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Materials challenges for successful roll-out of commercial fusion reactors

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EDITORIAL

Materials challenges for successful roll-out of commercial fusion reactors

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Abstract

As members of the UK fusion community (covering national laboratories, academia and industry), we approached various colleagues to put together articles for this special issue of the Journal of Physics: Energy covering the materials challenges through to successful roll-out of fusion reactors. This paper serves to introduce the special issue and gives our opinion on the key challenges, many of which are covered in more detail in the submitted papers. Others may have differing opinions about what the key challenges are, but what we will all agree on is that they are substantial and will require sizeable resources to be addressed. Further, while we are all UK-based, all humankind will benefit from successful commercial roll-out of fusion for energy production, and the effort has been and will continue to be global. Fusion has entered the engineering era. Moving from plasma science to experiments demonstrating the benefits of modified torus shapes and advanced divertor geometries, the ‘field’ has become an ‘industry’. Investors now focus on whether superconducting magnet joints are feasible in large tokamak designs and how to deliver net energy to the grid. As with all technology trajectories, materials (both structural and functional) are the key enablers. For fusion materials, the three major challenges remain resilience to the combined damaging effects of tritium, transmutation and neutron bombardment (a veritable ‘triple whammy’), achieving suitable irradiation strategies for adequate damage studies (with optimal use of modelling as complementary science) and defining material safety and waste guidance in an era of evolving regulation. In the following, we highlight issues around ‘the triple whammy’, the resulting need for testing facilities and modelling proxies, and aspects of regulating materials in, and waste generated from, operating fusion reactors.

1. Tritium, transmutation and neutron bombardment (‘the triple whammy’)

In this section we introduce both our thoughts on important aspects of ‘the triple whammy’ and topics which will be covered in more detail in the papers of the special issue. Materials in fusion reactors face a demanding combination of megaNewton (MN) linear and torsional forces, electromagnetic fields heading towards 20 Tesla, high (>500 °C) and low (cryogenic) temperatures and the corrosive environment of supercritical gas or molten salt/metal coolants, all coupled with a requirement for components to function in a highly precise manner for extended periods of time. Key issues for plasma-facing materials include very high heat fluxes (up to 20 MW m⁻² sustained [1]) and erosion. However, it is not performance under these stresses which dictates the choice of materials for tokamaks, but primarily the microstructural factors, including phase transformations and precipitate formation, which determine structural (e.g. mechanical) and functional (e.g. superconductivity) resilience in the face of (a) multiple atom displacements by neutrons, (b) distortions due to ingress, retention and release of hydrogen isotopes (especially tritium) and (c) the evolving composition of the materials (with resulting helium gas and transmutation products) through neutron-induced transmutation. Fission studies, in recent decades, define a typical damage range in displacements per atom (dpa) ranging from thousands for nuclear fuel, to 1–10 dpa for internal reactor

components to 0.1 dpa/annum for reactor pressure vessels. By contrast, the UK's anticipated Spherical Tokamak for Energy Production (the STEP prototype power plant, due to be in operation by 2040) will run with neutron energies and fluxes likely to inflict damage of the order of 20–200 dpa at the first wall. DEMO (the European Community's 2050 fusion DEMOnstration power plant project) currently sets thresholds for baseline material selection at 15 dpa per full power year, for front-wall steel damage in the breeder blankets [2]. In recent years, the commercial sector has made significant contributions to fusion developments, not least because the projects are small and flexible. While ITER is an important global programme, it has faced challenges with its massive scale, enormous cost and multinational partnerships, leading to limitations in innovation and evolution. Tokamak Energy (with their pulsed copper ST40 spherical tokamak in the UK and a future high-temperature superconductor (HTS) fusion demonstrator concept) and Commonwealth Fusion Systems (working on SPARC in North America) are both now focused on improved HTS magnet materials for application in fusion.

It is the structural materials, first and foremost, that will enable higher thermal operation of the fusion power plant but, since fission's next generation of advanced modular reactors (AMRs) also require steels operating above ~ 500 °C, there are synergies for research in the broader nuclear community. Fission and fusion studies on irradiated metals now run in parallel, although commercial realisation of reactors is likely to be sequential: light water reactors (LWRs), small modular reactors, AMRs and then fusion.

With irradiation, metals develop dislocation and cluster-type defects. A major avenue of development is that of defect sinks via oxide dispersions—nanoscale precipitates to focus and 'defuse' the growing dislocations under neutron impact and also to sequester H or He to minimise swelling, or to control grain boundaries [3]. Oxide dispersion strengthened steels are joined by castable nanostructured alloys and high-entropy alloys (HEAs) [4–6] in a growing field of manipulated microstructures, to exploit differential strain or to enhance kinetics and defect behaviour to encourage defect recombination. To limit transmutation damage (as one element or isotope evolves to another via ongoing neutron capture), fusion materials designers also aim to constrain compositions to those elements which do not transmute under neutron impact. Resultant products include the reduced activation ferritic-martensitic steels (RAFM structural materials), which require further work related to joining techniques and improving the consistency of manufacturing quality at an industrial scale [7]. Avoiding the presence of some elements, such as those with long-lived decay products, is also important from a waste-management perspective.

Early work looking to address the impact of surface damage by neutrons, on tungsten's subsequent ability to retain and release deuterium (a forerunner to tritium as fuel)—suggests some degree of saturation of defects may be likely [2, 3]. Thermal cycling in the fusion reactors of the future may also provide some annealing relief to damaged components and treatments to limit the formation of dust that may pose a radiological hazard. However, beyond saturation and stress relief, materials science must also look to sacrificial phases and suitable evolution of phases *in situ* to provide novel routes to extend component lifetime opportunities to design engineers.

Functional materials are being targeted for development in addition to the aforementioned structural materials. The limited space within a number of fusion reactor designs has pushed engineers to consider highly efficient shielding materials to protect high-temperature superconducting magnets that control the fusion plasma (e.g. high-entropy hydrides [8]), as well as components targeting and enabling the optimised breeding ratio of fuel in the fusion reactor to sustain the fusion reaction. This includes the use of Li-containing components, such as Li_2TiO_3 [9], and neutron-multiplying materials containing isotopes of Be and Pb [10]. Efficient thermal neutron absorber materials based upon borides (for example, tungsten borides [11]), are being considered alongside other high-neutron cross-section materials and gamma shielding materials with high Z values.

To deliver solutions, experimentalists require laboratories and suitable samples to accelerate innovation, and the development of mechanistic models that will efficiently predict safety margins and long-term behaviour. In fusion, this implies irradiation strategies.

2. Irradiation strategies: testing facilities and modelling proxies

Neutron source facilities offering suitable fluxes at high-neutron energies enable much-needed nuclear data experiments and neutron cross-section datasets that underpin shielding specifications, component lifetime estimates, waste calculations and diagnostics viability. Only a handful of these exist worldwide (including the high flux reactor (HFIR) in the USA, the high-intensity D–T fusion neutron generator (HINEG) in China, and Germany's DT neutron generator at the Technical University of Dresden (NG TUD)). These will be augmented in the UK when the University of Birmingham commissions a High-Flux Accelerator-Driven Neutron Facility in 2022. Novel rigs utilising benchtop and commercially available small neutron sources are also very much of interest to the R&D community, with Japan leading the way on the latter [12]. The

commercial sector is also bringing low and intermediate neutron sources to the market, for example, the Alectryon 300 T device from Phoenix LLC.

However, research to fully understand true surface and bulk damage in fusion materials is hampered by the limited number, globally, of neutron sources that provide both high energy (14 MeV) and high flux (greater than 10^{14} n cm⁻² s⁻¹). No test facilities currently exist with spectra that come close to those expected in an operating commercial fusion reactor, making it difficult to deconvolute the dpa-transmutation correlation required for some materials: e.g. W-based alloys, or when considering He generation in ferrous alloys. In a tokamak, the neutron spectra across the profile from first wall to vacuum vessel change according to the type of materials present, the coolant and component design. Such changes, especially in the percentage of thermal and fast neutrons, will generally have a significant impact on primary knock-on atoms (PKAs) that cause the initial radiation damage as well as impact transmutation rates (especially when coupled with moderating materials) [13]. While the fission community provides a suite of international materials test reactors with high neutron energies, fluxes are low by fusion standards and PKA replication is poor. Irradiation campaigns therefore require long exposures: each sequential year buys another dpa or two. The fusion community has a planned facility in the form of the International Fusion Materials Irradiation Facility—DEMO Oriented NEutron Source (IFMIF-DONES [14]), which started in 1994 but realisation is not expected until 2029. Dual-beam proton source experiments sometimes act as proxies and may offer the benefit of combined load (irradiation and mechanical load) evaluations. Ion proxy irradiations potentially offer good single variable data in damage experiments, for modellers seeking to utilise resulting data for mechanistic simulations (including atomic-scale simulations); however, they have limitations in terms of temperature control arising from, e.g. location of the thermocouple compared to the specimen, ion flux (beam current), whether the beam is rastered or defocused, rastering rate, material thermal conductivity and whether a heat sink is attached or not. It will be difficult to validate models to a regulator's satisfaction at the component scale using ion irradiations, which only penetrate the surface to a few microns; therefore, implementation of the IFMIF cannot come soon enough.

For the past decade or more, because of the lack of testing capabilities and the benefit of utilizing mechanistic models instead of empirically fitted trends, mechanistic modelling has become a mainstream proxy and underpinning route to reduce the irradiation burden (although it will never replace it). With atomistic modelling, the mechanisms of damage initialisation and recovery can be explored using frameworks such as density functional theory and classical molecular dynamics simulations [15, 16]. This solid-state physics approach has highlighted the benefits of body centred cubic (bcc) vs face centred cubic (fcc) crystallography in reducing dislocation slip in some materials [17], and has demonstrated dimensional changes that can result purely from stress relaxation effects in lattices exposed to neutron impact *in silico* [18]. Models to understand the decomposition of tungsten alloys and steels under irradiation are needed to predict the combined effects of dose, temperature and stress, for ITER, STEP and DEMO. Predictive atomic-scale algorithms for computing microscopic stresses, strain and swelling of tungsten, steels, beryllium (a tricky material to experimentally assess) and other down-selected baseline materials [19, 20] are being funded by the same international community that is building ITER and beyond. Given the timescales and length scales that need modelling, multiscale models (drawing the mechanisms from the atomic scale and implementing their effect in the mesoscale), must be developed to support design engineering and failure/safety analyses, much in the same manner that the fission community developed fuel performance codes. Component-level simulations are planned [21], relating dose, temperature and stress—derived from the analysis of microscopic and mesoscopic models for irradiated microstructures and validated using ion irradiation experiments (aided by digital image correlation) and other integral testing.

Beyond damage and failure mode analysis, modelling must also look to augment process innovation, *in situ* monitoring and probabilistic design in the absence of traditional (fission type) design codes [22]. All types of fusion reactors (experimental, demonstration and commercial) will be closely monitored, and so multiple sensor types need to be developed. This brings other materials' needs for this sensor development as well as analysis of big data, machine learning and other aspects of convergence science that need to be put forward to solve the engineering needs of fusion power.

3. Defining material safety and waste guidance in an era of evolving regulation

ITER engineering design codes currently look to the fission approach and require significant data for qualification of materials, premised in the first instance, on the development of suitable small-scale test techniques [23]. The burden of proof includes multiple industrial heats, ASTM or other certified testing standards for all data, testing results for the full operational range (in minimum 25–50 kelvin steps), non-destructive testing verified for joint performance, development of function-specific codes, cycling effect data and demonstration of negligible creep under irradiation.

Fission-to-fusion extrapolations have limitations though: DEMO has already noted underestimates in embrittlement [24] when the fission community used Reaction Pressure Vessel data to predict LWR degradation via formulaic extrapolation. The latter prompted risk mitigation surveillance programmes in LWRs and has led DEMO to prohibit formulaic degradation principles for licensing going forward [2].

In the UK and globally, opinion is evolving: to bring fusion power plant prototypes online by mid-century, traditional nuclear codes for materials acceptance and qualification will need to be replaced by a more creative—but robust—approach, potentially including *in situ* surveillance in the first prototype reactor, which will be needed *in operandi* in the reactors that are eventually used commercially, relying on advances in sensor and control systems (including with artificial intelligence) over the past decade or so [25]. Alternatives to the R5/R6 codes, so well maintained by industry mainstay EDF, may include pre-qualification proof testing on components in geometries designed around in-operation maximum stress areas, an approach advocated, for example, by Waldon *et al* [26]. In the USA, fusion design code development was recently triggered within the ASME section 3 organisational structure, via the creation of a new sub-group for ‘Fusion Energy Devices’ [27]. The latter is tasked with considering both magnetic and inertial confinement, and an early roadmap has been constructed to provide direction and concepts for the new section 3, Division 4 Code Rules.

From a waste-regulation perspective, materials selection and design criteria will need to move beyond safety to also take account of the increasing emphasis, this century, on sustainability. With reference to the latter, a research focus will be how to reduce materials’ tendency to dust formation during recycling processes, as dust presents a particularly high safety risk during these operations on first wall components [28]. Studies of isotope partitioning methods (gas centrifuging; metal vaporisation and ionisation followed by electromagnetic separation) are experiencing a resurgence as routes to lower-level waste classifications for potential fusion materials [29]: isotopes with lower half-lives are targeted both in materials development upfront, and also in recycling of waste post-operation. As fusion looks to develop a dedicated and fit-for-purpose regulatory framework, it must look to accommodate the coming decade’s materials science innovations that reduce disposal and storage burdens, and tackle the application-specific topic of detritiation. Japan’s risk-based approach [30] is viewed as a positive example of what is possible.

The benefits of developing a fusion materials strategy, including the UKAEA-led Fusion Materials Roadmap [31], will not only accelerate the development of fusion energy technologies to combat the climate emergency but will also accelerate other key technologies, including those related to the space industry (both near-Earth satellite technologies and beyond-Earth exploration and missions), as well as enhance other sustainable clean-energy systems, including fission-based AMRs, some of which need similar leaps in material development and radiation testing facilities. Fusion facilities will enhance international collaboration at a time when it is clear that global problem such as climate change can only be solved when experts come together to support a common goal.

Data availability statement

No new data were created or analysed in this study.

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