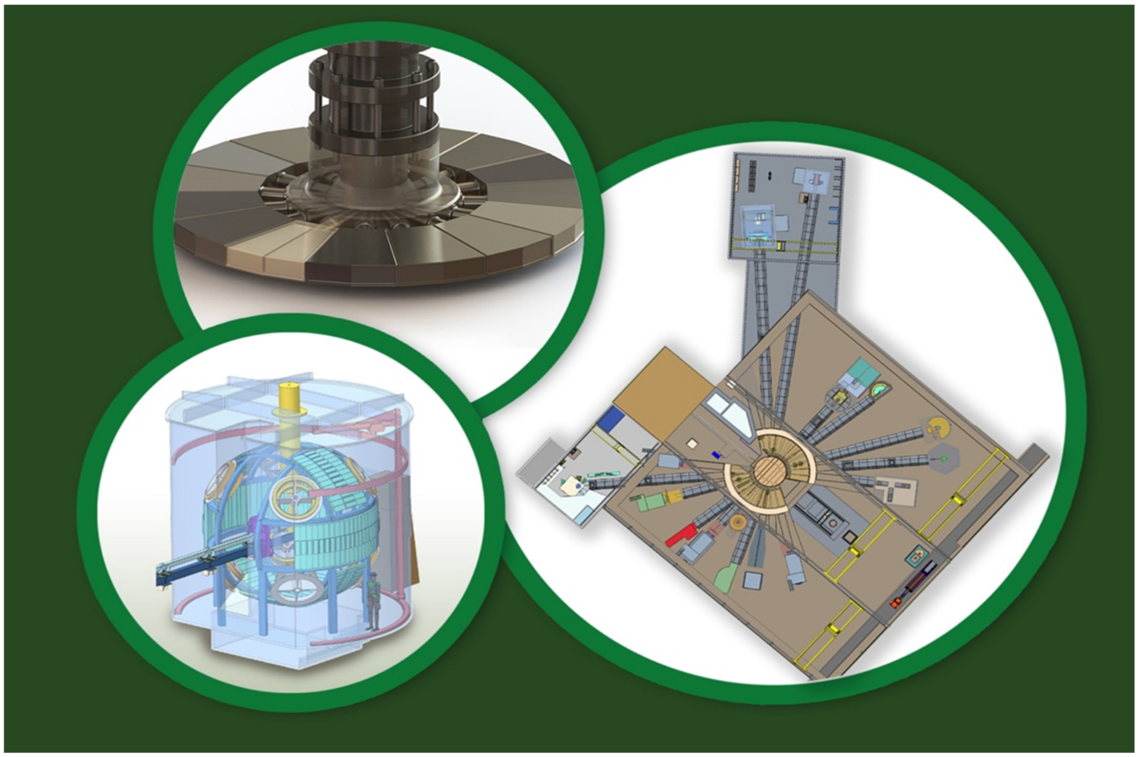
S03120100-TRT10015
ORNL/TM-2024/3371

Oak Ridge National Laboratory Analysis of Second Target Station Target Segment Removal Dose Rates



Tucker McClanahan, Ph.D.

April 2024

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Oak Ridge National Laboratory

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Second Target Station Project

Analysis of Second Target Station Target Segment Removal Dose Rates

Tucker McClanahan, Ph.D.

April 2024

Prepared by
OAK RIDGE NATIONAL LABORATORY
Oak Ridge, TN 37831
managed by
UT-Battelle LLC
for the
US DEPARTMENT OF ENERGY
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ABBREVIATIONS

MRA	Moderator Reflector Assembly
ORNL	Oak Ridge National Laboratory
SNS	Spallation Neutron Source
STS	Second Target Station
TVP	Target Viewing Periscope

1 SCOPE

This report documents the analysis of the dose rate fields in two configurations of the target system of the Second Target Station (STS) at the Spallation Neutron Source (SNS) at Oak Ridge National Laboratory (ORNL) in support of the remote handling target segment removal operation. The two configurations detailed in this report are both assuming 8 hours since beam was incident on the target. The first configuration assumes all shielding is in place just as it was during operation and allows for confirmation of hands-on maintenance capability of the target drive components. The second configuration assumes that a hatch in the target drive room ceiling has been opened to the high bay, the target segment removable core vessel shield block has been removed, and there is a direct line-of-sight to the target segment some 5 m below the target drive room elevation. Dose rate fields in both configurations are documented in this report along with details of the methods of computation. The dose rate fields included in this report are intended to support the engineering of remote handling special equipment and the planning of remote handing operations. The models and analysis detailed in this report are in support of the preliminary design of the STS and future analysis is needed to support the final design of the STS.

2 ACCEPTANCE CRITERIA

Not Applicable

3 ASSUMPTIONS AND LIMITATIONS

The main assumptions associated with the generation of the target assembly decay gamma sources detailed in McClanahan's report are also applicable to this report [8]. The decay gamma sources for the core vessel shielding, moderator reflector assembly (MRA) and target viewing periscope (TVP) are calculated using neutron fluxes and spallation products computed assuming 3.36×10^{15} protons per second incident on the target. The gamma sources for the target assembly, core vessel shielding and TVP were calculated assuming an operational year is defined as 2500 hours of beam on, 1880 hours beam off, 2500 hours beam on, and 1880 hours of beam off. The MRA gamma sources are calculated assuming an operational year consists of four sets of beam on and beam off, where a set is 1250 hr beam on and 940 hr beam off. The target is assumed to have been operated for 10 years, the MRA for 6 years, the TVP and the core vessel shielding for 40 years. The contribution to the dose in the target drive room from the decay gammas generated by the monolith steel shielding (located outside of the core vessel) and the proton beam window are deemed negligible and are not included in the analysis detailed in this report. All of the dose rates shown in this report are from photons only. The contribution from photoneutrons to the total dose rate in the target drive room and high bay regions is much smaller than the photon contribution for the two configurations analyzed in this report.

4 METHODOLOGY AND MODELS

Two general methodologies are utilized in the analysis detailed in this report. The first general methodology is applied to generate the decay gamma sources described in Section 4.1, and the second general methodology is used in the transport of the decay gamma sources to calculate dose rate maps as described in Section 4.2.

4.1 GENERATION OF DECAY GAMMA SOURCES

The methodology for generating the decay gamma sources for the target assembly is detailed in McClanahan's report [8]. The same methodology used to generate the target assembly sources was applied to the generation of the MRA, core vessel shielding and TVP with some minor variations. The operational time for the MRA is 6 years, and the operational times for the core vessel and TVP are 40 years and the normalization used for the fluxes and spallation products assumed 3.36×10^{15} protons per second incident on the target. The author would like to acknowledge Lukas Zavorka for his contribution of the MRA gamma sources, and the neutron fluxes and spallation products for the core vessel shielding and TVP.

4.2 TRANSPORT OF DECAY GAMMA SOURCES

Various components of the methodology for transporting the decay gamma sources to compute dose rate maps in the target drive room of the STS are detailed in the sections below. Section 4.2.1 describes the geometry used in the decay gamma transport in the two configurations of the STS target system. Section 4.2.2 details the isotopic composition of the materials used in the geometry. Section 4.2.3 shows the decay gamma sources used to compute the decay dose rate maps. Section 4.2.4 describes the two methods used to transport the sources to the target drive room. Section 4.2.5 includes details on the variance reduction used to streamline the Monte Carlo particle transport calculation, and Section 4.2.6 describes the tallies used to capture the results from the Monte Carlo or discrete ordinates solutions. Section 4.2.7 describes the post processing scripts used to view the dose rate maps.

4.2.1 Geometry

Two configurations of the geometry are analyzed in Section 5 and are shown below in Figures 1 & 3. Figure 1 shows the nominal geometry of the STS target system with all shielding and components in place where the major systems of the STS have been identified. The large voids between the TVP and MRA as well as below the target wheel are present due to a 10 mm gap along the proton beam between core vessel shielding blocks shown in Figure 2. This geometry is used to calculate the decay dose maps after 8 hours of decay to confirm hands-on maintainability of the target drive and confirm hand-removal of water lines at the top of the target segment vertical stave (elevation of 450 cm above beam center in Figure 1).

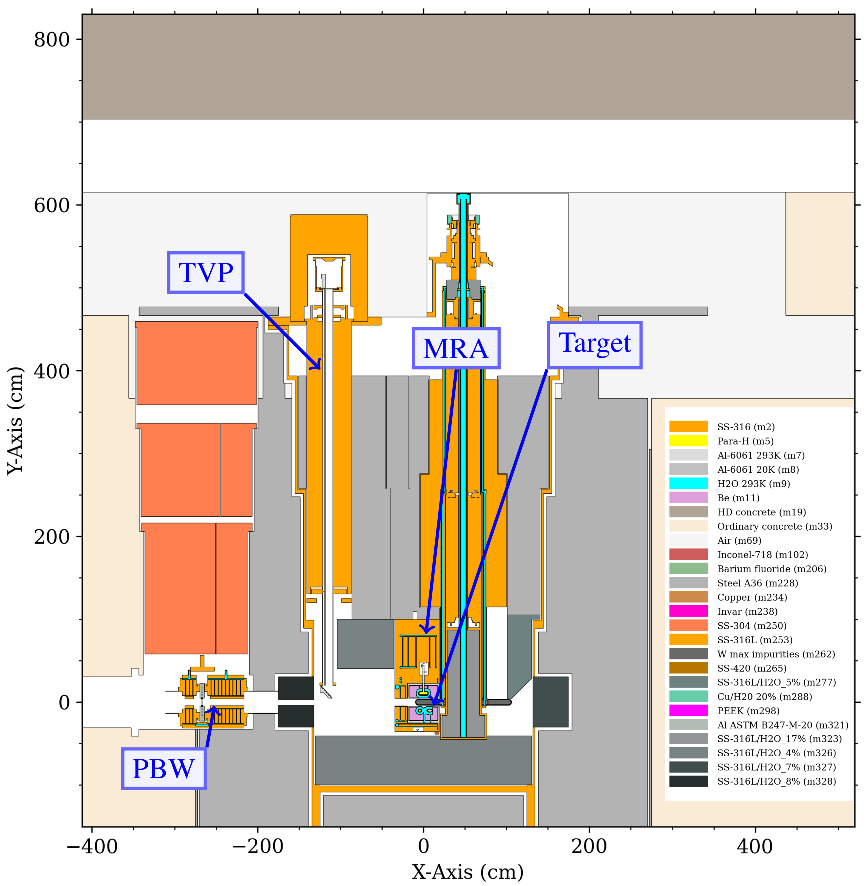

Figure 1. Cross section view of the geometry of the nominal configuration with all of the shielding in place.

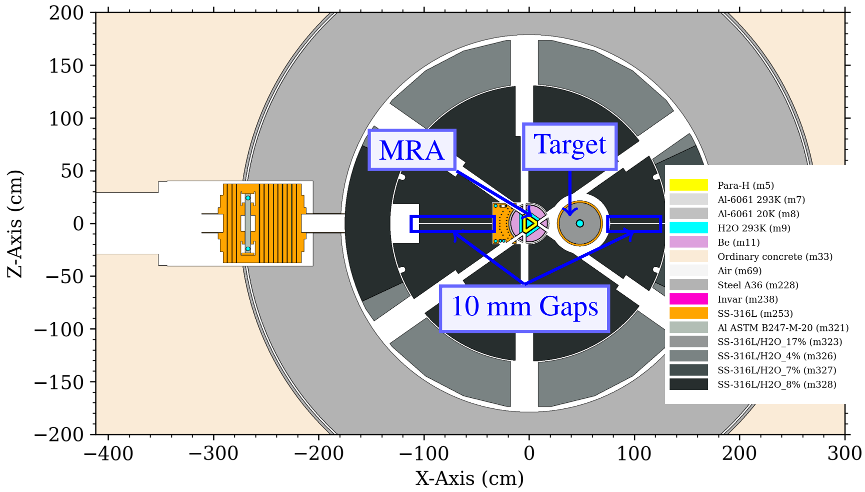

Figure 2. Plan view of the nominal geometry 10 cm below the proton beam elevation showing the 10 mm gaps between core vessel shielding blocks.

Figure 3 shows a cross section view of the STS target system in the segment removal configuration with a hatch opened in the target drive room ceiling to the high bay, the 15 cm thick lead gamma gate installed, and the removable target segment access shield block removed. The target wheel is still in operating position with all 20 target segments in place.

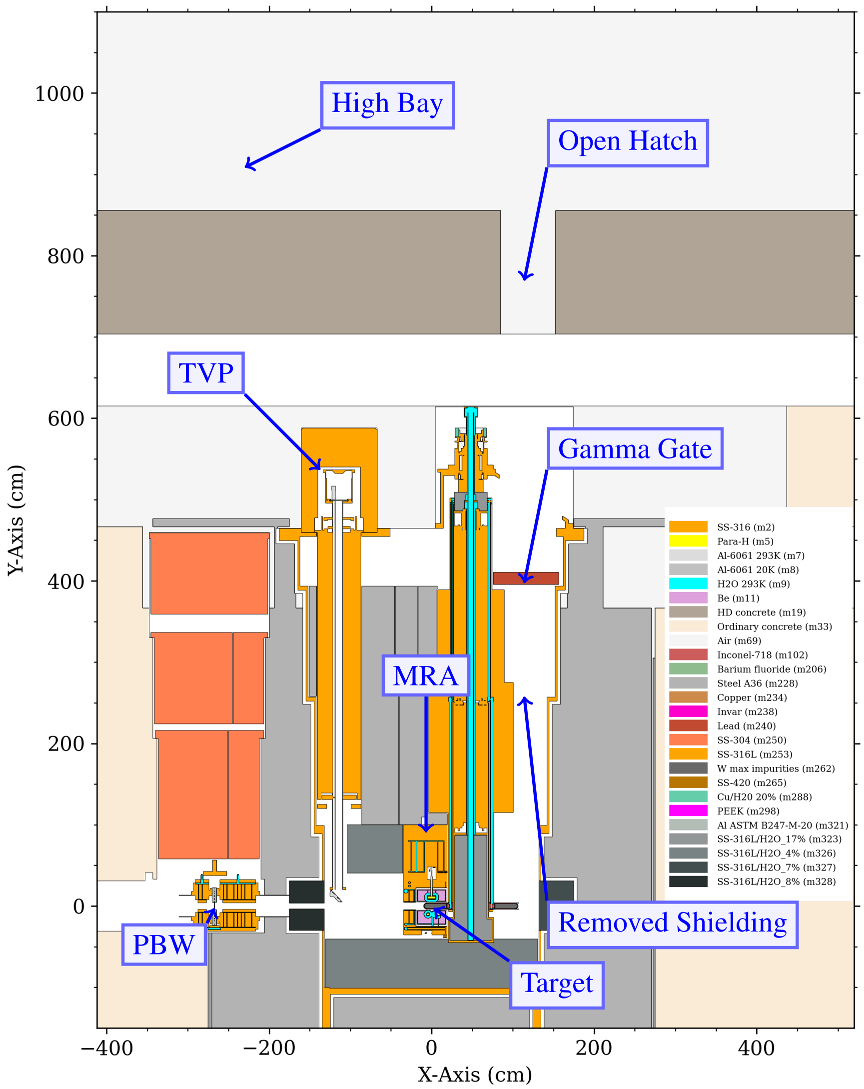

Figure 3. Geometry of the segment removal configuration with the removable target segment access shielding block removed, the gamma gate installed, and a hatch opened to the high bay

4.2.2 Materials

The materials used in the analysis described in this report are detailed in tables included in Appendix C. During the Monte Carlo transport runs where the photon dose rates are tallied, ENDF/B-VII.1 cross sections are used and the 27n19g multigroup library as a part of the ADVANTG 3.2.0 code package is used in the discrete ordinates transport calculations [9, 10].

4.2.3 Decay Gamma Source

The decay gamma source intensities calculated using the methodology described in Section 4.1 are shown in Figure 4 after 8 hours of decay since last beam on target. The most intense sources of decay gamma are the target wheel and MRA. Most of the decay gamma sources shown in Figure 4 are used in both geometry configurations except for the sources stemming from the removable target segment access shield blocks. The major components of the STS target system have been subdivided to spatially resolve the decay gamma source. If a space is white in Figure 4, that regions decay gamma source term was not included in the analysis of this report.

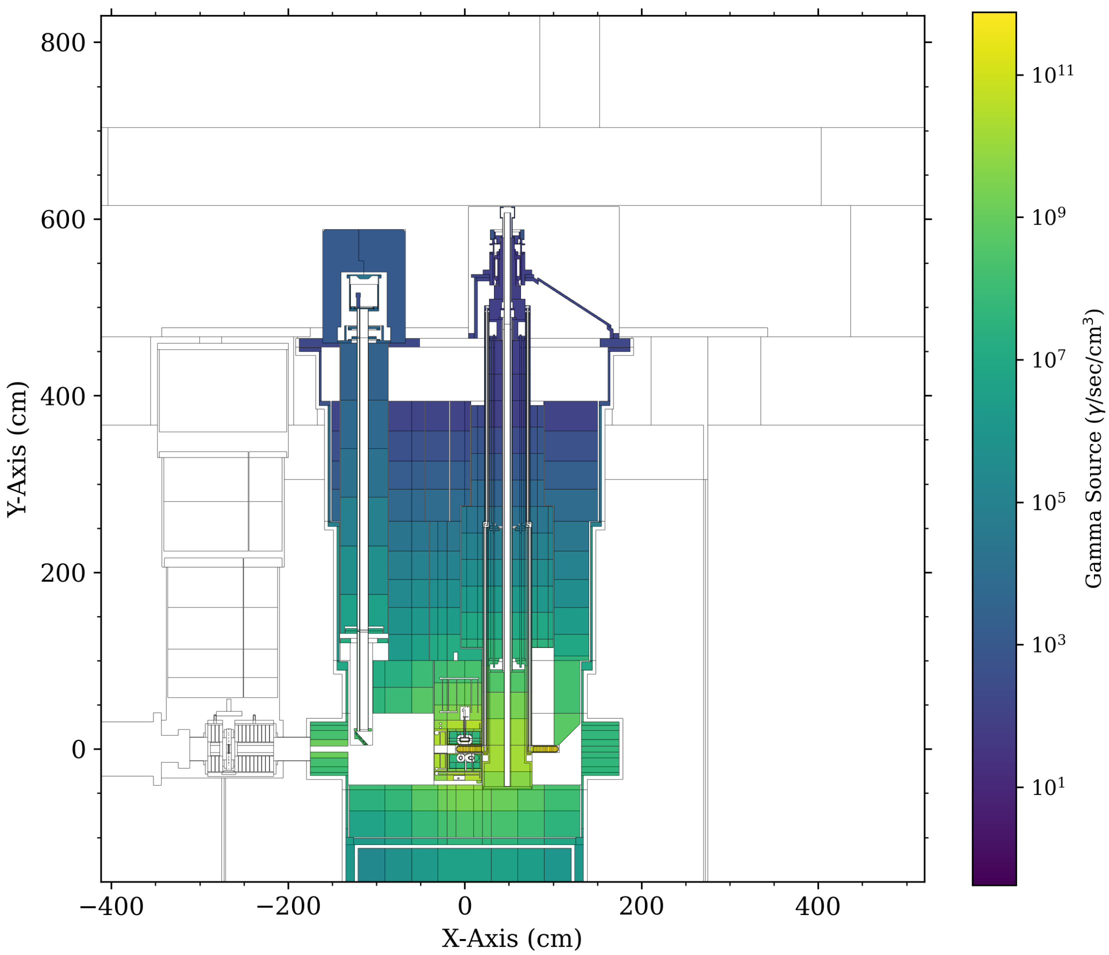

Figure 4. Cross section view of the decay gamma source intensity after 8 hours of decay for the STS target system

4.2.4 Particle Transport

MCNP® Code Version 6.2.0 is used to transport the decay gamma sources shown in Section4.2.3 to the target drive room and high bay areas and tally photon dose rates as discussed in Section 4.2.6[11]. Weight windows are applied as a variance reduction technique to expedite convergence in the regions of interest and the details of the weight window generation are discussed in Section 4.2.5. The results shown in Section 5 show both the Monte Carlo and discrete ordinates transport solutions to the decay gamma dose from MCNP® and Denovo respectively [10]. The discrete ordinates solution is generated as a part of generating weight windows for the Monte Carlo transport and prove to be in good agreement with the Monte Carlo solution.

4.2.5 Variance Reduction

ADVANTG 3.2.0 was used to produce variance reduction parameters in the form of weight windows and source biasing to aid in the timely convergence of the tallies discussed in Section 4.2.6. The tally-of-interest in the ADVANTG run was a mesh tally that covered the full extent of the target drive room for both configurations. The quadrature set used in the ADVANTG run was generated by Joel Risner and was a midpoint gauss quadrature set with 26 polar angles and 166 total angles per octant based on quadrature studies carried out by I.K. Abu-Sumays [12]. The spatial rectilinear grid used in the Denovo discrete ordinates calculation covered the spatial extent of the geometry and had a resolution of approximately 3 X 2 X 3 cm in the extent of the core vessel and target drive room resulting in 54 million mesh elements. Outside of the core vessel and target drive room, the resolution was coarse (>10 cm). The weight windows generated with this spatial grid were then collapsed in ADVANTG by a factor of 6.

4.2.6 Tally Details

The photon effective dose rates are tallied with volume-averaged flux mesh tallies in the MCNP® calculation modified by dose energy and dose function (DE/DF) cards. The DE/DF cards applied the photon flux to effective dose conversion factors shown in Table D.1 of Appendix D with logarithmic interpolation of energy [7]. Post processing scripts described in Section 4.2.7 apply the dose response function shown in Table D.1 with energy logarithmically interpolated to the photon fluxes calculated with Denovo.

4.2.7 Post Processing

A Python script was written to combine the photon effective dose tallies from over 150 Monte Carlo and 150 discrete ordinate runs. This script loads each meshtal file from each MCNP® run, sums the mesh tallies, and propagates the uncertainties to generate a total effective photon dose rate map along with an uncertainty map. The same script also loads in and each forward flux file from each Denovo run, applies the dose response function described in Section 4.2.6, sums all runs, and produces a total effective photon dose rate map. The geometry, source intensity, and dose plots are generated using the RTPlotter Python suite of tools developed by of Joel Risner.

5 ANALYSIS AND RESULTS

Two configurations supporting remote handling removing the target segment after 8 hours of decay are included in this section. A decay time of 8 hours is conservative for these analysis, and when considering operational logistics, the time frame for removing a target segment is considerably longer than 8 hours. Dose rates for the configuration of the STS target system with all shield blocks in place and every major component in operating position is detailed in Section 5.1. Section 5.2 shows the dose rates for the configuration where the target segment access core vessel shield block has been removed, a hatch from the target drive room to the high bay has been opened, and a gamma gate has been placed over the opening in the core vessel shielding.

The dose rates shown in this report are photon dose rates only. The contribution to the total effective dose rate from photoneutrons in the two configurations to the regions of interest is minimal.

All of the figures included in this section are colored according to the definitions of posted areas at ORNL [13]. The lowest level corresponds to a generally accessible area where dose rates are below 0.25 mrem/hr. The next highest level shows the extents of a controlled area where the dose rates are between 0.25 and 2.0 mrem/hr. A radiological buffer area (RBA) is represented by the zone between 2.0 and 5.0 mrem/hr. The zone of the figures between 5 and 100 mrem/hr represent the extents of a radiation area. A high radiation area is represented by the zone between 100 mrem/hr and 500 rem/hr. The highest zone shown in the figures shows the extents of a very high radiation area with dose rates greater than 500 rem/hr.

5.1 NOMINAL CONFIGURATION DOSE RATES

The results discussed in this section show the dose rates after 8 hours of decay for the nominal configuration of the STS target system. The nominal configuration consists of all core vessel shield blocks in place and all target system components are in operational positions.

Figure 5 shows the decay dose rates as calculated with the discrete ordinates method described in Sections 4.2.4 & 4.2.5 in a cross section view along the proton beam. These results in Figure 5 are in good agreement with the Monte Carlo results shown in Figure 6. The results in Figure 6 are not well converged but overall confirm the dose distribution shown in Figure 5. Based on the good agreement between the Monte Carlo and discrete ordinates solutions, the rest of the figures in this section will only include discrete ordinates solutions.

Figure 5 shows a very high radiation area exists deep within the core vessel shielding surrounding the target segment wheel and MRA, and is inaccessible to personnel. The high radiation area is mostly buried in the core vessel shielding except for the area within the TVP shielding in the target drive room, but is nevertheless inaccessible to personnel. The dose rates in the target drive room are maximally a RBA (2-5 mrem/hr) due to the radiation around the TVP shield block. Figure 5 shows that the target drive assembly is in the controlled area and confirms hands-on maintainability.

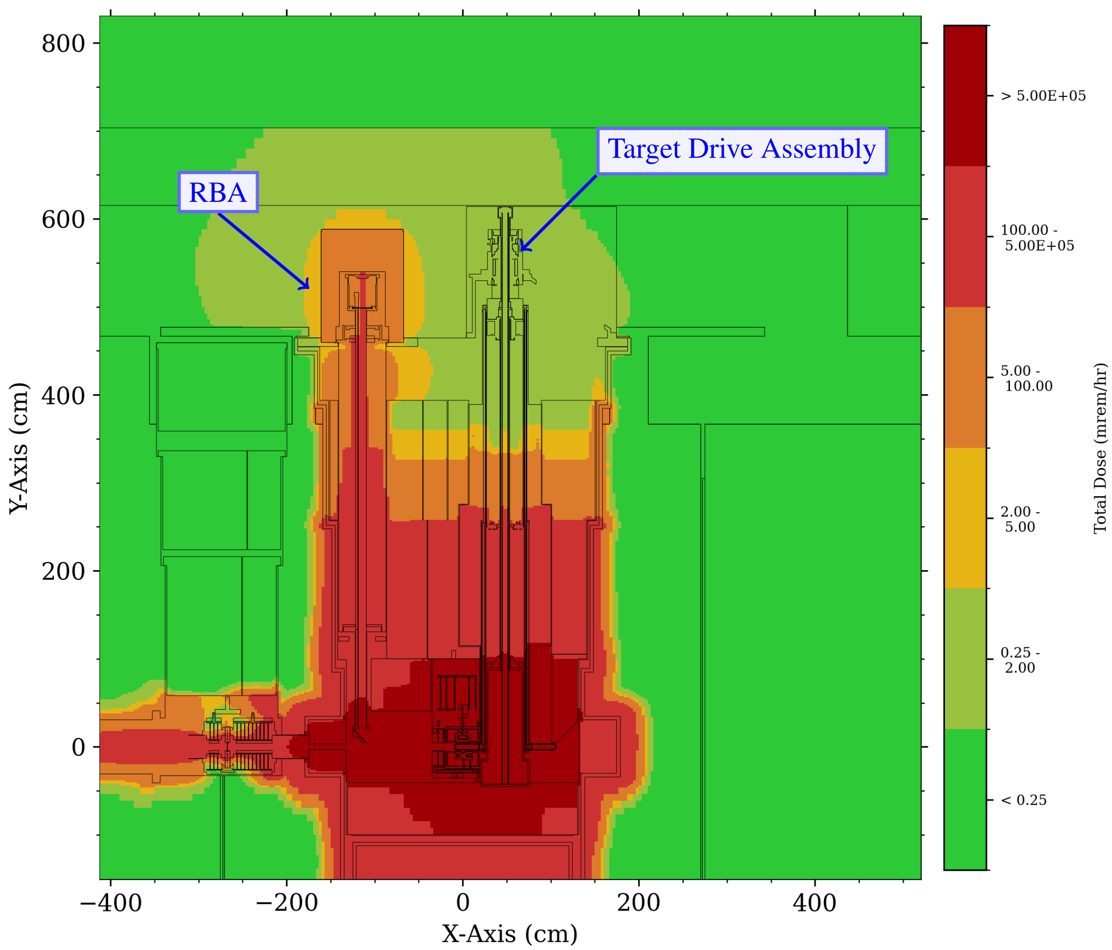

Figure 5. Cross section view of the discrete ordinates photon effective dose rate solution after 8 hours of decay in the target drive room and STS target system for the nominal configuration.

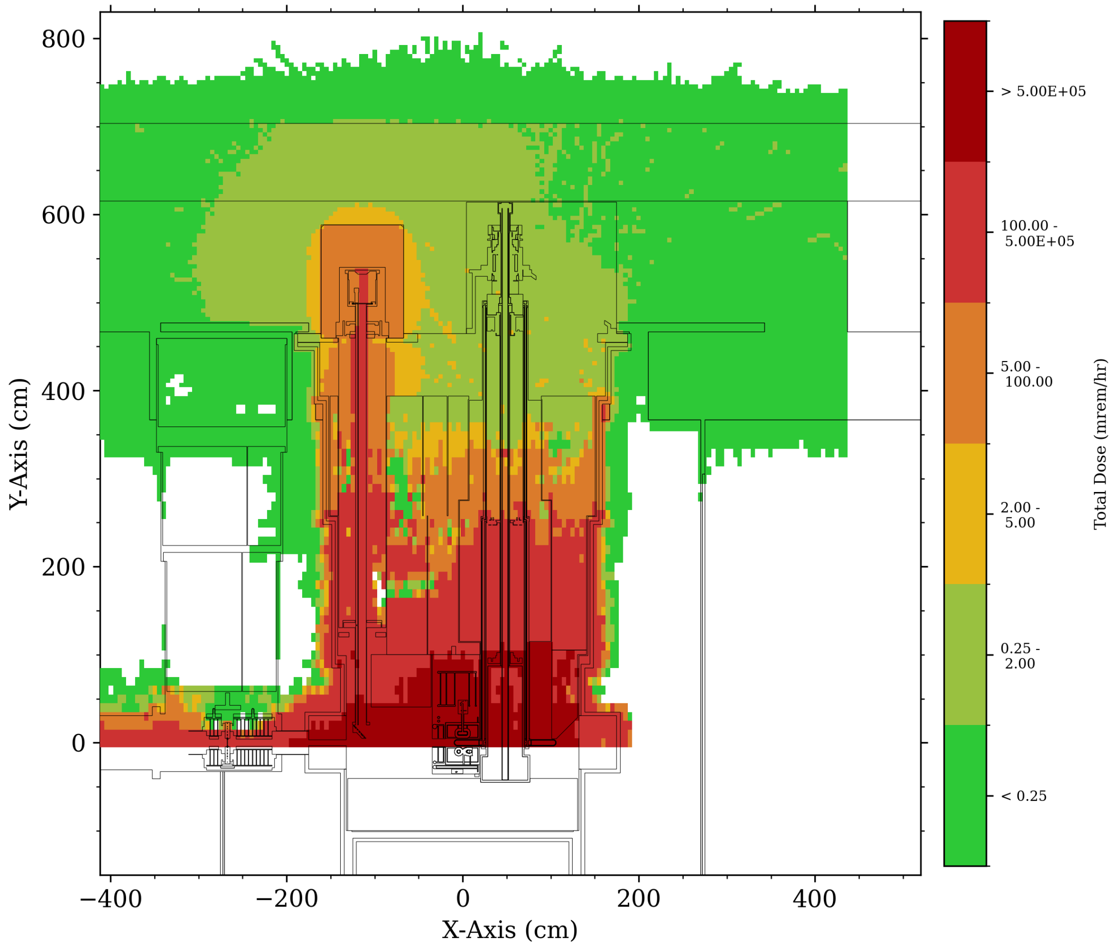

Figure 6. Cross section view of the Monte Carlo photon effective dose rate solution after 8 hours of decay in the target drive room and STS target system for the nominal configuration.

Figure 7 shows a plan view of the discrete ordinates dose rates at an elevation of 20 cm above the top of the core vessel shielding (415 cm above proton beam). The plan view in Figure 7 is taken at a working elevation if personnel are working under the target drive room floor elevation. Most of the accessible area upstream of X = 0 cm is a radiation buffer area along with the periphery of the core vessel except for the region within 20 cm of the TVP where it is a radiation area. The region surrounding the target is a controlled area except for the spot directly above the MRA hydrogen line penetration where the field enters the radiation area directly over the opening.

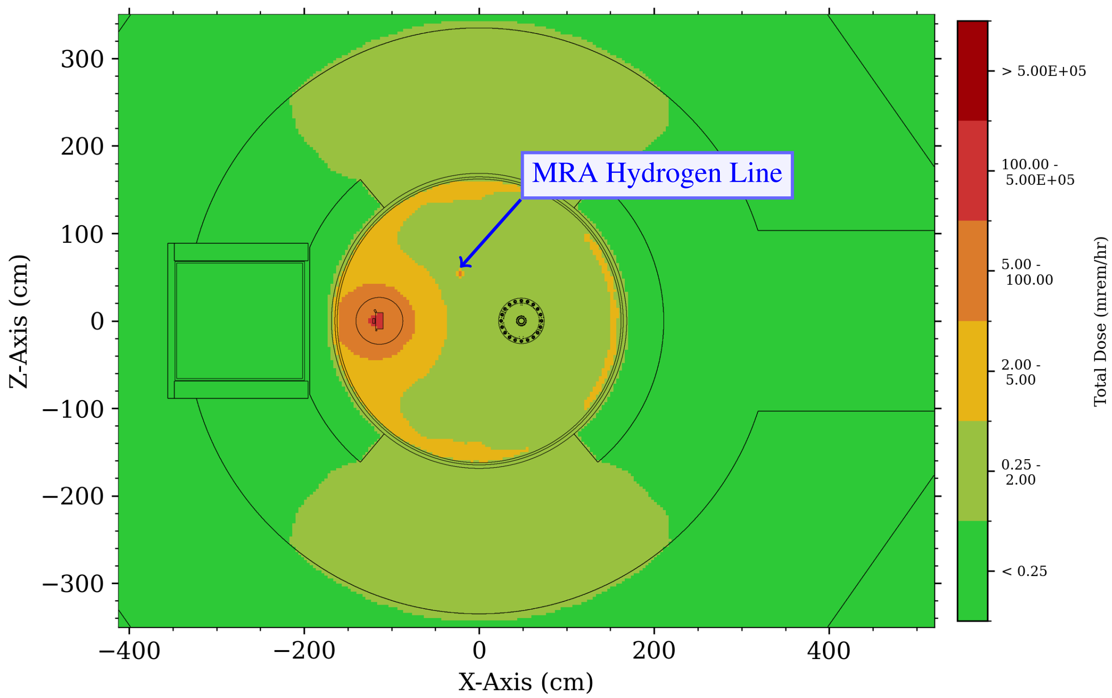

Figure 7. Plan view at a working elevation just below the target drive room floor (415 cm above beam center) of the discrete ordinates photon effective dose rate solution after 8 hours of decay in the target drive room for the nominal configuration.

Figure 8 shows a plan view of the discrete ordinates dose rates at an elevation of 20 cm above the target drive room floor (500 cm above proton beam). The only accessible radiation area is directly over the MRA hydrogen line penetration. Most of rest of the area directly over the core vessel shielding is a controlled area with the exception of the area surrounding the TVP, where the region is a radiation buffer area. The region of the target drive room outside of the core vessel is could be a generally accessible area based on dose rate.

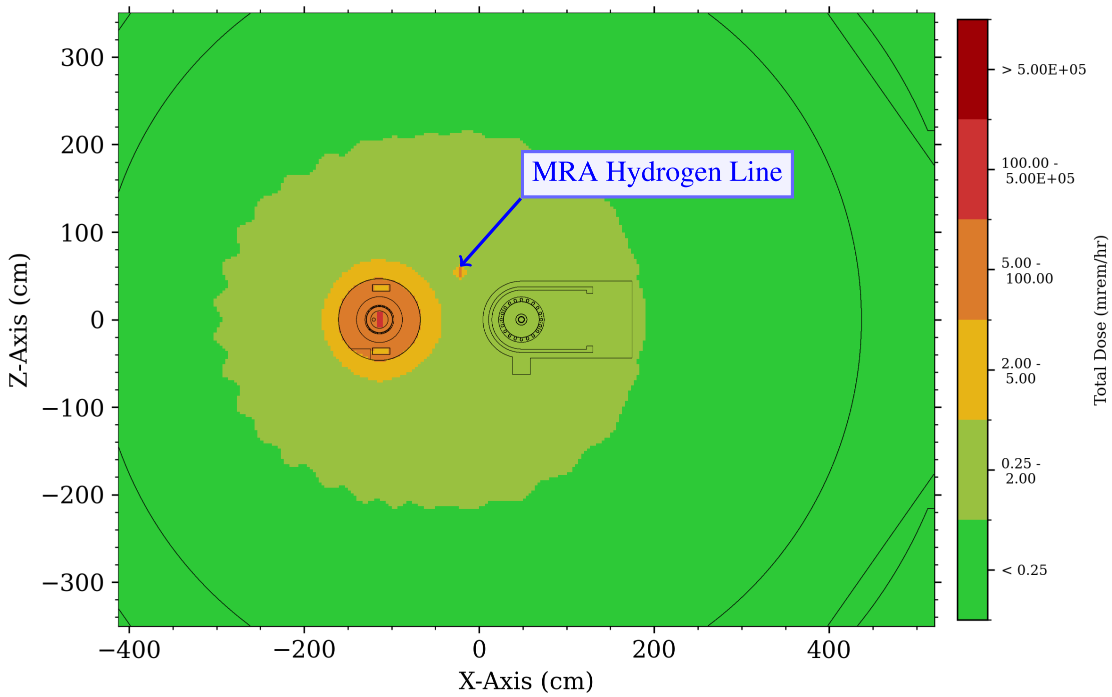

Figure 8. Plan view at 20 cm above the elevation of the target drive room floor (500 cm above beam center) of the discrete ordinates photon effective dose rate solution after 8 hours of decay in the target drive room for the nominal configuration.

5.2 TARGET SEGMENT REMOVAL CONFIGURATION DOSE RATES

The target segment removal configuration 8 hour decay effective dose rates are discussed in this section. This configuration of the STS target system has several notable differences from the nominal configuration discussed in Section 5.1: the core vessel target access removable shield block is absent, the lead gamma gate is installed, and a hatch from the target drive room to the high bay is open.

Figures 9 & 10 show the decay dose rates in a cross section view at the proton beam center without the gamma gate installed. The Monte Carlo solution to the dose rates shown in Figure 10 are in good agreement with the discrete ordinates solution shown in Figure 9. The high radiation area enters into the target drive room and up into the high bay. However, the very high radiation area remains deep within the core vessel. The radiation buffer area extends out some 3.5 m from the hatch opening in the high bay. After seeing the extents of the high radiation area, the gamma gate was designed and implemented.

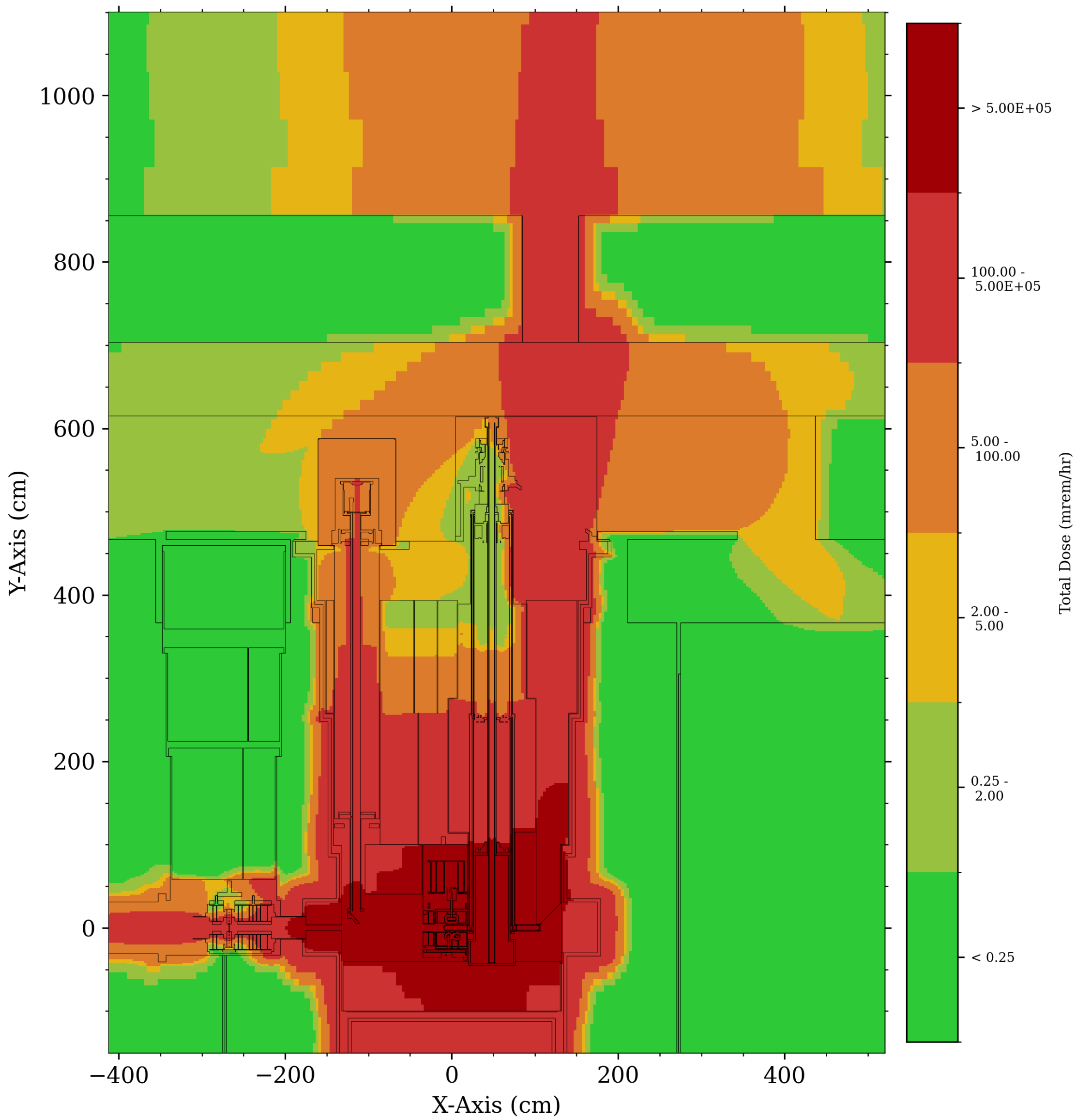

Figure 9. Cross section view of the discrete ordinates photon effective dose rate solution after 8 hours of decay in the target drive room and STS target system for the target segment removal configuration without the gamma gate.

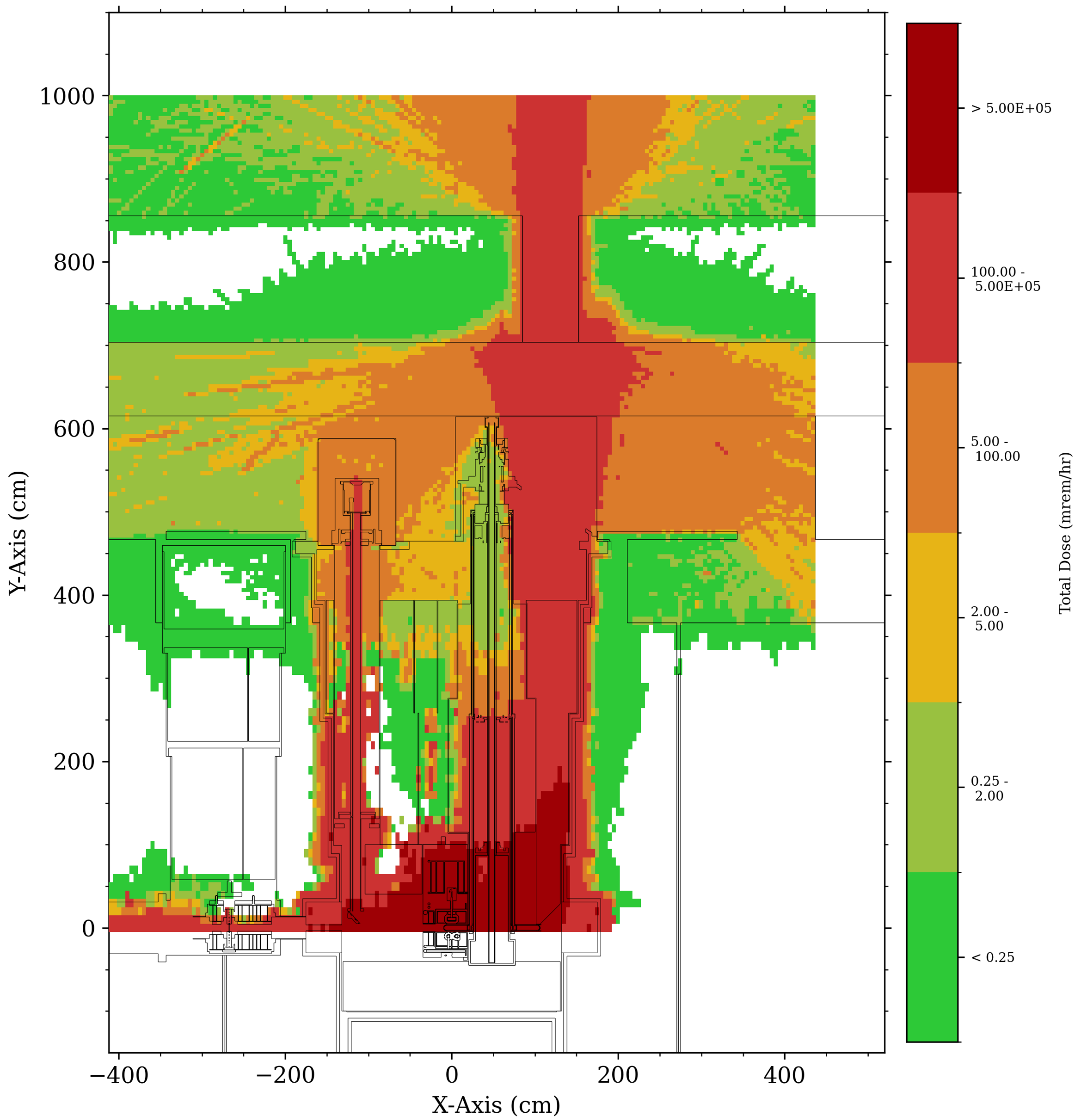

Figure 10. Cross section view of the Monte Carlo photon effective dose rate solution after 8 hours of decay in the target drive room and STS target system for the target segment removal configuration without the gamma gate.

Figures 11 & 12 show a cross section view along the proton beam of the discrete ordinates and Monte Carlo solutions respectively of the effective dose rates with the gamma gate installed, and the solutions are in good agreement. The gamma gate is 15 cm thick lead plate that is positioned directly over the opening generated by removing the target segment access core vessel shielding block. By blocking the direct line of site from the high bay to the exposed target segment foot, the high radiation areas are mostly contained below the top of the gamma gate.

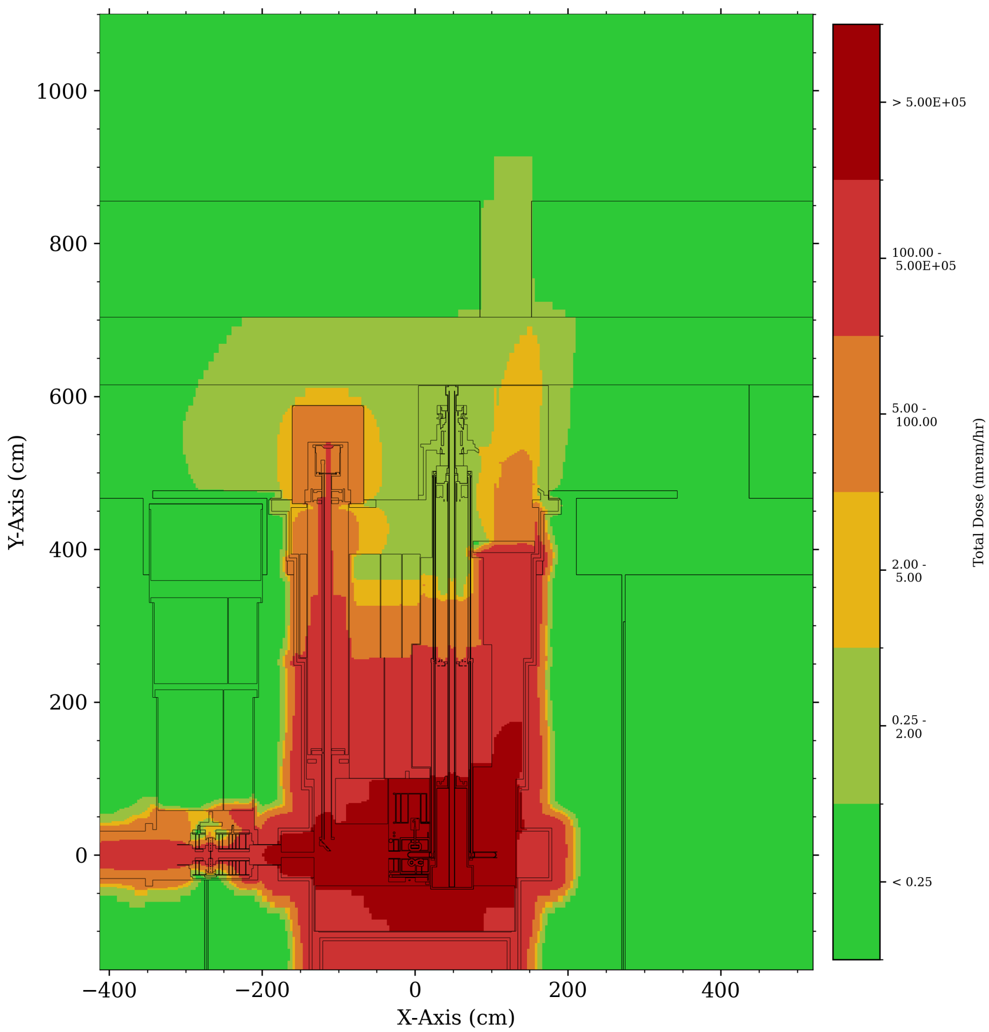

Figure 11. Cross section view of the discrete ordinates photon effective dose rate solution after 8 hours of decay in the target drive room and STS target system for the target segment removal configuration with the gamma gate.

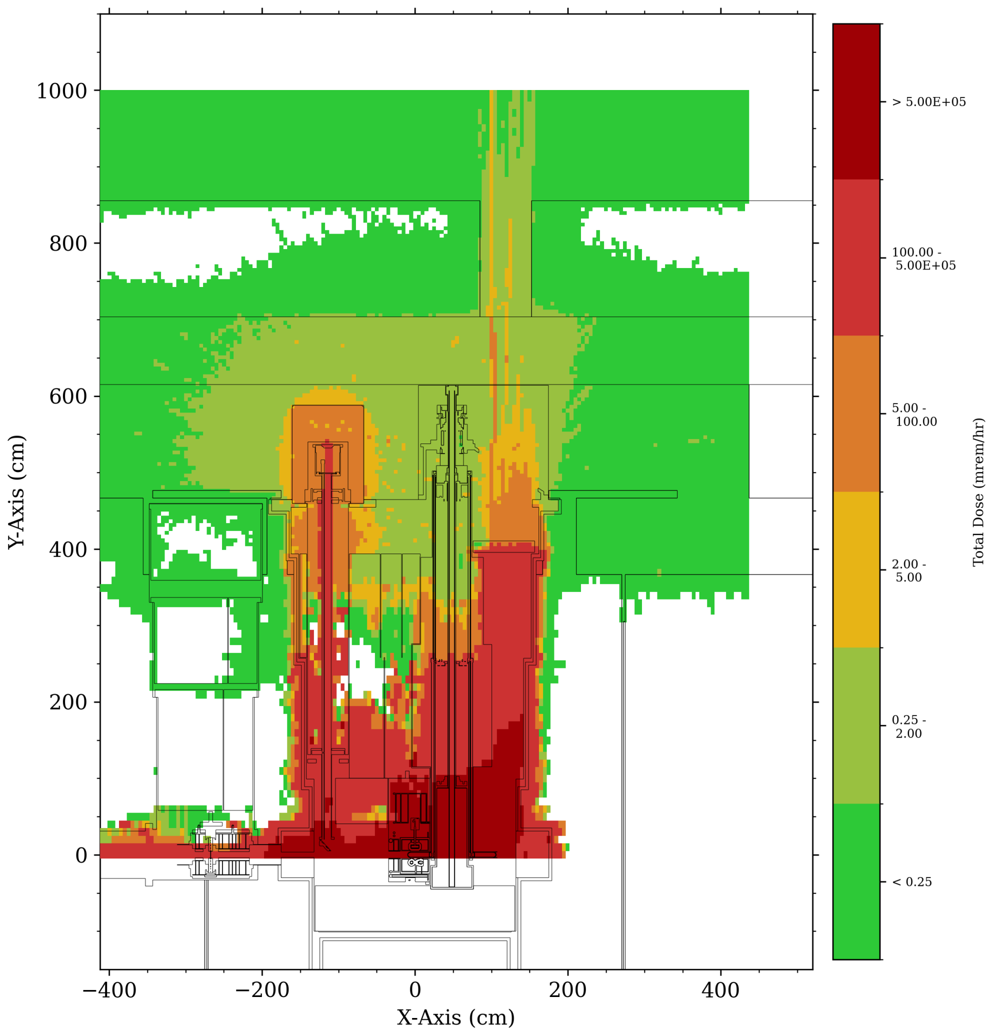

Figure 12. Cross section view of the Monte Carlo photon effective dose rate solution after 8 hours of decay in the target drive room and STS target system for the target segment removal configuration with the gamma gate.

Figure 13 shows a plan view of the discrete ordinates solution of the effective dose rates 5 cm above the top of the gamma gate. The high radiation area is shown streaming through the 5 cm gap between the gamma gate and core vessel. Supplemental shielding will have to be designed to mitigate the streaming through the 5 cm gap between the gamma gate and core vessel.

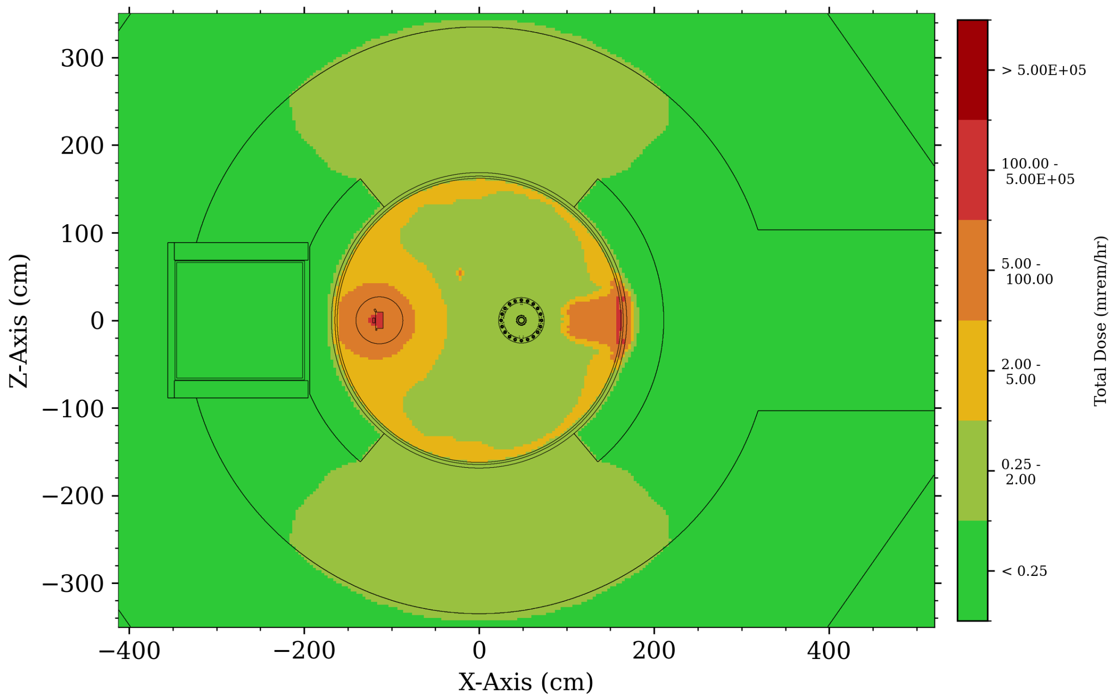

Figure 13. Plan view at an elevation of 5 cm above the gamma gate (415 cm above beam center) of the discrete ordinates photon effective dose rate solution after 8 hours of decay in the target drive room for the target segment removal configuration with the gamma gate.

Figure 14 shows a plan view of the discrete ordinates solution to the effective dose rates at the target drive room floor elevation (500 cm above beam center) with the gamma gate installed. A majority of the target drive room could be considered a controlled or generally accessible area with the gamma gate installed. There are a couple of radiation areas around the MRA hydrogen line penetration and over the gamma gate.

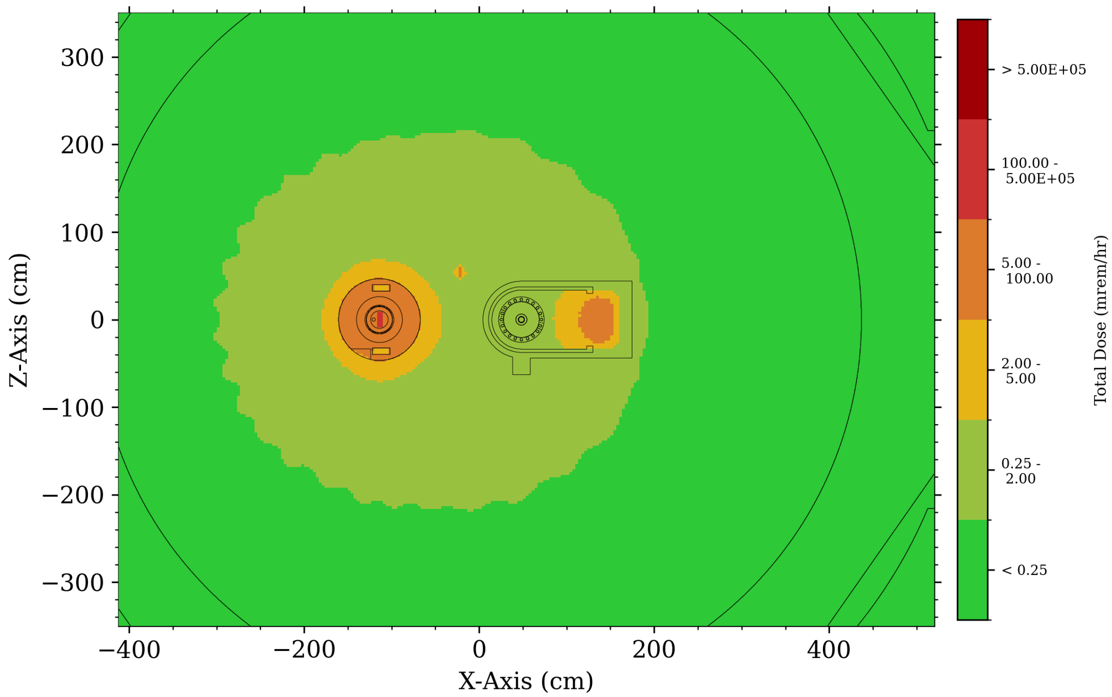

Figure 14. Plan view at the floor level of the target drive room (500 cm above beam center) of the discrete ordinates photon effective dose rate solution after 8 hours of decay in the target drive room for the target segment removal configuration with the gamma gate.

6 CONCLUSIONS

Analysis of two configurations of the STS target system have been detailed in this report. Decay gamma sources from the target assembly, MRA, TVP, and core vessel shielding are considered for all decay dose rates after 8 hours of decay. The dose rates after 8 hours of decay in the nominal configuration show that hands-on maintainability of the target drive is feasible, and that entry to the target drive room after 8 hours of decay is a reasonable expectation. With the installation of the gamma gate, dose rates in the target drive room and high bay are greatly reduced during the target segment removal procedure. The gamma gate allows for workers to enter the target drive room and perform maintenance activities on the water lines above the gamma gate all while being in a maximal dose rate field of a radiation area. Some supplemental shielding is required to mitigate streaming through the gap between the gamma gate and core vessel.

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APPENDIX A. COMPUTER HARDWARE AND SOFTWARE

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The Kryo cluster was used in this analysis. The mcnp/mcnp6.2rnucs_20230208 module was used for MCNP® and advantg/3.2.0-HILO module was used for the ADVANTG package.

APPENDIX B. LOCATION OF COMPUTATIONAL INPUT AND OUTPUT FILES

APPENDIX B. LOCATION OF COMPUTATIONAL INPUT AND OUTPUT FILES

On kryo:

/home/t25/Remote_Handling/Segment_Removal_Study

APPENDIX C. MATERIAL DEFINITION

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Table C.1. Stainless Steel 316 Material Definition [4]

Nuclide	Mass Fraction	Atom Fraction
^{12}C	7.907325e-04	3.652101e-03
^{13}C	9.267435e-06	3.950013e-05
^{28}Si	9.186648e-03	1.819917e-02
^{29}Si	4.833629e-04	9.245318e-04
^{30}Si	3.299884e-04	6.101713e-04
^{31}P	4.500000e-04	8.052171e-04
^{32}S	2.841460e-04	4.925669e-04
^{33}S	2.313622e-06	3.889095e-06
^{34}S	1.350673e-05	2.203821e-05
^{36}S	3.365101e-08	5.185460e-08
^{50}Cr	7.512636e-03	8.336537e-03
^{52}Cr	1.506589e-01	1.607618e-01
^{53}Cr	1.741246e-02	1.822910e-02
^{54}Cr	4.416056e-03	4.537609e-03
^{55}Mn	2.000000e-02	2.017675e-02
^{54}Fe	3.480204e-02	3.575949e-02
^{56}Fe	5.665270e-01	5.613476e-01
^{57}Fe	1.331759e-02	1.296396e-02
^{58}Fe	1.803390e-03	1.725266e-03
^{59}Co	2.000000e-03	1.880895e-03
^{58}Ni	9.407679e-02	8.999809e-02
^{60}Ni	3.748635e-02	3.466710e-02
^{61}Ni	1.656703e-03	1.506955e-03
^{62}Ni	5.368751e-03	4.804832e-03
^{64}Ni	1.411411e-03	1.223649e-03
^{92}Mo	4.244833e-03	2.559808e-03
^{94}Mo	2.710337e-03	1.599663e-03
^{95}Mo	4.718701e-03	2.755649e-03
^{96}Mo	5.002283e-03	2.890832e-03
^{97}Mo	2.896951e-03	1.656856e-03
^{98}Mo	7.405851e-03	4.192400e-03
^{100}Mo	3.021043e-03	1.675920e-03
Density (g/cm^3)	7.916	

Table C.2. Pure Para Hydrogen Material Definition

Nuclide	Mass Fraction	Atom Fraction
^{1}H	1.0000E+00	1.0000E+00
Density (g/cm^3)	7.29194E-02	

Table C.3. Aluminum 6061 Material Definition [5]

Nuclide	Mass Fraction	Atom Fraction
^{24}Mg	9.353999e-03	1.062335e-02
^{25}Mg	1.233612e-03	1.344898e-03
^{26}Mg	1.412390e-03	1.480733e-03
^{27}Al	9.600000e-01	9.691907e-01
^{28}Si	7.349319e-03	7.155696e-03
^{29}Si	3.866903e-04	3.635149e-04
^{30}Si	2.639908e-04	2.399121e-04
^{46}Ti	1.188014e-04	7.042324e-05
^{47}Ti	1.094667e-04	6.350896e-05
^{48}Ti	1.107676e-03	6.292850e-04
^{49}Ti	8.298286e-05	4.618057e-05
^{50}Ti	8.107320e-05	4.421726e-05
^{50}Cr	1.460790e-04	7.966940e-05
^{52}Cr	2.929478e-03	1.536345e-03
^{53}Cr	3.385756e-04	1.742092e-04
^{54}Cr	8.586775e-05	4.336436e-05
^{55}Mn	1.500000e-03	7.437428e-04
^{54}Fe	3.951891e-04	1.995730e-04
^{56}Fe	6.433107e-03	3.132870e-03
^{57}Fe	1.512258e-04	7.235163e-05
^{58}Fe	2.047811e-05	9.628674e-06
^{63}Cu	2.739168e-03	1.185683e-03
^{65}Cu	1.260832e-03	5.289705e-04
^{64}Zn	1.179404e-03	5.025373e-04
^{66}Zn	7.049062e-04	2.912589e-04
^{67}Zn	1.049306e-04	4.270755e-05
^{68}Zn	4.938952e-04	1.980664e-04
^{70}Zn	1.686429e-05	6.569592e-06
Density (g/cm^3)	2.70	

Table C.4. Water Material Definition

Nuclide	Mass Fraction	Atom Fraction
^{1}H	1.1187E-01	6.6659E-01
^{2}H	2.5714E-05	7.6667E-05
^{16}O	8.8569E-01	3.3252E-01
^{17}O	3.5858E-04	1.2667E-04
^{18}O	2.0482E-03	6.8333E-04
Density (g/cm^3)	1.0	

Table C.5. Beryllium (S-200-F) Material Definition [2]

Nuclide	Mass Fraction	Atom Fraction
^{6}Li	3.806693e-06	5.759518e-06

Table C.5 – continued from previous page

Nuclide	Mass Fraction	Atom Fraction
^{7}Li	5.405931e-05	7.012346e-05
^{9}Be	9.850000e-01	9.946928e-01
^{10}B	1.560769e-06	1.418600e-06
^{11}B	6.907430e-06	5.710042e-06
^{12}C	9.511475e-04	7.213555e-04
^{13}C	1.114751e-05	7.801985e-06
^{16}O	6.138928e-03	3.492958e-03
^{17}O	2.485293e-06	1.330557e-06
^{18}O	1.419624e-05	7.178007e-06
^{24}Mg	4.000580e-04	1.517977e-04
^{25}Mg	5.275994e-05	1.921733e-05
^{26}Mg	6.040602e-05	2.115828e-05
^{27}Al	6.415300e-04	2.163879e-04
^{28}Si	3.536106e-04	1.150292e-04
^{29}Si	1.860551e-05	5.843572e-06
^{30}Si	1.270185e-05	3.856633e-06
^{54}Fe	4.708333e-05	7.944053e-06
^{56}Fe	7.664486e-04	1.247046e-04
^{57}Fe	1.801724e-05	2.879974e-06
^{58}Fe	2.439788e-06	3.832717e-07
^{103}Rh	2.729070e-04	2.413564e-05
^{107}Ag	1.912303e-04	1.627950e-05
^{109}Ag	1.809856e-04	1.512446e-05
^{106}Cd	3.142915e-07	2.700803e-08
^{108}Cd	2.279967e-07	1.922972e-08
^{110}Cd	3.258909e-06	2.698642e-07
^{111}Cd	3.370219e-06	2.765622e-07
^{112}Cd	6.410594e-06	5.213630e-07
^{113}Cd	3.275535e-06	2.640305e-07
^{114}Cd	7.769129e-06	6.207526e-07
^{116}Cd	2.061025e-06	1.618321e-07
^{113}In	4.102730e-06	3.307091e-07
^{115}In	9.315327e-05	7.378127e-06
^{142}Nd	4.605641e-04	2.953703e-05
^{143}Nd	2.080353e-04	1.324822e-05
^{144}Nd	4.086799e-04	2.584490e-05
^{145}Nd	1.435157e-04	9.013136e-06
^{146}Nd	2.994594e-04	1.867782e-05
^{148}Nd	1.006023e-04	6.189744e-06
^{150}Nd	1.001764e-04	6.081152e-06
^{144}Sm	4.712410e-07	2.980086e-08
^{147}Sm	2.348958e-06	1.455097e-07
^{148}Sm	1.773314e-06	1.091080e-07

Table C.5 – continued from previous page

Nuclide	Mass Fraction	Atom Fraction
^{149}Sm	2.195132e-06	1.341524e-07
^{150}Sm	1.180092e-06	7.163855e-08
^{152}Sm	4.334566e-06	2.596655e-07
^{154}Sm	3.734998e-06	2.208370e-07
^{151}Eu	9.473295e-06	5.712647e-07
^{153}Eu	1.047830e-05	6.235998e-07
^{152}Gd	3.966575e-09	2.376206e-10
^{154}Gd	4.380516e-08	2.590064e-09
^{155}Gd	2.993283e-07	1.758392e-08
^{156}Gd	4.166744e-07	2.432046e-08
^{157}Gd	3.206084e-07	1.859381e-08
^{158}Gd	5.121195e-07	2.951247e-08
^{160}Gd	4.563976e-07	2.597193e-08
^{156}Dy	5.518974e-08	3.221271e-09
^{158}Dy	9.482643e-08	5.464657e-09
^{160}Dy	2.354198e-06	1.339704e-07
^{161}Dy	1.921296e-05	1.086546e-06
^{162}Dy	2.607291e-05	1.465391e-06
^{163}Dy	2.563798e-05	1.432085e-06
^{164}Dy	2.928094e-05	1.625592e-06
^{162}Er	8.228192e-07	4.624482e-08
^{164}Er	9.594299e-06	5.326472e-07
^{166}Er	2.032240e-04	1.114633e-05
^{167}Er	1.395573e-04	7.608438e-06
^{168}Er	1.656188e-04	8.975488e-06
^{170}Er	9.262479e-05	4.960506e-06
^{169}Tm	2.815680e-04	1.516870e-05
^{175}Lu	7.231065e-04	3.761785e-05
^{176}Lu	1.933653e-05	1.000208e-06
^{174}Hf	3.771174e-07	1.973148e-08
^{176}Hf	1.254038e-05	6.486725e-07
^{177}Hf	4.459682e-05	2.293785e-06
^{178}Hf	6.577850e-05	3.364218e-06
^{179}Hf	3.302597e-05	1.679642e-06
^{180}Hf	8.553820e-05	4.326127e-06
^{191}Ir	8.788808e-05	4.188601e-06
^{193}Ir	1.492859e-04	7.040892e-06
^{197}Au	3.408450e-04	1.574879e-05
^{196}Hg	4.745460e-07	2.203843e-08
^{198}Hg	3.186355e-05	1.464821e-06
^{199}Hg	5.418832e-05	2.478589e-06
^{200}Hg	7.457271e-05	3.393919e-06
^{201}Hg	4.276161e-05	1.936444e-06

Table C.5 – continued from previous page

Nuclide	Mass Fraction	Atom Fraction
^{202}Hg	9.736094e-05	4.387117e-06
^{204}Hg	2.262232e-05	1.009360e-06
^{234}U	1.703111e-09	6.622679e-11
^{235}U	2.281813e-07	8.835145e-09
^{238}U	3.184661e-05	1.217521e-06
Density (g/cm^3)	1.82922	

Table C.6. HD Concrete

Nuclide	Mass Fraction	Atom Fraction
^{1}H	3.772602e-03	1.015099e-01
^{16}O	3.240859e-01	5.494532e-01
^{23}Na	1.003297e-04	1.183444e-04
^{24}Mg	1.626067e-03	1.838444e-03
^{25}Mg	2.144469e-04	2.327439e-04
^{26}Mg	2.455250e-04	2.562511e-04
^{27}Al	5.396886e-03	5.424117e-03
^{28}Si	1.810028e-02	1.754437e-02
^{29}Si	9.523608e-04	8.912677e-04
^{30}Si	6.501700e-04	5.882176e-04
^{32}S	1.069726e-03	9.073068e-04
^{39}K	1.850072e-04	1.287600e-04
^{40}K	2.380656e-08	1.615401e-08
^{41}K	1.403619e-05	9.292281e-06
^{40}Ca	4.353449e-02	2.954148e-02
^{42}Ca	3.050688e-04	1.971647e-04
^{43}Ca	6.517153e-05	4.113946e-05
^{44}Ca	1.030385e-03	6.356808e-04
^{46}Ca	2.065631e-06	1.218947e-06
^{48}Ca	1.007687e-04	5.698577e-05
^{55}Mn	8.791030e-04	4.339293e-04
^{54}Fe	3.187682e-02	1.602580e-02
^{56}Fe	5.513945e-01	2.673202e-01
^{57}Fe	1.275490e-02	6.075011e-03
^{58}Fe	1.643375e-03	7.692384e-04
Density (g/cm^3)	3.84	

Table C.7. Ordinary Concrete

Nuclide	Mass Fraction	Atom Fraction
^{1}H	5.557053e-03	1.035669e-01
^{2}H	1.666089e-06	1.553741e-05
^{16}O	4.980096e-01	5.848136e-01
^{23}Na	1.710377e-02	1.397394e-02
^{24}Mg	1.999861e-03	1.566105e-03
^{25}Mg	2.637431e-04	1.982663e-04
^{26}Mg	3.019652e-04	2.182912e-04
^{27}Al	4.575257e-02	3.185007e-02
^{28}Si	2.895043e-01	1.943644e-01
^{29}Si	1.523250e-02	9.873861e-03
^{30}Si	1.039912e-02	6.516538e-03
^{32}S	1.279087e-03	7.514345e-04
^{39}K	1.788267e-02	8.620528e-03
^{40}K	2.301126e-06	1.081516e-06
^{41}K	1.356728e-03	6.221215e-04
^{40}Ca	8.018412e-02	3.768742e-02
^{42}Ca	5.618918e-04	2.515320e-04
^{43}Ca	1.200364e-04	5.248349e-05
^{44}Ca	1.897818e-03	8.109671e-04
^{46}Ca	3.804588e-06	1.555066e-06
^{48}Ca	1.856010e-04	7.269935e-05
^{54}Fe	7.066441e-04	2.460677e-04
^{56}Fe	1.139171e-02	3.825316e-03
^{57}Fe	2.654869e-04	8.758354e-05
^{58}Fe	3.601865e-05	1.167780e-05
Density (g/cm^3)	2.339	

Table C.8. Air

Nuclide	Mass Fraction	Atom Fraction
^{1}H	1.827995e-03	2.578500e-02
^{2}H	5.478753e-07	3.867032e-06
^{4}He	6.799543e-07	2.414986e-06
^{12}C	1.210184e-04	1.433665e-04
^{13}C	1.418344e-06	1.550613e-06
^{14}N	7.403705e-01	7.516284e-01
^{15}N	2.914111e-03	2.761781e-03
^{16}O	2.419992e-01	2.150847e-01
^{17}O	9.795671e-05	8.191905e-05
^{36}Ar	3.836730e-05	1.516449e-05
^{38}Ar	7.605713e-06	2.848131e-06
^{40}Ar	1.261762e-02	4.488523e-03
^{78}Kr	9.265869e-09	1.690490e-09
^{80}Kr	6.109216e-08	1.086744e-08
^{82}Kr	3.228267e-07	5.602623e-08
^{84}Kr	1.624868e-06	2.752796e-07
^{86}Kr	5.049375e-07	8.355420e-08
^{124}Xe	3.606639e-10	4.137978e-11
^{126}Xe	3.426133e-10	3.868487e-11
^{128}Xe	7.470250e-09	8.302904e-10
^{129}Xe	1.040535e-07	1.147533e-08
^{130}Xe	1.616947e-08	1.769507e-09
^{131}Xe	8.498247e-08	9.228908e-09
^{132}Xe	1.085234e-07	1.169613e-08
^{134}Xe	4.272612e-08	4.535997e-09
^{136}Xe	3.680591e-08	3.849927e-09
Density (g/cm^{3})	0.00121	

Table C.9. STS Inconel Material Definition

Nuclide	Mass Fraction	Atom Fraction
^{10}B	1.105857e-05	6.359251e-05
^{11}B	4.894143e-05	2.559678e-04
^{12}C	7.907325e-04	3.794172e-03
^{13}C	9.267435e-06	4.103673e-05
^{27}Al	8.000000e-03	1.707230e-02
^{28}Si	3.215327e-03	6.617498e-03
^{29}Si	1.691770e-04	3.361740e-04
^{30}Si	1.154960e-04	2.218677e-04
^{31}P	1.500000e-04	2.788470e-04
^{32}S	1.420730e-04	2.558642e-04
^{33}S	1.156811e-06	2.020193e-06
^{34}S	6.753363e-06	1.144776e-05
^{36}S	1.682550e-08	2.693591e-08
^{46}Ti	9.108109e-04	1.141265e-03
^{47}Ti	8.392450e-04	1.029214e-03
^{48}Ti	8.492181e-03	1.019807e-02
^{49}Ti	6.362019e-04	7.483932e-04
^{50}Ti	6.215612e-04	7.165761e-04
^{50}Cr	8.764741e-03	1.010431e-02
^{52}Cr	1.757687e-01	1.948516e-01
^{53}Cr	2.031453e-02	2.209460e-02
^{54}Cr	5.152065e-03	5.499814e-03
^{55}Mn	3.500000e-03	3.668289e-03
^{54}Fe	6.709181e-03	7.161935e-03
^{56}Fe	1.092158e-01	1.124271e-01
^{57}Fe	2.567382e-03	2.596431e-03
^{58}Fe	3.476597e-04	3.455373e-04
^{59}Co	2.500000e-03	2.442579e-03
^{58}Ni	3.695874e-01	3.673180e-01
^{60}Ni	1.472678e-01	1.414902e-01
^{61}Ni	6.508475e-03	6.150483e-03
^{62}Ni	2.109152e-02	1.961043e-02
^{64}Ni	5.544827e-03	4.994198e-03
^{63}Cu	2.054376e-03	1.879722e-03
^{65}Cu	9.456241e-04	8.386034e-04
^{93}Nb	5.450000e-02	3.377689e-02
^{92}Mo	4.669317e-03	2.925326e-03
^{94}Mo	2.981370e-03	1.828081e-03
^{95}Mo	5.190572e-03	3.149132e-03
^{96}Mo	5.502512e-03	3.303618e-03
^{97}Mo	3.186646e-03	1.893441e-03
^{98}Mo	8.146436e-03	4.791038e-03
^{100}Mo	3.323147e-03	1.915227e-03
^{180}Ta	5.966828e-08	1.909266e-08
^{181}Ta	4.999404e-04	1.590864e-04
Density (g/cm^3)	8.19	

Table C.10. Barium Fluoride

Nuclide	Mass Fraction	Atom Fraction
^{19}F	2.167279e-01	6.666721e-01
^{130}Ba	7.854040e-04	3.533275e-04
^{132}Ba	7.598710e-04	3.366612e-04
^{134}Ba	1.845988e-02	8.056536e-03
^{135}Ba	5.072296e-02	2.197298e-02
^{136}Ba	6.088104e-02	2.617958e-02
^{137}Ba	8.770738e-02	3.743939e-02
^{138}Ba	5.639556e-01	2.389895e-01
Density (g/cm^3)	4.89	

Table C.11. Steel A36 [6]

Nuclide	Mass Fraction	Atom Fraction
^{12}C	2.569881e-03	1.179344e-02
^{13}C	3.011916e-05	1.275546e-04
^{28}Si	3.674660e-03	7.233124e-03
^{29}Si	1.933452e-04	3.674483e-04
^{30}Si	1.319954e-04	2.425080e-04
^{31}P	4.000000e-04	7.111723e-04
^{32}S	4.735767e-04	8.156960e-04
^{33}S	3.856036e-06	6.440383e-06
^{34}S	2.251121e-05	3.649550e-05
^{36}S	5.608502e-08	8.587178e-08
^{55}Mn	1.200000e-02	1.202865e-02
^{54}Fe	5.524179e-02	5.639865e-02
^{56}Fe	8.992565e-01	8.853382e-01
^{57}Fe	2.113921e-02	2.044632e-02
^{58}Fe	2.862547e-03	2.721030e-03
^{63}Cu	1.369584e-03	1.198512e-03
^{65}Cu	6.304161e-04	5.346942e-04
Density (g/cm^3)	7.85	

Table C.12. Copper Material Definition [1]

Nuclide	Mass Fraction	Atom Fraction
^{16}O	4.986487e-06	1.981047e-05
^{17}O	2.018737e-09	7.546317e-09
^{18}O	1.153123e-08	4.071039e-08
^{31}P	3.000023e-06	6.154781e-06
^{32}S	1.420741e-05	2.823749e-05
^{33}S	1.156819e-07	2.229510e-07
^{34}S	6.753414e-07	1.263389e-06
^{36}S	1.682563e-09	2.972680e-09
^{55}Mn	5.000038e-07	5.783385e-07
^{54}Fe	5.645601e-07	6.650960e-07
^{56}Fe	9.190222e-06	1.044059e-05
^{57}Fe	2.160385e-07	2.411186e-07
^{58}Fe	2.925466e-08	3.208846e-08
^{58}Ni	6.719821e-06	7.370486e-06
^{60}Ni	2.677616e-06	2.839098e-06
^{61}Ni	1.183368e-07	1.234136e-07
^{62}Ni	3.834851e-07	3.934966e-07
^{64}Ni	1.008158e-07	1.002120e-07
^{63}Cu	6.847286e-01	6.914257e-01
^{65}Cu	3.151789e-01	3.084669e-01
^{64}Zn	4.717650e-07	4.689309e-07

Table C.12 – continued from previous page

Nuclide	Mass Fraction	Atom Fraction
^{66}Zn	2.819646e-07	2.717814e-07
^{67}Zn	4.197255e-08	3.985155e-08
^{68}Zn	1.975596e-07	1.848210e-07
^{70}Zn	6.745768e-09	6.130260e-09
^{75}As	5.000037e-06	4.240804e-06
^{74}Se	2.499696e-08	2.148784e-08
^{76}Se	2.702788e-07	2.262259e-07
^{77}Se	2.229893e-07	1.842160e-07
^{78}Se	7.036941e-07	5.738943e-07
^{80}Se	1.506352e-06	1.197766e-06
^{82}Se	2.717111e-07	2.107740e-07
^{107}Ag	1.284414e-05	7.634641e-06
^{109}Ag	1.215605e-05	7.092960e-06
^{106}Cd	1.177673e-08	7.066174e-09
^{108}Cd	8.543201e-09	5.031116e-09
^{110}Cd	1.221137e-07	7.060521e-08
^{111}Cd	1.262845e-07	7.235762e-08
^{112}Cd	2.402096e-07	1.364054e-07
^{113}Cd	1.227367e-07	6.907892e-08
^{114}Cd	2.911149e-07	1.624089e-07
^{116}Cd	7.722811e-08	4.234052e-08
^{112}Sn	1.828799e-08	1.038483e-08
^{114}Sn	1.266554e-08	7.065965e-09
^{115}Sn	6.581989e-09	3.640043e-09
^{116}Sn	2.839226e-07	1.556654e-07
^{117}Sn	1.512628e-07	8.222214e-08
^{118}Sn	4.811045e-07	2.592995e-07
^{119}Sn	1.720809e-07	9.196461e-08
^{120}Sn	6.581483e-07	3.488017e-07
^{122}Sn	9.509168e-08	4.956882e-08
^{124}Sn	1.208687e-07	6.198779e-08
^{121}Sb	2.272330e-06	1.194300e-06
^{123}Sb	1.727700e-06	8.932719e-07
^{120}Te	1.691407e-09	8.963889e-10
^{122}Te	4.872218e-08	2.539768e-08
^{123}Te	1.714466e-08	8.864290e-09
^{124}Te	9.205163e-08	4.720981e-08
^{125}Te	1.384106e-07	7.041633e-08
^{126}Te	3.717834e-07	1.876441e-07
^{128}Te	6.363039e-07	3.161265e-07
^{130}Te	6.939073e-07	3.394326e-07
^{204}Pb	6.890471e-08	2.146635e-08
^{206}Pb	1.197784e-06	3.695278e-07

Table C.12 – continued from previous page

Nuclide	Mass Fraction	Atom Fraction
^{207}Pb	1.103723e-06	3.388616e-07
^{208}Pb	2.629626e-06	8.034546e-07
^{209}Bi	1.000008e-06	3.040743e-07
Density (g/cm^3)	8.93	

Table C.13. Invar

Nuclide	Mass Fraction	Atom Fraction
^{12}C	1.976896e-04	9.338288e-04
^{13}C	2.316934e-06	1.010004e-05
^{28}Si	1.837511e-03	3.723014e-03
^{29}Si	9.657200e-05	1.889166e-04
^{30}Si	6.595600e-05	1.247320e-04
^{55}Mn	3.500082e-03	3.611352e-03
^{54}Fe	3.571855e-02	3.753624e-02
^{56}Fe	5.809240e-01	5.887094e-01
^{57}Fe	1.366307e-02	1.360288e-02
^{58}Fe	1.836184e-03	1.796606e-03
^{58}Ni	2.433729e-01	2.381186e-01
^{60}Ni	9.695980e-02	9.170785e-02
^{61}Ni	4.286004e-03	3.987298e-03
^{62}Ni	1.387092e-02	1.269640e-02
^{64}Ni	3.668452e-03	3.252795e-03
Density (g/cm^3)	8.05	

Table C.14. Lead

Nuclide	Mass Fraction	Atom Fraction
^{204}Pb	1.378084e-02	1.400000e-02
^{206}Pb	2.395550e-01	2.410000e-01
^{207}Pb	2.207430e-01	2.210000e-01
^{208}Pb	5.259212e-01	5.240000e-01
Density (g/cm^3)	11.34	

Table C.15. Stainless Steel 304 [4]

Nuclide	Mass Fraction	Atom Fraction
^{12}C	7.815745e-04	3.555325e-03
^{13}C	9.160102e-06	3.845343e-05
^{28}Si	9.186654e-03	1.792452e-02
^{29}Si	4.833628e-04	9.105788e-04
^{30}Si	3.299919e-04	6.009690e-04
^{31}P	4.500026e-04	7.930695e-04
^{32}S	2.841517e-04	4.851428e-04
^{33}S	2.313613e-06	3.830388e-06
^{34}S	1.350708e-05	2.170618e-05
^{36}S	3.365119e-08	5.107230e-08
^{50}Cr	8.347449e-03	9.123108e-03
^{52}Cr	1.674010e-01	1.759308e-01
^{53}Cr	1.934711e-02	1.994881e-02
^{54}Cr	4.906728e-03	4.965697e-03
^{55}Mn	2.000012e-02	1.987236e-02
^{54}Fe	3.706021e-02	3.750510e-02
^{56}Fe	6.032935e-01	5.887564e-01
^{57}Fe	1.418208e-02	1.359715e-02
^{58}Fe	1.920411e-03	1.809490e-03
^{59}Co	2.000012e-03	1.852519e-03
^{58}Ni	7.391743e-02	6.964556e-02
^{60}Ni	2.945417e-02	2.682792e-02
^{61}Ni	1.301708e-03	1.166178e-03
^{62}Ni	4.218324e-03	3.718268e-03
^{64}Ni	1.109006e-03	9.469636e-04
Density (g/cm^3)	8.0	

Table C.16. Tungsten Material Definition Courtesy of Aaron Jacques

Nuclide	**Mass Fraction**	**Atom Fraction**
^{12}C	9.884157e-05	1.507200e-03
^{13}C	1.158429e-06	1.630146e-05
^{14}N	9.961018e-05	1.301646e-03
^{15}N	3.898162e-07	4.755300e-06
^{16}O	9.972900e-05	1.140912e-03
^{17}O	4.037444e-08	4.346025e-07
^{18}O	2.306228e-07	2.344566e-06
^{28}Si	9.186648e-05	6.008548e-04
^{29}Si	4.833629e-06	3.052389e-05
^{30}Si	3.299884e-06	2.014512e-05
^{54}Fe	5.645558e-06	1.915189e-05
^{56}Fe	9.190152e-05	3.006436e-04
^{57}Fe	2.160369e-06	6.943173e-06
^{58}Fe	2.925444e-07	9.240088e-07
^{58}Ni	6.719770e-05	2.122381e-04
^{60}Ni	2.677596e-05	8.175373e-05
^{61}Ni	1.183359e-06	3.553778e-06
^{62}Ni	3.834822e-06	1.133100e-05
^{64}Ni	1.008150e-06	2.885671e-06
^{180}W	1.173871e-03	1.193683e-03
^{182}W	2.621131e-01	2.636049e-01
^{183}W	1.423206e-01	1.423466e-01
^{184}W	3.063980e-01	3.047869e-01
^{186}W	2.873944e-01	2.828033e-01
Density (g/cm^3)	19.3	

Table C.17. Tantalum Material Definition [3]

Nuclide	Mass Fraction	Atom Fraction
^{1}H	1.499655e-05	2.668715e-03
^{2}H	3.446954e-09	3.069375e-07
^{12}C	9.884157e-05	1.477251e-03
^{13}C	1.158429e-06	1.597754e-05
^{14}N	9.961018e-05	1.275781e-03
^{15}N	3.898162e-07	4.660809e-06
^{16}O	1.495935e-04	1.677361e-03
^{17}O	6.056166e-08	6.389500e-07
^{18}O	3.459343e-07	3.446967e-06
^{28}Si	4.593324e-05	2.944577e-04
^{29}Si	2.416814e-06	1.495868e-05
^{30}Si	1.649942e-06	9.872410e-06
^{46}Ti	7.920095e-06	3.091120e-05
^{47}Ti	7.297782e-06	2.787628e-05
^{48}Ti	7.384505e-05	2.762150e-04
^{49}Ti	5.532190e-06	2.027025e-05
^{50}Ti	5.404880e-06	1.940849e-05
^{54}Fe	5.645558e-06	1.877132e-05
^{56}Fe	9.190153e-05	2.946696e-04
^{57}Fe	2.160369e-06	6.805207e-06
^{58}Fe	2.925444e-07	9.056481e-07
^{58}Ni	6.719770e-05	2.080208e-04
^{60}Ni	2.677596e-05	8.012922e-05
^{61}Ni	1.183359e-06	3.483162e-06
^{62}Ni	3.834822e-06	1.110584e-05
^{64}Ni	1.008150e-06	2.828331e-06
^{93}Nb	1.000000e-03	1.930413e-03
^{92}Mo	2.829889e-05	5.522268e-05
^{94}Mo	1.806891e-05	3.450950e-05
^{95}Mo	3.145801e-05	5.944757e-05
^{96}Mo	3.334855e-05	6.236387e-05
^{97}Mo	1.931300e-05	3.574332e-05
^{98}Mo	4.937234e-05	9.044256e-05
^{100}Mo	2.014029e-05	3.615459e-05
^{180m}Ta	1.190484e-04	1.186516e-04
^{181}Ta	9.974660e-01	9.886444e-01
^{180}W	5.872878e-07	5.853328e-07
^{182}W	1.311353e-04	1.292610e-04
^{183}W	7.120302e-05	6.980094e-05
^{184}W	1.532910e-04	1.494550e-04
^{186}W	1.437835e-04	1.386751e-04
Density (g/cm^3)	16.6	

Table C.18. Stainless Steel 420

Nuclide	Mass Fraction	Atom Fraction
^{12}C	1.482685e-03	6.727218e-03
^{13}C	1.737716e-05	7.275976e-05
^{28}Si	9.187620e-03	1.788014e-02
^{29}Si	4.828610e-04	9.072860e-04
^{30}Si	3.297850e-04	5.990422e-04
^{31}P	4.000120e-04	7.031484e-04
^{32}S	2.842330e-04	4.840293e-04
^{33}S	2.313600e-06	3.820481e-06
^{34}S	1.337900e-05	2.144486e-05
^{36}S	6.730100e-08	1.018789e-07
^{50}Cr	5.431669e-03	5.921069e-03
^{52}Cr	1.088031e-01	1.140520e-01
^{53}Cr	1.257349e-02	1.293107e-02
^{54}Cr	3.195900e-03	3.225961e-03
^{55}Mn	1.000031e-02	9.910785e-03
^{54}Fe	4.790382e-02	4.835376e-02
^{56}Fe	7.791046e-01	7.583689e-01
^{57}Fe	1.832419e-02	1.752307e-02
^{58}Fe	2.462593e-03	2.314368e-03
Density (g/cm^3)	7.8	

Table C.19. 80% Copper 20% Water Mixture

Nuclide	Mass Fraction	Atom Fraction
^{1}H	3.046501e-03	1.523370e-01
^{2}H	7.002440e-07	1.752093e-05
^{16}O	2.412514e-02	7.601112e-02
^{17}O	9.766866e-06	2.895461e-05
^{18}O	5.578925e-05	1.562023e-04
^{31}P	2.918294e-06	4.748147e-06
^{32}S	1.382007e-05	2.178354e-05
^{33}S	1.125294e-07	1.719955e-07
^{34}S	6.569468e-07	9.746554e-07
^{36}S	1.636774e-09	2.293363e-09
^{55}Mn	4.863822e-07	4.461631e-07
^{54}Fe	5.491839e-07	5.130966e-07
^{56}Fe	8.939901e-06	8.054502e-06
^{57}Fe	2.101561e-07	1.860154e-07
^{58}Fe	2.845822e-08	2.475534e-08
^{58}Ni	6.536784e-06	5.686037e-06
^{60}Ni	2.604674e-06	2.190245e-06
^{61}Ni	1.151169e-07	9.521156e-08
^{62}Ni	3.730455e-07	3.035718e-07
^{64}Ni	9.807412e-08	7.731303e-08
^{63}Cu	6.660810e-01	5.334101e-01
^{65}Cu	3.065960e-01	2.379715e-01
^{64}Zn	4.589211e-07	3.617665e-07
^{66}Zn	2.742807e-07	2.096657e-07
^{67}Zn	4.082985e-08	3.074431e-08
^{68}Zn	1.921794e-07	1.425828e-07
^{70}Zn	6.562074e-09	4.729289e-09
^{75}As	4.863822e-06	3.271597e-06
^{74}Se	2.431620e-08	1.657709e-08
^{76}Se	2.629188e-07	1.745256e-07
^{77}Se	2.169169e-07	1.421162e-07
^{78}Se	6.845247e-07	4.427355e-07
^{80}Se	1.465372e-06	9.240610e-07
^{82}Se	2.643100e-07	1.626036e-07
^{107}Ag	1.249419e-05	5.889776e-06
^{109}Ag	1.182493e-05	5.471933e-06
^{106}Cd	1.145625e-08	5.451414e-09
^{108}Cd	8.310522e-09	3.881318e-09
^{110}Cd	1.187843e-07	5.446763e-08
^{111}Cd	1.228407e-07	5.581920e-08
^{112}Cd	2.336678e-07	1.052318e-07
^{113}Cd	1.193971e-07	5.329323e-08

Table C.19 – continued from previous page

Nuclide	Mass Fraction	Atom Fraction
^{114}Cd	2.831815e-07	1.252903e-07
^{116}Cd	7.512467e-08	3.266408e-08
^{112}Sn	1.778992e-08	8.011509e-09
^{114}Sn	1.232104e-08	5.451325e-09
^{115}Sn	6.402737e-09	2.808162e-09
^{116}Sn	2.761874e-07	1.200889e-07
^{117}Sn	1.471404e-07	6.343012e-08
^{118}Sn	4.679969e-07	2.000380e-07
^{119}Sn	1.673933e-07	7.094688e-08
^{120}Sn	6.402249e-07	2.690882e-07
^{122}Sn	9.250214e-08	3.824062e-08
^{124}Sn	1.175781e-07	4.782177e-08
^{121}Sb	2.210413e-06	9.213456e-07
^{123}Sb	1.680645e-06	6.891258e-07
^{120}Te	1.645334e-09	6.915275e-10
^{122}Te	4.739503e-08	1.959329e-08
^{123}Te	1.667805e-08	6.838604e-09
^{124}Te	8.954493e-08	3.642076e-08
^{125}Te	1.346404e-07	5.432336e-08
^{126}Te	3.616546e-07	1.447591e-07
^{128}Te	6.189702e-07	2.438783e-07
^{130}Te	6.750111e-07	2.618606e-07
^{204}Pb	6.702836e-08	1.656056e-08
^{206}Pb	1.165177e-06	2.850807e-07
^{207}Pb	1.073640e-06	2.614136e-07
^{208}Pb	2.557982e-06	6.198292e-07
^{209}Bi	9.727646e-07	2.345802e-07
Density (g/cm^3)	7.344	

Table C.20. Polyether Ether Ketone

Nuclide	Mass Fraction	Atom Fraction
^{1}H	4.904209e-02	3.912361e-01
^{2}H	1.127265e-05	4.499867e-05
^{12}C	7.750117e-01	5.192568e-01
^{13}C	9.083185e-03	5.616140e-03
^{16}O	1.663996e-01	8.364222e-02
^{17}O	6.736542e-05	3.186145e-05
^{18}O	3.847979e-04	1.718841e-04
Density (g/cm^3)	1.3	

Table C.21. 83% Stainless Steel 316 and 17% Water Mixture

Nuclide	Mass Fraction	Atom Fraction
^{1}H	2.792594e-03	1.275902e-01
^{2}H	6.418830e-07	1.467469e-05
^{12}C	2.860249e-04	1.097532e-03
^{13}C	3.352230e-06	1.187061e-05
^{16}O	2.211002e-02	6.365050e-02
^{17}O	8.951058e-06	2.424612e-05
^{18}O	5.112930e-05	1.308013e-04
^{28}Si	8.957287e-03	1.474250e-02
^{29}Si	4.712949e-04	7.489304e-04
^{30}Si	3.217530e-04	4.942832e-04
^{31}P	4.387675e-04	6.522815e-04
^{32}S	2.770573e-04	3.990188e-04
^{33}S	2.255849e-08	3.150406e-08
^{34}S	1.316985e-05	1.785283e-05
^{36}S	3.281103e-08	4.200580e-08
^{50}Cr	7.325077e-03	6.753139e-03
^{52}Cr	1.468993e-01	1.302292e-01
^{53}Cr	1.697738e-02	1.476645e-02
^{54}Cr	4.305869e-03	3.675813e-03
^{55}Mn	1.950077e-02	1.634456e-02
^{54}Fe	3.396059e-02	2.899093e-02
^{56}Fe	5.528371e-01	4.551019e-01
^{57}Fe	1.299532e-02	1.050991e-02
^{58}Fe	1.759848e-03	1.398755e-03
^{59}Co	1.950078e-03	1.523655e-03
^{58}Ni	9.172873e-02	7.290485e-02
^{60}Ni	3.655030e-02	2.808249e-02
^{61}Ni	1.615347e-03	1.220736e-03
^{62}Ni	5.234787e-03	3.892281e-03
^{64}Ni	1.376170e-03	9.912329e-04
^{92}Mo	4.138844e-03	2.073605e-03
^{94}Mo	2.642647e-03	1.295820e-03
^{95}Mo	4.600916e-03	2.232266e-03
^{96}Mo	4.877436e-03	2.341781e-03
^{97}Mo	2.824688e-03	1.342191e-03
^{98}Mo	7.221039e-03	3.396156e-03
^{100}Mo	2.945593e-03	1.357592e-03
Density (g/cm^3)	6.81	

Table C.22. 96% Steel 316 and 4% Water Mixture

Nuclide	Mass Fraction	Atom Fraction
^{1}H	5.798757e-04	3.063870e-02
^{2}H	1.332841e-07	3.523851e-06
^{12}C	2.914008e-04	1.293094e-03
^{13}C	3.415236e-06	1.398575e-05
^{16}O	4.589584e-03	1.527960e-02
^{17}O	1.858059e-06	5.820405e-06
^{28}Si	9.139002e-03	1.739479e-02
^{29}Si	4.808566e-04	8.836703e-04
^{30}Si	3.282775e-04	5.832036e-04
^{31}P	4.480065e-04	7.702131e-04
^{32}S	2.822557e-04	4.701024e-04
^{33}S	2.298232e-06	3.711729e-06
^{34}S	1.341690e-05	2.103316e-05
^{36}S	3.342720e-08	4.948976e-08
^{50}Cr	7.473811e-03	7.968224e-03
^{52}Cr	1.498800e-01	1.536590e-01
^{53}Cr	1.732244e-02	1.742369e-02
^{54}Cr	4.393227e-03	4.337128e-03
^{55}Mn	1.989628e-02	1.928498e-02
^{54}Fe	3.465039e-02	3.420746e-02
^{56}Fe	5.640577e-01	5.369835e-01
^{57}Fe	1.325952e-02	1.240126e-02
^{58}Fe	1.795531e-03	1.650385e-03
^{59}Co	1.990025e-03	1.798122e-03
^{58}Ni	9.359038e-02	8.602172e-02
^{60}Ni	3.729253e-02	3.313541e-02
^{61}Ni	1.648140e-03	1.440376e-03
^{62}Ni	5.340991e-03	4.592539e-03
^{64}Ni	1.404111e-03	1.169583e-03
^{92}Mo	4.222823e-03	2.446671e-03
^{94}Mo	2.696278e-03	1.528960e-03
^{95}Mo	4.694238e-03	2.633860e-03
^{96}Mo	4.976346e-03	2.763066e-03
^{97}Mo	2.881938e-03	1.583632e-03
^{98}Mo	7.367459e-03	4.007113e-03
^{100}Mo	3.005385e-03	1.601853e-03
Density (g/cm^3)	7.71992	

Table C.23. 93% Steel 316 and 7% Water Mixture

Nuclide	Mass Fraction	Atom Fraction
^{1}H	1.042784e-03	5.335202e-02
^{2}H	2.396836e-07	6.136187e-06
^{12}C	2.904242e-04	1.247938e-03
^{13}C	3.403790e-06	1.349736e-05
^{16}O	8.255761e-03	2.661441e-02
^{17}O	3.342268e-06	1.013809e-05
^{28}Si	9.101417e-03	1.677454e-02
^{29}Si	4.788785e-04	8.521599e-04
^{30}Si	3.269269e-04	5.624072e-04
^{31}P	4.460104e-04	7.424934e-04
^{32}S	2.813107e-04	4.536878e-04
^{33}S	2.290536e-06	3.582123e-06
^{34}S	1.337194e-05	2.029868e-05
^{36}S	3.331523e-08	4.776165e-08
^{50}Cr	7.442769e-03	7.683782e-03
^{52}Cr	1.492577e-01	1.481741e-01
^{53}Cr	1.725051e-02	1.680174e-02
^{54}Cr	4.374989e-03	4.182314e-03
^{55}Mn	1.981449e-02	1.859736e-02
^{54}Fe	3.450645e-02	3.298634e-02
^{56}Fe	5.617154e-01	5.178152e-01
^{57}Fe	1.320449e-02	1.195861e-02
^{58}Fe	1.788070e-03	1.591468e-03
^{59}Co	1.981044e-03	1.733308e-03
^{58}Ni	9.320135e-02	8.295073e-02
^{60}Ni	3.713751e-02	3.195247e-02
^{61}Ni	1.641289e-03	1.388954e-03
^{62}Ni	5.318785e-03	4.428581e-03
^{64}Ni	1.398272e-03	1.127827e-03
^{92}Mo	4.205315e-03	2.359350e-03
^{94}Mo	2.685097e-03	1.474390e-03
^{95}Mo	4.674766e-03	2.539853e-03
^{96}Mo	4.955711e-03	2.664451e-03
^{97}Mo	2.869972e-03	1.527104e-03
^{98}Mo	7.336900e-03	3.864092e-03
^{100}Mo	2.992909e-03	1.544675e-03
Density (g/cm^3)	7.50986	

Table C.24. 92% Steel 316 and 8% Water Mixture

Nuclide	Mass Fraction	Atom Fraction
^{1}H	1.202755e-03	6.087004e-02
^{2}H	2.764530e-07	7.000864e-06
^{12}C	2.904249e-04	1.234424e-03
^{13}C	3.403798e-06	1.335119e-05
^{16}O	9.524379e-03	3.037152e-02
^{17}O	3.855861e-06	1.156928e-05
^{28}Si	9.087662e-03	1.656776e-02
^{29}Si	4.781546e-04	8.416552e-04
^{30}Si	3.264327e-04	5.554743e-04
^{31}P	4.450114e-04	7.328059e-04
^{32}S	2.813118e-04	4.487752e-04
^{33}S	2.290547e-06	3.543340e-06
^{34}S	1.337202e-05	2.007893e-05
^{36}S	3.331538e-08	4.724450e-08
^{50}Cr	7.432062e-03	7.589618e-03
^{52}Cr	1.490429e-01	1.463582e-01
^{53}Cr	1.722572e-02	1.659587e-02
^{54}Cr	4.368700e-03	4.131065e-03
^{55}Mn	1.978550e-02	1.836900e-02
^{54}Fe	3.445669e-02	3.258198e-02
^{56}Fe	5.609047e-01	5.114670e-01
^{57}Fe	1.318542e-02	1.181200e-02
^{58}Fe	1.785492e-03	1.571960e-03
^{59}Co	1.978048e-03	1.711941e-03
^{58}Ni	9.306723e-02	8.193415e-02
^{60}Ni	3.708410e-02	3.156090e-02
^{61}Ni	1.638918e-03	1.371925e-03
^{62}Ni	5.311139e-03	4.374314e-03
^{64}Ni	1.396260e-03	1.114005e-03
^{92}Mo	4.199231e-03	2.330418e-03
^{94}Mo	2.681233e-03	1.456321e-03
^{95}Mo	4.668011e-03	2.508711e-03
^{96}Mo	4.948548e-03	2.631781e-03
^{97}Mo	2.865835e-03	1.508385e-03
^{98}Mo	7.326311e-03	3.816721e-03
^{100}Mo	2.988586e-03	1.525736e-03
Density (g/cm^3)	7.43984	

APPENDIX D. DOSE CONVERSION FACTORS

APPENDIX D. DOSE CONVERSION FACTORS

Table D.1. Photon flux to dose conversion factors [7]

Energy (MeV)	DCF (mrem hr^{-1} (γ/cm^2/sec)$^{-1}$)
1.0000E-02	1.7466E-05
1.5000E-02	4.5153E-05
2.0000E-02	7.3786E-05
3.0000E-02	1.0798E-04
4.0000E-02	1.2170E-04
5.0000E-02	1.2861E-04
6.0000E-02	1.3608E-04
8.0000E-02	1.5838E-04
1.0000E-01	1.8618E-04
1.5000E-01	2.7084E-04
2.0000E-01	3.6147E-04
3.0000E-01	5.4300E-04
4.0000E-01	7.1850E-04
5.0000E-01	8.8764E-04
6.0000E-01	1.0469E-03
8.0000E-01	1.3417E-03
1.0000E+00	1.6140E-03
1.5000E+00	2.2104E-03
2.0000E+00	2.6963E-03
3.0000E+00	3.5587E-03
4.0000E+00	4.3255E-03
5.0000E+00	5.0405E-03
6.0000E+00	5.7554E-03
8.0000E+00	7.1709E-03
1.0000E+01	8.5536E-03
1.5000E+01	1.0080E-02
2.0000E+01	1.1880E-02
3.0000E+01	1.4760E-02
4.0000E+01	1.6920E-02
5.0000E+01	1.8720E-02
1.0000E+02	2.3760E-02
2.0000E+02	2.7720E-02
5.0000E+02	3.1680E-02
1.0000E+03	3.3480E-02
2.0000E+03	3.4560E-02
5.0000E+03	3.5640E-02
1.0000E+04	3.6360E-02