Document Type	Report
Document Number	ESS-XXXXXXX
Date	Nov 9, 2016
Revision	1 (1)
State	Preliminary
Confidentiality Level	Internal
Page	1 (8)

C-SPEC phase 1 beamline and instrument cave shielding calculations

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1. PURPOSE

This report describes phase 1 out of line-of-sight shielding calculations for the instrument C-SPEC [1]. The calculations aim to provide preliminary shielding estimates for budgeting purposes and detailed safety calculations should be carried out in the future for phase 2 during detailed design, as described in [2]. The calculations in this report assume that the components considered below are sufficiently out of line-of-sight and that the radiation dose is dominated by photons resulting from neutron capture. The importance of the neutron dose should be estimated in an additional study using Monte-Carlo calculations, for example with MCNP.

2. METHODOLOGY

2.1. Beamline Shielding

A numerical integration was used to estimate the amount of shielding outside of line-of-sight. The flux at a single point on the outside of a shield, located at a distance from an infinitely long line source, is given by

$$\Phi = \frac{1}{4\pi} \sum \frac{S_i B_i e^{-\mu t_i} dl_i}{x_i^2}, \qquad (1)$$

where S_i is the source strength in photons/cm/s, B_i is the buildup factor, μ is the photon attenuation coefficient, t_i is the thickness of the shield seen by the point on the outside of the shield, and x_i is the distance from a point on the line source. This is a slight modification to formula (10.58) in [3]. The source intensity was considered to be uniform across the line. The photon production in photons/cm/s was calculated from the intensity of the neutrons entering the guide, divided by the collision length with the guide walls, defined by h/tan θ_{crit}, where h is the guide height and θ_{crit} is the critical angle for reflection for the guide [4], and multiplied by the neutron capture conversion to photons. The critical angle defines the maximum glancing angle for total reflection of the neutrons along the guide. The full calculation is given as

$$S\left[\frac{gammas}{cm\ s}\right] = F\left[\frac{n}{cm^2 s}\right] \frac{\tan\left(\theta_{crit}\right)}{h_{[cm]}} \cdot \left(A\left[cm^2\right]\right) \cdot C\left[\frac{gammas}{n}\right], \qquad (2)$$

where F is the flux of slow neutrons exiting the point where line-of-sight is lost (i.e. the bunker wall) with a beam area of A. The parameter C is the fraction of neutrons absorbed in the walls of the guide which is inferred from the data presented in Ref. [5]. It is assumed 100% conversion to gammas.

For the photon emission, resulting from neutron capture in the supermirror, a weighted average of Ni and Ti gamma-rays was used, corresponding to the materials in a Ni/Ti supermirror. The data for the calculations were taken from [6]. The calculations were carried out by first considering the atom density and micro-scopic cross-sections for Ti and Ni. Ti has a density that is roughly half, i.e. 4.51 g/cm^3 compared to 8.91 g/cm^3, and also has an atomic mass of 48 compared to 58 for nickel. This leads to an atom density for Ti which is around 60% lower than Ni. Weighting the atom densities with the micro-scopic cross-sections of 6.1 barns for Ti and 4.4 barns for Ni then gives almost equal macroscopic cross-sections of 0.35 cm^{-1} for Ti and 0.40 cm^{-1} for Ni. These were used to weight the gamma-ray emission from the supermirror which resulted in an average energy of around 4.5 MeV, considering a homogeneous mixture of Ni and Ti.

For the dose calculation, the density of 2.3 g/cm^3 for concrete was used, an attenuation coefficient of 0.030625 cm^2/g [7], and a flux to dose conversion factor of 0.0000125 μSv cm^2 for 4.5 MeV photons. The buildup factors were calculated using the Taylor form of the buildup factor, as described in Ref. [3]. Dose conversion factors were taken from [8].

2.2. Cave shielding

For calculations of the thickness's of the cave shielding walls, the process described in Ref. [9] was used. This included the conversion of the full neutron intensity at the location of the sample position into 2 MeV photons and emitted into 4π. This is similar to the 2.2 MeV emission from the (n,γ) reaction on hydrogen or an average 1.2 MeV emission from the (n,γ) reaction on Cd/Fe sample. The radiation dose on the outer surface of a cave wall is given by

$$\varphi = \frac{S \cdot B}{4\pi x^2} \exp(-\mu \cdot t) , \quad (3)$$

where S is the photon strength at the sample position, B the buildup factor, x the distance of the point on the outer surface of the wall from the source position, t the thickness of the shield, and μ the photon attenuation coefficient. For the dose calculations, a dose conversion coefficient of 0.0000075 μSv cm^2 [8] was used and an attenuation coefficient for concrete of 0.04557 cm^2/g [7].

2.3. Beamstop shielding

For the thickness of the beamstop, it was assumed that all neutrons could be absorbed in boron-rich layer placed on the surface of the beamstop. The dose behind the beamstop then arises from the 0.5 MeV photons from neutron capture in boron. For the dose calculations, a dose conversion coefficient of 0.00000250 μSv cm^2 [8] was used and an attenuation coefficient for concrete of 0.08915 cm^2/g [7]. Eq. (3) was used for the calculations.

2.4. Chopper-pit shielding

For the chopper-pit shielding, it was assumed that all the neutrons were absorbed in the chopper when closed. Two absorbers were considered, either boron or gadolinium. An average energy of 0.5 MeV was assumed in the first instance and 2 MeV in the latter. The shielding stand-off distances were used as given in section 9.1. Eq. (3) was used for the calculations.

3. ACCEPTANCE CRITERIA

[10] shows that the instrument halls are supervised zones. [11] sets the dose limit for a supervised area is 3 μSv/h. In accordance with [8] the acceptance criteria therefore is 1.0 μSv/h.

4. OPEN ITEMS

More precise shielding thicknesses may be expected from a detailed calculation of the losses along the length of the guide. This report addresses the radiation dose arising from neutron capture of slow neutrons. The neutron dose should be estimated from Monte-Carlo calculations using for example MCNP.

5. ASSUMPTIONS

The assumptions are as described in the methodology section.

6. LIMITATIONS

The shielding calculations assume that the instrument is sufficiently out of line-of-sight and that the radiation dose is dominated by photons resulting from neutron capture.

7. COMPUTER HARDWARE AND SOFTWARE

Calculations were carried out using standard spreadsheet software (LibreOffice) and also ROOT.

8. CALCULATION INPUTS

As described in the methodology section and also given in sections 9.1, 9.2 and 9.3.

9. RESULTS OF CALCULATIONS

The results of the calculations are shown in sections 9.1, 9.2, 9.3 and 9.4. For all calculations, two scenarios were considered. These included a flux of 4.3E9 n/cm^2/s going down the guide and 3E9 n/cm^2/s at the sample position [12]. The second case was these fluxes with a factor of 100 reduction. This factor of 100 comes from the opening size of the monochromator chopper (3 degrees / 360 degrees) which is placed around 150 m along the length of the instrument. All thicknesses are given to meet the 3 μSv/h requirement for a supervised radiation zone (including the safety factor for hand calculations).

9.1. Beamline shielding

Table 1: Beamline shielding results. The shielding thicknesses are for concrete.

Flux [n/cm^2/s]	m-value	Guide height [cm]	A	Standoff [cm]	Dose conversion [µSv cm^2]	Density [g/cm^3]	Attenuation µ/ρ [cm^2/g]	Thickness [cm]
4.3E9	2.5	8	0.3	50	0.0000125	2.3	0.030625	95
4.3E7	2.5	8	0.3	50	0.0000125	2.3	0.030625	34
4.3E9	3.0	8	0.3	50	0.0000125	2.3	0.030625	101
4.3E7	3.0	8	0.3	50	0.0000125	2.3	0.030625	39
4.3E9	4.0	8	0.3	50	0.0000125	2.3	0.030625	113
4.3E7	4.0	8	0.3	50	0.0000125	2.3	0.030625	51

9.2. Cave shielding

Table 2: Cave shielding results for the roof. The shielding thicknesses are for concrete.

Flux [n/cm^2/s]	Area [cm^2]	Distance [cm]	Dose conversion [µSv cm^2]	Density [g/cm^3]	Attenuation µ/ρ [cm^2/g]	B	Thickness [cm]
3E9	8.0	283	0.0000075	2.3	0.04557	10.4	85
3E7	8.0	235	0.0000075	2.3	0.04557	4.7	36

Table 3. Cave shielding results for the detector walls. The shielding thicknesses are for concrete.

Flux [n/cm^2/s]	Area [cm^2]	Distance [cm]	Dose conversion [µSv cm^2]	Density [g/cm^3]	Attenuation µ/ρ [cm^2/g]	B	Thickness [cm]
3E9	8.0	481	0.0000075	2.3	0.04557	9.0	73
3E7	8.0	429	0.0000075	2.3	0.04557	3.1	21

9.3. Beamstop calculations

For the beamstop calculations, the detector wall concrete thicknesses were checked if they could provide sufficient shielding for photons generated from the beam incident on a boron-rich layer placed in front of the beamstop and the full beam was absorbed. For the first scenario, with an 73 cm thick beamstop, a dose of 0.2 µSv/h was found. For the second scenario with 21 cm thick walls, a dose of 70 µSv/h was found. This means that the walls would not be sufficient for a beamstop in this situation and 41 cm of concrete would be needed to meet the requirements.

9.4. Chopper-pit shielding

For the chopper-pit shielding for the first scenario with a boron absorber it was found that 60 cm thick concrete shielding would be needed to stop the resulting photons. For the Gd absorber, 102 cm thick concrete shielding would be needed. For the reduced flux scenario, 34 cm of concrete were needed with the boron absorber and 59 cm with the gadolinium absorber.

10. SUMMARY

This document presents the results of shielding calculations for C-SPEC for the instrument cave and the beamline section that is out of line-of-sight. The shielding thicknesses ranged from around 20 cm to 110 cm of concrete, depending on the type of shielding component and the intensity of the radiation considered.

11. REFERENCES

[1] C-SPEC instrument proposal, https://europeanspallationsource.se/sites/default/files/c-spec_proposal_0.pdf

[2] ESS-0052625, NOSG phase 2 guidelines for designing instrument shielding for radiation safety

[3] J. R. Lamarsh and A. J. Baratta, "Introduction to Nuclear Engineering", Prentice Hall, Upper Saddle River, New Jersey 2001.

[4] B.T.M Willis and C.J. Carlile, Experimental Neutron Scattering, Oxford University Press Inc., New York 2009

[5] C. Schanzer, M. Schneider, and P. Böni, "Neutron Optics: Towards Applications for Hot Neutrons", Journal of Physics: Conference Series, Volume 746, Number 1.

[6] Database for Prompt Gamma-ray Neutron Activation Analysis, https://www-nds.iaea.org/pgaa/

[7] NIST, X-ray mass attenuation coefficients, https://www.nist.gov/pml/x-ray-mass-attenuation-coefficients

[8] ESS-0019931, ESS Procedure for designing shielding for safety

[9] ESS-0059811, NOSG phase 1 technical review checklist

[10] ESS-0057090, Zoning Plans for G-buildings

[11] ESS-0001786, Definition of Supervised and Controlled Radiation Areas

[12] Pascale Deen, C-SPEC, Neutron optics and shielding cost optimization workshop, https://indico.esss.lu.se/event/559/

DOCUMENT REVISION HISTORY

Revision	Reason for and description of change	Author	Date
1	First issue – modifications to earlier preliminary version	Douglas Di Julio	2017-2-03