

AN OVERVIEW OF UKAEA'S INTEGRATED FUSION TECHNOLOGY PROGRAMMES, EMPHASISING A DIGITAL FIRST STRATEGY

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Abstract

The UK Atomic Energy Authority (UKAEA) has undergone significant growth in its fusion technology programs, marked by the development of cutting-edge facilities supported by a robust technical expertise foundation. An overview of the breadth of our technology programs is presented and critical advancements are highlighted, including key results from Robotics and JET Decommissioning, Materials, Technology Development, and Tritium. A digital-first approach is implemented across the portfolio, leveraging advanced modelling to minimise the number of targeted experiments required to validate predictions and reducing reliance on exhaustive empirical testing. This allows for the adoption of a strategic approach, significantly accelerating delivery in line with public and private stakeholders' expectations. Examples of impactful results, emanating from this strategic digital first approach, are presented. The status of the world-leading fusion facilities H3AT, CHIMERA, and LIBRTI, are highlighted, emphasizing the digital-first approach adopted in these programs.

1. INTRODUCTION

Historically, fusion progress has relied on iterative, experiment-driven innovation: building devices, testing performance, learning from outcomes, and refining designs through successive generations. Although this empirical approach has yielded valuable insights, it is slow and resource-intensive, constraining the pace of advancement. Additionally, it limits our ability to take large leaps into untested physical environments. To meet the urgent global demand for affordable clean energy, the field should transition towards designing and optimizing systems *in silico* before constructing physical prototypes. Advanced computational modelling and digital-first methodologies can reduce reliance on costly trial-and-error experiments and potentially accelerate the delivery of viable fusion technologies. At the same time, the first generation of prototypic fusion power plants will introduce a step change in operating conditions compared with current scientific reactors [1,2]. In-vessel components will be exposed to substantially higher thermal and neutronic loads [3,4], while fuel cycles must operate continuously—unlike the batch-mode operation of JET [5,6]—and incorporate tritium breeding and coolant purification, neither yet demonstrated. These advances pose significant challenges for component development, material qualification, and tritium fuel cycle engineering. To ensure reliable deployment under these unprecedented conditions, comprehensive models capturing and predicting the behaviour of these systems are essential.

Established, highly regulated industries have a long history of test-driven qualification and certification, however, these industries are now investigating virtual system assessments as a means to accelerate timelines and reduce overall costs. For example, it has been suggested that widespread implementation of aircraft certification by digital analysis will be possible in 2040-2050 [7]. These are similar timescales to those targeted for the operation of prototypic fusion power plants, which will be first-of-a-kind devices without historical data to support qualification and operating in extreme multi-physics environments. This emphasises the need for accelerated research on simulation-led qualification for fusion. Prior to operation, there will be no mechanism by which to physically test in-vessel components under the exact environmental conditions of a fusion power plant [8], while these components need to be qualified to the satisfaction of key stakeholders, such as investors or a safety regulator. To resolve this, UKAEA's Fusion Technology Division is developing a roadmap to virtual qualification, explained in Section 2.

The predicted environment of fusion power plants includes a wide range of extreme conditions, including irradiation by 14.1 MeV neutrons, magnetic fields, cyclic thermal and mechanical stresses, and corrosive environments. The materials inside the vacuum vessel need to be able to operate under these conditions, while these environmental factors change their properties and performance. Desired properties include minimal tritium retention, radiation-tolerant microstructures, and “reduced activation”, meaning no high-level radioactive waste will be generated. Alloying elements such as Ni and Mo provide materials with excellent high temperature performance and radiation damage tolerance, but neutron absorption by these elements can result in transmutation and formation of long-lived radionuclides. These can decay via alpha- and proton-decay, producing radioactive waste and concomitant helium and hydrogen generation, resulting in significant swelling and embrittlement of the materials. To resolve these challenges, existing and new materials that can perform better in these environments are being developed and engineered by the Materials Division at UKAEA, as explored in Section 3.

Significant challenges also remain for the development of fusion fuel cycles. Of particular importance is the quantification and minimisation of tritium inventories required for power plant operation. Advanced tritium handling systems must be developed to maintain low tritium inventories, and analytical tools and digital systems will be required that can track the migration of tritium through the fuel cycle. Understanding tritium inventories required to operate a fuel cycle is a complex challenge requiring in depth understanding of the behaviour of tritium in evolving first wall and structural materials, as well as in every subsystem in the fuel cycle itself. The UKAEA approach to the issue of tritium inventory estimation is considered in Section 4.

Finally, the decommissioning of JET has introduced unprecedented challenges to the field of robotics. At UKAEA, robotic systems have been utilised for retrofitting and maintaining JET, in addition to undertaking measurements required for supporting scientific findings, since the 1980s [9]. The success of JET deuterium-tritium (DT) experiments and many other scientific achievements have demonstrated the necessity and capability of the remote maintenance system to enable the development of sustainable fusion power solutions [9,10,11]. The Robotics Division at UKAEA is optimising maintenance processes and developing new capabilities to enable decommissioning activities, as discussed in Section 5.

2. COMPONENT QUALIFICATION

The established approach to engineering simulation in fusion component qualification is to perform deterministic analysis (single result prediction with no uncertainty) of different physical phenomena in isolation and apply a range of design codes and standards to assess the component suitability [12]. An alternative approach, virtual qualification, uses simulations to determine the probability that a component will meet its functional and system requirements. An example workflow for virtual qualification is presented in Fig. 1. The key changes from traditional approaches are the emphasis on prediction of probability of component performance in isolation as well as within a wider, coupled, system. An evidence-based approach to demonstrating model credibility to facilitate risk-based component qualification in fusion is outlined below.

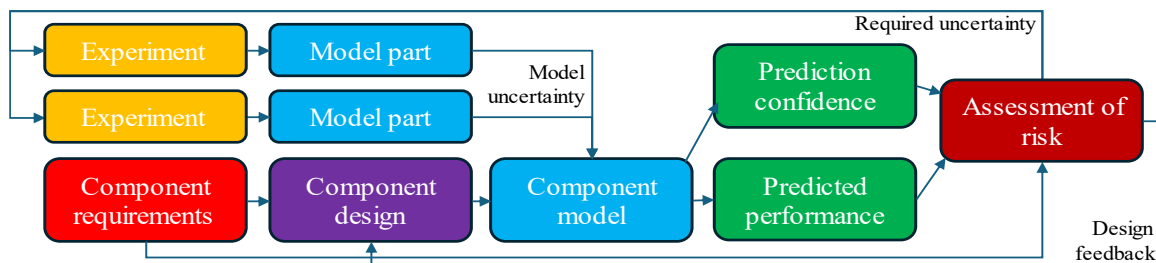


FIG. 1. An example workflow for virtual qualification of a component.

2.1 Roadmap to virtual qualification

A key outcome from the development of a virtual qualification process for fusion is the ability to provide a performance prediction against requirements that encompasses all sources of uncertainty in the system. This must include the uncertainty inherent to the models implemented, as well as input uncertainty encapsulating the limitations of the understanding of the operational environment. Quantification of both sources of uncertainty requires the understanding and processing of aleatoric uncertainty (statistical representation of system parameters that is well characterised) and epistemic uncertainty (systematic system error with limited characterisation).

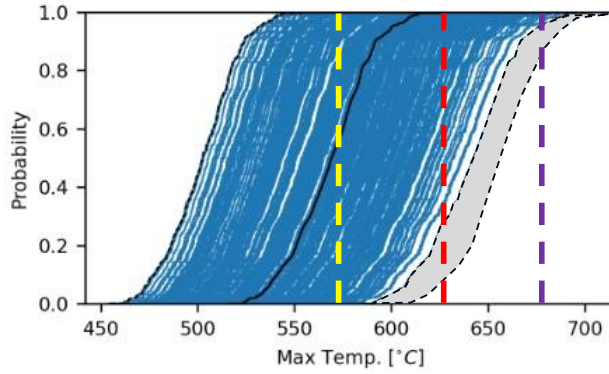


FIG. 2. An example report to a decision maker for a failure mode driven by maximum temperature in a component. The ensemble of CDFs captures the epistemic uncertainty of the prediction.

epistemic sample, shown in Fig. 2 by the blue lines and the mean result shown in black. The model uncertainty derived from validation against experiment is shown by the grey area. Three different failure conditions can be identified, shown by the yellow, red and purple lines. A high probability of failure that is not mitigated by a reduction in uncertainty (yellow) would likely require component redesign. A failure regime dominated by epistemic input uncertainty (red) could be shrunk by better understanding of the operational environment. Finally, a situation where the model validation uncertainty accounts for the majority of the failure region (purple) would motivate model development and additional validation experiments to reduce the model uncertainty.

The reality of implementing virtual qualification for complex systems operating in uncertain fusion environments involves four key technical challenges:

- (1) Demonstrating credible model validation.
The cornerstone of virtual qualification is the ability to credibly demonstrate that a simulation model replicates real-world behaviour. This is done by validation of models against carefully constructed experiments, in such a way that all uncertainty is accounted for and apportioned to either the model or the experimental setup.
- (2) Combining model validation uncertainties.
It must be possible to construct overall model validation from multiple independent validation sources, as it is likely that testing in a fully representative multi-physics environment will be prohibitively expensive or not possible.
- (3) Extrapolation of a validation case to untestable environments.
Component qualification is required for operational environments in which simulation models cannot be directly validated. Extrapolation of a validation case from experiments that can be undertaken is required, with robust quantification of the uncertainty introduced in the extrapolation.
- (4) A Credibility Assessment Framework (CAF) for fusion.
A CAF formalises the assessment of simulation credibility, including requirements on validation, experimentation, and uncertainty quantification. CAFs exist within adjacent engineering industry [13,14,15], but none cover all of the constituent parts required for virtual qualification in a fusion context.

Work within this roadmap has begun, and the work conducted on the first step is presented below, implemented for multi-physics loading of a mock-up of a high heat flux fusion component.

2.2 Demonstrating credible model validation

A model validation approach has been developed using a fusion relevant test case: a monoblock subjected to its dominant load source of high surface heat flux [16]. Experiments were performed using the HIVE facility [17], which uses high frequency induction heating to replicate surface heat loads. To aid method development, the monoblock was machined from 316LN steel as a well understood, simple proxy for the actual component design. Value from experiments is maximised by using Digital Image Correlation (DIC) to capture full field mechanical response over the front face of the monoblock, see Fig. 3. Further, pre-test simulations were utilised to drive an in-house sensor placement tool in optimally placing 10 thermocouples on the monoblock, shown in Fig. 4, minimising uncertainty in temperature field reconstruction from thermocouple readings.

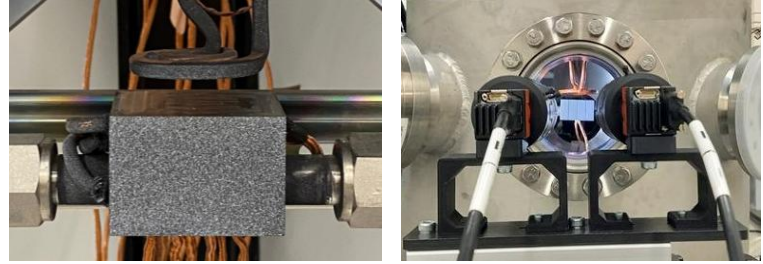


FIG. 3. The experimental setup in HIVE, showing the monoblock and induction coil coating with a speckle pattern for DIC measurements (left) and the stereo camera arrangement viewing the monoblock through a port (right).

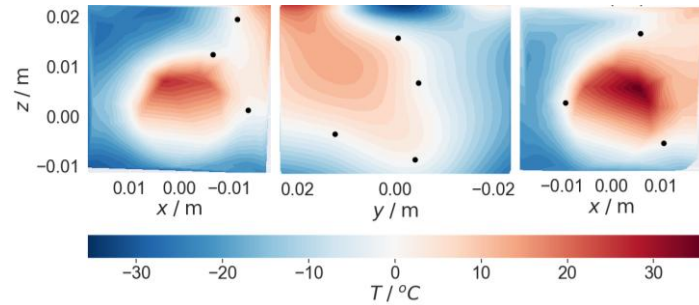


FIG. 4. The output from the thermocouple placement optimisation. Shown is the temperature field reconstruction error over three faces of the monoblock for optimally placed sensors. Sensor locations are also shown.

The basis of the simulation is an electromagnetic-thermal-mechanical finite element model, modelling the induction heating and thermal and mechanical response subject to monoblock coolant flow. The simulation is performed probabilistically; the input space derived from the experimental setup and its inherent uncertainty is sampled, and probabilistic predictions made using a statistical surrogate trained on data from the finite element model. An ensemble of CDFs is generated, with the extrema representing the bounds of the probabilistic simulation, which are then compared with experimental data as illustrated for thermocouple data in Fig. 5.

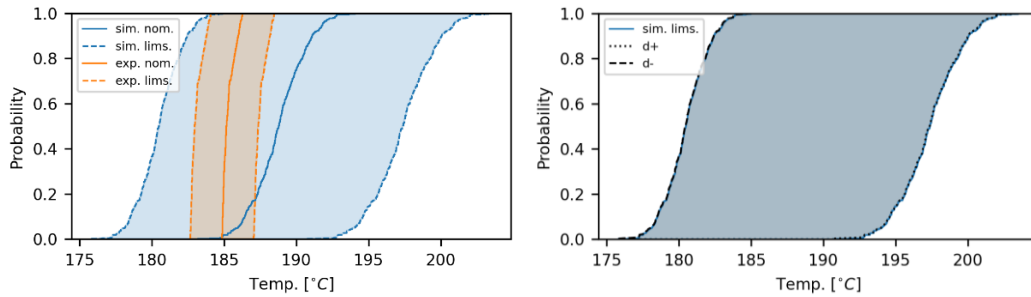


FIG. 5. Validation results for a thermocouple, showing a probabilistic result comparison (left) and the resultant MAVM validation plot (right).

The Modified Area Validation Metric (MAVM) described by Whiting et al. [18] is used to assess the agreement between the probabilistic simulation and the experimental data. This metric is calculated as the difference in area between the simulation and experiment CDFs. The upper and lower differences were calculated, of which the worst case upper and lower validation metric results, ‘d+’ and ‘d-’, are used to generate a conservative assessment of simulation validity. When interpreting the validation metric there are two possible scenarios; the ensemble of epistemic CDFs for the simulation completely overlaps that of the experiment (d+ and d- are zero), or the ensemble

of CDFs for the simulation and experiment contain some area which does not overlap (d^+ and/or d^- is non-zero). The first case is shown in Fig. 5 for the thermocouple data; the model's predictive capability is completely driven by the simulation epistemic uncertainty and there is no discrepancy with the experimental data.

In addition to the point sensor data, a comparison of the mean vertical strain field measured using DIC to the predicted field averaged over all epistemic and aleatoric samples is shown in Fig. 6. It can be seen in the third plot from the left that the mean simulation prediction tends to underestimate the strain near the top of the block by up to 1.5 milli-strain. However, this comparison is not sufficient to conclude whether this discrepancy is within the bounds of the simulation uncertainty. To assess this, the MAVM is applied pointwise across the field, and the maximum of the validation metric bounds is plotted as a field shown in the far-right plot of Fig. 6. This demonstrates that approximately 0.7 milli-strain of aforementioned 1.5 milli-strain is outside the simulation uncertainty bounds. This means that the predictive capability of the model for strain is driven by both the simulation uncertainty and model discrepancy as the validation metric limits are non-zero.

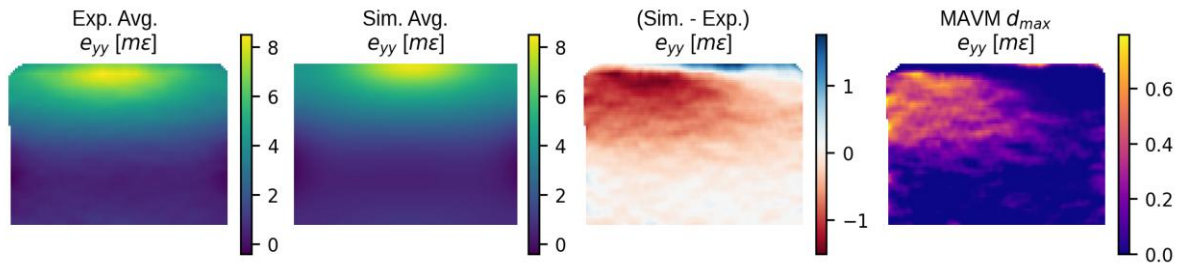


FIG. 6. Comparison of the mean result for an in-plane normal strain (left three plots) and the full field MAVM result accounting for the full probabilistic results (right).

These results demonstrate the first step in the roadmap to virtual qualification; validation of a probabilistic model against experiment, accounting for all uncertainty in the system. This work will form the foundation on which to continue through this roadmap to a viable solution for simulation led qualification.

3. MATERIALS DEVELOPMENT

To develop existing, and engineer new, materials that can perform better in the predicted fusion environment, simulation and experimentation are intrinsically linked, with computational tools used to inform both material selection and experiment design, and experimental data used to inform and validate computational models, which in turn allows for better understanding of fusion induced degradation mechanisms. Computational modelling is vital for predicting the impact that fusion neutrons and the fusion environment (e.g., stress, irradiation induced damage, and corrosion) will have on materials inside the vacuum vessel, which allows for experiments to be designed to simulate the predicted effects induced by the fusion environment, without the need to fully replicate the conditions inside a fusion power plant.

Neutron induced transmutations result in changes in material composition, e.g., pure W transmutes to Re and then Os, producing a brittle W-Os-Re alloy. The UKAEA's FISPACT-II [19] is an inventory code for modelling neutron- and proton-induced activation and transmutation using data from a wide range of nuclear data libraries, including the TALYS-based Evaluated Nuclear Data Libraries (TENDL) [20]. Using data produced from FISPACT-II, the concentration and activity contributions from all nuclides produced during transmutation can be displayed in “nuclide maps” as a function of operational time (see left part of Fig. 7), as well as the concentrations of He and H generated via reactions (n,α) and (n,p) , respectively. A key focus at UKAEA is to develop structural materials capable of operating at and above 600 °C, exceeding the capability of existing fusion grade steels, while maintaining lower temperature (< 350 °C) performance as radiation-induced low temperature embrittlement is of concern. Strategies to achieve this include modifying existing steels already used in high-temperature applications by replacing the high-activation elements with acceptable alternatives, modifying existing reduced activation ferritic martensitic (RAFM) steels by changing the chemistry and thermomechanical treatments to refine microstructure and optimise precipitate and solution strengthening mechanisms, and to develop non-metallic

alternatives such as silicon carbide fibre-reinforced silicon carbide composites (SiC_f/SiC). To design reduced activation materials such as EUROFER, FISPACT-II is utilised to predict activities of the radionuclides produced during operations (see right part of Fig. 7) and the change in composition, informing predictions of irradiation-induced secondary phase formations and impact on component lifetime and performance.

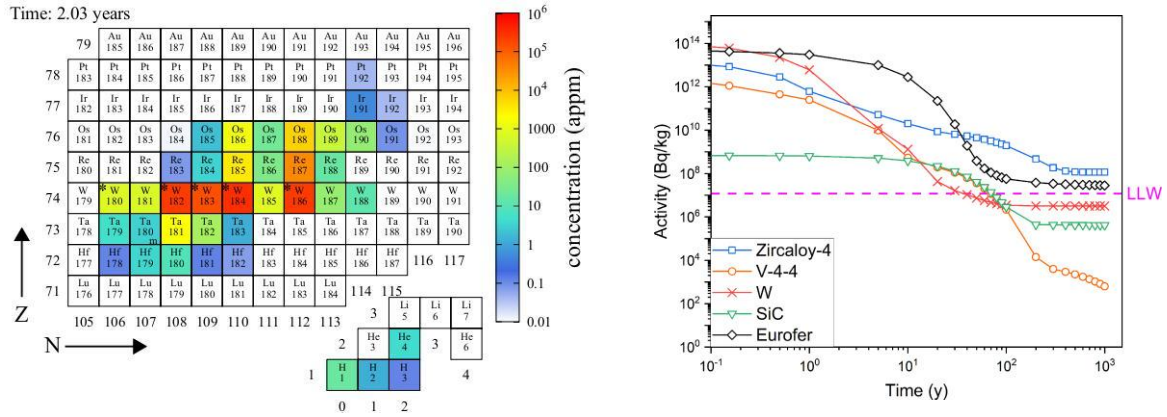


FIG. 7. Left: nuclide map showing the change in composition of initially pure W after a ~2 full power year irradiation under DEMO first wall armour conditions (total neutron flux = $8.25 \times 10^{14} \text{ n.cm}^{-1}.\text{s}^{-1}$), including the concentrations of He and H generated during this time [19]. Right: calculated activity of several candidate in-vessel materials as a function of time after 2 years of DEMO exposure. The UK low level waste limit (LLW) is denoted by a horizontal dashed line (reproduced from [21]).

Thermodynamical modelling, e.g., Thermo-Calc software [22], is used to predict crystal structures and secondary phases formed in our reduced activation alloys as a function of temperature, which informs material processing parameters as well as predicting temperature induced phase transformations during operation. For example, Fig. 8a) from [23] shows the equilibrium phase fraction with temperature for a boron-containing reduced activation ferritic martensitic (B-RAFM) steel, developed to replicate the delayed tertiary creep previously observed in Martensitic Boron and Nitride-strengthened (MarBN) steels, which can operate up to $\sim 650 \text{ }^\circ\text{C}$ in non-radiation environments, but are not reduced activation. Interrogation of Fig. 8a) enabled key phase transformation and precipitate dissolution temperatures to be identified and successfully used to form the desired tantalum carbides, with this new composition allowing for high normalising temperatures, to increase creep strength and hardness. Further, modelling can both inform the design of our irradiation experiments and interpretation of experimental data. Fig. 8b), from [24], shows dark-field transmission electron microscopy (TEM) images of an alloy engineered to have a higher density of fine MX-type nanoprecipitates (VN precipitates, identified by the bright dot contrast in the images) relative to conventional RAFM steels, with the experimentally induced damage profile calculated from the Stopping and Range of Ions in Matter (SRIM) [25] software shown in yellow.

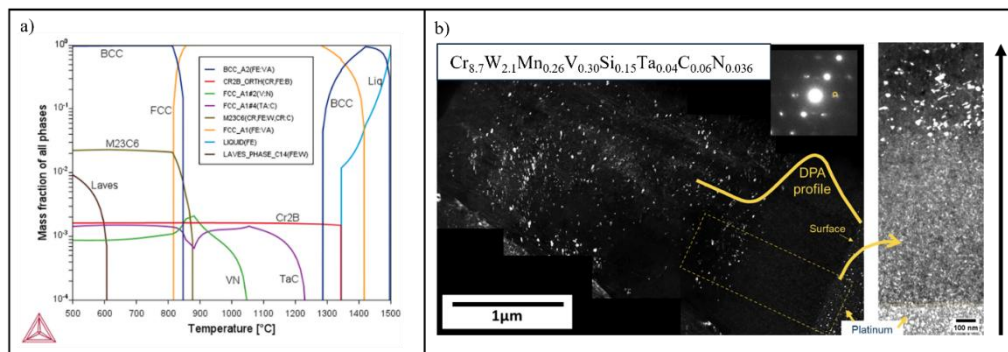


FIG. 8. a) The equilibrium phase diagram with temperature for a B-RAFM steel, predicted by Thermo-Calc 2 software using the TCFe8 database [23]. b) Dark-field TEM images showing VN precipitates (bright dot contrast) and 2 MeV Fe⁺ ion implantation profile overlay [24].

Results from this SRIM calculation predicted that implanting the alloy with 2 MeV Fe⁺ ions would produce relatively high levels of atomic displacements (from 40 to 100 dpa), simulating predicted end-of-life damage levels. After experimental implantation of these ions, the precipitates were found, using TEM and atom probe

tomography, to completely dissolve throughout the ion implanted region (as indicated by the loss of bright dot contrast in Fig. 8b). Whilst ion implantation can be an excellent tool for inducing fusion relevant defects over a relatively short period of time (e.g., hours), the high dose rates ($\sim 10^{-3}$ dpa/s) and size of the ion beam induced collision cascades relative to the precipitates under investigation, can result in complete dissolution which may not be seen under fusion neutron irradiation. Nonetheless, ion implantation has been successfully used to simulate transmutation induced modifications to materials, such as implanting He to simulate gas production from α -decay [26], and implanting transmutant elements to study changes in material composition under an irradiation environment.

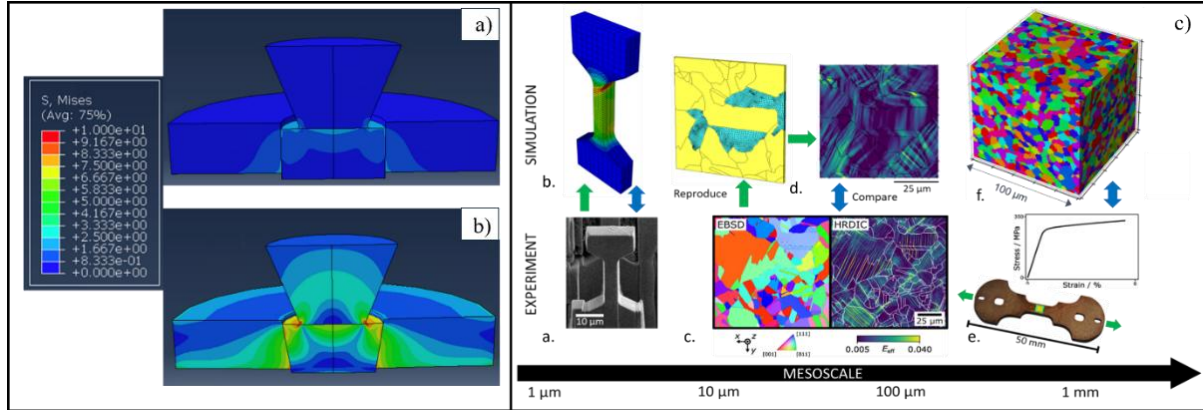


FIG. 9. Finite element analysis (FEA) simulations showing the von Mises stress distribution for pushed-out fibres during frictional sliding phase for a) parallel sided fibre and b) tapered fibre [27], stresses in MPa. c) describes the DbF strategy, intrinsically linking experiment and simulation across length scales [28].

However, ion implantation often only penetrates the first micron or so of material, and so surface sensitive methods are required to study this region. Furthermore, neutron irradiated materials must be sectioned into small volumes to be within the safe handling limits of the characterisation capabilities at the Materials Research Facility (MRF) at UKAEA. Therefore, we have developed novel micromechanical methods, combined with electron microscopy, high resolution digital image correlation (HRDIC), and computational modelling, to understand ion and neutron irradiation induced microstructural and mechanical property changes from within small volumes of materials, such as in-situ fibre push-out tests applied to SiC_f/SiC. SiC_f/SiC comprises SiC fibres within a SiC matrix, separated by a thin interphase layer of pyrolytic carbon. Irradiation can degrade this interphase leading to debonding and degradation of mechanical properties. To study the interfacial debond stress of ion implanted SiC_f/SiC composites, a short fibre push-out test was developed (see [27]), using an Alemnis Standard Assembly inside a Tescan Mira SEM with a 5 µm diameter diamond flat punch tip. This test was combined with finite element analysis (FEA) simulations to understand the mechanisms governing fibre debonding and push-out (Fig. 9a) and b)). In this case, FEA simulations revealed the importance and impact of experimental parameters on push-out mechanisms and material properties.

The Design by Fundamentals (DbF) programme further demonstrates our combined use of modelling and experimentation to understand and predict irradiation induced deformation and failure mechanisms in materials. DbF focusses on systematic calibration and validation of mechanical models, underpinned by crystal plasticity finite element methods (CPFEM), and related techniques, to comprehensively capture deformation mechanisms including plasticity, creep and fracture [28]. Strain softening and localisation, produced by micromechanical testing of irradiated materials and experimentally measured, has been successfully replicated using CPFEM (e.g., Fig. 9c (a) and (b)), with larger scale deformation achieved using HRDIC strain mapping coupled with electron backscattered diffraction (EBSD) measurements (e.g., Fig. 9c) (c) and (d)), and representative volume elements (RVE's) developed to facilitate *in silico* mechanical testing of components; for example, miniature CuCrZr tensile tests producing stress-strain data (e.g., Fig. 9c) (e) and (f)).

Production of high temperature performing radiation tolerant materials, understanding radiation and temperature induced failure modes, and development of strategies to mitigate these must be combined with manufacturability; this is a key focus of the Neutron Irradiation of Advanced Steels (NEURONE) programme. NEURONE is a

UKAEA-led consortium of UK academics and industrial partners, with a goal to develop and assess new, advanced, fusion-grade RAFM steels, for tonnage-scale production by 2028. Fig. 10 shows a recent success from the NEURONE programme, with the UK-first production of fusion-grade RAFM steel using a seven-tonne Electric Arc Furnace (EAF). This landmark achievement demonstrates new capability for the production of fusion grade steel with sufficiently low impurity levels and only a single production process required, resulting in significantly reduced costs and production timescales. This achievement was recently replicated with the production of a novel UK RAFM steel, designed by combining the experimentation and modelling capabilities described above.



FIG. 10. Fusion grade RAFM steel production at scale in the UK. Continuous casting used to produce an ingot sized at $0.3 \times 0.14 \times 13$ metres, weighing approximately 5.5 tonnes [29]

4. TRITIUM FUEL CYCLE MODELLING

Determining the tritium inventory requirements of the fuel cycle of future fusion power plants is a huge challenge; current literature estimates [30 – 35] range from 300 g up to 22 kg. These works are based on a mean residence time analysis, assuming that the overall fuel cycle is operating in continuous mode. This approach assumes steady state conditions within each subsystem of the fuel cycle with fixed residence times, fixed efficiencies, and fixed loss factors, and can as such provide useful insights on the impact of various factors on the overall tritium inventory, such as the Tritium Breeding Ratio (TBR), tritium burn-up ratio and inventory doubling time. However, it cannot be effectively used for ramp-up or maintenance scenarios and does not allow to incorporate batch technologies such as cryo-pumping, gas chromatography or storage of hydrogen isotopes on metal hydrides. Moreover, this approach does not account for transient behaviours over long timescales, for example retention of tritium in the first wall which is exacerbated by neutron-induced damage, with some studies, calculating the expected saturation of trap densities from first principles using Molecular Dynamics and Creation-Relaxation Algorithm, indicating that tungsten has the potential to trap up to 140 g of tritium per tonne of material [36]. For a DEMO-sized machine incorporating 3000 – 4000 tonnes of tungsten [37], this results in a potential retention of 420 – 560 kg of tritium. While the trap saturation occurs early on in the component lifetime, the timescale for tritium saturation is not yet understood. For a STEP-like machine an assessment has been made for the tritium retention of a 1 mm tungsten armour layer (excluding the divertor), resulting in 2.2 kg of tritium for 19 ton of tungsten [38]. This estimate, compared to the aforementioned fuel cycle inventory estimates, shows that in-vessel retention will have a massive influence on tritium distribution throughout the plant, and so far, there have been no mean residual time analyses that have accounted for it.

In order to minimise the overall tritium inventory, a bottom-up modelling approach is pursued in which each subprocess is dynamically modelled to allow for broader operational envelopes, potentially deviating from optimised process efficiency. For this to be realised, the underlying mechanisms in each subsystem process need to be understood at a fundamental level, where experimental data on the viability of these processes is currently unavailable for a wide range of operating parameters. To extend the available knowledge rapidly, efforts are focused on validation on non-active surrogate systems, keeping validation with tritium or neutron irradiation to a minimum. The aim is to obtain subsystem transfer equations based on physics principles to be interlinked in a process level model, linking in- and output flows based on fluctuating concentrations with varying efficiencies, and over the full spectrum of available length scales.

For this purpose, the Tritium Integrated Modelling (TIM) project has been instigated at UKAEA, with the aim to develop models that will provide the tools to determine the time evolution of tritium inventory required to sustain a viable fusion power plant of a given design. This incorporates multiple physics phenomena, multiple fusion fuel cycle systems and multiple length scales; dubbed the Multi³ approach (see Fig. 11).

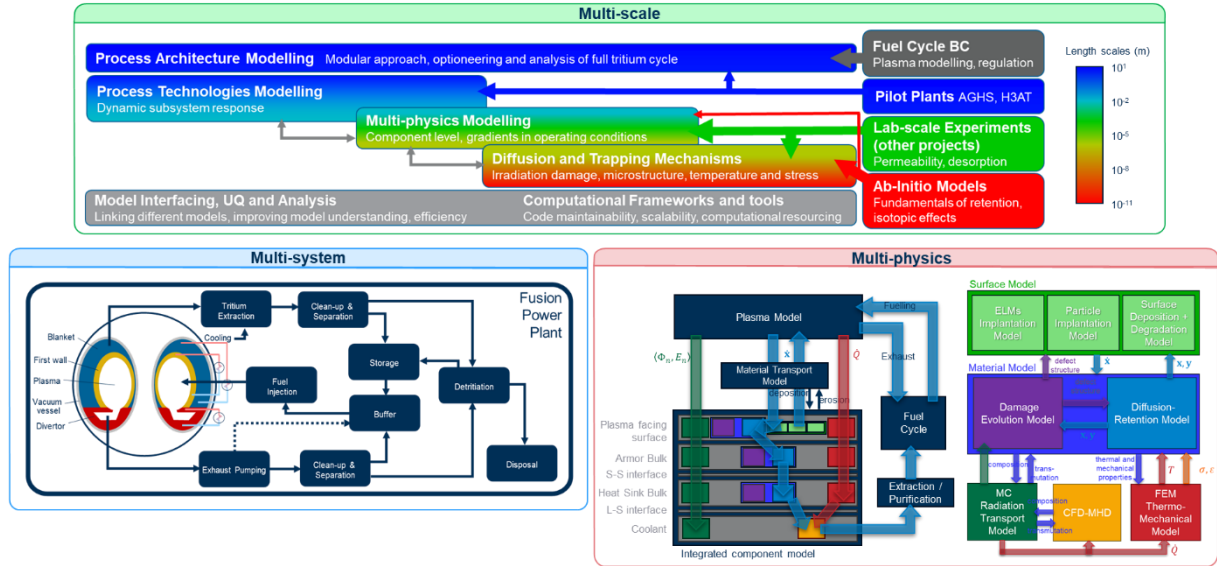


FIG. 11. The Multi³ approach of the TIM project.

An example of the work that has come out of the Multi³ approach is a fuel cycle architecture modelling tool, built in Simulink. This tool allows for the consideration of various fusion fuel cycle architectures and configurations and understanding the impact this will have on the tritium inventory requirements. The benefits of this model include the ability to model multiple gases and their interactions in a single model, including all hydrogen isotopes and helium, the capacity to simulate inherently batch processes, as well as investigating the impact of plant operating schedules, and to study more complex dynamic behaviours. Moreover, this tool is modular; it provides a base for the more complex unit models developed in parallel in the TIM project to be integrated into the system.

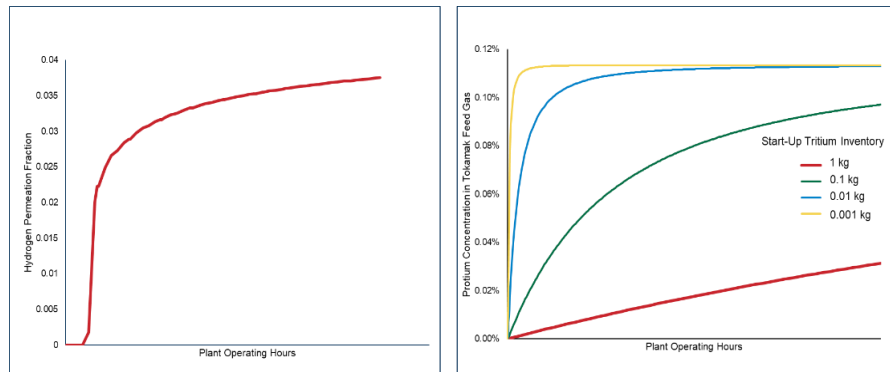


FIG. 12. Outcomes of the fuel cycle architecture modelling tool. Left: the increase in hydrogen permeation through tokamak walls with operating time. Right: build-up of protium concentration as function of tritium start-up inventory.

Some initial proofs of concept are shown in Fig. 12. The graph on the left side shows how the amount of hydrogen which permeates through the tokamak walls into the breeder blanket and coolant increases with operating hours. Repeated plasma pulses degrade the tokamak walls, increasing the fraction of hydrogen entering the tokamak that permeates through the walls. These degradation and permeation mechanisms are both very complex, but as a proof-of-concept simplified models for both have been integrated into the architecture model to simulate this effect. The graph on the right side shows an example of the tool analysing the build-up of protium in the fuel cycle, coming from a number of sources including moisture in the air leaking into the system. There are strict requirements imposed on the isotopic mix of hydrogen to be fed to the plasma, but as protium separation from the

deuterium-tritium mixture is very challenging there is a need to better understand this issue. It can be seen that there is a relationship between the start-up inventory of tritium and the rate at which the protium concentration builds up in the fuel cycle; given a set requirement on the protium concentration in the plasma, this can drive the overall inventory of tritium needed to start up a fusion power plant.

This relatively young project has the ambition to address several challenges in tritium modelling:

- (a) Develop the capability to demonstrate the feasibility of a self-sustaining tritium fuel cycle of a given design combining breeding, extraction, exhaust processing and losses.
- (b) Modelling synergistic effects between neutronics, hydrogen trapping, microstructural evolution under large temperature gradients and their resulting effects on thermal and kinetic transport and mechanical properties.
- (c) Mechanistic understanding of hydrogen diffusion at solid/solid and solid/fluid interfaces.
- (d) Linking model outcomes at component scale to subsystem scale.
- (e) Validation approaches for models and curation of available experimental data.

The overall aim of taking this comprehensive approach to tritium modelling is to allow for better understanding of the dynamic effects expected to have a considerable impact on the overall tritium inventory evolution.

5. ROBOTICS AND DECOMMISSIONING

After the final DT experiments with JET, the UKAEA started exploring the feasibility of using remote robotic systems to decommission JET. This is the world's first trial and application of disassembling a post-DT fusion device by remote systems. Drawing on decades of experience in remote operations, the robotic researchers from UKAEA have been developing novel "digital" functions that enable remote operations to be faster and safer. This research applies the digital first strategy to both well-known maintenance and novel decommissioning tasks in fusion devices, leading to improved operation efficiency at reduced cost and time.

In the context of fusion engineering, a common approach is to facilitate digital twins of remote robotic systems, primarily used for two purposes: as planning tools for the robotic operations, and as virtual representations twinned with the robotic systems, before and during mission-critical operations respectively (see examples in [39,40]). At UKAEA a digital twin platform of the JET maintenance systems has been developed, shown in Fig. 13. The platform can be operated offline as a simulation to plan, evaluate, and analyse prospective operations and the associated risks. When synchronised with the real-world maintenance robots, it can illustrate the live 3D postures of the robotic manipulators and display important metrics in operation practice. The in-vessel robotic systems can be viewed at virtual view angles, providing operators with spatial information that is difficult, sometimes impossible, to obtain using real cameras.

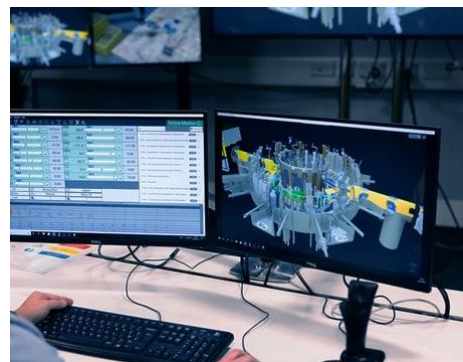


FIG. 13. The digital twin of the remote handling system for JET maintenance and decommissioning.

Since the launch of JET Decommissioning and Repurposing (JDR) programme [41], the remote handling system has been retrofitted for in-vessel decommissioning operations. In contrast to routine maintenance tasks, the operation requirements for decommissioning are significantly different in terms of manipulation movement ranges, variations in the vessel environment, and types of operation. Thus, the UKAEA robotic research group has developed novel digital functionalities, beyond the current understanding and practice. Particularly, to support remote decommissioning tasks, novel digital functionalities have been developed to realise new approaches, including the development of operations that can introduce arbitrary modifications to the existing system; to plan robot movements differently from routine maintenance trajectories allowing for decommissioning operations; and to enhance operation safety by introducing advanced digital twin techniques, incorporating complex nonlinear dynamics in addition to the current practice of a purely volumetric twin.

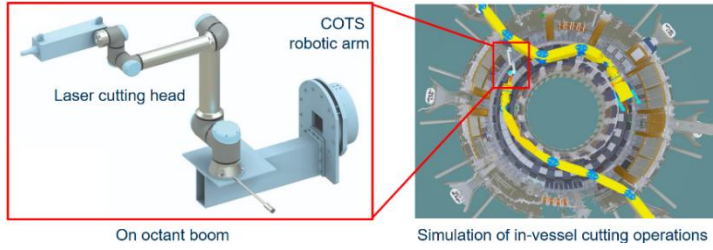


FIG. 14. Example of introducing a laser cutting tool and a lightweight manipulator to the JET remote handling system digitally, to analyse the feasibility to cut large components via this conceptual laser cutting system.

reduction, such as laser cutting tasks. However, there is a need for cutting large in-vessel assemblies to decommission JET. As part of planning these activities, conceptual hardware solutions for laser cutting these assemblies need to be developed and verified for operational feasibility. The concept of such a new operation has been analysed using the DMU function, as shown in Fig. 14. This allows for the generation of a concept hardware, consisting of a custom-off-the-shelf manipulator and a laser cutting head. The DMU is then used to integrate such a hardware within a digital simulation of the existing remote handling robots in JET. In addition to volumetrically representing the conceptual system, the new DMU can also simulate the interaction between the remote robots and the operation environment, by integrating bespoke physics engines, for example the separation of a cut-through assembly. Thus, the DMU allows development of the operation sequences, assuming the introduction of the new conceptual hardware configuration, and therefore, enables analysis of the operation feasibility.

Moreover, novel motion planning capabilities have been developed to support planning robotic movements customised for challenging decommissioning tasks. In JET, the articulated boom manipulators are operated as large transporters to move along fixed trajectories within the vacuum vessel [43]. The fixed trajectories have been designed for maintenance tasks, avoiding robot-vessel collisions and defining reach limits of the manipulators. In contrast, the long-reach boom manipulators need to reach extremely close to, or sometimes contact, the vacuum vessel in decommissioning tasks. Presently, the robotic movements are manually designed by operation engineers, which is time consuming and laborious considering that the in-vessel environment is highly constrained. Therefore, a novel digital functionality is developed to automatically and efficiently generate safe robotic movements for decommissioning operations. This movement planner is a multi-objective optimisation algorithm based on CHOMP [44], allowing for the generation of optimised movements for the boom manipulations along operator-specified waypoints. This novel functionality considers multiple objectives specifically for in-vessel decommissioning operations, including smoothness of the planned motions (described in terms of velocity, acceleration and jerk), clearance from obstacles and space constraints, and total irradiated air-kerma dose exposure on specific robot joints during the planned motions. This functionality has been integrated with the digital twin of the physical manipulators, see Fig. 15, and its effectiveness has been tested in simulations and experiments [45].

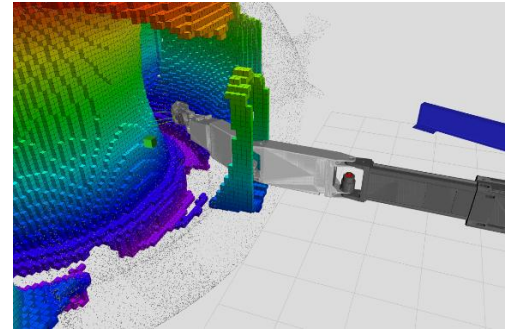


FIG. 15. Digital twin of a boom manipulator integrated with the novel movement generation functionality designed for decommissioning tasks. The colour signifies the geometric constraints with blue being low and red being high.

Lastly, long-reach boom manipulators used in fusion devices are typically driven at a slow speed to minimise the vibrations excited by its own actuating movements, a result of their slender body and inherent joint elasticity (see Fig. 16) leading to variant nonlinear dynamics with respect to its postures. For the same reason, these manipulators deform due to payloads (e.g., carried instruments for remote operations) and external disturbances (e.g., the contact force experienced from vessel or telemanipulation momentum). Such vibrations and deformations are not

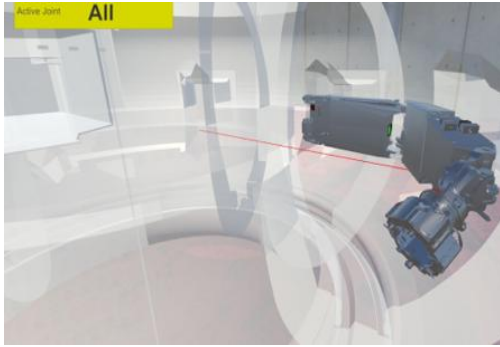


FIG. 16. Digital model of TARM, a slender manipulator with flexible nonlinear dynamics, in JET for decommissioning tasks.

properly considered yet in digital twins, which are typically developed for standard industrial manipulators. Apart from the uniqueness of these manipulators in fusion devices, it is very challenging to model variant nonlinear dynamics for a multi-body mechatronic system at high complexity. The robotic researchers at UKAEA have developed modelling and control techniques enabling digital simulations of the dynamic challenges, to verify associated risks and accelerate the decommissioning process. As a result, this novel functionality of digital twin technology demonstrates the possibility of operating long-reach boom manipulators at speeds up to 3 times higher for complex decommissioning movements, enhancing operational efficiency while not increasing risks [46].

These novel digital functionalities facilitate advanced remote operation capabilities for decommissioning, beyond the maintenance purposes of JET. Notably, these functionalities provide a digital toolset that enables maintenance on future fusion devices at improved speed and safety. Firstly, the digital toolset allows for verifying and analysing the feasibility of conducting new (or routine) remote operations whilst permitting significant flexibility of hardware adjustments. Secondly, with the novel movement generation capability, it realises a way to embrace novel motion planning algorithms developed by the robotic research community without losing the critical safety considerations required in fusion devices. Thirdly, by integrating novel physics engines enabled by advanced modelling and control algorithms, it enables the provision of live twinning of operation uncertainties and risks the operators face when operating flexible long-reach manipulators.

6. OUTLOOK AND CONCLUSION

Several critical technology issues for future fusion power plants remain, such as tritium retention in first wall materials and the requirement for component qualification via modelling due to lack of experimental facilities. These, along with materials and robotic developments being critical areas for the future of fusion power plants, are all addressed by UKAEA's research, spanning a broad range of technical areas with an emphasis on a digital-first approach. This digital-first approach has also been integral in the development of several new facilities currently in design and build at UKAEA. These include the UKAEA – Eni H3AT Tritium Loop facility, CHIMERA and LIBRTI. The H3AT facility is a 100g inventory, continuous, closed loop fuel cycle, designed to develop, validate and derisk fuel cycle technology. A digital twin of the H3AT facility has already been developed and will be underpinned by detailed models of tritium behaviour in development at UKAEA. CHIMERA will enable testing of prototype components in a fusion relevant environment, including high temperatures, high heat fluxes, high vacuum, and static and pulsed magnetic loads. A parallel programme of simulation development will enable CHIMERA to perform virtual qualification of built components in untestable conditions. Finally, LIBRTI is a tritium breeding facility currently being designed, which will generate tritium using a 14 MeV neutron source. Lithium materials will be handled in solids, liquids or molten salts, enabling testing of a wide range of blanket concepts, critical in developing the skills and knowledge required for the successful and predictable production of tritium in a power plant breeder blanket. A multi-physics platform is being developed in conjunction to this, modelling the production and transport of tritium throughout a breeder blanket, to be used to develop full powerplant breeder blanket simulations. Together with existing UKAEA programmes and capabilities, these new facilities aim to assist the early delivery of fusion power. Their designs incorporate a digital-first philosophy, ensuring that critical experiments are prioritised and that insights can be rapidly applied, driving innovation and progress across the fusion landscape.

By prioritising this digital-first strategy, UKAEA aims to accelerate the delivery of fusion power while potentially reducing development costs through decreased reliance on costly and time-intensive experimental facilities. Because fusion power plants will operate under unprecedented conditions, the development of comprehensive models is essential to predict component and system behaviour and to extrapolate with confidence beyond validated regimes.

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