ORNL/TM-2024/3274

ALTERNATIVE SOURCE VERIFICATION FOR THE NB5 BEAMLINE

Kyle B Grammer

February 12, 2024

OAK RIDGE National Laboratory

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Neutron Technologies Division

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Prepared by
OAK RIDGE NATIONAL LABORATORY
Oak Ridge, TN 37831
managed by
UT-BATTELLE LLC
for the
US DEPARTMENT OF ENERGY
under contract DE-AC05-00OR22725

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	REV 0	REV 1	REV 2	REV 3
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LIST OF ABBREVIATIONS

CGH Cold Guide Hall

HB4 horizontal beamtube 4

HFIR High Flux Isotope Reactor

NB1 neutron beamline 1

NB2 neutron beamline 2

NB3 neutron beamline 3

NB4 neutron beamline 4

NB5 neutron beamline 5

NB6 neutron beamline 6

SSR surface source read

SSW surface source write

ABSTRACT

This report details the calculation and comparison of secondary neutron sources for the purpose of performing NB5 velocity selector shielding calculations without relying on the primary HB4 source and the use of a modified MCNP code to run the full model.

1. INTRODUCTION

The goal of this exercise is the production and verification of alternative sources along the NB5 beamline, which is one of the cold neutron beamlines in the Cold Guide Hall (CGH) at the High Flux Isotope Reactor (HFIR). The primary horizontal beamtube 4 (HB4) source in the CGH illuminates 6 neutron guide networks (named NB1, NB2, NB3, NB4, NB5, and NB6) and neutron trajectories that progress down NB1 may not efficiently use compute time for a calculation that focuses on NB5 alone. Therefore, alternative sources can be advantageous compared to the primary HB4 source due to the difficulty in reaching satisfactory statistical results at locations 10s of meters from the HB4 source, as can be seen in figure 1. Furthermore, a calculation that begins upstream of the location of interest for one of these beamlines will rely on the use of a non-standard, in-house version of MCNP6.2 that features code extensions for neutron guides [1] [7], single crystal scattering [2] velocity selectors [6], small angle neutron scattering [5], and gravity [4]. In particular, the product of this specific exercise is Source 3, which is a tabulated source at the exit of the last guide segment entering the NB5 velocity selector shielding which can be handed off to others who have access to MCNP 6.2 [8] but not to the internally modified code.

The implementation of the primary source will be discussed, followed by the development of 3 alternative sources.

- **Source 0.** The primary HB4 source, including neutrons and photons, for 85 MW operation [3].
- **Source 1.** A surface source for neutrons at the entrance of NB5.
- **Source 2.** A surface source for neutrons at the exit of the last guide segment before the NB5 velocity selector.
- **Source 3.** A tabulated neutron energy distribution at the last guide segment before the NB5 velocity selector.

The geometry of the NB5 velocity selector shielding box is shown in figure 2. The colors identify different materials; steel (magenta), lead (yellow), concrete (beige), air (gray), and boron carbide (cyan). The annotations in figure 2 are locations where dose rate results are selected and are used to compare each source calculation. The upstream end of this last guide segment is the tally surface used for one of the SSW/SSR sources and the tabulated source described later.

1.1 SOURCE 0

First as an aside, the coordinate system used in this document begins with an origin at $(0, 0, 0)$ at the the HB4 beam tube origin and with the HB4 cold source translated by 11.89 cm along the z axis inside the beam tube. The neutron beam is directed from this point along the z axis. The positive y direction is upward (away from the floor) for a neutron traveling along z, and the positive x direction is “beam left” for this neutron. All calculations have been performed with a modified version of MCNP 6.2 [8].

The primary HB4 source is derived from SNS-107000000-TR0008-R00 [3], with expanded solid angle coverage in order to illuminate all 6 neutron beamlines (NB1-NB6). The primary source, named Source 0 or

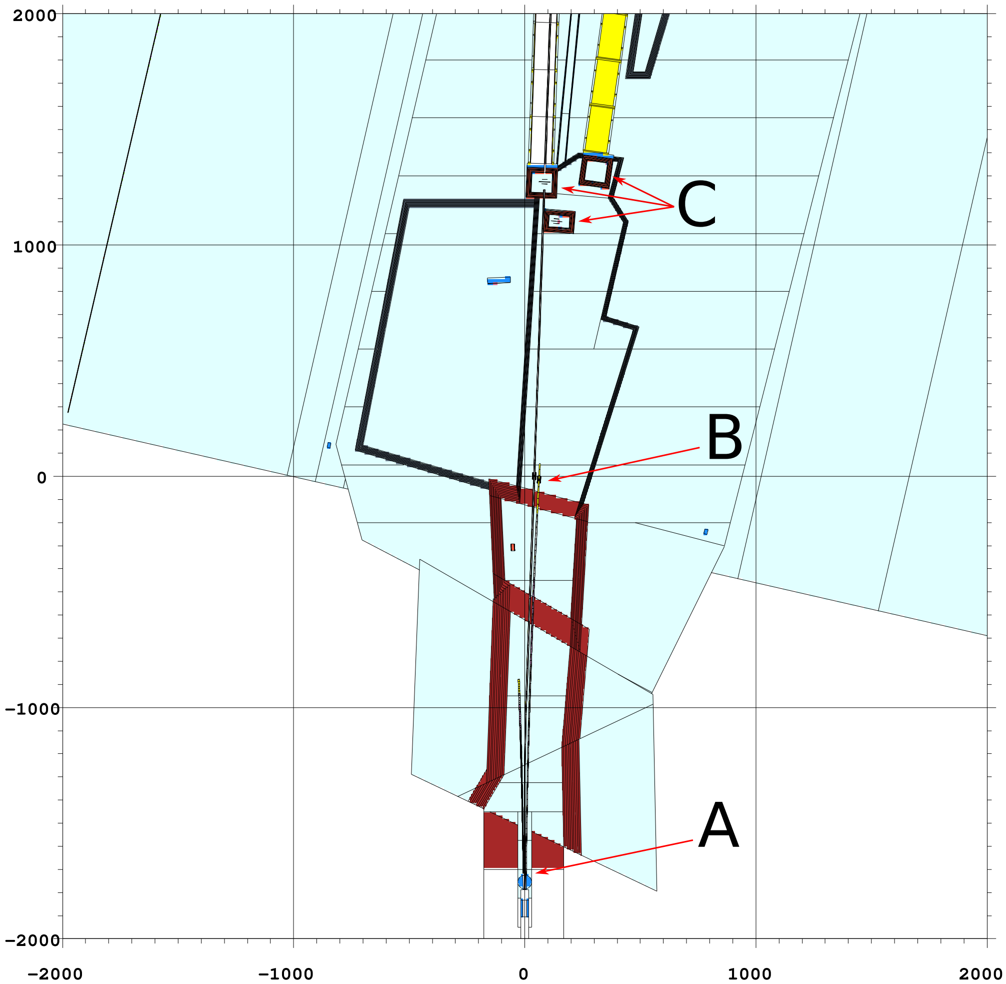

Figure 1. The layout of the HFIR CGH from the HB4 source to the velocity selectors. Neutrons begin at the bottom and traverse to the top. A is the location of the guide entrances, B is the location of the secondary instrument shutters, and C is the location of the NB5, NB4, and NB3 velocity selectors (from left to right). Axes are in centimeters.

S0, is an 8.52×8.52 cm square source centered along the axis of HB4 and viewed by NB1-NB6 and begins at the cold source location of position $z_0 = 11.89$ cm. This source has a brightness of 4.1569×10^{13} n/s/cm^2/ster at 85 MW and illuminates a cone with half-angle 1.2233°. The geometry of the upstream region of HB4 near the source, primary HB4 shutter, and guide entrances can be seen in figure 3. For a source subtended by a 0.00143 ster (1.2233°) cone, this brightness corresponds to an initial weight, $w_n = 4.315 \times 10^{12}$ n/s, which is from the original source file [3] input for HB4. This original source is expanded and aimed at the entrance of the internal collimator at a position of $z_c = 295.09$ cm and with a radius of $r_c = 9$ cm in order to illuminate all 6 guides, which begin at approximately $z_g = 500$ cm. The angle, θ_c, corresponding to the internal collimator position is given by,

$$\theta_c = \arctan \frac{r_c}{z_c - z_0} \tag{1}$$

which corresponds to 1.7441°. The solid angle of this new illumination cone is then given by,

$$\Omega = 2\pi(1 - \cos\theta), \tag{2}$$

which corresponds to 0.00317 ster. Therefore, the new initial neutron weight should be increased according

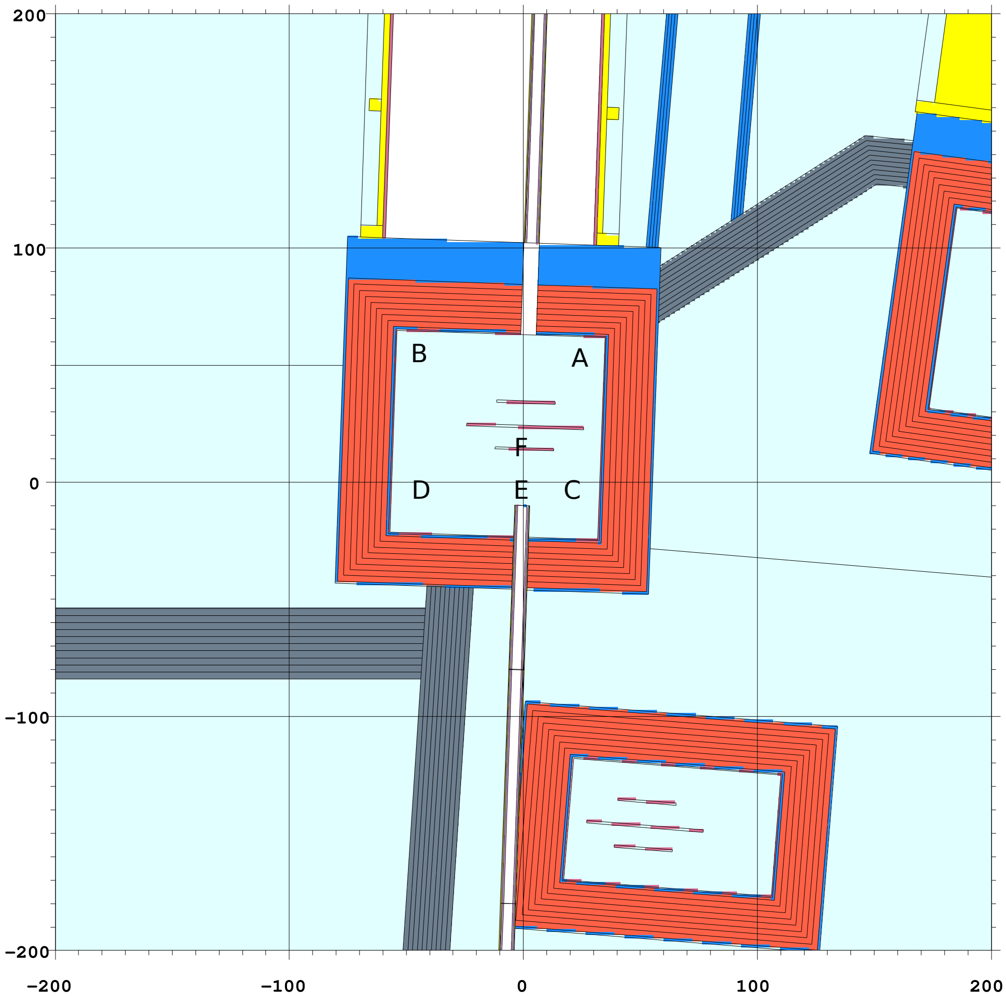

Figure 2. NB5 velocity selector shielding box. Neutrons enter from the guide penetration on the bottom. The NB4 velocity selector box is at the bottom and the NB3 velocity selector box is partially visible to the top right. Axes are in centimeters.

to the ratio of the solid angles, and the new weight is 9.553×10^{12}. The same process is applied to an initial photon source for HB4, which has an initial photon weight, w_p, of 1.569×10^{13}, corresponding to a new photon weight of 3.4737×10^{13}. The source is flat enough near the HB4 moderator such that the assumption that widening the source cone from 1.2233° to 1.7441° requires only an adjustment to the weight by the ratio of the solid angles. The total source weight for S0 is then the sum of $w_T = w_n + w_p = 4.429 \times 10^{13}$ and the photon distribution is sampled at the rate of $\frac{w_p}{w_T} = 0.7843$ and similarly the neutron distribution is sampled at a rate of $\frac{w_n}{w_T} = 0.2157$.

The alternative sources below are calculated from the primary source using SSW with 10^8 starting histories. The secondary shutters for beamlines NB1, NB2, NB3, NB4, and NB6 were closed in this configuration with a boron carbide plates in the vicinity of 22 m from the source (location B in fig. 1) so that the adjacent beamlines do not contribute to the neutrons reaching the NB5 velocity selector box (fig 2, and location C in fig. 1).

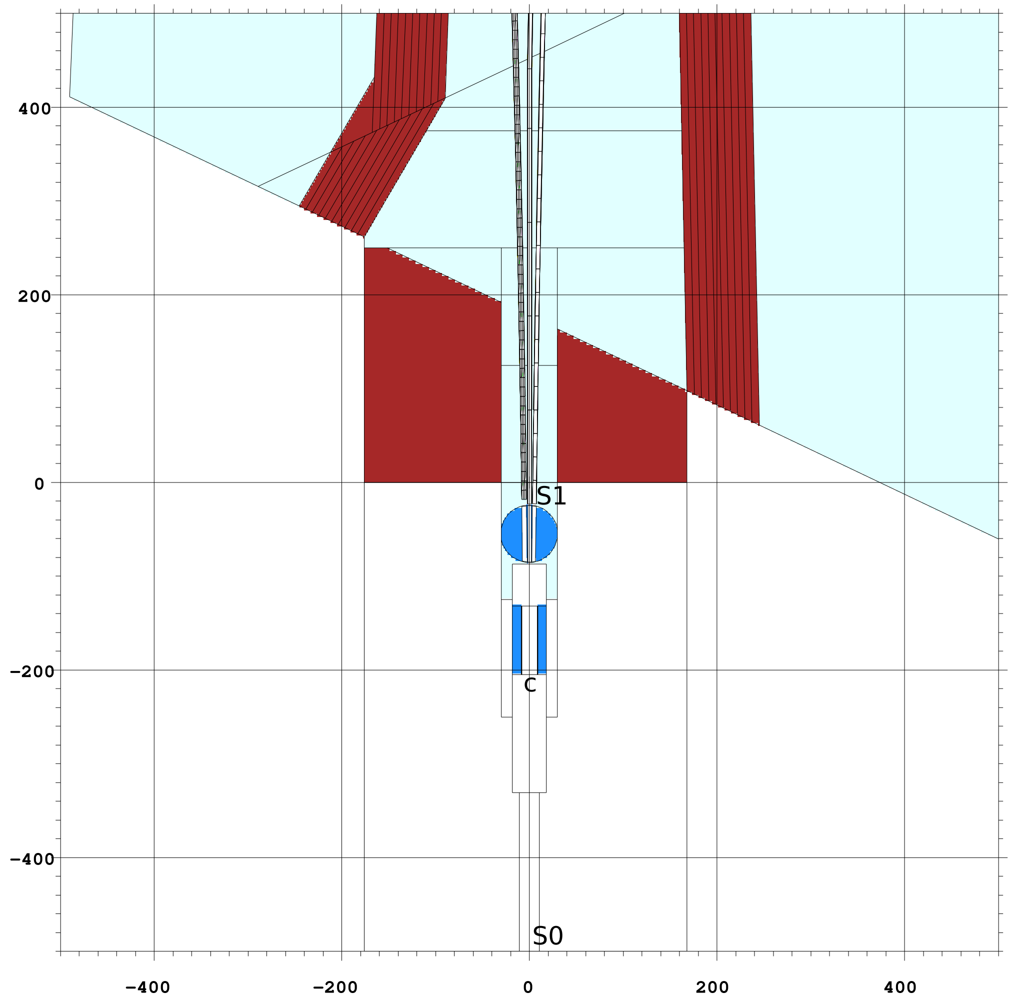

Figure 3. Upstream section of the HB4 geometry. Neutrons begin at S0 and are aimed in a cone at a 9 cm radius circle located at C. The neutron guides begin at S1, and 3 guide systems are visible in this horizontal slice. Axes are in centimeters.

1.2 CALCULATION OF ALTERNATIVE SOURCES S1-S3

Source 1 (S1) corresponds to an SSW that is written at surface 30004, which is the upstream face of cell 30000. A calculation using the primary HB4 source, S0, with an SSW,

```
ssw    30004 (30000) pty=n
```

is used to record only the neutrons entering the first guide segment of NB5 and written to a file named `ssw.NB5` containing 3161638 tracks from 549930 intependent histories at surface 30004 (fig. 4). Calculations using this surface source should agree with the primary source calculations for tallies that are influenced by NB5 alone, which includes the NB5 velocity selector shielding box as well as surface crossing tallies along NB5. This file would not be useful for performing NB5 velocity selector shielding calculations without using the modified MCNP6.2 executable because it requires simulating the neutron guides along the beamline. Therefore S1 serves as a comparison with S0 for tallies and a check that the process of calculating alternative sources along NB5 produces results that agree.

Source 2 (S2) corresponds to an SSW written at surface 31379, which is the downstream face of the final

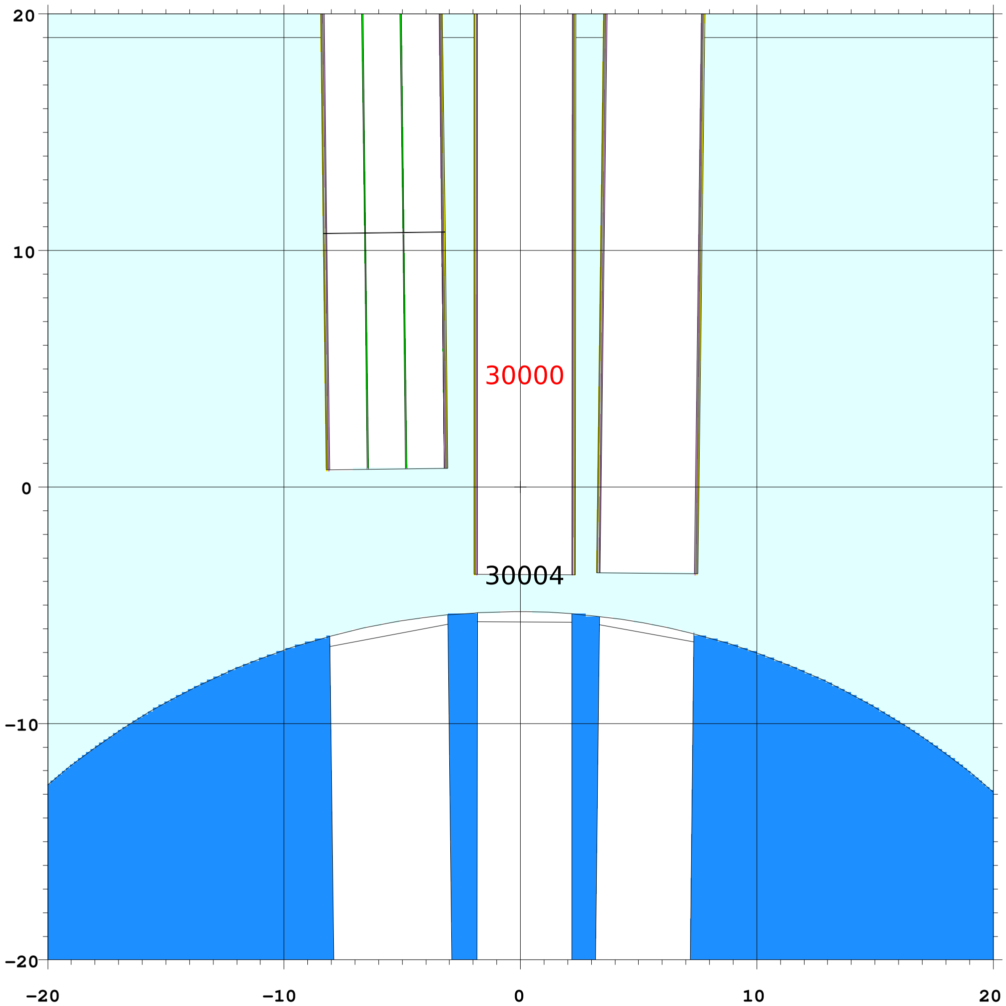

Figure 4. Entrance of the NB6, NB5, and NB4 guides. Neutrons that cross surface 30004 into cell 30000 become part of the S1 SSW. Axes are in centimeters.

guide before the NB5 velocity selector (cell 30228). A calculation using the primary HB4 source, S0, with an SSW,

```
ssw    31379 (-30228) pty=n
```

is used to record the neutrons leaving the last guide segment in the NB5 velocity selector (fig. 5). This is written to a file named `ssw.NB5_31379`. It contains 1523632 tracks from 88856 independent histories. Tallies produced using this surface source should agree with primary source calculations inside the NB5 velocity selector shielding box. In contrast to S1, S2 could be used for NB5 velocity selector shielding calculations because it does not rely on neutron guides at all and successfully isolates the shielding box geometry from the rest of the geometry.

Source 3 (S3) is determined using a type 1 tally on surface 31379 segmented by the boundaries of cell 30228 and in angular bins from 180° to 90° and 90° to 0° such that it tallies the neutrons passing through surface 31379 from cell 30228. The forward directed (90° to 0° relative to the surface normal) neutrons are converted to an neutron source with extent equal to the cross section of the neutron guide and with a divergence matching the S0 source divergence, which is a safe assumption because NB5 is not a tapered guide system. Similar to S2, this source could be used for NB5 velocity selector shielding calculations and

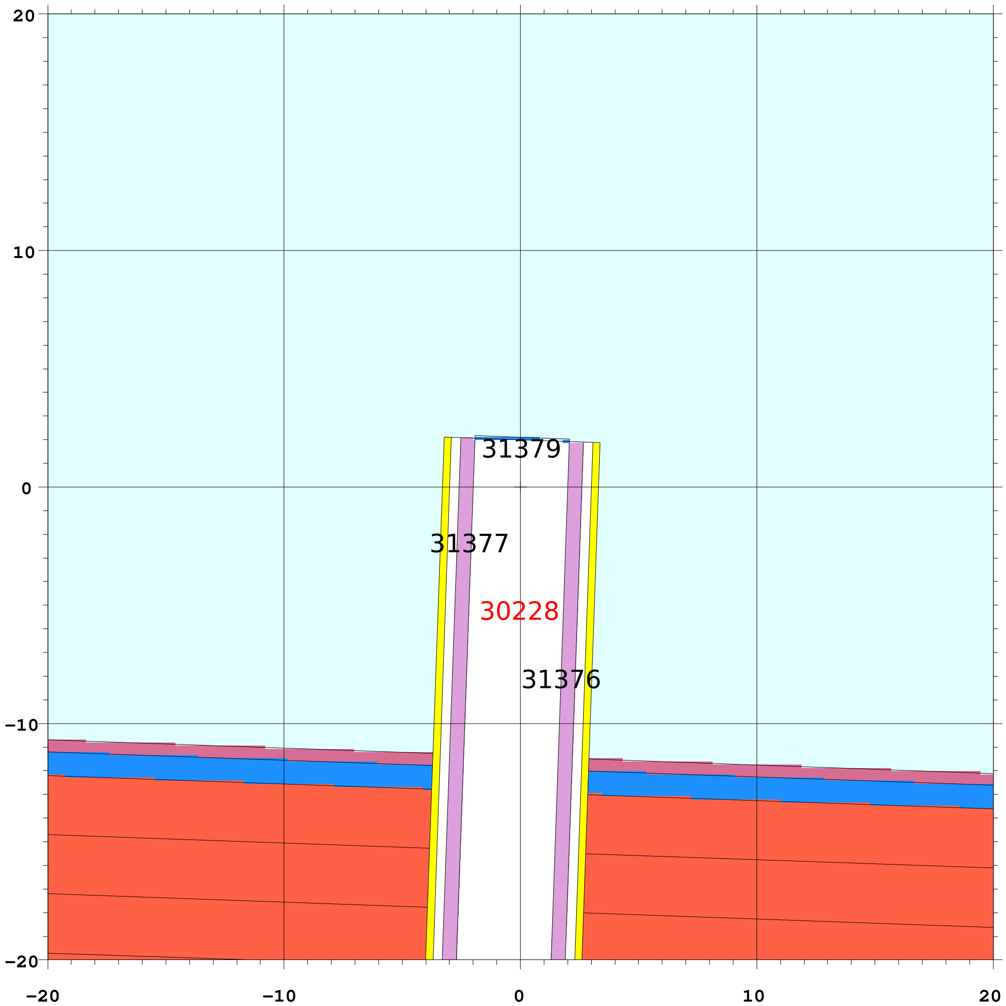

Figure 5. Exit of the last guide segment before the NB5 velocity selector. Neutrons that cross surface 31379 from cell 30228 become part of the S2 SSW. Axes are in centimeters.

has the advantage of requiring a small tabulated file rather than a large SSW file like S2. The tabulated source that is used for the S3 calculation and is contained in appendix B.

An `f1` tally is used to tally the neutrons crossing surface 31379 with segmentation sense relative to surfaces 31374, 31375, 31376, and 31377 such that the final bin corresponds to neutrons crossing surface 31379 within the boundaries of the interior of the guide cell 30228 (fig. 6). This is done because surface 31379 also corresponds to the downstream end of other cells, such as the glass, vacuum, and casing corresponding to guide cell 30228. The tally is binned in energy with 10 bins per decade and it is also binned in angle relative to the normal of surface 31379. When converting this tally to a tabulated `sdef`, only the forward directed component relative to the surface normal of surface 31379 is used; in other words only neutrons leaving cell 30228 as they cross surface 31379. The tally used to generate S3 is as follows:

```
f3022801:n    31379
fs3022801      +31374  -31375  +31376  -31377
sd3022801     1.0 1.0 1.0 1.0 1.0
e3022801      0.0 1e-12 1e-11 1.2589e-11 1.5849e-11 1.9953e-11 2.5119e-11
              3.1623e-11 3.9811e-11 5.0119e-11 6.3096e-11 7.9433e-11
```

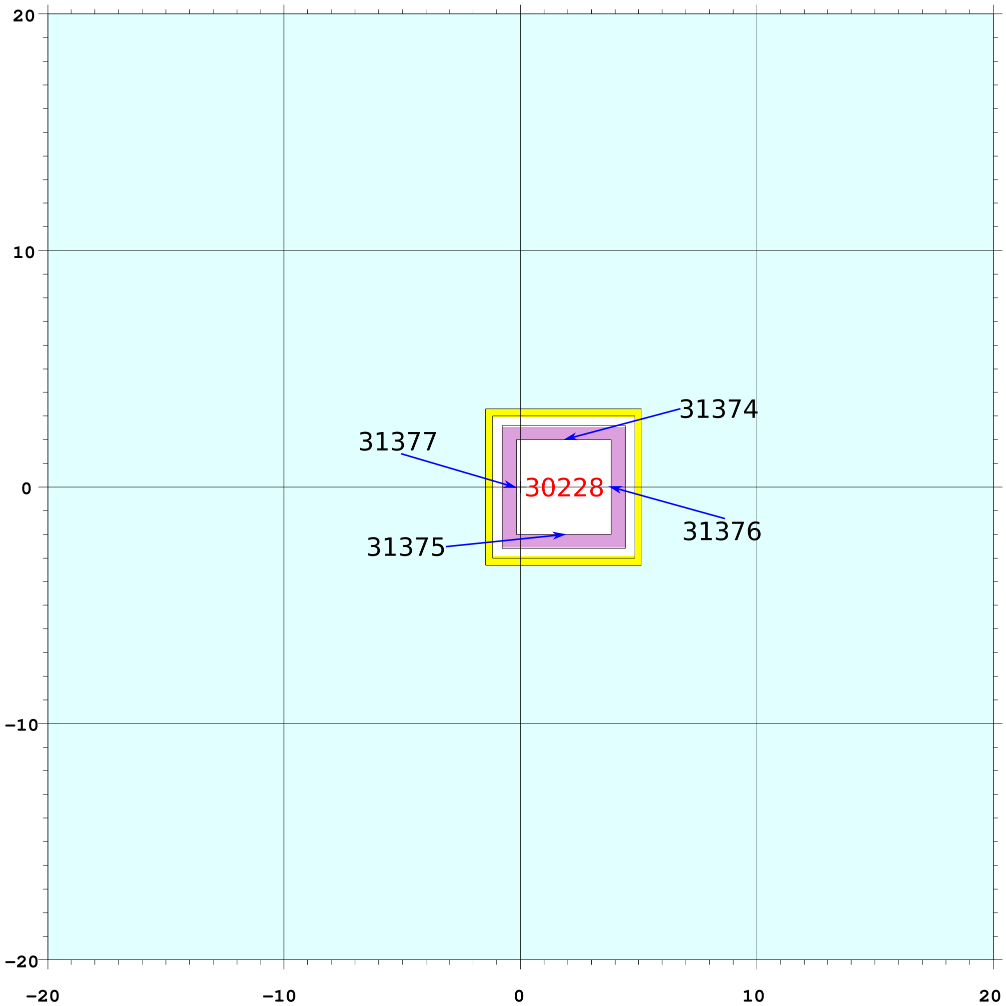

Figure 6. Exit of the last guide segment before the NB5 velocity selector. Neutrons that cross surface 31379 and are bounded by the 4 surfaces surrounding the interior cell 30228 (red) become part of S3. Axes are in centimeters.

```
1e-10 1.2589e-10 1.5849e-10 1.9953e-10 2.5119e-10
3.1623e-10 3.9811e-10 5.0119e-10 6.3096e-10 7.9433e-10
1e-09 1.2589e-09 1.5849e-09 1.9953e-09 2.5119e-09 3.1623e-09
3.9811e-09 5.0119e-09 6.3096e-09 7.9433e-09 1e-08
1.2589e-08 1.5849e-08 1.9953e-08 2.5119e-08 3.1623e-08
3.9811e-08 5.0119e-08 6.3096e-08 7.9433e-08 1e-07 1.2589e-07
1.5849e-07 1.9953e-07 2.5119e-07 3.1623e-07 3.9811e-07
5.0119e-07 6.3096e-07 7.9433e-07 1e-06 1.2589e-06
1.5849e-06 1.9953e-06 2.5119e-06 3.1623e-06 3.9811e-06
5.0119e-06 6.3096e-06 7.9433e-06 1e-05 1.2589e-05 1.5849e-05
1.9953e-05 2.5119e-05 3.1623e-05 3.9811e-05 5.0119e-05
6.3096e-05 7.9433e-05 0.0001 0.00012589 0.00015849
0.00019953 0.00025119 0.00031623 0.00039811 0.00050119
0.00063096 0.00079433 0.001 0.0012589 0.0015849 0.0019953
0.0025119 0.0031623 0.0039811 0.0050119 0.0063096
```

```
              0.0079433 0.01 0.012589 0.015849 0.019953 0.025119
              0.031623 0.039811 0.050119 0.063096 0.079433 0.1 0.12589
              0.15849 0.19953 0.25119 0.31623 0.39811 0.50119 0.63096
              0.79433 1.0 1.2589 1.5849 1.9953 2.5119 3.1623 3.9811
              5.0119 6.3096 7.9433 10.0
*c3022801      90 0.0
```

2. COMPARISON OF RESULTS

A source that begins at the NB5 guide entrance should produce the same results as the primary full HB4 simulation with all 6 beamlines provided that crosstalk between adjacent beamlines can be ignored.

2.1 COMPARISON OF SPECTRA

Source 0 and Source 1 both calculate the trajectory of neutrons along the full path of NB5 from the beginning of the guide system to the velocity selector shielding box. Along this trajectory, type 1 tallies are taken at the end of each guide segment and these tallies should agree when there is no crosstalk between beamlines. Figure 7 shows the spectra for the Source 0 (S0) and Source 1 (S1) calculations at cells 30004, 30044, 30076, and 30228, which are the exits of guides 1, 6, 10, and 27, respectively. There is strong agreement between each pair of calculations (S0-S1 and S2-S3). The high energy component (E_n > 1 eV) has nearly disappeared by guide 10 and is completely gone by the velocity selector guide segment (guide 27), thus the spectrum of neutrons reaching the inside of the velocity selector shielding box is only cold neutrons. The disagreement between S0 and S1 for high energies for guide 10 is due to high energy neutrons that are not part of the SSW, but this is not a concern for the NB5 velocity selector region. Additionally, a comparison of the neutron activity tables (an MCNP table of neutron tracks and weight for each cell) shows that there is considerable difference between S0 and S1 for the earliest 5-10 guide segments, but that this difference is no longer present for later guide segments. Therefore, a surface source read (Source 2) and a surface current tally at the last guide segment (Source 3) should produce results that agree with Sources 0 and 1.

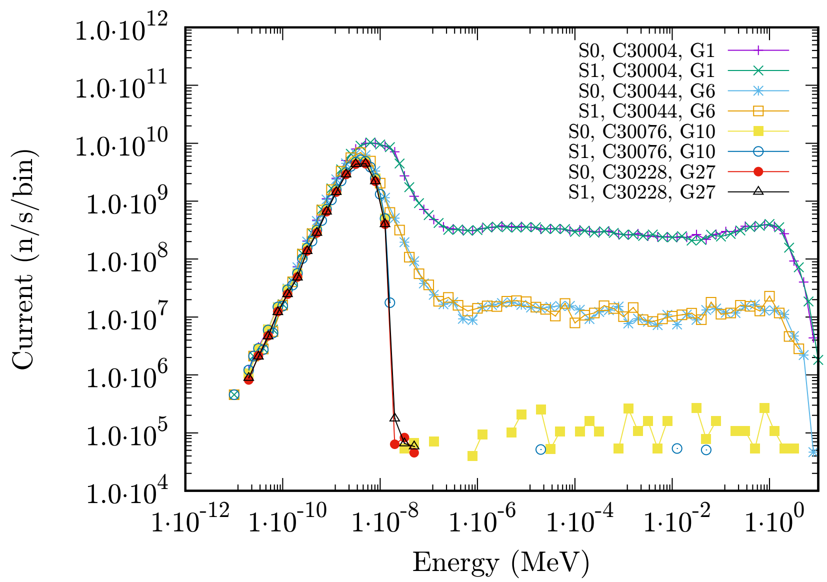

Figure 7. Comparison between Source 0 and Source 1 derived neutron energy spectra at different locations along the guide system.

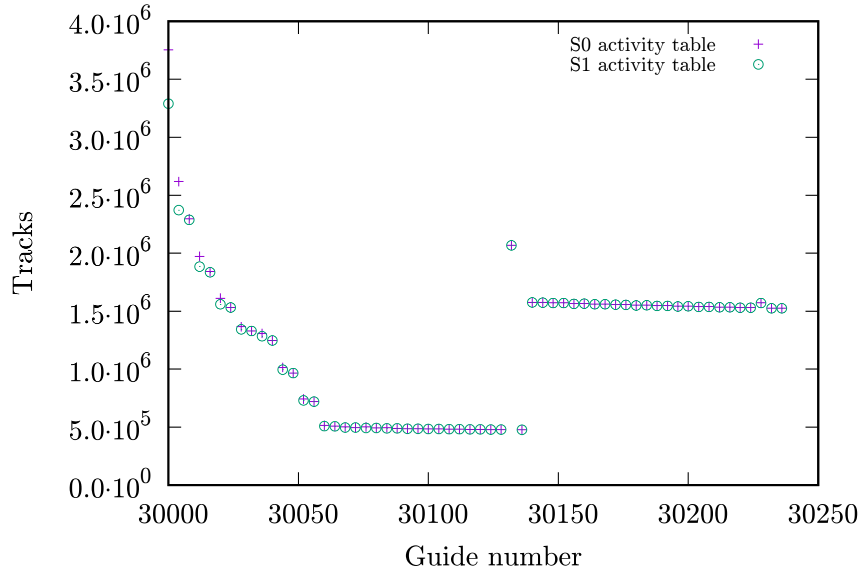

Figure 8. Comparison between Source 0 and Source 1 neutron activity tables showing the number of neutron tracks entering each cell.

2.2 COMPARISON OF DOSE MAPS

Calculations were performed with each source to establish whether each source produces dose rates consistent with the primary source, S0. A graphical comparison is performed between each configuration as well as a consitency check at specific locations inside the velocity selector shielding box. The dose rate is determined from the mesh pixel at locations A through F (fig. 2):

- **Point A.** The downstream beam right corner after the velocity selector, at (-107.5, 0, 3502.5).
- **Point B.** The downstream beam left corner after the velocity selector, at (-37.5, 0, 3502.5).
- **Point C.** The upstream beam left corner before the velocity selector, at (-107.5, 0, 3442.5).
- **Point D.** The upstream beam right corner before the velocity selector, at (-37.5, 0, 3442.5).
- **Point E.** The end of the last guide segment at the beam window, at (-82.5, 0, 3442.5).
- **Point F.** The first boron carbide plate, representing the shutter, at (-82.5, 0, 3462.5).

The tallies used for this comparison are MCNPX type 1 TMESH tallies with a dose functions for neutrons and photons applied. The voxel size for this tally is $10 \times 10 \times 10$ cm^3 and the tallies are plotted below in the $y = 0$ plane, which corresponds with beam height for NB5. The comparison of the average values in the vicinity of points A-F is shown in table 1 for neutrons and table 2 for photons. The values of the points A through F are determined by extracting the value of the mesh pixel at the locations listed above. There is good agreement between all sources (S0-S3) within 5-20%, which is acceptable for shielding calculations.

The tallies shown in the figures in appendix A have been placed onto the same color scale, since each contains different contributions from adjacent beams upstream of the velocity selector and the dose at regions upstream of the velocity selector is substantially different. The Source 0 calculation can be seen in figures 11 and 12. The brightest gamma sources in these two figures are the window and the boron carbide shutter, and the neutron dose displays a consistent shape in the contour lines.

The dose meshes are also sampled along lines parallel and perpendicular to the beam axis in order to illustrate the agreement between all 4 calculations. In the case of the samples along the beam axis (fig. 9, $x = -82.5$ cm)

Table 1. Average neutron dose rates in mrem/hr at 6 points inside the velocity selector box for each source configuration (y=0 for all points)

ID	X	Z	S0	S1	S2	S3
A	-107.5	3502.5	2.84×10^{-1}	1.45×10^{-1}	0.0	4.36×10^{-1}
B	-37.5	3502.5	1.35×10^{1}	1.57×10^{1}	1.65×10^{1}	1.53×10^{1}
C	-107.5	3442.5	3.23×10^{2}	3.19×10^{2}	3.17×10^{2}	3.38×10^{2}
D	-37.5	3442.5	7.66×10^{1}	8.12×10^{1}	8.00×10^{1}	7.30×10^{1}
E	-82.5	3442.5	5.94×10^{5}	5.94×10^{5}	5.91×10^{5}	5.91×10^{5}
F	-82.5	3462.5	3.15×10^{5}	3.15×10^{5}	3.15×10^{5}	3.13×10^{5}

Table 2. Average photon dose rates in mrem/hr at 6 points inside the velocity selector box for each source configuration (y=0 for all points)

ID	X	Z	S0	S1	S2	S3
A	-107.5	3502.5	9.67×10^{2}	9.68×10^{2}	9.87×10^{2}	9.75×10^{2}
B	-37.5	3502.5	6.22×10^{2}	6.57×10^{2}	6.93×10^{2}	6.21×10^{2}
C	-107.5	3442.5	4.29×10^{3}	4.33×10^{3}	4.28×10^{3}	4.36×10^{3}
D	-37.5	3442.5	1.26×10^{3}	1.24×10^{3}	1.30×10^{3}	1.27×10^{3}
E	-82.5	3442.5	7.45×10^{4}	7.43×10^{4}	7.42×10^{4}	7.42×10^{4}
F	-82.5	3462.5	7.92×10^{4}	7.92×10^{4}	7.91×10^{4}	7.89×10^{4}

there is good agreement for photons along the lines beginning at the NB5 window and extending downstream. There is also good agreement for neutrons except upstream of the source origin for S2 and S3, which is expected because the neutrons begin at z = 3438 cm rather than being propagated from the beginning of the guide system. Similarly, the agreement is excellent for the mesh samples perpendicular to the beam axis (fig. 10, z = 34.525 m).

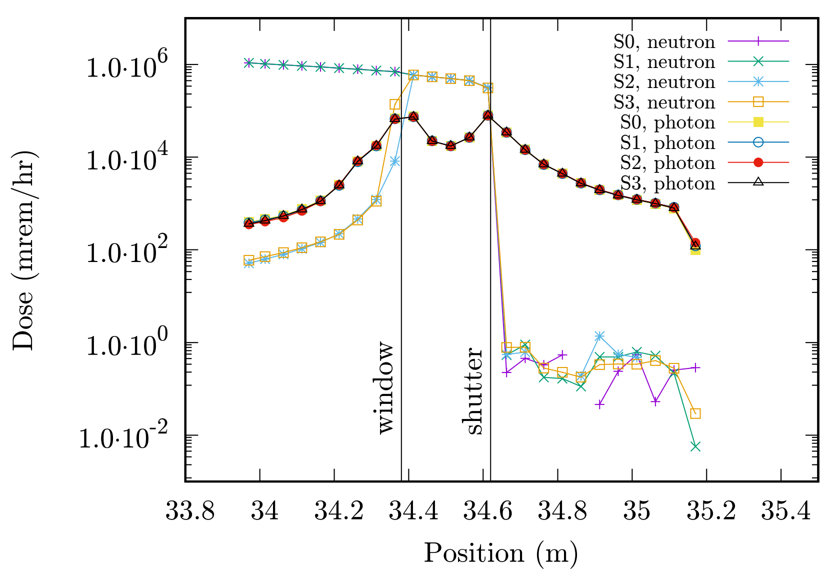

Figure 9. Neutron and photon dose lines parallel to the neutron beam for each source.

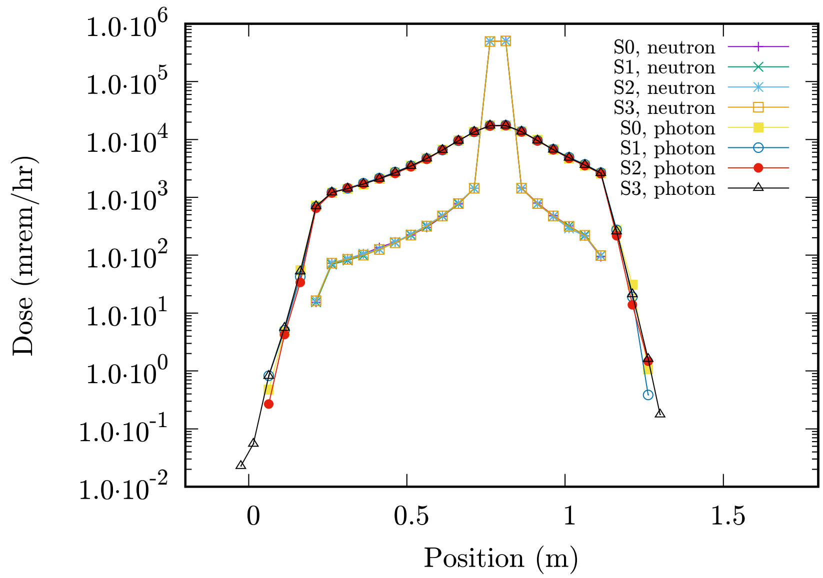

Figure 10. Neutron and photon dose lines perpendicular to the neutron beam for each source.

The activity table output is also compared for each calculation in three cells, 30236, 36037, and 35237, which are the guide window, boron carbide shutter, and velocity selector air cell, respectively, and these tables are presented in tables 3 and 4. The quantities for collision x weight, number weighted energy (NWE), flux weighted energy (FWE), and mean free path (MFP) are consistent between all 4 calculations for each cell for both neutrons and photons.

Table 3. Neutron activity table for 3 cells for each calculation along with collisions x weight (CW), number weighted energy (NWE), flux weighted energy (FWE), and average mean free path (MFP)

Source	Cell	CW	NWE	FWE	MFP (cm)
S0	30236	3.1189E+09	2.9004E-09	3.7838E-09	1.2228E+00
S1	30236	3.1129E+09	2.9084E-09	3.8010E-09	1.2224E+00
S2	30236	3.1156E+09	2.9030E-09	3.7871E-09	1.2228E+00
S3	30236	3.0465E+09	2.9160E-09	3.8189E-09	1.2251E+00
S0	36037	3.0374E+10	3.5597E-09	4.3098E-09	4.6791E-03
S1	36037	3.0362E+10	3.5598E-09	4.2980E-09	4.6778E-03
S2	36037	3.0357E+10	3.5551E-09	4.2998E-09	4.6751E-03
S3	36037	2.9780E+10	3.5817E-09	4.3428E-09	4.6963E-03
S0	35237	6.4644E+08	2.9343E-09	3.8806E-09	1.2432E+03
S1	35237	6.4445E+08	2.9405E-09	3.8921E-09	1.2438E+03
S2	35237	6.4695E+08	2.9387E-09	3.8902E-09	1.2436E+03
S3	35237	6.3355E+08	2.9505E-09	3.9152E-09	1.2451E+03

Table 4. Photon activity table for 3 cells for each calculation along with the collisions x weight (CW), number weighted energy (NWE), flux weighted energy (FWE), and average mean free path (MFP)

Source	Cell	CW	NWE	FWE	MFP (cm)
S0	30236	5.0496E+08	4.1275E+00	4.1275E+00	3.5178E+00
S1	30236	4.9242E+08	4.0941E+00	4.0941E+00	3.5039E+00
S2	30236	4.9805E+08	4.1249E+00	4.1249E+00	3.5148E+00
S3	30236	5.1794E+08	3.9862E+00	3.9862E+00	3.4393E+00
S0	36037	9.5625E+09	4.4904E-01	4.4904E-01	4.5463E+00
S1	36037	9.5345E+09	4.4949E-01	4.4949E-01	4.5480E+00
S2	36037	9.5567E+09	4.4818E-01	4.4818E-01	4.5446E+00
S3	36037	9.3673E+09	4.4882E-01	4.4882E-01	4.5460E+00
S0	35237	3.1332E+08	6.6511E-01	6.6511E-01	9.7536E+03
S1	35237	3.1740E+08	6.6484E-01	6.6484E-01	9.7535E+03
S2	35237	3.0538E+08	6.6436E-01	6.6436E-01	9.7512E+03
S3	35237	3.1115E+08	6.5893E-01	6.5893E-01	9.7309E+03

3. CONCLUSION

Excellent agreement has been demonstrated for the alternative sources S1, S2, and S3 for use in NB5 velocity selector shielding calculations. This validates the process of the generation of SSW files from the primary source as well as the conversion of `f1` surface current tallies to tabulated `sdef` surface definitions. Any of these sources can in principle be used to perform NB5 velocity selector shielding calculation. However, each of these sources may not be equivalent in their rate of convergence, which is reported in table 5. The S0-S2 sources all use 10^8 source particles (including source photons) with the S1 and S2 calculations using the number of tracks recorded at their respective SSW locations from the original 10^8 source particle calculation. The S3 calculation used 10^8 source neutrons at the end of guide cell 30228. The S1 and S2 calculations have the same statistics as S0 because they use an SSW that is read once, and this is significantly faster than running the full S0 calculation. S3 took significantly longer than S0, but used a factor of 1125 more neutron tracks than are present at the exit of cell 30228 in sources S0-S2 and has significantly better statistics on the result.

Table 5. The number of particle histories used with each source along with number of source particles (NPS), calculated histories per hour, run time, point F neutron dose relative error, and point F photon dose relative error

Source	NPS	M histories/hr	Run Time (min)	Neutron rel error	Photon rel error
S0	1×10^8	12.62	482	5.30e-03	4.10e-03
S1	1×10^8	2.46	23	5.30e-03	4.10e-03
S2	1×10^8	0.60	19	5.30e-03	4.00e-03
S3	1×10^8	6.52	1049	3.00e-04	4.00e-04

The tables 1 and 2 indicate that dose calculations due to neutrons reaching the interior of the NB5 velocity selector shielding box can be performed with a surface source written at the end of cell 30228, which is the last cell entering the box. This is a considerably large file and is cumbersome to transfer to other users. Therefore in some cases it may be desirable to instead use a tabulated source that is comprised of a simple text file. This file accumulates statistics substantially faster than the other representations and may also be preferable for that reason.

4. REFERENCES

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APPENDIX A. DOSE MAPS

APPENDIX A. DOSE MAPS

Dose maps for each configuration are included below.

A.1 SOURCE 0 DOSE MAPS

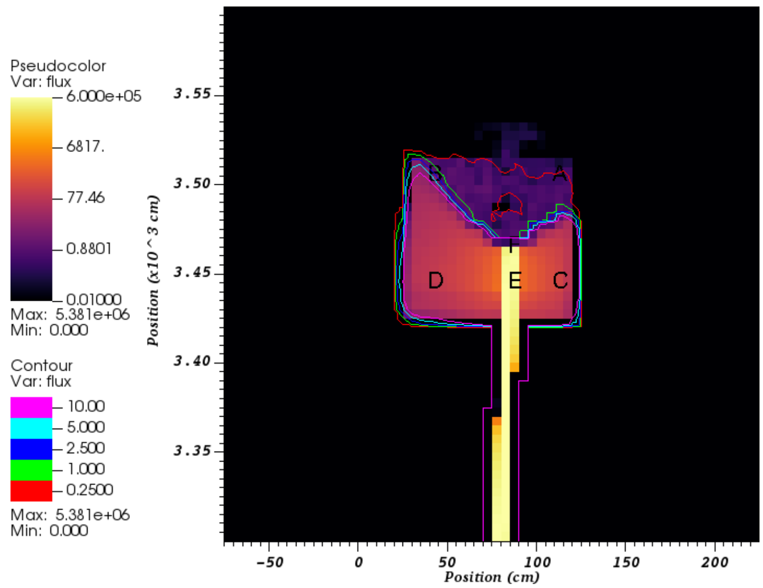

Figure 11. Source 0 neutron dose map. Neutron dose map for the primary moderator source calculation.

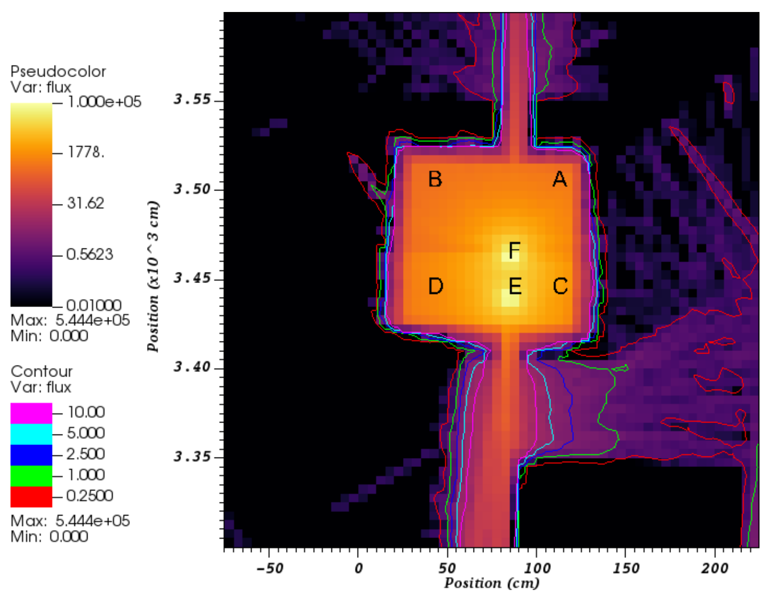

Figure 12. Source 0 photon dose map. Photon dose map for the primary moderator source calculation.

A.2 SOURCE 1 DOSE MAPS

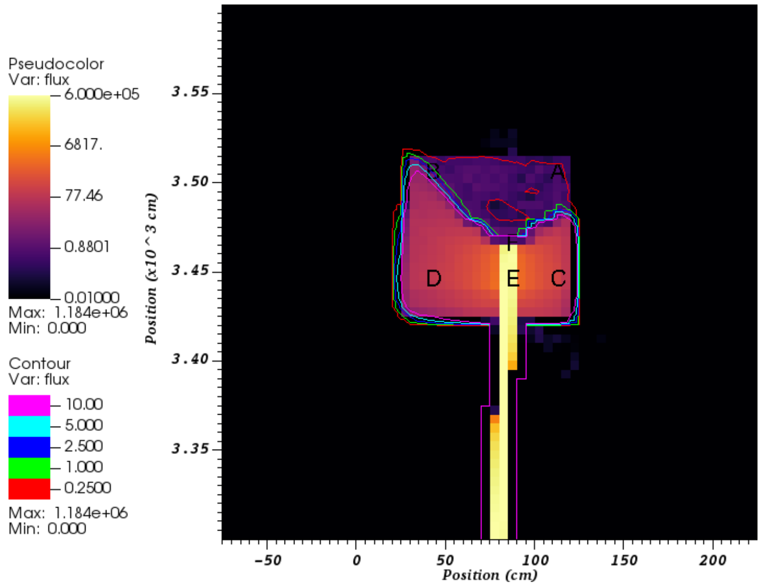

Figure 13. Source 1 neutron dose map. Neutron dose map for the NB5 SSR calculation.

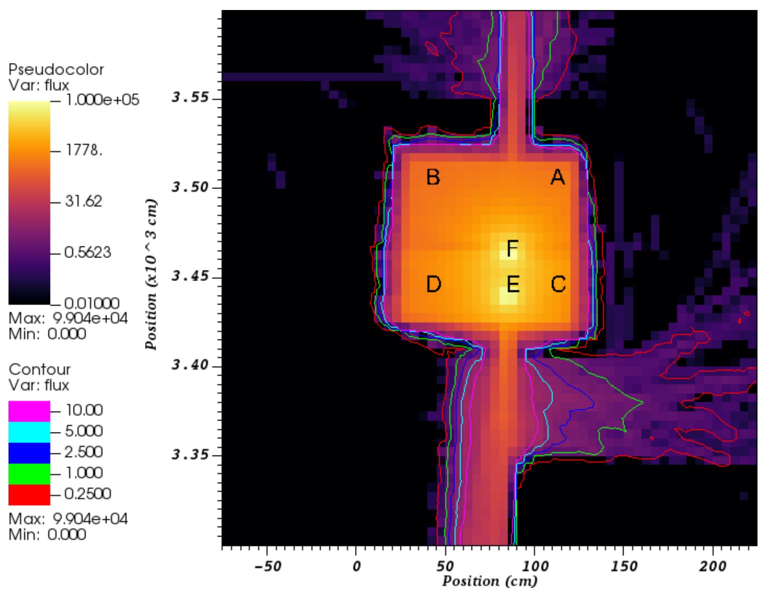

Figure 14. Source 1 photon dose map. Photon dose map for the NB5SSR calculation.

A.3 SOURCE 2 DOSE MAPS

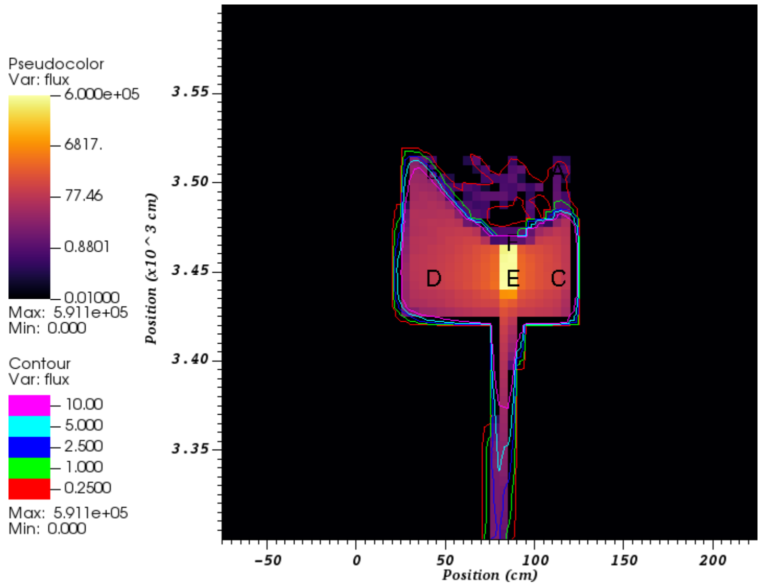

Figure 15. Source 2 neutron dose map. Neutron dose map for the NB5 velocity selector SSR calculation.

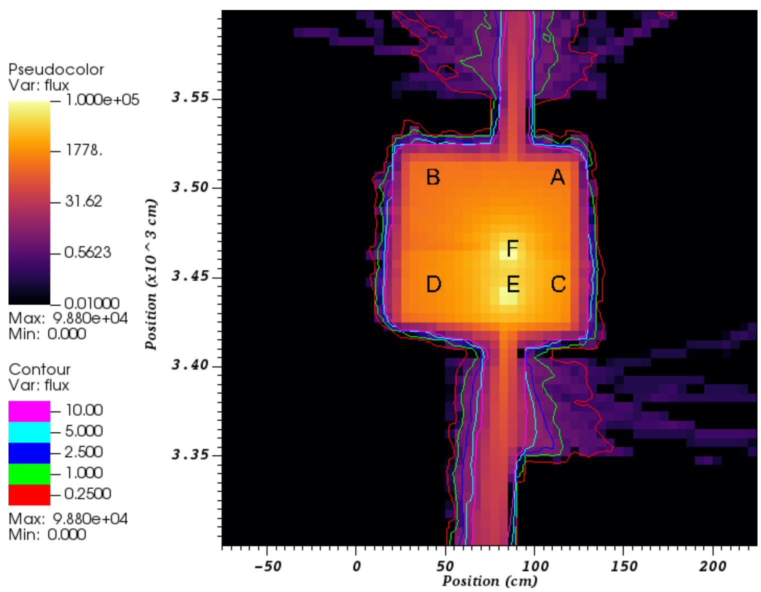

Figure 16. Source 2 photon dose map. Photon dose map for the NB5 velocity selector SSR calculation.

A.4 SOURCE 3 DOSE MAPS

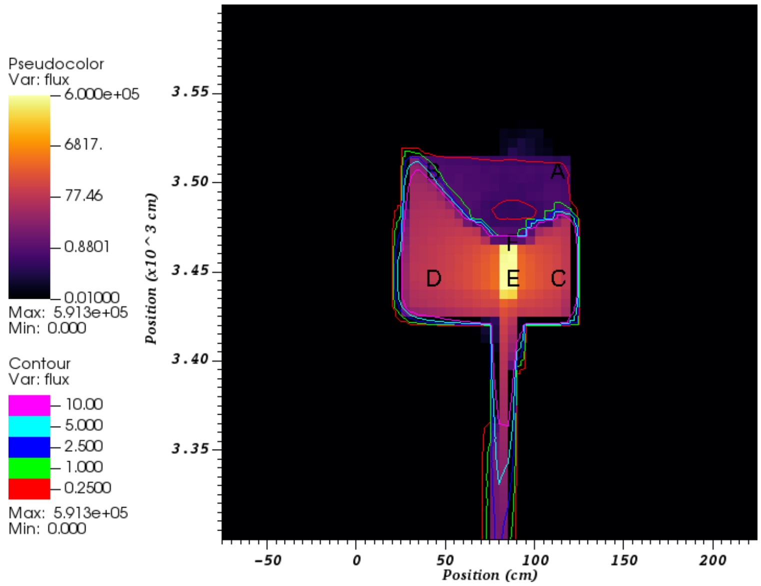

Figure 17. Source 3 neutron dose map. Neutron dose map for the tabulated source calculation.

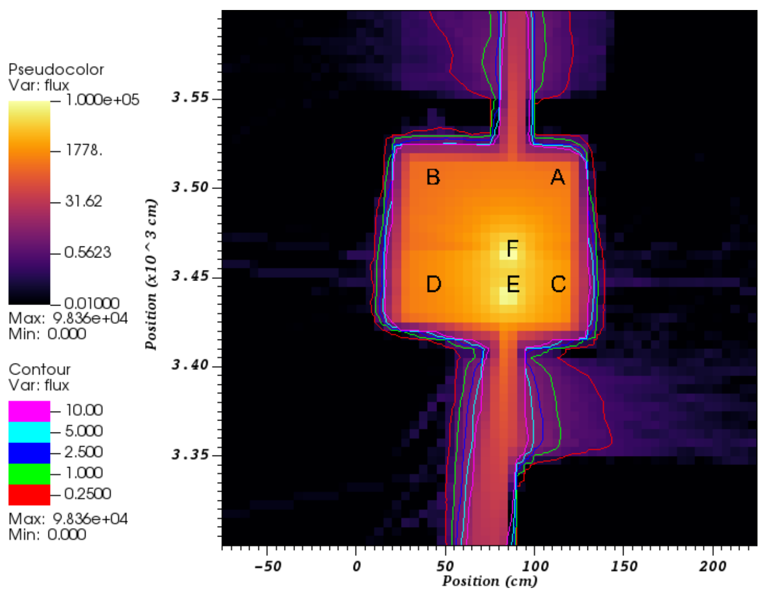

Figure 18. Source 3 photon dose map. Photon dose map for the tabulated source calculation.

APPENDIX B. TABULATED SOURCE

APPENDIX B. TABULATED SOURCE

The following is the complete S3 tabulated source.

```
c source at surface 31379
tr30228    -84.543941 -0.500000 3438.997013
           0.999377 0.000000 0.035283
           0.000000 1.000000 0.000000
           -0.035283 0.000000 0.999377
sdef   par n x d1 y d2 z 1.0e-6 wgt 33758800000.0 tr 30228
vec 0 0 1 dir d3 erg d10
si1     -1.9993572215500928 1.9993572215500928
sp1     0    1
si2     -1.9993572215501922 1.9993572215501922
sp2     0    1
si3     0.999536730968665  1
sp3     0      1
si10   H 1.0000E-12
         1.0000E-11 1.2589E-11 1.5849E-11 1.9953E-11 2.5119E-11 3.1623E-11
         3.9811E-11 5.0119E-11 6.3096E-11 7.9433E-11 1.0000E-10 1.2589E-10
         1.5849E-10 1.9953E-10 2.5119E-10 3.1623E-10 3.9811E-10 5.0119E-10
         6.3096E-10 7.9433E-10 1.0000E-09 1.2589E-09 1.5849E-09 1.9953E-09
         2.5119E-09 3.1623E-09 3.9811E-09 5.0119E-09 6.3096E-09 7.9433E-09
         1.0000E-08 1.2589E-08 1.5849E-08 1.9953E-08 2.5119E-08 3.1623E-08
         3.9811E-08 5.0119E-08 6.3096E-08 7.9433E-08 1.0000E-07 1.2589E-07
         1.5849E-07 1.9953E-07 2.5119E-07 3.1623E-07 3.9811E-07 5.0119E-07
         6.3096E-07 7.9433E-07 1.0000E-06 1.2589E-06 1.5849E-06 1.9953E-06
         2.5119E-06 3.1623E-06 3.9811E-06 5.0119E-06 6.3096E-06 7.9433E-06
         1.0000E-05 1.2589E-05 1.5849E-05 1.9953E-05 2.5119E-05 3.1623E-05
         3.9811E-05 5.0119E-05 6.3096E-05 7.9433E-05 1.0000E-04 1.2589E-04
         1.5849E-04 1.9953E-04 2.5119E-04 3.1623E-04 3.9811E-04 5.0119E-04
         6.3096E-04 7.9433E-04 1.0000E-03 1.2589E-03 1.5849E-03 1.9953E-03
         2.5119E-03 3.1623E-03 3.9811E-03 5.0119E-03 6.3096E-03 7.9433E-03
         1.0000E-02 1.2589E-02 1.5849E-02 1.9953E-02 2.5119E-02 3.1623E-02
         3.9811E-02 5.0119E-02 6.3096E-02 7.9433E-02 1.0000E-01 1.2589E-01
         1.5849E-01 1.9953E-01 2.5119E-01 3.1623E-01 3.9811E-01 5.0119E-01
         6.3096E-01 7.9433E-01 1.0000E+00 1.2589E+00 1.5849E+00 1.9953E+00
         2.5119E+00 3.1623E+00 3.9811E+00 5.0119E+00 6.3096E+00 7.9433E+00
         1.0000E+01
sp10     0.00000E+00
         3.98621E+05 0.00000E+00 0.00000E+00 8.19387E+05 1.55019E+06 2.14812E+06
         2.32529E+06 4.71701E+06 3.72046E+06 1.24237E+07 1.36417E+07 2.48252E+07
         3.01180E+07 4.89196E+07 8.78959E+07 1.38499E+08 1.81195E+08 2.84106E+08
         4.21010E+08 6.59872E+08 9.61496E+08 1.43725E+09 2.05821E+09 2.89210E+09
         3.67575E+09 4.35695E+09 4.76632E+09 4.44656E+09 3.50290E+09 2.20780E+09
         1.12822E+09 4.00393E+08 6.30352E+06 6.37242E+04 9.92033E+04 8.29762E+04
         8.56614E+04 4.51677E+04 2.14305E+04 0.00000E+00 1.04452E+04 0.00000E+00
         0.00000E+00 0.00000E+00 0.00000E+00 0.00000E+00 0.00000E+00 0.00000E+00
         0.00000E+00 0.00000E+00 0.00000E+00 0.00000E+00 0.00000E+00 0.00000E+00
```

```
       0.00000E+00 0.00000E+00 0.00000E+00 0.00000E+00 0.00000E+00 0.00000E+00
       0.00000E+00 0.00000E+00 0.00000E+00 0.00000E+00 0.00000E+00 0.00000E+00
       0.00000E+00 0.00000E+00 0.00000E+00 0.00000E+00 0.00000E+00 0.00000E+00
       0.00000E+00 0.00000E+00 0.00000E+00 0.00000E+00 0.00000E+00 0.00000E+00
       0.00000E+00 0.00000E+00 0.00000E+00 0.00000E+00 0.00000E+00 0.00000E+00
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       0.00000E+00 0.00000E+00 0.00000E+00 0.00000E+00 0.00000E+00 0.00000E+00
       0.00000E+00 0.00000E+00 0.00000E+00 0.00000E+00 0.00000E+00 0.00000E+00
       0.00000E+00 0.00000E+00 0.00000E+00 0.00000E+00 0.00000E+00 0.00000E+00
       0.00000E+00 0.00000E+00 0.00000E+00 0.00000E+00 0.00000E+00 0.00000E+00
       0.00000E+00
sb10   0.0
       1.0 0.0 0.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0
       1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0
       1.0 1.0 1.0 1.0 1.0 0.0 1.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
       0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
       0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
       0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
       0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
       0.0 0.0
```