Radiological Shielding Design for the Neutron High-Resolution Backscattering Spectrometer EMU at the OPAL Reactor

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Abstract. The shielding for the neutron high-resolution backscattering spectrometer (EMU) located at the OPAL reactor (ANSTO) was designed using the Monte Carlo code MCNP 5-1.60. The proposed shielding design has produced compact shielding assemblies, such as the neutron pre-monochromator bunker with sliding cylindrical block shields to accommodate a range of neutron take-off angles, and in the experimental area - shielding of neutron focusing guides, choppers, flight tube, backscattering monochromator, and additional shielding elements inside the Scattering Tank. These shielding assemblies meet safety and engineering requirements and cost constraints. The neutron dose rates around the EMU instrument were reduced to $< 0.5 \mu\text{Sv/h}$ and the gamma dose rates to a safe working level of $\leq 3 \mu\text{Sv/h}$.

1 Introduction

In this paper we present modelling and design of compact radiation shielding required for operation of the EMU instrument, located at Australia's OPAL nuclear reactor. The acceptance criteria for the shielding design were (i) safety – dose rate $\leq 3 \mu\text{Sv/h}$ at external surfaces of the instrument's experimental area, (ii) floor load limit $< 20 \text{ tonnes/m}^2$, (iii) low cost, and (iv) for maintenance purposes “easy access” to components of the instruments [1, 2].

Prior to presenting our radiation shielding analysis a brief overview of the EMU instrument is given. It is worth noting that the design process integrated concurrent consideration of neutronic, engineering, and shielding requirements. An extensive description of the neutronic design and performance of this instrument will be presented elsewhere [3].

The EMU instrument is a cold-neutron backscattering spectrometer designed to measure inelastic neutron scattering. Its distinctive feature is that it has a tight elastic energy transfer resolution, of about $1 \mu\text{eV}$. The instrument provides unique opportunities to study diffusion in complex materials, e.g. water molecules in confinement, polymers or biological molecules, particularly in the Asia-Oceania region [4].

EMU is the first instrument located on the CG3 neutron beam line of the OPAL Neutron Guide Hall [5]. The layout of the instrument is shown in Figure 1.

Figure 1. A sliced section view of the EMU instrument with the pre-monochromator bunker, focusing neutron guide sections, choppers, backscattering monochromator mounted onto the Doppler drive and Scattering Tank.

A pre-existing evacuated neutron guide of dimensions $200 \text{ mm (height)} \times 50 \text{ mm (width)}$ feeds into the shared EMU/KOOKABURRA pre-monochromator bunker shielding assembly, and its bottom cross section will be intercepted $\sim 200 \text{ mm}$ further in air by the highly orientated pyrolytic graphite (HOPG) EMU pre-monochromator (take-off angles from 125.4° to 148°). The bunker shielding assembly for EMU also contains a beryllium filter and Focusing Guide Section D (FGD, entrance guide cross section $170 \text{ mm (height)} \times 50 \text{ mm (width)}$). To accommodate the range of take-off angles Pb cylindrical shielding blocks of radius 140 mm and 500 mm height have been designed. These blocks will be located at the section of the bunker where the neutron beam will exit towards the experimental area and they will reside on top of a hollow steel base (sides 10 mm thick), on which they move by sliding and are integrated

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with the tertiary shutter. The layout of the CG3 neutron guide shielding, shared EMU/KOOKABURRA pre-monochromator bunker is shown in Figure 2.

Figure 2. Inside view of the CG3 neutron guide shielding, shared EMU/KOOKABURRA pre-monochromator bunker walls (blue) and cylindrical blocks (blue).

The EMU instrument experimental area is enclosed by a pre-existing concrete wall shared with the KOOKABURRA instrument, which is of 2.5 m height and 300 mm thick up to the pre-monochromator bunker cylindrical blocks and 100 mm thick at the back of the cylindrical blocks. Also, enclosing the rest of the experimental area will be Gyprock Plasterboard panels with viewing windows, a wall from the pre-existing Out-of-Pile cold-neutron guide Bunker and the pre-existing CG3 shielding (Figure 3).

Figure 3. Elevated view of the EMU instrument's experimental area on the left and the KOOKABURRA instrument's experimental area on the right. The concrete wall and the Gyprock Plasterboard panels are shown.

The neutron beam will enter the EMU experimental area via the tertiary shutter, into the evacuated Focusing Guide Section C (FGC), which has an entrance guide cross section of 158 mm (height) $\times$ 79 mm (width) and exit guide cross section of 149 mm (height) $\times$ 85 mm (width) and is of length 816 mm. The guide surface is coated with $m=2.5$ supermirrors (SM) [6]. The vacuum chamber of FGC will be connected to the vacuum chamber of the Background Chopper (BC, spinning disc

of outer radius 350 mm), to avoid the use of Al windows, which will minimise radiation levels. The BC disc consists of neutron absorbing material (^{10}B) and the backing support for the chopper and its vacuum chamber are composed of high purity AlMg4.5Mn. Focusing Guide Section B (FGB) is aligned with FGC and its vacuum shared with the BC vacuum, again to avoid use of Al windows. The FGB has an exit guide cross section of 50 mm (height) $\times$ 49 mm (width) and is of length 4046 mm, which will focus the neutron beam vertically and horizontally towards the N16 Al-window (0.82 mm thickness). The latter is the entrance to the evacuated Scattering Tank assembly. The FGB guide surface is coated with $m=3.5$ SM [6]. The Scattering Tank assembly will be constructed from 20 mm – 40 mm thickness stainless steel and will be under vacuum $< 1 \times 10^{-3}$ mbar.

Inside the Scattering Tank after the N16 Al window, there is another section of Focusing Guide (FGA), with an exit guide cross-section of 30 mm (height) $\times$ 30 mm (width) and of length 417 mm. The guide surface is coated with $m=5$ SM [6]. The neutron beam exiting FGA will be reflected by the HOPG crystal pieces (5 mm thickness) of the Graphite Chopper (GC) with 88 % efficiency towards the Backscattering Monochromator (BM) and the remaining 12 % will be transmitted to be fully absorbed by the ^{10}B -loaded epoxy layer set behind the HOPG crystals (Figure 4). The GC is also located within the Scattering Tank and serves as the second pre-monochromator (Figure 5). The reflected neutron beam from the GC is divergent and, before it reaches the Backscattering Monochromator (BM), will first pass through the N17 Al window (0.82 mm thickness) of the Scattering Tank and then enter into an air flight tube constructed from steel of 10 mm thickness with exit dimensions of 400 mm (height) $\times$ 240 mm (width).

Figure 4. Graphite Chopper spinning disc (close-up at left, assembly at right) with HOPG crystal pieces at its periphery. See main text for a description of its interaction with the neutron beam.

The BM is formed in an 1800 mm spherical radius array of Si crystal elements (0.87 mm thickness) and is oscillated by the linear motor Doppler drive. The neutron beam will be reflected at 180° (i.e. back-scattered) from, and focussed by the BM to re-enter the Scattering Tank through the N17 Al window. It will then pass through the GC (HOPG crystals rotated out of the way) and will

Also, inside the Scattering Tank there will be ^3He linear position-sensitive neutron detectors, and Analyser Arrays formed in 1800 mm radius spherical arrays of Si crystal elements (0.87 mm thickness) glued on aluminium support frames (10 mm thickness) and spanning $\sim 160^\circ$ arc. The sample scatters neutrons into 4π sr. If a scattered neutron reaches the analyser and fulfils the backscattering Bragg condition, it is reflected back towards the sample. At which point, it will traverse the sample again and normally arrive at the detectors.

A model of the EMU instrument shielding was constructed using MCNP 5-1.60 [7, 8], which took into consideration acceptance criteria (ii) – (iv). The effectiveness of the shielding design to meet acceptance criteria (i) was estimated by the Monte Carlo Method, considering neutrons and generated prompt γ -radiation. In the modelling the average surface flux tally (type F2) and the average cell flux tally (type F4) were used and the geometry splitting variance reduction method was implemented. The cross sections were based on ENDF/B-VI neutron data and MCPLIB04 photon data. Conversion from radiation fluxes to doses was in correspondence with NCRP-38, ANSI/ANS-6.1.1-1977 and ICRP-21 [9-11].

The geometry of the EMU model is shown in Figures 6 – 10, which was constructed to match the neutronic component description given in the previous section. The pre-monochromator bunker shielding walls (top, bottom and sides) were Pb encased in steel, which is a combination of Fe (10 mm thick)/Pb (200 mm thick)/Fe (10 mm thick) and the internal surfaces of these walls, including the ceiling and base, were lined with MirroBor™ (5 mm thick) [12]. The gap size between the cylindrical block shields is 5 mm. These gaps have been covered with MirroBor™ of 5 mm thickness on the bunker internal face.

The experimental area bounding perimeter walls were treated as external surfaces at which dose rates were determined. This approach mirrors the operational requirement that personnel are prohibited from the experimental area when the tertiary shutter is open and the neutron beam is on; dose rates within the experimental area were nonetheless determined at a few locations as well. The bounding perimeter walls were sectioned appropriately up to a height of 5.5 m and each section of size 0.5 m (vertical) $\times$ 0.5 m (horizontal). The distances used were defined by the Neutron Guide Hall and instrument layout.

Surface “1” is the common wall between the EMU and KOOKABURRA instruments. The wall is 300 mm thick standard concrete and height of 2.5 m. Surface “2” is the extension of Surface “1” but it will be made out of Gyprock Plasterboard panels with viewing window. Gyprock Plasterboard panels do not provide any radiation shielding per se and were thus modelled as air (or void). Also, Surfaces “3” and “4” will be made out of

Gyprock Plasterboard panels with viewing windows. Surfaces “5” and “6” are at 1 m and 2 m distances from Surface “4” respectively, and represent the elevated walkway and viewing area in the southern section of the Neutron Guide Hall. Surface “7” is the Out-of-Pile Bunker wall external surface and straight above it. Surfaces “8” and “9” are on top of the Out-of-Pile Bunker at 1 m and 2 m distances from Surface “7” respectively, and represent its accessible area. Surface “10” is at distance of 2 m from the EMU pre-monochromator and CG3 guide.

Figure 8. MCNP model showing the plan view of the FGC, FGB and BC surrounded by MirroBor™, Fe and Pb shielding.

Figure 9. Schematic view of the BC disc and shielding above the control arm.

The instrument itself was modelled in the 135° take-off angle because, for most of its operation it will be very close to this configuration. The internal surface of the Scattering Tank is lined with Cd of 0.5 mm thickness and the exterior is covered with Polyethylene of 50 mm thickness, the latter mainly to slow down environmental neutrons and so reduce the neutron background noise in the detectors.

Figure 10. MCNP model showing the plan view of the EMU Scattering-Tank with external and internal shielding.

Also, all the void regions in the model were filled with air except the evacuated volumes of the focusing neutron guide (FGC, FGB, and FGA) and the Scattering Tank.

Figure 11. MCNP model showing the plan view of the EMU BM and its Doppler drive, with external and internal shielding.

2.2 Neutron sources

The simulations were performed using two sets of neutron sources for the pre-monochromator bunker and cylindrical block shields (Source 1 and Source 2) and four sets of neutron sources for the shielding design inside the experimental area and around its perimeter (Sources 3 to 6).

Source 1:

Maxwellian ($T=20$ K) mono-directional beam (along the CG3 neutron beam guide axis) and with a neutron current of 1×10^{12} neutrons.s⁻¹.

Sources 2 to 6 were derived from Vitess simulations [13].

Source 2:

Table 1. The energy spectrum from the EMU pre-monochromator.

Energy (meV)	Intensity (neutrons.s ⁻¹)
0 – 2.08	6.33×10^9
2.08 – 8.32	5.17×10^9
8.32 – 18.72	9.23×10^8
18.72 – 33.29	9.82×10^7

While the physical energy spectrum from the pre-monochromator consists in bands centred at 2.08, 8.32, 18.32, and 33.29 meV for most of its operation at 138° take-off angle, the above representation is a very good approximation for the purpose of our MCNP simulations. The total integrated reflected neutron current was 1.25×10^{10} neutrons.s⁻¹.

Sources 3 and 4:

Simulated as downstream mono-directional beams with energy 2.08 meV and neutron currents of 2.67×10^9 n.s⁻¹ and 1.52×10^9 n.s⁻¹, respectively, these were used to determine dose rates resulting from the Al windows immediately before FGC and after FGB and at the Scattering Tank entrance and from neutrons absorbed by the Ni and Ti supermirror (SM) layers of the guides [14].

Source 5:

Represents the neutrons directed towards the BM with energy 2.08 meV and neutron current of 7.66×10^8 n.s⁻¹.

Source 6:

A mono-directional beam with a radius of 0 to 5 mm and directed towards the scattering sample, with energy of 2.08 meV and neutron current of 1.09×10^7 n.s⁻¹. To determine dose rates resulting from sample scattering simulations were carried out with typical samples of H₂O; Al₂O₃; SiO₂.

The MCNP code supplies a relative error associated with the number of events recorded in a tally cell. In the calculations performed for EMU, this relative error was lower than 5%, except those for which the dose rates were < 0.1 μSv/h. The total dose rates were evaluated as the sum of those resulting from each calculation performed with Source 1 and Source 2, and Sources 3 to 6, respectively.

3 Results and discussion

In the simulations performed, the neutrons were relatively easy to stop, the neutron dose rates around the EMU/KOOKABURRA pre-monochromator bunker and perimeter of the EMU experimental area were reduced to < 0.5 μSv/h by using 5 – 10 mm thick high density MirroBor™ on the internal surfaces of the pre-monochromator bunker, focusing guide and BC shielding, Flight Tube and BM shielding, covering gaps and lining the external surfaces of components, e.g., aluminium or steel.

Gamma radiation results from capture of neutrons by the selected shielding and various component materials. In the simulations performed, the gammas produced are from the capture of neutrons by the ²⁷Al (and also, from decay of ²⁸Al), found in the material of components, casings, and Al windows. As well, gamma radiation results from the ¹⁰B in the GC, the Si of the BM, the steel material, and from neutrons absorbed by the ¹⁰B, ^{nat}B, Si, Na and K contained in the neutron guide glass. The MirroBor™ used to attenuate the neutrons also contains ¹⁰B. When irradiated with low energy neutrons ⁴He (alpha particles) and ⁷Li nuclei are emitted plus gammas of energy 0.48 MeV. ¹¹B does not activate on thermal neutron capture. For thermal neutron capture by ²⁷Al, the highest energy transition of gamma rays occurs at ~7.7 MeV. For Si it is ~3.5 MeV but there is another strong transition for Si occurring at ~4.9 MeV, which is equivalent to 90% of the strongest transition intensity. Therefore, relatively thick gamma absorbers were employed and in the models presented here Fe, Pb, and a combination of Fe/Pb/Fe was used.

3.1. MCNP simulations of shielding around the pre-monochromator bunker

When the sample shutter is closed the total ($n + \gamma$) dose rates around the cylindrical blocks and near the beam opening were ≤ 2.5 μSv/h. The total dose rate at the rear external surface of the pre-monochromators bunker shielding, near to where the pre-monochromator access doors will be located, was ≤ 6 μSv/h. On top of the bunker the maximum total dose rate was calculated to be 11.2 μSv/h. In order to meet the safety criteria time restrictions will be placed on personnel access to the bunker roof while the neutron beam is on; these restrictions have minimal operational impact. At other areas of the pre-monochromator bunker the total dose rates on the external surfaces were ≤ 3 μSv/h.

3.2 MCNP simulations inside the experimental area and around its perimeter

Following numerous simulations the shielding design inside the experimental area and around its perimeter was refined to include the following,

- (i) The internal surfaces were lined with MirroBor™ of 5 mm thickness.

- (ii) The FGC section's shielding walls (top, bottom and sides) – steel of 30 mm thickness and Pb of 60 mm thickness (Figure 8).
- (iii) The BC shielding walls (top, bottom and sides) – Pb of 30 mm thickness (Figure 9).
- (iv) The FGB section's shielding walls (top, bottom and sides) – steel of 30 mm thickness and Pb of 30 mm thickness (Figures 8 and 10).
- (v) Shielding elements “1” to “8” inside the Scattering Tank – Pb of 50 mm thickness (Figure 10).
- (vi) Pb of 25 mm thickness attached to the external rear surface of the Scattering Tank, with dimensions – arc length ~ 2570 mm $\times$ 1580 mm (height). The angle spread relative to the Scattering Tank centre is $\sim 80^\circ$ (Figure 10). Alternatively a Pb wall of 25 mm thickness can be installed at the projection of this Pb shielding element onto Surface “4”.
- (vii) Flight Tube, BM and linear Doppler drive and support block shielding walls (top, bottom and sides) – Pb of 50 mm thickness (Figure 11).

The steel layer in (ii) and (iv) above should prevent any high energy gammas that may eventuate from the SM coatings of neutron guide interacting with the Pb shielding to produce fast neutrons. Alternatively additional polyethylene-type shielding could be required on the outside of the Pb shielding.

For the combined neutron and gamma dose rates and BC in the open position the radiological doses were below the design limit of ≤ 3 $\mu\text{Sv/h}$ in most of the sections on the external surfaces of the experimental area's perimeter, for heights up to 5.5 m. The only exceptions were in Section 1 of Surface “3” where the dose rates were ~ 3.2 $\mu\text{Sv/h}$ (for height regions ≤ 2.5 m) and in Section 1 of Surface “7” the dose rates were in the range 3 $\mu\text{Sv/h}$ to 5.1 $\mu\text{Sv/h}$ (for height regions 3.5 m to 5.5 m). Similarly, when the BC is in the closed position Sections 1 to 4 of Surface “7” show that directly above the Out-of-Pile Bunker wall surface (i.e., > 3.5 m height) the gamma dose rate varies from 3 $\mu\text{Sv/h}$ to 11.4 $\mu\text{Sv/h}$. However, there are existing barriers to keep persons standing on top of the Out-of-Pile Bunker away from its edge whereas persons may walk through or stand at areas located 1 m to 2 m away (Surfaces “8” and “9”) and in these regions the dose rates are expected to be ≤ 3 $\mu\text{Sv/h}$. Also, at Surface “10” the photon dose rates are expected to be ≤ 3 $\mu\text{Sv/h}$.

When the tertiary shutter is open and the neutron beam is on, close to the BC shielding the dose rates were calculated to be in the range 15 $\mu\text{Sv/h}$ – 30 $\mu\text{Sv/h}$ and near the beginning of the FGC shielding and its Al window the dose rates were 100 $\mu\text{Sv/h}$ – 500 $\mu\text{Sv/h}$ (located at the positions of spheres labelled “1”, “2”, “3” and “4” shown in Figure 8). Therefore (as anticipated), while the instrument is operating persons will not be allowed to enter the experimental area.

The Pb shielding elements “1” to “8” in (v) were arranged with “1” to “5” and “8” positioned as vertical plates (Figure 10), while the other elements “6a” to “6b”

are the top and bottom vertical plates above and below the FGA end section and “7” is the top cover. These Pb shielding elements were arranged such that the gammas produced from the Al window at the end of the FGB and the N16 and N17 Al windows were contained at the location which they were generated at, and such that those produced from the BM material were contained inside the Scattering Tank.

On the top of all shielding assemblies persons are not expected to be walking over, or spending any amount of time in the area while the neutron beam is on. Further, if the 3 $\mu\text{Sv/h}$ limit criterion is not required to be strictly adhered to in certain areas depending on the area occupancy factors for persons, then the above mentioned thicknesses for the shielding are conservative. Also, the results have shown that while the EMU instrument is operating the dose rates at the adjacent KOOKABURRA [15] and PELICAN [16] instruments and Polarised He-3 Station will be ≤ 3 $\mu\text{Sv/h}$.

At the time the above simulations were performed MCNP 5-1.60 was the standard and validated code available, however, some of these results were checked with MCNP 6-1.0 [17, 18].

3.3 Radiation Surveys

Radiation surveys were conducted by ANSTO Health Physicists outside and inside of the instrument enclosure at 18 Radiation Base Points (RBP) E1 to I18, and permanent gamma radiation monitoring points GRM-1 and GRM-2 marked as γ , shown in Figure 12. The surveys were undertaken for the following configurations:

1. Tertiary shutter closed (baseline).
2. Tertiary shutter open, chopper system stopped (BC fully open, GC fully reflecting).
3. Tertiary shutter open, chopper system stopped (BC fully closed).
4. Tertiary shutter open, maintenance beam stop in place, chopper system stopped (BC and GC fully open).

Figure 12. Locations of Radiation Base Points (RBP) E1 to I18, and permanent gamma radiation monitoring points GRM-1 and GRM-2 marked as γ , for radiation dose surveys.

Table 2. The radiation dose survey results ($\mu\text{Sv/h}$) for configuration 4 with the tertiary shutter closed.

RBP	neutron	photon
E1	0.0	3.1
E2	0.0	0.3
E3	0.0	0.2
E4	0.0	0.2
E5	0.0	0.2
E6	0.0	0.1
E7	0.0	0.1
E8	0.0	0.2
E9	0.0	0.3
E10	0.0	0.5
E11	0.0	0.7
E12	0.0	0.6
E13	0.0	2.3
E14	0.0	2.0
E15	0.0	1.7
I16	0.0	0.6
I17	0.0	0.8
I18	0.0	0.2
GRM-1		0.6
GRM-2		0.5

The radiation surveys conducted for instrument configurations 1 to 3 have shown that the dose rates at the RBPs and permanent gamma radiation monitoring points were $\leq 3 \mu\text{Sv/h}$.

4 Conclusion

To meet the acceptance criteria and achieve radiological doses below the allowed limits, the shielding design for the EMU instrument has been refined by means of MCNP calculations. The latest shielding arrangement has confirmed the effectiveness of the design for the FGC; the BC; FGB; Al windows of the Scattering Tank; Flight Tube; BM and linear Doppler drive. Additional Pb shielding elements (vertical, top and bottom plates) of 50 mm thickness were arranged inside the Scattering Tank. These arrangements are consistent with safety requirements, more than meet the floor load limit ($< 20 \text{ tonnes/m}^2$ limit), and cost constraints.

The current state of the instrument along with the shielding arrangement is shown in Figure 13. The instrument is in its initial stage of user operation at the time of this report.

Figure 13. Current state of the EMU instrument with the shielding arrangement.

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