The UK Atomic Energy Authority's mission is to lead the delivery of sustainable fusion energy and maximise scientific and economic benefit

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UK Atomic Energy Authority

UK FUSION MATERIALS ROADMAP 2.0

Foreword

Dear researcher, funder, design engineer, regulator, curious reader...

The danger with any roadmap is a tendency to generic commentary because of the scale of the subject. In this document, an attempt has been made to provide overarching commentary on big themes for materials in fusion but we invite you to dive into the detail in the tables too, to see highly specific solutioneering. As with the first version of this Roadmap in 2021, the invitation remains to respond to the ideas here with your own additions and amendments, if you know more about any aspect of this highly challenging field!

A key theme of UK Fusion Materials Roadmap 2025 is that of powerplant readiness. The learnings emerging from close working with the STEP (UK fusion powerplant) design team increasingly inform perspectives with respect to synergistic testing requirements, fuel breeder maturity and supply chain gaps.

While this national 'labour of love' provides UK perspectives, the audience intended is global: we hope the Roadmap will be seen as a calling card from the academic, industrial and national lab community in UK fusion and that collaborators further afield will use this document as an entry point for new discussions.

My warm thanks to the many who contributed time so generously, and in particular, to our Editor in Chief, Professor Amy Gandy, for a comprehensive synthesis.

Amanda Quadling
Executive Director for Materials, Blankets and Research Programme
UKAEA

Contents

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.

This work has been funded by the EPSRC Energy Programme.

Fusion energy promises to be a safe, low carbon and sustainable part of the world's future energy supply

What is fusion?

Fusion takes place at the heart of the stars and provides the power that drives the universe.

How does it work?

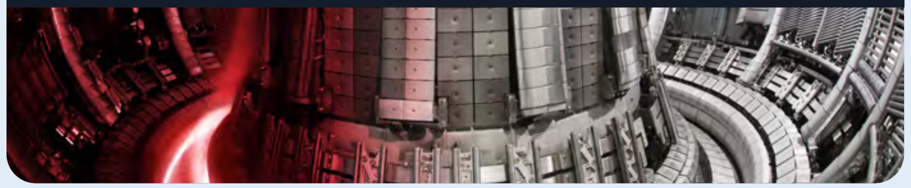
Fusion energy can be thought of as the opposite of nuclear fission – combining lighter atoms rather than splitting heavier ones.

When two forms of hydrogen, deuterium (D) and tritium (T), are heated at extreme temperatures (10 times hotter than the core of the sun) they form a plasma and can fuse together and release energy. When this happens, helium is produced, and huge amounts of carbon-free energy is released.

There is more than one way of achieving this. All require heat and pressure.

Keeping a plasma well confined and stable enough to sustain fusion is hard. If the plasma cools, fusion will instantly cease. This is one reason why fusion is inherently safer than fission.

At UKAEA, we hold this hot plasma using strong magnets in a ring-shaped machine called a 'tokamak'.



Benefits of fusion

Low carbon

Fusion energy is carbon-free at the point of generation.

Lower hazard

A chain reaction cannot occur, and the waste produced will be shorter lived, lower level than from fission.

Continuous

Fusion energy is continuously deployable, as it does not depend on external factors such as wind or sun.

Sustainable

Fusion fuel is potentially abundant in our seas and the Earth's crust.

High fuel efficiency

Fusion produces more energy per gram of fuel than any other process that could be achieved on Earth.

Summary

Globally, there have been significant advances made in the development of fusion power. However, there are still many scientific and engineering challenges that need to be solved to realise commercial fusion in the coming decades. Many of those challenges relate to the materials that are to be used in the construction of future fusion power stations. For example, the energetic particles that are produced during fusion will collide with materials, changing their internal structure and chemical composition, which ultimately changes the performance of those materials in operation. In magnetic confinement fusion, the strong magnets used can be easily affected by fusion radiation, so we must develop ways to protect the magnets or develop materials that are more tolerant to that radiation. We also need to produce tritium, one of the primary fuels for fusion. We can do this using the neutrons produced in the fusion reaction, which can be absorbed by lithium, transforming the lithium into tritium, which can then be fed back into the core of the fusion power station. However, we don't yet know the optimal lithium containing materials to use, nor the materials required to contain the fuel components.

Throughout 2024 and early 2025, over 100 researchers from across UK industry, academia and national labs, already working to develop materials for fusion energy, came together to identify the key materials related challenges that need to be solved in order for the UK to achieve commercial fusion. As well as identify the skills, infrastructure and capabilities that are needed to solve those challenges.

The UK fusion materials communities identified five major research areas, as well as four cross-cutting themes. The research areas include continued development of radiation damage tolerant and high temperature performing materials that can be used in the construction of the fusion core, as well as radiation tolerant materials for the magnets, neutron shielding, and radiation hardened materials for sensors and diagnostics. They also identified the need to develop tritium breeding materials and the associated infrastructure, as well as the modelling and simulation methodologies that underpin all these research areas. The cross-cutting themes included the need to develop a UK materials supply chain, and increasing our capabilities to simulate a fusion environment here in the UK, specifically by developing our existing, and creating new, irradiation testing facilities.

This roadmap aims to take a deep dive into the technical challenges identified and highlights specific facilities and infrastructure required. However, **we hope the roadmap is accessible to those of you not currently working in fusion, but in adjacent areas where your skills and expertise can be applied to solve these challenges. And we hope this roadmap serves as an open invitation to our international colleagues to continue to work together to make fusion power a reality.**

Amy Gandy
Head of Programme for
Materials Science and Engineering
UKAEA

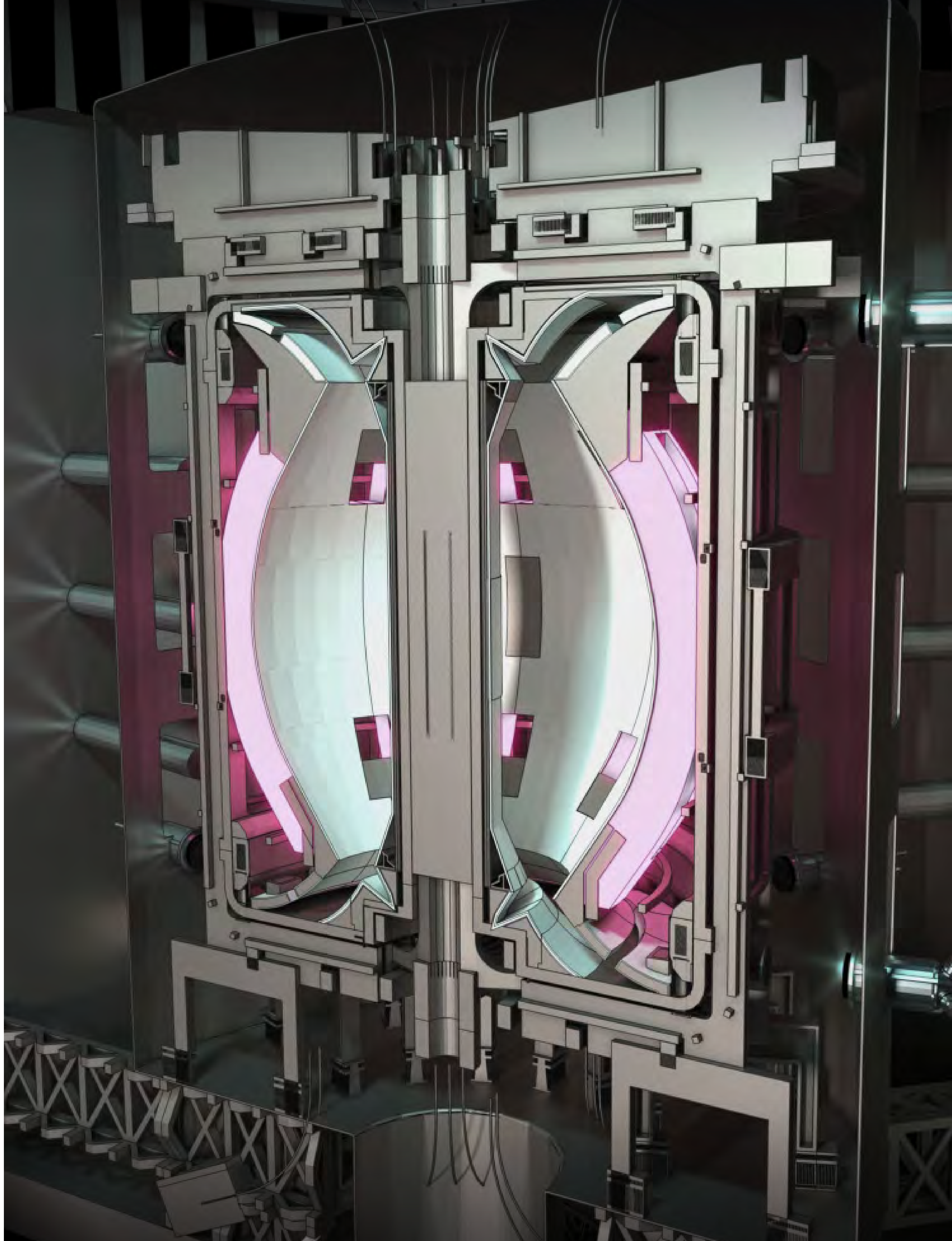
Near term and stretch targets identified by the UK fusion materials communities

	2025	2028	2035	Early 2040s	Beyond STEP
	STEP Tranche 2A starts	LIBRTI generates first data Materials for STEP long lead times	IFMIF-DONES begins operation Materials for STEP short lead times	STEP first plasma	Commercial fusion powerplants

	NEAR TERM	STRETCH TARGETS
Simulate the fusion environment	• Establish UK capabilities to irradiate, handle and test irradiated HTS tape at relevant temperatures in high magnetic fields (20 T) under strain (+/- 0.5%) and determine the critical current of HTS tape under operating conditions. • Develop in-situ, synergistic testing capabilities to simulate local operational conditions (e.g., material testing under irradiation, at temperature, in predicted environmental conditions) for all fusion materials. • Determine optimum tritium breeding material using data from IFMIF-DONES, LIBRTI and other fusion relevant neutron facilities.	• Use STEP surveillance sampling (and other demonstration power plants and fusion relevant capabilities), in collaboration with remote robotics teams, to develop in-situ monitoring and repair methodologies and to determine the impact of the real fusion environment on materials. • Commission and utilise a UK fission materials test reactor for fusion materials assurance.
Establish material supply chains for green, sustainable commercial fusion	• Establish UK supplier of HTS tapes and develop Quality Assurance strategy for HTS tapes. • Develop methods for fabricating complex geometries, joining similar (e.g., shielding ceramics) and dissimilar materials, (e.g. ceramics or tungsten to steels), and producing functionally graded materials (e.g., multi-barrier coatings for corrosion resistance and tritium anti-permeation onto structural materials). • Develop industrial scale manufacturing processes of breeder materials and components. • Secure or develop a continuous supply of high quality/purity raw elements or materials in sufficient quantities. • Develop reduced activation structural materials (e.g., steels or vanadium alloys to operate up to 650 °C, and SiC/SiC for up to 1000 °C operation), at industrial scale.	• Develop recycling routes and materials selection for sustainability, including recovery of high-value materials (e.g., Re and W). • Determine strategies for impurity control and radioisotope waste reduction. • Develop advanced manufacturing techniques such as additive manufacturing to improve reliability or open new design possibilities and scaling up. • Develop suppliers and industries for high-temperature, fusion-specific materials that are not used extensively in other sectors (e.g. vanadium base materials).
Develop predictive models for assurance in support of materials qualification	• Develop multi-scale modelling techniques for the prediction of material property evolution under fusion conditions. • Design integrated modelling/experimental matrices for the development of small specimen testing and surveillance sampling protocols, and their validation with large specimen tests following industry standards. • Provide qualified, engineering scale data on candidate materials (e.g., shielding efficacy, structural integrity) utilising fission (or other) neutrons, targeting irradiation induced damage and transmutation effects.	• Develop plant and component scale modelling techniques, capable of extrapolation significantly beyond the experimental envelope.

RETURN TO CONTENTS

Spherical Tokamak for Energy Production (STEP) concept, with breeder blankets highlighted.



RETURN TO CONTENTS

The road to commercial fusion in the UK

In the UK, whilst magnetic confinement fusion is the prominent technology pursued for commercialisation via the government funded Spherical Tokamak for Energy Production (STEP) programme and privately funded Tokamak Energy, privately funded First Light Fusion continues to develop inertial confinement fusion technologies. STEP will be a prototype fusion power plant aiming to demonstrate net fusion energy generation and fuel self-sufficiency by the early 2040s. In 2022, the Secretary of State selected the site of the decommissioned West Burton power station as the location for STEP and in September 2024 UK Industrial Fusion Solutions Ltd. (UKIFS), a wholly owned subsidiary of the UKAEA Group, was established to lead delivery of the STEP programme. In January 2025, UKIFS announced the shortlist for the Engineering and Construction Partners for STEP. Tokamak Energy, in addition to operating their own spherical tokamak ST40, have developed world-leading High Temperature Superconducting (HTS) magnet technology, positioning them as a key HTS magnet supplier for fusion and other, adjacent, industries.

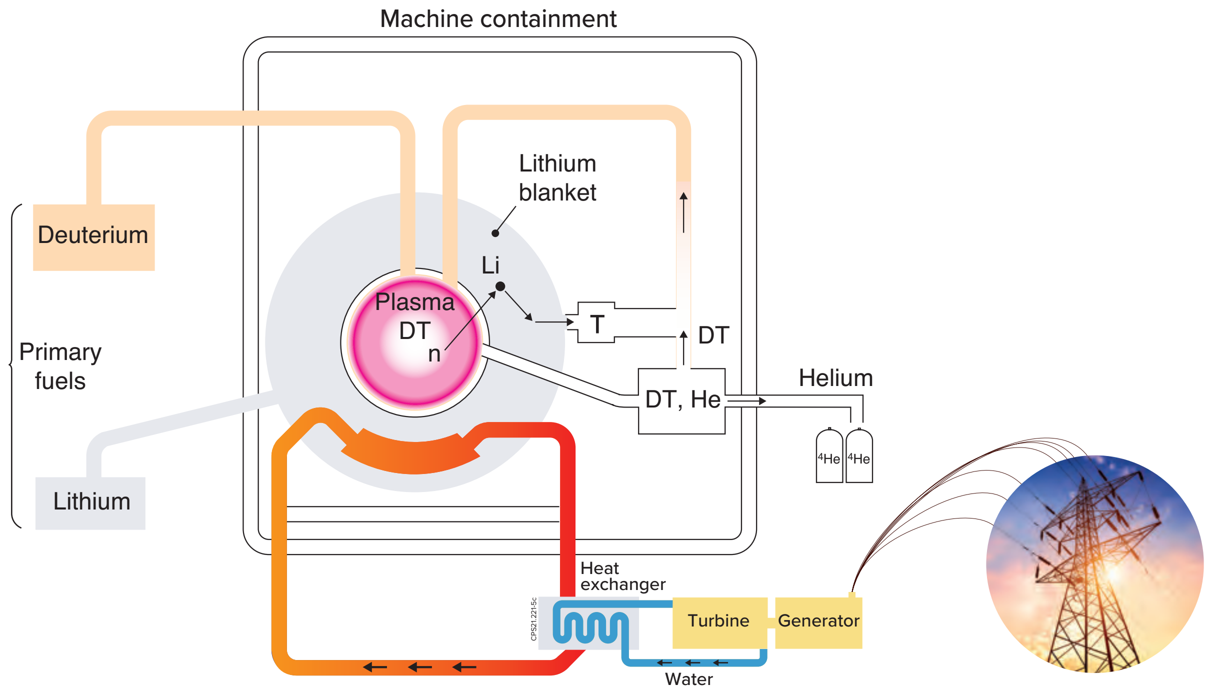
Beyond these programmes, research institutes, national laboratories, and UK industry are supporting fusion materials and fusion skills development, including creation of a new Fusion Engineering Centre for Doctoral Training (CDT), complementing the existing Fusion Power CDT, and development of fusion relevant skills and capabilities in UK industries via the Fusion Industry and Fusion Futures programmes facilitating formation of critical fusion materials supply chains. All these initiatives represent important pathways and milestones for commercialisation, but they are not the end point. **This roadmap describes how these endeavours will support development and assurance of fusion materials, whilst highlighting further critical infrastructure, capabilities and skills needed to realise commercial fusion in the UK.**

Fusion material challenges

The core of any fusion power station will arguably provide the most extreme environment on Earth. For magnetic confinement fusion using High Temperature Superconducting (HTS) magnets (such as STEP), materials that comprise the fusion core will experience fluctuating thermal, mechanical, magnetic, and electrical loads, including: phenomenal temperature gradients from the plasma facing materials to the cryogenically cooled superconducting magnets mere metres away; the production of high energy (14.1 MeV) fusion neutrons which cause transmutations in materials, leading to changes in material composition, production of radioactive materials, and significant helium and hydrogen gas generation; fusion neutron induced atomic displacements, orders of magnitude greater than in current fission reactors, leading to secondary phase formation and dissolution, and crystal structure transformations; and high (> 17 T) magnetic fields applying significant stress on materials. These effects will change the properties and therefore performance of materials in operation, and significant work is ongoing to determine life limiting factors such as critical failure modes and how to improve materials to better withstand these conditions.

One of the greatest material challenges, unique to fusion, is the tritium breeder blanket: a major component surrounding the fusion core where the fusion fuel, tritium, will be produced. The breeder blanket is expected to comprise structural materials, tritium breeding materials and potentially neutron multipliers, coolants to remove heat generated by radiation induced processes, purge gases to facilitate extraction of the produced tritium, and potentially corrosion resistant and tritium permeation barriers. Beyond the breeder blanket, neutron shielding materials are required to protect HTS magnet materials, and materials used for diagnostics and sensors (Rad Hard materials) as well as cabling and insulation materials.

Lithium breeder blanket – for illustrative purposes

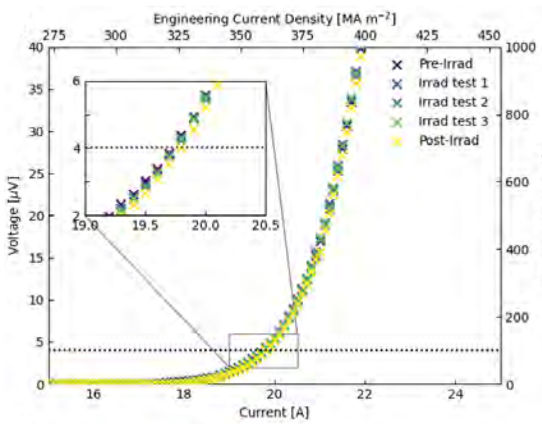


Presently, no facility exists anywhere in the world that fully mimics the fusion environment. The development and qualification of fusion materials can therefore not follow traditional routes. Instead, the fusion materials communities currently utilise existing irradiation facilities to mimic certain aspects of the fusion environment and are developing computational methods to extrapolate and predict material behaviour under fusion conditions. STEP and other demonstration fusion power plants and fusion specific irradiation facilities (e.g., Lithium Breeding Tritium Innovation (LIBRTI) and the International Fusion Materials Irradiation Facility – Demo Oriented NEutron Source (IFMIF-DONES)) are expected to provide critical data to validate computational models and determine critical failure modes in materials. **However, a major gap in UK (and global) capabilities identified during the roadmap workshops, linking across all material challenges, is the lack of facilities for synergistic, in-situ testing of materials under fusion relevant conditions.**

Purpose of the updated UK Fusion Materials Roadmap

Since the publication of the first UK Fusion Materials Roadmap in 2021, there have been significant advances in fusion materials development, and substantial progress has been made in UK and global fusion programmes. The following gives four examples of challenges that were identified in the previous roadmap and progress made in solving those challenges.

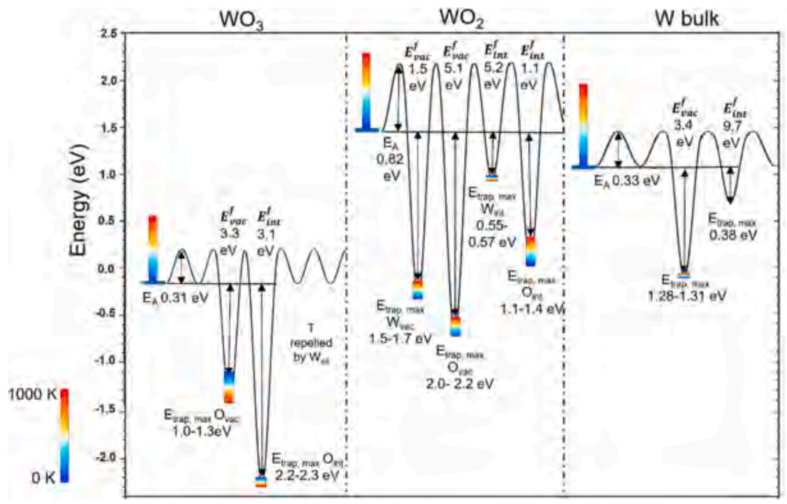
CHALLENGE	PROGRESS TOWARDS SOLUTION
Previously, there were no reported in-situ measurements of the critical current density of Rare-earth-barium-copper-oxide (REBCO) tapes during fusion-relevant irradiation.	Researchers from UKAEA undertook in-situ measurements of the self-field critical current at 77 K, of several REBCO coated conductor tapes during Co-60 gamma ray exposure at a dose rate of 86 Gy min^{-1}, which is approximately equal to the peak flux expected on the magnets of proposed fusion pilot power plants. The samples were fully submerged in liquid nitrogen throughout the measurements. No change was observed in the critical current of any sample during or after irradiation which is a promising result for high temperature superconducting (HTS) magnet operation.



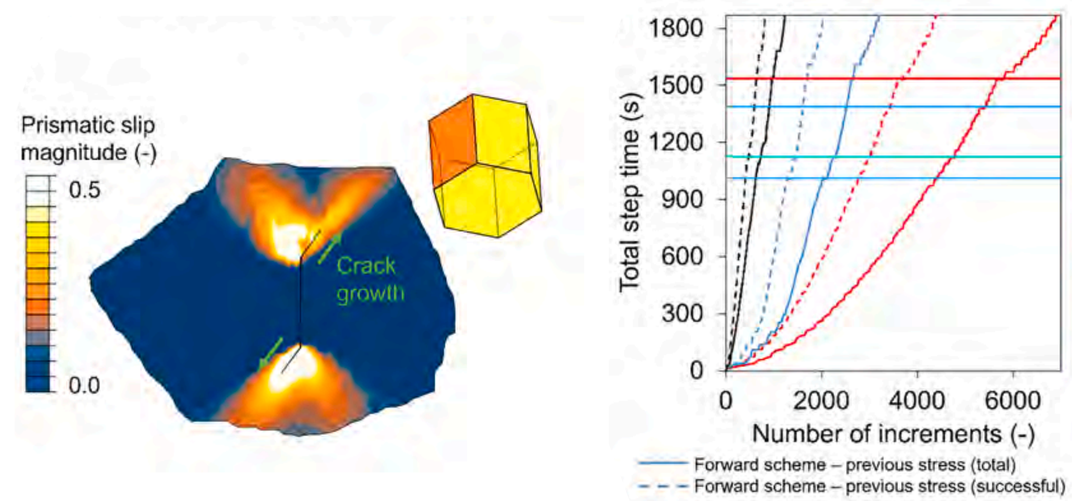
The image [1] shows 77 K self-field I-V traces of SuperPower (Gd,Y) BaCuO tapes, before, during and after irradiation. The critical current is where the curve crosses the dotted line at 4 muV.

CHALLENGE	PROGRESS TOWARDS SOLUTION
Tungsten is a main plasma-facing material candidate but can easily oxidise during fusion operation. Retention of tritium in tungsten and its oxidation is a concern but tritium permeation experiments are challenging.	A collaboration between Materials Design in France and UKAEA conducted atomistic simulations using ab initio density functional theory and machine-learned potentials to map the structural, thermodynamic, and kinetic properties of the T-WO_x system (x = 0 to 3). The simulations reveal that T permeability is low in WO_2, intermediate in W, and relatively high in WO_3. Diffusion of T is slowest in WO_2 suggesting this oxide could be used as a tritium permeation barrier.

The image [2] shows computed energy diagram of T in a stack of W-WO_2-WO_3.d.

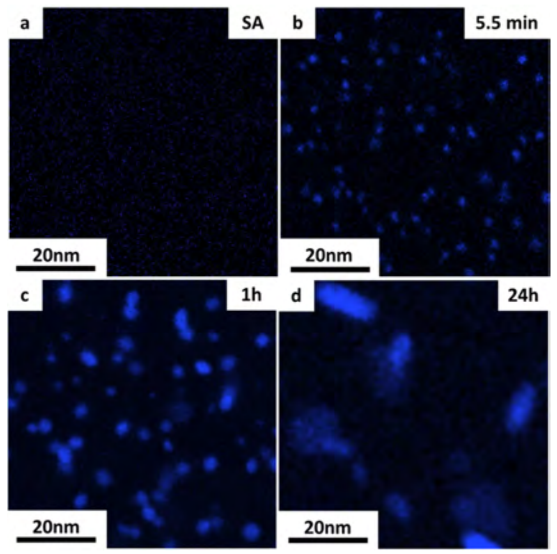


CHALLENGE	PROGRESS TOWARDS SOLUTION
Modelling of irradiated material requires capturing highly non-linear material behaviour which is difficult or impossible to simulate using conventional crystal plasticity solvers.	A novel, robust solver has been developed by the Design by Fundamentals team, a collaboration between UKAEA, University of Oxford and Imperial College London, which can better cope with these highly non-linear material responses, making simulations more efficient and in some cases possible where they were otherwise impossible to solve.



The image [3] shows simulation performance for a highly nonlinear model on polycrystalline Zircaloy4, including cyclic loading, non-linear hardening and crack propagation using the eXtended Finite Element Method (XFEM). Data in the graph highlights that the developed solver can complete the simulation using far fewer increments and is more computationally efficient compared to conventional solvers.

CHALLENGE	PROGRESS TOWARDS SOLUTION
CuCrZr alloy is the leading material candidate to act as the heat sink in the divertor and first wall components. Its mechanical integrity depends on a very fine dispersion of Cr-rich nano-precipitates. The precipitates' behaviour and stability under service conditions depend on their structure and local chemistry which must be optimised during alloy procesing and shown to be retained under service conditions.	A UK-Japan multipartner consortium undertook the challenge of unravelling the formation and evolution of the nano-precipitates during the last ageing phase of alloy processing, by using a combination of high-resolution techniques including positron annihilation spectroscopy, analytical electron microscopy and atom probe tomography. Results revealed the presence of spherical Cr-rich precipitates after only 5.5 min at 480 °C aging, with Zr segregation at the precipitate locations; whereas at longer times precipitates coarsened, and they evolved into a disc-like morphology with a Zr-rich outer shell. These results point at the Zr role in stabilising the intermediate fcc structure and potentially affecting the overaged precipitate morphology.



The image [4] shows representative Cr K_α maps of the nano-precipitate evolution during the ageing of CuCrZr alloy at 480 °C: (a) in the initial solution annealed (SA) state, and after ageing for (b) 5.5 min, (c) 1 h, and (d) 24 h.

Given the advances made, it is timely to update the current state-of-play, drawing on knowledge from researchers and industry already working in fusion materials who are best placed to identify and articulate not only material challenges, but critically the skills, capabilities and infrastructure that are required to solve these challenges. To that end, a series of workshops were held throughout 2024 and early 2025, with participants from academia, national labs, and industry. Initially, online workshops with research area leads (identified as leading in a specific field of fusion materials research) were held to capture the broad fusion research challenges and identify people already working in fusion materials who should contribute to updating the roadmap. In June 2024, in collaboration with, and co-funded by, the Henry Royce Institute, via the Royce Nuclear Research Theme, a hybrid workshop, held online and in person at the University of Manchester, enabled over 100 participants to define the purpose and structure of the roadmap, ensure all material challenges were captured, and identify research area specific as well as cross-cutting challenges. Smaller, online workshops were held later on in 2024 and early 2025 to develop specific roadmap areas and draft versions of the roadmap were shared with an editorial board comprising external subject matter experts and iterated on to produce this final version.

Five main research areas were identified, with a further four cross-cutting challenges identified, which impacted all research areas. All are addressed in detail within this roadmap.

RESEARCH AREAS

1 Magnets and Shielding
2 Tritium Breeding: production; anti-permeation barriers; and corrosion resistant coatings
3 High Temperature Materials: plasma facing and structural materials
4 Radiation Hardened (Rad Hard) Materials
5 Modelling and Simulation

CROSS-CUTTING CHALLENGES

1 Regulation, codes and standards, assurance and qualification
2 People: skills, training, and developing UK capabilities
3 Waste management
4 Supply chain

Global fusion and adjacent materials research

The UK alone cannot solve all of the fusion materials challenges identified, with international collaborations that enable knowledge exchange and unique facility access imperative for achieving global fusion energy. Karlsruhe Institute of Technology (KIT) has a rich history developing lithium-containing ceramics as a fuel source for fusion. The EU, Japan and the US have spent decades developing their own versions of reduced activation steels, Eurofer97, F82H and nanostructured alloys, respectively, for use in fusion core structural components. In the UK, the Neutron Irradiation of Advanced Steels (NEURONE) project recently demonstrated UK capability in producing fusion-grade reduced activation ferritic/martensitic (RAFM) steels using an industrially scalable process. This roadmap builds on the progress made by these, and other, global leaders in fusion materials research and describes routes to developing materials for the particularly demanding environments of commercial fusion power plants. Furthermore, given the similarities in materials challenges between fusion and next generation fission reactors (e.g., High Temperature Gas-cooled Reactors (HTGR) and Molten Salt Reactors (MSRs)), the fusion and fission materials communities must ensure clear pathways for communication and collaboration. Funders must recognise that fission and fusion cannot and should not be siloed when it comes to materials research. For example, joint neutron irradiation campaigns comprising both fission and fusion relevant materials will provide critical data to support development of both technologies. Even the seemingly unique to fusion challenge of using tritium as a fuel source has crossovers with fission. In the US, Idaho National Laboratory hosts the Molten Salt Tritium Transport Experiment (MSTTE) utilising a fluorine salt loop to measure hydrogen transport through metals and evolution from free surfaces. Whilst developed for MSRs, this technology can be directly applied to understanding tritium transport in molten salt tritium breeder blankets for fusion. **It is hoped that our international colleagues will see this roadmap as an invitation to continue existing and initiate new collaborations with the UK, to work together to solve one of the greatest challenges of our time.**

UK National User Facilities

The UK has an extensive range of National User Facilities that are accessible to academia and industry for fusion (and other) research via a range of access schemes. The below list is not exhaustive but gives links to some of the key facilities, networks and institutes currently used for development and assurance of materials for fusion.

National Nuclear User Facility

The National Nuclear User Facility (NNUF) project is a Government investment in the UK's nuclear future, providing state-of-the-art experimental facilities for research and development in nuclear science and technology, including the High Flux Accelerator-Driven Neutron Facility and high-energy light-ion Cyclotron Facility, both at the University of Birmingham, for neutron and proton irradiation of materials, as well as post-irradiation examination (e.g., following proton or neutron irradiation) of radioactive materials at the Materials Research Facility (MRF) at UKAEA ***https://www.nnuf.ac.uk***.

The UK National Ion Beam Centre (UKNIBC)

The UKNIBC provides and state-of-the-art ion beam facilities and capability for the UK academic and industrial communities, via a collaborative delivery partnership between facilities at the Surrey Ion Beam Centre at the University of Surrey, the MIAMI & MEIS Facilities at the University of Huddersfield, and the Dalton Cumbria Facility (DCF) of the University of Manchester. DCF allows proton irradiation of materials, including development of in-situ, synergistic, testing of materials (e.g., at strain, under irradiation, at temperature) ***https://uknibc.co.uk/wp***.

Science and Technology Facilities Council (STFC)

STFC is a multidisciplinary science organisation, with large-scale scientific facilities in the UK and Europe, and includes the ISIS Neutron and Muon Source which allows the study of materials under neutron irradiation (e.g., the ChipIr beamline to study microelectronics) ***https://www.ukri.org/councils/stfc***.

The Henry Royce Institute

Royce is a partnership of nine leading institutions – the universities of Cambridge, Imperial College London, Liverpool, Leeds, Oxford, Sheffield, the National Nuclear Laboratory, and UKAEA. Royce's associate partners are the universities of Cranfield and Strathclyde. There are extensive materials facilities and research expertise available at these institutes, including development of advanced materials and manufacturing processes and post-irradiation examination capabilities ***https://www.royce.ac.uk***.

Global fusion landscape

Since the release of the first UK Fusion Materials Roadmap in 2021, despite changes in political parties and policies, and against the backdrop of ongoing economic challenges, harnessing energy from fusion continues to receive significant global support. In June 2024, leaders of the G7 stated “Fusion energy technology has the potential to provide a lasting solution to the global challenges of climate change and energy security” and announced they “…will promote international collaborations to accelerate the development and demonstration of fusion plants to foster private investments and public engagement” [5] and have established the G7 Working Group of Fusion Energy to facilitate this. In November 2024, the IAEA hosted the inaugural ministerial meeting of the World Fusion Energy Group (WFEG), facilitating discussions on public-private partnerships, commercialisation strategies, policy frameworks and regulation [6]. Globally, as of 2024, private and public funding in fusion equated to over £5.5 billion, with £700 million provided in 2024 alone [7]. The Fusion Industry Association Report 2024 [7] identified there are over 45 companies working towards commercial fusion, with a significant increase in public funding directed into private companies of nearly £400 million in 2024.

National, international, public and private sector collaborations are key to developing fusion energy

Soichiro Imaeda
Japanese
Science Minister

Tokamak Energy visit

The Rt Hon Ed Miliband MP
Secretary of State for Energy
Security and Net Zero

Examples of national and international, government and private fusion industry visitors to UKAEA

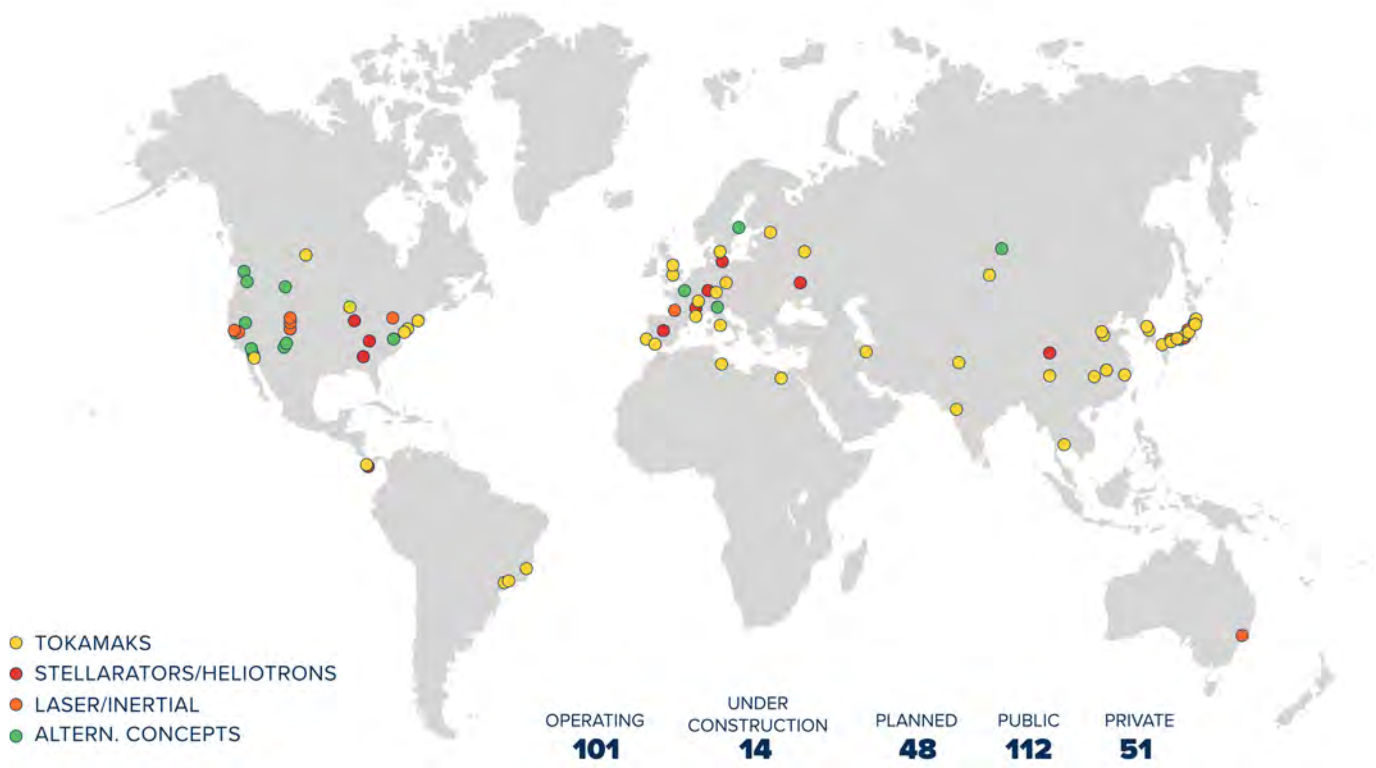
National fusion programmes continue at pace. In April 2023, Japan announced its National Fusion Energy Innovation Strategy, a ten-year strategy “Towards the practical realization of fusion energy, the world’s next-generation energy source” [8] and South Korea’s KSTAR superconducting Tokamak produced a record-breaking plasma operation of 48 seconds at 100 million degrees Celsius. In July 2024 the South Korean government announced $866 million investment to further develop fusion machines and related infrastructure [9]. China’s fusion programme continues to make significant strides, with the Comprehensive Research Facility for Fusion Technology (CRAFT) nearing completion, to support the China Fusion Engineering Test Reactor (CFETR) which aims to demonstrate fusion energy power up to 200 megawatts and a tritium breeding ratio >1 for tritium self-sufficiency [10]. In 2023, to facilitate development of fusion technologies in the UK, the UK government announced a £650 million “fusion package” to support UK industry and academic institutes in developing infrastructure, skills, and industrial and commercial opportunities. In January 2025, both the UK and US governments announced significant investment in their national fusion programmes, with the UK’s Department of Energy Security and Net Zero (DESNZ) committing £410 million in 2025/26 to accelerate development of fusion energy and kickstart economic growth [11] including continuation of funding for STEP, and the US Department of Energy (DOE) announcing $107 million for six projects in the Fusion Innovative Research Engine (FIRE) Collaboratives [12].

Despite these national fusion initiatives, international collaborations remain critical to achieving commercial fusion, and fusion continues to receive public and private funding to facilitate these. Indeed, in December 2023, JT-60SA, developed via a Japan-European Union collaboration facilitated by a Broader Approach Agreement, became the world’s largest operational tokamak [13]. In December 2024, a £40.5 million joint US-UK project (between the DOE, DESNZ’s Fusion Futures Programme, and Tokamak Energy), was announced to advance fusion science and technology, including enhancing the efficiency and durability of plasma-facing components [14]. In the same month, Novatron Fusion Group announced a €3 million collaboration with UKAEA, KTH Royal Institute of Technology, Kharkiv Institute of Physics and Technology (KIPT) and EIT InnoEnergy, funded by the European Innovation Council Pathfinder Program, to enhance plasma confinement time by integrating three different confinement techniques [15]. Private investment in fusion continues at pace, with US company Pacific Fusion securing over $900 million funding to support its combined magnetic-inertial confinement technology [16] and Kyoto Fusioneering announcing involvement in Japan’s Fusion by Advanced Superconducting Tokamak (FAST) programme which aims to “…accelerate the way forward to a clean energy future by demonstrating electricity generation by the 2030s, via a tokamak approach” [17].

Current and planned fusion programmes

According to the IAEA’s Fusion Device Information System [18], as of January 2025, there are a reported 101 operational fusion devices, 14 under construction, and 48 planned. These comprise Tokamaks (conventional and spherical), Stellarators/Heliotrons, Laser/Inertial, and Alternative Concepts. Whilst magnetic confinement fusion (Tokamaks, Stellarators/Heliotrons) is the most mature fusion technology, other concepts have made significant recent progress. In 2022, the inertial confinement fusion device at the National Ignition Facility (NIF) at Lawrence Livermore National Laboratory (LLNL) reported achieving the world’s first fusion energy gain [19] and in 2024 General Fusion’s magnetized target fusion (MTF), where plasma is mechanically compressed to achieve fusion, reported its first plasma production [20]. **Irrespective of the concept, significant materials challenges remain and many of these challenges are common to all fusion technologies, e.g., the need for high temperature performing and radiation damage tolerant structural materials, tritium breeding materials, neutron shielding materials, and radiation damage resilient materials for magnets, diagnostics and sensor materials.**

Map showing all current and planned global public and private fusion devices
(as of December 2024) **from [18]**



Cross-cutting themes

Outputs from the workshops identified four “cross-cutting themes” common to all research areas.

1. Regulation, codes and standards, assurance and qualification
The UK's Energy Act 2023 confirmed that “fusion energy facilities will not be subject to nuclear licencing requirements, and therefore will not be regulated under the same regulatory regime as nuclear fission” [21]. Instead, this allows the Environment Agency (EA) and the Health and Safety Executive (HSE) to regulate fusion research and development (R&D) using the flexible “goal-setting regulatory approach” deemed appropriate for “an emerging, lower safety risk area of technology, which involves ongoing innovation and evolution” such as fusion [22]. This flexibility offers the use of best engineering practice to support the fusion materials (and other) communities opportunity to influence the codes and standards to be used, as well as appropriate routes to materials qualification, which have yet to be determined for fusion.

Risks and hazards in fusion
The principle that all human or organisational activities carry some risk of harm, and that this risk must be balanced against the benefits, is well established. When the risk involves exposure to ionising radiation, this balancing act becomes more formalised. In the UK, the requirement to weigh risks against benefits is enshrined in law through both case law and the Health and Safety at Work Act (1974). The terms "As Low as Reasonably Practicable" (ALARP) and "So Far As Is Reasonably Practicable" (SFAIRP) are considered equivalent in this context.

A unique hazard for power-producing fusion machines, compared to other industrial activities, arises from the presence of tritium in pressurised systems within the fusion core and radioactive structural components created by neutron activation. The UK’s Pressure Systems Safety Regulations 2000 (PSSR) are overseen by the Health and Safety Executive (HSE), with an Approved Code of Practice (ACOP) providing guidance on compliance. These regulations apply to all pressure systems, which include pressure vessels, associated pipework, and protective devices containing a relevant fluid, defined as steam, water, liquid or any gas at a pressure exceeding 0.5 bar(g). In fusion systems, this means that coolants within vacuum vessels and in-vessel components using a coolant pressure above this threshold will be subject to PSSR requirements. Regulators mandate the use of best engineering practices, if available, to ensure quality and assurance of safety requirements are demonstrated and substantiated, of pressure-retaining components, including those confining radioactive materials.

For pressure systems exposed to high radiation, extreme temperatures, and neutron irradiation (such as vacuum vessels and in-vessel components, depending on design), ASME BPV Section III (for nuclear devices) and RCC-MRx (for sodium-cooled fission and fusion mechanical components) are appropriate. In ASME BPV, new materials must be qualified according to BPV Section II, Part D, Mandatory Appendix V, while RCC-MRx requires qualification under AFCEN/RX.17.006A. These codes identify the amount and type of data required to formulate the allowable stresses / strains for materials operating under specific conditions (e.g., time at high temperature, fluctuating or constant loading). Environmental effects (e.g., behaviour in aggressive coolants, under damaging radiation) are not included, leaving the onus on the operator / designer to identify and provide suitable data. Following the codes and standards provides quality assurance within the specified operational conditions. These codes and standards only provide quality assurance within their allowable stress values.

Codes and Standards
Codes and Standards define best practices, ensuring safety and structural integrity by incorporating state-of-the-art knowledge, operational experience, and experimental data. They prevent poor engineering practices and facilitate consistency across suppliers, researchers, designers, manufacturers, and regulators. These documents evolve over time as scientific advancements and operational experience improve.

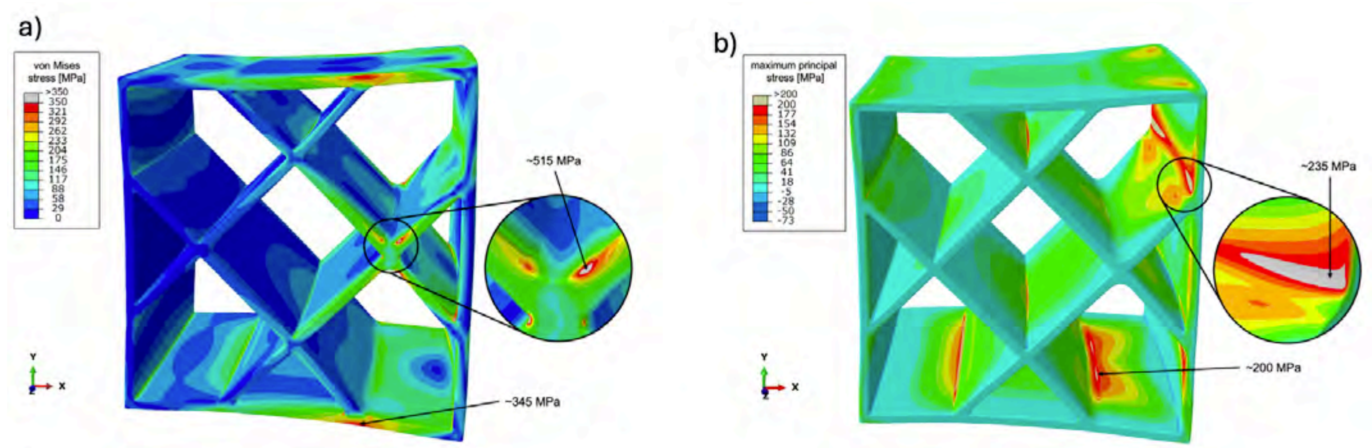
For pressurised systems operating in a nuclear environment, three main primary design codes apply (not exclusive):

- ASME Boiler and Pressure Vessel Code (BPV)
- AFCEN RCC-M and RCC-MRx
- EN 13445

Towards qualification for fusion
At the time of writing, the HSE and EA have just begun a series of workshops with STEP and UKAEA to determine fusion specific hazards, and help to develop accompanying legislation for STEP to demonstrate compliance with safety principles, as well as appropriate materials and component qualification routes. Staged qualification or co-qualification of materials is expected to be acceptable. It is anticipated that STEP will provide surveillance samples, therefore, qualification of materials to be used in commercial fusion power stations post-STEP, in line with the best practice outlined in codes and standards such as ASME BPV Section III NB-2330, may be adopted.

Material qualification routes for pressure retaining components in safety critical components require assessment of material property data from all practical combinations of parameters expected in commissioning, operation, and decommissioning. This includes evaluating mechanical properties, radiation induced embrittlement, thermal fatigue resistance and transmutation effects. In the absence of an operational fusion power plant, or analogous facility, generating the unique environmental data is not yet possible for fusion materials, specifically neutron irradiation and exotic cooling mediums. Therefore, fusion materials assurance currently relies on generating experimental data from facilities that simulate or emulate the fusion environment, combining with validated computational modelling to determine fundamental defect formation mechanisms and failure modes, with the goal to ultimately extrapolate models to fusion specific conditions. **However, a critical concern is that no material has yet to be qualified using data from computational models.**

The difficulty of defining and acquiring the data required to show safety requirements have been met, in combination with the need to provide engineering assurance and qualification for materials that cannot be tested under their operating environment, cannot be overstated. However, the positive recent engagement between the regulators, UKAEA and STEP has initiated an ongoing dialogue to determine what evidence the fusion materials communities need to generate to ensure substantiation of meeting the safety requirements. Whilst regulation is commensurate to the risk imposed by the activity, routes to ensure financial protection should also be considered without compromising the safety requirements - stakeholders will need assurance that the risk of significant failure to the physical assets of the plant has been managed. Therefore, even if a component is not safety critical (e.g. plasma facing materials) appropriate qualification will be required to demonstrate substantiation against the desired performance requirements (to ensure better reliability of the component, and thus commercial models). **Irrespective of the specific regulatory framework, to facilitate materials assurance and qualification, irradiation facilities which better mimic the fusion core environment will de-risk development and be required to validate and calibrate computational models, and experimentally determine critical failure modes.**

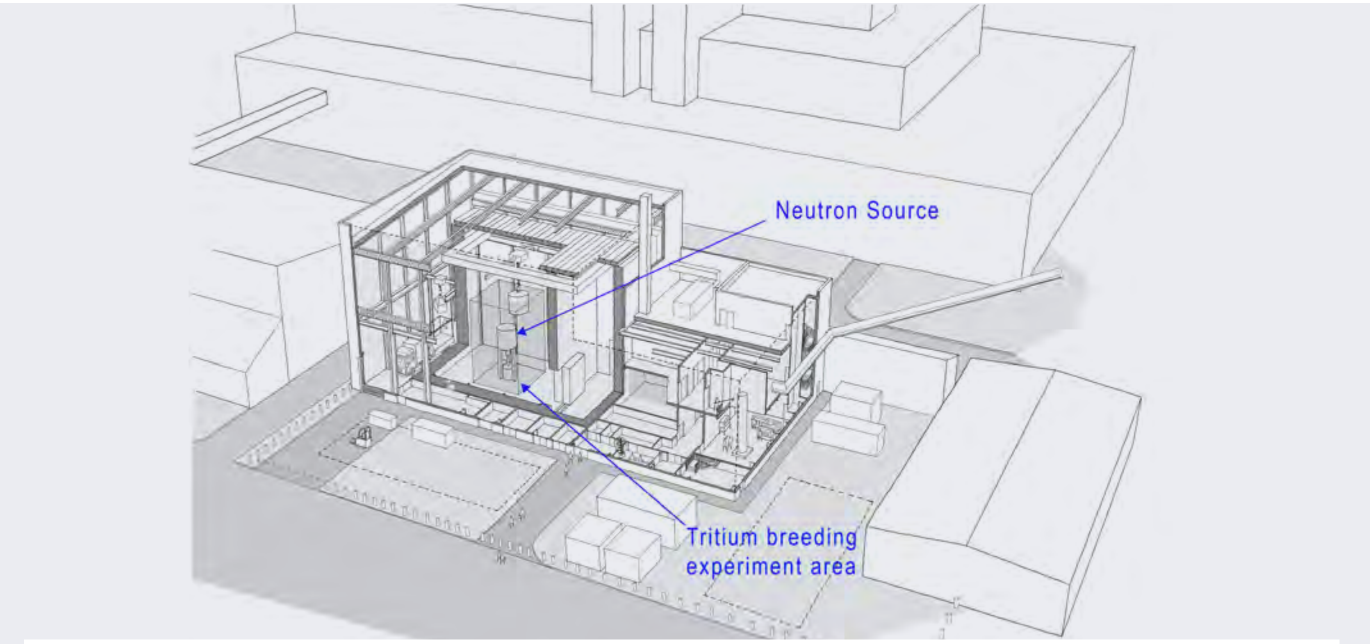


Contour plots of (a) the local von Mises stress and (b) the maximum principal stress, computed for the modified blanket module design. The colour scale bars are the same in both figures.

Reference: Luca Reali, Max Boleininger, Mark R. Gilbert and Sergei L. Dudarev Macroscopic elastic stress and strain produced by irradiation. 2022 Nucl. Fusion 62 016002.

Key Challenge: Irradiation facilities

By far the greatest challenge identified across all research areas, for materials development, qualification and assurance, is the **lack of fusion specific irradiation test facilities**, not just in the UK, but globally. Whilst STEP and other demonstration fusion power plants will provide some key data, their operational conditions will not be fully representative of a commercial fusion power plant (e.g., intermittent neutron production in STEP vs. sustained operation in a commercial fusion power plant). Other fusion specific irradiation facilities planned, e.g., the International Fusion Materials Irradiation Facility-DEMO Oriented NEutron Source (IFMIF-DONES) in Spain (expected to be operational in 2034) will enable material testing under high-energy neutrons and in component specific environments (e.g., in lead-lithium for liquid tritium breeding technologies), and the UK's Lithium Breeding Tritium Innovation (LIBRTI) facility (expected to be operational 2028) aims to experimentally demonstrate quantified tritium breeding in engineering scale prototype breeders, but will not produce the neutron induced damage required to study structural and function degradation of materials.



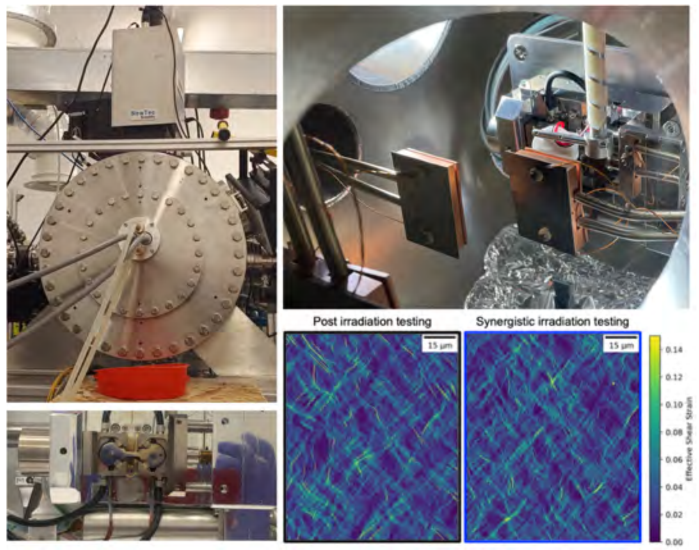
Schematic of the UK's Lithium Breeding Tritium Innovation (LIBRTI) facility, where 14.1 MeV neutrons will be used to breed tritium in a range of candidate tritium breeding materials.

In the absence of a fusion specific irradiation facility, the fusion materials communities must currently rely on using surrogate sources to, as best as possible, simulate the effects expected from fusion neutron interactions in materials. Fission neutron test reactors allow materials to be irradiated at different temperatures and in different atmospheres and produce damage in materials across several centimeters allowing for bulk mechanical testing of samples post-irradiation, which can be used to generate engineering data. However, due to the different energy spectra of fission and fusion neutrons, fusion neutron induced transmutation effects are not fully captured in fission test reactors. For example, it is predicted that a fusion power plant will produce, in candidate structural materials such as steels, He and H at concentrations of one or two orders of magnitude greater than in fission reactors. Nonetheless, as fission neutron irradiation can induce damage in bulk samples, neutron irradiation campaigns are still viewed as critical for fusion materials development and assurance. However, as the UK does not have a fission materials test reactor, irradiating materials with fission neutrons requires access to international facilities, which can be prohibitively expensive, requires around a 12-month planning phase before an irradiation campaign can start, and national level collaboration agreements to facilitate access. **Funding is required to develop such agreements,** for example, a UK-Japan agreement could enable UK researchers to access Japan's sodium-cooled fast reactor in Joyo for the development of fusion materials. **There was overwhelming support from workshop attendees for the UK to have its own fission materials test reactor which would provide key data (e.g., neutron attenuation and shielding efficiency data) not possible with other, surrogate methods.**

Development of end-stations for the UK's existing irradiation facilities, to test miniaturised samples, was identified as one solution to many fusion specific irradiation challenges. The development of end stations for testing must go hand in hand with the validation of correlations between results from standard and miniaturised specimens for most of the properties mentioned in the Table below. The UK National Ion Beam Centre (UKNIBC) includes the Dalton Cumbria Facility (DCF) which allows in-situ testing of materials under proton irradiation, for example tensile tests conducted at temperature under irradiation. Similarly, the University of Birmingham has both proton and neutron irradiation facilities and supports development of novel in-situ testing capabilities, including investigating radiation effects on fatigue performance of high temperature steels, and enabling simultaneous neutron irradiation of vanadium alloys within a liquid lithium environment. **However, a significant increase in these capabilities is required to solve the research area specific challenges identified in this roadmap.** Key missing capabilities include end stations to:

Superconducting magnets	Measure current simultaneously under irradiation, in high magnetic fields and at cryogenic temperatures.
Shielding materials	Provide neutron attenuation data and shielding efficacy; develop and validate testing techniques on small scale ceramic samples.
Tritium breeding materials	Develop in-situ test capabilities to investigate material performance (tritium breeding, structural integrity, corrosion resistance, tritium permeation) with synergistic interactions between materials, environment and irradiation.
High temperature structural materials	Develop in-situ test capabilities to determine effects of synergistic loading and environment on materials. Develop capabilities to irradiate up to 1000 °C for SiCf/SiC and other materials for high temperature power plant concepts.
Radiation hardened materials	Develop in-situ testing under high neutron/gamma flux, thermal cycling, and strong magnetic fields to validate new materials and designs.

To facilitate the significant number of new material testing capabilities required (e.g., new end stations), new irradiation facilities are also needed, with ion energies, fluxes and fluences complementary to existing UK facilities.



Images show development of synergistic thermomechanical-irradiation testing capability. Photographs detail the in-situ testing capability installed on the ion accelerator end station at Dalton Cumbrian Facility for application typically during proton irradiations. Firstly, the optical rig mounted on top of the end station with the electronics and cooling to control the rig (top-left), a standard specimen loaded in the rig (bottom-left) and the rig mounted inside the end station (top-right). An example of results from post-irradiation and synergistic-irradiation testing in terms of high-resolution strain maps (bottom-right) at 4.5% applied strain, where preliminary findings suggest a more homogeneous response after synergistic testing.

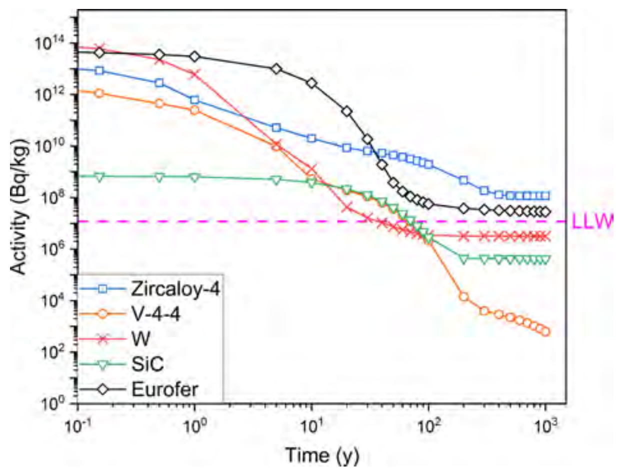
Credit: Design by Fundamentals team/Applied Materials Technology group and Dalton Cumbrian Faciliity.

2. People
The UKAEA's Workforce Accelerator white paper estimates up to 3,000 new people across all levels and skill types are needed to enter the fusion workforce over the next 5 years and identified that "Current training programmes within the UK do not have the capacity to develop the skills that this increase in workforce demands". A shortage of training programmes leading to an inevitable fusion skills shortage was identified as a major challenge across all research areas. The Fusion Opportunities in Skills, Training, Education and Research (FOSTER) programme aims to train over 2200 people by 2030 to join the UK fusion workforce. FOSTER is a £multi-million programme delivered by UKAEA on behalf of the UK fusion sector. Many of the skills required for fusion will also be required for fission, a sector which is also facing a significant skills gap. In March 2024, it was announced that, due to the UK Government's ambitious nuclear energy targets, the UK's nuclear industry is expected to need 123,000 more people by 2030 [23].

In addition to continuing to train scientists and mathematicians in "traditional" fusion subjects (plasma physics, materials science), the roadmap workshops identified the following research area specific skills shortages, across all skill types and levels - technicians, engineers and scientists with expertise in vacuum; cryogenics; superconductivity; high temperature superconducting magnets; mechanical engineering; manufacturing; radiation damage; processing and mechanical performance of ceramics; and mathematicians and physicists interested in computational methodologies that can be applied to fusion such as crystal plasticity modelling. **Funding, such as levies on fusion-related industrial partners, and bursaries for on-the-job training and conversions into fusion-required areas, to support training across all levels (from apprenticeships to PhDs), continued professional development and up-skilling scientists and engineers from different sectors, and for networks to support workshops, collaboration across sectors and information dissemination were viewed as solutions to this challenge.**

3. Waste management
Whilst fusion promises to produce energy without creating long-lived, high-level radioactive waste, it is important to recognise that intermediate and low-level radioactive waste will be generated and this will require management, as described in the Committee on Radioactive Waste Management (CoRWM) preliminary position paper: Radioactive Wastes from Fusion Energy [24]. Most fusion machine concepts utilise the DT reaction, which will produce 14.1 MeV neutrons. The interaction of the neutrons with materials comprising the machine will lead to transmutation and the creation of radioactive isotopes, thereby producing radioactive waste. The volume of radioactive waste could be large in prototype machines and in future commercial fusion machines due to the expected size of GW-scale fusion plants. However, by careful materials selection and materials processing to ensure strict impurity control, we can ensure virtually no high-level radioactive waste will be produced, such as long-lived actinides – a key decommissioning challenge in nuclear fission. Therefore, many of the components in the fusion machine would decay to a point when they can be disposed of as low-level waste (LLW) within decades. However, since the in-vessel components experience higher neutron flux, they could remain radioactive for hundreds of years and will therefore require the development of disposal and treatment routes for intermediate level waste (ILW).

Inventory calculations, such as those performed using the UKAEAs FISPACT-II code, help identify the radionuclides that will produce the long-lived, higher activity waste. These calculations also predict the most likely pathway for generating the problematic longer-lived nuclides. This information can be fed back to inform material and design choices. Many of the relevant long-lived radioisotopes are produced from alloying elements, such as niobium, molybdenum, nickel, carbon, nitrogen, copper and aluminium and from uncontrolled impurities (e.g. cobalt, potassium). Previous EUROFusion and STEP activities have predicted the waste arising from fusion machines and identified some of the important parameters affecting the generation and classification of waste from fusion. These important parameters include the choice of coolant and structural material, impurity content in the materials, operation time, preferred waste disposal time, shielding geometry and thickness, tritium removal efficiency through the fuel cycle, and tritium permeation and migration rates into materials.



Activity of Zr-4 (blue squares), V-4–4 (orange circles), W (red crosses), SiC (green triangles) and EUROFER 97 (black diamonds) as a function of time. The UK low level waste limit (LLW) is denoted by a horizontal fuchsia dashed line. Activities calculated using FISPACT-II.

Whilst material design and impurity control during manufacture will help to minimise waste, particularly ILW, there are still many challenges to maintenance, re-use, recycling and disposal of fusion neutron irradiated materials:

- **Absence of official standards and guidelines for nuclear fusion plants and fusion waste:** Regulatory frameworks are set up by each country in the case of fission. No fusion-specific guidelines yet exist. This creates uncertainty in the amounts of waste likely to be produced in each category given the current uncertainties in component materials and the likely requirements around disposal.

- **Detritiation methods and facilities:** Tritium migrates and diffuses through all standard materials (concrete and metals) that are the main constituents of a radioactive disposal facility. Therefore, tritiated waste poses a great challenge for waste transport and disposal. Methods of detritiation like heat treatment, melting and acid etching are being explored in the UK but require significant further investment.

- **Recycling:** Recycling and reusing fusion core components and materials can greatly improve the lifetime cost-efficiency of fusion power plants, particularly for rare and expensive materials such as Be or LiPb and/or for materials representing large quantities (bioshield, magnets, steel). At present, there exists a scarcity of available infrastructure or operators to make decontamination and recycling possible.

- **Disposal:** The waste disposal sites for LLW[1] have limited capacity. There are limited repositories that would accept ILW[2]. The availability of disposal facilities in the future is uncertain.

- **Impurity Control during manufacturing:** Through various studies, it has been demonstrated that impurities such as Co, K, Pt, Nb etc can lead to the generation of long-lived radionuclides. The UK has recently demonstrated capability in producing "fusion grade" steel with strict impurity control [see pages 50 and 51] but further significant investment is required to support scale-up and expansion of this technology to other materials.

[1] LLW – Low Level Waste. Waste with a radioactive content not exceeding 4 Giga Becquerels per tonne of alpha activity, or 12 Giga Becquerels per tonne of beta/gamma activity.
[2] ILW – Intermediate Level Waste. Waste exceeding the upper boundaries for low level waste that does not generate enough heat to be considered in the design of storage or disposal facilities.

4. Supply chain
Another key challenge identified during the roadmap workshops was the lack of supply chains for many candidate fusion materials. General supply chain challenges identified were:

- **Material Security and Scarcity:** Potential material shortages could impact future scalability. Current unstable global geopolitical situations emphasise the importance of focusing on developing a domestic supply chain for materials where possible, and where this is not possible, via politically stable international partners. Limited suppliers and high demand across industries (e.g., nuclear, defence, and space) increase the risk of supply chain bottlenecks, especially without committed funding and orders.

- **Supply Chain Strength and Capability:** Domestic heavy engineering and large-scale manufacturing facilities are essential. Without them, the supply chain could be dependent on complex overseas capabilities. The industry also requires a flexible funding model that encourages early private sector involvement, especially given that large scale material suppliers are focused on short term <5-year timescales with a commercial focus on return on investment within that time.

- **Funding and Investment Shortfall:** Roadmap contributors from UK industry noted that fusion projects are often underfunded, with small businesses having to provide 30% of project funding, which hampers testing, facility access, and the establishment of necessary infrastructure. Private companies often require confirmed orders or interim funding to participate.

- **Dynamic Material Requirements:** As fusion technology evolves, material specifications will likely change, necessitating adaptive supply chains. This dynamic nature demands a techno-economic analysis to assess material viability and prepare the supply chain for adjustments over time. This makes it hard for large materials companies to commit to supporting fusion, as even the base material may change to a material outside of their possible product portfolio e.g. if Eurofer or Oxide Dispersion Strengthened (ODS) reduced activation ferritic martensitic (RAFM) steels are replaced by V44, steel manufacturers do not have capability to produce vanadium alloys.

Research areas specific supply chain challenges identified were:

Magnets	Limited UK high temperature superconducting (HTS) tape manufacturer.
Shielding	No UK capabilities for upscaling or production of shielding ceramics.
Shielding	Borides may need isotopic enrichment to B-10. No UK capability for producing isotopically enriched B-10
Tritium breeding materials	No Li-6 enrichment facilities for solid breeders.
Tritium breeding materials	No industrial scale production capability for any tritium breeding material currently considered.
High temperature materials	Significant material volumes required, and tight chemical compositions.
Neutron multiplier	Limited Be resource and no supply chain identified.
Heat sink materials	No industry scale, fusion grade CuCrZr production.
Tungsten	Risk in tungsten availability. The UK has the second largest deposits of tungsten ore, but this might be low grade and unavailable.
Industry scale fusion grade steel	Whilst the UK has demonstrated capability in producing fusion grade steel using industrial processes, significant further investment is required for facilities to further upscale to produce the significant volumes of steel required.
SiC fibres	No UK supplier of SiC fibres and limited international suppliers.
SiC/SiC and ODS steels,	No proven component scale manufacturing route of SiC/SiC or ODS steel components.

A note on timelines

The following research area specific chapters comprise a technical summary, the research area specific challenges identified, suggested solutions (e.g., new facilities and capabilities required), with the impact of solving those challenges defined, and a timeline of when certain challenges need to be solved by / facilities need to be commissioned by. In this context, "short term" is defined as within the next 5 years, "intermediate term" is defined as towards STEP (e.g., by 2040), and "long term" is defined as towards commercial fusion, post-STEP.

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Magnets and Shielding

For magnetic confinement fusion, high strength (> 17 T) magnetic fields are required to confine the fusion plasma [1]. High Temperature Superconducting (HTS) magnets are considered an enabling technological priority for fusion. The USA company Commonwealth Fusion Systems (CFS) raised ~ $2B in philanthropy and investment and reported manufacturing magnets that achieved a HTS world-record field strength of 20 T [2]. In the UK, Tokamak Energy reported delivery of a complete set of HTS coils [3]. In both companies, these magnets will soon be assembled into tokamak magnet configurations (but with no neutron irradiation) for systems testing under asymmetric forces and quench conditions.

Despite these advances, many challenges must still be met to utilise HTS magnets in the extreme fusion environment of high neutron fluence and operational flux[1]. For example, manufacturing HTS fusion magnets has no synergies with fission, space, or defence industries and the Technology Readiness Levels (TRLs) are low, e.g., 2 to 4 [6]. Many free-market defaults are therfore ruled out and the entry cost is high to industrialise HTS materials in tape, cable, and magnet forms for fusion. Significantly, there is currently no UK HTS materials development facility for HTS magnets, nor is there a UK strategic supplier of HTS tapes. Furthermore, the impact of irradiation fluence on the lifetime of HTS materials as well as their properties under operational conditions of > 17 T magnetic field, 20 K temperature, +- 0.5% strain, high fluence and high (in-situ) fusion flux is not known. The critical current density of HTS magnets is known to first improve and then severely degrade at high neutron fluences above 10^{22}n/m^2 [4], however the measurement capability to test tapes under fusion conditions (simultaneously) does not currently exist. These extreme conditions are particularly acute for the UK compact spherical tokamak designs (i.e. for both STEP and Tokamak Energy's designs) where only small volumes are available for shielding HTS magnets in the central column, and must comprise advanced shielding and coolant materials, as well as facilitate remote maintenance of replaceable magnets. The figure below, from [5, 8] gives an example of a compact spherical tokamak design with the radial space available for neutron shielding being only 0.32 m.

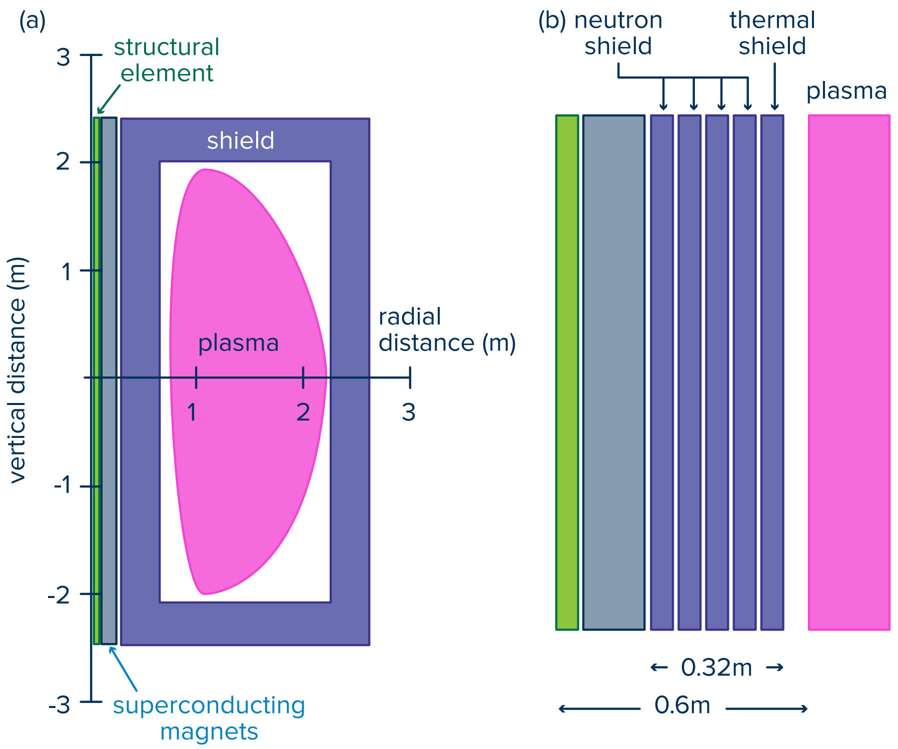


Figure shows (a) Pilot plant design with 1.35 m major radius, allowing 0.6 m for the central column region, modified from [8]. (b) Closeup of central column region, showing shield of 0.32 m thickness, comprising five concentric layers of shield material with water cooling channels in between [5].

This section describes technological challenges relating to HTS magnets and neutron shielding, and details the skills, facilities and expertise required to address these challenges, including high efficiency neutron shielding to protect the HTS magnets from the high-power density plasma flux and replaceable HTS magnets with life-limited magnet components that require remote maintenance and replacement.

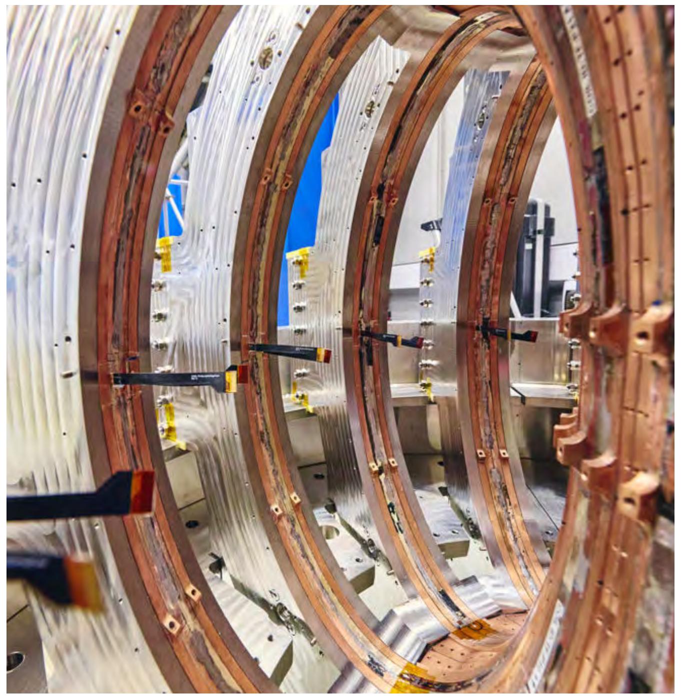
[1] Flux = fluence per unit time (i.e., fluence = flux x time). Here we distinguish the role of fluence that, over the lifetime of the HTS tape, has produced high levels of disorder in the lattice, from the (real-time) flux that may affect the superconducting properties through dynamic equilibrium with the mobile oxygen ions and the superelectrons.

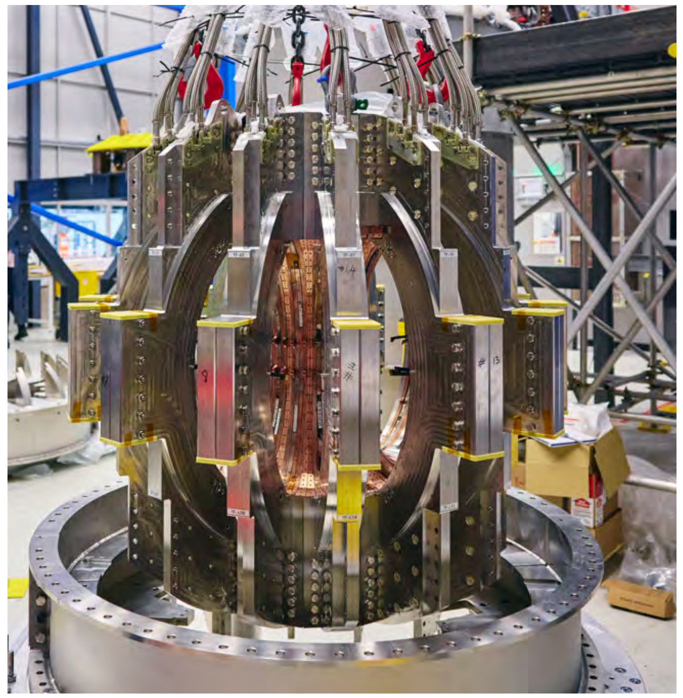
Magnets

High temperature superconducting (HTS) magnets comprising rare earth barium copper oxide (REBCO) are the current leading candidates for fusion magnets. However, due to their as yet unknown response to synergistic fusion conditions, it is envisaged that further development of HTS magnet materials may be required. For fusion, HTS magnets must have resistance to high mechanical forces and irradiation induced damage, as well as high current density. However, the UK currently does not have capability to test HTS tapes under simultaneous fusion conditions and testing of conductors at > 17 T is not routinely possible in any R&D lab. Therefore, development of existing and novel magnetic materials for fusion is challenging and availability of key data for fusion magnet design is limited. Improvements in the critical current density and mechanical properties of HTS tapes are currently driven by ultra-high-field (small magnet) and particle accelerator applications by non-UK industry which do not offer the improvements required for fusion. Determining performance under synergistic fusion operational conditions, as well as scalability and supply chain were identified during the roadmap workshops as major challenges that remain for fusion magnets.

HTS tape and cable components and current candidate materials

Component	Material
HTS tapes	REBCO
HTS-cable connecting material	Soft alloy (e.g. PbSn)
Conduit	Copper
Structural	Steel
Insulations	Epoxy-based (e.g. Kapton) or metal-insulator, radiation tolerant (e.g. V_2O_3)
Remountable cable joints	Solder
Cryogenics (+infrastructure)	Helium





Tokamak Energy's DEMO4 fusion magnet system, is a complete balanced set of high-field HTS magnets in a tokamak configuration. It comprises of 44 individual HTS coils assembled into 14 toroidal field limbs and two poloidal field coils. The system will operate in a vacuum at 20 Kelvin (-250 °C) and will have a magnetic field strength nearly a million times stronger than the Earth's magnetic field.

CHALLENGES

Scalability and Supply Chain

Supply and Demand	It is estimated that, for a STEP-like power plant design, 100,000 km of HTS tape will be required, 20,000 km estimated for CFS's SPARC and 10,000 km estimated for Tokamak Energy's ST1 machine. Global HTS tape production capacity is currently c.a. 10,000 km per year (x10 increase since 2020). The tape manufacturing market is heavily Japan-, US- and China-centric with only one EU tape manufacturer and one UK HTS fusion magnet manufacturer (Tokamak Energy).
IP and Commercialisation	Very high entry costs and the small pre-commercialisation UK HTS industry means developing IP and commercialisation of HTS materials and know-how for tapes, and fusion HTS cables for fusion magnets, is challenging.
Supplier Quality and Assurance	Quality and Assurance practices among current, and future, HTS tape suppliers must be standardised.

Materials selection, baseline and performance testing, and qualification

Performance scaling laws	The behaviour of the critical current of HTS materials under standard operational conditions must be measured and the (performance) scaling laws for critical current versus magnetic field, temperature, strain, fluence and flux must be devised. The performance scaling laws are required to optimise choice of HTS materials and magnet design.
Quality Assurance Strategy for small-scale testing	A qualification assurance (QA) strategy for HTS materials, equivalent to the 7 QA measurements for the ITER tokamak [9], is required. In addition, the community will need to know how much small-scale testing is required to guarantee long (> 1 km) length performance. Measurements under full operating conditions of magnetic field, temperature, strain, fluence and flux will be required.
Codes and Standards	Codes and standards for testing and qualification of tapes are required to ensure common per length performance across manufacturers and developers.
Material Grades and Manufacturing Specifications	Material grades and manufacturing specifications for HTS tapes must be determined in line with UK regulatory requirements.
Insulating Materials	Preferred insulating materials for fusion magnets, and QA strategy for these insulators, must be determined.
HTS materials during plasma disruption	The response of HTS materials in the extremely demanding asymmetric electromagnetic environment, generated during a plasma disruption (high impact event), must be determined. Currently, neither measurements nor computational models are available.

Irradiated materials testing

Testing HTS tapes under fusion conditions	There is currently no capability to test HTS tapes under fusion conditions nor for active HTS materials handling, transport, and storage at cryogenic temperatures anywhere in the world. No superconductor has been irradiated under operational conditions, thus, yielding significant gaps in design and lifetime confidence. Superconductors must be irradiated under a fusion flux spectrum (using proxy irradiations) whilst carrying current, at cryogenic temperatures, in high magnetic fields, under strain.
Effect of irradiation on multi-layered HTS tapes	The effect of irradiation on the composite properties of multi-layered HTS tapes must be determined in order to optimise the properties of remountable joints (e.g. delamination of the layers, current transfer into the HTS layer).

Sustainability

Recycling and Disposal	Recycling and disposal routes for tapes and tape materials must be determined. The UK will need to design tapes with cradle-to-grave in mind, for example, given current substrates are Ni-based which will become highly activated.

Joint and HTS high current cable technology

Joints under irradiation	The mechanical reliability and performance under irradiation (e.g. embrittlement) of in-cable joints and remountable cable joints (using soft solders) is broadly unexplored
Fusion cable design	The optimisation of fusion cable design is limited to a few (non-UK) specialist manufacturers (in USA and China).

Insulators

Radiation resistant insulators	The commonly used insulators in non-fusion magnets are plastic-based (epoxy, etc.) and not very radiation tolerant. The optimum smart-insulator materials choices for fusion are not known. The properties of smart-insulators (e.g. V_2O_3 ceramics) under the operational conditions of high-fields and irradiation are not known.

Modelling

Models to describe radiation effects under fusion conditions	The current carrying capacity of HTS tapes must be optimised. However, there are currently no detailed computer models to describe flux pinning in commercial materials with irradiation defects, nor any models that describe the effect of the very broad fusion flux of photons and neutrons on the critical current of HTS superconducting materials.

Quench

Detection and Protection during quench	Detection and protection methods for HTS materials during quench in magnets must be determined.

People

HTS magnet engineers	There are very few HTS magnet engineers.
Continued Professional Development	There are few UK HTS prototype projects that offer continued professional development (CPD), resulting in a significant skills shortage of trained HTS materials engineers. UK engineers in fusion are concerned about procuring a HTS machine with no expertise in HTS materials. The UK needs to establish a more substantial supply-chain of middle- and senior- industrial fusion engineers with CPD opportunities in HTS materials.

The table below identifies infrastructure and capabilities required to solve some of the challenges described

SOLUTIONS	CHALLENGES	IMPACTS
Develop new UK facility(s) to irradiate and test HTS tapes under cryogenic temperatures, in high magnetic fields under strain.	Irradiated materials testing People	• Provide first-of-a-kind data on activated HTS tapes for fusion magnets. • Provide first-of-a-kind data from superconductor materials irradiated with neutrons, or proxy ions, whilst carrying current, at cryogenic temperature, in high magnetic fields, under strain, addressing the significant gaps in design and lifetime confidence. • Provide shield material and shield design dependant lifetime performance understanding, with well-defined uncertainties. • Facilitate the development of a first-of-a-kind irradiation programme for HTS tapes. • Develop Quality Assurance protocols for km long HTS tapes. • Train PhD physicists, engineers, and computer science students with expertise in activated HTS materials at cryogenic temperatures in high magnetic fields under strain.
Key Challenge: Irradiation facilities **Develop capabilities at existing national and international irradiation facilities.**	Irradiated materials testing Joint and HTS high current cable technology Insulators	• Facilitate measurement of critical current under flux in magnetic fields, providing data until a full, synergistic test facility is built. • Determine radiation induced degradation. • Develop radiation resistant insulators.
Utilise UK HPC computational capability to model fusion magnets under extreme conditions. Supporting the creation of AI data centre at UKAEA.	Modelling	• Develop models to understand flux pinning under neutron irradiation in HTS tapes and identify HTS optimisation strategies and limits. • Develop models of superconducting materials under operational plasma disruption conditions to develop mitigation strategies. • Develop models to optimise HTS tape architecture to identify optimisation, and quench and plasma disruption mitigation strategies. • Develop models of fusion magnets and joints under operational and quench conditions, to identify optimisation. • Develop systems engineering, magnet engineering, and materials engineering modelling capabilities utilising UK National HPC facilities and the new AI data centre at UKAEA.

SOLUTIONS	CHALLENGES	IMPACTS
Support UK HTS tape and cable early-supply-chain industrial partner.	Scalability and Supply Chain People	• Ensure standard strategic supplier requirements for high entry cost materials are met. • Provide HTS tapes to build a prototype HTS fusion magnet in the UK. • Provide a UK strategic supplier for HTS materials and contribute to a UK HTS national strategy for HTS fusion materials. • Develop a supply-chain of engineers trained in HTS fusion materials. • Support a small strategic supplier of HTS fusion tape for the UK.
Develop capabilities to fabricate and test existing and innovative HTS fusion materials.	Materials selection, baseline and performance testing, and qualification Sustainability Insulators	• Enable baseline and performance testing under a range of conditions. • Facilitate significant improvements in material performance, such as ductility and current transfer, to de-risk the tokamak. • Engineer reduced activation tapes. • Develop radiation resistant insulators. • Thin film fabrication facility for innovative high strength, high ductility, HTS fusion tapes. • Testing capability of innovative materials after radiation.
Develop UK HTS cable testing facility.	Joint and HTS high current cable technology	• Provide a strategic resource to measure and optimise cable designs. • Facility to optimise fusion cables for low inductance fusion magnets, with high-field and high current capability.
Funding for apprenticeships, UG-, MSc-, and MEng-level training, PhD studentships and CPD of existing scientists and engineers.	People	• Develop a growing base of technicians and engineers with expertise in vacuum, cryogenics, superconductivity, materials, mechanical engineering, and manufacturing.

During the workshops the following key facility was identified as missing and requiring significant investment in order for critical challenges to be met.

Facilities, infrastructure, and industry	Capabilities
UK Facility to test irradiated HTS tapes at cryogenic temperatures in high magnetic fields under strain and real-time irradiation.	• Measure HTS tapes under fusion relevant conditions: Temperature 10 K – 100 K, > 20 T, strains > +- 0.5 %, neutron (or proxy) fluences > 10^{22} n/m^2. • Handle and measure the critical current of activated HTS tapes to assess magnet performance and fluence lifetime. • Measure HTS tapes under strains, relevant for magnet engineers. • Active HTS materials handling, transport, and storage at cryogenic temperatures. • High-field, real-time irradiation capability to measure the critical current of HTS tapes at cryogenic temperatures under low (in-situ) predicted operational flux. • Develop a quantitative predictive model for critical current performance under irradiation flux, magnetic field and strain.

TIMELINE

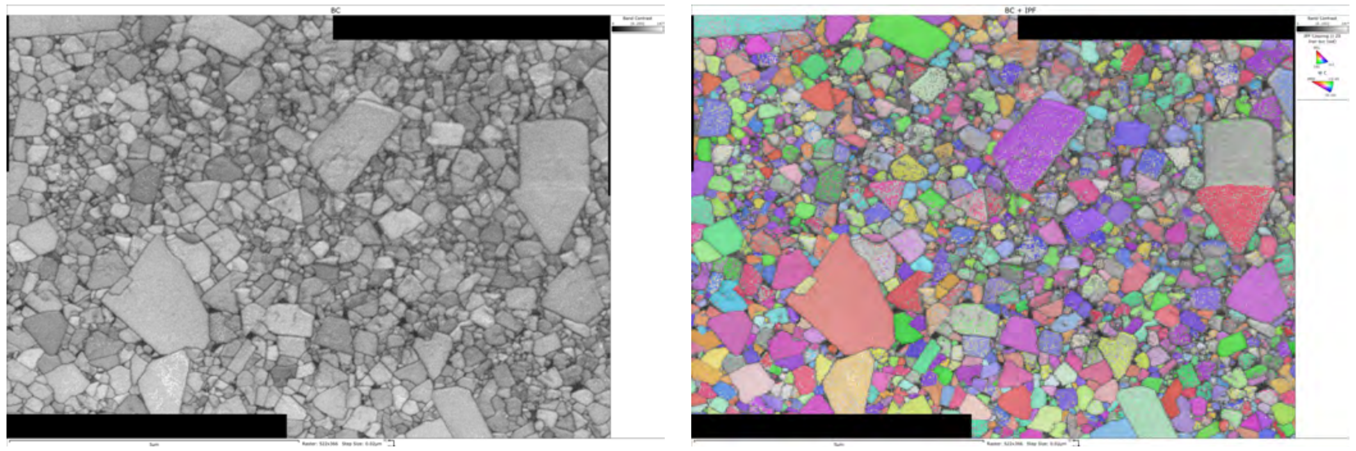
SHORT TERM	INTERMEDIATE TERM	LONG TERM
Establish new UK facility to handle and test irradiated HTS tape at relevant temperatures in high magnetic fields (20 T) under strain (+/- 0.5%). Determine the critical current (I_c) performance of HTS tape under operating conditions (including irradiation). Understand effects of plasma disruption on superconducting magnets. HTS tape manufacture scale up. Develop models for irradiation damage of HTS and validate with experiments. Increase the supply of trained engineers and scientists with interdisciplinary expertise in HTS, magnet design, irradiation, cryogenics, robotics, vacuum technology.	Establish UK supplier of HTS tapes. Develop Quality Assurance strategy for HTS tapes. Understand broader effects of irradiation on magnet components (e.g. joints, mechanical degradation, insulators). Develop quench detection and protection methods for HTS magnets. Establish an R&D thin film deposition facility for materials development of HTS tapes. Establish a UK cable testing facility.	Standardise QA practices of HTS tape manufacturers. Develop recycling routes and materials selection for sustainability. Establish reliable supply chains for fusion cables and magnets. Establish a UK facility to test irradiated HTS tapes and cables at cryogenic temperatures in high magnetic fields under strain and real-time irradiation.

Shielding

Cemented and binderless tungsten borides (WB) and carbides (WC) are the current shielding materials of choice, with zirconium (ZrH_2) and hafnium hydrides (HfH_2) also being explored as strong neutron and gamma attenuators, alongside more traditional materials of tungsten (W) and boron carbide (B_4C). Despite their predicted effectiveness as neutron shielding, WB and WC are still at a relatively low TRL and require further development and assurance for use in commercial fusion. Key areas for further investigation include: determination of baseline material properties (for low activation variants); improved understanding of material responses to irradiation damage; measurement of post-irradiation properties, and the development of design rules for brittle materials. Although existing UK ion implantation facilities can and are being used to investigate some of these effects, neutron irradiations are required to assess material stability and for collection of engineering datasets required in the prediction of lifetime performance. A lack of data on the irradiation performance of WC and WB was viewed as one of the most important issues by the community. A supply chain capable of producing "fusion-grade" tungsten boride and carbide shielding blocks also requires development: the production of raw powders for some variants are currently not at an industrial-scale capable of meeting the requirements of the sector.

Current candidate materials for neutron and gamma shielding for fusion

Material
Tungsten borides
Tungsten carbide
Metallic tungsten and its alloys
Metal hydrides
Boron carbide
Concrete, geopolymers, etc.



Transmission Kikuchi Diffraction (TKD) of cemented-WC, a candidate shielding material supplied by Hyperion (image provide by Dr. Max Emmanuel, UKAEA).

CHALLENGES

Lifetime performance validation	
Neutronics model validation	Experimental neutron attenuation assessments using fusion spectrum are required to validate neutronics models.
Predictive performance models	Predictive performance models of irradiated material are required. These models need experimental data as inputs and for verification / validation, capturing irradiation-induced changes in strength, fracture toughness, thermal conductivity, alongside physical effects such as differential irradiation-induced swelling, crack nucleation, and void formation. New modelling techniques are required to address the transmutation-induced microstructural changes in materials under neutron irradiation.

Design rules of brittle materials	
Failure mode assessment	Failure mode assessment is required using standardised and miniaturised thermomechanical testing and characterisation
Weibull moduli considerations	A high number of repeats and / or knowledge of largest flaw size in a given component is required to establish statistical significance.
Size effect thresholds	Due to brittle materials' propensity for fast fracture from a single stress centre, larger test pieces are more likely to contain critical defects and thus strength is often inversely proportional to test piece size - the 'size effect'. Therefore, characterisation of mechanical properties, including Weibull distributions, in brittle shielding materials can only reliably be achieved by understanding the size effect using a distribution of test piece sizes. This understanding is also required for benchmarking small-scale testing techniques and micromechanical methods, which must be relied upon for characterising irradiated material properties due to the limited sample sizes available.
Nuclear codes	Current nuclear codes (e.g. RCC-MRx) do not include brittle materials. Therefore, there is a need to develop bespoke rules based on design requirements for fusion.

Material development	
Optimisation of material properties and manufacturing processes	Candidate materials are currently at low TRL, and further development is required for their optimisation. For example, high efficiency shielding materials such as WB and metal hydrides require development of processes relating to powder manufacturing, shaping and sintering; and physical property optimisation.
Standardise grades and specifications	Material grade and manufacturing specifications need to be standardised across all manufacturing, testing and scientific research activities.
Isotope enrichment	Borides may need isotopic enrichment of boron to >96% B-10.
Impurity controls	Strict impurity controls on high activation elements are required.
Binder development	Development of efficient, low-activation, binders (e.g., FeCr and geopolymers) that can both lower porosity and prevent unwanted ternary phases in carbides and borides is required.
Microstructural engineering	Microstructural engineering may improve irradiation stability and inhibit cracking due to anisotropic swelling of hexagonal material systems.

Baseline testing	
Material properties	Low TRL materials (WB, metal hydrides) need extensive thermophysical, mechanical (including creep for metal hydrides) and microstructural characterisation. For example, high fracture toughness, thermal conductivity and compressive strength are fundamental properties for semi-structural shielding components.
Compatibility	Compatibility assessments with coolant candidates, joint interface materials and accident-driven atmospheres are required.

Irradiated materials data	
Neutron irradiations	There are good irradiation datasets on W and B_4C, however very little relevant neutron irradiation data exists for high-efficiency shielding materials, such as WB, WC, and metal hydrides. Doses up to 10 dpa are required for these materials at temperatures between RT and 800 °C.
Simulating in-service conditions	Irradiations (neutrons or ions) that produce radiation damage, transmutation rates and thermal gradients that simulate components in-service are required.
Helium production	Effect of significant gas production via thermal neutron-induced transmutation in borides needs exploration, up to 50,000 appm He at relevant operational temperature and dpa.
Transmutation	Effect of W and other heavy element transmutation on precipitate formation and material/component properties are currently unknown in WC, WB and metal hydrides.
Swelling and amorphisation	Swelling rates are currently unknown in WC, WB, and metal hydrides and there is limited understanding of irradiation temperature and dose windows for lattice amorphisation and void formation in WC, WB, and metal hydrides.
Small-scale test methodologies	Development and validation of techniques for radiation damage characterisation on small-scale ceramic samples is required to support studies on damage and transmutation effects using ion irradiations. For example, micromechanical and microthermal methods, High Resolution Digital Image Correlation (HRDIC), Transient Grating Spectroscopy (TGS), Time-Domain ThermoReflectance (TDTR), and Raman spectroscopy.

Sustainability	
Low activation binders	Use of low activation binder elements such as Fe and Cr required in place of conventional Co or Ni-based solutions (for cemented WC and WB), potentially at the expense of physical properties.
Recycling and Disposal	Separation and recycling of active materials needs investigation. For example, investigations into radioactive "dust" generation and material oxidation following removal from the power plant.
Recovery of valuable transmutant products	Recovery of W transmutant products such as Re, which have the potential for economic benefit, is required.

CHALLENGES

Joining and Integration	
Complex geometries	The shielding components for fusion are not anticipated to be monolithic. Plates/bricks with integrated cooling channels supported by external structures are anticipated. Stresses from thermal and radiation dose gradients are therefore likely to be high around defects, channels, and joints. This is a concern for particularly brittle shielding materials.
Graded structures and layered designs	Graded and/or layered designs should be considered and incur different requirements. I.e. integrating two shielding materials: one to perform at higher temperatures and to moderate neutrons, the other to perform at lower temperature and to attenuate/absorb neutrons.

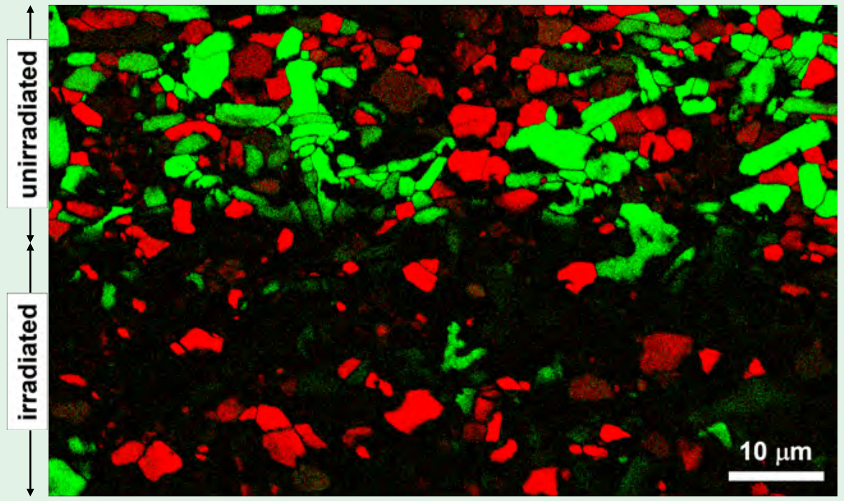
People	
Skills shortage	We need to train more scientists and engineers with expertise in processing, radiation damage, and mechanical performance of ceramics. This issue extends to the fission sector where there is also major shortfall in these skills and expertise.

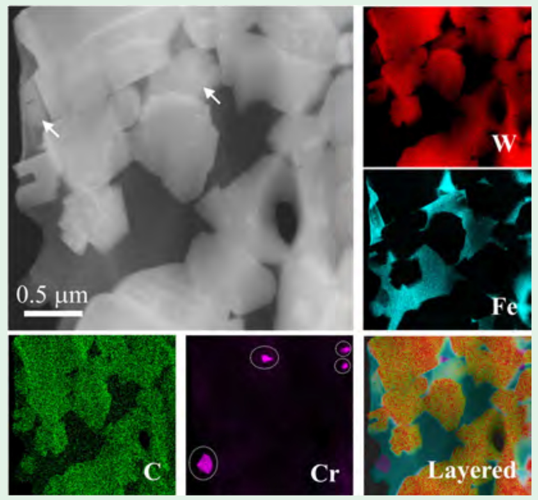
The table below identifies infrastructure and capabilities required to solve some of the challenges described.

SOLUTIONS	CHALLENGES	IMPACTS
Key Challenge: Irradiation facilities **Develop capabilities at existing national and international eradiation facilities.**	Irradiated materials data	• Develop and validate testing techniques on small-scale ceramic samples. • Use these new techniques to determine in service, synergistic effects in shielding materials.
Development of a small-scale materials test reactor for neutron irradiation of high B-10 content materials.	Lifetime performance validation Irradiated materials data	• Provide neutron attenuation data. • Provide information on the effect of transmutation and radiation damage on shielding material in-service properties and performance. • Facilitate meso-scale mechanical testing of irradiated materials, irradiation testing of joints and functionally graded structures. • Determine shielding efficiency of candidate shielding materials.
Form a UK Shielding Materials Network and provide investment at undergraduate, masters, and PhD level education.	People	• Ensure development of relevant skills and expertise.

During the workshops the following key facility and community network were identified as missing and requiring significant investment in order for critical challenges to be met.

Facilities, infrastructure, and industry	Capabilities
Small-scale materials test reactor for neutron irradiation of high B-10 content materials	• Small-scale (<50 MW) materials test reactor for neutron irradiation of high B-10 materials to >10 dpa. • Due to the flux poisoning nature of WB when enriched, access to existing neutron irradiation facilities is limited. Therefore, a neutron test facility that can accept boron containing materials is required, preferably with the ability to load materials to study synergistic irradiation effects.
UK Shielding materials network	• A programme level activity is needed to develop and validate new shielding materials (synthesis, thermomechanical testing, fracture, irradiated testing, neutronic modelling, material damage modelling, radiation transmission testing, large scale synthesis, link to end users). • Regular workshops to disseminate progress, generate momentum around important topics, and encourage collaboration. • Linking industry, academia, national labs with policy makers, funders and regulators.





Electron Backscattered Diffraction (EBSD) phase map of a WB_2-WB composite (green and red phases, respectively) showing loss of crystallinity in the WB_2 phase within the irradiated region.

The loss of crystallinity is related to a lower rate of recovery of radiation induced point defects. This may be associated with higher rates of swelling in the WB_2 phase. The irradiations were carried out to approximately 10 dpa at 300 °C using ~2 MeV helium ions (which is the approximate energy of a transmuted helium atom formed after a neutron is captured by boron).

T. Zagyva and S. Humphry-Baker (in collaboration with Tokamak Energy), personal communication, 2025.

High-angle annular dark-field (HAADF) image of a WC-FeCr composite showing WC(light) and FeCr (dark). Smaller images - EDS dot maps showing W(red), Fe (blue), Cr (purple), C (green) and their sum (Layered). Cr-carbides are indicated by dotted circles and M_6C by arrows. The presence of the FeCr binder improves the fracture toughness and lowers the processing temperature, which may enable increased complexity in part geometry.

S. Humphry-Baker et. al, Scripta Materialia 155 (2018) 129-133.

TIMELINE

SHORT TERM	INTERMEDIATE TERM	LONG TERM
Develop low TRL material and manufacturing and low activation metallic binders.	Develop brittle material failure mode models, and regulation and qualification strategies.	Develop W, B, B-10 raw material and powder supply chain.
Determine brittle shielding material thermomechanical, thermophysical and microstructural properties and undertake coolant compatibility assessments.	Determine material grades and manufacturing specifications.	Determine strategies and methodologies for impurity control and radioisotope waste reduction.
Undertake ion and proton irradiation studies to simulate transmutation and in-service synergistic effects and develop and validate techniques for radiation damage characterisation in small-scale ceramic samples.	Develop supply chain and production upscaling in the formation of a demonstrator assembly.	Determine neutron (fission MTR) radiation damage and transmutation effects at relevant temperatures (>20 dpa).
Determine neutron (fission MTR) radiation damage and transmutation effects at relevant temperatures (RT-800 °C; <10 dpa).	Develop methods for fabricating complex ceramic geometries, e.g. integrated pipe channels or tessellation edges for monoblocks.	Determine strategies and methodologies for recycling high-value materials and elements, e.g. Re and W, waste assessments, storage and decommissioning of radioactive component materials.
Determine accident tolerance and in-service, environmental (e.g., oxidation) effects.	Develop methods for joining to similar (shielding ceramics) and dissimilar materials, e.g. CuCrZr, steels.	Create scaled manufacturing of shielding ceramics in the UK.
Increase the supply of trained engineers and scientists with expertise in processing, radiation damage, and mechanical performance of ceramics	Produce functional grading and anisotropic materials, e.g. composite comprising two shielding materials.	
	Use STEP (or similar such as ChipIR or LIBRTI) for neutron attenuation performance validation experiments (commercial fusion).	

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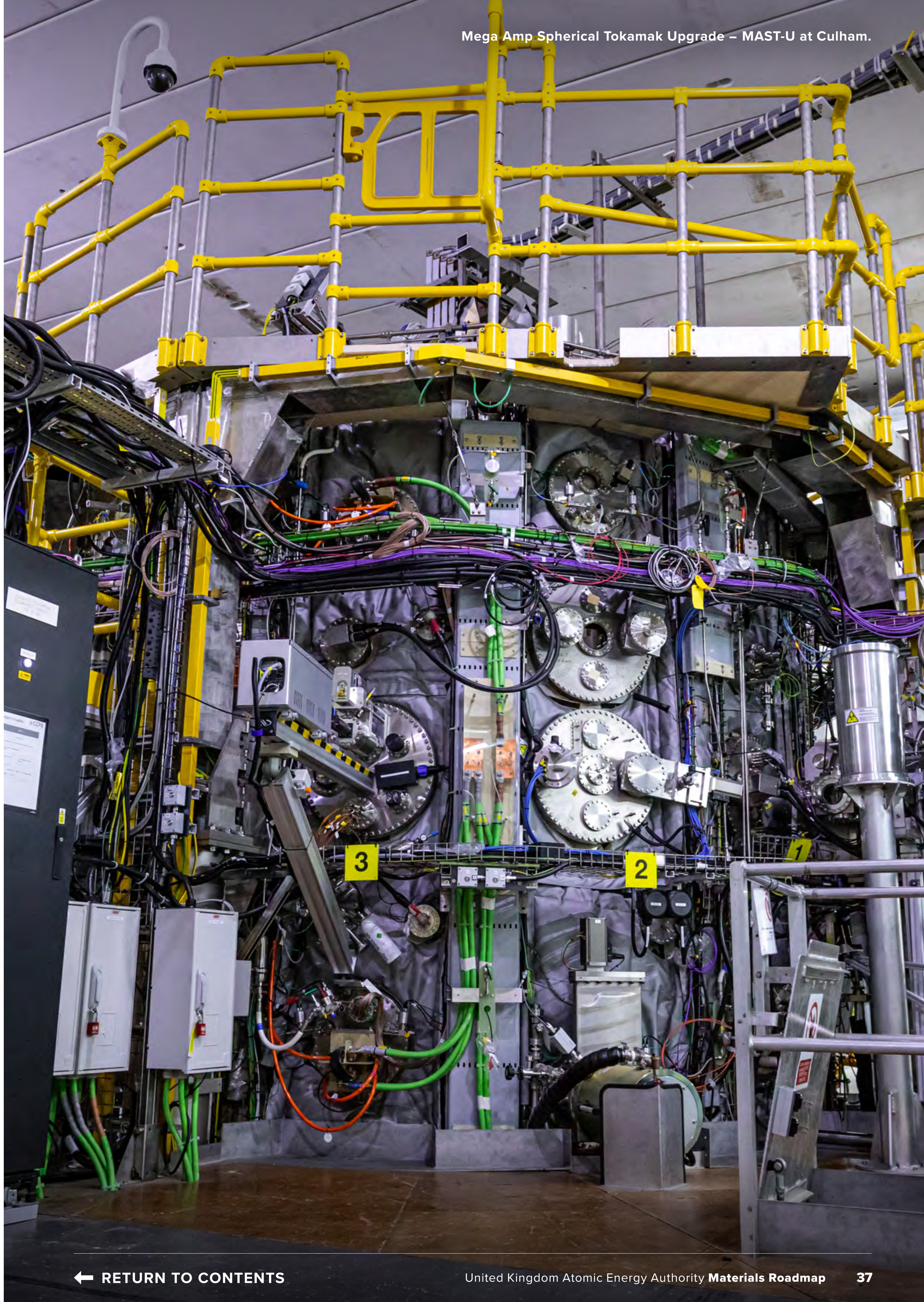
Mega Amp Spherical Tokamak Upgrade – MAST-U at Culham.

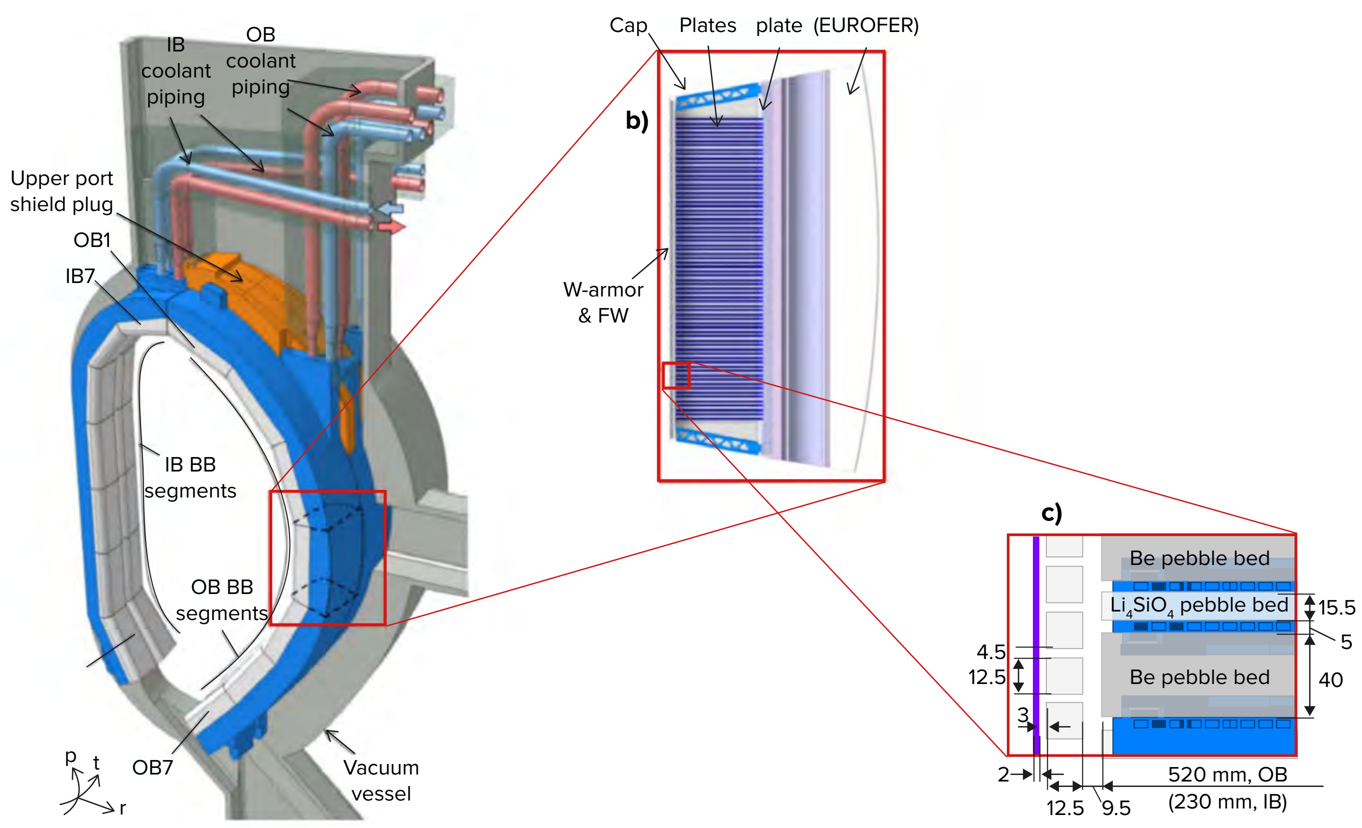


Tritium Breeding: production; tritium permeation barriers; and corrosion resistant coatings

A critical component of any self-sustaining fusion power station is the tritium breeder blanket. For commercial fusion, tritium will be produced (bred) in a region surrounding the fusion plasma, called the breeder blanket. Tritium breeding materials comprising lithium are proposed, as the absorption of a fusion neutron by lithium results in its transmutation to tritium and helium. In addition to breeding tritium, the high heat deposited by the fusion neutrons will be extracted from the breeder blanket and used to generate energy.

There is currently no global consensus on the choice of tritium breeding material, tritium carrier gas, nor coolant, and both liquid and solid concepts are under development. Until recently, ITER's Test Blanket Module (TBM) Program had aimed to test four blanket module concepts: water-cooled lithium-lead (Europe); water-cooled ceramics breeder (Japan); helium-cooled ceramics breeder (China); and helium-cooled ceramic pebbles (Europe/Korea) [1] IFMIF-DONES (anticipated to be operational by 2034) will enable irradiation of candidate ceramic breeder materials, and materials in liquid lead-lithium, by fusion relevant neutrons, via their In-Situ Ceramic Breeder Irradiation module and In-Situ Liquid Breeder Validation Module, respectively. The BABY experiment, precursor to the Liquid Immersion Blanket: Robust Accountancy (LIBRA) experiment (MIT, USA), has made the first tritium breeding ratio measurements in molten salts [2]. By 2028, the UK's Lithium Breeding Tritium Innovation (LIBRTI) programme aims to experimentally demonstrate quantified tritium breeding in engineering scale breeder prototypes for a given neutron flux in a specified lithium substrate, with solid, liquid lithium, and molten salt breeder modules being developed for testing. Whilst liquid breeders provide the highest tritium breeding ratio (TBR[1]) (TBR > 1.1 is required for power plant self-sufficiency), concerns over safety and complexity in tritium extraction systems for liquid breeders makes ceramic alternatives attractive.

[1] Tritium breeding ratio (TBR) is defined as the ratio of the rate of tritium breed in the blanket to the rate of tritium burned in plasma.



This figure is an example of a solid breeder concept. This is a schematic overview of an EU blanket design utilising a lithium ceramic (Li_4SiO_4) and beryllium pebble neutron multiplier with helium cooling, from [3].

Component	Liquid breeder concepts	Solid breeder concepts
Breeder	Lithium, lead-lithium, molten salts (e.g., FLiBe, and other molten salts not containing F).	Li_2TiO_3, Li_4SiO_4, KALOS (composite comprising Li_2TiO_3-Li_4SiO_4), octalithium ceramics.
Structural material	Vanadium-alloys (e.g., V-4Cr-4Ti), SiCf/SiC.	Reduced activation ferritic / martensitic steels such as Eurofer97 and F82H, oxide dispersion strengthened (ODS) steel.
Coolant	He, H_2O,	He, H_2O, supercritical CO_2
Purge gas	He	He/H_2O
Tritium permeation and / or corrosion barrier	AlN, Er_2O_3, Y_2O_3, Fe-Al, Al_2O_3*, ZrO_2,	Al_2O_3, SiC, Er_2O_3

*not compatible with liquid Li

To achieve a sufficient TBR, it is anticipated that for both liquid and solid concepts a neutron multiplier is required, where absorption of one neutron will result in the production of two new neutrons which can be used to increase tritium breeding. Typically Pb and Be have been proposed for this, but owing to toxicity and availability, other elements are being explored. Tritium is highly permeable in many materials, and so barriers (coatings) are required to ensure breeder blanket components do not retain tritium and there is no danger to the workforce or general public from tritium emissions. Tritium retention is problematic for remote handling and waste management, and for retrieving sufficient tritium for breeding. Breeder blanket concepts comprise multiple components including structural, shielding, coating materials, and coolants. This section deals with materials to produce tritium (breeders), tritium permeation barriers, and corrosion resistant coatings. Tritium extraction, corrosion and irradiation induced damage remain key challenges when selecting breeder blanket materials.

Matrix describing known compatibility between candidate breeding materials, blanket structural materials and expected operating conditions

		Breeder material			
		Liquid lithium	**Pb-Li alloy**	**Molten salt e.g. FLiBe**	**Ceramic pebble**
	Blanket coolant	• Self-cooled • Helium	• Self-cooled • Helium • Water	• Self-cooled • Helium	• Helium • Water • sCO_2
	Temperature range (T_m – structural limit)	$180_{(Tm)}$ - 650°C	$235_{(Tm)}$ - 1000°C	$460_{(Tm)}$ – 1000°C	RT - 1000°C
Blanket structural material	**Vanadium**	√ 450-650°C With permeation coating	x *not specifically required*	x *High tritium retention and low solubility in salt*	x *not specifically required*
Blanket structural material	**RAFM**	x corrosion	√ 50-550°C With permeation coating and insulating flow channel insert.	√ 460-550°C (creep limited) With permeation coating and insulating flow channel insert.	√ 350-550°C (creep limited) With permeation coating
Blanket structural material	**ODS**	x corrosion	√ 400-650°C With permeation coating and insulating flow channel insert.	√ 460-650°C (creep limited) With permeation coating and insulating flow channel insert.	√ 400-650°C With permeation coating
Blanket structural material	**SiC/SiC**	x corrosion	√ 600 - 1000°C Not with water cooling.	√ 600 - 1000°C	√ 600 - 1000°C Not with water cooling.
	Other issues	• Reactivity with water, air	• Dense, high pumping power. • Galvanic corrosion if dissimilar materials are used.	• Beryllium toxicity. Corrosion accelerated by impurities. Galvanic corrosion if dissimilar materials are used. • Low Tritium solubility – higher requirement on permeation barrier.	• Tritium extraction. • Contact corrosion with structural material.

For liquid breeder concepts, magnetohydrodynamic (MHD) effects are a concern. For conductive fluids moving through strong magnetic fields, the electromotive force generates eddy currents that have a force opposing the motion of the fluid. This resistance, known as MHD drag, increases the power required for pumping the fluid[2]. When there are strong drag forces, pumping requirements can be a significant parasitic load for the power plant. MHD turbulence is an expected issue for all currently proposed liquid blanket concepts. MHD effects are expected to impact corrosion, tritium transport and mixing. Whilst there are many synergies with molten metal fission-based reactors, there are little to no data describing the synergistic effects of the complete breeder blanket environment.

The candidate breeder material palette and associated environmental conditions in the breeder blanket are currently too extensive for full investigation. **Therefore, in the absence of a concept design, the fusion materials community has an opportunity to define current best designs, which can be modified and improved following testing under fusion relevant synergistic conditions.** In addition to the interaction with the breeders, the breeder blanket sections will also rely on coolant(s) for heat extraction, such as light or heavy water (H_2O or D_2O), supercritical CO_2 and He. Interaction with the proposed coolants and the coolant facing materials can lead to general or localised forms of corrosion and environmentally assisted cracking that can affect both the lifetime of the coolant facing materials and the cooling performance.

[2] In the presence of strong magnetic fields, quasi-2D turbulence develops (with anisotropic properties) and features an energy cascade, where energy is transported from smaller to larger eddies. Frequently, a liquid breeder is also considered as a medium for heat transport. MHD drag forces can also lead to thermal and pressure losses due to inefficiencies. Flow predictions, including MHD pressure drop, are challenging due to the massive size of the blankets and the very thin boundary layers formed under strong magnetic fields. Typically, the overall MHD pressure drop is significant.

CHALLENGES

Liquid breeders: current candidates include Li, PbLi, and molten salts e.g., FLiBe.

Tritium production and extraction	
Hydrogen isotope diffusion and solubility	Some excellent global studies notwithstanding, there is generally a lack of fundamental data to inform models on tritium trapping and transport. To address this, experimental data on H isotope diffusion and solubility under different conditions and with different impurities is required.
Tritium inventory	The impact of tritium extraction efficiency on wider fuel cycle systems is required to maintain suitable tritium inventory.
Tritium trapping in oxides	Formation of oxide layers in the PbLi system may result in tritium trapping. Therefore, an assessment of tritium extraction from these oxides is required.

Corrosion	
Breeder purity control	Impurities in the liquid breeder can lead to non-metallic impurity assisted attack on structural materials. It must be determined, therefore, whether corrosion can be controlled through maintaining Li and PbLi purity, establishing acceptable levels of C, N and O impurities and their effects on corrosion. Specifically for molten salt breeders, promotion of Cr-rich carbides at grain boundaries and leaching of C needs investigation. Galvanic corrosion in molten salts, which promotes preferential leaching of metallic elements and deposition of C, may be controlled by careful materials selection.
Metallic impurities	The dissolution of structural materials by the liquid breeder can lead to metallic impurities. Therefore, the solubilities of metallic impurities in the liquid breeder as a function of environmental conditions, and their impact on the operation of the breeder blanket, must be determined.
Mass transport corrosion	Flowing Li and PbLi tests should be used to determine allowable material loss rates, deposition rates, and flow patterns, to determine mass transport corrosion mechanisms and to identify potential for pipe blockages and transport of radioactive materials.
Environmentally assisted corrosion	A mechanistic understanding of environmentally assisted corrosion, e.g., liquid metal embrittlement, and the effect of flow rate on the corrosion of structural materials is required. Development of corrosion resistant barriers could mitigate environmentally assisted corrosion.
Tritium fluoride formation	For molten salts, there is a concern around the formation of tritium fluoride (TF), during salt re-purification, corrosion, and tritium extraction. Moisture control (for example, in the purge gas) is expected to mitigate this but needs investigation.

Magnetohydrodynamics (MHD)	
MHD effects on tritium transport	Uniform mixing of tritium in a liquid metal is important for successful lithium/tritium separation. Strong magnetic fields suppress mixing.
MHD effects on flow and corrosion	Accurate modelling from first principles of the near-wall flows is important for predictions of tritium permeation, retention combined with oxidation and corrosion.
Unsteady effects	Electrical currents, which result in flows, are induced during ramp-up, ramp-down, and other moments of unsteadiness (e.g., plasma disruptions).
Plasma stability	Currents induced in a blanket could jeopardise plasma control measures used for plasma stabilisation and movement.

Solid breeders: current candidates include Li_2TiO_3, Li_4SiO_4, octalithium ceramics and composite variants.

Tritium production and extraction	
Improve tritium-breeding-ratio (TBR)	Current candidate solid breeders have a lower tritium breeding ratio (TBR) compared to liquid breeders. However, development of ceramic breeders to include neutron multipliers (e.g., Pb or Be) may increase the TBR to acceptable levels.
Engineer ceramics for optimum tritium extraction	Tritium extraction efficiency (i.e., tritium permeation and retention) is expected to be strongly dependent on solid breeder microstructure, including grain size and porosity, as well as irradiation induced defects that may act as tritium trapping sites (e.g., Frenkel pairs and helium). Ceramic composition and microstructure may be tuned for optimum tritium extraction, breeding (by inclusion of a neutron multiplier) and radiation damage resistance, but this requires significant investigation.

Corrosion	
Unknown corrosion mechanisms	Solid breeders can induce contact corrosion with the surrounding structural material, interact with purge gasses resulting in lithium hydroxide (LiOH) formation and attack, and can interact with the neutron multiplier (e.g., Be). The mechanisms governing these corrosion processes, their effect on materials, and pathways to mitigation are largely unknown and require significant investigation.

Breeder stability	
Irradiation-, and corrosion-induced degradation	Significant work is required to determine the changes in performance of the breeder in service. Irradiation induced damage, including lithium burn-up, and corrosion will have a deleterious effect on the properties and performance of the solid breeder. Whilst an "optimum" breeder may be produced by careful manufacturing processes, the ceramic will experience compositional and density changes, and phase transformations, leading to, for example, a reduction in structural integrity (crush load) resulting in ceramic dust formation and pipe blockages, and reduction in tritium diffusion and extraction from the solid breeder.

Tritium permeation barriers and corrosion resistant coatings: to suppress tritium retention and reduce corrosion in structural components.

Manufacture

Coating internal, complex geometries	Manufacture of coatings inside the complex geometries of breeder blanket components remains a key technological challenge. To facilitate this, optimum coating quality (e.g., acceptable surface roughness) and adhesion must be determined for any candidate coating being developed.

Thermal stability

Temperature-induced phase transformations	Thermally induced phase transformations can lead to cracking and exfoliation of the coating. This may be mitigated by the development of multilayer coating systems or optimisation of coating chemistry.
Thermal expansion coefficient	Difference in thermal expansion coefficient between metallic substrate and ceramic coating can be significant, leading to cracking of the coating during thermal cycling. This can be mitigated through use of interlayers or graded coatings.

Irradiation performance

Irradiation-induced changes	Irradiation induced changes (e.g., swelling, phase transformations, cracking) must be investigated under operational conditions to determine critical failure modes and component lifetimes.

Corrosion

Coating–breeder compatibility	As with liquid and solid breeders, the compatibility of the coating with the breeding material must be determined.
Lithium ingress	Routes of lithium ingress through the coating must be determined and the extent of lithium ingress quantified.
Secondary phase formation	Secondary phase formation in coatings exposed to lithium and the effect on coating performance must be identified.
Corrosion-induced mass loss	Corrosion induced material mass loss rates must be quantified.
Synergistic effects on barrier performance	The effect of impurities in the breeder and in the barrier on tritium permeability and barrier performance, all as a function of temperature, breeder purity, irradiation, environment, etc must be determined.

Tritium trapping and permeation

Tritium permeation	Whilst hydrogen isotope permeation has been studied in accident tolerant fuels and coatings for fission reactors, there is limited data on permeation for fusion specific candidate coatings operating in fusion-relevant conditions. A combined experimental and modelling approach is required to determine key parameters such as solubility, diffusivity and trap energies, informing tritium transport models. The effect of trapping on permeation must be incorporated.
Tritium trapping	The effects of microstructural and irradiation defects, interfaces, and transmutants (e.g., helium) on hydrogen isotope trapping in ceramics must be determined. Understanding isotope exchange effects between different hydrogen isotopes is essential. Experimental data is essential for informing and validating tritium inventory models. This includes spatial mapping of trapped hydrogen isotopes across different length scales within materials and accurately quantifying hydrogen isotopes within these materials.

Coolant-induced corrosion of breeder blanket structural materials.

High temperature water (H_2O, D_2O)

Corrosion deposits	General corrosion of steels and Cu-base alloys, whist slow because they are passive or immune, may still occur and promote the release of metal ions (e.g. Fe^{2+}, Fe^{3+}) into the cooling water. These cations can be transported and eventually redeposited with formation of the so-called CRUD (Chalk River Unidentified Deposits) in different locations of the pipe (e.g. cold-legs and orifices), altering the flow pattern of the coolant and potentially leading to the full blockage of the pipe.
Activated corrosion products	High energy fusion neutrons can transmute cations, forming activated corrosion products (ACPs), and therefore introducing a health and safety hazard during maintenance operations if these cations are eventually transported outside the bio-shield.
Localised corrosion and environmentally assisted cracking	Localised corrosion can lead to pitting or environmentally assisted cracking (e.g. corrosion fatigue and / or stress corrosion cracking) with ultimately pipe cracking. Developing a suitable water chemistry is necessary to have confidence in the durability and activation of the coolant-facing alloys to avoid / minimise corrosion and environmentally assisted cracking.
Irradiation-assisted corrosion and - stress corrosion cracking	Proper assessment of material release rate with synergistic ionising radiation is required to understand and quantify cation release rate, transport and redeposition of the ACPs and irradiation-induced stress corrosion cracking.
Flow-accelerated corrosion	The expected high flow rates of the cooling media coupled with the geometry and configuration of the pipes, may induce flow-accelerated corrosion with enhanced material loss due to the synergistic chemical interaction with the coolant and the shear stress of the coolant on the inner wall of the pipes. Tests are required to understand if the expected flow rates are below the breakdown velocity (flow accelerated corrosion can occur above this value) and determine how ionising radiation will affect the overall corrosion behaviour.
H/T embrittlement	Hydrogen may be used to scavenge oxygen, to limit radiolysis of H_2O and to control the corrosion of pipes, however hydrogen (and tritium) can diffuse into the facing alloy degrading the fracture toughness of the alloy itself. Assessment of H/T permeation will help in identifying the potential H/T concentration inside the alloys, whereas the development of a barrier layer will avoid H permeation.

Supercritical CO_2

Carburisation	sCO_2 can induce carburisation with undesired alloy consumption (e.g. Cr) with microstructural changes of the near surface region. An assessment of the impact of CO_2 with different O_2 partial pressures is required to determine the impact of gas chemistry on carburisation behaviour. E.g., to understand the formation of the stable C barrier Cr_2O_3, which suppresses further alloy carburisation, and determine the effect of irradiation on its formation.
Carbonaceous deposits	Formation of carbonaceous deposits and/or localised oxide growth can lead to heat transfer reduction and insufficient cooling. Experiments to determine acceptable levels of carbonaceous deposits are required.
Environmentally assisted cracking	Material synergistically exposed to flowing sCO_2 and under tensile stress can develop forms of environmentally assisted cracking, creep, or a combination of both. It will be necessary to understand the dominant failure mechanism (e.g. fatigue, creep) as a function of load, microstructure, and stress concentration locations.
Irradiation induced oxidation	Assessment of the ionising radiation is necessary to understand its impact on the oxide stability formed on the coolant-facing alloy. Ionising gamma irradiation can affect the gas stability, with formation of radiolitic and more aggressive chemical species that can affect the heat transfer efficiency of the sCO_2 and ultimately the oxide formed on the coolant facing alloys. Whereas neutron irradiation can directly impact the material microstructure and the stability of its protective oxide.

Helium

Impurity driven corrosion	Despite a high level of purification, a helium coolant is still expected to be contaminated by low levels of H_2, CH_4, H_2O, and CO as impurities. These impurities could cause the corrosion of materials at elevated temperatures. Corrosion rates as a function of flow rate, temperature and impurity concentrations need to be quantified and acceptable levels defined.
Impurity- and irradiation-induced corrosion	Understanding the formation, transport and redeposition of corrosion products with impact of coolant flow as as a function of the concentration of impurities and ionising radiation is required.

Challenges common to all breeding concepts

Tritiated materials

Handling and characterising tritiated materials	Tritium is radioactive and there are limited facilities that can handle and characterise tritiated materials, therefore research currently relies heavily on using hydrogen and deuterium as surrogates. To satisfy expected regulatory requirements and owing to the differences reported between H, D and T interactions in materials, research must also be carried out on tritiated materials.

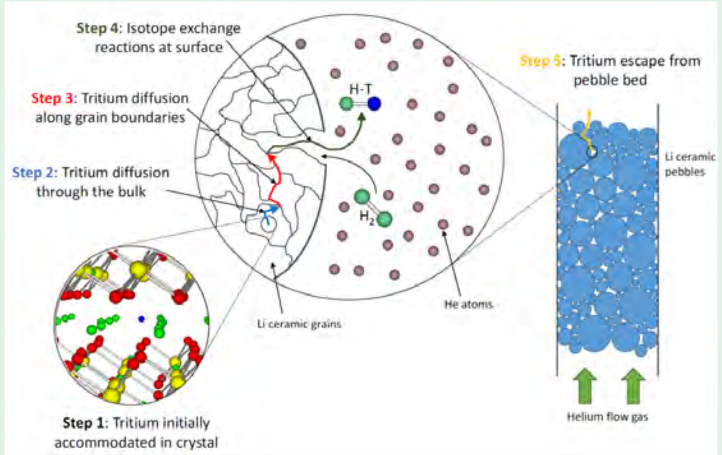
Synergistic testing

Effect on properties and performance in operation	Corrosion is known to be accelerated due to irradiation induced defect formation and liquid flow rates. Therefore, for all the breeding and coatings concepts considered, in-situ testing under synergistic operational conditions is required to determine if and how critical failure mechanisms are altered. Effects to be studied include corrosion effect on hydrogen isotope permeation; neutron irradiation effects on hydrogen isotope permeation; neutron irradiation effects on corrosion. Currently, no facility exists in the UK that enables in-situ, synergistic testing under predicted breeder blanket conditions.

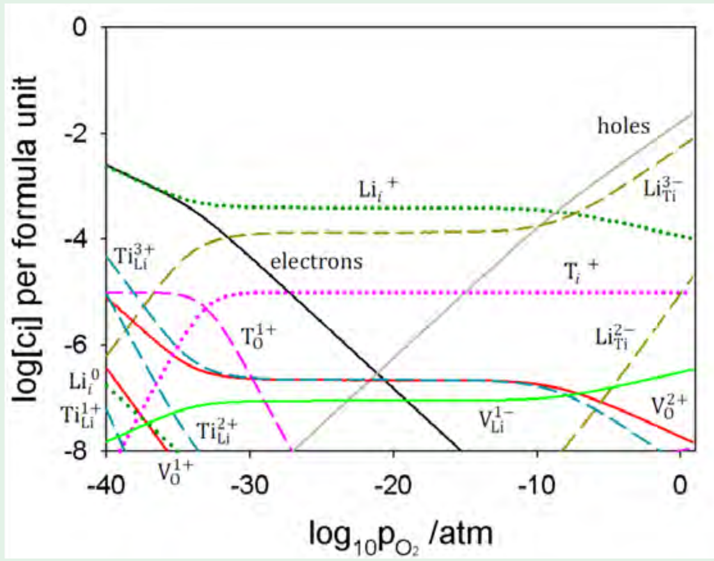
Supply chain

Li-6 enrichment	Natural lithium comprises about 7.6 % Li-6 and 92.4 % Li-7. For a self-sufficient fusion power station, enrichment of Li-6 to greater than 10% is expected, with some solid breeder designs targeting around 60% enrichment. Whilst Li enrichment and isotope separation processes do exist, there is currently no facility that can meet the predicted demand of fusion power plant.

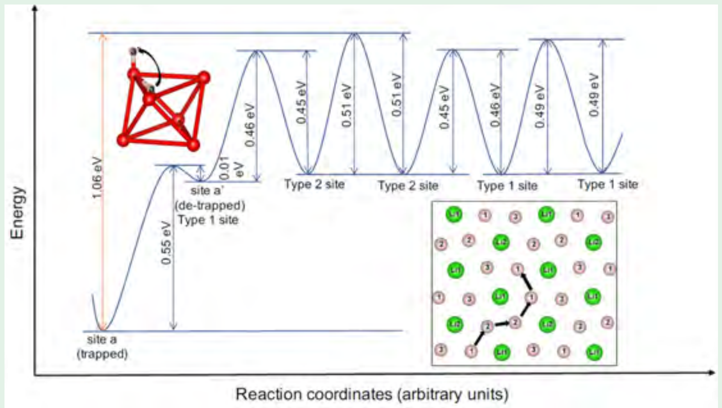
TRITIUM BREEDING



Schematic describing tritium diffusion and extraction from solid lithium ceramic pebbles. With permission from Samuel Murphy, University of Lancaster.



Brouwer diagram showing the defect chemistry of fresh, lithium-rich Li_2TiO_3 and how tritium is accommodated in the material. Under these conditions the defect chemistry is dominated by lithium interstitial defects, with different defects providing charge compensation, depending on oxygen partial pressure. At this stage in the breeder's life tritium is predicted to exist as a highly mobile interstitial defect. From [4].



Energy barrier for tritium to escape from a lithium vacancy defect in Li_2TiO_3 calculated using Density Functional Theory (DFT). This plot shows that as lithium undergoes transmutation and the concentration of lithium vacancy defects increases it may become more difficult to extract tritium from the ceramic. From [5].

The table below identifies infrastructure and capabilities required to solve some of the challenges described

SOLUTIONS	CHALLENGES	IMPACTS
Key Challenge: Irradiation facilities **Develop capabilities at existing national and international irradiation facilities.**	All materials: synergistic testing	• Provide critical data on material performance under expected operational conditions, taking account of holistic interactions between materials, environment and irradiation.
Develop UK-based routes for gas soaking of materials in deuterium and tritium	All materials: Tritium production and extraction	• Provide access to tritiated materials essential for material and fuel cycle development and assurance. • Provide tritium inventory measurements and insight into trap energies via e.g., thermal desorption spectroscopy of T soaked materials. • Spatial mapping of tritium in exposed samples can be used to validate and inform tritium inventory models.
Develop static and flowing Li corrosion rigs with good control over impurities	Liquid breeders: Corrosion	• Determine solubilities of metallic impurities in the liquid breeder as a function of environmental conditions. • Determine if corrosion can be controlled through maintaining Li purity by establishing acceptable levels of C, N and O impurities and their effects on corrosion. • Determine allowable material loss rates, deposition rates, and flow patterns, to determine mass transport corrosion mechanisms and to identify potential for pipe blockages and transport of radioactive materials.
Develop static and flowing FLiBe corrosion rigs with a method for salt purification	Liquid breeders: Corrosion	• Establish design controls to safely manage tritium fluoride (TF) production e.g. purge gas. • Determine the role of carbon including promotion of Cr-rich GB carbides and / or leaching of C. • Determine the extent of leaching of metallic elements and the rates of re-deposition of these elements, to determine the potential for pipe blockages and transport of radioactive materials.
Develop static and flowing PbLi corrosion rigs with good oxygen control	Liquid breeders: Corrosion	• Determine solubilities of metallic impurities in the liquid breeder as a function of environmental conditions. • Determine if corrosion can be controlled through maintaining PbLi purity by establishing acceptable levels of C, N and O impurities and their effects on corrosion. • Understand feasibility of oxygen control during operations to enable formation of protective oxides. • Determine allowable material loss rates, deposition rates, and flow patterns, to determine mass transport corrosion mechanisms and to identify potential for pipe blockages and transport of radioactive materials.

TRITIUM BREEDING

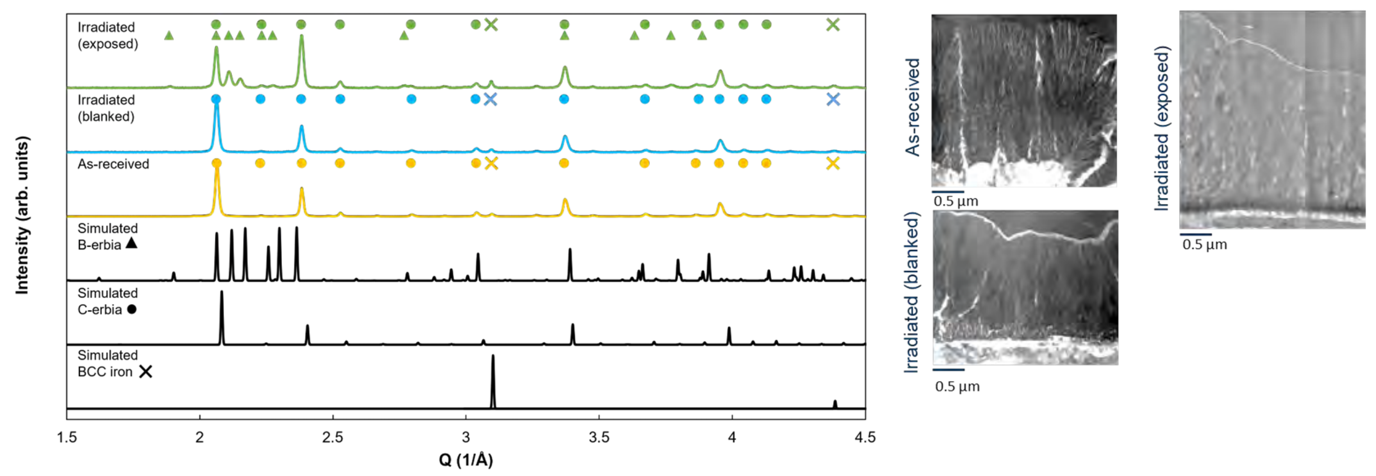
SOLUTIONS	CHALLENGES	IMPACTS
Develop tritium permeation rigs for testing ceramic materials	Solid breeders: Tritium production and extraction	• Undertake permeation rate measurements as a function of pressure to determine diffusion mechanisms. • Undertake permeability measurements as a function of temperature, which will allow calculation of permeation reduction factors for coated systems.
Develop capability for spatial mapping of light elements (Li and hydrogen isotopes, including T)	Solid breeders and coatings: Tritium production and extraction, trapping and permeation	• Determine interaction / trapping mechanisms of T with defects, morphologies and structures, to optimise for efficient T extraction from ceramic breeders, and efficient tritium permeation in coatings.
Develop rigs for annealing solid breeders in contact with structural materials under flowing purge gas	Solid breeders: Corrosion	• Determine contact corrosion mechanisms. • Determine the extent of Li ingress from the solid breeder into structural materials. • Determine the degree of oxidation in structural materials.
Develop capability to assess H_2O/D_2O coolant compatibility with materials	Corrosion from high temperature water (H_2O, D_2O)	• Determine material (cation) release rate with formation of CRUD and ACPs, crack growth rate and crack initiation time for different water chemistries. • Determine acceptable level of impurities (e.g., chlorine, sulphates) to avoid localised corrosion and environmentally assisted cracking.
Develop capability to investigate sCO_2 coolant compatibility with materials	Corrosion from supercritical CO_2	• Determine the impact of CO_2 with different O_2 partial pressures to understand the impact of gas chemistry on carburisation behaviour and suppress further alloy carburisation. • Determine the dominant failure mechanism (e.g., fatigue, creep) as function of load, microstructure, and stress concentration locations (geometric features) to define crack growth rate and crack initiation time. • Provide a mechanistic understanding of oxidation and quantify acceptable level of carbonaceous deposits.
Develop capability to investigate He coolant compatibility with materials	Corrosion from helium	• Quantify corrosion products as function of impurity level. • Quantify corrosion / cracking rate as function of impurity level.

During the workshops the following key facilities were identified as missing and requiring significant investment in order for critical challenges to be met.

Facilities, infrastructure, and industry	Capabilities
Static and flowing Li corrosion rigs with good control over impurities	• Operate at temperatures 300-700 °C. • Facilitate long duration tests >5000 hours. • Ability to control impurities in both the Li (metallic and non-metallic impurities, through use of hot and cold traps) and the environment (moisture, oxygen, nitrogen). • Facilitate development of in-situ experiments in ionising radiation.
Static and flowing FLiBe corrosion rigs with a method for salt purification	• Operation at temperatures 300-700 °C. • Facilitate long duration tests >5000 hours. • Ability to purify FLiBe and control impurities in the environment (moisture, oxygen, nitrogen). • Facilitate development of in-situ experiments in ionising radiation.
Rig for annealing solid breeders in contact with structural materials under flowing purge gas to assess contact corrosion	• Operation at temperatures up to 900 °C. • Exposure times up to 100s of days. • Purge gas at flow rate of 20 sccm and pressure of 1200 mbar. • Impurity control of moisture and oxygen. • Facilitate development of in-situ experiments in ionising radiation.
UK-based routes for gas soaking of materials in deuterium and tritium	• Exposure to (ideally pure) deuterium and tritium. • Pressures up to 1 bar. • Temperatures from room temperature up to 600 °C.
Tritium permeation rig suitable for testing ceramic materials	• Exposure to (ideally pure) deuterium and tritium. • Operation temperature up to 1000 °C. • Pressures of 10^{-4} mbar (low pressure) up to 1000 mbar (high pressure). • Residual gas analyser with quadrupole mass spectrometer tuned to light elements. • Ability to clamp ceramic samples as well as metallic samples. • Facilitate development of in-situ ionising radiation experiments.
Spatial mapping of light elements (Li and hydrogen isotopes)	• Technique development/assessment for detection, mapping, and quantification of Li within materials (relevant to all breeder options). • Technique development for spatial mapping and quantification of tritium (and other hydrogen isotopes) within the microstructure of material.
Testing of H_2O/D_2O coolant compatibility with materials	• Recirculating flow loops with water chemistry and monitoring system • Temperatures in between 150 °C - 300 °C and pressures up to 155 bar • Flow rates up to ~20 m/s. • Short (~100 h), medium (~500 h) and long duration tests (>5000 h) to assess corrosion products, oxidation and environmentally assisted cracking behaviour. • Facilitate development of in-situ experiments in ionising radiation.
Testing of sCO_2 coolant compatibility with materials	• Flow loop system with chemistry management system with in-line chemistry monitoring. • Operation at temperatures up to ~700 °C and pressures up to ~100 bar. • Short (~100 h), medium (~500 h) and long duration tests (>5000 h) to assess carburation, corrosion products, oxidation and environmentally assisted cracking / creep behaviour. • Facilitate development of in-situ experiments in ionising radiation.
Testing of He coolant compatibility with materials	• Flow loop system with chemistry management system with in-line chemistry monitoring. • Operation at temperatures up to ~600 °C and pressures up to ~100 MPa. • Short (~100 h) and medium duration tests (~1000 h) to assess corrosion products, oxidation and environmentally assisted cracking behaviour. • Facilitate development of in-situ experiments in ionising radiation.

TIMELINE

SHORT TERM	INTERMEDIATE TERM	LONG TERM
Develop in-situ testing capabilities to simulate operational conditions, including irradiation. Determine "best performing" materials by testing new and existing materials under fusion relevant conditions incrementally increasing experimental load types (thermal, magnetic, chemical, etc)".	Industrial scale production of breeder materials. If ceramics, demonstrate industrial scale reproducibility of required microstructure, spheronicity (for pebble concepts), porosity, etc.	Production of fuel performance codes to manage machine operations.



Erbium oxide permeation barrier grown by chemical vapour deposition undergoes cubic to monoclinic phase transformation under ion irradiation at breeder blanket relevant operating temperatures. Sample was irradiated at the Dalton Cumbrian Facility using 33 MeV Au $^{6+}$ ions at 550 °C up to a fluence of 2.1x10 ^{16} Au/cm^2. From [6].

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HIGH TEMPERATURE MATERIALS

High temperature materials: plasma facing materials and blanket structure

Materials that are closest to the fusion plasma (e.g., the first wall, divertor and limiters), and structural materials that comprise the tritium breeder blanket will experience extreme heat and particle fluxes, simultaneously with variable thermo-mechanical loads and other environmental degradation effects. The precise operational conditions locally, and therefore materials requirements and life expectancy of those engineered components before their replacement or decommissioning, will depend on the specifics of the fusion power plant design. A recent publication from the STEP's Vacuum-vessel and In-Vessel Systems (VIVS) team [1] has provided valuable insights into predicted heat fluxes, coolant selection, and structural materials for a potential prototype power plant, shown schematically in the figure opposite. The table on page 52 describes current candidate structural and plasma-facing materials for a STEP-like design (maximum outlet temperature of 600 °C), and for a high temperature design (maximum outlet temperature of 1000 °C) suitable for cogeneration of process heat and hydrogen.

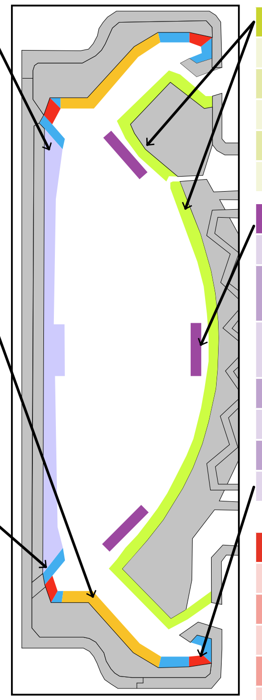
The exact fusion component requirements, (and consequently the coolant, tritium breeding and other materials that comprise the fusion machine) are specific to a power plant design. However, there are several key, albeit general, "gates" through which all materials must pass. Wide operating temperature windows, minimal tritium retention, and radiation-tolerant microstructures are required irrespective of power plant design. Candidate plasma-facing materials must also demonstrate compatibility through low erosion rates, robustness against loss-of-vacuum or loss-of-coolant accidents (LOVA / LOCA), and resistance to plasma-related microstructural changes such as recrystallisation of tungsten. However, it should not be forgotten that materials selected must allow components to be manufacturable, joinable, with sufficient structural integrity, and ideally accessible within the power plant and repairable.

The STEP VIVS design concept requires an outlet coolant temperature of 600 °C. However, the higher the coolant temperature the more efficient the fusion power plant. Therefore, structural materials capable of operating at 600 °C and potentially above are being developed within UK research programmes. The low temperature performance and integrity of all of these components must also be considered, with many candidate structural and first wall materials exhibiting low temperature (but well above room temperature) hardening and embrittlement. Furthermore, plasma facing materials experience plasma-induced surface erosion and tritium retention leading to radioactive dust generation, which is a concern for LOVA, maintenance and disposal. The following section describes materials that are currently considered candidates for use in high temperature applications in the fusion power plant, and their limitations.

Inboard First Wall	
Heat flux estimate	1.3 MW/m^2
Coolant	D_20
Heat sink type	Integrated Tile-on-heat sink
Structural Material	CuCrZr
Armour	Solid tungsten

Divertor medium heat flux targets	
Flat top heat flux estimate	<10 MW/m^2
Ramp-up heat flux estimate	<10 MW/m^2
Coolant	D_20
Heat sink type	Integrated Tile-on-heat sink
Structural Material	CuCrZr
Armour	Solid tungsten

Divertor high heat flux targets	
Flat top heat flux estimate	<10 MW/m^2
Ramp-up heat flux estimate	<20 MW/m^2
Coolant	D_20
Heat sink type	Monoblock
Structural Material	CuCrZr pipe, tungsten block
Armour	Solid tungsten



Outboard First Wall	
Heat flux estimate	1.4 MW/m^2
Coolant	Helium
Heat sink type	Tile-on-heat sink
Structural Material	Vanadium
Armour	Solid tungsten

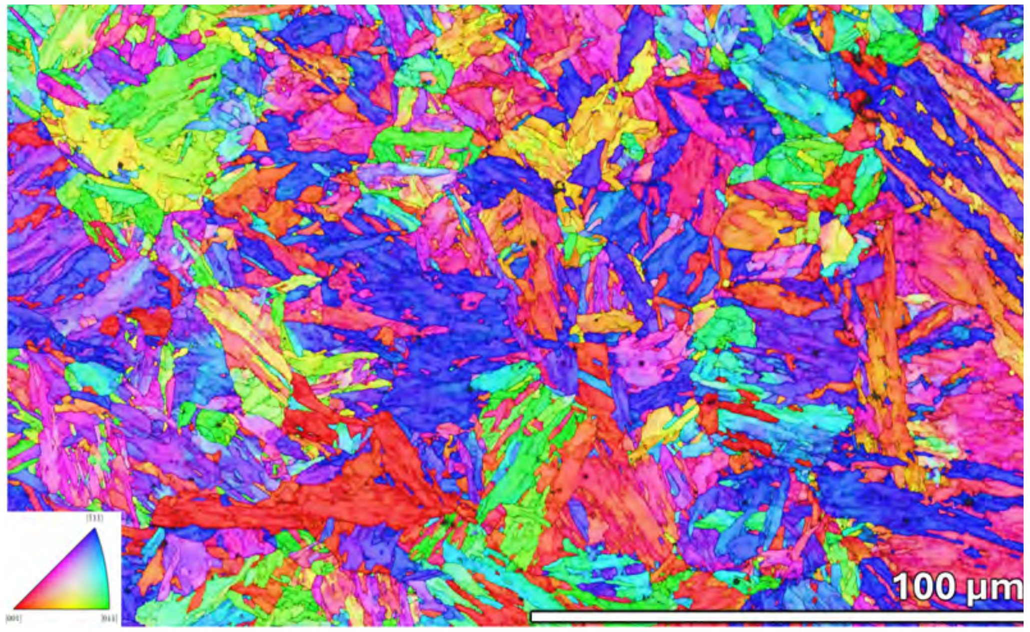
Outboard Limiters	
Steady state heat flux	1 MW/m^2
Transient long duration heat flux	5.0 MW/m^2
Mitigated disruption heat flux	2.2 GW/m^2(0.75 ms)
Coolant	Helium
Heat sink type	Pipe-in-pie jet impingement
Structural Material	Tungsten alloy
Armour	Solid tungsten

Divertor strike point targets	
Flat top heat flux estimate	<10 MW/m^2
Ramp-up heat flux estimate	<10 MW/m^2
ELM heat flux estimate	0.1-1 MJ/m^2
Coolant	D^20
Heat sink type	Dual channel drilled block
Structural Material	CuCrZr pipe, tungsten block
Armour	Capillary Porous Structure tin LiquidMetal Armour

Figure summarises the plasma facing component design selected by VIVS to meet varying functional requirements of a prototype fusion power plant, showing the estimated heat flux (*indicates peak steady state), coolant, heat sink, structural materials, and armour for each component, from [1]

NEURONE Continuous Cast
The first UK reduced-activation ferritic-martensitic (RAFM) steel was produced at the Materials Processing Institute as part of the NEURONE programme. This process utilised electric arc furnace (EAF) technology, improving the potential for economically viable, volume production of these steels. The RAFM steel billet leaves the EAF into a continuous caster, which subsequently enters the product straightener. The resulting ingot weighs 5.5 tonnes and will be studied extensively to support ongoing research into developing fusion-grade steels within the UK.

Photographic credit: Andrew Watson, Materials Processing Institute



NEURONE EBSD
The NEURONE alloys produce ferritic-martensitic microstructures. The electron backscatter diffraction (EBSD) image shown for a new high-strength NEURONE alloy variant, allows us to view these microstructures and understand the morphology and orientation of crystal structures, such as those that form within steel. Understanding these aspects is crucial for steel development, as microstructural features govern the macroscopic properties of materials when they are used in service.

Candidate plasma facing and structural materials for a STEP-like design and high temperature design.

Component	STEP-like design Indicative operational temperature range: 150 to 600 °C	High temperature design Indicative operational temperature range: 600 to 1000 °C
Inboard first wall: structural material	CuCrZr (which has an operating temperature range of 150 to 300 °C)	SiCf/SiC
Inboard first wall: armour	Solid tungsten	
Outboard first wall: structural material	• Vanadium • Reduced activation ferritic/martensitic steels (e.g., Eurofer97, F82H) (which have a minimum operating temperature of 200 °C) • Oxide dispersion strengthened (ODS) steel • SiCf/SiC	SiCf/SiC
Outboard first wall: armour	Solid tungsten	
Outboard limiters: structural material	Tungsten alloy	
Outboard limiters: armour	Solid tungsten	
Divertor medium heat flux targets: structural material	CuCrZr	• Cu-based composite e.g. Cu/SiC_f or Cu/W_f • He-cooled SiCf/SiC pipe w/ graded SiC-W block
Divertor medium heat flux targets: armour	Solid tungsten	
Divertor high heat flux targets: structural material	CuCrZr pipe, tungsten block	• Cu-based composite e.g. Cu/SiC_f or Cu/W_f • He-cooled SiCf/SiC pipe w/ graded SiC-W block
Divertor high heat flux targets: armour	Solid tungsten	
Divertor strike point targets: structural material	CuCrZr pipe, tungsten block	• Cu-based composite e.g. Cu/SiC_f or Cu/W_f • He-cooled SiCf/SiC pipe w/ graded SiC-W block
Divertor strike point targets: armour	Capillary porous structure tin Liquid Metal Armour	

The table below describes materials challenges specific to current candidate high temperature materials for fusion, including fusion radiation induced effects that are not yet known. The challenges described below highlights the need for continued investigation of other, novel, materials which may display superior performance over current candidates.

Material	Specific challenges
CuCrZr	• Creep resistance at relevant appm He/dpa ratios not known. • Development of novel Cu alloys for higher temperatures beyond CuCrZr. • Corrosion resistance against potential coolants. • Interface with tungsten plasma facing materials (PFM). • Reduction of inclusions and increase in microstructure homogeneity when scaling up to machine components.
Tungsten	• Minimisation of sputtering and deposition under low energy plasmas. • Helium bubble formation and embrittlement. • Synergistic damage and transmutation effects. • Development of novel tungsten-based coatings for specific components or environments in the machine. • Surface quality and lack of porosity of additive manufactured components for good stability and structural integrity. • Interface with CrCrZr heat sink. • Complex shape manufacture and joining. • Effects of radiation damage on ductile to brittle transition temperature (DBTT).
Vanadium and V-alloys	• Irradiation creep resistance. • Compatibility with lithium-based breeders. • Control of light impurities during production to reduce secondary brittle phases. • Limited data on radiation damage effects. • High affinity for O and H leading to strict environmental controls needed during both manufacture and joining operations. • Limited creep data and high creep rates at elevated temperature.
RAFM steels	• Control of microstructure during processing. • Stability of martensitic structures above 550-600 °C to increase Tmax. • Coolant compatibility concerns (particularly liquid metals / molten salts) • Weldability and integrity of joints. • Tight compositional controls. • Current RAFM alloys (e.g., Eurofer-97) experience a rapid loss of creep rupture life above 550 °C.
ODS steels	• Fabrication and scaling up. • Control of ODS distribution and stability during irradiation. • Weldability. • Limited creep data at relevant conditions for new ODS formulations. • Coolant compatibility concerns (particularly liquid metal / molten salts)
SiCf/SiC	• Transmutation changes Si:C ratio and generates new species with unknown effects on functional properties. • Low thermal conductivity after irradiation - predicted high thermal stresses. • Hydrogen isotope interactions - very low permeation rate, potentially strong trapping by C-H bonding. • Radiation defects increase electrical conductivity - potentially different with transmutation. • Susceptible to irradiation-induced swelling at low temperatures. • Representative mechanical testing requires larger specimens than can be irradiated in a beamline - centimetre scale. • Joining and assembly. • Limited engineering design experience with ceramic matrix composites (CMCs) in other industries - fundamentally different approach compared to metals. • Quality control and defect detection in manufactured components – CMCs have less tolerance than metals to hidden pores and cracks.
Liquid metal armour	• Tin embrittles certain grades of steel.

HIGH TEMPERATURE MATERIALS

CHALLENGES

Scalability and Supply Chain

Material volumes	The approximate materials requirements for a STEP-like machine can be estimated as ~100 tons CuCrZr/Cu, ~1000 tons of W armour with an additional ~250 tons of W_2B_5 shielding. These will be supported by ~1000 tons of fusion-grade structural steel, equivalent to ~450 tons of SiC.
Industry scale fusion grade CuCrZr production	While there is no native production of copper, in 2022 UK scrap copper exports amounted to 252,734 metric tons [2]. While suppliers of highly clean, CuCrZr would need to be evaluated for Quality and Assurance purposes, material availability is likely not too concerning. However, keeping Cr and Zr contents within recommended limits, and material homogeneity when scaling up can be a concern.
Access to tungsten raw materials	Described by the government as “a critical mineral”, tungsten availability is potentially a significant risk. In 2025, a comprehensive study by Day-San and Blackett [3] on the supply and demand of tungsten for fusion power plants was published. The study highlighted that without domestic tungsten sources, the supply for these plants would likely fall drastically short, making it undeliverable without significant investment and expansion. The UK has the potential to be in a strong position in this regard; the Hemerdon mine near Plymouth may contain the second-largest tungsten deposit in the world [4], despite closing in 2017. Additionally, according to a United States Geological Survey, the United Kingdom has the world's fourth-largest tungsten reserves that amount to 43,000 metric tons of tungsten [5]. Tungsten cleanliness may become problematic as high purity tungsten is regarded as a dual-use material. [3]
Industry scale fusion grade steel production	The UK has historically been a world expert in the production and export of steel, and a strong steel supply chain still exists within the UK. Nationally steel production is struggling in the global market, having plummeted to historical lows of 5.6 million tons [6], and with the closure of blast furnace steelmaking in Port Talbot, primary steelmaking is limited to the single British Steel blast furnace at Scunthorpe. Nevertheless, clean, technically-advanced steel is where the UK is finding its globally-competitive niche, recently demonstrated by the electric arc furnace production of a 5T fusion-steel specification billet. However, facilities to increase production volumes are required.
Limited SiC fibre supply chain	The supply chain for high quality SiC fibres is a global challenge, with the majority of production located in Japan where the fibres are made in limited volumes via batch processes [7].

Materials selection, baseline and performance testing, and materials qualification

Synergistic effects	There is an urgent need for synergistic testing, e.g., high temperature tensile and creep testing combined with irradiation and corrosion. Radiation and corrosion effects are thermally sensitive and as such are difficult to extrapolate, meaning that long testing times will be required to sufficiently satisfy regulators. Synergistic effects can lead to different mechanisms and material phenomena, which may not be explainable based on existing models of single effects, and therefore may also need new, reliable predictive modelling developments.
LOCA / LOVA response	The response of plasma facing materials in loss of coolant accident (LOCA) / loss of vacuum accident (LOVA) scenarios, and the influence of tritium retention, dust formation and tritiated coolant must all be determined.
Testing standards	Appropriate standards for testing require defining and should be accessible to the wider UK fusion community.
Low TRL material development	Low TRL materials (e.g., medium/high entropy alloys, zirconium alloys, novel steel chemistries, vanadium alloys, enhanced W-based plasma facing materials) need decades of extensive thermophysical, mechanical (including long-term creep and fatigue) and advanced microstructural characterisation in order to meet the materials requirements and provide sufficient confidence in materials down-selection campaigns.

Irradiated materials testing

No UK materials fission test reactor	The UK has no materials test reactor, and must rely on overseas facilities (HFIR, BR2, HFR) at great expense and complexity to generate neutron-irradiated (active) materials using a fission neutron energy spectrum, and to transport active materials to carry out post-irradiation examinations.
Lack of fusion relevant test capabilities	Despite reasonable ion beam facilities (Dalton Cumbria Facility, Surrey Ion Beam Centre, and the MC40 Cyclotron Facility at Birmingham), the capability of synergistic testing with creep or corrosion is so limited as to be functionally impossible given the demands on these facilities. Extended fusion materials testing often competes with other sectors or demands for beamtime.
Existing accelerated methods unrepresentative	For steel, end-of-life damage levels are expected to be of the order of 100 dpa and 1000 appm of helium. For SiC 10,000 appm of He is expected. The costs and timescales involved in generating this effectively limits researchers to heavy-ion irradiation, and thus damage confined to the first few microns of a material's surface. It is unclear how results generated on these (near-surface) scales can be used to inform engineering-scale qualification. Furthermore, those accelerated heavy-ion irradiations may not be directly comparable to lower dose rates expected in neutron irradiations.
Computational models to extrapolate data from small-scale tests	The testing of irradiated materials necessarily takes place on limited sample volumes and small specimen geometries. There are currently no detailed computer models that can reliably and mechanistically extrapolate between engineering components and small-scale tests that often demonstrate higher strengths and reduced occurrence of fracture. Such models are essential to qualify components. Necessary to reduce the gap within multi-scale materials modelling hierarchy by establishing a strong link between engineering scale with mesoscopic and atomistic modelling to address the microstructure evolution of engineering materials.
Regulator engagement	Even if these models existed, no regulator will accept modelling data without experimental validation. It must be determined what levels of validation are acceptable, e.g. are proton-irradiated but engineering-scale test specimens suitable? Is small scale testing, in many cases post-irradiation, representative of macro-scale testing?
Need for in-situ, synergistic testing	Materials characterisation, and in most cases also performance testing, is mostly performed post-irradiation at the end of the irradiations, therefore introducing potential artefacts and limiting the amount of information gathered for model validation. There is an urgent need therefore to develop and undertake in-situ testing under synergistic fusion relevant conditions to capture, for example, real-time damage accumulation and recovery processes.

Manufacturing	
Joining blanket module components	Joining standard and similar materials, such as steel plates to form blanket modules, has been identified as a significant challenge, given the extreme demands on components and the weaknesses that welding techniques introduce into the material.
Manufacturing high temperature performing materials	Advanced manufacture techniques not yet developed are required for high-temperature machines. They are needed to produce difficult-to-manufacture components at scale and potentially with complex geometries, such as those made from tungsten, oxide-dispersion strengthened alloys and SiC composites.
Joining dissimilar materials	The joining of dissimilar materials is an area that requires significant research, especially considering many of the materials (e.g. tungsten) have never had to undergo joining before. The differences in thermal expansion coefficient between many of the candidate materials, and the introduction of an abrupt interface, mean that these joints are fundamental points of failure within a component.
Synergistic effects on welds / joints	Joints are regarded as another unique material within the fusion environment and their changes under (synergistic) fusion conditions must be studied. Ideally the joint area should be minimised as much as possible, but it may be that the heat affected zone is the weak point of failure rather than the joint itself. Damage localisation in welded structures, especially with other environmental (synergistic) effects, would require extended testing and optimisation for best fusion-relevant welding and joining approaches.
Transmutation products	Transmutation products, in particular He, affect the weldability of steels, due to the embrittlement of the heat-affected zone, thus limiting opportunities for weld repair. 0.1 appm He is the US Nuclear Regulatory Commission limit for welding austenitic stainless steel, 5-10 appm He is considered unweldable by conventional methods , but higher helium content steels have been successfully joined by laser welding.
Functionally graded components	Development of additive manufacture (AM) techniques should be explored to facilitate functionally graded components, as these could be used to improve component joining whilst maintaining high functionality where required. AM techniques introduce other challenges such as complex microstructures, and surface imperfections, that may require post-manufacture treatments.
People	
Nuclear relevant skills shortage	At all levels from technicians to PhD candidates, there is a shortage of skilled people in the nuclear sector. During roadmap workshops it was generally agreed the undergraduate (BSc) level is too soon to specialise in nuclear, especially when most recruitment is done at the post-master's level. However, it was noted that standalone master's qualifications are often prohibitively expensive, and strict visa criteria and export control constraints in nuclear-related research causes big drop off between the BSc and MSc levels.

The table below identifies infrastructure and capabilities required to solve some of the challenges described

SOLUTIONS	CHALLENGES	IMPACTS
Key Challenge: Irradiation facilities **Develop capabilities at existing national and international irradiation facilities.**	Materials selection, baseline and performance testing, and materials qualification Irradiated materials testing	• Determine the effect of synergistic loading and environmental effects on material response. • Generate first-of-a-kind data on materials exposed to synergistic environments. • Generate irradiated materials for post irradiation examination, increasing TRL. • Move towards integration of materials characterisation in-situ during irradiation.
Creation of UK public-private partnerships for scalability and manufacture.	Scalability and Supply Chain	• Drive investment into UK tungsten, steel and SiC supply chains, creating sovereign capabilities.
Develop and / or access a dedicated fusion materials test facility.	Irradiated materials testing	• Generate qualified, engineering-scale data on qualified test specimens to ensure safe plant operation.
Develop linear plasma devices capable of simulating plasma wall interactions.	Materials selection, baseline and performance testing, and materials qualification Irradiated materials testing	• Qualified data on plasma-facing materials to ensure safe plant operation. • Apply synergistic conditions to plasma-facing materials, such as LOCA/LOVA simulations. • Provide qualified data on plasma-facing materials to ensure safe plant operation.
Develop UK HPC computational capability to model fusion materials under extreme conditions conditions in a connection with the new AI data centre at UKAEA.	Irradiated materials testing	• Develop, generate and apply detailed computer models that can reliably and mechanistically extrapolate from small-scale experimental tests to engineering components. Those models would need to undergo a suitable validation campaign experimentally to transit from small to large scales reliably. • Form digital twins at power plant scales to allow robust virtual designs to be iterated that are prohibitively expensive to carry out in reality.
Invest in and develop cross-industry knowledge and R&D.	Manufacturing	• Learn from existing welding and joining technologies.

During the workshops the following key facilities and capabilities were identified as missing and requiring significant investment in order for critical challenges to be met.

Facilities, infrastructure, and industry	Capabilities
UK public-private partnerships for scalability and manufacture	• Generate private sector involvement, potentially with a public-private partnership model, which may work well for such critical infrastructure projects. • Tungsten carbide is a critical material for the cutting, machining and mining industries, and tungsten also has applications in the defence industry, therefore there are a number of private and government-led parties that would be interested in a UK tungsten supply chain. • If fusion power plants are (very reasonably) designated as nationally-important infrastructure projects, then the use of UK-made steel can be incentivised or mandated in certain quantities. They too suggest public-private partnerships to drive investment into the UK steel supply chain. • For SiC, fibre manufacture remains the limiting step. Supporting research programmes looking at alternative manufacturing solutions that allow low-cost crosslinking solutions for the precursor polymers (that will not require e-beams or gamma rays) may allow for a significant increase in availability.
Dedicated fusion materials test facility	• Facilities such as a fission reactor as a materials test reactor, a bespoke fusion neutron source, or an intermediate energy proton facility dedicated to fusion materials research.
Develop capabilities at existing national and international facilities	• Multiple ion accelerators for synergistic radiation exposure (damage, plus helium and / or hydrogen) • Multiple compatible end stations for synergistic testing (creep, corrosion, tritium permeation) • Increased number of end stations to allow for long-term tests (e.g. creep).
Linear plasma devices capable of simulating plasma wall interactions	• Synergistic testing of plasma-facing materials and components under realistic conditions: high temperature, plasma exposure, ELM simulation, magnetic stresses, potentially tritium retention.
UK HPC computational capability to model fusion materials under extreme conditions.	• Develop modelling capabilities and digital twins using UK National HPC facilities and UKAEA AI data centre.
Cross-industry knowledge and R&D	• As the joining of (dissimilar) materials is not a unique problem to the fusion industry, there should be development and investment in cross-industry knowledge and R&D. • This can be done through institutions such as the High Value Manufacturing Catapult, which draws funding from Innovate UK and could therefore could be expanded through existing funding streams.

TIMELINE

SHORT TERM	INTERMEDIATE TERM	LONG TERM
Develop dissimilar joining methodologies for tungsten to structural materials (e.g., to steel and CuCrZr). Mitigate dust generation and its effects. Develop structural reduced activation steels to operate up to 650 °C. Select and test materials that are radiation tolerant and compatible with lithium corrosive environments (e.g. vanadium alloys).	Continued development of the Gen-2 "High Temperature" materials, particularly SiC and SMART W alloys. Increase TRL of novel structural materials e.g. MEAs/HEAs, Zirconium, Vanadium.	Identify and develop alternatives to armour materials e.g. isotopically enriched Mo, CVD-Diamond, Liquid Metals. Assess and develop the capability of advanced manufacturing techniques such as additive manufacturing to improve reliability or open new design possibilities and scaling up. Utilise STEP subservience sampling for the development of in-situ monitoring and repair techniques to extend plant lifetime, reduce maintenance windows, and recover from accident scenarios.

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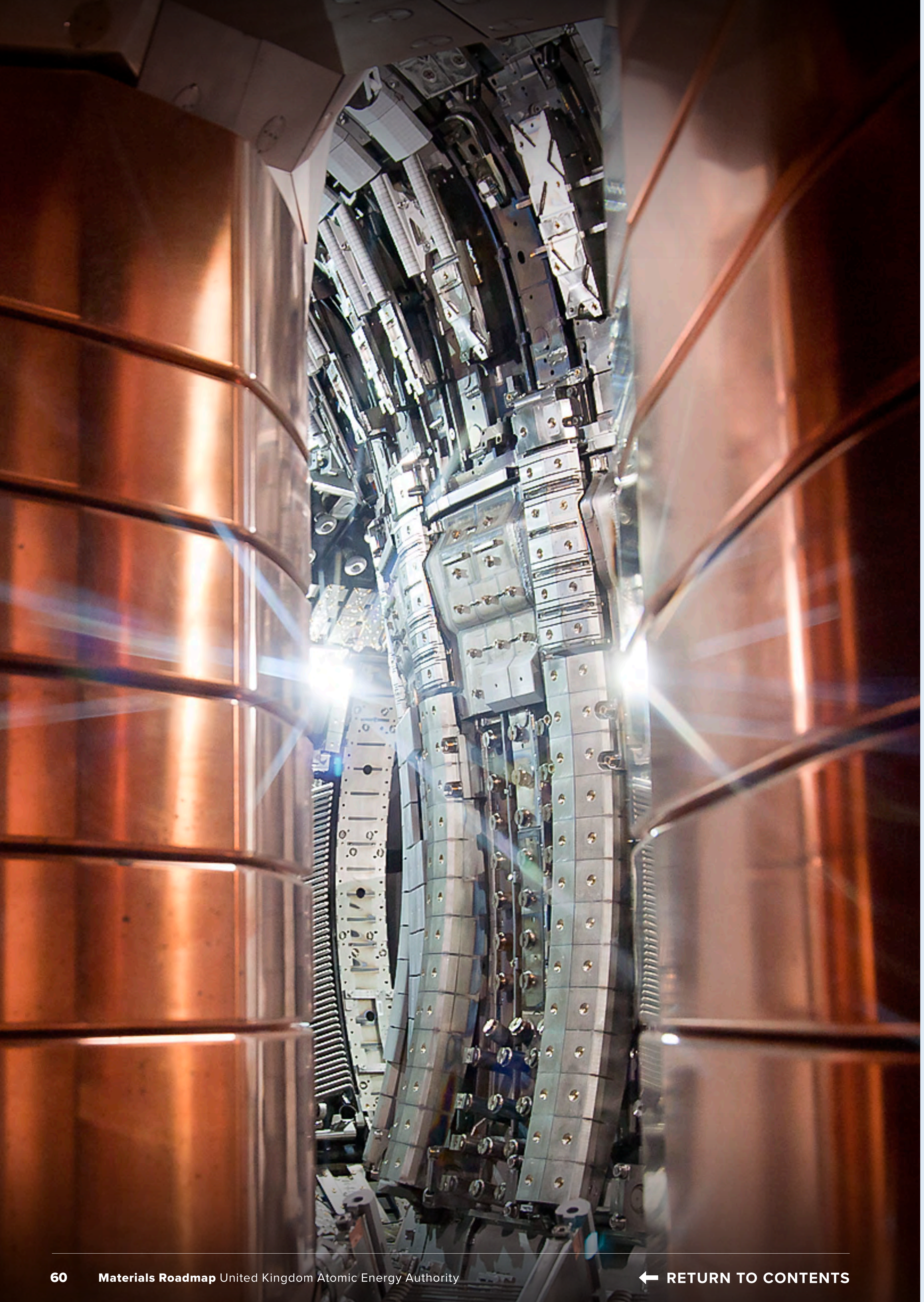


Radiation Hardened (Rad-Hard) Materials

Radiation-hardened (rad-hard) materials include electronic components (e.g., transistors, resistors, capacitors, etc), connectors, and cables that are designed to be resistant to radiation damage for use in nuclear applications. In fusion, sensors, diagnostics, electronics and cables will be required to monitor and control key systems, such as piezoelectrics developed to monitor integrity of the vacuum vessel and electronics required for diagnostic systems monitoring exhaust gas composition using residual gas analysis or in-situ tritium inventory in wall materials (such as Laser Induced Desorption Quadruple Mass Spectrometry (LID-QMS)). These electronic components will be exposed to extreme heat fluxes, intense neutron bombardment, and high magnetic fields, all of which can degrade performance over time. Depending on their function and location, each diagnostic component must be appropriately shielded. For example, sensitive measuring instrumentation should ideally be placed in less hostile areas whenever possible, the control electronics for the detectors, kept at a safe distance to ensure proper functionality, and the actual detector units should be magnetically, neutron and heat shielded. However, placing control units remotely necessitates the use of very long cables, which in turn can introduce signal degradation, latency, and noise. Because not all electronics can function reliably over such extended distances, careful consideration must be given to both individual components shielding and the optimal positioning of these systems.

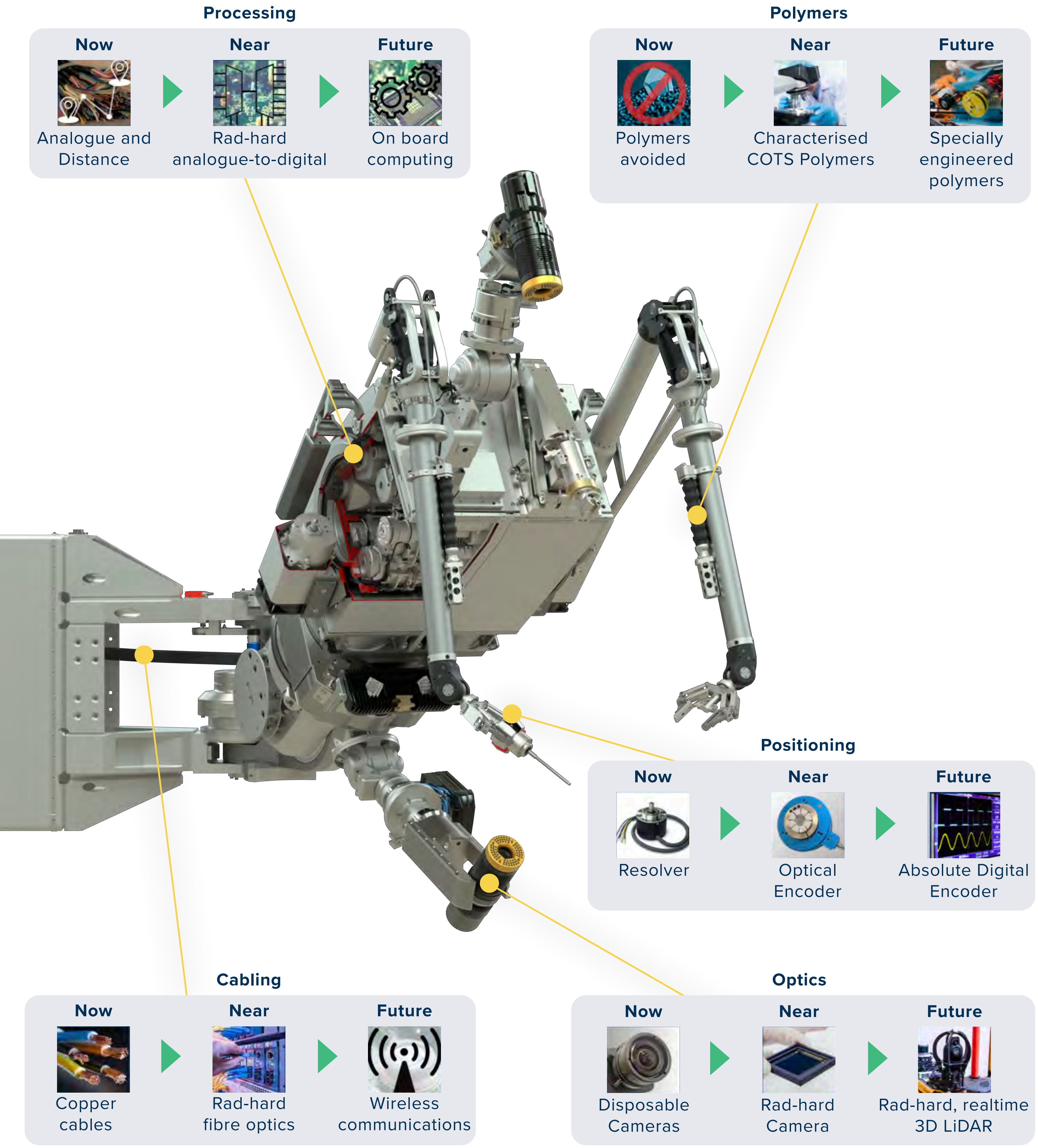
Furthermore, rad-hard materials will be used in the remote maintenance of in-vessel components. Remote maintenance systems are required to carry out extremely complex operations, lifting large loads quickly, safely, and reliably, as well as interacting with the internals of the tokamak to carry out a range of inspection, repair, and replacement tasks to a nuclear standard. Whilst the maintenance systems will not be present in the fusion core during operation, and so are not expected to experience neutron irradiation, gamma radiation emitted during decay processes of radioactive in core components pose significant challenges for the multiple electronic systems that robots rely on to work to the required standards: sensors (cameras, LIDAR, etc), motor drivers, and the provision of computational power needed to control and automate tasks. Modern integrated circuits degrade quickly in gamma irradiated environments, and Commercial-off-the-shelf (COTS) devices are not built to tolerate any significant radiation dose. A major technical risk remains the ability to control the challenging payload with only limited measurements of the real-world physical deformation of the component as well as the challenges of running motors on long wires. Automated or semi-automated Remote Maintenance solutions using modern AI techniques rely heavily on electronic components being placed inside the high-radiation environments, such as sensors (cameras, LIDAR, structured light cameras, etc), motor drivers, and local processors to run the automation logic, including AI. This risk could be substantially mitigated by the development of more radiation-robust sensing devices and motor drivers.

For the proper and reliable functionality of diagnostics and sensors in a fusion environment, there are a series of challenges that need to be addressed:

- **The extreme operational conditions:** radiation-hardened materials are required to withstand extreme heat, high neutron damage and intense magnetic fields.
- **Proper shielding and ideal location:** a fine balance between ideal shielding materials and distance from the harsh fusion environment need to be considered for all the electronic components, sensors and detection systems for their optimum functionality.
- **Remote Maintenance Capabilities:** modular designs and integrated remote repair strategies are critical to address inevitable component failures in environments inaccessible to human personnel.

Addressing these challenges is vital for the success of future commercial fusion power plants, where maintaining diagnostic functionality under extreme conditions will directly impact overall system reliability and operational efficiency.

A bird's eye view of rad-hard within Remote Applications in Challenging Environments (RACE) at UKAEA



RADIATION HARDENED MATERIALS

CHALLENGES

Extreme and complex fusion environment	
High Neutron Flux and Ionizing Radiation	14 MeV neutrons along with significant gamma radiation induce displacement damage, Total Ionizing Dose (TID) effects, and Single Event Effects (SEEs) in materials and electronic components.
Extreme Heat Fluxes and Thermal Transients	Plasma–facing surfaces are exposed to intense heat loads (up to 10 MW/m^2) along with rapid temperature cycling. Diagnostic and sensors in the vicinity of a fusion machine must dissipate heat efficiently and maintain calibration despite thermal shock.
Strong Magnetic Fields	Strong magnetic fields can interact with electronic systems and induce stray currents or signal interference.
Long-Term Operational Demands	The devices must operate continuously over long lifetimes while accumulating radiation damage and, hence, reducing functionality. This makes a self-calibration capability a critical requirement.
Radiation resistant integrated circuits	There is a need to deploy control systems in 1 kGy/hr gamma environment and therefore integrated circuit components that can operate under these conditions are required.
Cryogenic temperatures	Magnet cables and joints will operate at ~ 20 K.

Operation of Sensors and Diagnostics in fusion environment	
Calibration Drift and Sensitivity Loss	Semiconductor-based detectors and photonic sensors suffer damage from neutron and gamma irradiation, which will affect threshold levels and sensitivity. Materials for devices that can withstand high defect rates while providing consistent readout, are needed.
Compatibility with Extreme Thermal and Magnetic Conditions, and neutron irradiation	Sensors and diagnostics must operate in environments with high heat flux, rapid thermal cycling, neutron irradiation and strong magnetic fields without performance loss. Advanced ceramics, composite coatings, and novel doped sensor materials need to be developed to meet these stringent requirements.
Compatibility with magnetic fields	Diagnostics must operate in environments with strong magnetic fields without performance loss. Advancements in novel doped sensor materials are needed to meet these stringent requirements.
Signal Integrity and Shielding	Cables must maintain consistent conductivity and effective electromagnetic shielding in environments where radiation may alter material properties or induce noise. Innovative conductor alloys and shielding techniques that resist both radiation damage and thermal degradation are needed.
Long-Term Reliability under fusion relevant conditions	The cumulative effects of neutron fluence, thermal cycling, magnetic field cycling and mechanical stress over decades of operation require extensive testing and accelerated aging studies to validate cable designs for commercial fusion machines.

More challenges please turn over

CHALLENGES

Electronics	
Total Ionizing Dose (TID) and Threshold Shifts	Conventional complementary metal–oxide–semiconductor (CMOS) electronics experience shifts in threshold voltage and increases in leakage current under high radiation, leading to functional degradation. Innovations in process technologies, such as silicon-on-insulator (SOI) or the use of wide–bandgap materials, are required to extend device lifetimes.
Single Event Effects (SEEs) and Transient Errors	Energetic particles may induce transient errors or even permanent leakage in microelectronic circuits. Mitigation strategies like triple modular redundancy (TMR), error-correcting codes (ECC), and hardened latch designs are critical but must be balanced with power and performance constraints
Advanced Process Maturity	As semiconductor nodes shrink, maintaining radiation tolerance without compromising performance or cost remains a substantial research challenge.
Radiation resistant high bandgap semiconductors.	Semiconducting materials which can operate under gamma irradiation to 1 MGy+ are required. Limited silicon-based rad-hard solutions exist but need extending. Candidate high-bandgap materials that require development include SiC, GaN, and diamond.

Cables	
Insulation and Dielectric Stability	Radiation (especially ionizing doses) can deteriorate the typical polymer insulators, causing cracking, embrittlement, or changes in dielectric properties that can limit the signal transmission. Research must focus on developing advanced polymer formulations or composite insulators that retain flexibility and dielectric performance under high-dose conditions.
Signal Integrity and Shielding	Cables need to have consistent conductivity and proper electromagnetic shielding in locations where radiation might affect the material properties or cause noise. For this, innovative conductor alloys and shielding methods that are resistant to both radiation damage and thermal degradation, are required.
Long-Term Reliability under fusion relevant conditions	The cumulative effects of neutron fluence, thermal cycling, magnetic field cycling and mechanical stress over decades of operation require extensive testing and accelerated aging studies to validate cable designs for commercial fusion machines.
Radiation resistant mechanical seals	Pipe connections are key for fusion power. Therefore, mechanical seals (e.g., O-rings) that can keep their sealing properties (sealing, flexibility) under gamma radiation need to be developed.

The table below identifies infrastructure and capabilities required to solve some of the challenges described

SOLUTIONS	CHALLENGES	IMPACTS
Key Challenge: Irradiation facilities **Develop capabilities at existing national and international irradiation facilities**	Extreme and complex fusion environment Sensors and Diagnostics Electronics Cables Operation of sensors and diagnostics in fusion enironment.	• Develop fusion relevant testing and qualification methodologies. • Extended in-situ testing under fusion–relevant conditions (high neutron/gamma flux, intense heat loads, and strong magnetic fields) is essential for validating new materials and designs.
Develop capabilities to fabricate and test novel materials, diagnostic systems, and mechanical and electrical interconnections.	Extreme and complex fusion environment Sensors and Diagnostics Electronics Cables	• Develop new radiation-resistant polymers, ceramics, and composite materials that are thermal, electrical, and mechanically stable. • Progress on diagnostics that can autonomously recalibrate or self-diagnose changes caused by radiation damage to improve sensor and electronic lifetimes. • Improve radiation–hardened semiconductor development without compromising performance or incurring excessive cost. • Using unique design methodologies and materials testing, ensure that connectors and cables retain hermeticity and low resistance for lengthy periods of time in fusion relevant conditions.
Develop UK capability for the advancement of radiation tolerant electronics and materials, and development and utilisation of UK Gamma irradiation test facility.	Extreme and complex fusion environment Sensors and Diagnostics Electronics Cables Operation of sensors and diagnostics in fusion enironment.	• Development of gamma irradiation resistant control systems. • Development of gamma irradiation resistance high bandgap semiconducting materials. • Development of polymers and ceramics resistance to gamma irradiation induced degradation.
Develop facilities to fabricate and test novel materials, diagnostic systems, and mechanical and electrical interconnections.	Operation of sensors and diagnostics in fusion enironment.	• Produce new radiation-resistant polymers, ceramics, and composite materials that combine thermal, electrical, and mechanical stability. • Develop diagnostics that can autonomously recalibrate or self-diagnose changes due to radiation damage to improve sensor and electronic lifetimes. • Improve radiation–hardened semiconductor development without compromising performance or incurring excessive cost. • Using unique design methodologies and materials testing, ensure that connectors and cables retain hermeticity and low resistance for lengthy periods of time in fusion relevant conditions.

FACILITIES, INFRASTRUCTURE AND INDUSTRY

Facilities, infrastructure, and industry	Capabilities
Gamma irradiation test facility	• To enable materials testing and development • Co-60 sources for testing against well-established standards across the nuclear sector. • More representative sources made from expected vessel wall materials (activated tungsten, stainless steel, etc) to enable testing in representative gamma fields.
UK Capability to develop radiation tolerant electronics and materials	• Meet anticipated requirements of 10s of millions of electronic devices per year to supply fusion power plant construction phases. • Established supply chains for electronic devices and sensors for fusion.
UK capability to fabricate and test novel materials, diagnostic systems, and mechanical and electrical interconnections.	• Development of new radiation-resistant polymers, ceramics, and composite materials that combine thermal, electrical, and mechanical stability. • Improve radiation–hardened semiconductor development without compromising performance. Development of connectors and cables capable of operation over long periods in fusion environment.
Cross-industry knowledge and R&D	• Development of cross-industry research on radiation-hardened materials for sensors and diagnostics.

TIMELINE

SHORT TERM	INTERMEDIATE TERM	LONG TERM
De-risk materials choices to provide confidence for design and supply chain of first generation fusion power plants. Testing of novel materials under gamma irradiation, and relevant fusion environments. Develop supply chain for rad-hard materials for fusion.	Development of new materials and electronic components for novel sensors and diagnostics. Well developed UK supply chain with alternative suppliers.	Rad-hard material solution for novel sensors, diagnostics and remote access for next generation fusion power plant.

Modelling and Simulation

The development of materials, their fabrication into components and the qualification of the systems constructed from these components, will require significant input from modelling and simulation-based research. If staged qualification or co-qualification of materials is to be adopted, then a role for modelling and simulation would be in defining the most important measurements to make on limited amounts of appropriately-exposed materials (according to the different models of material degradation, etc), and in assisting demonstration power plant design, such that components and specimens can be removed for testing after limited operation. Drivers for a particularly prominent role for modelling and simulation in the case of fusion are:

- the rapid pace of progress required,
- the breadth of options currently under consideration,
- the lack of facilities for direct experimental testing in a fully representative environment,
- the high cost of experiment and testing,
- the need to design and qualify novel, highly radiation-tolerant materials for fusion,
- the need for integrated neutronics simulations with materials modelling.

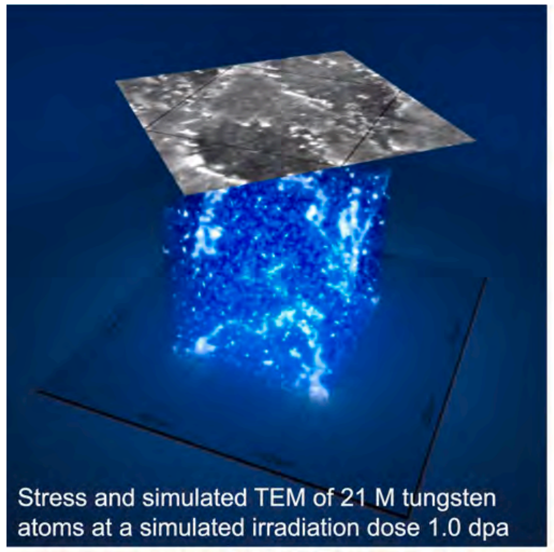
Historically, modelling and simulation of materials have tended to focus on the following approaches:

1. exploring the behaviour and properties of materials to arrive at a mechanistic understanding,
2. predictions from first principles of properties at the small scale (most typically atomistic),
3. predictions of material behaviour at larger scales based on empirical models.

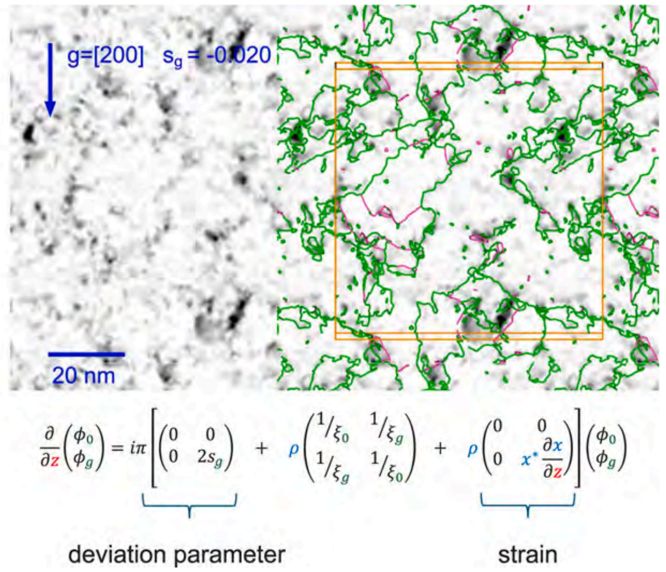
These approaches remain relevant in the fusion context, but we also have a need for models with predictive capability at larger length and time scales. These models will need to work well beyond the envelope of direct empirical validation and so must be largely physics based.

A note on scope: Each of the preceding research area specific chapters identify materials challenges in which modelling and simulation will implicitly play a role alongside experiment. Some of these chapters also explicitly identify particular modelling and simulation challenges. We do not duplicate this content here, instead identifying overarching challenges and solutions applicable across the range of fusion materials and systems.

In addition to modelling and simulation, we also include challenges related to the opportunities offered by artificial intelligence (mainly machine learning) and issues related to the collection, curation, storage and use of data in the development and deployment of materials for fusion.



Stress and simulated TEM of 21 M tungsten atoms at a simulated irradiation dose 1.0 dpa



Daniel R. Mason, Max Boleininger, Jack Haley. Eric Prestat, Guanze He, Felix Hofmann, Sergei L. Dudarev. Simulated TEM imaging of a heavily irradiated metal, Acta Materialia. Volume 277, 15 (2024), 120162

The following experimental challenges highlight the need for computational modelling and simulation.

CHALLENGES

Lack of facilities for direct testing of components in the full fusion environment	
Lack of a source of 14 MeV neutrons	The lack of availability of sources of 14 MeV neutrons makes the use of direct testing of candidate materials under any significant 14 MeV neutron fluence a practical impossibility for the qualification of materials. Neutron transmutation rates, and therefore He and H gas generation, in fusion will be different than in fission, and understanding of radiation effects in materials over long durations is crucial.
Challenges in accessing fission neutron sources for fusion material testing	Accessing testing capacity in research and commercial fission reactors remains a challenge, as does efficiency (in terms of cost and timescale) of access to samples after irradiation. Models must be able to translate/extrapolate the effects of irradiation using a fission energy spectrum to that anticipated for fusion.
Scarcity of in-situ testing and characterisation facilities	No facility capable of simulating the full fusion environment currently exists. Facilities capable of replicating subsets of the conditions in a fusion power plant remain globally scarce (and in some cases may be under threat). Direct empirical exploration of the full synergistic effects of all aspects of the fusion environment are therefore currently impossible, hence the need for theory and modelling.

High cost of irradiation and handling of active material	
Only limited amounts empirical data are available for the fitting (training) and validation of models	Due to the high cost and limited capacity at irradiation facilities and active labs, it is not possible to generate large scale databases of empirical data for the purpose of training and validating empirical or data-centric models.

Volumes of material available for testing and qualification are small	
Experimental irradiation of materials produce only small volumes of irradiated material	Low penetration of charged particles (such as protons and heavy ions) produces only small irradiated volumes, inconsistent with standard test specimen geometries. Samples irradiated in fission based, materials testing reactors (MTR) are sub-sized, which are not in scope of accepted testing standards.

Uncertainty in material choice for demonstration fusion power plants	
The selection of materials for demonstration fusion power plants components is not yet locked down and is likely to be subject to future change	Whilst novel materials can be developed for commercial fusion, demonstration fusion power plants, such as STEP, are constrained by aggressive timelines and therefore it is likely will use existing materials. However, ongoing uncertainty in the material choices for STEP means that (the other challenges not withstanding) a normal material development timescale cannot be completed before the target date for STEP, and other global demonstration fusion power plants, commissioning.

CHALLENGES

Ongoing uncertainty in material performance	
Our chosen materials will be subject to emergent problems not predicted prior to operation	Fusion requires the deployment of many new materials in a completely new environment. Any predictions we make about performance will be subject to rapidly changing uncertainty as the time horizon of prediction increases and we will need to rapidly analyse, understand and mitigate emergent problems related to material property evolution. Some emergent phenomena may be completely unexpected.
Multiscale effects	Nuclear materials behaviour spans multiple length-scales from sub-nanometre, picosecond atomic radiation damage processes, through to metre scale components deployed for years in service. Simulation of the response and behaviour of materials in the fusion environment must account for the initial origins of radiation damage, that require representation of atomic interactions, whilst scaling up to engineering relevant outputs that inform the structural and functional integrity through service. This points towards a multiscale modelling approach, yet gaps and error propagation when passing information from one model to the next must be quantified and reduced for this approach to be successful.

Modelling and simulation capabilities	
Development of simulation methodologies for materials interfaces that can be applied rapidly to respond to new designs in fusion systems (such as blankets and shields).	One of the key problems for tritium breeding components is the migration of tritium across interfaces between materials – this will strongly influence the ability of a breeding solution to enable self-sufficiency for a fusion device. As the community explores different options for tritium breeding, different interfaces between materials must be understood and modelled (this includes, for example, the interfaces between materials designed to create tritium barriers). While we can model, with effort and using first principles calculations and approximations at the dynamic scale, specific interfaces, it is not sufficiently rapid to respond to the evolving technology landscape.
Direct translation of neutron induced damage events to models predicting evolution of damage	Tools exist to predict the energy, location, frequency of damage events created by neutron irradiation in fusion device designs. But this data cannot be readily used by models predicting the formation, evolution and impacts of radiation damage because of the mismatch between timescales and length scales of neutron events compared to length and timescales in atomistic or other materials modelling.
Uncertainty quantification in materials modelling to be fed into engineering predictions.	Uncertainty quantification is a rapidly improving landscape in nuclear simulation predictions, covering uncertainties in nuclear data, material composition and fusion component geometry. But there is no routine application of uncertainty to predictions of property changes from material modelling.

CHALLENGES	SOLUTIONS	IMPACTS
Lack of facilities for direct testing of components in the full fusion environments.	• Develop modelling frameworks for predicting property changes in fusion materials, including multi-element materials such as advanced reduced-activation ferritic martensitic (ARAFM) steels, over long time and length scales (incorporating relevant effects of irradiation dose, corrosion and chemical effects, heat flux and magnetic flux). • Exploit simulation in concert with experiment to develop protocols to use alternative irradiating species as surrogates for fusion neutrons and to support model calibration. • Work in close collaboration with fission materials community to exploit the experience, capacity and data available in this adjacent field. • Develop component and plant scale models (digital replicas), capable of extrapolation significantly beyond the experimental envelope and incorporating rigorous uncertainty quantification, suitable for making engineering design decisions. • Develop above approaches in consultation with regulators to ensure model-based output can be used in materials qualification.	• Enable more rapid multi-component and interface materials development and qualification in absence of full-environment testing facilities.
High cost of irradiation and handling of active material	• Ensure models incorporate uncertainty quantification from first principles so that the implications of small sample sizes are quantified. • Ensure that experimental matrices make full use of optimal experimental design and incorporate the requirements for interfacial model development and validation (which may suggest alternative datapoints to those required solely for direct empirical testing). • Establish databases, policies for data sharing and best practice for reproducibility to ensure that expensive and scarce results are available for maximum value extraction.	• Enables informed, robust and integrated modelling/experimental decision making in design and qualification of machines. • Ensures that a limited number of experiments provides the maximum impact. • Ensures that all researchers (ideally globally) benefit fully from all work carried out.
Volumes of material available for testing and qualification are small	• Use existing and new modelling tools from first principles to support development of testing techniques suitable for small volumes of material, in consultation with regulators.	• Enable the use of a greater range of irradiated specimens in materials qualification.

CHALLENGES	SOLUTIONS	IMPACTS
Uncertainty in material choice	• Develop high-throughput machine-learning methods for materials simulation (including optimal design, online optimisation, surrogate models etc.) to enable rapid filtering of candidate materials to support quicker design decisions.	• Modelling and Simulation can be used to shorten time to decision making and reduce uncertainty in plant development programmes.
Ongoing uncertainty in material performance	• Develop protocols for the "materials digital twin" to incorporate material-level information into digital twins to support handling of uncertain material property evolution in management of plant in service. Such operational digital twins relate closely to the digital replicas required to support engineering design.	• Enable developing issues in service to be caught at the materials level, ideally before expensive failures manifest at the component scale.
Modelling and Simulation capabilities	• Develop rapid machine learning algorithms for interatomic potentials, but these need a precise methodology to be defined (e.g. to specify the calculations that are needed to provide sufficient training data). • Alternatively, develop universal potentials trained on all available data (regardless of material) but these are presently too slow or methods for on-the-fly learning in some cases, but balanced against the increased computational costs of these universal/adaptive methods. • Develop new methods to bridge the length and timescales between real-life neutron events and atomistic models, to improve the engineering relevance of damage evolution modelling to the scenarios in fusion devices. These could include acceleration methods to evolve atomistic systems between the comparatively rare (in space and time) neutron damage events and conversion algorithms to switch between atomistic/damage modelling and the nuclear simulation tools that can predict the next damage event (including changes of composition [transmutation]) for an evolving system (e.g. if damage modelling predicts solute clustering then the nuclear simulations can predict the relative frequency of damage events in bulk vs. precipitates, but only if codes can transfer data between the two). • Application of statistical methods (random number generation, etc.) to modelling methods to represent uncertainties in input parameters and thus provide ranges for predictions. Exploring uncertainties provided through machine learning methods, where changing the training data changes the "learnt" fit and thus provides a range of predictions.	• Methods that can be more flexibly and universally applied to the wide variety of material scenarios (interfaces, mixtures, temperatures, scales, etc.) will allow more rapid digital prototyping of engineering solutions before committing to physical mock-ups. • Linking the full simulation lifecycle for neutrons, from their generation, through nuclear interactions, leading to the generation, accumulation and evolution of radiation damage will make those latter (damage) modelling activities to be more relevant to fusion systems and, furthermore, will help to guide the designing of surrogate experiments to study the impact of fusion-neutron irradiation on materials. • Developing techniques to quantify uncertainties in modelling and simulation will enable engineering ranges to be provided, thereby helping to assess the relative importance of phenomena on the future operation of fusion machines (at least until physical engineering feedback is available).

Facilities, infrastructure and industry

Facilities, infrastructure, and industry	Capabilities
UK research computing infrastructure	• Accessibility to UK infrastructure for the purposes of tackling the above challenges should be monitored on an ongoing basis to ensure access does not become a bottleneck to fusion plant development. • Some of the models developed for fusion (e.g. plant scale digital replicas) may require best-in-class infrastructure in order to be useful, so infrastructure needs should be continuously assessed as the tools evolve. • UKAEA is ready to host a new high-computing facility and Artificial Intelligent (AI) data centre for supporting fusion research projects.
Research software infrastructure	• Tackling the fusion modelling challenges will require the development of new techniques and related software. Resource must be allocated for the development, maintenance and dissemination of these new tools.

TIMELINE

SHORT TERM	INTERMEDIATE TERM	LONG TERM
Involve modelling community in discussions with regulators to ensure development of digital tools is consistent with materials qualification needs. Develop guidelines for data-sharing and best practice in reproducibility.	Develop multi-scale modelling techniques prediction of material property evolution under fusion conditions. Develop hardware, software and human infrastructure required for data sharing and reproducibility from machine-learning techniques. Develop protocols for uncertainty quantification in simulation outputs from first principles. Engage modelling community in design of integrated modelling/experimental matrices and in development of small specimen testing protocols. Develop protocols for plant scale digital replicas and twins incorporating information from the material scale.	Develop plant and component scale modelling techniques, capable of extrapolation significantly beyond the experimental envelope.

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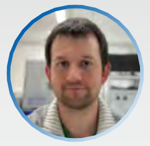

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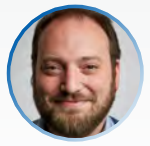

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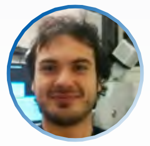

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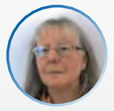

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