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Accelerating Breeder Blanket Design with Scalable Multi-physics Modelling and Digital Engineering Workflows

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Fusion breeding blankets must fulfil multiple competing objectives: maximising the extraction of both tritium and heat, minimising damaging irradiation to less resilient components (such as magnets), whilst maintaining temperatures, stresses and radiation doses below safe operational limits. To reduce costs and timescales, exploring those trade-offs efficiently is desirable, mandating an integrated modelling approach. It is necessary to incorporate several models arising from disparate domains, including neutronics, materials science, heat transfer, solid mechanics, fluid dynamics, electromagnetism, and magnetohydrodynamics.

Recognising that such a system is governed by physical regimes that are both multi-scale and non-linear implies that emergent (and potentially surprising) behaviour must be anticipated. Since transport phenomena in particular are sensitive to geometry, retaining a high degree of fidelity is also required, culminating in a large number of degrees of freedom. Therefore, it is sensible to ensure that software implementations may be easily deployed and scalable upon high-performance computing architectures.

Furthermore, the extreme conditions to which plasma-facing components are subjected (such as high neutron fluxes and thermo-mechanical gradients) are not commonly replicated within experiments, and thus data coverage of those conditions is sparse. To ensure confidence in any conclusions derived from simulation will require sensitivity analysis of stochastic and empirical model parameters, as well as the flexibility to interchange between qualitatively different theoretical approaches. Where such uncertainties are intolerable, this can lead to targeted design of experiments at prospective facilities, such as the UK Atomic Energy Authority's future breeder mock-up test facility LIBRTI.

In recognition of these challenges, a scalable multi-physics simulation framework, suitable for modelling of breeder blankets and prospective tritium production experiments, has been developed at the UK Atomic Energy Authority. In this contribution we review its current status, commenting on the requirements of fidelity, scalability and flexibility. The MOOSE (Multi-physics Object-Oriented Simulation Environment) finite element library, with its native modules for solid mechanics and heat transfer, is taken as a starting point. This is integrated with a number of MOOSE-derived applications, including TMAP8 for tritium transport, and a coupling to OpenMC for Monte Carlo neutronics. We consider not only tritium production but also its permeation and retention in materials and explore implications for extractability.

Beyond capability for the analysis of individual design points, we explore additional software developments that facilitate a systematic approach to design exploration and qualification. Taking a Helium-Cooled Pebble Bed (HCPB) blanket concept as a test bed, we demonstrate a digital engineering pipeline to perform an optimisation over geometric parameters using active learning, as well as a sensitivity analysis to model parameters governing tritium permeation. We close with a perspective on the opportunities and challenges to improve upon this multi-physics approach to modelling and design of tritium breeding blankets.

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