Geant4 simulations for the design of radiation resilient ultrasound transducer technologies for use in the nuclear industry

Dr Katherine Krawec, Dr Ian Dawson, Dr Paul Miyagawa

Department of Physics and Astronomy, University of Sheffield, UK

Keywords: Radiation, simulation, ultrasound, non-destructive testing, radioactive decay, nuclear

Introduction

Ultrasonic transducer (UT) systems are used for non-destructive testing and evaluation across a wide range of industries, including nuclear. We have used the Geant4 simulation toolkit to support the development of radiation resilient UT technologies for application in and around nuclear reactor cores.

Radiation damage of UTs can lead to performance degradation or complete failure. By simulating the radiation environment, and understanding how radiation quantities of interest, such as ionising dose, vary within the UT probes we can study strategies to mitigate against radiation effects.

As a first step in the investigation, the performance of the UTs was tested as a function of total ionising dose (TID). Gamma irradiations were carried out at the Dalton Cumbrian Facility (DCF) Co-60 irradiator, UK. The two dominant energies (1.17 and 1.33MeV) are considered representative of the fission photons found in nuclear reactors.

Simulation

The simulations were performed using Geant4 10.5 on either SLC6 or CentOS 7 with physics list FTFP_BERT_EMZ_HP.

An accurate geometry and material description was created utilizing GDML for the DCF Co-60 irradiator, see Figure 1, as well detailed models of the UT probes under test. The Co-60 source was simulated directly though the use of the Geant4 radioactive decay package.

These were electromagnetic transport simulations scoring gamma and electron fluences along with ionising dose.

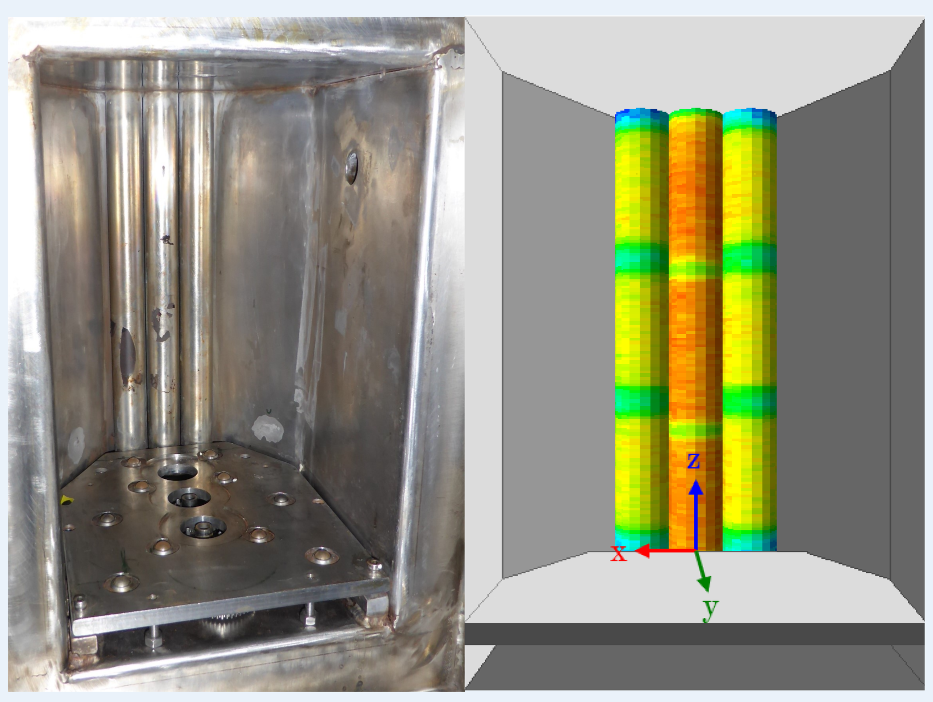
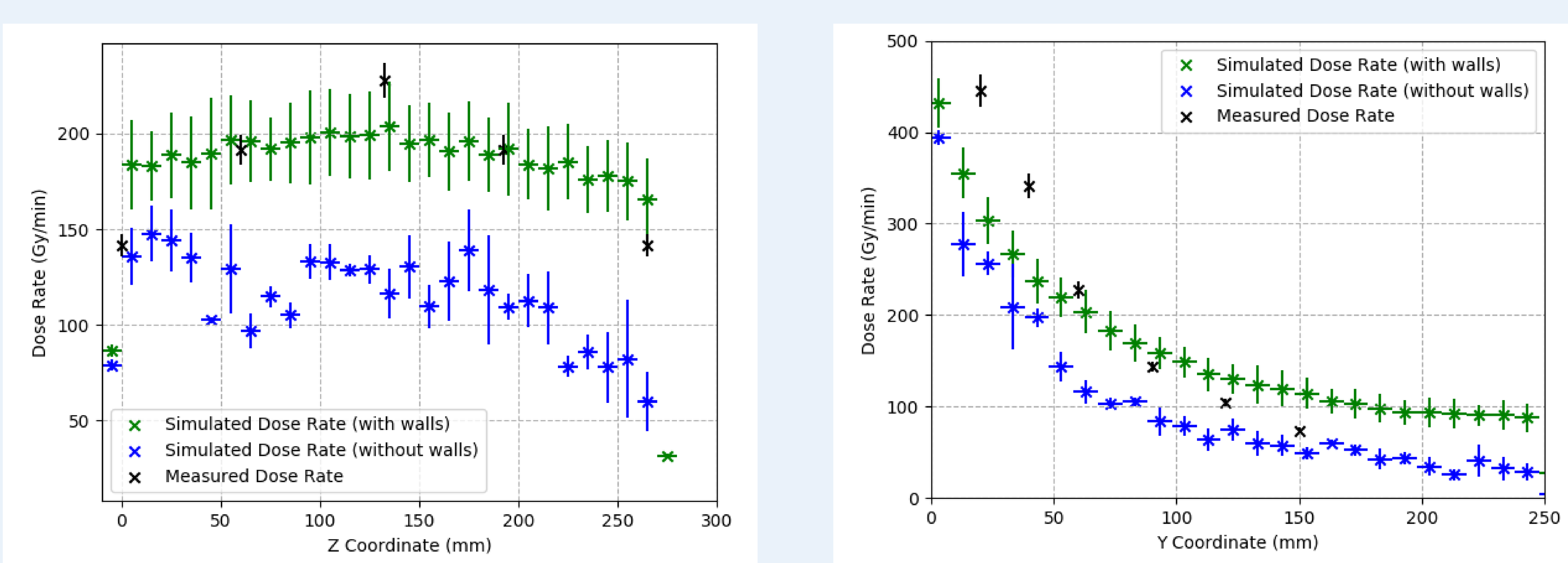


Figure 1: Photograph of the DCF Co-60 irradiator and the geometry of the simulation with the photon flux exiting the source guide tubes overlaid

Results



a) Dose rates at x=0mm and y=60mm

b) Dose rates at x=0mm and z=135mm

Figure 2: Simulated dose rates of the DCF Co-60 irradiator with and without the steel chamber walls along with measured dose rates for an empty chamber. The inclusion of the steel walls increased the simulated dose rate and increased the accuracy, especially in Figure 2a. A rectangular mesh with 10mm bins was used. Green: 47 million Co-60 decays Blue: 15 million Co-60 decays

Probe Number	Probe Body Material	Dose Rate PVDF (Gy/min)	Dose Rate Probe Front (Gy/min)	Ratio PVDF/ Probe Front
1	PEEK	403	515	0.78
2	PEEK	261	348	0.75
3	Macor	293	456	0.64
4	Macor	233	337	0.69

Table 1: Ratios of the dose rate at the PVDF inside the probes and the front of the probe. 71.5 million Co60 decays.

Results continued ...

Figure 2 compares simulated dose rates inside the Co-60 chamber with measurements. The inclusion of the surrounding steel walls significantly improved the accuracy of the model due to backscattering.

Figure 3 shows the dose rate at 7mm from the Co-60 sources. The dose rate is strongly dependent on position. This is due to the differences in the 9 sources leading to variations in the photon field within the chamber.

Table 1 compares the dose rate at the front of the probe to the dose rate at the sensitive component for the PEEK and Macor probes built by PA. The Macor provides more shielding to the sensitive component, as expected due to the higher density (2.25g/cm³ for Macor compared to 1.32g/cm³ for PEEK).

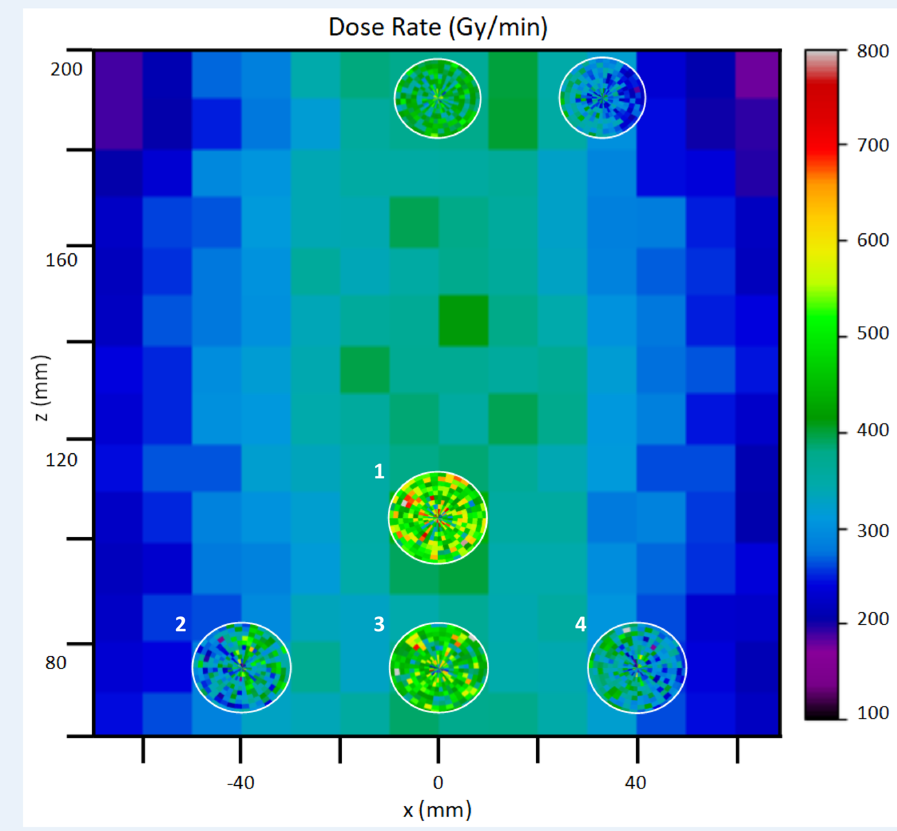


Figure 3: A scale representation of the simulated dose rate 7mm from the sources during irradiation of the UTs at the Dalton Cumbrian Facility Co-60 irradiator. The probes are outlined in white. There is a strong directional component to the magnitude of the dose rate. 61.5 million Co -60 decays.

Summary

Geant4 simulations have provided a reasonable description of the DCF Co-60 facility, giving confidence in any future gamma radiations, whatever the technology being tested. However, at 20mm from the source guide tubes the simulation underestimates by 30%, whilst at 150mm the simulation overestimates the dose rate by up to 50%. The cause of this is under investigation.

Of the two materials used in the construction of the PA UT's the Macor provides greater reduction to the dose absorbed by the sensitive component.

Further Work

We are actively working to reduce the statistical uncertainty but are having issues with execution time (1 million Co-60 decays takes 40 hours).

The UTs were also irradiated at the Jožef Stefan Institute (JSI) research nuclear reactor, Slovenia. Geant4 simulations are currently being performed to investigate neutron quantities, such as Kerma and NIEL, and the results will be compared to predictions from MCNP.

This work will include the reproduction of a neutron energy spectrum within Geant4. Figure 5 shows a neutron spectrum from an MCNP simulation of the JSI reactor along with the output energies of Geant4 simulation where the spectrum has been specified using a GPS user defined histogram.

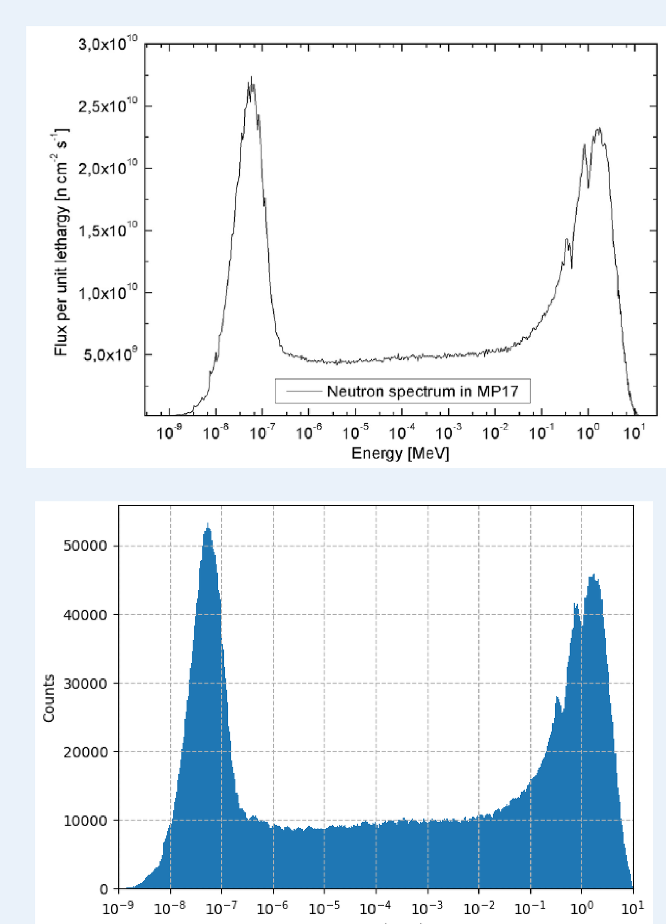


Figure 5: Energy range split into 640 log groups. **Top:** Neutron spectrum from an MCNP simulation of the JSI nuclear reactor. **Bottom:** Recreated neutron spectrum in Geant4.

Acknowledgements

This work was funded as part of the Innovate UK ReDRESS project, which has members from Precision Acoustics, Ionix, TWI and the University of Sheffield. Irradiation experiments were carried out using the Co-60 irradiator at the Dalton Cumbrian Facility (DCF), University of Manchester and the JSI TRIGA Mark II Reactor in Slovenia.

Contact email: k.krawec@sheffield.ac.uk