SNS -106100200-TR0219-R00

Design Analysis of the SNS Target Station Biological Shielding Monolith with Proton Power Uprate

April 12, 2017

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DESIGN ANALYSIS OF THE SNS TARGET STATION BIOLOGICAL SHIELDING MONOLITH WITH PROTON POWER UPRATE

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Date Published: April 12, 2017

Prepared by Oak Ridge National Laboratory
for

UT-BATTELLE, LLC
under contract DE-AC05-00OR22725
for the
U.S. DEPARTMENT OF ENERGY

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EXECUTIVE SUMMARY

This report documents the analysis of the dose rate in the experiment area outside the Spallation Neutron Source (SNS) target station shielding monolith with proton beam energy of 1.3 GeV. The analysis implemented a coupled three dimensional (3D)/two dimensional (2D) approach that used both the Monte Carlo N-Particle Extended (MCNPX) 3D Monte Carlo code and the Discrete Ordinates Transport (DORT) two dimensional deterministic code. The analysis with proton beam energy of 1.3 GeV showed that the dose rate in continuously occupied areas on the lateral surface outside the SNS target station shielding monolith is less than 0.25 mrem/h, which complies with the SNS facility design objective. However, the methods and codes used in this analysis are out of date and unsupported, and the 2D approximation of the target shielding monolith does not accurately represent the geometry. We recommend that this analysis is updated with modern codes and libraries such as ADVANTG or SHIFT. These codes have demonstrated very high efficiency in performing full 3D radiation shielding analyses of similar and even more difficult problems.

1. INTRODUCTION

The neutrons produced at the Spallation Neutron Source (SNS) mercury target are slowed down via moderators surrounding the target. The moderated neutrons exit the shielding monolith to the area where scientists and engineers perform neutron scattering experiments. Analyzing the dose rate outside the SNS target station shielding monolith is necessary to ensure personnel safety during SNS operation. In compliance with 10 CFR 835.1001, "Design and Control," and 10 CFR 835.1002, "Facility Design and Modification," the SNS facility design objective is to limit prompt radiation in continuously occupied areas to less than 0.25 mrem/h [1,2].

The SNS proton beam Power Upgrade Project (PUP) received US Department of Energy (DOE) Critical Decision CD-0 approval in November 2004, and a conceptual design report and cost range was completed [3]. The PUP project was put on hold by DOE, and revived in the Proton Power Upgrade (PPU) Project [4] in conjunction with the Second Target Station project [5]. PPU requires that the linear accelerator beam energy be increased from 1.0 to 1.3 GeV. This report documents the assessment of the dose rate with proton beam energy of 1.3 GeV at 2 MW power in the experiment area outside the SNS target station shielding monolith without the need for any new modifications.

Analyses completed in 2001 assessed the dose rate in the experiment area with different shielding materials in the shielding monolith and different configurations of a beamline shutter [6,7]. These analyses implemented a coupled three dimensional (3D)/two dimensional (2D) approach that used both the Monte Carlo N-Particle Extended (MCNPX) 3D Monte Carlo code [8] and the Discrete Ordinates Transport (DORT) 2D deterministic code [9] with a HILO multigroup library [10] of 75 neutron groups and 22 photon groups. The same methodology was used to assess the dose rate around the existing SNS target station shielding monolith with the proton beam energy of 1.3 GeV.

Multiple updates to the MCNPX source code and to the data libraries of both MCNPX and HILO have occurred after analyses were completed in 2001. Additionally, the original 2001 analysis used only the surface source information between -20° and 20° relative to the proton beam incident direction, and normalized this information to create an azimuthally symmetric boundary source for the subsequent 2D (R-Z) DORT calculations. This made the initial source conservatively high because the neutron beam lines do not begin to appear until ± 35 degrees from the forward direction. Verification studies were performed with the same 1 GeV proton beam energy used in the original 2001 analysis. In these studies, the effect of updating the MCNPX code and its libraries, the effect of updating the HILO library, and the effects of changing the angle that is used to normalize the 3D MCNPX surface source to a 2D azimuthally symmetric boundary source for DORT calculations were assessed. The results of the calculations with the updated source codes and libraries and with the different normalization angle were compared to the dose rates computed in the original 2001 analysis. The analysis was then performed with 1.3 GeV proton beam energy with the updated MCNPX version and the updated libraries. It is necessary to mention that the methods and codes used in our analysis are still out of date and unsupported. For example, ORNL has stopped supporting DORT since 2007. Additionally, the 2D approximation of the target shielding monolith does not accurately represent the geometry, especially for the localized gaps that are modeled as 360° rings. We recommend that this analysis is updated with modern codes and libraries that are currently being supported and regularly updated. The full 3D analysis can be performed if ADVANTG [11] is used to generate the variance reduction needed for the final MCNPX or MCNP6 [12] calculation. The analysis can also be performed using the ORNL cross-cutting SHIFT [13] code that utilizes the Denovo deterministic code [14] to generate the variance reduction parameters.

This report introduces the calculation methodology and computational models used in the analyses, discusses the results from the verification studies, and concludes with the results from the analyses performed with 1.3 GeV proton beam energy.

2. METHODOLOGY

In the 2001 analysis, design calculations were performed in two steps.

1. An MCNPX model was used to model the neutron and photon leakage spectrum from a cylinder surrounding the mercury target, moderators, and associated reflector region. MCNPX performed the particle transport simulations with this model and saved the leakage spectrum in the form of a surface source file for the subsequent DORT calculation.
2. A 2D axisymmetric cylindrical DORT model of the target monolith was then used to calculate the dose distributions throughout a section of the target monolith. The interface code MCNP-to-DORT (MTD) [15] converted the MCNPX surface source to the DORT boundary source. This DORT model simulated the gaps as continuous rings in the target monolith and represented a conservative modeling approach. DORT performed the transport calculations with the defined 2D model, a boundary source computed by MTD, and the HILO multigroup cross section library to compute the scalar fluxes throughout the geometry. Both photon and neutron dose rates, as well as the total neutron and photon dose rate, were then calculated as a post-processing stage using the DORT computed scalar fluxes.

Figures 1 and 2 show the MCNPX and DORT models used in this analysis. The MCNPX model was provided to the authors of this report by the Neutronics Analysis team of the Instrument and Source Division of the Neutron Science Directorate at ORNL. The model was created in October 2000 and represents a special version of the SNS target model specific for generating a cylindrical boundary crossing for shutter calculations. The MCNP input file of this model contains 3,665 lines, 33 materials, and a detailed proton source distribution. This model was used in Miller 2001 [7], which describes the 2001 analysis. Table 1 describes the materials used in the DORT 2D model. The surface source in the DORT target monolith calculations is a cylinder with an axis extending from $z = -50.8$ cm to $z = 50.8$ cm, and a radius extending from $r = 0.0$ cm to $r = 48.26$ cm. A black absorber is modeled inside this cylinder to prevent the particles that enter the cylinder from leaving because this effect has already been considered in the MCNPX calculation. In each of the DORT monolith models, the mercury target is at the origin, and the proton beam line height is at $z = 0.0$ cm.

In each case of this analysis, the peak dose rate was calculated outside the shielding monolith along two surfaces. The first surface is the lateral outer surface of the shielding monolith. The second surface is the top of the shielding monolith. These two surfaces are clearly illustrated in Fig. 2.

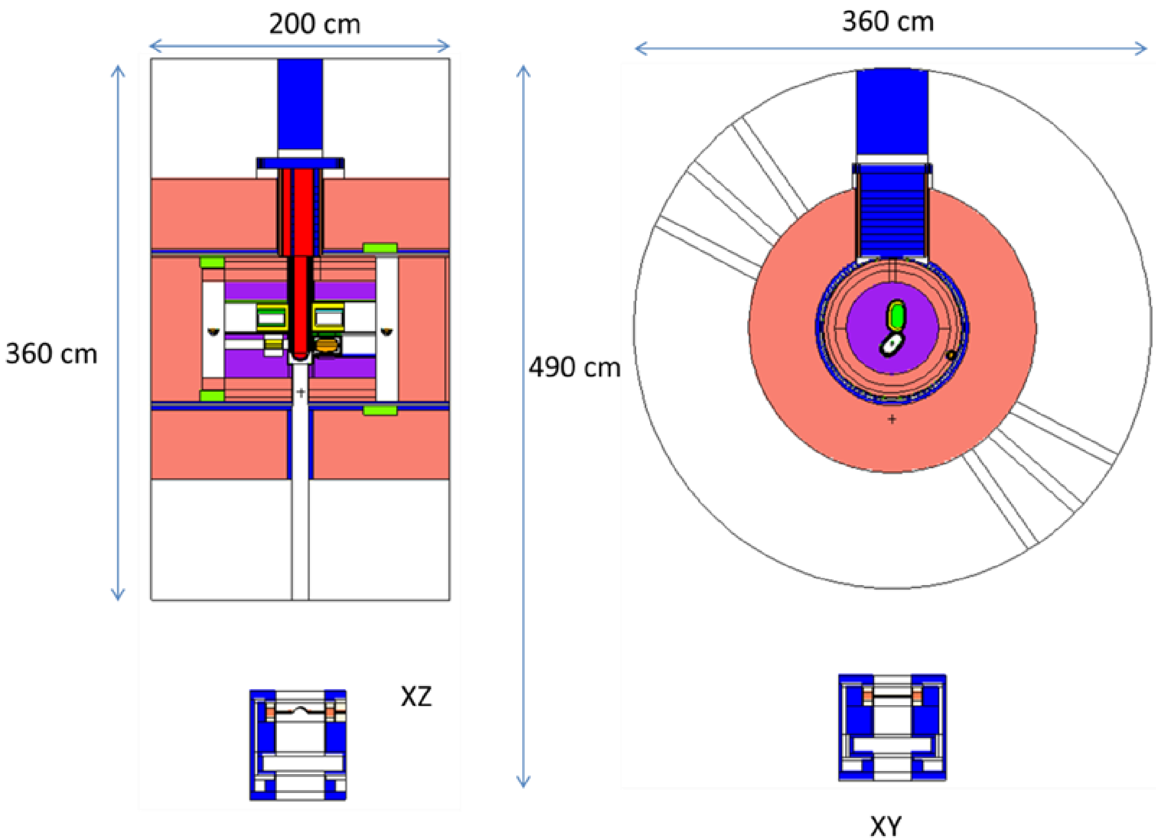

Fig. 1. MCNPX model used to compute neutron and photon source.

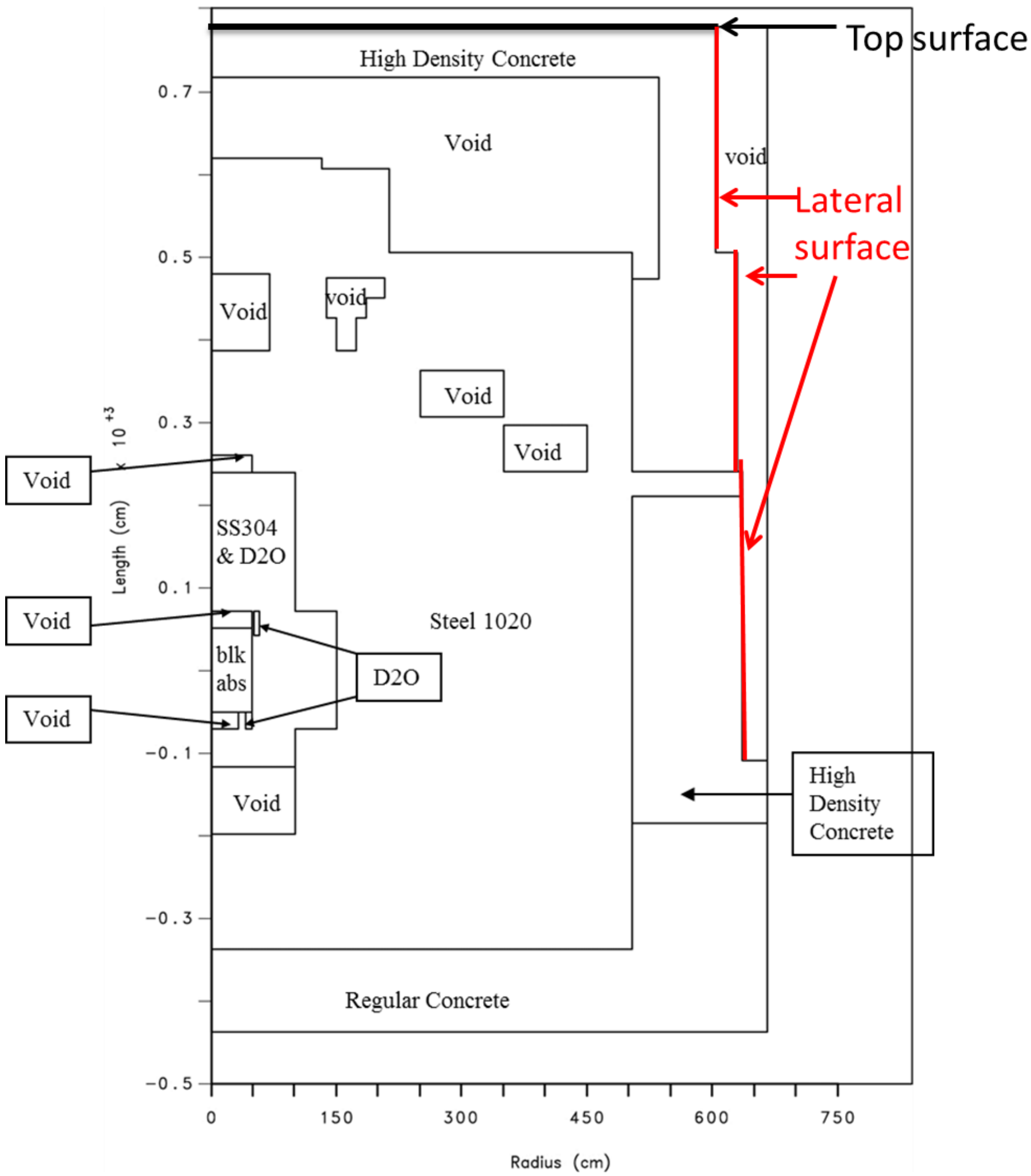

Fig. 2. 2D (R-Z) geometry of the SNS target shielding monolith (Reference 7).

Table 1. Materials chemical composition (Reference 7)

Name	Density (g/cm^3)	Chemical composition (wt. % or * indicates atom %)
D_2O*	1.099	deuterium (66.500%), oxygen (33.333%), hydrogen (0.167%)
Steel 1020	7.03908	iron (99.1 %), manganese (0.45 %), silicon (0.25 %), carbon (0.2 %)
Stainless steel 316	8.03	iron (65.375 %), chromium (17.0 %), nickel (14.5 %), manganese (2.0 %), silicon (1.045 %), carbon (0.08 %)
High density concrete*	3.93	oxygen (55.714 %), iron (28.026 %), hydrogen (10.293 %), calcium (3.09 %), silicon (1.929 %), aluminum (0.55 %), magnesium (0.236 %), sulfur (0.092 %), manganese (0.044 %), potassium (0.014 %), sodium (0.012 %)
Regular concrete*	2.3	oxygen (58.147 %), silicon (20.948 %), hydrogen (10.571 %), calcium (3.865 %), aluminum (3.167 %), sodium (1.771 %), potassium (0.919 %), iron (0.415 %), magnesium (0.197 %)
Tungsten	17.415	Tungsten (100%)

As part of the PUP shielding analysis scope, a computational sequence was designed to perform the code and data verification calculations rigorously, as well as the PUP dose rate assessment. A simplified code flow of the developed sequence is depicted in Fig. 3. The setup process for a new calculation sequence is defined in the user input with predefined keywords and some user options. One main advantage of this sequence is its restart capability at each computational step, which enables the user to setup a new calculation sequence for a set of components rather than for the entire calculation. For example, a calculation sequence can be set up by starting with the boundary source data, DORT input, and the already calculated group-organized cross section input program (GIP) cross section data from the 2001 analyses to compute the flux moments and corresponding dose rates. Alternatively, the same boundary source data and DORT input from the 2001 analyses can be used, but with an up-to-date HILO library to compute the same quantities—namely flux moments and dose rates. Comparison plots for these calculation sequences demonstrate the effects of the changes in the codes and libraries on the dose rate results.

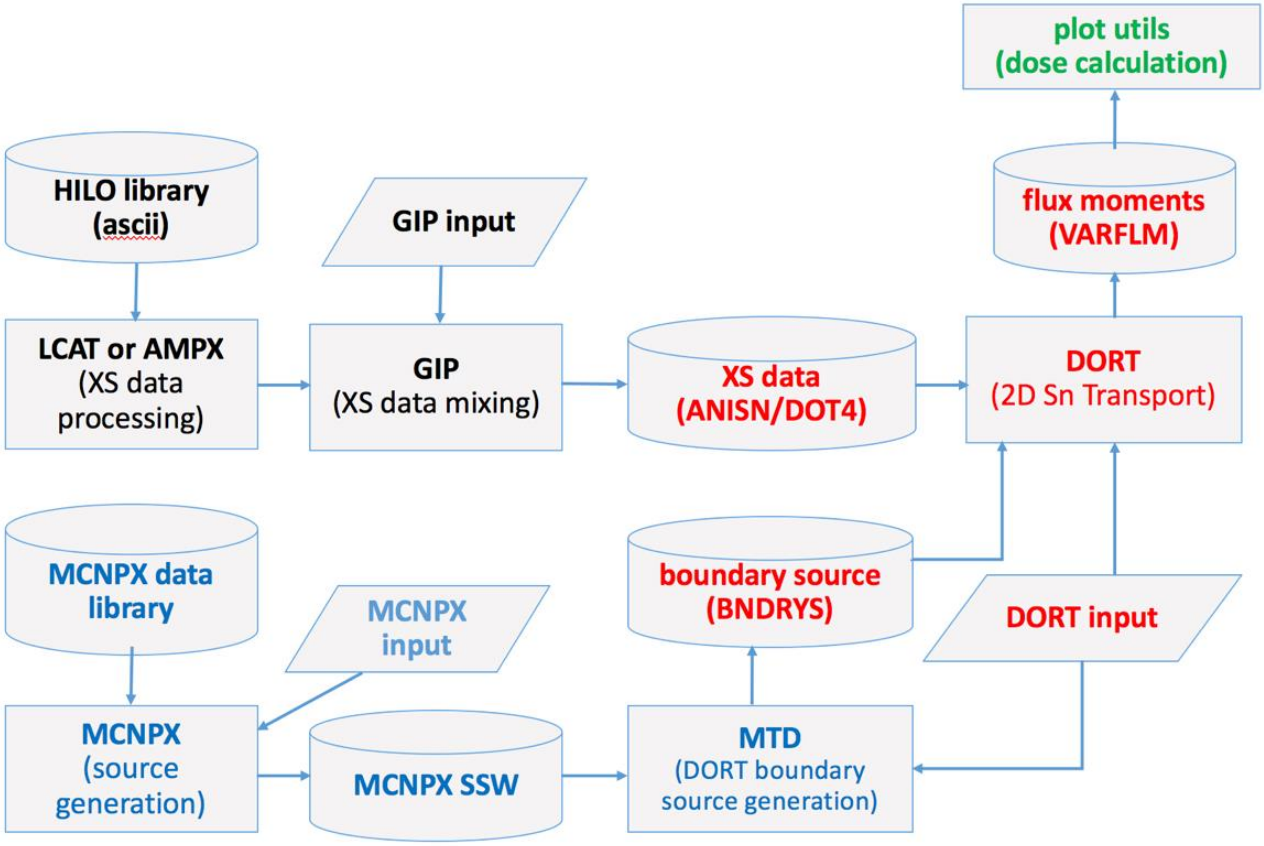

Fig. 3. Computational sequence designed for SNS PUP analysis.

The developed computational sequence can also read and process different data formats for the output and intermediate files (VARFLM, VARSCL, BNDRYS, GIP, etc.) used by the codes in this sequence. It can also convert the old machine-dependent binary data used in the 2001 analysis to a format readable by current computers, even when it has different endianness. This sequence can also perform two sets of calculations, compare the results from these calculations, and automatically generate comparison plots between them. All these features provide consistency between the components in the calculation sequence to minimize possible errors in the analyses.

3. RESULTS

3.1 VERIFICATION STUDIES WITH 1 GEV PROTON BEAM ENERGY

Because the codes and data have been updated several times since the original 2001 analysis was performed and because the previous analysis used only the surface source information between two specific angles, verification studies were performed with proton energy set at 1GeV and power at 2MW. The goal of these verification studies was to assess the adequacy of each component in the developed computational sequence (codes, data, and computational models) to determine radiation dose rates around the monolith shielding with the increased proton power and energy. The results of these verification studies were compared to the 2001 results to assess the effects of code and data updates and the normalization angle used in the original analysis.

3.1.1 Assessing the Effects of Updating MCNPX and Its Libraries

In the original analyses of Miller 2001 [7], MCNPX 2.1.5 was used to calculate the boundary source for the subsequent DORT calculation. These MCNPX calculations used data libraries ENDF3, ENDF4, ENDF5, and ENDF6. To assess the effects of updates in the MCNPX code and its libraries, the same calculations at a proton beam energy of 1 GeV were repeated with MCNPX2.7 and the latest ENDF7 data when it was available. As in the 2001 analysis that used MCNPX2.1.5 and ENDF3-6 data, the 1999 HILO release [16] was used with the updated MCNPX code and libraries. Figures 4 and 5 show the total dose rate results calculated using MCNPX-2.7 and ENDF7 data, as well as the original results calculated using MCNPX-2.1.5 and ENDF3-6 data. Figures 6 and 7 show the relative difference and the ratio between the total dose rates calculated with MCNPX-2.7 and ENDF7 and the dose rates calculated using MCNPX2.1.5 and ENDF3-6.

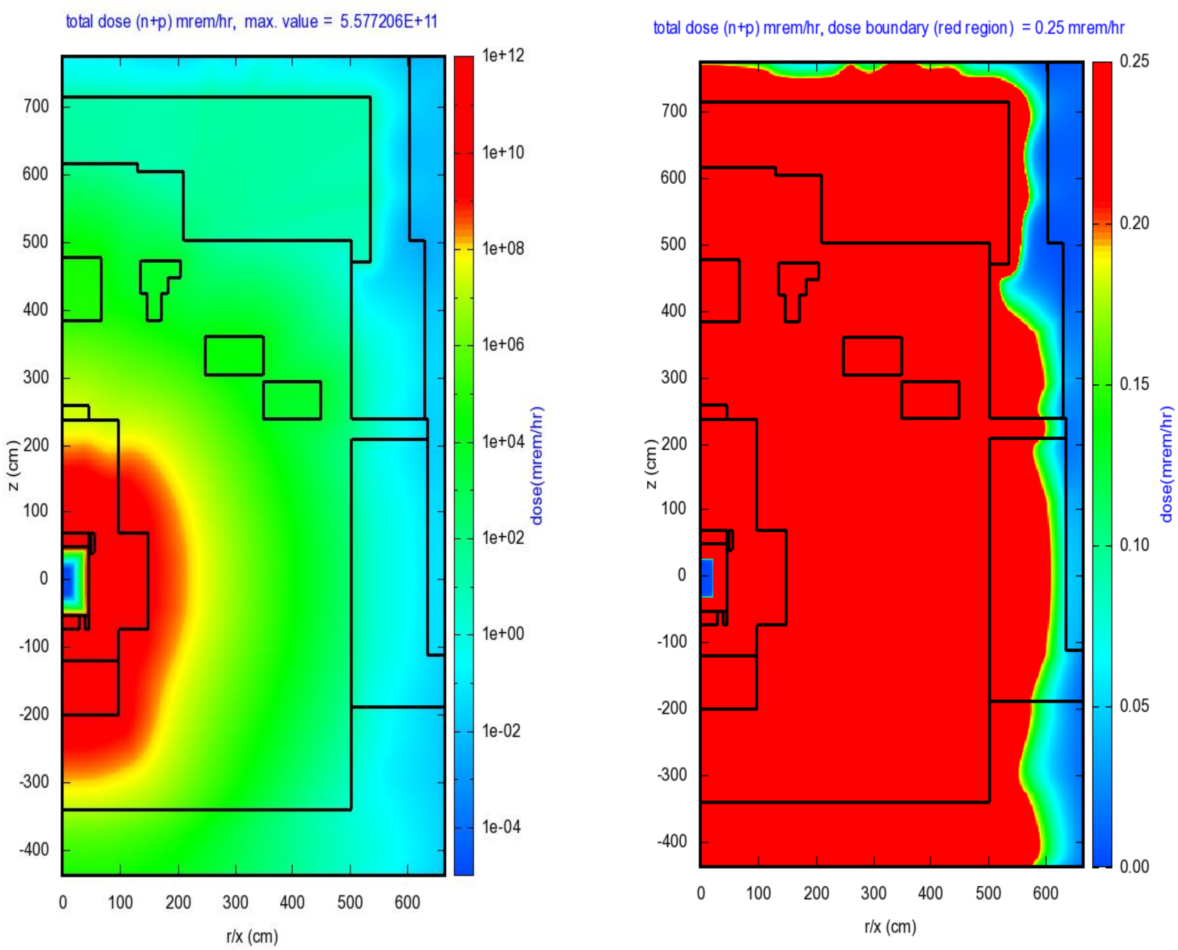

Fig. 4. Dose rates calculated by DORT with proton beam energy of 1.0 GeV using MCNPX2.1.5 and ENDF3-6 (left – logarithmic scale, right – linear scale)

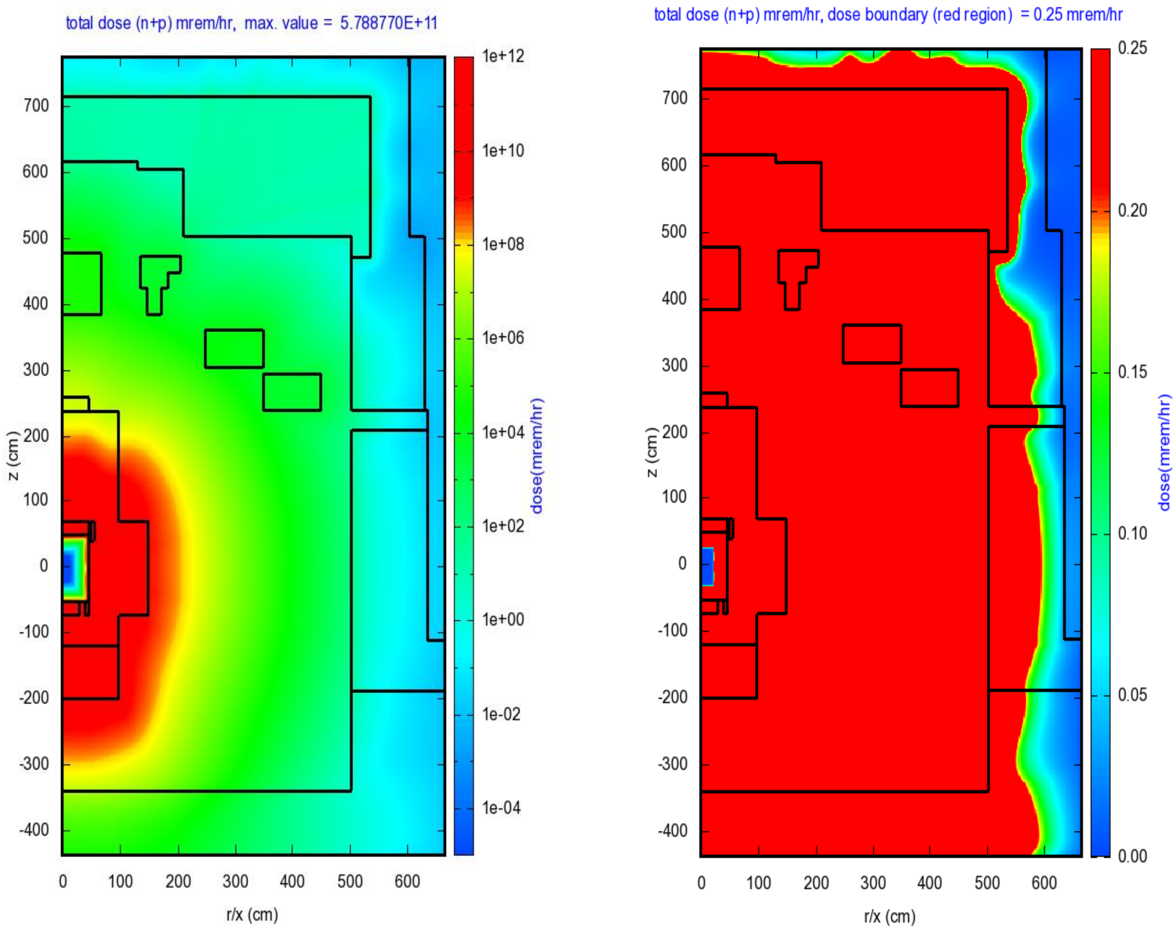

Fig. 5. Dose rates calculated by DORT with proton beam energy of 1.0 GeV using MCNPX2-7 simulations using ENDF7 data (left – logarithmic scale, right – linear scale).

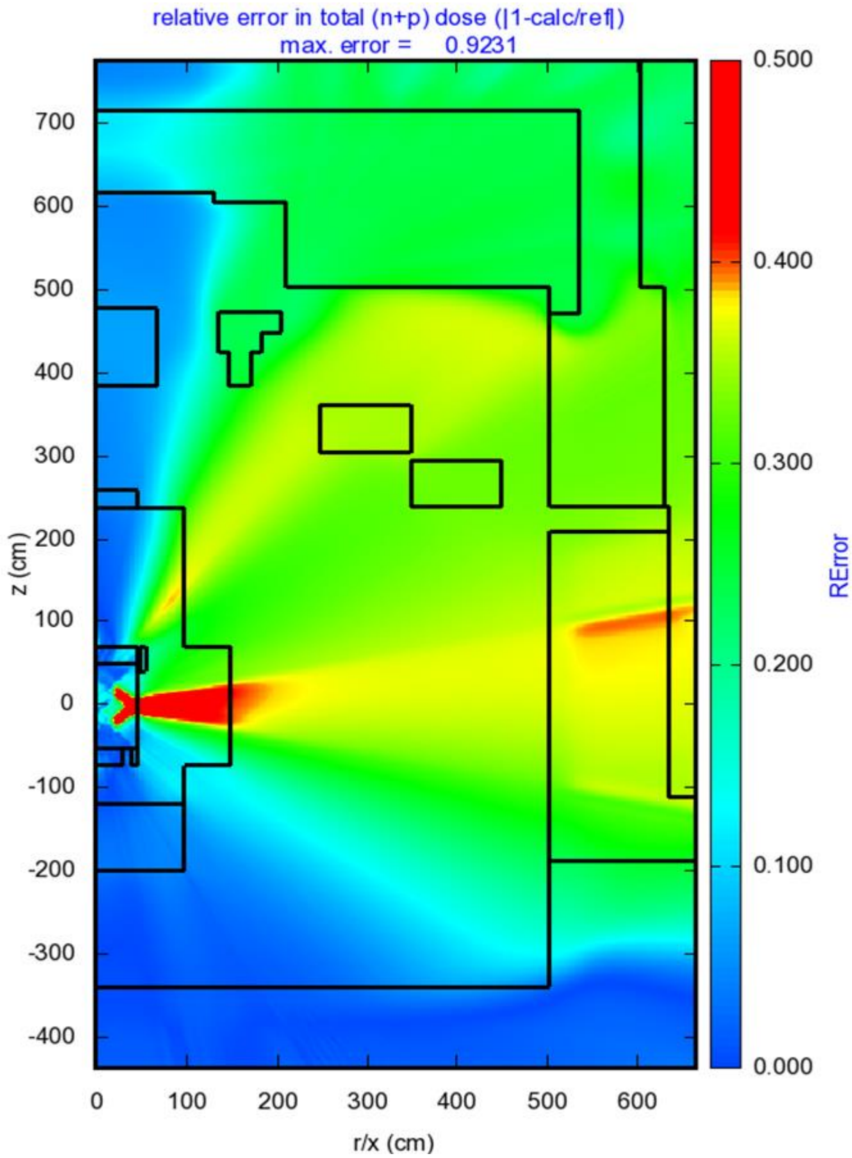

Fig. 6. Relative difference between the DORT dose rates with MCNPX2.7 and ENDF7 simulations and the dose rates with MCNPX2.1.5 and ENDF3-6 simulations.

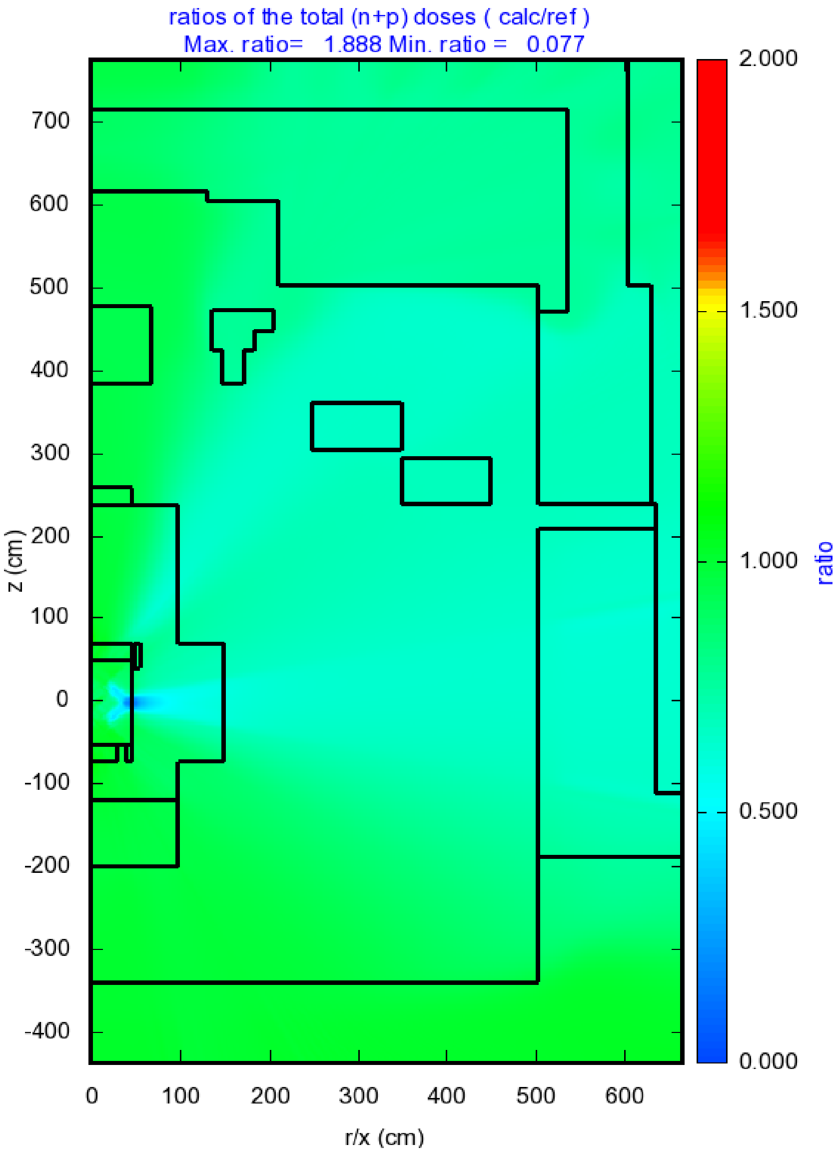

Fig. 7. Ratio of DORT dose rates calculated with MCNPX2.7 and ENDF7 simulations to dose rates calculated with MCNPX2.1.5 and ENDF3-6 simulations

The total neutron and photon source calculated with the MTD conversion of the MCNPX surface source was 1.75×10^{17} (n + p)/sec with MCNPX2.7 and the updated MCNPX libraries, which is 15% lower than the total of 2.05×10^{17} (n + p)/sec source calculated in the 2001 analysis. The difference between the two calculations with the updated and older codes and libraries did not exceed 50% except at the target area, which is separated by several meters of shielding materials around the human accessible areas. The dose rate values decreased when the updated source code and libraries were used. With the updated MCNPX source code and libraries and the 1999 HILO release, the maximum total dose rate at the lateral surface of the shielding monolith was 0.030 mrem/hr, and the maximum dose rate was 0.288 mrem/hr along the top of the shielding monolith. The calculations shown in Fig. 4 used the same surface source that was used in the 2001 analysis, but the dose rate was recalculated using DORT and the 1999 HILO for this case. In this calculation, the maximum dose rate was 0.358 mrem/hr along the top of the shielding monolith, which is exactly the value calculated in the 2001 analysis. This confirms that the library used in the DORT calculation (1999 release) is the same library that was used in the 2001 analysis, and that any changes in the DORT deterministic solver did not affect its accuracy.

3.1.2 Assessing the Effects of Updating the HILO2K Library

In the 2001 analyses, the 1999 release of the HILO library was used with DORT models to compute dose rates around the monolith shielding. We setup a new calculation sequence to verify the effects of the HILO library updates on the results. In this verification study, the boundary source calculated by MCNPX2.7 and ENDF7 data was used, but the two different sets of HILO raw data were processed by GIP and used in two separate calculations. An up-to-date multigroup HILO2K library (2004 release) with 75 neutron groups and 22 photon groups was used to compute the dose rates in one calculation. The dose rate results with this library are shown in Fig. 8. These dose rates were compared to those shown in Fig. 5, which used the same 1999 release of the 75 neutron groups and 22 photon groups HILO library of the 2001 analysis. Results from both calculations with the 2004 release of the HILO2K library and the 1999 HILO release were compared using the relative difference and the ratios in Figs. 9 and 10.

The DOORS package was also updated in 2007 to the DOORS-3.2a. In a separate comparison of calculations performed using the same library, the effect of the updates in the DORT solver were negligible.

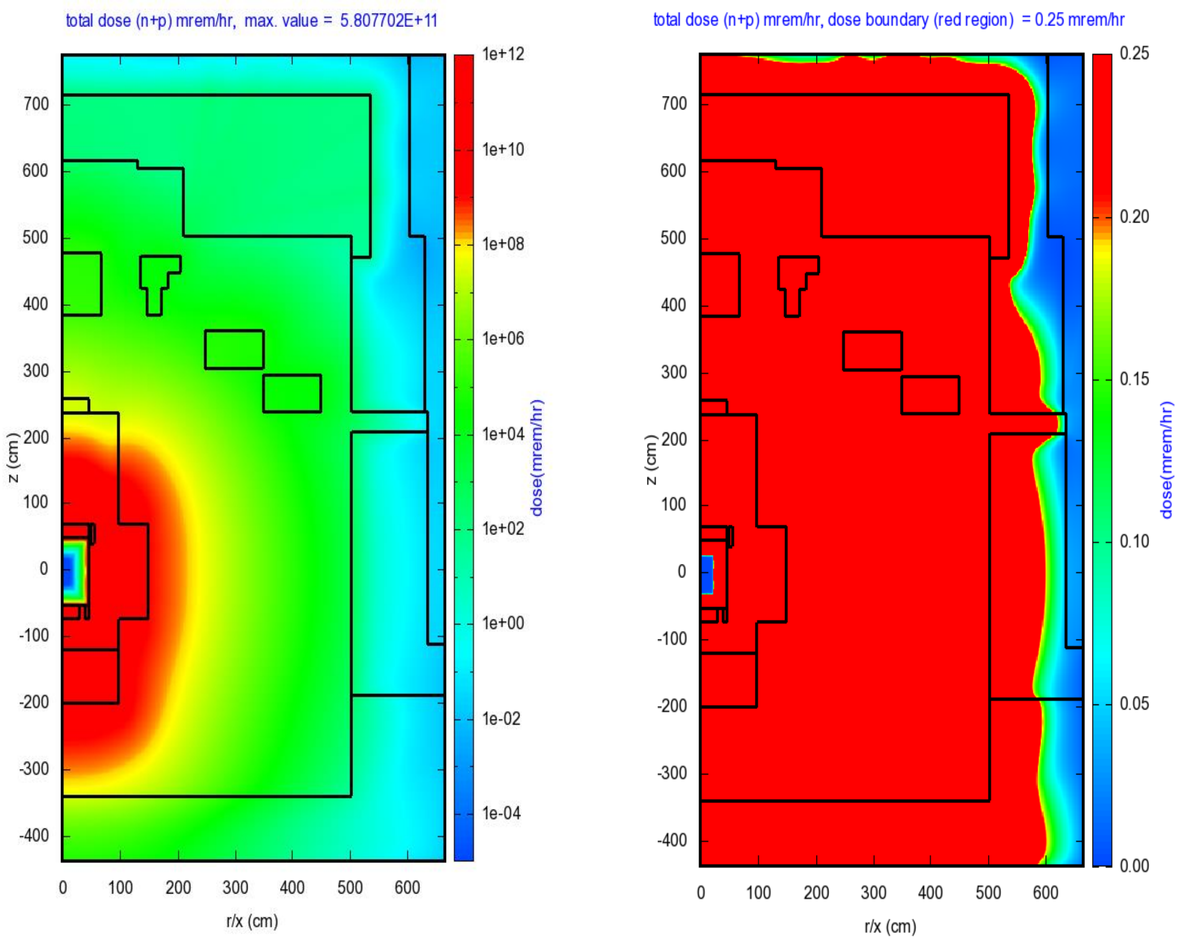

Fig. 8. Dose rates calculated calculated by DORT with the 2004 release of the HILO2K library (left – logarithmic scale, right – linear scale).

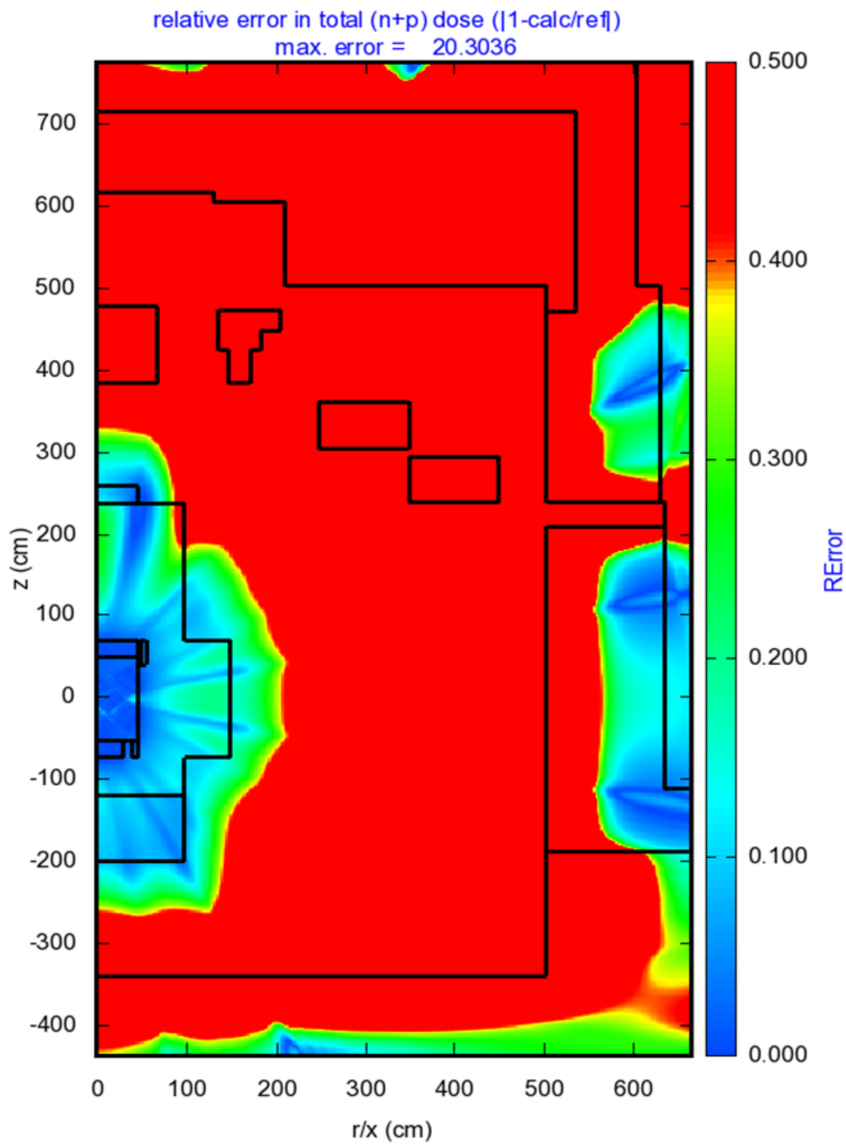

Fig. 9. Relative difference between DORT dose rates calculated with the up-to-date 2004 HILO release and the 1999 HILO release that used in the 2001 analysis.

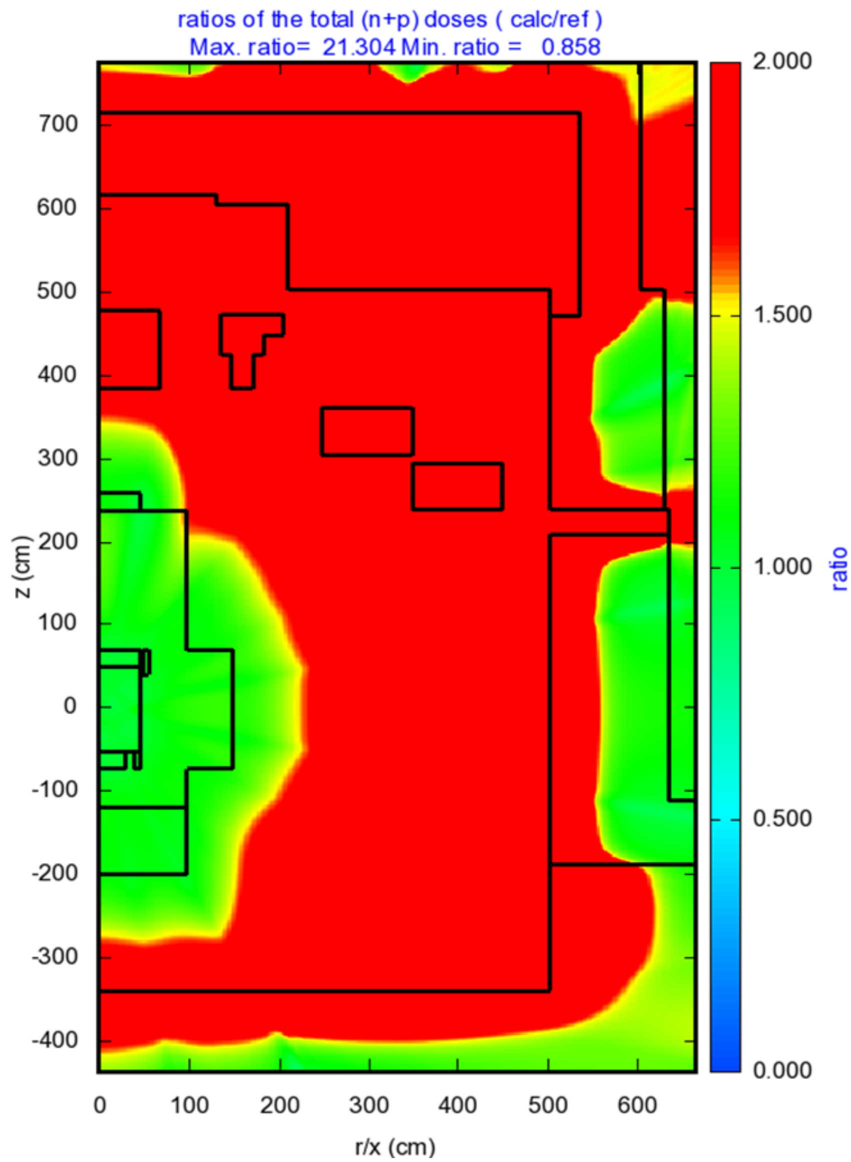

Fig. 10. Ratio of DORT dose rates calculated with the up-to-date 2004 HILO release to the dose rates calculated with the 1999 HILO release that was used in 2001 original analysis

The dose rate results show significant differences, especially inside the stainless steel monolith. Detailed comparisons between the two libraries confirmed that iron, tungsten, and some gadolinium cross sections were updated in HILO 2004 release. This shows that the use of 2004 release of the HILO2K library is necessary in this analysis. As a result of this update, significant differences are shown in both total dose rates inside the monolith shielding, but the differences are smaller at the boundaries of the shielding (around the high density concrete shield). With the updated MCNPX source code and libraries and the up-to-date 2004 HILO2K release, the maximum total dose rate was 0.052 mrem/hr at the lateral surface of the shielding monolith and 0.267 mrem/hr at the top of the shielding monolith.

3.1.3 Assessing the Effects of Changing the Normalization Angle

The 2001 analysis normalized the MCNPX surface source information in the forward ± 20° (relative to the proton beam incident direction) to create an azimuthally symmetric boundary source for the 2D

(R-Z) DORT target monolith calculations. This made the initial source conservatively high because this approach normalizes the neutron and photon populations that have relatively higher energy in the forward direction, even though the neutron beam lines do not begin to appear until ± 35° from the forward direction. Figure 11 shows the dose rates with a proton beam energy of 1.0 GeV and with the MCNPX source information normalized between 20° and 60°. Figures 12 and 13 show the relative difference and the ratio between the dose rates calculated with normalizing the boundary source between 20° and 60° to the dose rates with normalizing the boundary source between 20° and 60°All calculations used to develop Figs. 11–13 used MCNPX2.7, the ENDF7 data library for MCNPX2.7, and the 2004 HILO2K data library release for the DORT calculation.

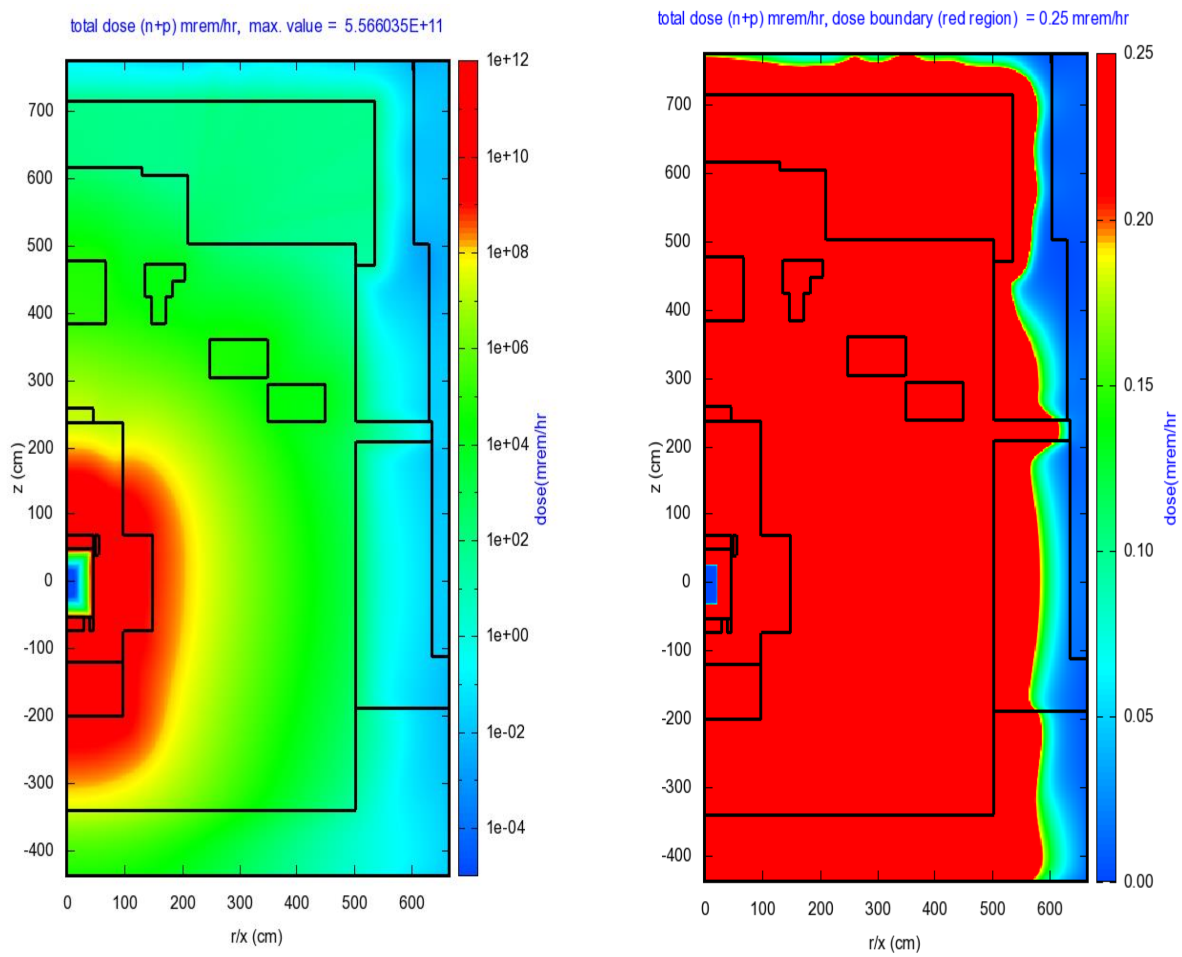

Fig. 11. Dose rates calculated by DORT with proton beam energy of 1.0 GeV and with the MCNPX source information normalized between 20° and 60° (left – logarithmic scale, right – linear scale).

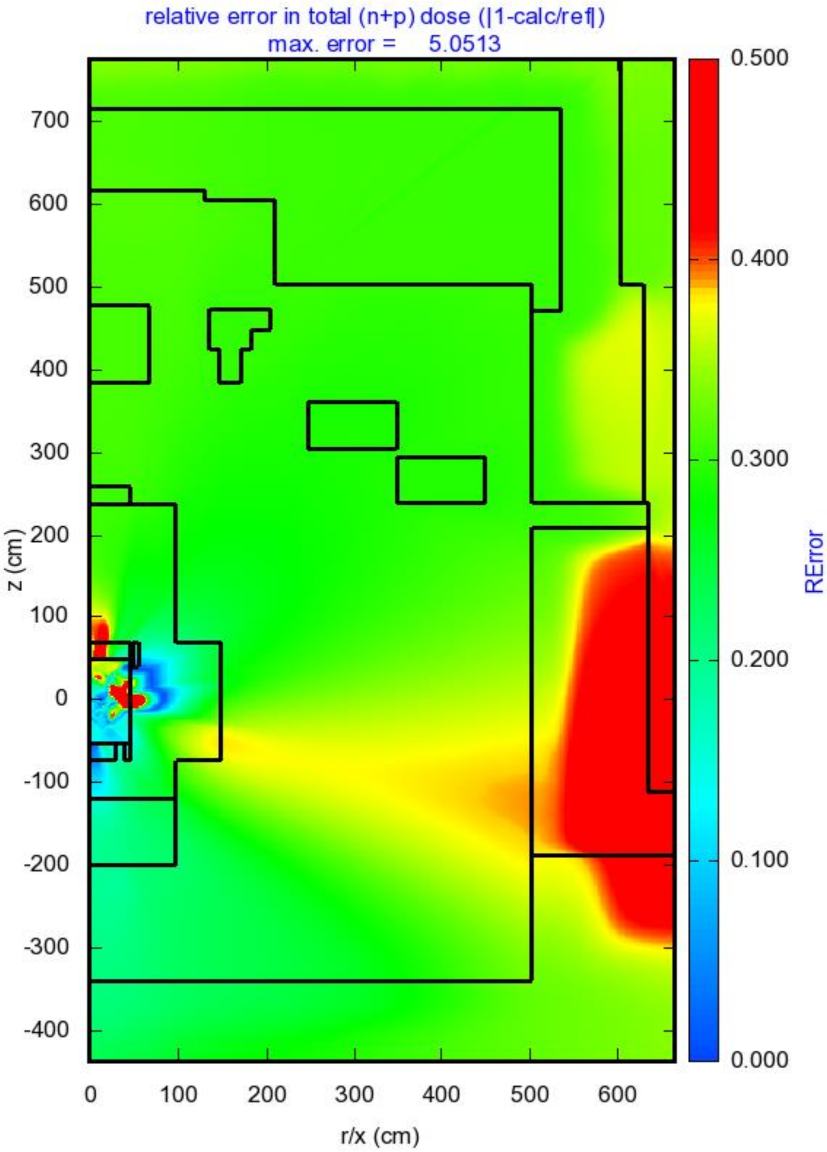

Fig. 12. Relative difference between DORT dose rates calculated with normalizing the boundary source between 20° and 60° and dose rates calculated with normalizing the boundary source between -20° and 20°.

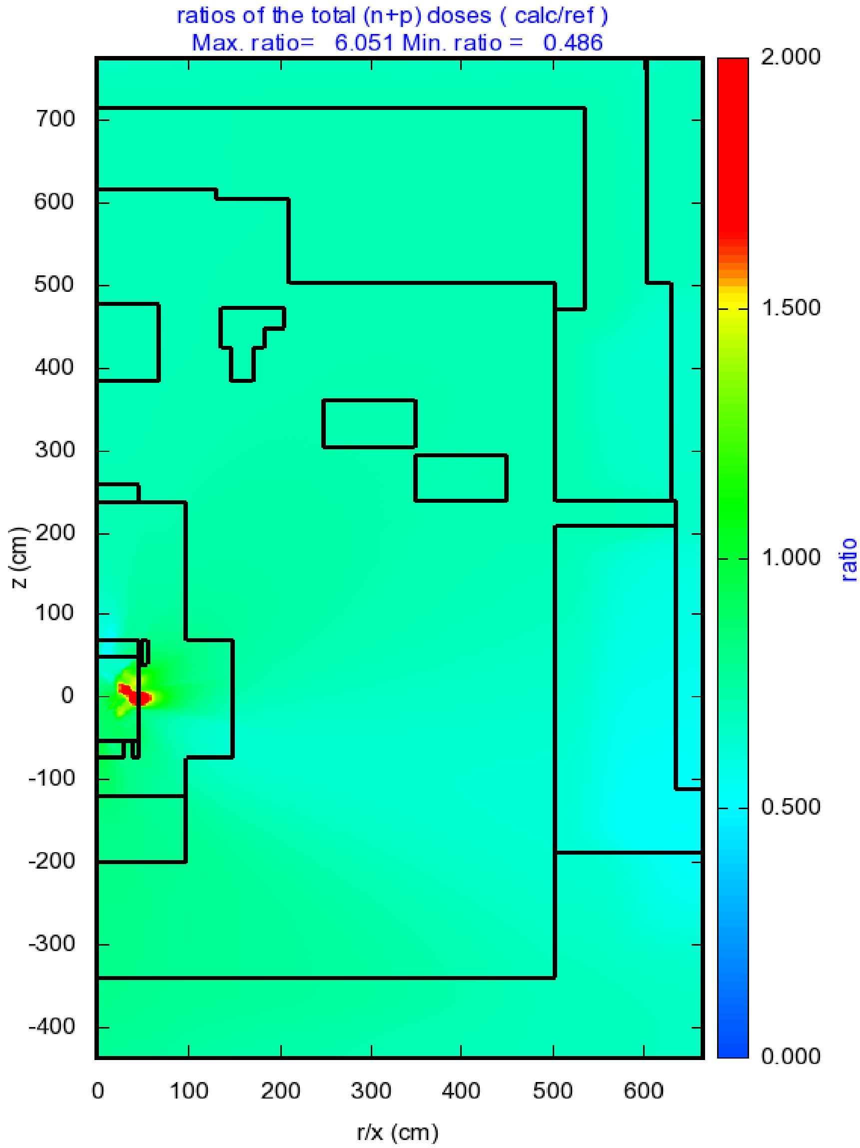

Fig. 13. Ratio between the DORT dose rates calculated with normalizing the boundary source between 20° and 60° to the dose rates calculated with normalizing the boundary source between -20° and 20°.

Even though the change of the normalization angle from between -20° and 20° to between 20° and 60° increased the total neutron and photon source from 1.75 × 10^{17} (n + p)/sec to 2.16 × 10^{17} (n + p)/sec, the total dose rate outside the shielding monolith decreased. This is because the spectrum of the neutrons and the photons emitted from the SNS target is shifted toward higher energies with the normalization angle between -20° and 20°. For example, the number of neutrons with energies above 100 MeV is 26% higher with normalization angle between -20° and 20° than with normalization angle between 20° and 60°. The higher neutron source with normalization angle between 20° and 60° is caused by higher number of low energy neutrons. The number of neutrons with energies below 1 MeV is 39% lower with normalization angle between -20° and 20° than with normalization angle between 20° and 60°. With a normalization angle between 20° and 60°, the maximum total dose rate was 0.035 mrem/hr at the lateral surface of the shielding monolith and 0.180 mrem/hr at the top of the shielding monolith. Because the neutron beam lines do not begin to appear until ± 35° from the forward direction, the results with a normalization angle between 20° and 60° are expected to be closer to reality.

3.2 ANALYSIS WITH 1.3 GEV PROTON BEAM ENERGY

3.2.1 Results with Normalization Angle between -20° and 20°

Figure 14 shows the dose rates with a proton beam energy of 1.3 GeV. The MCNPX source information was normalized between -20° and 20° for the dose rate calculations shown in Fig. 14. Figure 15 shows the relative difference between these dose rates with a proton beam energy of 1.3 GeV and the corresponding dose rates with a proton beam energy of 1.0 GeV. Figure 16 shows the ratio between these dose rates with a proton beam energy of 1.3 GeV to the corresponding dose rates with a proton beam energy of 1.0 GeV.

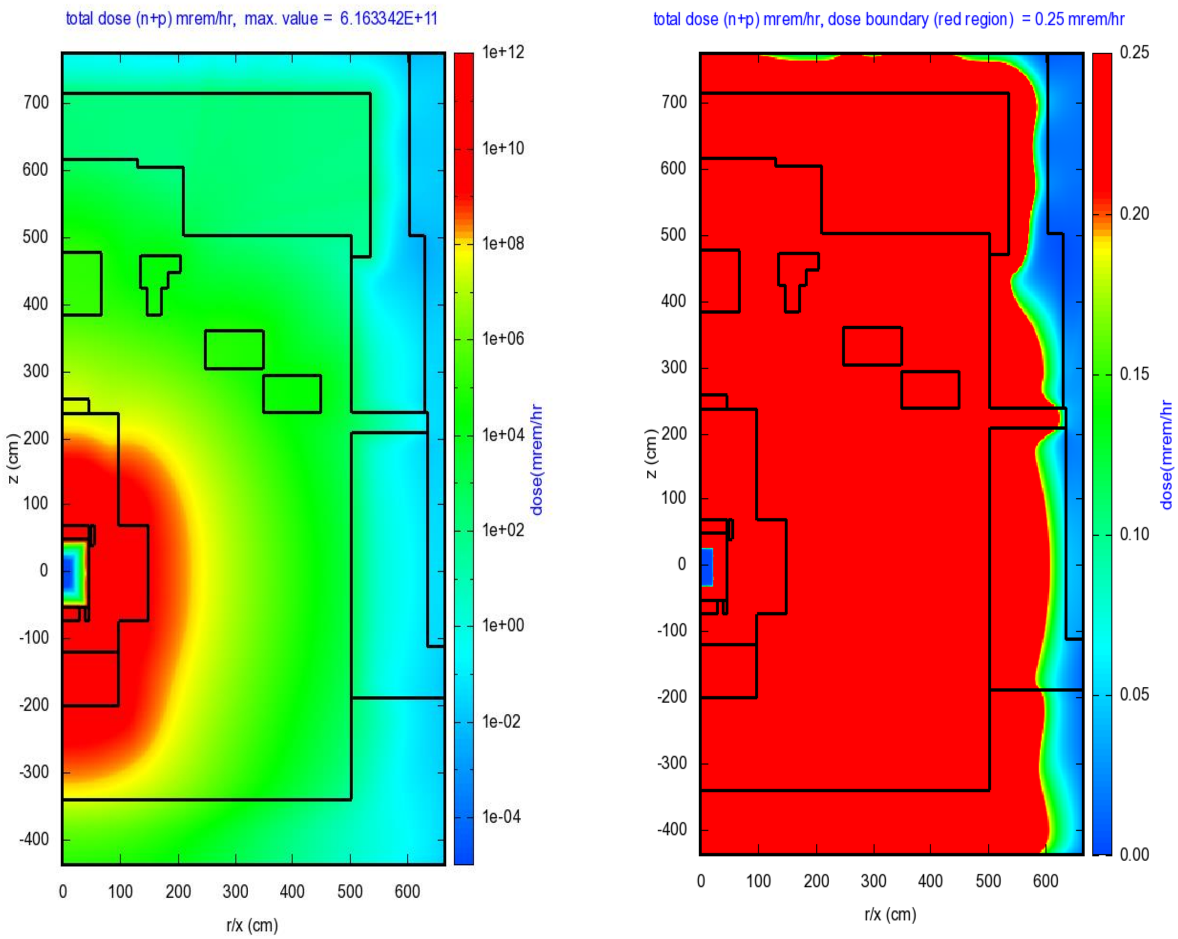

Fig. 14. Dose rates calculated by DORT with a proton beam energy of 1.3 GeV with the MCNPX source information normalized between -20° and 20° (left – logarithmic scale, right – linear scale).

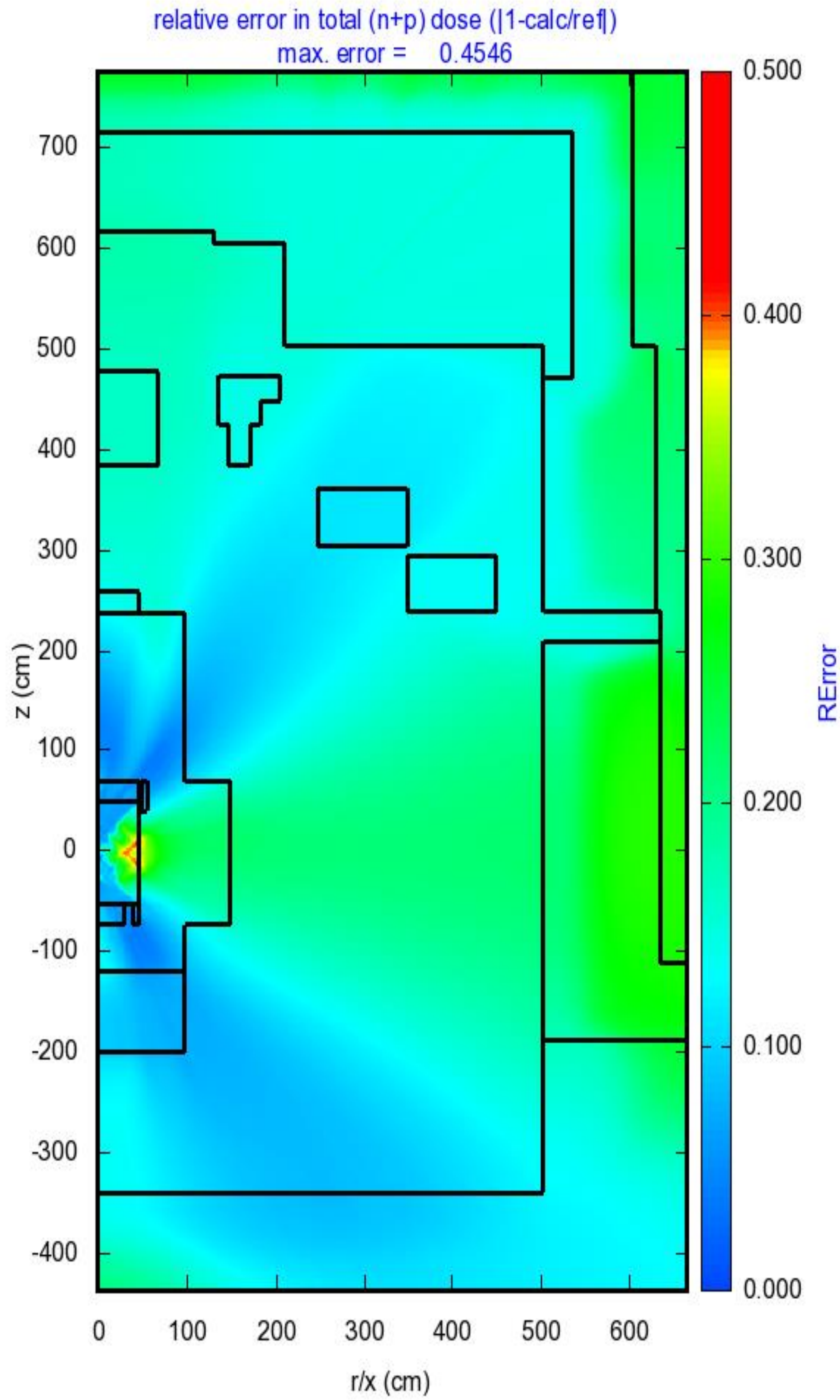

Fig. 15. Relative difference between DORT dose rates with a proton beam energy of 1.3 GeV and the corresponding dose rates with a proton beam energy of 1.0 GeV with normalizing the boundary source between -20° and 20°.

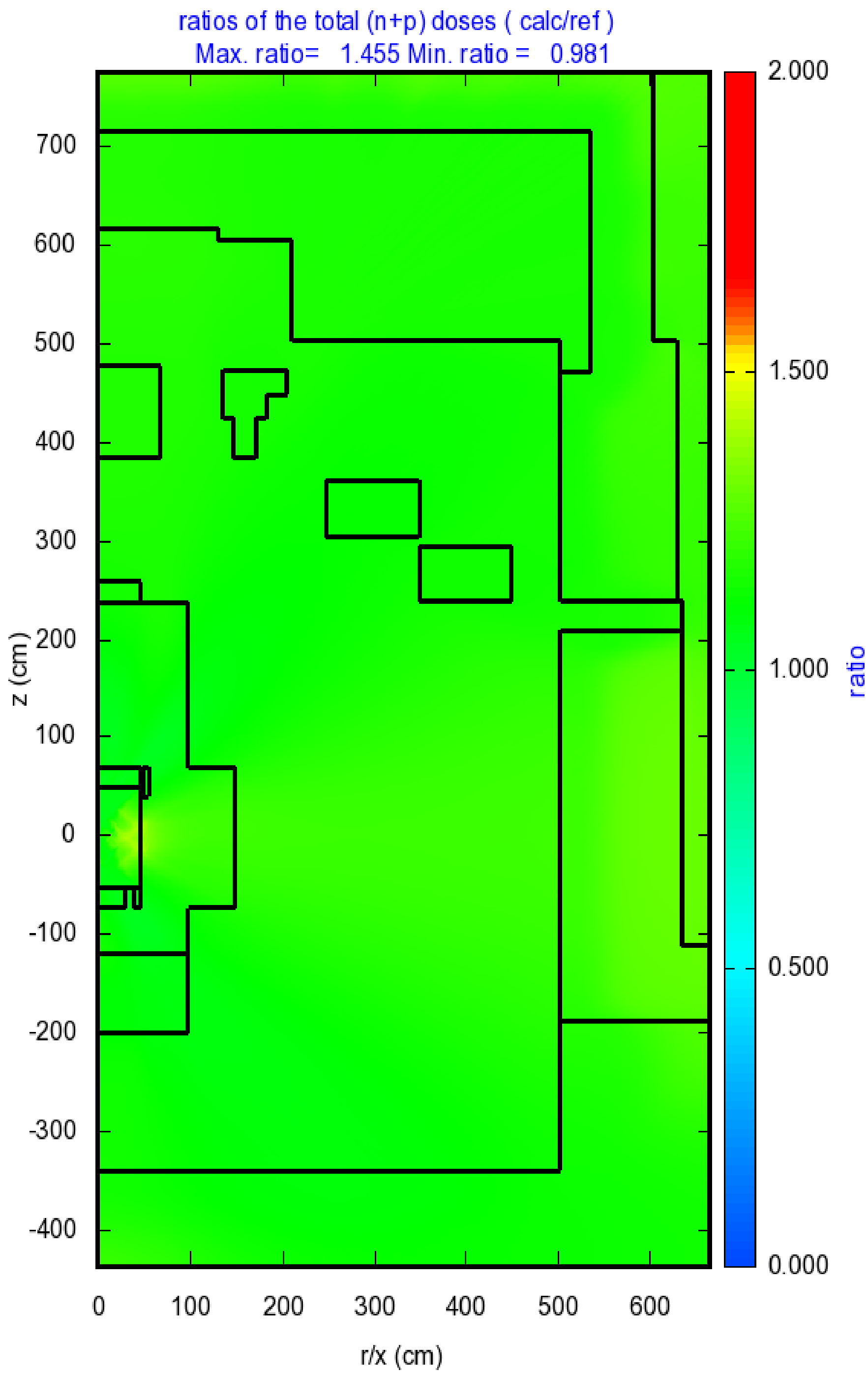

Fig. 16. Ratio between DORT dose rates with a proton beam energy of 1.3 GeV and the corresponding dose rates with a proton beam energy of 1.0 GeV with normalizing the boundary source between -20° and 20°.

The increase of the proton beam energy from 1 GeV to 1.3 GeV increased the neutron and photon source by 15% from 1.75×10^{17} (n + p)/sec to 2.08×10^{17} (n + p)/sec. However, the dose rate outside the monolith did not increase by more than 30% in any region. With a 1.3 GeV proton beam energy and a normalization angle between -20° and 20°, the maximum total dose rate was 0.062 mrem/hr at the lateral surface of the shielding monolith and was 0.334 mrem/hr at the top of the shielding monolith.

3.2.2 Results with Normalization Angle between 20° and 60°

Figure 17 shows the dose rates with proton beam energy of 1.3 GeV with the MCNPX source information normalized between 20° and 60°. Figures 18 and 19 show the relative difference and the ratio between the dose rates calculated with normalizing the boundary source between 20° and 60° to the dose rates with all the codes and libraries updated (Fig. 8), which was calculated with normalizing the boundary source between -20° and 20°. All the calculations used to develop Figs. 17–19 used MCNPX2.7, the ENDF7 data library for MCNPX2.7, and the 2004 HILO2K data library release for the DORT calculation.

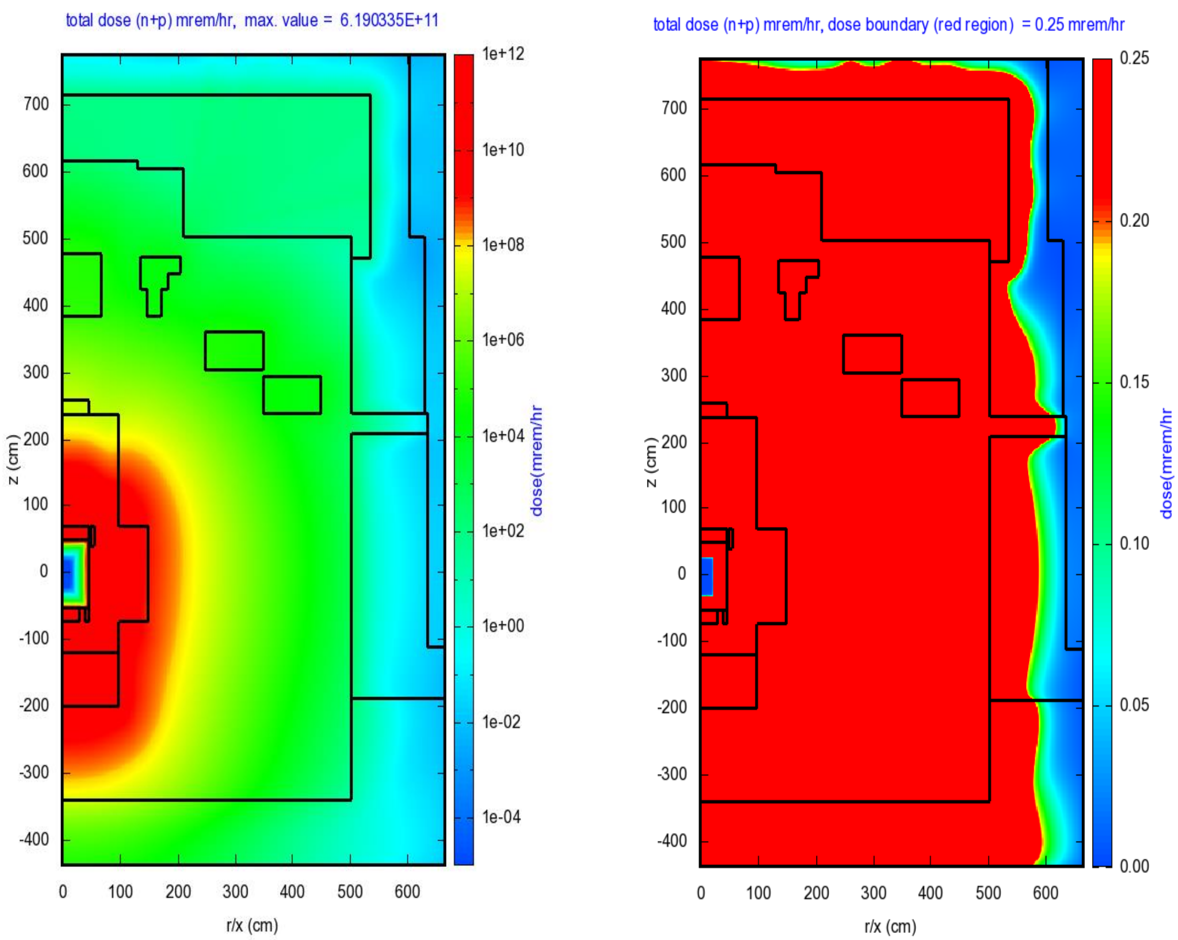

Fig. 17. Dose rates calculated by DORT with a proton beam energy of 1.3 GeV with the MCNPX source information normalized between 20° and 60°.

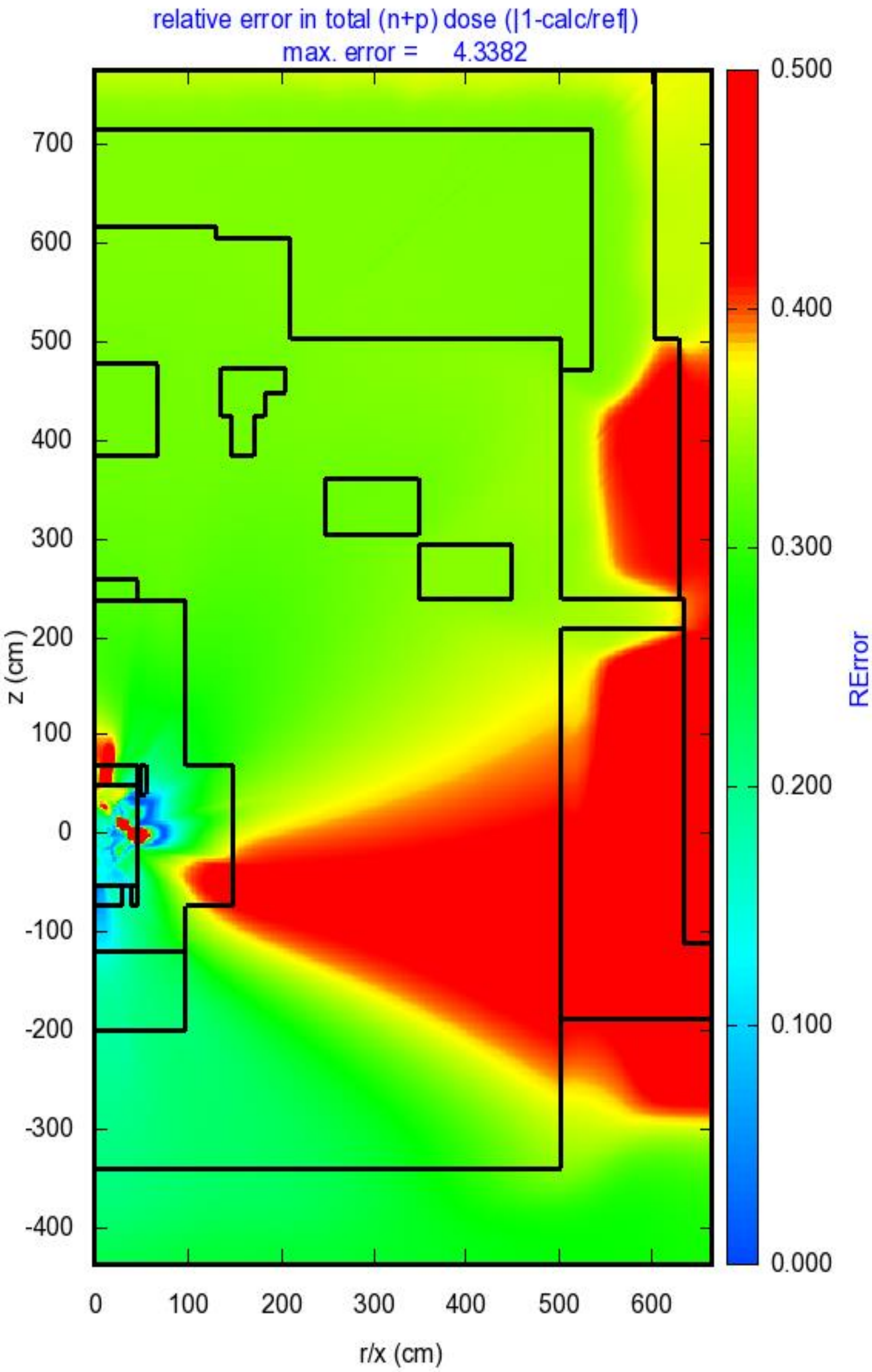

Fig. 18. Relative difference between the DORT dose rates for a proton beam energy of 1.3 GeV calculated with normalizing the boundary source between 20° and 60° and the dose rates calculated with normalizing the boundary source between -20° and 20°.

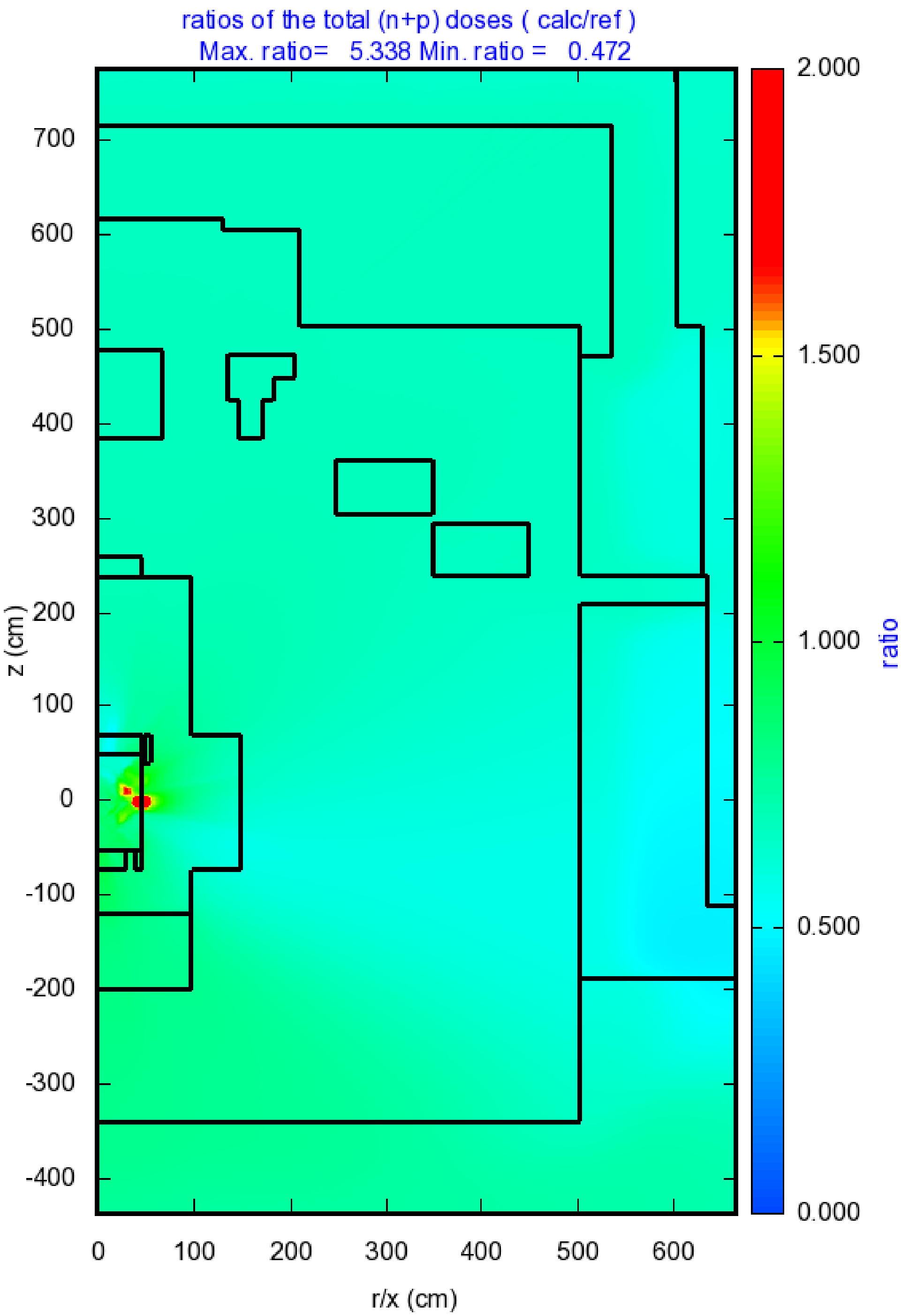

Fig. 19. Ratio between the DORT dose rates for a proton beam energy of 1.3 GeV calculated with normalizing the boundary source between 20° and 60° to the dose rates calculated with normalizing the boundary source between -20° and 20°.

The change of the normalization angle from between -20° and 20° to between 20° and 60° increased the total neutron and photon source from 2.16×10^{17} (n + p)/sec to 2.42×10^{17} (n + p)/sec. However, the total dose rate outside the shielding monolith decreased due to the change of the normalization angle because of the decrease in the energy of the neutrons and photons in the DORT boundary source. The number of neutrons with energies above 100 MeV is 37% higher with normalization angle between -20°

and 20° than with normalization angle between 20° and 60°. The higher neutron source with normalization angle between 20° and 60° is caused by the higher number of low energy neutrons. The number of neutrons with energies below 1 MeV is 31% lower with normalization angle between -20° and 20° than with normalization angle between 20° and 60°. With a normalization angle between 20° and 60°, the maximum total dose rate was 0.038 mrem/hr at the lateral surface of the shielding monolith and 0.21 mrem/hr at the top of the shielding monolith.

4. CONCLUSION

A previous analysis implemented a coupled 3D/2D approach that used both the MCNPX 3D Monte Carlo code and the DORT 2D discrete ordinates deterministic code with a HILO 75 neutron groups and 22 photon groups library to perform the shielding analysis of the SNS target station with a proton beam energy of 1.0 GeV. The same methodology was used with the updated codes and data libraries to assess the dose rate around the existing SNS target station shielding monolith with the proton beam energy of 1.3 GeV. Verification studies were performed with the same 1 GeV proton beam energy used in the original analysis. Table 2 shows the results of this analysis.

Table 2. Peak dose rates outside and on the top of the target shielding monolith

Proton energy (Gev)	MCNPX version	HILO release	Normalization angle	Peak dose rate on lateral surface (mrem/hr)	Peak dose rate on top of shield (mrem/hr)
1.0	2.1.5	1999	-20°−20°	0.047	0.358
1.0	2.7	1999	-20°−20°	0.030	0.288
1.0	2.7	2004	-20°−20°	0.052	0.267
1.0	2.7	2004	20°−60°	0.035	0.180
1.3	2.7	2004	-20°−20°	0.062	0.334
1.3	2.7	2004	20°−60°	0.038	0.211

The updates in the MCNPX code and libraries caused a factor of ~36% decrease in the dose rate outside the SNS target station shielding monolith. On the contrary, the update of the HILO2K library caused the dose rate outside the shielding monolith to increase by ~73%. The previous analysis normalized the MCNPX source information between -20° and 20° to create an azimuthally symmetric boundary source for the subsequent 2D DORT calculations that use R-Z cylindrical geometry. Changing the normalization angle from -20° and 20° to 20° to 60° decreased the dose rate outside the shielding monolith by ~33%.

After verifying the effect of the updates in the codes and libraries used in this analysis and assessing the effect of changing the normalization angle, the analysis with 1.3 GeV proton beam energy was performed using the same 3D/2D approach. The increase of the proton beam energy from 1 GeV to 1.3 GeV increased the dose rate outside of the monolith by ~77%. Similar to the case with a proton beam energy of 1.0 GeV, changing the normalization angle from -20° and 20° to 20° to 60° decreased the dose rate outside the shielding monolith by ~39% with a proton beam energy of 1.3 GeV. With a1.3 GeV proton beam energy and a normalization angle between 20° and 60°, the maximum total dose rate was 0.038 mrem/hr at the lateral surface of the shielding monolith and 0.211 at the top of the shielding monolith. The dose rate along the lateral surface of the shielding monolith is a factor of 6.5 lower than the 0.25 mrem/hr objective for limiting the prompt dose rate in continuously occupied area. The dose rate at the top of the shielding monolith is only slightly lower than the objective dose, but this area is not continuously occupied. Based on this preliminary analysis, modifications to the shielding monolith should not be needed, especially after considering the over conservatism caused by the 2D approximation that transforms the localized gaps around the shutter (the void regions in Fig. 2) to 360° rings. However, it is necessary to mention that the methods and codes used in this analysis are out of date and unsupported and the 2D approximation of the target shielding monolith does not actually represent the actually geometry. We recommend that this analysis is updated with modern codes and libraries that are currently being supported and regularly updated. The full 3D analysis can be performed if ADVANTG is used to generate the variance reduction needed for the final MCNPX or MCNP6 calculation. The analysis can also be performed using the ORNL cross-cutting SHIFT code that utilizes the Denovo deterministic code to generate the variance reduction parameters.

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