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PERFORMANCE EVALUATION OF TAILORED SHIELDING FOR ENERGY-SELECTIVE NEUTRON DETECTION IN REACTOR ENVIRONMENTS

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Abstract

With nuclear reactor technology rapidly advancing and the plan to raise the nuclear energy production by a factor of 4, the need for advanced detectors, geometries and shields has become apparent.To support this development there is a strong need for advanced instrumentation, as precise and reliable measurement of the neutron flux is not only relevant for the safe operation of nuclear reactors, but also for future reactor experiments essential for progressing the technology. In the presented work, simulations were performed using MCNP-6.3 to investigate the effects of various common reactor materials in different shield geometries on the performance of benchmark detectors. This was performed using a validated simulation of a 1 Ci Am/Be neutron source located at the University of Liverpool for a detailed experiment to simulation evaluation, followed by simulations of the detector in use near a zero power molten salt reactor. The use of a conical shield/reflector material around a thermal neutron detector showed an increase in efficiency for the detection of thermal neutrons when compared to the results for no additional material. The tailored measurement of neutrons of specific energies is highly relevant not only for reactor experiments on innovative technologies, but also has applications in neutron beam monitoring.

INTRODUCTION

The transition to a low-carbon, stable energy system is one of the major challenges of our time. Nuclear power is expected to be at the forefront of this transition, offering a stable source of very low-carbon electricity that is complementary to the intermittency of current renewables.

The International Energy Agency (IEA) has pointed out that nuclear energy is today the world's second-largest source of low-carbon electricity and has already avoided over 60 gigatonnes of CO_2 emissions over the last half-century [1]. Most recently, more than 20 nations pledged at COP28 to tripling global nuclear capacity by 2050, recognising its contribution to reaching net-zero goals and improving energy security [2].

Yet fulfilling these hopes will require more than simply enlarging existing reactor designs. Many of the world's older nuclear fleet, particularly in OECD countries, is ageing, meanwhile new large-scale projects, are often beset by delays and escalating costs. A central part to overcoming this challenge is the development of zero-power reactors (ZPR). ZPRs have historically provided the essential experimental data required to validate reactor physics models, qualify design codes, and demonstrate system behaviour in a safe, controlled low-power environment. They also serve as training facilities, such as AKR-2 at TU Dresden, for example, for students, reactor operators, scientists, and regulators, building the technical expertise required for eventual implementation.

It is obvious that this massive expansion of nuclear power capacities should go hand in hand with an improvement of the sustainability indices, increased fuel use and reduced waste production. To provide answers to this challenges, the iMAGINE concept has been developed [3].

One of the many opportunities provided by such a facility is the ability to operate reactors and design and implement new reactor instruments, using Monte-Carlo methods, and then experimentally test and validate them. New detector materials, along with new ways of placing detectors and shielding them all offer the opportunity to create a tailored detector system for each type of reactor.

In this paper, the design and simulation of a new conical reflector will be discussed, in two settings: firstly, in a neutron facility, using a 1 Ci Am/Be source, to validate the model, and secondly, once the model is validated, in a reduced reactor model of a zero power NaCl-UCl based molten salt reactor.

MODELLING

Simulations were carried out using MCNP-6.3, and started with the modelling and validation of the facility and detector used at the University of Liverpool (UoL). For this, a model was created as shown in Fig. 1 including the source, water tank, moderating materials present in the room and the structure of the room itself.

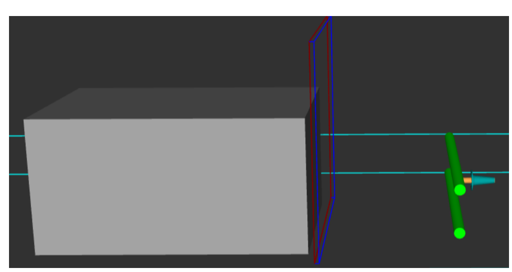

Figure 1: Wireframe view inside neutron tank facility at UoL, with He^3 detectors alongside test detector with reflector cone.

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Using the He^3 detectors shown in Fig. 1 in green, spectra were recorded experimentally, using moderating materials as a comparison basis, analysed and compared to the output of the MCNP model. With the simulated detector performing as expected, the model for simulating the reactor environment was created. For this, data was taken from a previous study on molten salt reactor inventory [4]. Using the model for the reactor shown in Fig. 2, a void cell was created to tally all information, photonic and neutronic, providing the necessary information to create a point source. As the detector used was not photon sensitive, the information regarding photonic modelling has been omitted, as it is outside the scope of this experiment.

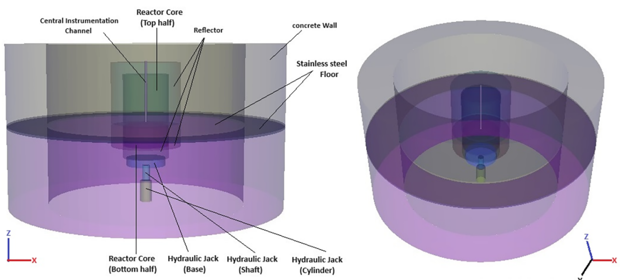

Figure 2: Design of the zero-power MSR core [5].

Finally, the data was analysed using the source yield and detector geometry information to produce efficiency graphs to allow for comparison between the types of reflector used.

RESULTS

Preliminary/Validation Data

Figure 3 shows the comparison between the experimental and modelled results, for 15 million particles, with moderating sheets of polyethylene placed between the source and detector. The figure shows good agreement between the simulated and experimental results, indicating the model is correct. The difference in the results comes as a result of model details, i.e. where structures have been modelled simpler, or have been removed in the case of small complex items, as the program has limited memory.

Reactor Environment Data

With the model validated, the reactor environment simulation was carried out, with Fig. 4 showing the results for detector efficiency. The efficiency was calculated using the geometry of the detector, source yield (neutron/s) and the probability for interaction inside the detector volume. The detection tally was modified using the flux modifier card for the interaction of neutrons with He^3.

The simulations were run for 300 million particles, to obtain good statistics, and the use of a void cell, and thus a point source and detector set up, massively increased the figure of merit of the simulation.

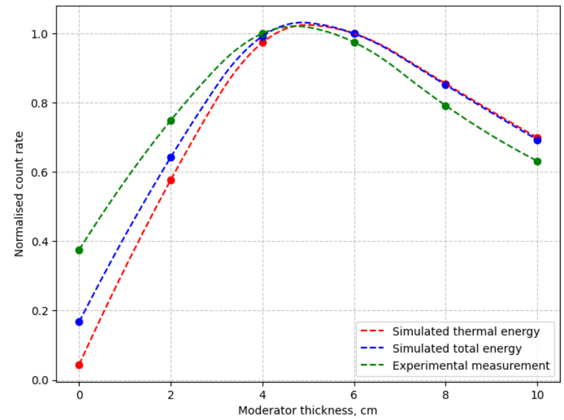

Figure 3: Preliminary validation results of simulated detector. Note: Errorbars are present, however, not visible.

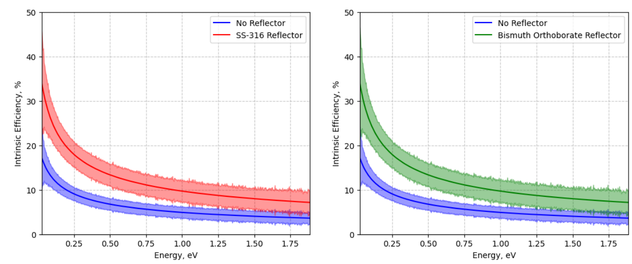

Figure 4: Simulated efficiency of a He^3 with and without reflector materials in a reactor environment

CONCLUSION

The modelling and simulation of new detectors, detector geometries and related materials underpins one of the key areas of developing the new generation of reactors. This paper covered why it is important to consider not only the use of zero and low power facilities for such reactor experiments to support the development of advanced reactors, but also how and why the use of shielding and reflector materials in ways previously unexplored can provide opportunities for instrument development. The results show a drastic increase to the intrinsic efficiency of a typical detector used for neutron detection, due to thermalisation and reflection, and leaves the door open for other types of emerging detectors, such as CYLC and CLLBC to be tested in a similar fashion. Such work on detectors and shielding geometries also has applications in thermal neutron beam monitoring, and opens new possibilities for collaboration.

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