MCNPX vs Handbook Calculations for Radiation Streaming in the SNS Target Carriage

I. Popova
Spallation Neutron Source Project
Oak Ridge National Laboratory
701 Scarboro Road, RM-369, Oak Ridge, TN 37830
Email: irt@ornl.gov

Abstract - *The movable carriage has been designed to support the mercury target in the Spallation Neutron Source in a cantilevered fashion, and to supply the mercury flowing to and from the target. As a part of design process, the fluxes and dose rates in the hot cell downstream of the carriage have been analyzed. The transport of radiation from the proton beam, which hits the mercury target, to the hot cell downstream of the carriage is a specific task that includes solving of both deep penetration and streaming problems. The handbook analyses and MCNPX analyses using different techniques have been performed. The comparisons of the MCNPX results and handbook results show that both are in good agreement and that the handbook analyses are reliable for the first estimation.*

I. INTRODUCTION

The Spallation Neutron Source (SNS) target carriage [1] is located just downstream of the main (1.0-GeV, 2-milliamp) mercury target and is heavily shielded to minimize fluxes and dose rates in the hot cell downstream of the carriage. Out of necessity, there are a number of different streaming paths in and along the sides of the carriage, including:

(a) the thin air-filled clearance gaps along the top and sides of the carriage;
(b) the long void regions that contain a multiplicity of coolant lines;
(c) the void or partially shielded regions between the wheels of the carriage and the supporting rails.

The biggest and most significant source of radiation propagation through those various streaming paths is the long void region surrounding the water and mercury coolant lines inside the carriage (Fig. 1 and 3). The radiation source is the proton beam that hits the mercury target and causes spallation events, which release the wide variety of particles including high-energy neutrons and gammas, which can penetrate and stream through the voids in the shield configuration. The main objective is to estimate the radiation propagation through the streaming paths inside the carriage (Fig. 3, 4 and 5), and to calculate the dose rates in the area downstream of the carriage, in the hot cell (Fig. 1) due to the radiation streaming.

The target and the target carriage assembly (including all the necessary steel shielding and interfaces) are huge objects, and both have complex construction. Due to this complex construction, radiation transport calculations must address two types of problems: (a) deep penetration through the target and inside the core vessel, and (b) streaming through the pipe chases inside the 5-meter-long target carriage. Both problems are complex and involve time consuming input preparation and particles tracking. For the streaming problem, both the MCNPX [2] analyses and handbook calculations [3] have been performed.

II. METHODS

As mentioned above, the target plug interface is a complex and large object. The distance from the target center to the front carriage wall is 224-cm. The distance from the target to the hot cell, which begins immediately after the carriage flange (picture frame), is 725-cm. The calculation of radiation transport toward the coolant lines from the target center to the carriage front wall involves mostly a deep penetration analysis of the radiation. The calculation of radiation transport from the carriage front wall to the hot cell (picture frame location, Fig. 1) through the air gap that surrounds the mercury cooling lines is a radiation-streaming problem. Due to that, the task has been performed into two steps.

The first step has been to obtain the rigorous boundary source terms, which will be used on the next step, on the carriage front wall using the Monte Carlo code MCNPX. The second step includes calculations further downstream in two ways: (a) by direct application of MCNPX with sophisticated biasing schemes, and (b) by applying elementary (handbook) shielding calculations [3] through the pipe chases inside the target carriage.

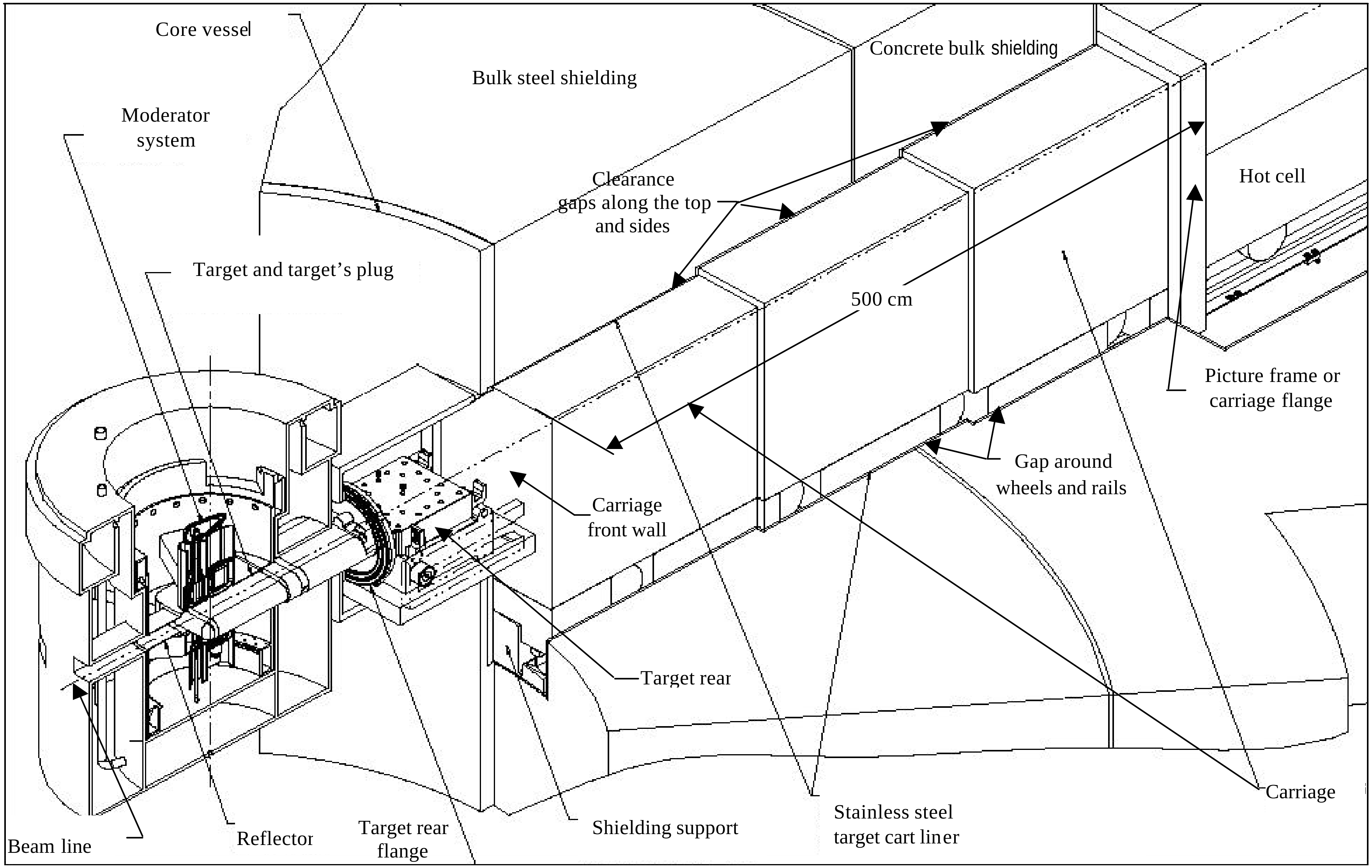

Figure 1. Target plug interface.

II.I. Source Terms Calculation on the Carriage Front Wall

The detailed MCNPX model of the TMR (target, moderator, reflector and partial shielding), the target rear with surrounding air, part of the carriage that supports target rear, the shielding inside the core vessel, and the front part of the carriage is illustrated (Fig. 2). There is a lot of void in the core vessel that surrounds the target rear. The calculation of radiation transport from the proton beam line to the carriage front wall involves a large penetration through the TMR, the shielding inside the core vessel and target rear. Simple geometry splitting was applied to obtain a boundary source. Due to the geometry complexity, it is difficult and almost impossible to apply any other techniques.

The MCNPX “ssw” option has been used, which allows writing and saving an energy-dependent boundary source on the carriage front wall. It is the location from which the streaming paths start inside and along the carriage. The dose rates and fluxes tallied on the front carriage surface near the beginning of the streaming paths have also been used for the subsequent hand calculations.

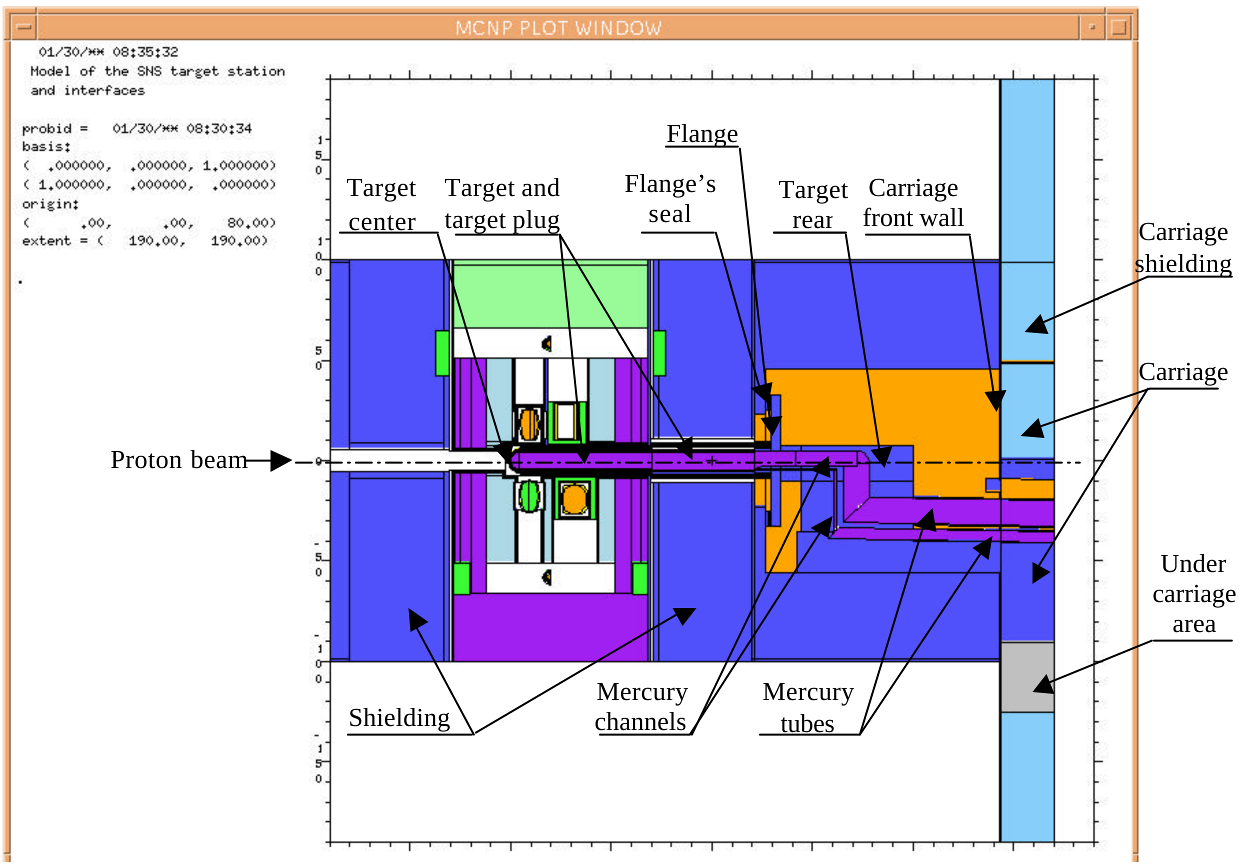

Figure 2. MCNPX geometry model.

II.II. MCNPX Streaming Calculation

The second step involves solving the steaming problem through the 5-meter-long air gap near the mercury cooling lines, using the MCNPX code. The carriage is surrounded by bulk steel and concrete shielding, and generally consists of a stainless steel part on the bottom and a carbon steel part on the top, with mercury and water cooling lines in between (Fig. 1 and 3). The gap around cooling lines is not constant along the length of the carriage, which complicates the task. Even more, the cooling lines and the gaps are slanted relative to the beam line. Figure 3 shows the bottom part of the carriage with the air gaps and coolant lines.

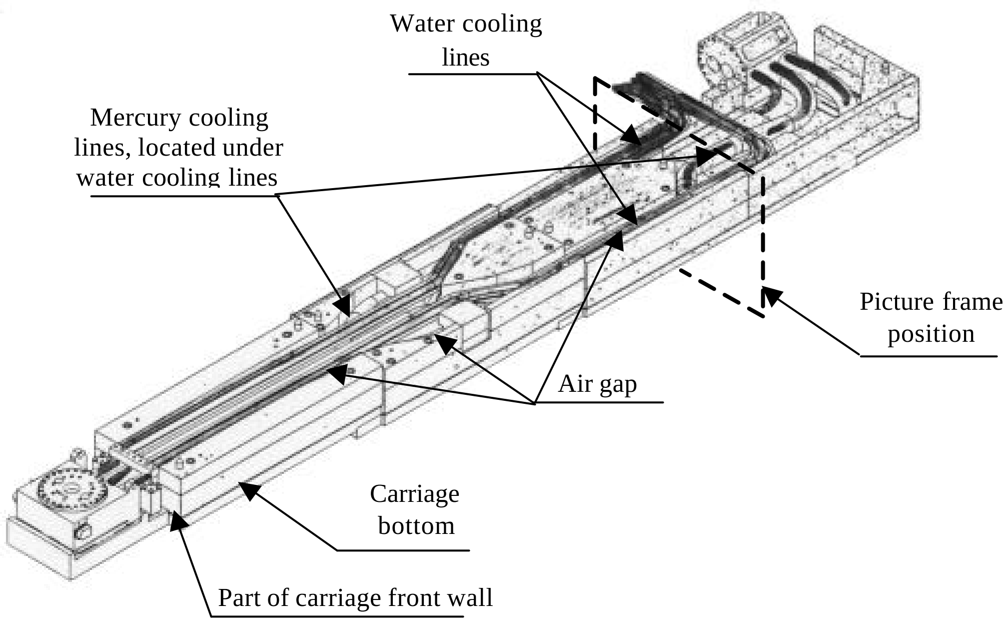

Fig.3. The streaming path inside the target carriage.

The MCNPX model of the carriage area includes:

- the mercury inlet, outlet, and target window tubes (cooling lines);
- the air gaps, that pass trough the carriage around mercury cooling lines;
- the carriage and under carriage area, which is filled with stainless steel balls;
- the carriage shield including the air gap between the carriage and the carriage shield.

The small water-cooling lines are omitted in order to simplify the geometry model. Figure 4 shows a plan view of the MCNPX model of the carriage as a horizontal section, 31-cm below the beam centerline. Figure 5 shows elevation views, which are perpendicular to the beam centerline. The views are in different locations, before and after acute geometry changes of the gap.

The geometric complexity does not allow using weight windows. Results on the carriage front wall, where the boundary source was calculated on the first step and used on this step, show that there remains a significant amount of radiation above 20 MeV. That makes it impossible to use DXTRAN spheres or point detectors since they don't work above 20 MeV. The way to solve this complex streaming problem is by direct application of MCNPX using multiple importance zones combined with a second boundary source downstream of the carriage front wall. First the carriage and its shielding have been divided by an elliptical cylinder along the gap into 2 areas: an outside one, that includes primary shielding and some part of the carriage, and an inside one that includes the air gap surrounding the cooling lines and most of the carriage (Fig. 5). The first area is far enough from the air gap surrounding the cooling lines and the importance there has been set up to be "zero". The elements inside the elliptical cylinder have been modeled in 25-cm increments (Fig. 4) along the gap for geometry biasing.

Application of simple biasing with the same importances in each 25-cm long carriage elements lying in the same level along the gap is impossible due to the wide variation in materials. Thus, a biasing scheme was used in which the general idea was to keep the neutron population the same in each material along the air gap and to keep the ratio between importances in the adjacent zones not bigger than a factor of 5. Table 126 of the MCNPX output has been used to help perform this task. A few preliminary MCNPX runs were made before final values for the importances were chosen. Because it was impossible to keep the ratio of importances in different geometry zones less than 5, a second boundary source was calculated 226-cm away from the first one (Fig. 4).

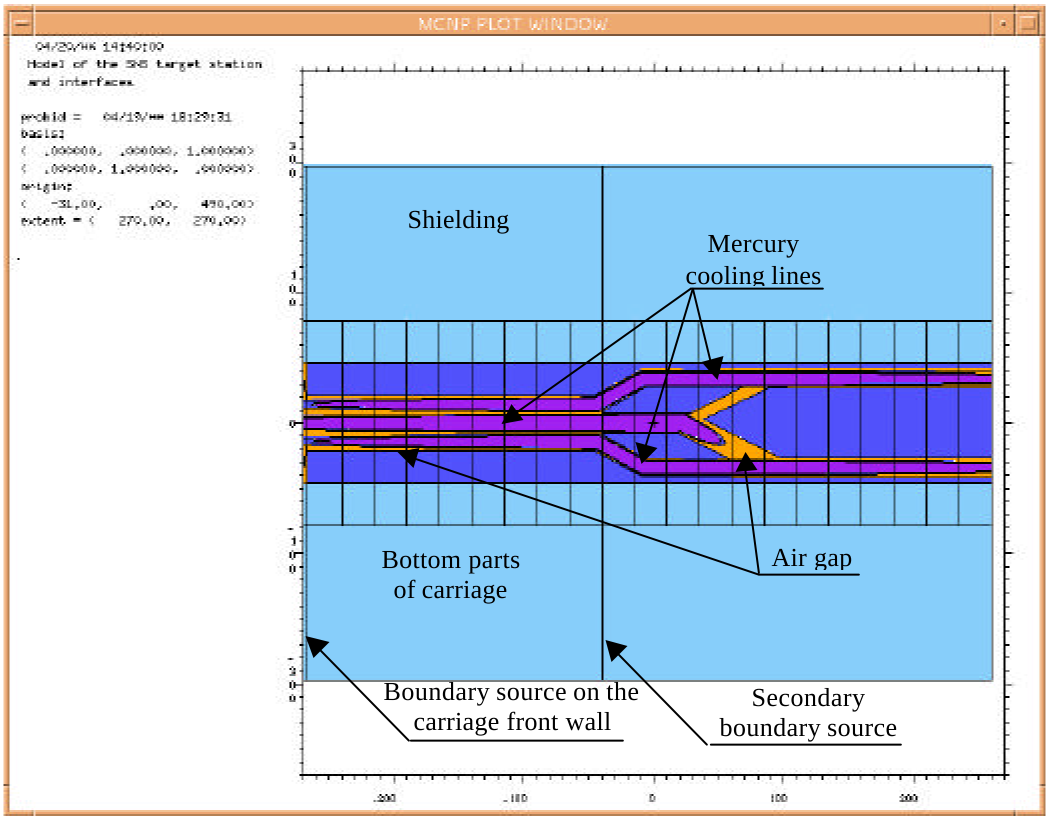

Figure 4. Plan view of the MCNPX model of the carriage in the horizontal section.

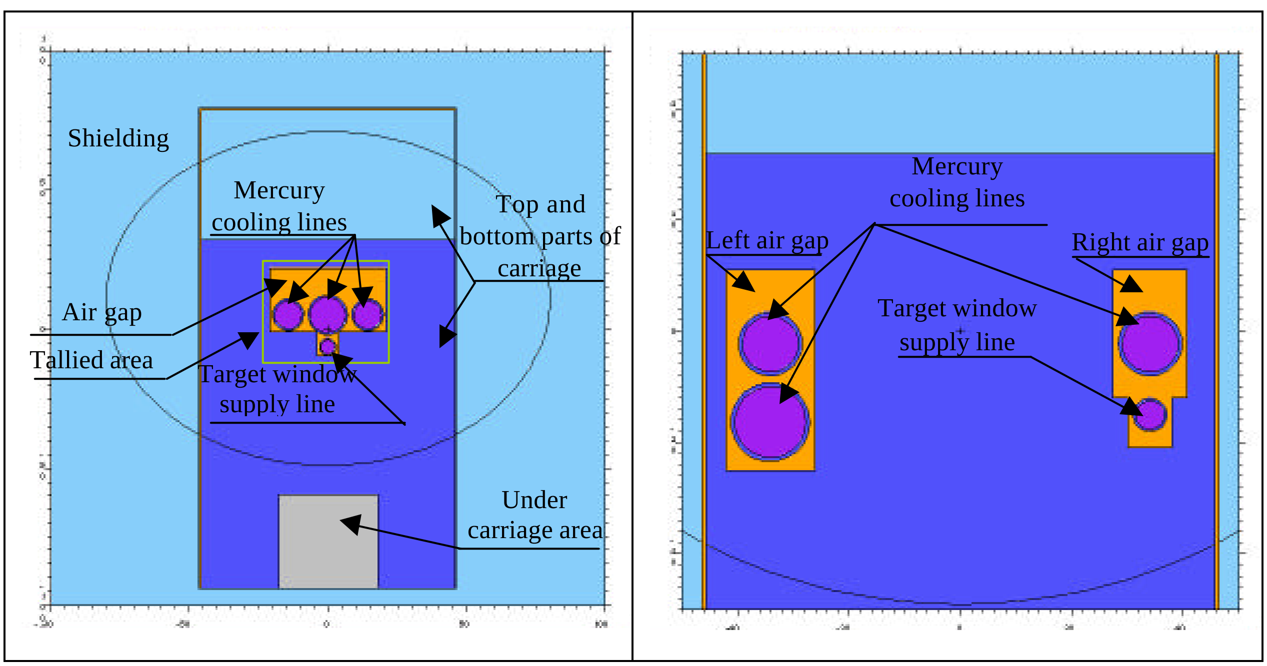

Figure 5. Elevation views of the MCNPX model of the carriage before and after changes in the vertical sections.

Then, using the second boundary source, the calculation has been continued to the picture frame area. No additional boundary sources were used at further axial locations due to the relatively small number of particles available for the transport. Again a few pilot runs were necessary to set up the importances in geometry splitting zones in order to keep the number of progressively lower-weight particles nearly constant. The dose rates in the area located 725-cm downstream of the target center, that covers the left air gap (Fig 5), have been tallied. The results have been obtained with fractional standard deviations of 28%, which means a real uncertainty of several hundred percent.

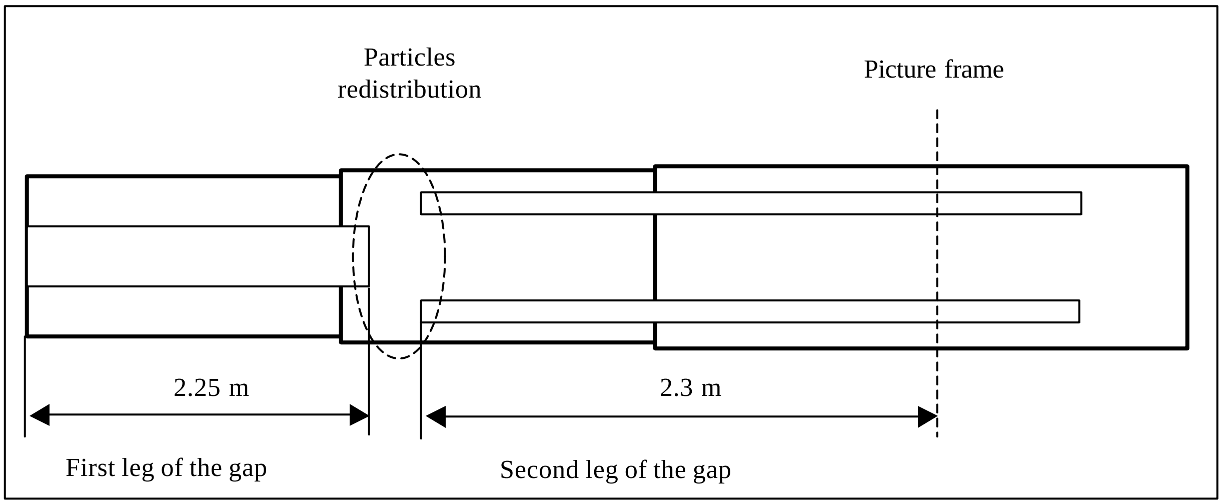

Figure 6. The model for hand calculation of dose propagation through the voided gap near mercury inlet and outlet tubes.

II.III. Handbook Shielding Calculation

As mentioned in the introduction, solving this complex streaming task with the MCNPX code is a time consuming process. A handbook calculation [3] has also been applied to estimate the radiation propagation through the air gap surrounding the main cooling lines inside the carriage. The starting point for the hand calculation is a rectangular region on the carriage front wall near the void space that contains the coolant lines (Fig. 5), where the average MCNPX neutron dose rate is 1.42e+9 mrem/hr. The air gap for the cooling lines 2.25-m downstream of the carriage front wall changes its shape and, about 0.7-m further downstream, separates into 2 gaps. One gap is for the inlet and outlet mercury lines, and the second is for the inlet and target window supply lines. In the simplified model for the hand calculation (Fig. 6) the gap was modeled as two legs with one offset. The first leg represents the gap before it changes its shape (only one gap); the second leg represents the gap after the separation and consists of two gaps located independently in the shielding material with equal area. It has been assumed that the particles, which pass through the first leg, scatter in the material before they enter the second leg. The particles coming from the first leg have a forward angular distribution. Due to the scattering in the material, the new resulting angular distribution is more isotropic. These particles form the source for the second leg. Moreover, it is assumed that this source has the same intensity as at the outlet of the first leg.

It should be noted, however, that the real neutron flux is not isotropic upstream of the gaps (starting location) due to the specific geometry of the assembly (Fig. 2). The degree of anisotropy there was estimated using data obtained from the MCNPX calculation, in which the directional currents were tallied in various angular bins, including a 30-degree cone about the most forward direction. The degree of anisotropy (K^{30}) has been estimated as the ratio of the current in the most forward 30-degree (I^{30}) cone to the average current over the entire 4π sphere (I):

$$K^{30} = \frac{I^{30}/\Omega^{30}}{I/\Omega} \quad (1)$$

where Ω^{30} is a 30 deg solid angle, and Ω is the entire 4π solid angle sphere.

In this particular case the degree of anisotropy (K) is 2.495, which has been used as a multiplication factor to adjust the average MCNPX tallied neutron dose at the starting point in the handbook calculations.

The attenuation of the dose rate in the gap is proportional to the solid angle that we can see from the starting point [3]. In other words, the attenuation (A^G) of the dose rate through a gap is proportional to ¼ of the area of the gap over the length squared:

$$A^G = S/\left(4 \cdot L^2\right) \quad (2)$$

where S is the area of the gap, and L is the gap length.

The adjusted neutron dose on the starting location (D^0) has been multiplied by the calculated attenuation (Eq. 2) for the first leg to obtain the value of the neutron dose (D^1) at the end of this leg. Then, this value has been subsequently used as a starting dose to calculate the neutron dose (D^2) at the location of the picture frame (Fig. 6).

III. COMPARISON OF MCNPX RESULTS AGAINST HAND CALCULATIONS

The prediction of the radiation propagation is much easier with simple handbook calculations, than with a complex MCNPX analysis. However, care must be always exercised because the handbook methods are only general guidelines and every particular task needs some adjustments and assumptions, such as the anisotropic correction used here for the source in the starting location (carriage front wall) and the assumption that the intermediate source in the middle of the model is isotropic. The handbook methods have an approximate nature and it is both interesting and important to have the results for comparison that are calculated using more precise methods such as MCNPX.

Results for these streaming calculations are presented in Tables I and II. Three locations along the air gap in the carriage have been chosen for the comparisons:

1. before the air gap separates into two gaps, 226.5-cm downstream of the carriage front wall;
2. after the air gap separates into two gaps, about halfway to the end point of the calculation, 401-cm downstream of the carriage front wall;
3. after the air gap separates into two gaps, at the end point of the calculation, hot cell (picture frame area), 501-cm downstream of the target carriage front wall.

Table II compares the handbook dose rates against MCNPX results in three locations. The last column is the ratio between the dose calculated by the handbook methods to that calculated by MCNPX.

Table I. Handbook calculated dose rates.

Location from the carriage front wall, cm	Carriage front wall	226.5	401.0	501.0
Area (S), cm^2		632.71	293.3	293.3
Length (L), cm		226.5	139.7	239.7
$S/4L^2$		3.1e-3	3.8e-3	1.3e-3
Dose rate, mrem/h	3.5e+9	1.1e+7	4.2e+4	1.4e+4

Table II. Comparison of dose rates by hand calculations against MCNPX results.

Location from the carriage front wall, cm	Handbook calculation, mrem/h	MCNPX calculation, mrem/h	Ratio, Hand/MCNPX
226.5	1.1e+7	2.78e+06	4.0
401.0	4.1e+4	9.70e+04	0.42
501.0	1.4e+4	5.89e+03	2.4

In this case, the more rigorous, complex, and highly-biased Monte Carlo results all appear to be within a factor of 2 to 4 of the more basic hand calculation. This tends to add credibility to both sets of results, at least to within the "order of magnitude" accuracy required by the project in the target carriage assembly.

IV. CONCLUSION

The MCNPX analysis of radiation propagation from the mercury target to the picture frame location, through almost 7-m of different materials and along the central streaming path has been performed. The target and the target carriage assembly (including all the necessary steel shielding) are huge objects, and both have complex construction. Due to this complex construction, radiation transport calculations address two types of problems: (a) deep penetration through the target and core vessel assemblies, and (b) streaming through the pipe chases inside the 5-meter-long target carriage.

Dose calculations have been performed using rigorous boundary source terms on the front carriage wall as obtained using the MCNPX code to calculate radiation transport from the target center. Calculations further downstream have been performed in two ways: (a) by direct application of MCNPX with sophisticated biasing schemes, and (b) by applying elementary (handbook) shielding calculations through the pipe chases inside the 5-meter-long target carriage. The dose rates near be picture frame have been calculated and compared.

Comparisons of the MCNPX results and the handbook results show that the two are in good agreement relative to the accuracy required by the project in the target carriage assembly.

REFERENCES

1. I. I. Popova, J. A. Bucholz, "Shielding in the Gaps around the Target Carriage," ORNL/SNS, SNS-106100200-DA0007-R00 (March 16, 2001).
2. L. S. Waters, ed., "MCNPX User's Manual – Version 2.1.5," Los Alamos National Laboratory, NM, TPO-E83-G-UG-X-00001, Nov. 1999.
3. A. H. Sullivan, "A Guide to Radiation and Radioactivity Levels near High Energy Particle Accelerators," Nuclear Technology Publishing, Ashford, Kent, TN23 1JW, England.

SNS is managed by UT-Battelle, LLC, under contract DE-AC-5OR22725 for the U.S. Department of Energy.