EPSRC Engineering and Physical Sciences Research Council | Imperial College London | Rolls-Royce | Centre for Nuclear Engineering

Two EPSRC and Rolls-Royce Co-Sponsored PhDs in Nuclear Engineering at Imperial College London

High Performance, Deterministic, Radiation Transport Methods on Geometry Conforming Meshes with Ray-Effect Mitigation Algorithms for Radiation Shielding Analyses of Small Modular Reactors (SMRs)

The aim of this PhD project is to develop novel numerical algorithms on modern, multi-core and many-core, high performance distributed computing (HPC) architectures for radiation shielding analyses of small modular reactors (SMRs) such as the steam raising nuclear power plants (NPPs) of nuclear submarines or the new Rolls-Royce, civil nuclear, SMR concept. An example of a typical industrial reactor shielding problem is shown **Figure 1**. This shows a reactor shielding experiment conducted by UKAEA (United Kingdom Atomic Energy Authority) using the NESTOR (Neutron Source Thermal Reactor) reactor in the 1960s. The shielding arrangement shows a fission plate placed in front of the reactor. The neutrons from the reactor cause fission neutrons to be produced from this fission plate in a controlled manner. The trolley carrying various large slabs of shielding material (iron, water, concrete etc.) was placed in front of the fission plate. The neutron and gamma fluence was measured at various locations as the radiation penetrated into the reactor shield using standard radiation detectors (BF_3 and He^3). The shielding trolley itself was called the ASPIS trolley after the name for a large wooden shield used by Greek soldiers (Ancient Greek: ἀσπίς).

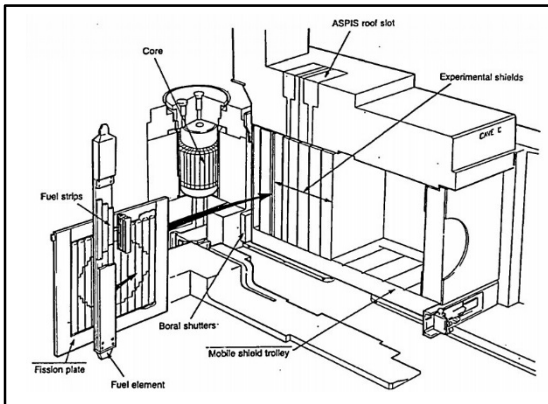

Figure 1: NESTOR reactor and ASPIS radiation shield configuration (United Kingdom Atomic Energy Authority, Winfrith in Dorset, United Kingdom).

The computational analysis of radiation shielding and dosimetry problems, in general, requires the solution of a complex transport equation that describes the migration of neutral particles through a prescribed host medium such as a radiation shield. This transport equation is central to a wide variety of academically and industrially important areas of engineering and physics including: nuclear reactor physics, reactor shielding, nuclear criticality safety assessment, medical imaging, nuclear security, cloud and solar radiative transfer physics, photon transport in plasmas and nano-scale electronic devices. However, there are many challenges posed in obtaining numerical solutions of the transport equation due to the seven dimensional phase space of solution variables – position, energy, angle and time (x, y, z, E, θ, χ, t)**.** Its application to the modelling and simulation of nuclear power plants (NPPs) is challenging because of the complex three-dimensional (3D) geometries involved as well as the presence of void or ducts within the geometry; especially in reactor shielding analyses. In terms of reactor shielding analyses, nuclear engineers are primarily interested in reducing the dose to workers and the radiation damage to the reactor pressure vessel (RPV) caused by the ionising radiation emanating from the reactor core. The dose received by workers is meant to be as low as reasonably practicable (ALARP) or as low as reasonably achievable (ALARA). The dose must be below a certain threshold value prescribed by the nuclear regulators (ONR in the UK or US DoE in the USA). For NPPs the dose and radiation damage assessment involves a wide range of different calculations that may involve interdisciplinary nuclear experts. However, one of the most important types of radiation shielding and dosimetry analyses is the analysis of primary and secondary radiation shields within NPPs. These reactor shields must be designed with the three basic principles of: safety, reliability and cost-efficiency in mind as well as the

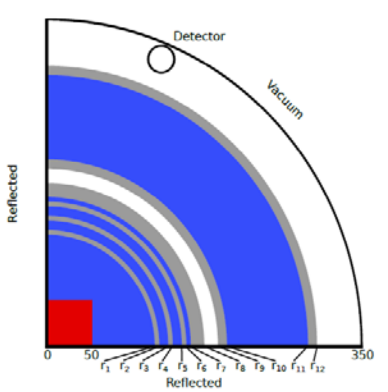

Figure 2: An Example two-dimensional nuclear reactor radiation shielding verification benchmark test case.

additional constraint of minimal physical size for submarine NPPs. These types of problems not only involve complex three-dimensional (3D) geometries but also involve coupled radiation phenomena such as coupled neutron and gamma-ray photon radiation physics analyses. This further complicates the analysis of reactor shields within NPPs. One other important issue is that as the radiation penetrates and migrates through the shield then the radiation itself becomes more anisotropic in its variation in angle. For instance, the radiation penetrating through the primary shield of a nuclear reactor will become attenuated as it progresses in a particular direction through the shield becoming more biased (or peaked) in the forward direction. This highly anisotropic nature of the angular distribution of neutrons and gamma-ray photons can be challenging to model using deterministic transport theory methods. In particular, if the angular variables of the transport equation are discretised using a discrete set of radiation directions (often called the discrete ordinate or S_N method) this can lead to unphysical spatial oscillations in angularly integrated quantities of interest (QoI) such as the absorption and dose rates internal and external to the shield. These unphysical oscillations are called "ray-effects" by reactor shielding experts and they distort the overall solution field for angularly integrated QoI. One of the biggest challenges facing reactor shielding experts is the elimination or amelioration of "ray-effects" within discrete ordinate reactor shielding simulations. One way of eliminating "ray-effects" is to use spherical harmonic (P_N) angular discretisations which are rotationally invariant on the unit sphere. However, algorithms employing spherical harmonics (P_N) methods tend to be computationally inefficient and can also lead to unphysical "Gibbs-oscillations" in the angular distribution of radiation. Alternative approaches focus on the use of self-adaptive angular discretisation's including self-adaptive discrete ordinate (S_N) methods as well as more advanced angular basis functions. Therefore, these two PhD students, co-funded by both EPSRC and Rolls-Royce, will focus on such self-adaptive angular discretisation methods. The aim of the R&D is to develop computationally efficient, self-adaptive, angular discretisation methods that are computationally efficient on multi-core and many-core high performance computing (HPC) architectures. These new ray-effect mitigation algorithms will then be verified and validated (V&V) against Rolls-Royce benchmarks as well as international benchmark validation databases such as the joint RSICC/OECD/NEA SINBAD (Shielding Integral Benchmark Archive and Database). The SINBAD radiation shielding benchmark archive and database contains 46 reactor shielding, 31 fusion neutronics and 23 accelerator shielding experiments in which reactor shielding specialists can verify and validate (V&V) their methods and codes.

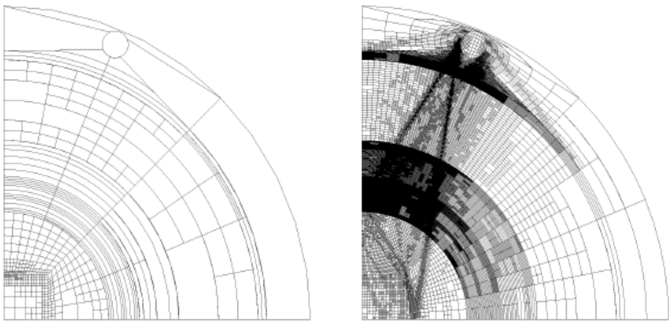

Figure 3: The IGA spatial meshes for the solution of the adjoint transport equation for the reactor shielding verification benchmark test case. The picture on the left depicts the mesh used for neutron energy group 13 and picture on the right depicts the mesh used for gamma-ray photon group 3 (overall group 50).

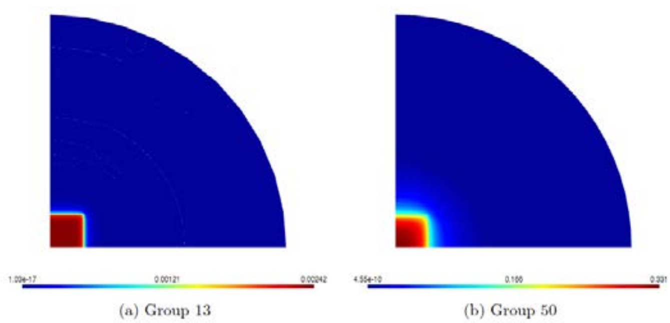

Figure 4: The spatial radiation fluence field for the reactor shielding verification benchmark test case. The picture on the left shows the spatial variation in the neutron fluence for neutron energy group 13. The picture on the right shows the spatial variation in the gamma-ray fluence for gamma-ray group 3 (overall group 50).

An example of a verification benchmark is shown in **Figure 2**. This is a typical reactor primary shielding configuration that might be analysed by a reactor shielding analyst. This reactor shielding problem consists of a reactor zone or core (depicted as the red square in **Figure 2**) that provides the source of fast neutrons. The reactor is surrounded by concentric annuli of water, steel and void regions. The water region is used to slow down (or thermalize) neutrons and the steel regions are used for absorption of neutrons. The detector is depicted as a circular ring in the outer annulus region. This particular reactor shielding problem was solved using microscopic neutron and gamma-ray photon nuclear cross-section data provided by the

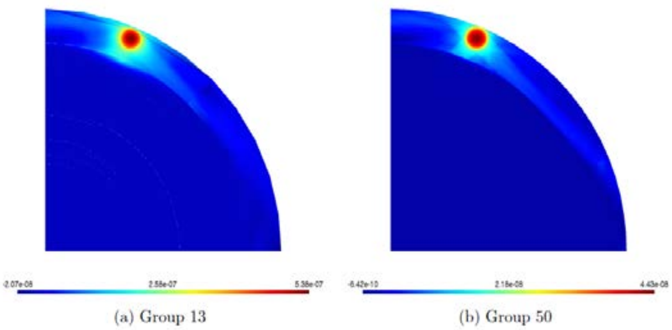

Figure 5: The spatial adjoint radiation fluence field for the reactor shielding verification benchmark test case. The picture on the left shows the spatial variation in the neutron fluence for neutron energy group 13. The picture on the right shows the spatial variation in the gamma-ray fluence for gamma-ray group 3 (overall group 50).

BUGLE-96 reactor shielding library. This library consists of 47 neutron energy groups and 20 gamma-ray photon groups. A detector response function in 67 neutron and gamma-ray photon energy groups was also prescribed for this problem as well as the prescribed energy and spatial distribution of neutrons emanating from the reactor zone or core. The problem was solved using a novel coupled neutron and gamma-ray photon radiation transport code that used self-adaptive isogeometric analysis (IGA) spatial discretisation methods. These IGA methods locally adapt the spatial mesh resolution for each energy group independently in order to model the radiation field optimally for a prescribed spatial error tolerance. The adaptive spatial mesh methods are based upon solving both the forward transport equation as well as the dual (or adjoint) form of the transport equation. The "optimal" spatial mesh for the adjoint solution of the transport equation is shown in **Figure 3**. Solving both the forward and adjoint forms of the transport equation enable dual weighted residual (DWR) or goal oriented error measures to be used to drive the spatial adaptivity algorithm. The adjoint problem to the forward problem essentially uses the detector as the source region and then solves the adjoint form of the transport equation. In this case the goal, for the goal oriented spatial mesh adaptivity, would be the error in the response at the detector. The solution of the forward and adjoint transport equations for neutron energy group 13 and gamma-ray photon group 3 (overall group 50) are presented in **Figure 4** and **5** respectively. It is important to note that such self-adaptive algorithms can be applied to angular variables and this forms the focus of these particular PhD projects.

The successful candidate will join, and be supported by, a vibrant and dynamic group with world class expertise in the numerical modelling of radiation transport and multiphysics phenomena for nuclear engineering. In the course of their three and a half years of study they will be trained in the latest state-of-the-art numerical methods for simulating radiation transport in nuclear reactor cores, parallel high performance computing (HPC) techniques, object oriented programming, and scalable solvers as well as trained in the use of the industrial reactor shielding software for verification and validation (V&V) purposes. The successful candidate will be sent on a wide variety of international training courses such as the international nuclear engineering summer school in Paris and the Frederic Joliot/Otto Hahn Summer School in reactor physics (FJOH) which are held in France and Germany (http://www.fjohss.eu). In addition the successful candidate will be sent on an experimental reactor physics course that is held annually in Prague. This is in addition to courses in numerical analysis, MPI and OpenMP programming, reactor physics and radiation shielding at Imperial College London.

The successful candidate will have the opportunity to develop their career, transferable skills and profile by presenting at international conferences and publishing in high impact nuclear engineering and numerical analysis journals. Imperial College London also has a wide variety of professional development (PD) courses that PhD students must undertake as part of their studies in addition to all the technical training. The professional development courses that the successful candidate will undertake will help develop their non-technical transferable skills. This will help widen their recruitment appeal to both engineering/science and non-science/engineering based companies. The successful candidate will have the opportunity to work with engineers and scientists from the industrial sponsor (Rolls-Royce) during their PhD studentship to help broaden their industrial experience. Candidates for this PhD industrial CASE studentship should have a good mathematical background and a good degree (First Class or Upper Second Class honours) in an appropriate field such as physics, mathematics, computer science or engineering. Applications from candidates with an MSc in scientific computing or numerical modelling are particularly welcome. It cannot be over-emphasized that the candidate must have very good mathematical skills and the ability to put physical models into a mathematical form. The successful candidate must be willing, and able to achieve, security clearance (SC) by the industrial sponsor (Rolls-Royce) as well as being eligible for EPSRC PhD studentship funding. To apply for this PhD industrial CASE studentship please email Dr Matthew Eaton (m.eaton@imperial.ac.uk) with a copy of your curriculum vitae (CV).