insulating materials	Neutronics				
Magnet materials • resistive aluminium • Nb_3Sn / NbTi doped • REBCO						
Window materials • Beryllium		Neutronics (MRG)				

Not attempted   Underway   Completed

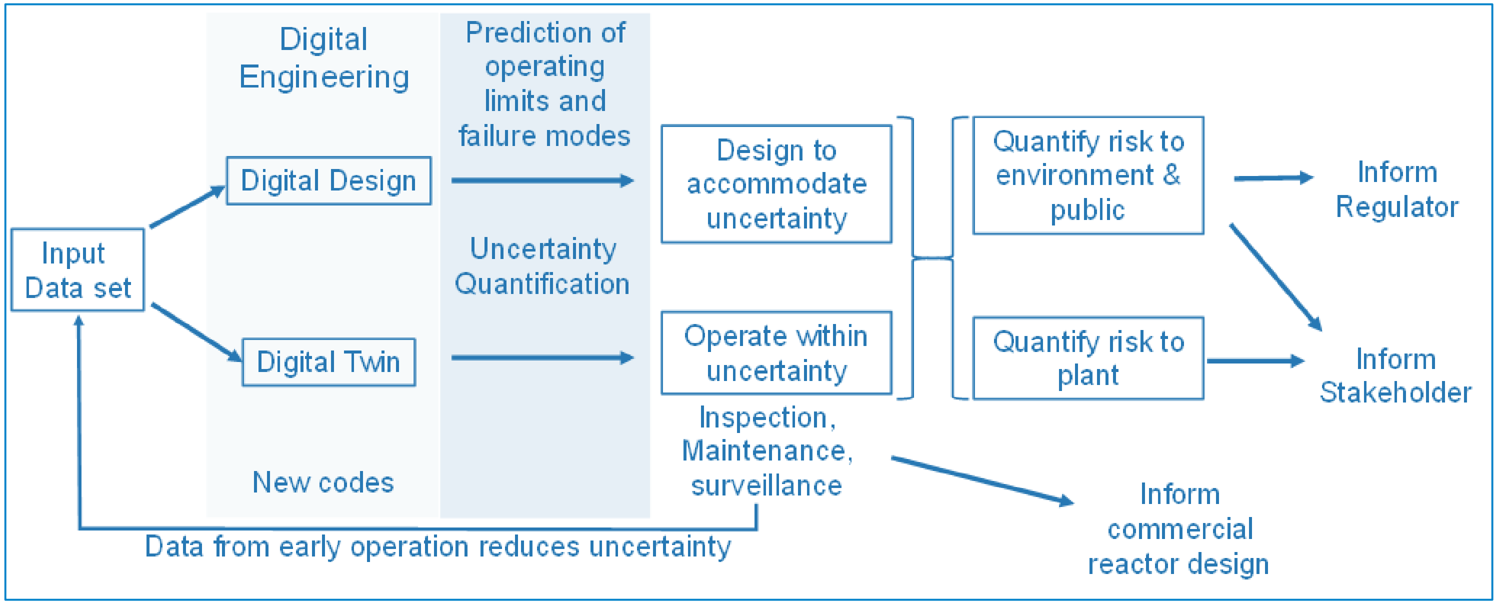
MODELLING FOR PERFORMANCE ASSURANCE ON IRRADIATED MATERIALS – UKAEA effort to 2021

Baseline materials for STEP and DEMO, and some nearest alternatives	Engineering scale				
	Base materials: displacement damage	Base materials: transmutation damage (including gas)	Base materials: Tritium retention	Engineering materials: radiation hardness	Engineering materials: Failure mechanisms
Structural materials • EUROFER • Castable RAFM complex nanostructured alloy • ODS	Fe, FeCr	Fe, FeCr	Only relevant with sub-optimal barrier coatings	Only for FeCr	
Armour materials • Tungsten • Other metals & alloys (Be, SMART)			Only relevant with sub-optimal barrier coatings	W, less for alloys	
High heat flow materials • CuCrZr	Cu				
Breeder materials (substrate / breeder / amplifier) • SiCf-SiC composite • Li ceramics • $BeTi_{12}$ • Liquids (LiPb)		Basic neutronics	N\A – extraction based on destructive methods as required		
Magnet materials • resistive aluminium • Nb_3Sn / NbTi doped • REBCO		Neutronics	N/A		
Window materials • Beryllium, Molybdenum, Silica		Neutronics			

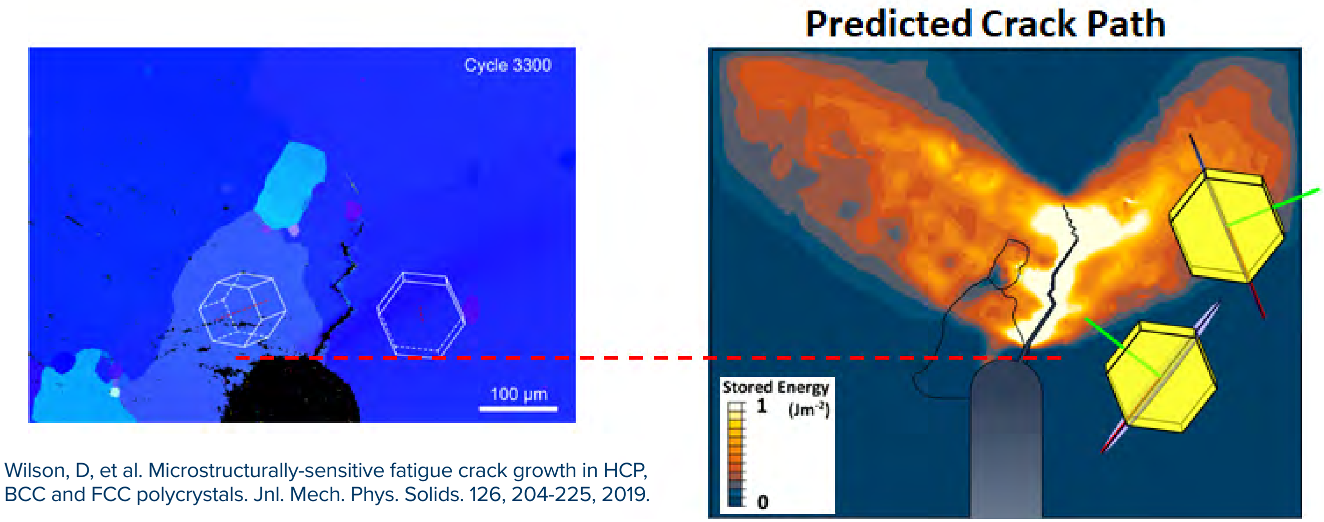
Not attempted   Underway   Completed

MATERIALS 4.0

In the context of a global and current **digital revolution**, fusion will see use of **digital twins** in the design, monitoring, maintenance and repair of its reactors and plants. Materials performance data (real and predicted) will be part of this. To begin with, low-fidelity computational models will be required for communication of confidence to stakeholders. With time, procedures for defining appropriate levels of granularity in digital twins are required.



Design by Rule (utilising handbooks of materials property data, with the latter disconnected from application conditions) will give way to **Design by Fundamentals** – intended to harness more holistic representations of materials performance in context (derived from crystal plasticity modelling, peridynamics and similar).



Wilson, D, et al. Microstructurally-sensitive fatigue crack growth in HCP, BCC and FCC polycrystals. Jnl. Mech. Phys. Solids. 126, 204-225, 2019.

MATERIALS SUPPLY CHAIN & REGULATION

LEARNINGS FROM OTHER NEW INDUSTRY SUPPLY CHAINS

- The UK approach to electric vehicle batteries has highlighted the need for early and aspirational pace and size in setting up supply chains, to better leverage sovereign competitive edge at the outset
- Flexibility to incorporate ongoing innovations and developments must be built in
- Insistence on UK manufacturing has aided local supply chain in recent vaccine research ecosystems
- Attention should be paid to the benefits of agglomeration (getting as much as the supply chain in the same place within country) and allocation of specific sites for large single facilities (giga-factories)
- Public private partnerships (e.g. The Submarine Enterprise PP between MoD, BAE, Rolls-Royce and Babcock) are a useful model, and more generally, fails in past fission nuclear builds should be learnt from
- Failures logged by the ONR, HSE and EA are all important ‘lessons learnt’ repositories for fusion

ROLE OF UK CATAPULTS

- It is key that commercial, industry and RTOs such as Nuclear AMRC, TWI etc. can work effectively together to generate the IP and capabilities needed for the next phase of fusion:
    - Development of pilot plant lines to develop materials and processing specifications
    - Component demonstration and prototyping
    - De-risking activities
    - Convening of multi-partner collaborations across all tiers of the supply chain
- Nuclear AMRC is already the sponsor of the UK's-IWG ASME BPV III Codes and Standards community involving design, manufacturing, performance assurance etc. offering significant supply-chain tributaries
- UK needs schemes to encourage and facilitate secondment from industry to Universities/catapults and vice-versa

LARGE SCALE EQUIPMENT INVESTMENT

UK requirements include:

- Large-scale Hot Isostatic Pressing (HIP) capability – for testing diffusion bonding and manufacture of structures with improved material efficiency and complexity vs forging
- Large-scale thick-section joining capability (electron-beam or laser test resources)
- High field strength magnet testing capability (at high current densities)
- Demonstrators needed on how to use material properties (e.g. stiffness) to aid remote handling and repair
- A low/no mercury Li-enrichment plant
- Scaled testers for linear friction bonding, induction or pyro heat diffusion bonding, rotary friction welding, cold or laser assisted ('warm') high velocity spray techniques etc

SPECIFIC SUPPORT REQUIRED FOR SMALL SUPPLIERS

UK requirements include:

- Equipment access grants (e.g. through HVMC facilities) to support skills development and to provide exposure to new methods
- Significant and stable programmatic government support for development projects with a high grant value/ contribution ratio to ensure long-term strategic approach
    - For example, Assystem has had success in engaging SMEs in F4E (Fusion for Energy) fusion projects where the long duration and typical £5-7m contract value supports strategic planning and more opportunities to buy-in specialist capability
    - Consideration of SME's being supported by a Fit4Fusion manufacturing philosophy encompassing both business and engineering systems
    - UK government stake or investment in R&D at suppliers of critical materials and related IP - as opposed to current, match funded, model - would encourage small (and large) suppliers to 'play the long game'

BRINGING MATERIALS SUPPLY CHAIN IN-HOUSE

- A centralised materials supply chain for the engineering contractors ensures use of approved materials without the challenges of procurement of niche products, but materials development is a multi-partner process: Designers, OEMs, end users all need to work hand in had with raw materials suppliers, materials, manufacturers, fabricators and assemblers. Formal vehicles for these partnerships are required

- In nuclear and aerospace, material supply has generally not been brought in house (with some exceptions in fuel and some turbine parts). Rather, rigorous and well controlled Equipment Qualification (EQ) and Quality Assurance (QA) Processes have evolved to deliver consistent supply. The same will be needed for fusion

- In addition to EQ, there is a need to consider Structures, Systems and Component (SSC) – Vee model mitigation and levels of built-in redundancy

SUPPLY CHAIN QA PROTOCOLS

- Examples are available from Aerospace, Fission, Oil and Gas, Defence, Chemicals and Automotive, on supplier qualification, full traceability and relevant levels of material testing; consultation with those who are to abide by the standards is an obvious pre-requisite
- Developing Equipment Qualification / Quality Assurance requirements for fusion is a strategic opportunity for the UK to build a fusion supply chain for materials and components. In the fission nuclear industry, well established supply chains for the EPR programme make it difficult for a UK manufacturer to be more cost-effective than an established supplier with existing Equipment Qualification programme and records. For Fusion there is no existing supply chain - it is truly first-of-a-kind technology and the door is open to plan and grow a UK supply chain with a full range of manufacturing and qualification capabilities for fusion
- A number of other industries are developing the technologies, datasets and process control to enable "virtual certification". Relevant aspects of this approach should be considered as early as possible in the alloy supply chain development
- Utilise the benefits of Manufacturing 4.0: In-line process monitoring for contamination and defect identification; embedded sensing; accelerated validation and automated inspection

MATERIALS ASPECTS IN REGULATION

RISK

Fusion has limited risks: exposure to activated materials if vacuum vessel is breached, concentration of tritium in tritium plant, electrical safety concerns – similar to safety cases for large scale particle accelerator facilities (usually not under nuclear regulation).

As risk mitigation, materials should lend themselves to remote maintenance, easy change of components, repairability and surveillance (e.g. embrittlement of vacuum vessel, window seals).

ACCIDENT SCENARIOS

Relevant accident scenarios should be explored - specifically loss of various coolants, loss of vacuum and loss of magnetic field during neutral beam injection - with effects on materials evaluated (tungsten oxide of specific interest) and development of lead indicators on path to materials failure.

CURRENT MATERIAL TESTING STANDARDS

These must move beyond the premise of homogeneity of loading condition and of material response – invalid in fusion applications.

CONVENTIONAL COMPONENT TESTS

Established standards are useful for unirradiated baseline (plant at t=0). For certain components and joints, combinatorial load experiments (e.g. UKAEA's CHIMERA) mimicking operational conditions will be useful to prove suitability of materials in a complex environment.

FUSION APPROACH

Combining conventional handbook data with property degradation due to irradiation requires demonstration of equivalence and will need to be proven through modelling/ small scale tests.

Further development of techniques for tests at miniature scale (e.g. small punch test, instrumented indentation, KLST master curve approach, miniature tensile) is a priority to make the most out of available neutron irradiated materials.

FISSION LEARNINGS

Irradiation conditions within fission plants (used for qualification) are obtained by physics based models, and phenomeno-logical models for component lifetime predictions are used for safety qualification.

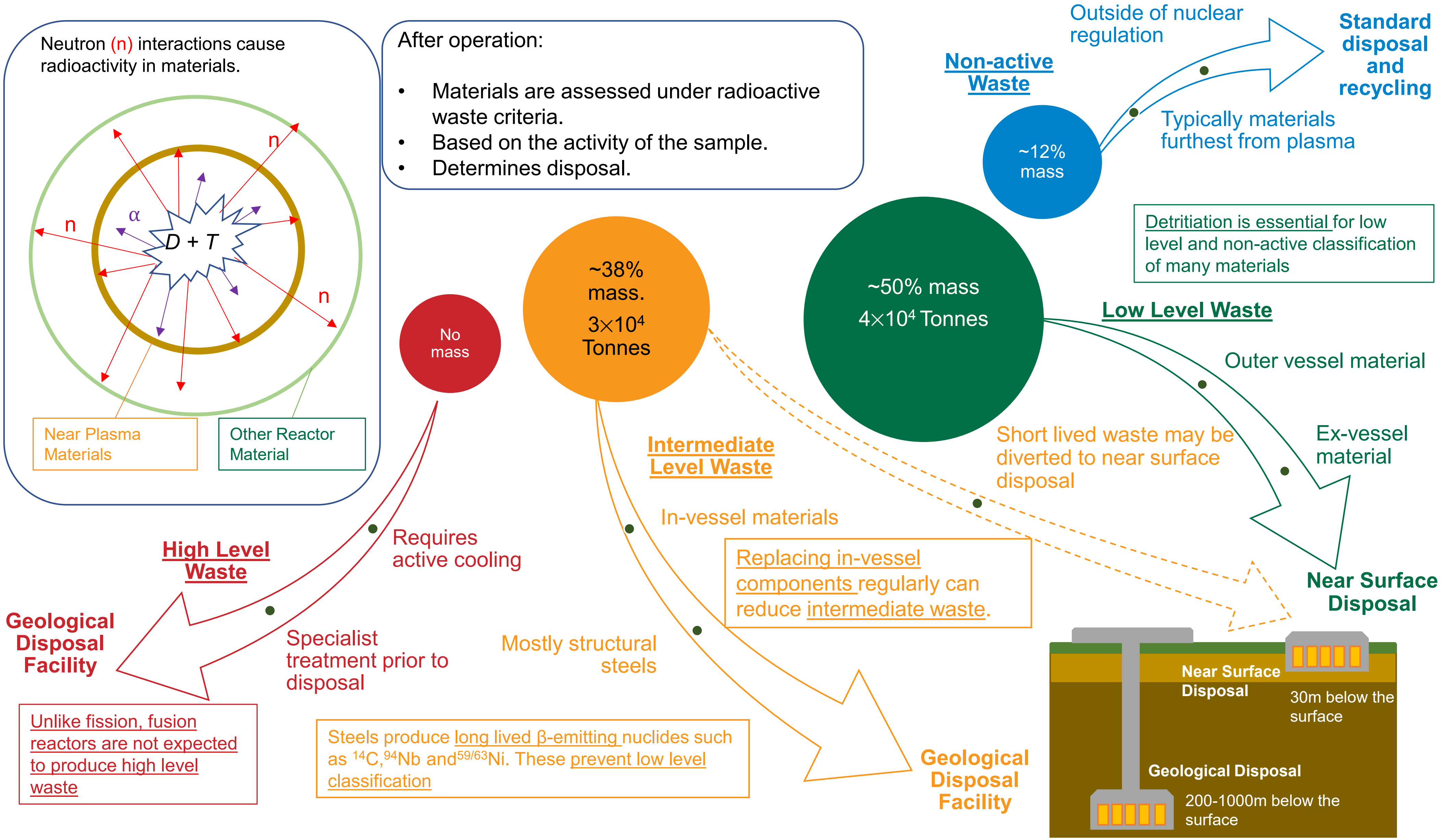
Determine performance data required for those materials critical to the safety case of a fusion powerplant (e.g. Be, Li performance in the breeding blanket system).

Establish toxicity, post irradiation for known and potential toxic candidates in fusion materials shortlist (e.g. Be, smart W oxide? alloys).

Develop ASME 'code cases' for materials up to the operating limit of confidence to enable initial reactor operations.

Use operational data from ITER / STEP to assess synergistic effects on materials degradation through life. Update codes for high fidelity future design of commercially viable plant and components.

APPROXIMATE DEMO WASTE OUTLOOK AFTER 50-100 YEARS



MATERIALS INNOVATION IN REGULATION

- A recent report by the Regulatory Horizons Council points to cooperation between the EA, HSE and BEIS to produce guidance on an emerging regulatory framework for fusion. A modern approach (goal-based, as opposed to rule-based) is likely

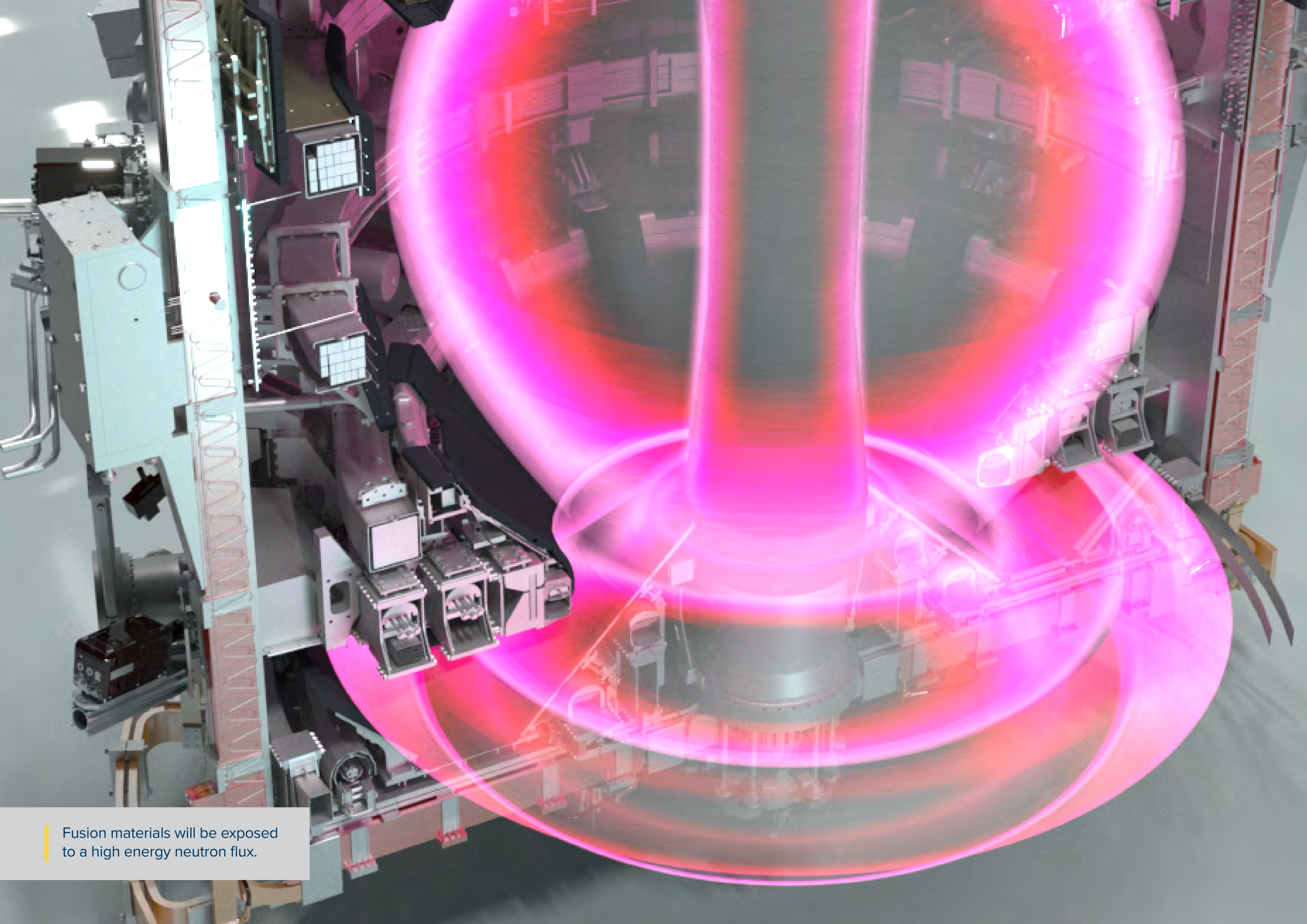
- Regulatory goals will include minimised danger to humans and environment but also sustainability

- A **focus on innovation** and flexibility in waste storage (until more is understood on disposal options and requirements), is desirable

- Multiple avenues of **materials innovation** become relevant:

  - Fusion raw materials and compositions should be selected / developed to **minimise half lives** or deliver transmutations that allow for material recycling: materials partitioning and isotope tailoring (via centrifuging / electromagnetic separation) are possibilities
  - Fusion materials (and their welds and coatings) should be selected / developed to **reduce process complexity in waste disposal** and recycling
  - Material deconstruction – swarfing and compaction to **maximise waste packing factors** could involve a parallel development of cutting tool materials and geometries optimised against the irradiated material's breakdown response: ductile conditions result in extremely long swarf runs, brittleness results in chips, dust / particulates etc
  - Increased fusion materials performance will **decrease volumes** required in some instances (and reduce active waste)
  - Materials stability should be optimised to **reduce dust formation** in operation, decommissioning (e.g. move from graphite to tungsten dropped JET erosion: dust conversation rate by an order of magnitude: 40% to 4% on current data) and waste processing (where, for example, vacuuming is higher risk due to particle exposure)
  - The potential use of new materials to improve filtration and induced electro-static capture would aid in the production of a **cleaner decommissioning** system that allows for improved automation of this process

- Moving focus from a material's radioactivity towards its radiotoxicity (impact of radioactivity on living organism), will enable a risk based approach to regulation which accommodates different metrics for different nuclides and their respective mobilities



Fusion materials will be exposed to a high energy neutron flux.

ACKNOWLEDGEMENTS

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“Developing the right materials to enable the design and successful demonstration of practical small fusion power plants will be a transformative project for the Materials Science community in the next 10 years – similar in impact to the growth of single crystal turbine blades for aircraft engines or materials for the integrated circuit."

- Chris Grovenor, Lead Investigator, National Nuclear User Facility Management Group

“With fusion moving towards a demonstration of power generation, and the challenges laid down by the Energy White Paper, it is the right time to look at the materials we need to deliver deployable fusion power, and this roadmap will be a vital guide to their development.”

- Francis Livens, Professor of Radiochemistry, Academic Director of Dalton Institute

“UK Fusion materials are key requirements for a bright, low-carbon future.”

- Robin Grimes, Chief Scientific Adviser in the Ministry of Defense for Nuclear Science and Technology

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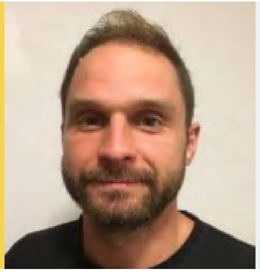
ROADMAP TEAM

Dr David Bowden
Lead -
Materials for Fusion
UKAEA



Dr Chris Hardie
Lead -
Materials of STEP
UKAEA

Dr Mark Gilbert
Head of Programme -
Neutron Materials Interactions
UKAEA

Dr Frank Schoofs
Lead -
Engineering Innovation
UKAEA

Dr Amanda Quadling
Director of Materials
UKAEA

EDITORIAL TEAM

Dr David Armstrong
Oxford University

David is Associate Professor of Materials Science and sits on the EPSRC Fusion Advisory Board. His research interests are centered around the understanding degradation and performance of materials for extreme environments.

Dr Amy Gandy
University of Sheffield

Amy is a Lecturer in Nuclear Engineering with 17 years experience investigating radiation effects and defect formation in single crystal, poly-crystalline and amorphous materials. She is a member of the EPSRC's Fusion Advisory Board.

Dr Sandy Knowles
University of Birmingham

Sandy is a UKRI Future Leaders Fellow and RAEng Associate Research Fellow and Senior Lecturer in Nuclear Materials at the University of Birmingham. Sandy's group develops novel high temperature alloys, including bcc-superalloys, for application in fusion, Gen-IV fission, gas turbines and concentrated solar power.

Dr Karl Whittle
University of Liverpool

Karl is Professor of Zero Carbon and Nuclear Energy. With a background in nuclear materials for use within fusion/fission reactors, his current focus is on the impacts arising from radiation damage, and how materials can be developed to overcome the limitations in use.

Dr Andrew Bowfield
Henry Royce Institute
Andrew is Business Development Manager: Nuclear Materials for Royce, with an industrial background as a validation engineer and technical sales manager.

Dr Steven Jones
Nuclear Advanced Manufacturing Research Centre
Steven is NAMRC's CTO and the University of Sheffield's Professor of Welding Technologies. He leads the High-Value Manufacturing Catapult's Joining technology theme and is responsible for the NAMRC's strategic technology development.

Dr Jon Hyde
National Nuclear Laboratories
Jon is Senior Fellow in Materials and Head of R&D at NNL with visiting professorships at Manchester, Liverpool and Oxford. He is the nuclear champion for Royce and UK representative on the Jules Horowitz Reactor Board and Gen IV task force on R&D Infrastructures, as well as Co-chair of the International Group on Radiation Damage Mechanisms (IGRDM).

Dr Jack Astbury
Tokamak Energy
Jack is Reactor Technology Manager for Tokamak Energy Ltd. He is a Chartered Engineer and Physicist with expertise in radiation transport (shielding/neutronics) in nuclear plants and space.

CONTRIBUTORS

NAME	AFFILIATION	NAME	AFFILIATION	NAME	AFFILIATION
Neil Irvine	-	Fionn Dunne	Imperial College London	Allan McLelland	Morgan Advanced Materials
David Crudden	Alloyed	Robin Grimes	Imperial College London	Jonathan Phillips	Morgan Advanced Materials
Atsushi Sato	Alloyed	Mark Wenman	Imperial College London	Gary Shuttleworth	Morgan Sindall
Gary Reed	Assystem	John Maddison	Jacobs	Peter Giddings	National Composites Centre
Alice Laferrere	Atkins	John Stairmand	Jacobs	Jonathan Hyde	National Nuclear Laboratory
Duncan Broughton	AWE	Andrew Wisbey	Jacobs	Susan Ortner	National Nuclear Laboratory
Richard Gover	AWE	Jack Buxton	James Walker	Andrew Sherry	National Nuclear Laboratory
Jon Joy	AWE	Patrick Stephen	James Walker	Steve Jones	NAMRC
Dave Osborne	AWE	Yosuke Hirata	Kyoto Fusioneering	Will Kiffin	NAMRC
Andrew Randewich	AWE	Satoshi Konishi	Kyoto Fusioneering	Ashwin Rao	PA Consulting
Simon Rice	AWE	Keisuke Mukai	Kyoto Fusioneering	Alasdair Morrison	Qdot Technology Ltd
Iuliia Ipatova	Bangor University	Richard Pearson	Kyoto Fusioneering	Ian Edmonds	Rolls Royce
Bill Lee	Bangor University	Keishi Sakamoto	Kyoto Fusioneering	Neil Glover	Rolls Royce
Simon Middleburgh	Bangor University	Satoshi Konishi	Kyoto University	Al Lambourne	Rolls Royce
Michael Rushton	Bangor University	Malcolm Joyce	Lancaster University	Michael Martin	Rolls Royce
Laurence Williams	Bangor University	Sam Murphy	Lancaster University	Andrew Perry	Rolls Royce
Sohail Hajatdoost	Centre for Process Innovation	Cathy Bell	Liberty Steel	Tony Razzell	Rolls-Royce
Stewart Williams	Cranfield University	Simon Pike	Liberty Steel	David Homfray	Satellite Applications Catapult
Thomas Davis	Davis & Musgrove	Richard White	Lucideon	Jesus Talamantes-Silva	Sheffield Forgemasters
Christopher Ferrie	Doosan Babcock	Timothy Bullman	M&I Materials Ltd	Llion Evans	Swansea University
Bert Holt	Doosan Babcock	Tom Galvin	M&I Materials Ltd	Jack Astbury	Tokamak Energy Ltd
Juan Sanchez-Hanton	Doosan Babcock	Richard Stevenson	M&I Materials Ltd	Alan Costley	Tokamak Energy Ltd
Fraser Wood	Doosan Babcock	Charley Carpenter	Manufacturing Technology Centre	David Kingham	Tokamak Energy Ltd
Damian Hampshire	Durham University	Nick Cruchley	Manufacturing Technology Centre	Robert Slade	Tokamak Energy Ltd
Andy Barron	Element	Matt Thomas	Manufacturing Technology Centre	Rob Akers	UK Atomic Energy Authority
Marie Halliday	Element	Peter Barnard	Materials Processing Institute	Lee Aucott	UK Atomic Energy Authority
Rod Martin	Element	Andrew Buchanan	Materials Processing Institute	David Bowden	UK Atomic Energy Authority
Jamie Darling	First Light Fusion	John Fernie	Materials Processing Institute	Peter Daniels	UK Atomic Energy Authority
Nicholas Hawker	First Light Fusion	Michael Greenfield	Materials Processing Institute	Ted Darby	UK Atomic Energy Authority
Steven Lawler	Frazer-Nash	Stephen Shepherd	Monitor Coatings Ltd	Andrew Davis	UK Atomic Energy Authority

NAME	AFFILIATION	NAME	AFFILIATION
Sergei Dudarev	UK Atomic Energy Authority	Graeme Greaves	University of Huddersfield
Mark Gilbert	UK Atomic Energy Authority	Jonathan Hicks	University of Huddersfield
Paul Goodwin	UK Atomic Energy Authority	Konstantina Lambrinou	University of Huddersfield
Michael Gorley	UK Atomic Energy Authority	Bo Chen	University of Leicester
Chris Hardie	UK Atomic Energy Authority	Hongbiao Dong	University of Leicester
Anthony Hollingsworth	UK Atomic Energy Authority	Andrew Dunsmore	University of Leicester
Monica Jong	UK Atomic Energy Authority	Eann Patterson	University of Liverpool
Simon Kirk	UK Atomic Energy Authority	Karl Whittle	University of Liverpool
Heather Lewtas	UK Atomic Energy Authority	Grace Burke	University of Manchester
Joven Lim	UK Atomic Energy Authority	Frederick Currell	University of Manchester
Andy London	UK Atomic Energy Authority	Aneeqa Khan	University of Manchester
Daniel Mason	UK Atomic Energy Authority	Francis Livens	University of Manchester
Lyndsey Mooring	UK Atomic Energy Authority	Juan Matthews	University of Manchester
William Morris	UK Atomic Energy Authority	Joseph Robson	University of Manchester
Lee Packer	UK Atomic Energy Authority	Kevin Warren	University of Manchester
Jim Pickles	UK Atomic Energy Authority	Ian Maskery	University of Nottingham
Amanda Quadling	UK Atomic Energy Authority	Dave Armstrong	University of Oxford
Aidan Reilly	UK Atomic Energy Authority	Chris Grovenor	University of Oxford
Ed Shelton	UK Atomic Energy Authority	James Marrow	University of Oxford
Steven Van Boxel	UK Atomic Energy Authority	Susannah Speller	University of Oxford
Anna Widdowson	UK Atomic Energy Authority	Edmund Tarleton	University of Oxford
Steven Wray	UK Atomic Energy Authority	Amy Gandy	University of Sheffield
Martin Freer	University of Birmingham	Russell Goodall	University of Sheffield
Sandy Knowles	University of Birmingham	Neil Hyatt	University of Sheffield
Ben Phoenix	University of Birmingham	Iain Todd	University of Sheffield
Mahmoud Mostafavi	University of Bristol	Salah Rahimi	University of Strathclyde
Tom Scott	University of Bristol	Brad Wynne	University of Strathclyde
Paul Wilcox	University of Bristol		
Angelo Maligno	University of Derby		
Tim Dodwell	University of Exeter		

GLOSSARY

ADN	Accelerator Driven Neutrons
AGR	Advanced Gas-cooled Reactor
AM	Additive Manufacturing
ARIA	Advanced Research and Invention Agency
BEIS	Department for Business, Energy & Industrial Strategy
CCA	Compositionally Complex Alloys
CNA	Complex Nanostructured Alloys
CVI	Chemical Vapour Infiltration
DBTT	Ductile Brittle Transition Temperature
DCF	Dalton Cumbria Facility
DEMO	DEMOnstration fusion power plant, e.g. EU-DEMO, K-DEMO
DFT	Density Functional Theory
DLS	Diamond Light Source
DONES	DEMO-Oriented Neutron Source
dpa	displacements per atom
DSC	Differential Scanning Calorimetry
EA	Environmental Agency
EBSD	Electron Backscatter Diffraction
EELS	Electron Energy Loss Spectroscopy
EPR	Electron Paramagnetic Resonance
EPR	Evolutionary Power Reactor
EQ	Equipment Qualification
FAST	Field Assisted Sintering Technique
FEA	Finite Element Analysis
FIB	Focused Ion Beam
HEA	High Entropy Alloys
HIP	Hot Isostatic Pressing
HSE	Health & Safety Executive
HVMC	High Value Manufacturing Catapult
IBA	Ion Beam Analysis
IEC	Inertial Electrostatic Confinement
IFMIF	International Fusion Materials Irradiation Facility
IP	Intellectual Property
ITER	Large scale fusion device, see www.iter.org
JET	Joint European Torus
KLST	Denomination for miniaturised specimen type, from the German Kleinstprobe
MCA	Multi Component Alloys
MoD	Ministry of Defence
MRF	Materials Research Facility (UKAEA)

MSR	Molten Salt Reactor
MTR	Materials Test Reactor
NAMRC	Nuclear Advanced Manufacturing Research Centre
NITE	Nano-powder Infiltration and Transient Eutectic Phase [Processing]
NNL	National Nuclear Laboratories
ODS	Oxide Dispersion Strengthened
OEM	Original Equipment Manufacturer
ONR	Office of Nuclear Regulator
PIE	Particle Induced Excitation
PiP	Polymer Infiltration and Pyrolysis
PPP	Public Private Partnership
PWR	Pressurised Water Reactor
QA	Quality Assurance
RAFM	Reduced Activation Ferritic Martensitic [steel]
REBCO	Rare Earth Barium Copper Oxide
RTO	Research & Technology Organisation
SAXS	Small Angle X-ray Scattering
SEM	Scanning Electron Microscopy
SIMS	Secondary Ion Mass Spectrometry
SME	Small and Medium-sized Enterprises
SMR	Small Modular Reactor
STARS	Surface Treatments of gas Atomized powder followed by Reactive Synthesis
STEP	Spherical Tokamak for Energy Production
TEM	Transmission Electron Microscopy
TGA	Thermogravimetric Analysis
TPLB	Transient Phase Liquid Bonding
UKRI	UK Research & Innovation
XRD	X-ray Diffraction

The UK Atomic Energy Authority's mission is to deliver sustainable fusion energy and maximise scientific and economic impact

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Find out more
www.gov.uk/ukaea

United Kingdom Atomic Energy Authority
Culham Science Centre
Abingdon
Oxfordshire
OX14 3DB

t: +44 (0)1235 528822