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Shielding activated return water at the ESS

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Abstract. ESS utilises water both for moderating neutrons to thermal energies, as well as to cool beryllium - and steel reflectors, the shielding and plugs. This means that the water, in separate loops, will be subject to a significant proton and neutron irradiation causing the water to activate. After irradiation, the water is led to delay tanks situated inside the target building. Before returned to the target monolith $\sim 10\%$ is led to the ion exchanger.
This paper aims at determining the shielding required to ensure that the biological dose-rate requirements in the target building and neighbouring instrument halls are met during operation of facility.

1. Introduction

The construction of the European Spallation Source (ESS) is ongoing in Lund, Sweden. At ESS it is necessary to operate water loops to remove heat from the thermal moderators and as well as the beryllium- and the steel reflectors, shielding blocks and plugs. The water in each of these circuits is exposed to a very high level of radiation, from as well protons and neutrons at various energies. This causes activation of the water and impurities therein. In this work the measures for safe handling of the return water are investigated. The work presented here focusses on operations (i.e. proton driver is on) as opposed to maintenance, which require a separate dedicated study (ongoing).

2. Methods and Modelling

The radiation shielding calculations are performed following the ESS Procedure for designing shielding for safety [1]. Monte Carlo radiation transport calculations are performed with the MCNPX-2.7 code [2]. To determine the source term the MCNPX master model of the ESS target-moderator-reflector system (v. 2.000) is run with NPS=1E6 to produce a *F4* tally and *histp* file of a cell which includes the combined water of the moderators and reflectors. Impurities are added to the water according to [3]. Next, based on the produced *histp* file and *F4* tally, a CINDER'90 (v. 1.05)[4, 6] activation calculation is carried out using as irradiation scenario the expected ESS operations schedule for two years of full power operations.
As seen in figure 1 the piping leading the water through the various systems is complex, and is not modelled in detail in this study. Instead, focus is put on the moderator loop, which is the most challenging in terms of activation. Approximate water volume of various fractions of the pipe circuits is used to define volumetric source terms (scaling the full source term), at various cooling times to account for the water flow. The cooling times considered fall in two categories:

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Isotope	Half-life [s] [s]	Decay mode	Time step [0s]	Time step [90s]
^{3}H	3.89E8	β	621.3	621.3
^{7}Be	4.61E6	EC$\beta + \gamma[477keV]$	445.1	445.1
^{11}C	1223	β	1473	1400
^{14}O	70.6	$\beta + \gamma[2.3MeV]$	92.3	38.5
^{15}O	122	β	4511	2723
^{16}N	7.1	$\beta + \gamma[6.1MeV]$	4462	0.8
Total			12380	7161

Table 1: Total activity in Curies. Only isotopes contributing in excess of 10Cu at 60 s cooling are listed, but all are included in the total sum.

10s relevant to describe water flowing in pipes toward the delay tanks and 10 s - 90 s relevant for water in the delay tank.
To determine the required shielding, the radiation zoning of ESS is applied [5]. Both in the case of the moderator exhaust pipe as well the for the delay tanks, the limiting factor driving the shielding thickness, is the 3 μSi/h requirement of the instrument hall - see figure 1.

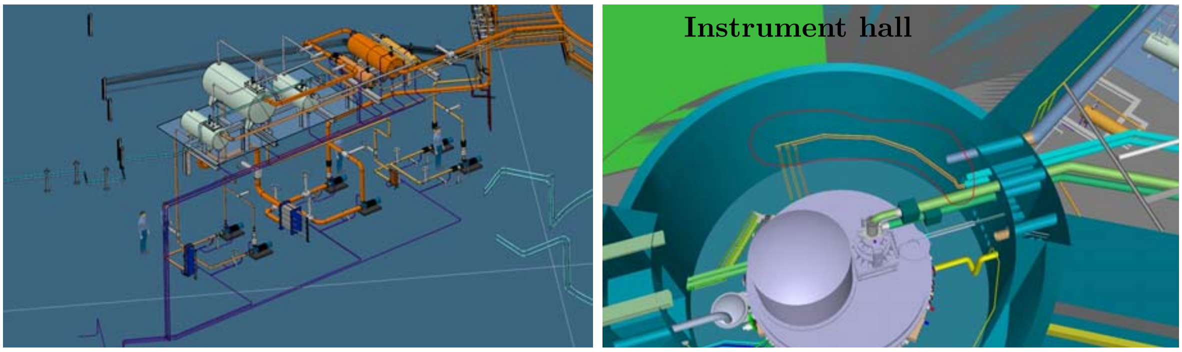

Figure 1: Left: CAD drawing of triangular rooms, showing the three orange delay tanks and connecting pipes. Right: connections cell, showing the exhaust pipe mounted on the wall toward the instrument hall.

For each cooling time considered, a source term is prepared (SDEF card) by executing the *gamma script* [6]. Next, a gamma transport simulation is carried out using MCNPX based on a simplified geometry of the target building and surroundings (next section). To determine dose-rate maps, in each configuration, $\geq$1E8 gammas are simulated, and the biological dose-rates are calculated using ICRP-116 gamma flux-to-dose conversion factors [7]. Importance biasing is implemented to ensure efficient calculations of radiation transport through the shielding.

3. Results

Table 1 lists the isotopes giving the largest contributions to the total activity at selected cooling times. As expected ^{16}N (^{16}O$(n,p) \rightarrow^{16}$N) is the main gamma emitter at short cooling times whereas ^{9}Be plays this role at longer cooling times. The combination of the very energetic gammas of ^{16}N with the fact that it's 7.1 s lifetime is of the same order as the time it takes the water to reach the connections cell from the moderator, makes this isotope particular challenging.

3.1. Shielding pipes in the connections cell

The pipes submerge from the protection steel of the target monolith in the connections cell and are routed toward the delay tanks in the triangular room as shown in figure 1(right). To describe the water source in the pipe following the circumference of the room, a cooling time of 10 s is assumed, accounting for the time it takes for the water to flow there from the moderators, situated 4 m below the floor.

The water volume present in the pipes correspond to about 1/4 of that present in the moderators, wherefore the source term is re-scaled by this factor. The resulting biological dose-rate maps are shown in Figure 2, for different shielding configurations as explained in the figure caption.

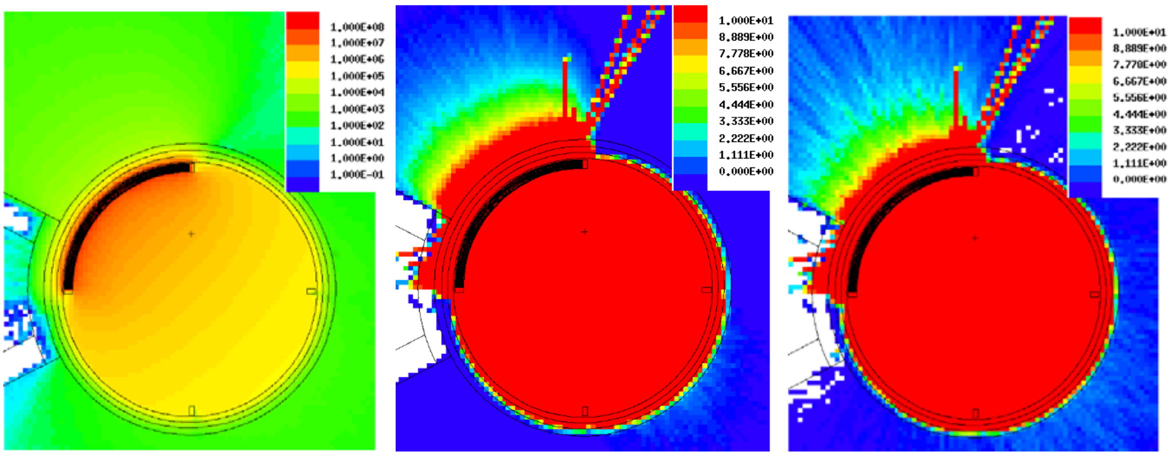

Figure 2: Biological dose-rate in μSv/h due to the delay tank inlet pipe. Shielding thickness: 0 cm (left), 12 cm lead (middle) and 6 cm lead + heavy concrete(right). Note the difference in scales: left-hand figure: $10^{-1} - 10^{8}\mu$Sv/h, middle and right-hand figures: 0-10μSv/h.

As seen in the left-hand insert of this figure, the challenge of shielding the exhaust water is significant. Two options are proposed, which provide sufficient shielding: either the pipe is surrounded by 12 cm of lead, or the composition of the wall towards the instrument hall is changed from regular concrete (ρ =2.35 g/cm^3) to heavy concrete (ρ =3.85 g/cm^3) in which case equivalent shielding is reached using 6 cm lead. At present it is being evaluated which of the two options is more practical and economic.

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3.2. Delay tank shielding

The water circuits, of course, are not exactly steady. Moreover the timescales relevant to the water flow are similar to the half-life of ^{16}N, which according to table 1 is main contributer to the activity on a one-minute timescale. To accurately model the source term to be used for delay tank shielding calculations, the following observations are made:

- Moderator water content: 9L
- Moderator exhaust speed: 0.6 L/s (or 2 m/s) so the average cooling time, at the time of exiting the moderator: 7.5 s.
- Pipe length: ∼10 m. ∼5 m vertical and ∼5 m horizontal

Thus, *SDEF* cards are prepared corresponding to cooling times between $7.5\ \mathrm{s} + \frac{10\ \mathrm{m}}{2\mathrm{m/s}} \approx 13\ \mathrm{s}$ and 37 s in 9 equidistant steps - see table 2.

Cooling time [s]	13	16	19	22	25	28	31	34	37
Source weight [%]	12	12	12	12	12	12	12	12	4

Table 2: Source definitions used to model the delay tank.

The resulting dose-rate map due to the presence of activated primary coolant water in the delay tank is shown in figure 3. The dose-rate requirements in the instrument hall are met only after introducing 16 cm of lead shielding. It should be noted that the delay tank need shielding on all horizontal directions, though the shielding requirements on the side facing the center of the room, can be reduced by approximately two orders of magnitude due to the geometrical dilution between the delay tank and the instrument hall on the opposite side of the connection cell.

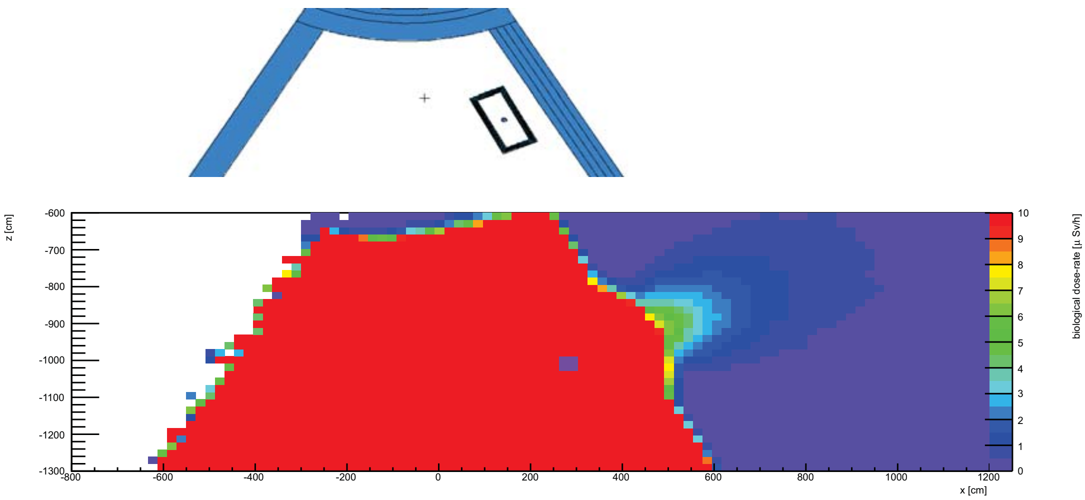

Figure 3: Biological dose-rate in μSv/h due to the delay tank - the geometry used in the biological dose-rate map (below), is indicated above. Shielding thickness: 16 cm lead.

4. Conclusions

The shielding requirements of the primary coolant return water is studied using a MCNPX neutron and gamma transport calculations in combination with CINDER'90. Immediately

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after returning from the moderators/reflectors ^{16}N is the most challenging isotope, while after the cooling for 90 s in the delay tanks, ^{9}Be claims this role. For irradiated water present in the connections cell, the most challenging biological dose-rate limit to be met is that of the instrument hall. To meet the 3μSv/h limit, the following shielding must be installed:

- 12cm lead around delay tank inlet pipe
- 16cm lead between delay tanks and instrument hall

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