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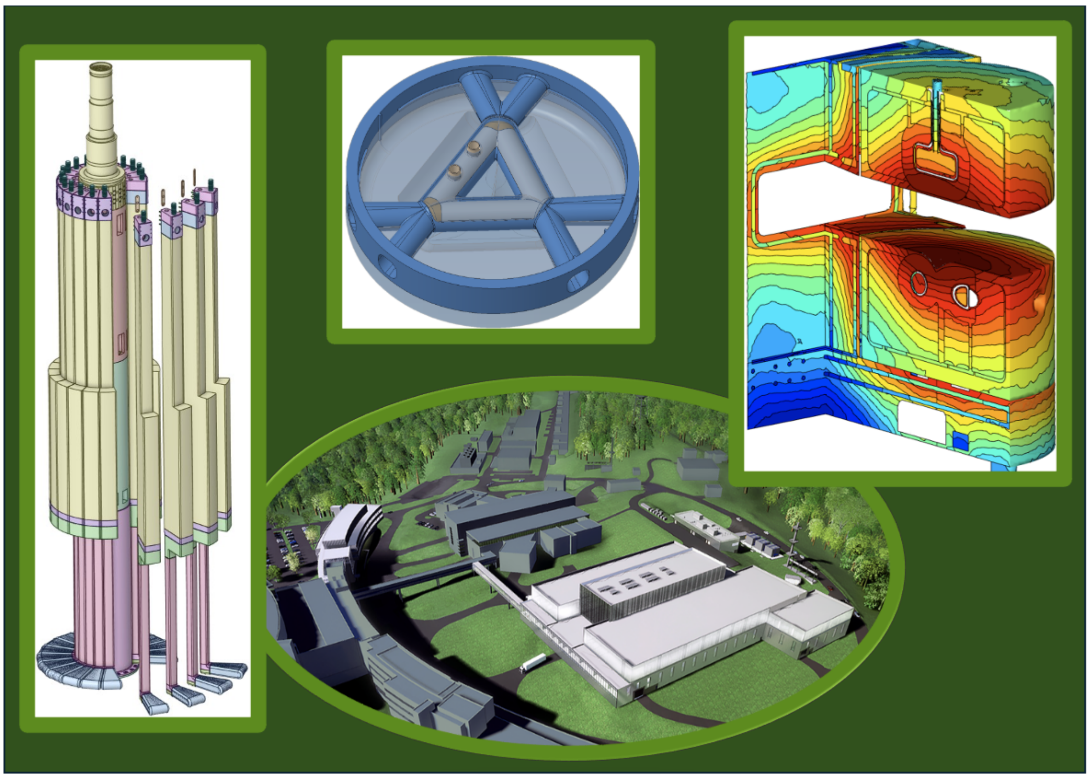
ORNL/TM-2026/4596

Oak Ridge National Laboratory Second Target Station Target Drive Room Beam-on Dose Rates



Tucker McClanahan, Ph.D.

June 2026

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OAK RIDGE National Laboratory

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Second Target Station Project

Oak Ridge National Laboratory
Second Target Station Target Drive Room Beam-on Dose Rates

Tucker McClanahan, Ph.D.

June 2026

Prepared by
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managed by
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Approvals

Second Target Station Target Drive Room Beam-on Dose Rates		ISSUE DATE: June 2026
PREPARED BY Tucker McClanahan, Ph.D.	PROJECT Second Target Station	DOCUMENT NUMBER: S03120100-TRT10017

	Signature/Date					
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STS Technical Director						
STS Target Systems Lead						
STS Neutronics Group Lead						
Lead Engineer						
Technical Reviewer						
Primary Author						

Revision	Description
00	Initial Release
01	Updated for Final Design

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ABBREVIATIONS

CAD	Computer-Aided Design
CSG	Constructive Solid Geometry
ESS	European Spallation Source
MRA	Moderator Reflector Assembly
ORNL	Oak Ridge National Laboratory
SNS	Spallation Neutron Source
STS	Second Target Station
TDR	Target Drive Room
TVP	Target Viewing Periscope

EXECUTIVE SUMMARY

This report presents an analysis of dose rate fields generated by two primary sources in the Oak Ridge National Laboratory (ORNL) Spallation Neutron Source (SNS) Second Target Station (STS): the radiation produced by the proton beam incident on the target and the activated cooling water in the target assembly's pipes. The analysis provides support for estimating the lifetime of target drive components and confirming the design of conventional facilities. Assuming the STS target system is in operational configuration with all shielding in place, the study calculates dose rate fields in the target drive room (TDR) and through the ceiling into the high bay. This report confirms that the current design of the high-density concrete ceiling in the target drive room reduces effective dose rates in the high bay to below 0.25 mrem/hr where the primary sources considered are the protons-on-target and activated loop 1 water in the target drive room. Additionally, the report provides detailed characterization of the dose field surrounding the target drive assembly, enabling accurate estimates of the deposited dose in components due to both radiation streaming and decay of activated water. This report shows satisfaction of all of the requirements evaluated in this report.

1 SCOPE

This report presents an analysis of dose rate fields generated by two primary sources in the Oak Ridge National Laboratory (ORNL) Spallation Neutron Source (SNS) Second Target Station (STS): the radiation produced by the proton beam incident on the target and the activated cooling water in the target assembly's pipes. The analysis provides support for estimating the lifetime of target drive components and confirming the design of conventional facilities. Assuming the STS target system is in operational configuration with all shielding in place, the study calculates dose rate fields in the target drive room and through the ceiling. A primary objective of this report is to confirm the required thickness of the high-density concrete ceiling in the target drive room to meet the stringent 0.25 mrem/hr dose limit in the high bay above. Additionally, the report provides detailed characterization of the dose field surrounding the target drive assembly, enabling accurate estimates of the deposited dose in components due to both radiation streaming and decay of activated water. The analysis reveals that prompt neutrons and gammas generated by the proton beam primarily stream through gaps between the target assembly and core vessel shielding. Based on the STS final design, this report provides a robust foundation for ensuring the safe and efficient operation of the target system.

2 ACCEPTANCE CRITERIA

The requirements evaluated in this report are as follows:

1. Effective dose rates in the high bay above the target drive room shall be less than 5 mrem/hr during beam-on-target operation [1].
2. Requirement S.03.02.02-10978 - Material Radiation Damage [2]:
   - "The accumulated radiation dose (or damage) for each component and its constituent materials, evaluated at that component's end of life (i.e., at the planned replacement or retirement point), shall not exceed the applicable limits specified in the STS Materials Handbook (S03010300-TDO10000) or in manufacturer-published radiation tolerance data. Note: Dose/damage limits may be expressed in different units (e.g., Gy, rad, DPA). Where DPA is used, DPA-NRT shall be applied."
3. Requirement S.03.02.03-2301 - Material Radiation Damage [3]:
   - "The accumulated radiation dose (or damage) for each segment component and its constituent materials, evaluated at that component's end of life (i.e., at the planned replacement or retirement point), shall not exceed the applicable limits specified in the STS Materials Handbook (S03010300-TDO10000) or in manufacturer-published radiation tolerance data. Note: Dose/damage limits may be expressed in different units (e.g., Gy, rad, DPA). Where DPA is used, DPA-NRT shall be applied."

Requirements that are supported but not evaluated are as follows:

4. Requirement S.03.02-1454 - Radiation Safety Geometry [4]
   - "Target Assembly geometry and materials of construction must match those references in the calculations used to verify requirement #1017. NOTE: The target is partially responsible for maintaining a gap that reduces radiation streaming to the High Bay. The target has to maintain this geometry gap, but is not fully responsible for the requirement. The overall requirement is met by careful coordination of gaps between the target, shielding in the core vessel and shielding between the Target Drive Room and the High Bay."
5. Requirement S.03.04-3593 - MRA Shielding Requirement [5]
   - "The MRA design shall support the Target Systems Monolith meeting the Target Systems Radiation Shielding Requirement. Note: The MRA design must be carefully coordinated with surrounding structures to minimize the impact of streaming gaps."

3 ASSUMPTIONS AND LIMITATIONS

Assumptions were made for the two source terms considered in this report. It is assumed that the proton beam delivers 3.36×10^{15} protons per second onto the target with 1.3 GeV energy, resulting in a total power of 700 kW. The activated water has several assumptions about the residence and decay times detailed in Section 4.3.2.

The gaps between the target segment and core vessel shielding are 22.5 mm from 4.4 cm above the proton beam to the top of the core vessel shield stack.

For the requirements 2-3 that reference the STS Materials Handbook, Table 1 provides a summary of assumed requirements from the handbook [6] and all materials in the target crown are assumed to have a lifetime of 6 years. The radiation damage in metals of the target crown is assumed to be negligible. Given the energy-integrated neutron fluxes in any metal component do not exceed 1×10^{6} n/cm^2/sec, the estimated DPA assuming all neutrons have an energy of 1 MeV is around 1×10^{-8} DPA/yr. This very low DPA rate is assumed to have negligible effects on the metal in the target crown. The DPA caused by gamma interactions is assumed to also be negligible in the target crown region.

Table 1. STS Handbook Material Limits

Major Component	**Quantity**	**Limit**
Target Motor and Resolver		
	NdFeB Maximum Allowed Fast Neutron Fluence (> 0.1 MeV)	1×10^{13} n/cm^2
	NdFeB Lifetime Dose Limit	2.8 MGy
	PEEK Lifetime Dose Limit	2 MGy
Seals and Lubricant		
	Fluorine Rubber (Viton) Lifetime Dose Limit	20 kGy
	PPE Oil Lifetime Dose Limit	0.2 MGy
	EPDM Lifetime Dose Limit	80 kGy

4 METHODOLOGY AND MODELS

Various components of the methodology for calculating the dose rate maps are detailed in this section. Section 4.1 discusses the geometry, and Section 4.2 discusses the materials. The proton and activated water source terms are described in Section 4.3. The details of the radiation particle transport methodologies are provided in Section 4.4. Variance reduction techniques, tally details, and post-processing scripts are described in Sections 4.5, 4.6, & 4.7 respectively.

4.1 GEOMETRY

Figure 1 presents a cross-sectional view of the STS target system, illustrating the proton beam path along the X-axis from left to right. The target system components, including the target drive room roof at the high bay elevation, are identified in the figure. The roof between the target drive room and high bay is modeled in full fidelity, complete with removable hatches and stacked shielding in the high bay. To facilitate simulations, the target systems components, including the target assembly and core vessel geometries, were converted from computer-aided design (CAD) models to constructive solid geometry (CSG) using the GEOUNED conversion toolkit [7]. David Hartman cleaned many of the CAD models for GEOUNED by removing small features, such as rounds and off-axis tori, and resolving overlaps. A key design feature is the step out of the target vertical stave, which has a diameter of 92.8 cm and begins 130 cm above the proton beam, stepping in at 250 cm above the beam. The diameter of the stave below the step out is 54 cm and the diameter of the stave above the step out is 74 cm. This design mitigates streaming up the gaps between the target assembly and core vessel shielding. Additionally, the water channels in the target staves are oriented to balance the delay of freshly irradiated water flowing up from the proton beam region with the need to mitigate radiation streaming up the water channel. The vertical portions of the water channels are intentionally offset to prevent a direct line-of-sight for high-energy particles emanating from the beam-on-target region. The larger pockets of water in the target staves are intentionally sized to delay the highly radioactive water on its way out of the target staves.

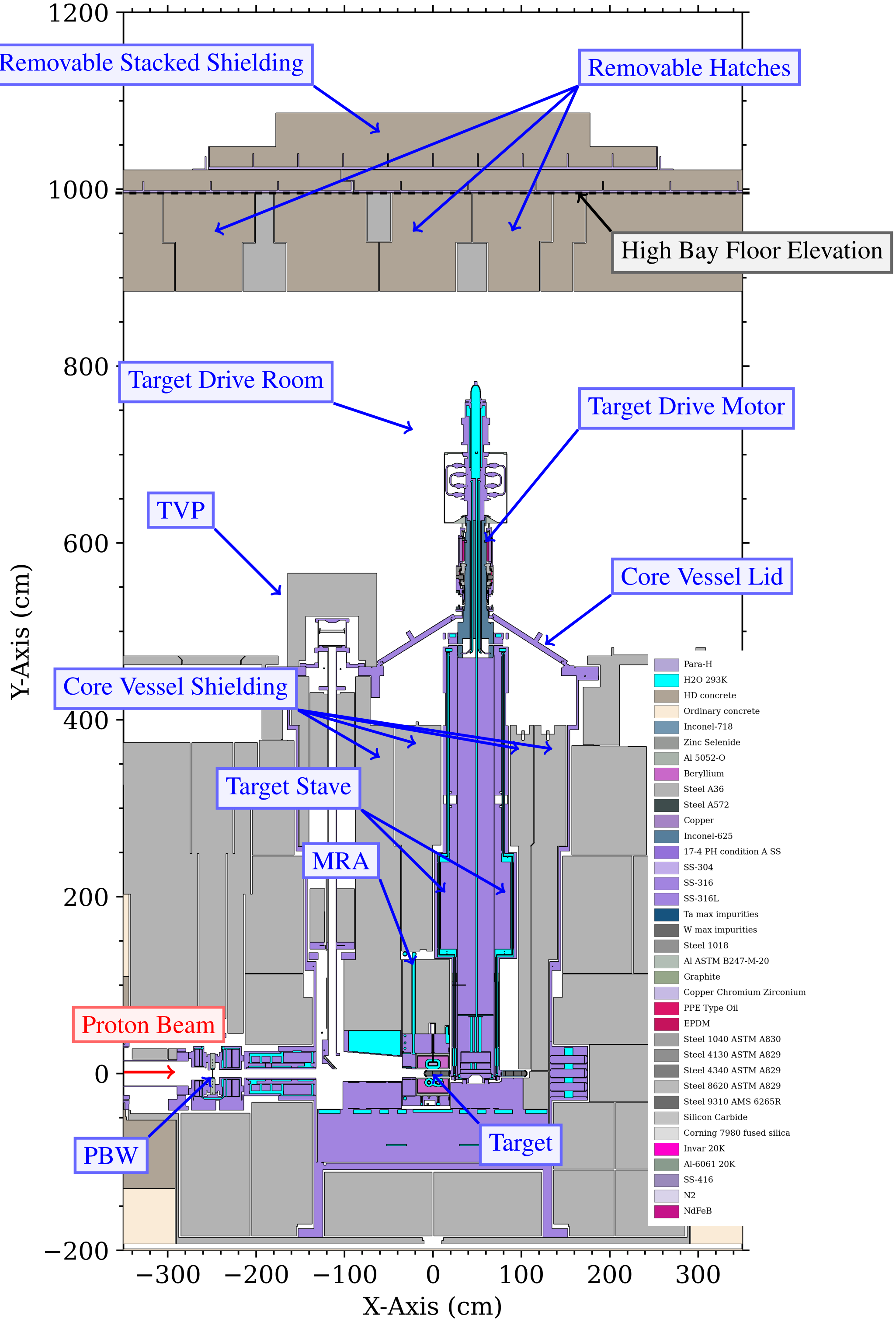


Figure 1. Cross section view of the geometry of the STS target system in operational configuration.

Figure 2 highlights the cylindrical gaps between the target segment and core vessel shielding. These gaps are the primary pathway for neutrons and gammas to stream through to the TDR and drive the thickness of the TDR ceiling. These gaps between the target segment and core vessel shielding are 22.5 mm from 4.4 cm above the proton beam to the top of the core vessel shield stack.

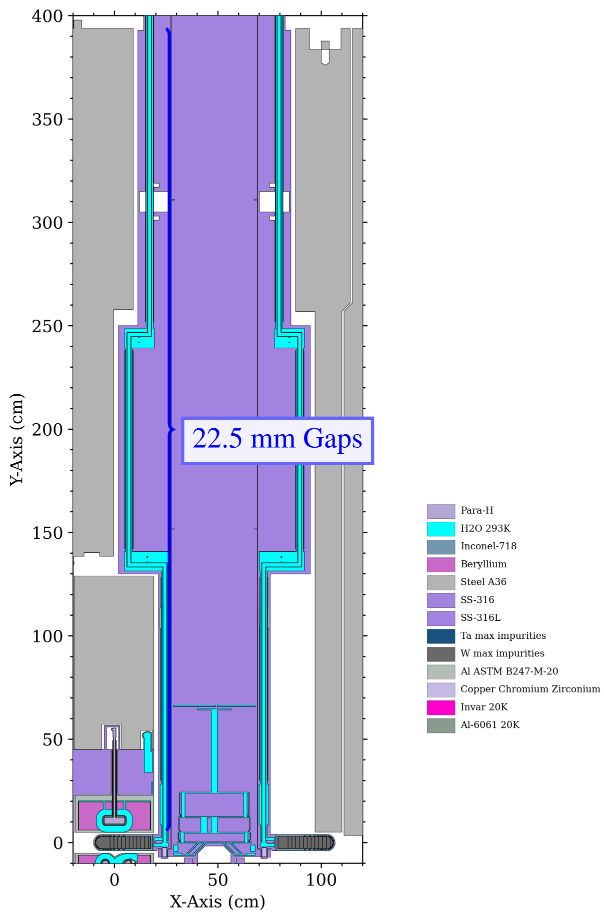


Figure 2. Cross section view of the geometry of the STS target system in operational configuration, detailing the gaps between the target assembly and core vessel shielding.

Figure 3 shows a plan view of the target return pipe throughout the target drive room at an elevation of 765 cm above the proton beam. The activated water flows out of the target crown and out of the target drive room into the hot process vault.

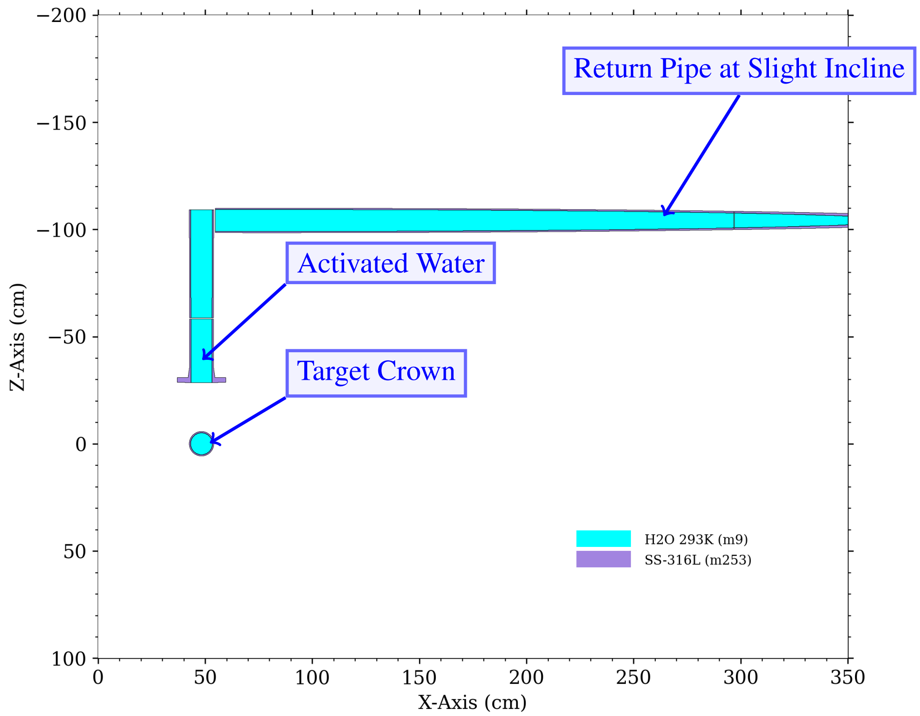
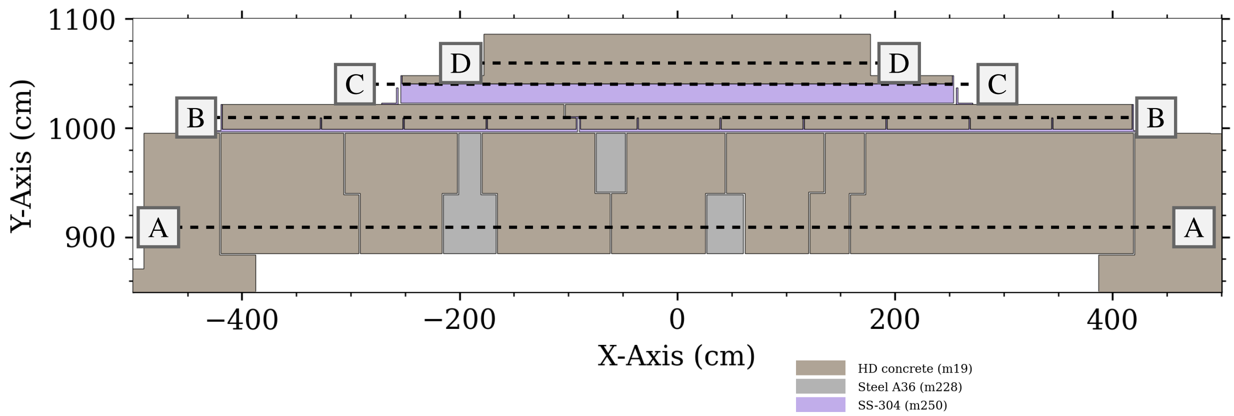
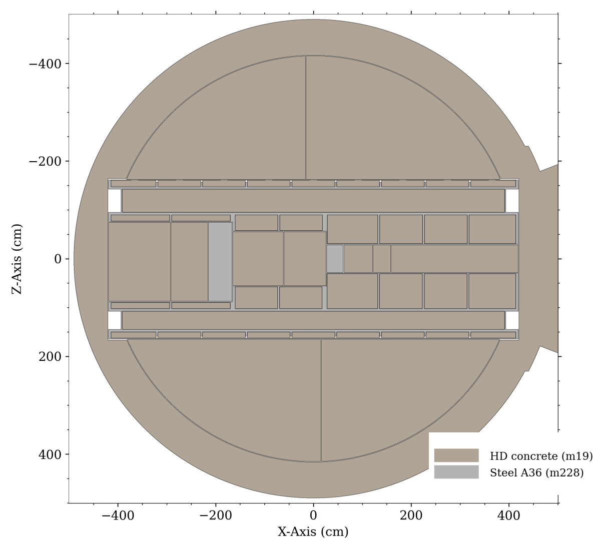


Figure 3. Plan view of the target return water geometry at 765 cm above the proton beam

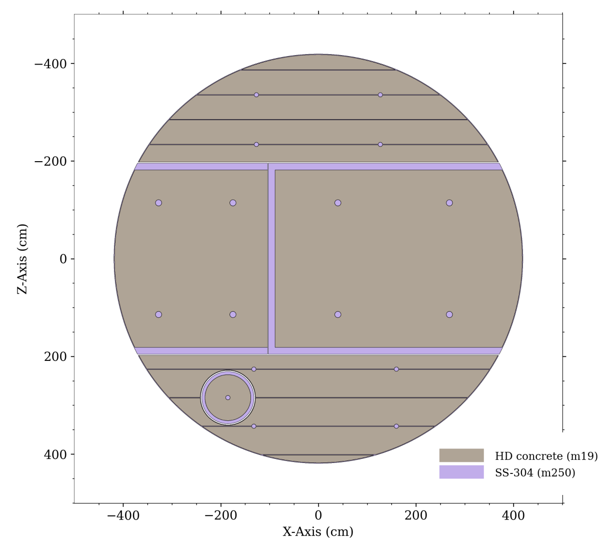
Figure 4 shows details of the TDR roof system. Figure 4a gives a detailed elevation view of the TDR roof and denotes the location of the plan views shown in Figures 4b-4e. Figures 4b-4e show plan views through each of the layers of the TDR roof system showing the steel ribbing and concrete along with the details of the removable hatches and their respective gaps between them and the rest of the roof system. These gaps were evaluated in Section 5.



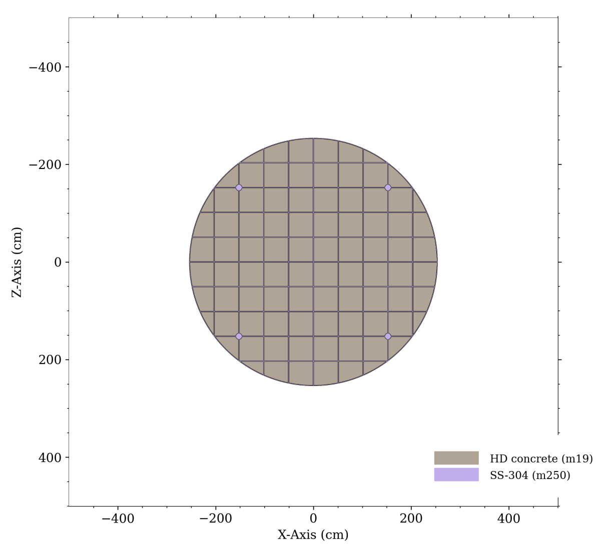
(a) Cross section view of the TDR roof.



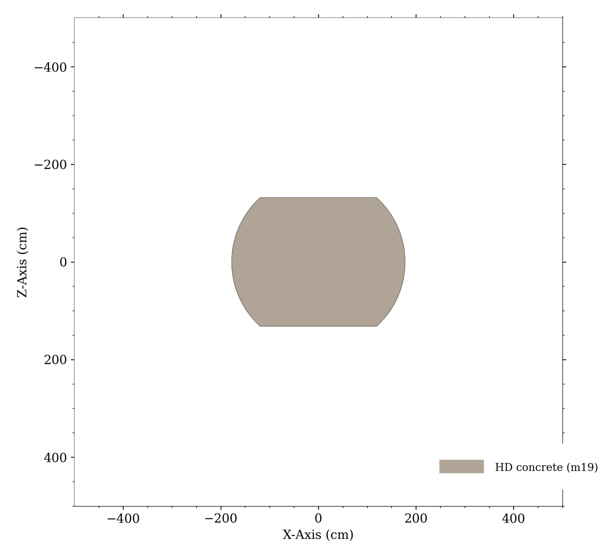
(b) Detail plan view A-A (Y=908 cm) .



(c) Detail plan view B-B (Y=1010 cm).



(d) Detail plan view C-C (Y=1040 cm).



(e) Detail plan view D-D (Y=1040 cm).

Figure 4. Detail views of the TDR roof.

4.2 MATERIALS

The materials used in the analysis described in this report are detailed in tables included in Appendix D. During the Monte Carlo transport runs, where the dose rates are tallied, ENDF/B-VII.1 cross sections are used, and the HILO-2K multigroup library, as a part of the ADVANTG 3.2.0 code package, is used in the discrete ordinates transport calculations [8, 9].

4.3 SOURCES

The dose rate maps shown in Section 5 use two sources detailed in the sections below. Section 4.3.1 describes the proton source used in the protons on target particle transport calculations, and Section 4.3.2 discusses the target water source term.

4.3.1 Proton Source

The proton source starts 300 cm upstream of the target, just upstream of the proton beam window. The spatial distribution is constructed by sampling the original proton beam profile for the quadrapole magnet configuration of the accelerator, and converting the sampling into a MCNP®-compatible source. Wouter de Wet provided the proton beam profile using accelerator systems' analysis, and converted it to MCNP® format.

The spatial profile of the source is shown in Figure 5 and 95% of the beam falls within an area of 62.5 cm^2 on the face of the target. The proton energy is 1.3 GeV, the proton beam power is 0.7 MW, and it arrives on target in pulses at a 15 Hz repetition rate, resulting in a source strength of 3.36×10^{15} protons per second. The proton transport run calculates the dose rates from the neutrons and photons generated with a source weight of 1.0. The source strength normalization of 3.36×10^{15} protons per second is applied during post-processing as discussed in Section 4.7.

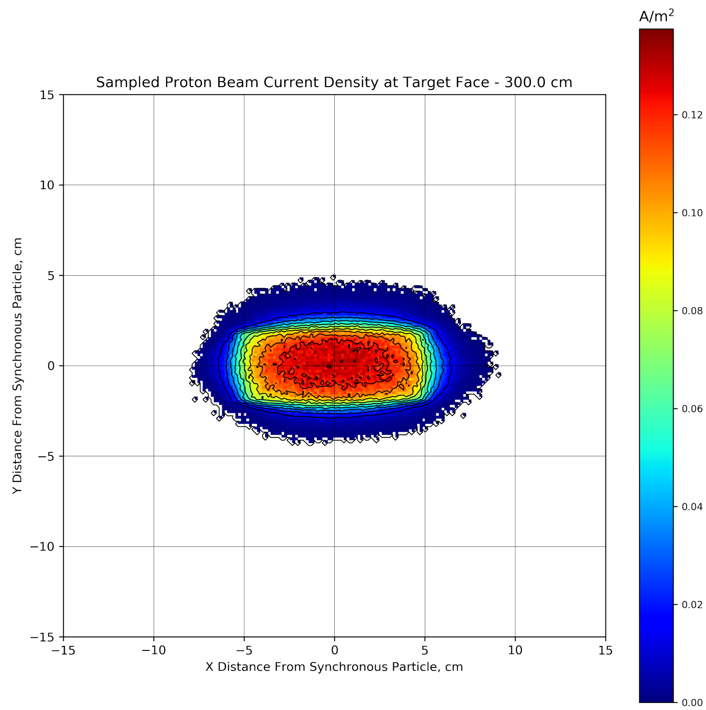


Figure 5. Proton source spatial distribution courtesy of Wouter de Wet.

4.3.2 Target Water Source

In spallation systems, interactions between protons and neutrons with target nuclei in the coolant water induce radioactivity by spallation and nuclear transmutation reactions. The radioactive nuclei are carried via the flowing water loops from the irradiation regions within the core vessel to areas not directly exposed to primary radiation. Managing this induced radioactivity is essential to ensure the safety and integrity of the entire facility.

To estimate the deposited dose in the target drive assembly components, only the water in loop 1 was considered because the water pipes carrying this water are closest to the target drive room ceiling and are completely unshielded in the target drive room. All other pipes are at least 1 m further away and under a 10 cm thick steel floor.

The cooling water flow is described as follows: a volume element of water travels a specific time (residence time) through the irradiation zone, takes a transient time to arrive at the target drive room elevation, and requires an overall loop time. The overall loop time is measured by two successive passes through the entrance into the irradiation zone to complete one cycle through the loop. The water methodologies discussed in this section have been peer-reviewed and compared with measurements [10, 11, 12]. The loop volume, flow rate, total loop time, irradiation volumes, and residence times are give in Table 2.

Table 2. Parameters for Water Activation

Parameter	Quantity	Unit
Total loop volume	1470	gallon
Total loop flow rate	157.5	gallon/minute
Total loop time	560	second
Target segments flow rate	150	gallon/minute
Target segments irradiation volume	5666.48	cm^3
Target segments residence time	0.5989	second
Target shaft flow rate	7.5	gallon/minute
Target shaft irradiation volume	8798.56	cm^3
Target shaft residence time	18.593	second

The water in the target assembly is broken up in six sources corresponding to either target segment or target shaft irradiation zone and varying transient times as shown in Table 3 below. There are only two irradiation zones included in the analysis of this report: target segment and target shaft. These two irradiation zones are used to construct the six water sources used in this report. For Water Sources 1 & 2, only the water in the target segment is used and decayed at two different times. Source 3 uses a combination of target segment and target shaft water decayed at two difference times (transient times). The use of two transient times for Source 3 is because the water exiting the target foot traveling up the target stave takes a longer route than the water exiting the bottom of the target shaft and going straight up (without jogging) the target shaft. Sources 4 & 5 use only the target shaft water. Source 6 uses a combination of target segment and target shaft water where the transient times are the time it takes the water to traverse the entire loop. Source 6 represents the fresh water entering the target system. The transient time is the amount of time it takes the water at exit of the irradiation zone (where it spends the residence time) to move upward to another height of interest. The Delta Transient Time column in Table 3 shows the time it takes the water to traverse the length of water channel or pipe for the specific source. For conservatism, this time is ignored and the transient time is held constant over the length of the water channel or pipe.

Table 3. Water Activation Source Transient Times

Source Number	Irradiation Zone	Target Segment Transient Time seconds	Target Shaft Transient Time seconds	Delta Transient Time seconds
1	Target Segment	0.0	N/A	8.19
2	Target Segment	8.19	N/A	1.30
3	Target Segment and Shaft	9.486	3.2256	1.0049
4	Target Shaft	N/A	0.0	2.0516
5	Target Shaft	N/A	2.0516	1.174
6	Target Segment and Shaft	560	560	N/A

The irradiated water decays by both photon and neutron emission. Both the photon and neutron emission from the water are considered in the quantities of interest discussed in Section 5.

4.4 PARTICLE TRANSPORT

MCNP® Code Version 6.2.0 is used to transport the sources shown in Section 4.3 throughout the target drive room and into the target drive room ceiling, and tally dose rates as discussed in Section 4.6 [13]. 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 4.5. The results shown in Section 5 are combinations of both the Monte Carlo solutions from the prompt protons on target and the target water decay gamma sources. For the transport of the target water decay gamma and neutron sources, a very simple source biasing scheme was implemented where for any non-zero cell or energy probability, the source biasing parameter was set to 1.0.

Table 4 shows the various data cards related to controlling the physics processes MCNP® uses during the proton beam to target calculation. Descriptions of the options are also included in the table. The cards shown in Table 4 were selected due to the relevance to high-energy physics calculations for the STS.

Table 4. Physics Card Options for Activation Calculations

Card	Options	Description
mode	n p | h ! / z k % ^ d t s a * ?	Include all relevant particles
phys:n	1400 6j 20	Set the upper energy limit to 1400 MeV and the transition from cross section tables to physics models to 20 MeV
phys:p	1400 2j -1	Set the upper energy limit to 1400 MeV and photonuclear physics to on but unbiased
phys:h	1400 j 1	Set the upper energy limit to 1400 MeV and the transition from cross section tables to physics models to 1 MeV
lca	2 1 1 0023 1 1 0 1 1 0 66	Use the default CEM 3.03 model
lcb	3.49E+03 3.49E+03 2.49E+03 2.49E+03 8.0E+02 8.0E+02 -1 -1	Using the defaults
lea	1 4 1 0 1 0 0 1	Using the defaults
leb	1.5000E+00 8.0000E+00 1.5000E+00 1.0000E+01	Using the defaults

4.5 VARIANCE REDUCTION

ADVANTG 3.2.0 was used to produce variance reduction parameters in the form of weight windows to aid in the timely convergence of the tallies discussed in Section 4.6. ADVANTG 3.2.0 is strictly limited to neutral particles, and a surrogate neutron source was used to generate the weight window parameters using a source conversion method that has been rigorously tested and validated [14]. To construct the surrogate neutron source, a structured mesh-based neutron tally binned in energy was placed over the entire target wheel. This mesh-based tally was then post-processed into an ADVANTG-compatible source with the proper spatial and energy dependence of the actual source but approximated the angular component of the source as isotropic. The tally-of-interest in the ADVANTG run for the protons on target source was a set of mesh tallies of neutron and photon doses in the target drive room ceiling. A duplicate ADVANTG run was also executed with the same parameters except the motivating tally was changed from the whole target drive room ceiling to an area covering $\approx$ 1 m from the peak of the 0.25 mrem/hr contour. Another ADVANTG run was executed where the tally-of-interest was set to the energy deposition tallies in the target crown region for the Monte Carlo run calculating the dose to target drive materials. 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 [15].

4.6 TALLY DETAILS

The photon and neutron effective dose rates are tallied with volume-averaged flux mesh tallies in the MCNP® calculation modified by the (DE/DF) cards. The DE/DF cards applied the photon and neutron flux to effective dose conversion factors shown in Tables E.1 & E.2 of Appendix E with logarithmic energy interpolation [16]. To tally the absorbed dose to materials in the target drive, collision heating (+F6) tallies were applied to many of the cells in the target drive region.

4.7 POST-PROCESSING

A Python script was written to combine the effective dose tallies from the protons on target and activated water sources. This script loads each meshtal file from each MCNP® run, sums the mesh tallies, and propagates the uncertainties to generate a total effective dose rate map along with an uncertainty map. This total effective dose is plotted with an additional two sigma worth of Monte Carlo uncertainty in the dose rates in Section 5. For the total effective dose rate maps in Section 5, two beam-on-target runs were considered in the final plots where one run was executed with weight windows optimizing the whole target drive room roof and the other run was executed with weight windows optimizing the peak of the 0.25 mrem/hr contour. In the python post-processing script, the relative uncertainty in each voxel in the mesh tallies for both runs are compared, and the results in the run with the least relative uncertainty is shown in the final plots. Another python script was generated to combine the absorbed dose rates in the target crown across the beam-on-target, water photons, and water neutrons sources Monte Carlo runs. The geometry and dose plots are generated using the RTPlotter Python suite of tools developed by Joel Risner and Wouter de Wet.

5 ANALYSIS AND RESULTS

This section details the results of propagating the two sources described in Section 4.3 to the target drive room and through the target drive room ceiling. Section 5.1 shows the dose rate field in the target drive room and discusses sizing the target drive room ceiling based on the dose rate field. Section 5.2 gives a detailed view of the dose rate field surrounding the target drive and crown. All effective dose rate plots in this section are showing dose plus two sigma Monte Carlo uncertainty.

5.1 SIZING TARGET DRIVE ROOM CEILING

The proton beam on target source described in Section 4.3.1 is transported up through the target assembly and core vessel shielding to the target drive room. The activated target water source described in Section 4.3.2 is transported throughout the target drive room. Figure 6 shows the combined total effective dose plus two sigma error from the two main sources in the target drive room. The dashed red line shows the 0.25 mrem/hr dose rate boundary. Figure 7 shows the estimated relative error of the total dose rates due to the statistical uncertainty of the Monte Carlo calculations only. The 0.25 mrem/hr contour line is shown in red in Figure 6 is going through the oversized target drive room roof. The designed permanent and removable target drive room roof design is sufficient to meet the 0.25 mrem/hr dose rate on contact with the high bay floor. The current high bay floor elevation is shown in Figure 6 to provide context for the size of the removable portion of the target drive room roof. Figures 6 - 8 show that Requirement 1 in Section 2 is satisfied.

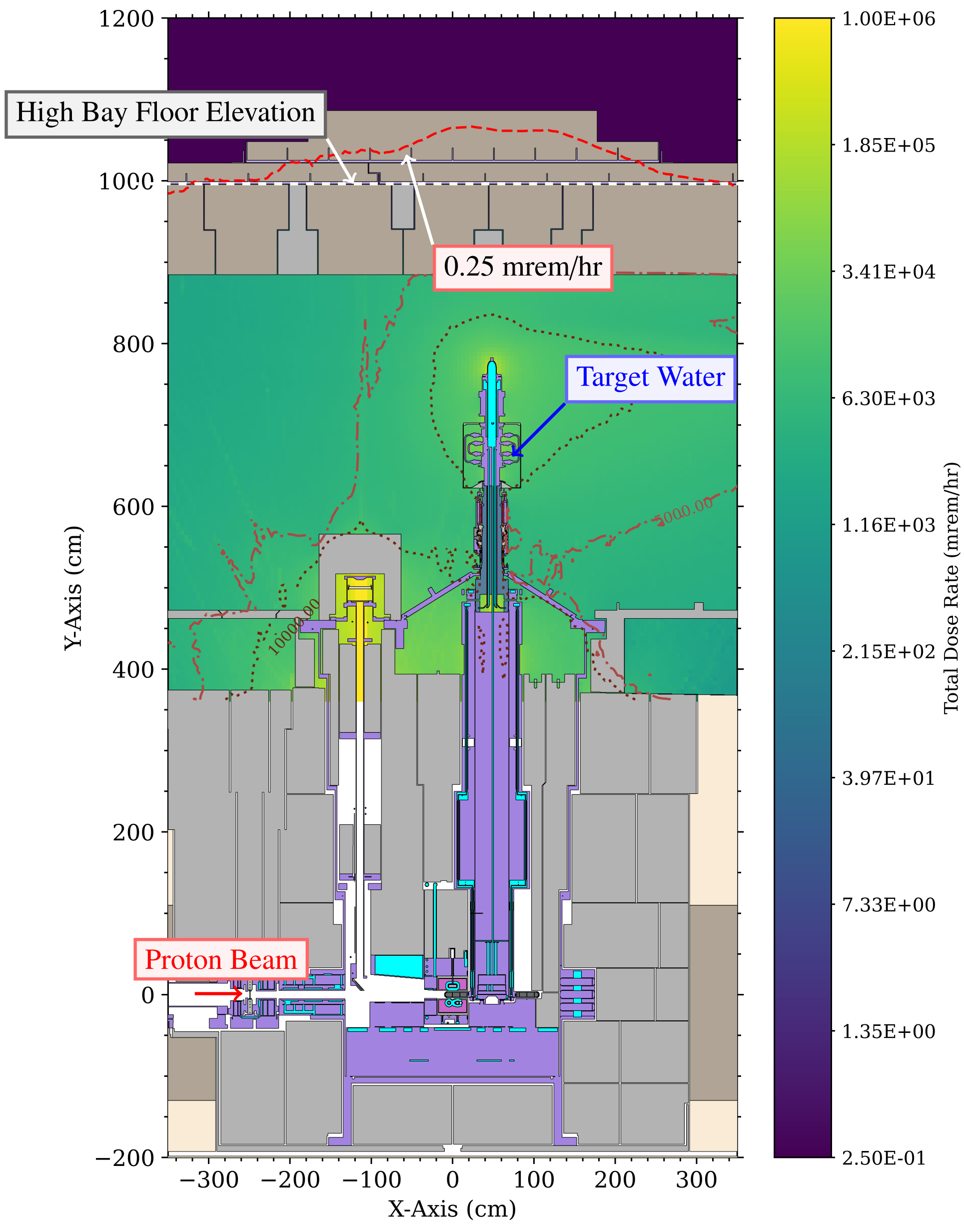


Figure 6. Cross section view 0.51 cm off the proton beam of the total effective dose rates in the target drive room and through the target drive room ceiling.

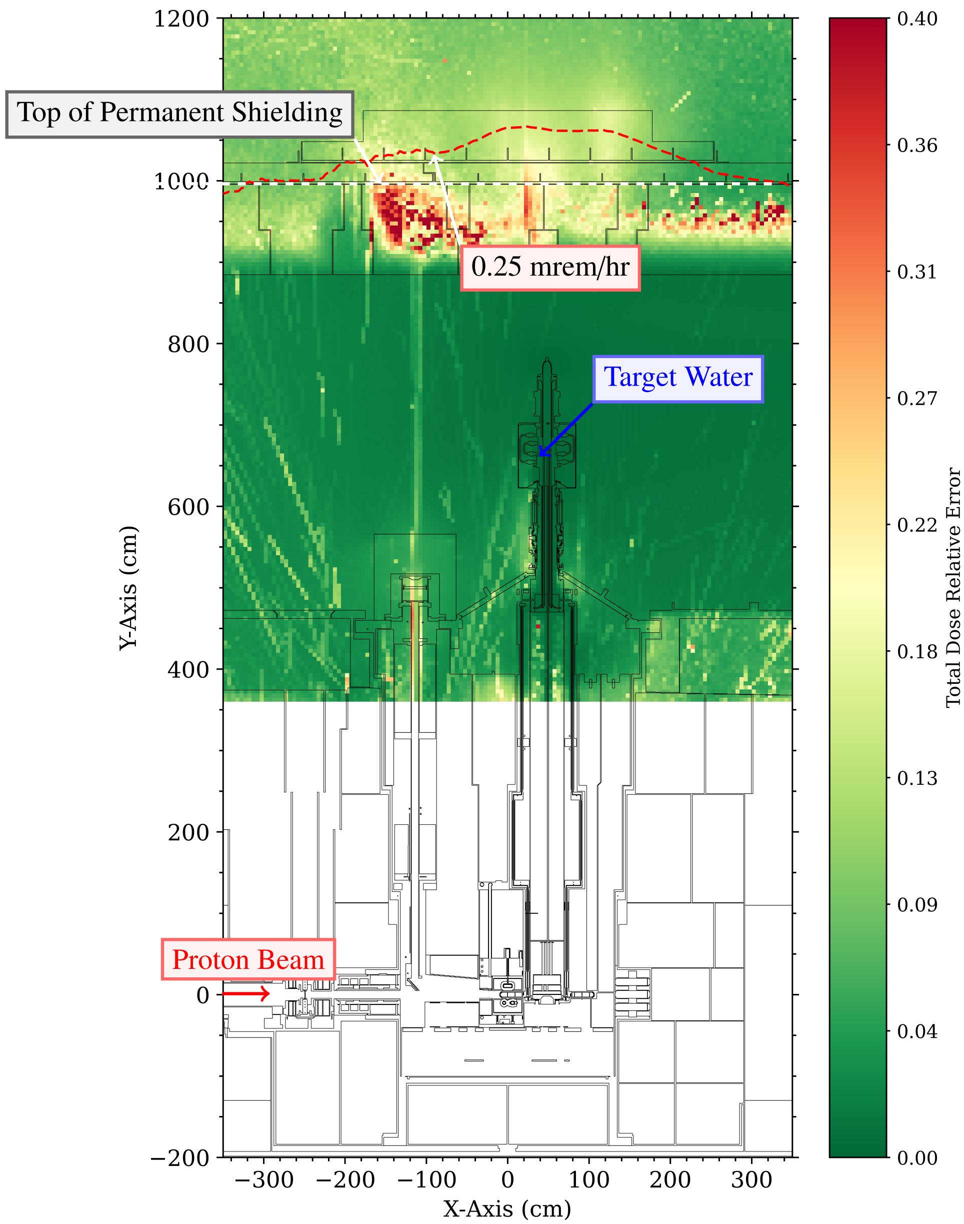
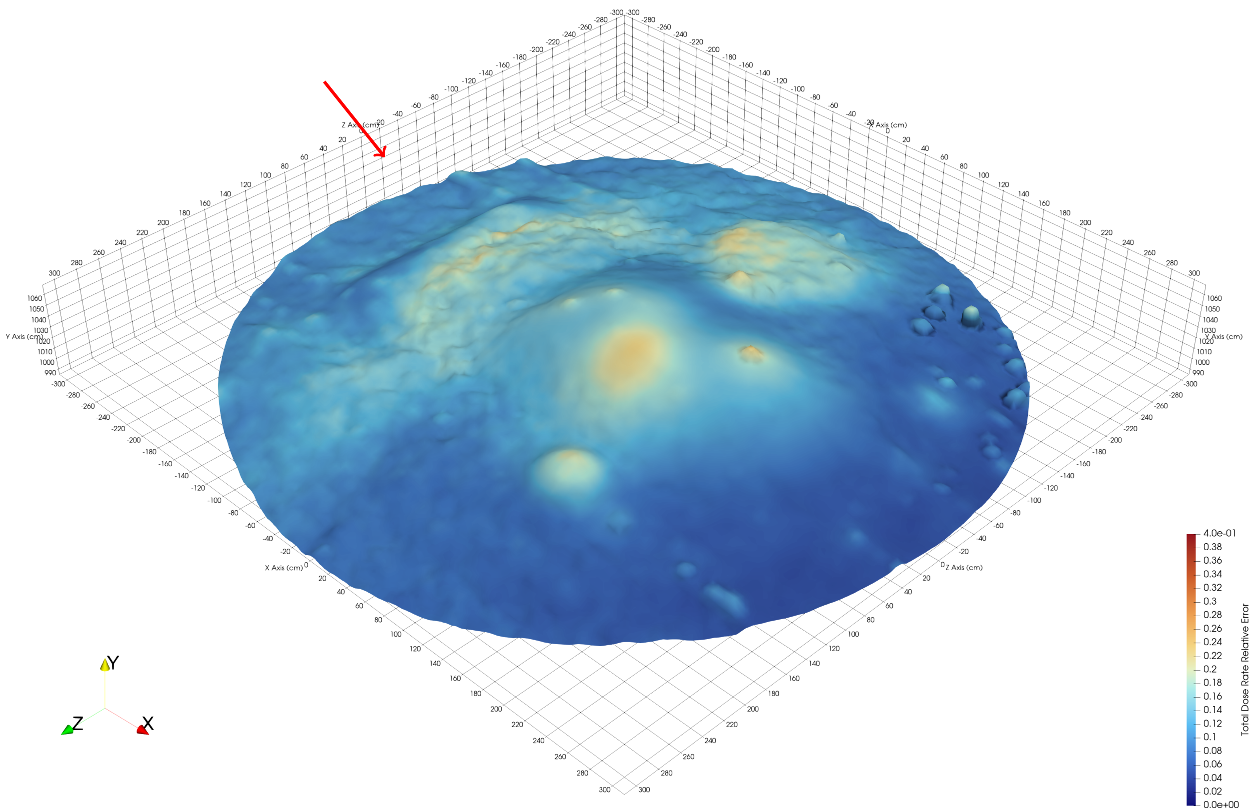
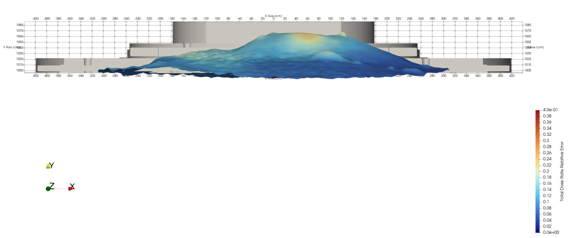


Figure 7. Cross section view 0.51 cm off the proton beam of the total effective dose rate uncertainties in the target drive room and through the target drive room ceiling.

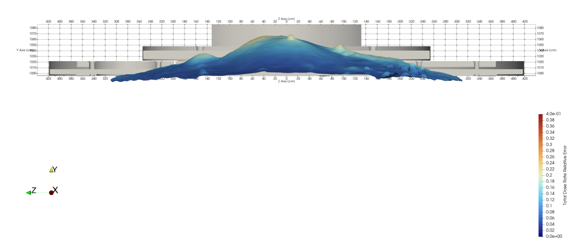
Figure 8 shows the 3-D total dose 0.25 mrem/hr contour colored by relative Monte Carlo uncertainty in the target drive room roof. Figure 8a shows the full isometric view of the 0.25 mrem/hr contour without geometry to show that all of the contour is defined with dose rates with less than 40% relative uncertainty. Figures 8b & 8c show the 0.25 mrem/hr contour with the supplemental shielding geometry (located on top of the permanent portion of the TDR roof in the high bay) shown behind the 3-D contour surface to show that the contour does not enter the high bay through the TDR roof system.



(a) Isometric view of the total dose 0.25 mrem/hr contour in the target drive room ceiling with a red arrow indicating the proton beam direction.



(b) Elevation view perpendicular to the proton beam of the total dose 0.25 mrem/hr contour.



(c) Elevation view along the proton beam of the total dose 0.25 mrem/hr contour.

Figure 8. Overview of the total dose 0.25 mrem/hr contour in the target drive room roof.

Figure 9 shows a cross section view 0.51 cm off of the proton beam of the ratio of neutron over photon dose in the target drive room and ceiling. The color scale depicts a red hue if photons are the main contributor, a blue hue if neutrons are the main contributor, and a yellow hue if the contributions are evenly split. Photon dose is the dominant contributor to total dose for a majority of the target drive room whereas neutron dose is the main contributor to total dose under the core vessel lid. The top contributor to total dose changes as the photons are attenuated in the target drive room ceiling leaving the neutrons to drive the overall thickness of the target drive room ceiling. Appendix F contains figures showing the dose rates from each source separately.

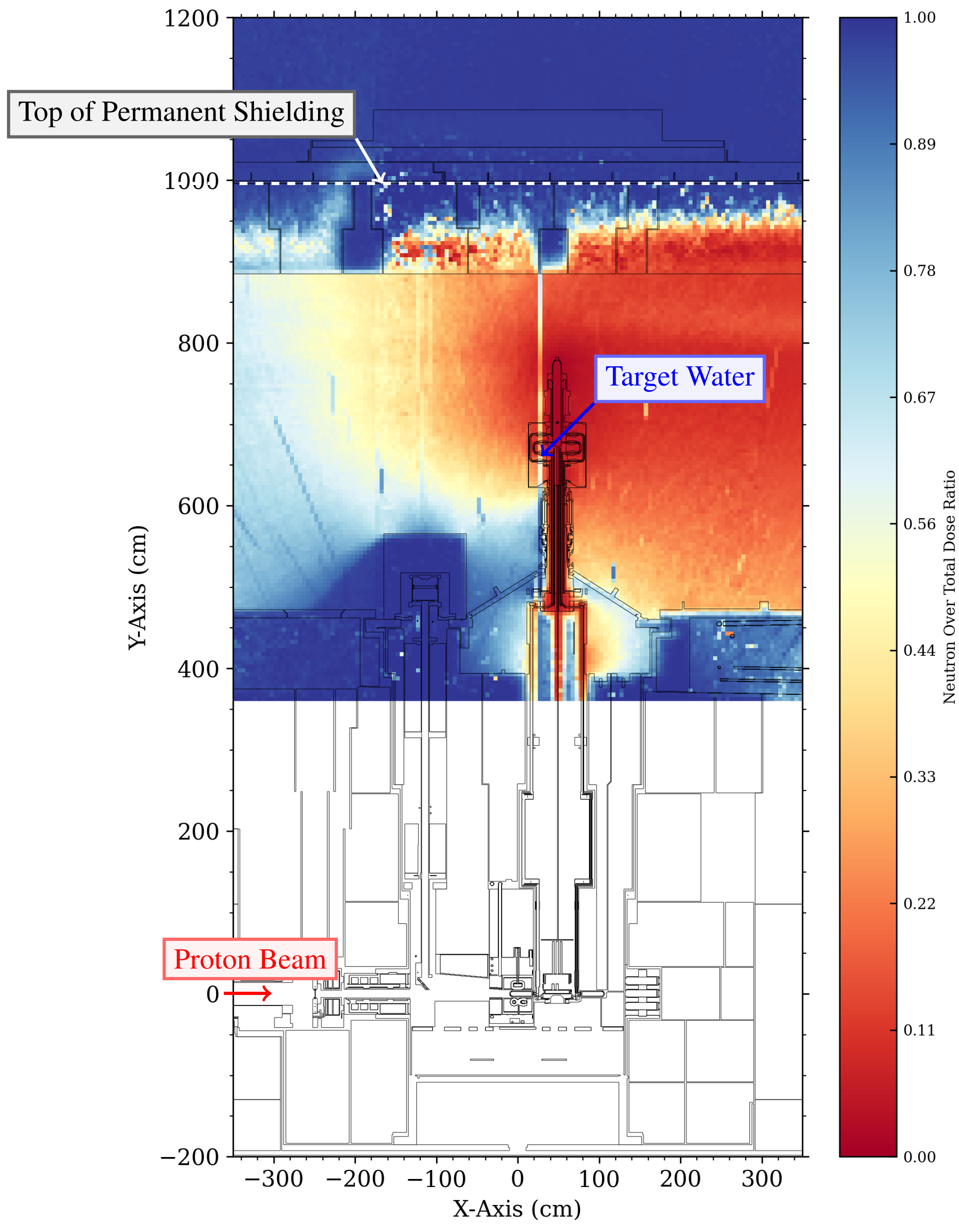


Figure 9. Cross section view along the proton beam of the neutron dose to photon dose ratio in the target drive room and through the target drive room ceiling.

Figure 10 shows a plan view of the total effective rate through the center of the target return water pipe exit of the target crown (Y = 765.37 cm). This plan view of the target drive room total effective dose rates show that the water is the dominant contributor to the dose.

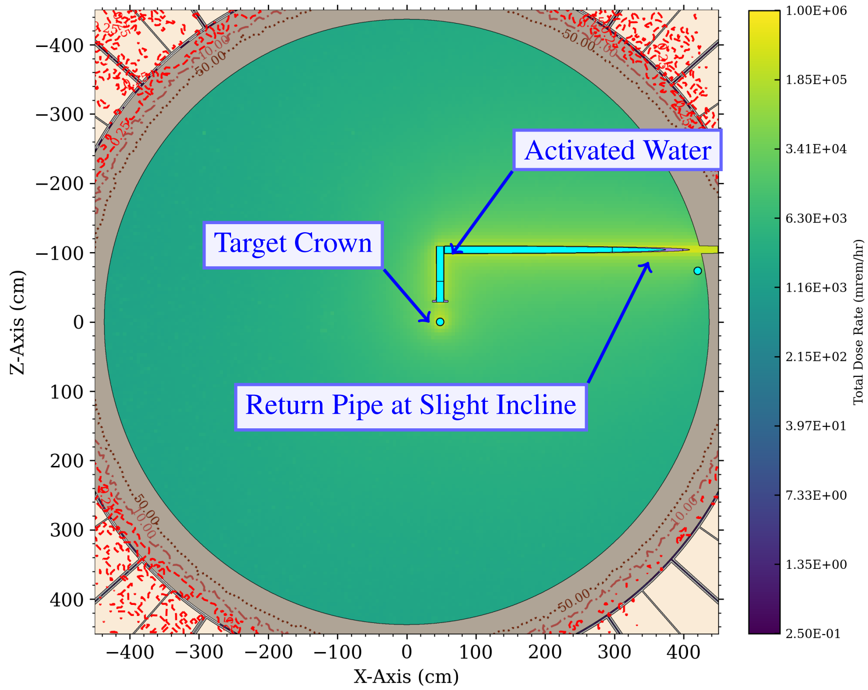


Figure 10. Plan view of the total effective dose rate through the center elevation of the target water return pipe (Y = 765.37 cm).

To illustrate the need for the removable portion of the TDR roof, Figure 11 shows a plan view of the total effective dose rates at the high bay floor elevation. The removable portion of the TDR roof is still in the geometry in Figure 11, and due to the backscatter from this removable shielding, the dose rates in Figure 11 will be slightly conservative as compared to reality if the removable portion of the TDR roof is removed. The high bay is divided in radiological areas according to the dose rates [17]. The radiation zone levels used in the legend are the following: 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. Figure 12 shows the statistical uncertainty in the total effective dose rates shown in Figure 11.

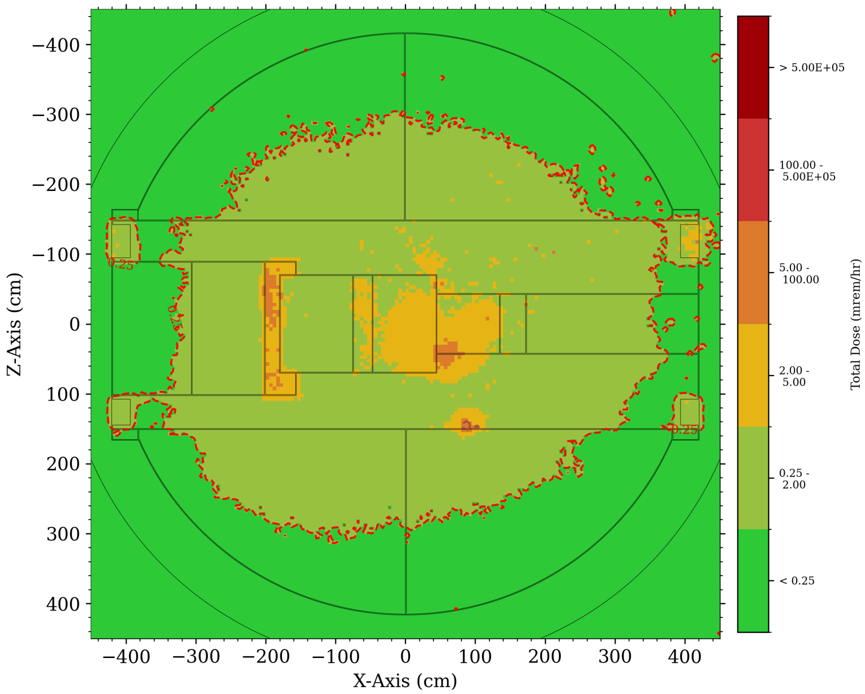


Figure 11. Plan view of the total effective dose at the high bay floor elevation.

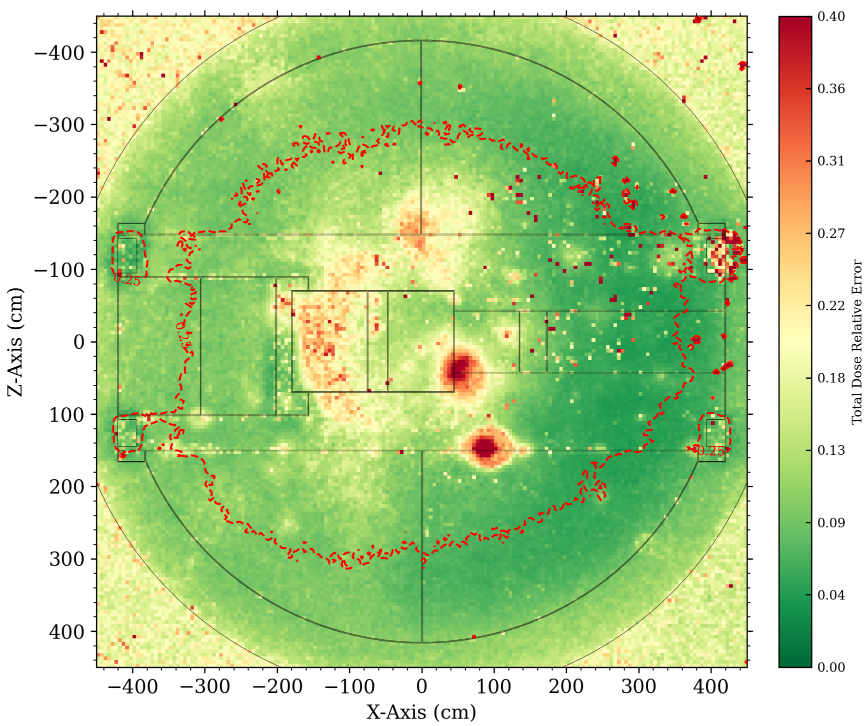
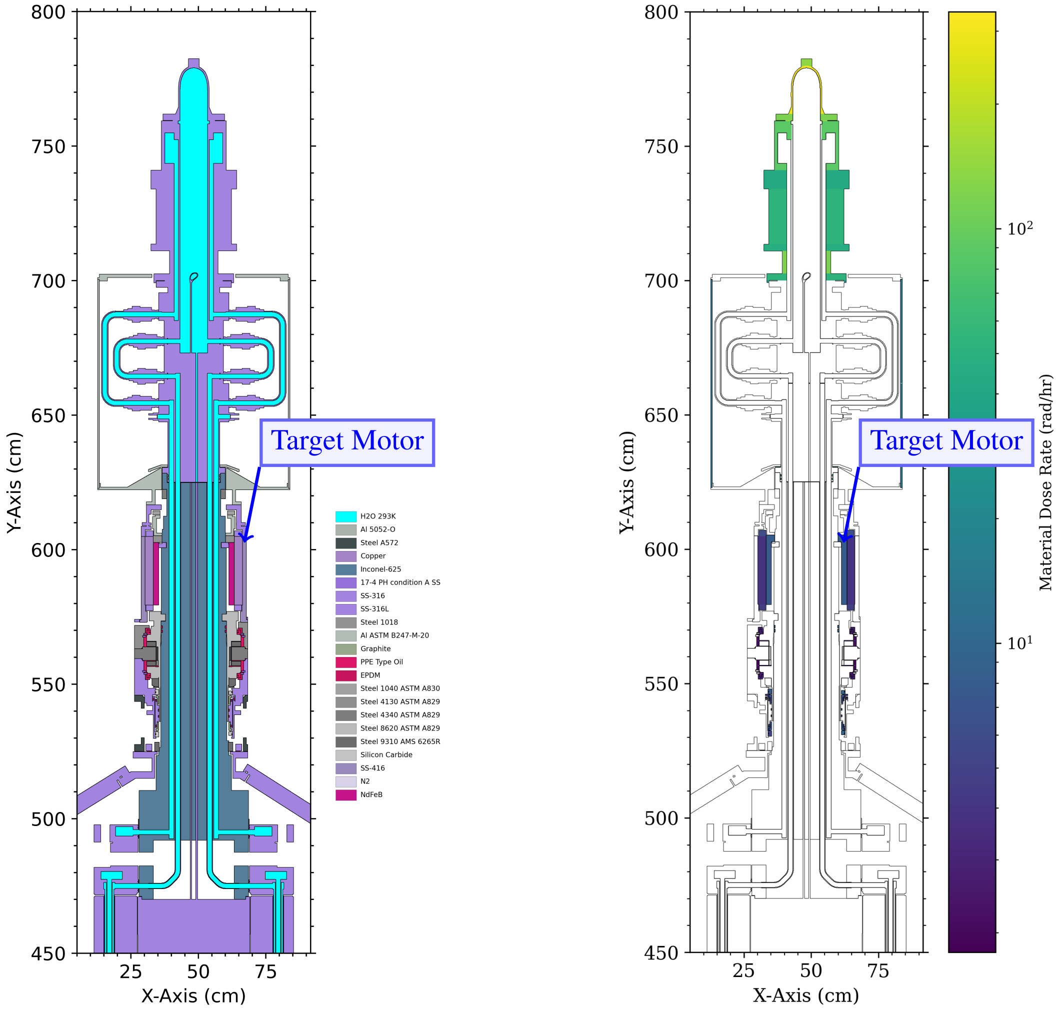


Figure 12. Plan view of the total effective dose uncertainty at the high bay floor elevation.

5.2 TARGET DRIVE AND CROWN DOSE

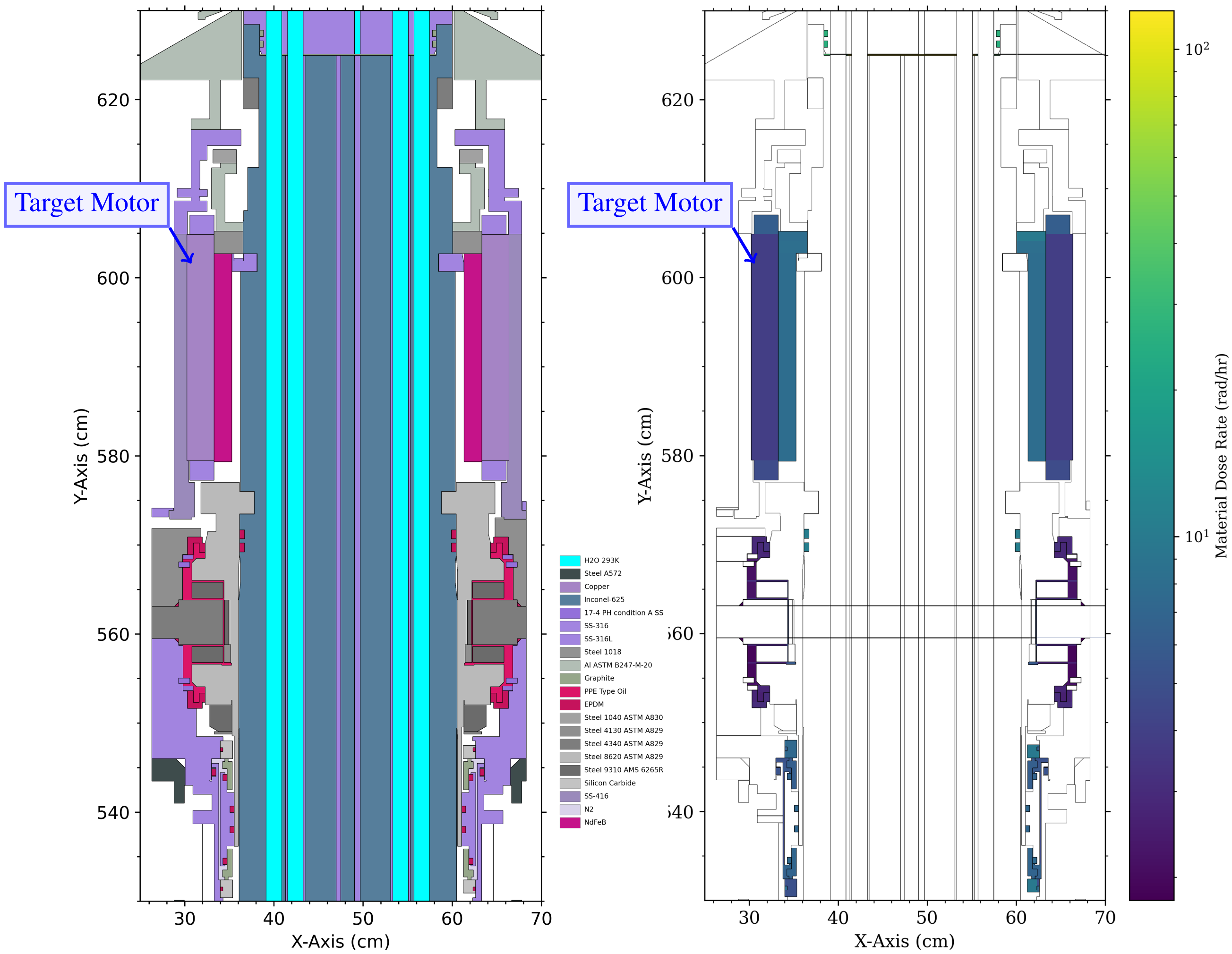
This section provides a detailed evaluation of the material dose in and around the target drive and crown. The purpose of this section is to provide a means of estimating dose to target drive grease, o-rings, seals, etc. This section shows that Requirements 2 & 3 from Section 2 are satisfied given the assumptions in Section 3.

Figure 13 shows a detailed cross section view along the proton beam of the target drive geometry in Figure 13a and a detailed view of the total absorbed dose rate in the same orientation in Figure 13b. The scales of Figure 13 are different from other figures where the dose rate is the dose absorbed in each material in units of rad/hr. The material doses are calculated using the sum of three source types: beam-on-target, decay photons from water, and decay neutrons from water. A more detailed view of the material doses in the target motor region is provided in Figure 14. Table 5 shows the average and peak absorbed dose rates by material along with the average tissue-equivalent by material in the target drive and crown. Absolute Monte Carlo uncertainties are included in the tables in this section, and these uncertainties do not account for uncertainty in the underlying cross section data or assumptions in the Monte Carlo source generation.



(a) Geometry **(b)** Total absorbed dose rates in materials

Figure 13. Cross section view of the target drive and crown.



(a) Geometry

(b) Total absorbed dose rates in materials

Figure 14. Cross section view of the target motor region.

Table 5. Target Crown Material Dose Rates

Material	Average Absorbed Dose (rad/hr)	Peak Absorbed Dose (rad/hr)	Average Tissue-Equivalent Dose (rem/hr)
Fluorine rubber (Viton)	$(9.7 \pm 0.3) \times 10^0$	$(1.13 \pm 0.08) \times 10^1$	$(1.23 \pm 0.04) \times 10^1$
PEEK	$(5.7 \pm 0.3) \times 10^0$	$(7.0 \pm 0.4) \times 10^0$	$(8.8 \pm 0.3) \times 10^0$
Reactor Grade Graphite	$(1.305 \pm 0.008) \times 10^1$	$(1.2 \pm 0.01) \times 10^2$	$(1.76 \pm 0.01) \times 10^1$
PPE Oil	$(2.62 \pm 0.03) \times 10^0$	$(5.8 \pm 0.3) \times 10^0$	$(4.59 \pm 0.03) \times 10^0$
EPDM	$(5.01 \pm 0.04) \times 10^0$	$(2.44 \pm 0.04) \times 10^1$	$(7.0 \pm 0.05) \times 10^0$
Silicon Carbide	$(6.89 \pm 0.09) \times 10^0$	$(1.1 \pm 0.7) \times 10^1$	$(1.04 \pm 0.01) \times 10^1$
NdFeB Magnet	$(7.86 \pm 0.06) \times 10^0$	$(7.86 \pm 0.06) \times 10^0$	$(8.24 \pm 0.05) \times 10^0$

Table 6 shows a breakdown of the average total material dose by neutron and photon dose. Overall, the material doses in the target crown are dominated by the gamma dose contribution.

Table 7 shows the calculated quantities of interest with a factor of safety of 2 applied alongside the limits for the quantities of interest. The factor of safety stems from the uncertainties in the underlying physics data and the assumptions of the proton and water sources. The "Margin" column in the table shows the limit over calculated ratio for each quantity of interest. All of the ratios in this column are above 1.0 indicating that Requirements 2 & 3 are satisfied.

Table 6. Target Crown Material Particle Dose Rates

Material	**Average Absorbed Dose (rad/hr)**	**Neutron Absorbed Dose (rad/hr)**	**Photon Absorbed Dose (rad/hr)**
Fluorine rubber (Viton)	$(9.7 \pm 0.3) \times 10^{0}$	$(2.9 \pm 0.2) \times 10^{-2}$	$(9.7 \pm 0.3) \times 10^{0}$
PEEK	$(5.7 \pm 0.3) \times 10^{0}$	$(1.28 \pm 0.05) \times 10^{-1}$	$(5.6 \pm 0.3) \times 10^{0}$
Reactor Grade Graphite	$(1.305 \pm 0.008) \times 10^{1}$	$(2.94 \pm 0.06) \times 10^{-2}$	$(1.302 \pm 0.008) \times 10^{1}$
PPE Oil	$(2.62 \pm 0.03) \times 10^{0}$	$(9.93 \pm 0.09) \times 10^{-2}$	$(2.52 \pm 0.03) \times 10^{0}$
EPDM	$(5.01 \pm 0.04) \times 10^{0}$	$(2.34 \pm 0.03) \times 10^{-1}$	$(4.77 \pm 0.04) \times 10^{0}$
Silicon Carbide	$(6.89 \pm 0.09) \times 10^{0}$	$(1.26 \pm 0.02) \times 10^{-2}$	$(6.88 \pm 0.09) \times 10^{0}$
NdFeB Magnet	$(7.86 \pm 0.06) \times 10^{0}$	$(1.325 \pm 0.005) \times 10^{-2}$	$(7.85 \pm 0.06) \times 10^{0}$

Table 7. Target Crown Material Limit Comparison

Quantity	**Lifetime (years)**	**Calculated at Lifetime**	**Limit**	**Margin** $\frac{Limit}{Calculated}$	**PASS/FAIL**
NdFeB Fast Neutron Fluence (> 0.1 MeV)	6	$(7.48 \pm 0.02) \times 10^{12}$ n/cm^2	1×10^{13} n/cm^2	1.337 ± 0.004	PASS
NdFeB Lifetime Dose	6	4.72 ± 0.04 kGy	2.8 MGy	593 ± 5	PASS
PEEK Lifetime Dose	6	4.2 ± 0.2 kGy	2 MGy	480 ± 20	PASS
Fluorine Rubber (Viton) Lifetime Dose	6	6.8 ± 0.4 kGy	20 kGy	2.9 ± 0.2	PASS
PPE Oil Lifetime Dose	6	3.5 ± 0.2 kGy	0.2 MGy	57 ± 3	PASS
EPDM Lifetime Dose Limit	6	14.6 ± 0.2 kGy	80 kGy	5.48 ± 0.08	PASS

6 CONCLUSIONS

This report details analysis of the dose rates in the target drive room arising from the radiation radiating from the target in operation through the shielding, and the contribution from the decay gammas and neutrons from the activated cooling water flowing through the pipes in the TDR. The gaps between the target assembly and the core vessel shielding are the primary routes for neutrons and photons to stream through to the target drive room. The activated water in the target drive and crown is the major contributor to the total effective dose in the target drive room. However, the target water source does not drive the overall thickness of the target drive room ceiling. The neutrons streaming up the gaps drive the target drive room thickness and the as-designed supplemental shielding is sufficient to mitigate the dose in the high bay to below 0.25 mrem/hr. Estimates for the material dose rates to materials in the target crown have also been provided. This report shows that Requirements 1-3 are satisfied.

7 REFERENCES

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APPENDIX A. COMPUTER HARDWARE AND SOFTWARE

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The Kryo and Saturn clusters were used in this analysis. The mcnp/mcnp6.2mod_20230411 module was used for MCNP® and advantg/3.2.0-HILO module was used for the ADVANTG package, and the AARE package was used for the activation.

APPENDIX B. LOCATION OF COMPUTATIONAL INPUT AND OUTPUT FILES

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The computational input and output files are located in the sts_archive located at:

/home/sts_archive/S.03.12_Neutronics/S.03.12.01_Neutronics_Analysis_Support/S03120100-TRT10017_STS_Target_Drive_room_Beam_On_Dose_Rates/Supporting_Data.tar.gz

This .tar.gz file contains the following three folders:

- Target_Drive_Room_Roof_Calculations
  - This folder contains the inputs and outputs for the Target Drive Room Roof calculations where the folders inside are marked by the source:
    - BOT (Beam On Target)
    - Water_Neutrons (neutron source from activated water)
    - Water_Photons (photon source from activated water)
  - Inside of each source folder is an MCNP directory, and for the BOT source, an ADVANTG directory containing the respective inputs and outputs.
  - There is also a Post_Processing_Water_Meshtals directory that houses the Python script that was used to merge the water meshtal files together.
- Target_Crown_Material_Dose_Rates
  - This folder contains the inputs and outputs for the Target Crown Material Dose Rate calculations where the folders inside are marked by the source:
    - BOT (Beam On Target)
    - Water_Neutrons (neutron source from activated water)
    - Water_Photons (photon source from activated water)
  - Inside of each source folder is an MCNP directory, and for the BOT source, an ADVANTG directory containing the respective inputs and outputs.
  - There is also a Post_Processing directory that houses the Python script that was used to process the mctal files from the various sources.
- Generating_Figures
  - This folder contains plotting scripts used to generate the figures in this document. There are two folders inside: one for using the MCNP ray tracer and one for the omnibus ray tracer. The plots in this document use figures from both ray tracers.

APPENDIX C. TECHNICAL REVIEW DOCUMENTATION

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TECHNICAL REVIEW CHECKLIST

	Yes	No	N/A
Is the calculation well organized, legible, and complete?			
If excerpts from other sources are included in the calculation package, are the excerpts legible and properly referenced?			
Do the calculations cover the expressed purpose?			
Are all necessary elements included?			
Is the method used appropriate considering the purpose and type of analysis and the use and acceptability of the results (i.e. margin to limits)?			
Is the method in accordance with codes, standards, and regulatory requirements?			
Has the method been employed similarly elsewhere in industry?			
Are assumptions necessary to perform the analysis adequately described, justified, and reasonable?			
Are there any Unverified Assumptions (UVAs)?			
Were UVAs justified?			
Are the inputs sufficiently documented considering the purpose of the analysis?			
Is all the software used identified correctly (name, version, manual reference, OS, and compilers are documented)?			
Are the computer codes suitable for the present analysis?			
Does the model adequately represent the physical systems?			
Is the magnitude of the result reasonable?			
Are the directions of trends reasonable?			

Additional comments:

Technical Reviewer Date

ADVANCED REVIEW CHECKLIST

Method of Advanced Review used

____ In-Depth Calculation Review

____ Alternate Calculation

____ Qualification Test

Supporting Material: (Title, number of pages)

Independent Review Verification

	Yes	No
Did you perform the original calculation?		
Did you specify a single analytical approach?		
Did you rule out certain analytical considerations?		
Did you establish any input to the calculation being verified?		

Justification for any "Yes" to a question above:

Does the independent review support the calculation findings? What differences were observed?

Additional comments:

____

Reviewer Date

APPENDIX D. MATERIAL DEFINITION

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Table D.1. Para-H Material Definition

Nuclide	Mass Fraction	Atom Fraction
^{4}H	1.0000E+00	1.0000E+00
Density (g/cm^3)	0.0729194	

Table D.2. H2O 293K Material Definition

Nuclide	Mass Fraction	Atom Fraction
^{1}H	1.1190E-01	6.6659E-01
^{2}H	2.5720E-05	7.6667E-05
^{16}O	8.8772E-01	3.3321E-01
^{17}O	3.5865E-04	1.2667E-04
Density (g/cm^3)	1.0	

Table D.3. HD concrete Material Definition

Nuclide	Mass Fraction	Atom Fraction
^{1}H	3.7726E-03	1.0151E-01
^{16}O	3.2409E-01	5.4945E-01
^{23}Na	1.0033E-04	1.1834E-04
^{24}Mg	1.6261E-03	1.8384E-03
^{25}Mg	2.1445E-04	2.3274E-04
^{26}Mg	2.4553E-04	2.5625E-04
^{27}Al	5.3969E-03	5.4241E-03
^{28}Si	1.8100E-02	1.7544E-02
^{29}Si	9.5236E-04	8.9127E-04
^{30}Si	6.5017E-04	5.8822E-04

Table D.3 – continued from previous page

Nuclide	Mass Fraction	Atom Fraction
^{32}S	1.0697E-03	9.0731E-04
^{39}K	1.8501E-04	1.2876E-04
^{40}K	2.3807E-08	1.6154E-08
^{41}K	1.4036E-05	9.2923E-06
^{40}Ca	4.3534E-02	2.9541E-02
^{42}Ca	3.0507E-04	1.9716E-04
^{43}Ca	6.5171E-05	4.1140E-05
^{44}Ca	1.0304E-03	6.3568E-04
^{46}Ca	2.0656E-06	1.2189E-06
^{48}Ca	1.0077E-04	5.6986E-05
^{55}Mn	8.7910E-04	4.3393E-04
^{54}Fe	3.1877E-02	1.6026E-02
^{56}Fe	5.5139E-01	2.6732E-01
^{57}Fe	1.2755E-02	6.0750E-03
^{58}Fe	1.6434E-03	7.6924E-04
Density (g/cm^3)	3.84	

Table D.4. Ordinary concrete Material Definition

Nuclide	Mass Fraction	Atom Fraction
^{1}H	5.5571E-03	1.0357E-01
^{2}H	1.6661E-06	1.5537E-05
^{16}O	4.9801E-01	5.8481E-01
^{23}Na	1.7104E-02	1.3974E-02
^{24}Mg	1.9999E-03	1.5661E-03
^{25}Mg	2.6374E-04	1.9827E-04
^{26}Mg	3.0197E-04	2.1829E-04
^{27}Al	4.5753E-02	3.1850E-02

Table D.4 – continued from previous page

Nuclide	Mass Fraction	Atom Fraction
^{28}Si	2.8950E-01	1.9436E-01
^{29}Si	1.5232E-02	9.8739E-03
^{30}Si	1.0399E-02	6.5165E-03
^{32}S	1.2791E-03	7.5143E-04
^{39}K	1.7883E-02	8.6205E-03
^{40}K	2.3011E-06	1.0815E-06
^{41}K	1.3567E-03	6.2212E-04
^{40}Ca	8.0184E-02	3.7687E-02
^{42}Ca	5.6189E-04	2.5153E-04
^{43}Ca	1.2004E-04	5.2483E-05
^{44}Ca	1.8978E-03	8.1097E-04
^{46}Ca	3.8046E-06	1.5551E-06
^{48}Ca	1.8560E-04	7.2699E-05
^{54}Fe	7.0664E-04	2.4607E-04
^{56}Fe	1.1392E-02	3.8253E-03
^{57}Fe	2.6549E-04	8.7583E-05
^{58}Fe	3.6019E-05	1.1678E-05
Density (g/cm^3)	2.339	

Table D.5. Air Material Definition

Nuclide	Mass Fraction	Atom Fraction
^{1}H	1.8280E-03	2.5785E-02
^{2}H	5.4787E-07	3.8670E-06
^{4}He	6.7995E-07	2.4150E-06
^{0}C	1.2244E-04	1.4492E-04
^{14}N	7.4036E-01	7.5162E-01
^{15}N	2.9141E-03	2.7618E-03

Table D.5 – continued from previous page

Nuclide	Mass Fraction	Atom Fraction
^{16}O	2.4200E-01	2.1508E-01
^{17}O	9.7956E-05	8.1918E-05
^{20}Ne	1.2228E-05	8.6950E-06
^{36}Ar	3.8367E-05	1.5164E-05
^{38}Ar	7.6056E-06	2.8481E-06
^{40}Ar	1.2618E-02	4.4885E-03
^{78}Kr	9.2658E-09	1.6905E-09
^{80}Kr	6.1091E-08	1.0867E-08
^{82}Kr	3.2282E-07	5.6026E-08
^{84}Kr	1.6248E-06	2.7528E-07
^{86}Kr	5.0493E-07	8.3553E-08
^{124}Xe	3.6066E-10	4.1379E-11
^{126}Xe	3.4261E-10	3.8685E-11
^{128}Xe	7.4702E-09	8.3028E-10
^{129}Xe	1.0405E-07	1.1475E-08
^{130}Xe	1.6169E-08	1.7695E-09
^{131}Xe	8.4981E-08	9.2288E-09
^{132}Xe	1.0852E-07	1.1696E-08
^{134}Xe	4.2726E-08	4.5360E-09
^{136}Xe	3.6805E-08	3.8499E-09
Density (g/cm^3)	0.0011988	

Table D.6. Inconel-718 Material Definition

Nuclide	Mass Fraction	Atom Fraction
^{10}B	1.1059E-05	6.3593E-05
^{11}B	4.8941E-05	2.5597E-04
^{0}C	8.0000E-04	3.8351E-03

Table D.6 – continued from previous page

Nuclide	Mass Fraction	Atom Fraction
^{27}Al	8.0000E-03	1.7072E-02
^{28}Si	3.2153E-03	6.6175E-03
^{29}Si	1.6918E-04	3.3617E-04
^{30}Si	1.1550E-04	2.2187E-04
^{31}P	1.5000E-04	2.7885E-04
^{32}S	1.4207E-04	2.5586E-04
^{33}S	1.1568E-06	2.0202E-06
^{34}S	6.7534E-06	1.1448E-05
^{36}S	1.6826E-08	2.6936E-08
^{46}Ti	9.1081E-04	1.1413E-03
^{47}Ti	8.3924E-04	1.0292E-03
^{48}Ti	8.4922E-03	1.0198E-02
^{49}Ti	6.3620E-04	7.4839E-04
^{50}Ti	6.2156E-04	7.1658E-04
^{50}Cr	8.7647E-03	1.0104E-02
^{52}Cr	1.7577E-01	1.9485E-01
^{53}Cr	2.0314E-02	2.2095E-02
^{54}Cr	5.1521E-03	5.4998E-03
^{55}Mn	3.5000E-03	3.6683E-03
^{54}Fe	6.7092E-03	7.1619E-03
^{56}Fe	1.0922E-01	1.1243E-01
^{57}Fe	2.5674E-03	2.5964E-03
^{58}Fe	3.4766E-04	3.4554E-04
^{59}Co	2.5000E-03	2.4426E-03
^{58}Ni	3.6959E-01	3.6732E-01
^{60}Ni	1.4727E-01	1.4149E-01
^{61}Ni	6.5085E-03	6.1505E-03
^{62}Ni	2.1091E-02	1.9610E-02
^{64}Ni	5.5448E-03	4.9942E-03
^{63}Cu	2.0544E-03	1.8797E-03

Table D.6 – continued from previous page

Nuclide	Mass Fraction	Atom Fraction
^{65}Cu	9.4562E-04	8.3860E-04
^{93}Nb	5.4500E-02	3.3777E-02
^{92}Mo	4.6693E-03	2.9253E-03
^{94}Mo	2.9814E-03	1.8281E-03
^{95}Mo	5.1906E-03	3.1491E-03
^{96}Mo	5.5025E-03	3.3036E-03
^{97}Mo	3.1867E-03	1.8934E-03
^{98}Mo	8.1464E-03	4.7910E-03
^{100}Mo	3.3231E-03	1.9152E-03
^{181}Ta	5.0000E-04	1.5910E-04
Density (g/cm^3)	8.19	

Table D.7. Zinc Selenide Material Definition

Nuclide	Mass Fraction	Atom Fraction
^{64}Zn	2.1369E-01	2.4129E-01
^{66}Zn	1.2772E-01	1.3984E-01
^{67}Zn	1.9012E-02	2.0505E-02
^{68}Zn	8.9486E-02	9.5099E-02
^{70}Zn	3.0555E-03	3.1543E-03
^{74}Se	4.5581E-03	4.4510E-03
^{76}Se	4.9284E-02	4.6860E-02
^{77}Se	4.0661E-02	3.8158E-02
^{78}Se	1.2832E-01	1.1888E-01
^{80}Se	2.7468E-01	2.4810E-01
^{82}Se	4.9545E-02	4.3660E-02
Density (g/cm^3)	5.27	

Table D.8. Al 5052-O Material Definition

Nuclide	Mass Fraction	Atom Fraction
^{24}Mg	2.1826E-02	2.4613E-02
^{25}Mg	2.8784E-03	3.1159E-03
^{26}Mg	3.2956E-03	3.4306E-03
^{27}Al	9.5900E-01	9.6134E-01
^{28}Si	2.2967E-03	2.2204E-03
^{29}Si	1.2084E-04	1.1280E-04
^{30}Si	8.2497E-05	7.4443E-05
^{50}Cr	1.4608E-04	7.9107E-05
^{52}Cr	2.9295E-03	1.5255E-03
^{53}Cr	3.3858E-04	1.7298E-04
^{54}Cr	8.5868E-05	4.3058E-05
^{55}Mn	1.0000E-03	4.9233E-04
^{54}Fe	2.2582E-04	1.1323E-04
^{56}Fe	3.6759E-03	1.7775E-03
^{57}Fe	8.6412E-05	4.1051E-05
^{58}Fe	1.1701E-05	5.4629E-06
^{63}Cu	6.8479E-04	2.9433E-04
^{65}Cu	3.1521E-04	1.3131E-04
^{64}Zn	4.7190E-04	1.9965E-04
^{66}Zn	2.8204E-04	1.1571E-04
^{67}Zn	4.1984E-05	1.6967E-05
^{68}Zn	1.9761E-04	7.8690E-05
^{70}Zn	6.7476E-06	2.6100E-06
Density (g/cm^3)	2.68	

Table D.9. Beryllium Material Definition

Nuclide	Mass Fraction	Atom Fraction
^{6}Li	3.8068E-06	5.7596E-06
^{7}Li	5.4060E-05	7.0124E-05
^{9}Be	9.8503E-01	9.9471E-01
^{10}B	1.5608E-06	1.4186E-06
^{11}B	6.9076E-06	5.7101E-06
^{0}C	9.5117E-04	7.2071E-04
^{16}O	6.1391E-03	3.4930E-03
^{17}O	2.4854E-06	1.3306E-06
^{24}Mg	4.0007E-04	1.5180E-04
^{25}Mg	5.2761E-05	1.9218E-05
^{26}Mg	6.0408E-05	2.1159E-05
^{27}Al	6.4155E-04	2.1639E-04
^{28}Si	3.5362E-04	1.1503E-04
^{29}Si	1.8606E-05	5.8438E-06
^{30}Si	1.2702E-05	3.8567E-06
^{54}Fe	4.7084E-05	7.9441E-06
^{56}Fe	7.6647E-04	1.2471E-04
^{57}Fe	1.8018E-05	2.8800E-06
^{58}Fe	2.4399E-06	3.8328E-07
^{103}Rh	2.7292E-04	2.4136E-05
^{107}Ag	1.9123E-04	1.6280E-05
^{109}Ag	1.8100E-04	1.5125E-05
^{106}Cd	3.1430E-07	2.7008E-08
^{108}Cd	2.2801E-07	1.9230E-08
^{110}Cd	3.2590E-06	2.6987E-07
^{111}Cd	3.3703E-06	2.7657E-07
^{112}Cd	6.4108E-06	5.2137E-07
^{113}Cd	3.2756E-06	2.6403E-07

Table D.9 – continued from previous page

Nuclide	Mass Fraction	Atom Fraction
^{114}Cd	7.7693E-06	6.2076E-07
^{116}Cd	2.0610E-06	1.6183E-07
^{113}In	4.1028E-06	3.3071E-07
^{115}In	9.3155E-05	7.3782E-06
^{142}Nd	4.6057E-04	2.9537E-05
^{143}Nd	2.0804E-04	1.3249E-05
^{144}Nd	4.0869E-04	2.5845E-05
^{145}Nd	1.4352E-04	9.0135E-06
^{146}Nd	2.9947E-04	1.8678E-05
^{148}Nd	1.0060E-04	6.1897E-06
^{150}Nd	1.0018E-04	6.0815E-06
^{144}Sm	4.7125E-07	2.9801E-08
^{147}Sm	2.3491E-06	1.4551E-07
^{148}Sm	1.7733E-06	1.0911E-07
^{149}Sm	2.1952E-06	1.3415E-07
^{150}Sm	1.1801E-06	7.1640E-08
^{152}Sm	4.3347E-06	2.5967E-07
^{154}Sm	3.7351E-06	2.2084E-07
^{151}Eu	9.4735E-06	5.7127E-07
^{153}Eu	1.0478E-05	6.2359E-07
^{152}Gd	3.9667E-09	2.3763E-10
^{154}Gd	4.3806E-08	2.5901E-09
^{155}Gd	2.9934E-07	1.7584E-08
^{156}Gd	4.1668E-07	2.4321E-08
^{157}Gd	3.2062E-07	1.8594E-08
^{158}Gd	5.1213E-07	2.9513E-08
^{160}Gd	4.5641E-07	2.5972E-08
^{156}Dy	5.5191E-08	3.2213E-09
^{158}Dy	9.4828E-08	5.4647E-09
^{160}Dy	2.3543E-06	1.3397E-07

Table D.9 – continued from previous page

Nuclide	Mass Fraction	Atom Fraction
^{161}Dy	1.9214E-05	1.0866E-06
^{162}Dy	2.6074E-05	1.4654E-06
^{163}Dy	2.5639E-05	1.4321E-06
^{164}Dy	2.9282E-05	1.6256E-06
^{162}Er	8.2284E-07	4.6246E-08
^{164}Er	9.5945E-06	5.3266E-07
^{166}Er	2.0322E-04	1.1146E-05
^{167}Er	1.3956E-04	7.6087E-06
^{168}Er	1.6562E-04	8.9757E-06
^{170}Er	9.2627E-05	4.9606E-06
^{169}Tm	2.8158E-04	1.5169E-05
^{175}Lu	7.2313E-04	3.7619E-05
^{176}Lu	1.9337E-05	1.0003E-06
^{174}Hf	3.7713E-07	1.9732E-08
^{176}Hf	1.2540E-05	6.4866E-07
^{177}Hf	4.4598E-05	2.2938E-06
^{178}Hf	6.5781E-05	3.3643E-06
^{179}Hf	3.3027E-05	1.6797E-06
^{180}Hf	8.5540E-05	4.3262E-06
^{191}Ir	8.7890E-05	4.1887E-06
^{193}Ir	1.4929E-04	7.0412E-06
^{197}Au	3.4086E-04	1.5749E-05
^{196}Hg	4.7456E-07	2.2039E-08
^{198}Hg	3.1865E-05	1.4649E-06
^{199}Hg	5.4189E-05	2.4786E-06
^{200}Hg	7.4575E-05	3.3940E-06
^{201}Hg	4.2763E-05	1.9365E-06
^{202}Hg	9.7364E-05	4.3872E-06
^{204}Hg	2.2623E-05	1.0094E-06
^{234}U	1.7031E-09	6.6227E-11

Table D.9 – continued from previous page

Nuclide	Mass Fraction	Atom Fraction
^{235}U	2.2819E-07	8.8352E-09
^{238}U	3.1848E-05	1.2176E-06
Density (g/cm^3)	1.82922	

Table D.10. Steel A36 Material Definition

Nuclide	Mass Fraction	Atom Fraction
^{0}C	2.6000E-03	1.1921E-02
^{28}Si	3.6747E-03	7.2333E-03
^{29}Si	1.9335E-04	3.6746E-04
^{30}Si	1.3200E-04	2.4251E-04
^{31}P	4.0000E-04	7.1119E-04
^{32}S	4.7358E-04	8.1572E-04
^{33}S	3.8560E-06	6.4405E-06
^{34}S	2.2511E-05	3.6496E-05
^{36}S	5.6085E-08	8.5874E-08
^{55}Mn	1.2000E-02	1.2029E-02
^{54}Fe	5.5214E-02	5.6371E-02
^{56}Fe	8.9880E-01	8.8491E-01
^{57}Fe	2.1128E-02	2.0436E-02
^{58}Fe	2.8611E-03	2.7197E-03
^{59}Co	5.0000E-04	4.6723E-04
^{63}Cu	1.3696E-03	1.1985E-03
^{65}Cu	6.3042E-04	5.3471E-04
Density (g/cm^3)	7.85	

Table D.11. Steel A572 Material Definition

Nuclide	Mass Fraction	Atom Fraction
^{0}C	2.3000E-03	1.0554E-02
^{28}Si	3.6748E-03	7.2394E-03
^{29}Si	1.9335E-04	3.6777E-04
^{30}Si	1.3200E-04	2.4272E-04
^{31}P	4.0001E-04	7.1179E-04
^{32}S	4.7357E-04	8.1638E-04
^{33}S	3.8560E-06	6.4458E-06
^{34}S	2.2511E-05	3.6526E-05
^{36}S	5.6085E-08	8.5944E-08
^{55}Mn	1.3501E-02	1.3544E-02
^{54}Fe	5.5287E-02	5.6492E-02
^{56}Fe	8.9949E-01	8.8631E-01
^{57}Fe	2.1157E-02	2.0480E-02
^{58}Fe	2.8649E-03	2.7256E-03
^{59}Co	5.0000E-04	4.6761E-04
Density (g/cm^3)	7.8	

Table D.12. Copper Material Definition

Nuclide	Mass Fraction	Atom Fraction
^{16}O	4.9865E-06	1.9810E-05
^{17}O	2.0187E-09	7.5462E-09
^{31}P	3.0000E-06	6.1547E-06
^{32}S	1.4207E-05	2.8237E-05
^{33}S	1.1568E-07	2.2295E-07
^{34}S	6.7534E-07	1.2634E-06
^{36}S	1.6826E-09	2.9727E-09

Table D.12 – continued from previous page

Nuclide	Mass Fraction	Atom Fraction
^{55}Mn	5.0000E-07	5.7833E-07
^{54}Fe	5.6456E-07	6.6509E-07
^{56}Fe	9.1902E-06	1.0440E-05
^{57}Fe	2.1604E-07	2.4112E-07
^{58}Fe	2.9255E-08	3.2089E-08
^{58}Ni	6.7198E-06	7.3704E-06
^{60}Ni	2.6776E-06	2.8391E-06
^{61}Ni	1.1834E-07	1.2342E-07
^{62}Ni	3.8349E-07	3.9350E-07
^{64}Ni	1.0082E-07	1.0022E-07
^{63}Cu	6.8473E-01	6.9142E-01
^{65}Cu	3.1518E-01	3.0847E-01
^{64}Zn	4.7177E-07	4.6893E-07
^{66}Zn	2.8196E-07	2.7178E-07
^{67}Zn	4.1973E-08	3.9852E-08
^{68}Zn	1.9756E-07	1.8482E-07
^{70}Zn	6.7458E-09	6.1303E-09
^{75}As	5.0000E-06	4.2408E-06
^{74}Se	2.4997E-08	2.1488E-08
^{76}Se	2.7028E-07	2.2623E-07
^{77}Se	2.2299E-07	1.8422E-07
^{78}Se	7.0369E-07	5.7389E-07
^{80}Se	1.5064E-06	1.1978E-06
^{82}Se	2.7171E-07	2.1077E-07
^{107}Ag	1.2844E-05	7.6345E-06
^{109}Ag	1.2156E-05	7.0929E-06
^{106}Cd	1.1777E-08	7.0663E-09
^{108}Cd	8.5432E-09	5.0311E-09
^{110}Cd	1.2211E-07	7.0603E-08
^{111}Cd	1.2628E-07	7.2355E-08

Table D.12 – continued from previous page

Nuclide	Mass Fraction	Atom Fraction
^{112}Cd	2.4021E-07	1.3641E-07
^{113}Cd	1.2274E-07	6.9081E-08
^{114}Cd	2.9111E-07	1.6241E-07
^{116}Cd	7.7228E-08	4.2340E-08
^{112}Sn	1.8288E-08	1.0385E-08
^{114}Sn	1.2666E-08	7.0662E-09
^{115}Sn	6.5820E-09	3.6400E-09
^{116}Sn	2.8392E-07	1.5566E-07
^{117}Sn	1.5126E-07	8.2220E-08
^{118}Sn	4.8110E-07	2.5930E-07
^{119}Sn	1.7208E-07	9.1964E-08
^{120}Sn	6.5815E-07	3.4880E-07
^{122}Sn	9.5092E-08	4.9569E-08
^{124}Sn	1.2087E-07	6.1988E-08
^{121}Sb	2.2723E-06	1.1943E-06
^{123}Sb	1.7277E-06	8.9327E-07
^{120}Te	1.6914E-09	8.9638E-10
^{122}Te	4.8722E-08	2.5397E-08
^{123}Te	1.7145E-08	8.8644E-09
^{124}Te	9.2052E-08	4.7210E-08
^{125}Te	1.3841E-07	7.0416E-08
^{126}Te	3.7178E-07	1.8764E-07
^{128}Te	6.3630E-07	3.1612E-07
^{130}Te	6.9391E-07	3.3943E-07
^{204}Pb	6.8905E-08	2.1466E-08
^{206}Pb	1.1978E-06	3.6953E-07
^{207}Pb	1.1037E-06	3.3885E-07
^{208}Pb	2.6296E-06	8.0344E-07
^{209}Bi	1.0000E-06	3.0407E-07

Table D.12 – continued from previous page

Nuclide	Mass Fraction	Atom Fraction
Density (g/cm^3)	7.144	

Table D.13. Inconel-625 Material Definition

Nuclide	Mass Fraction	Atom Fraction
^{0}C	9.8998E-04	4.8513E-03
^{27}Al	3.9600E-03	8.6386E-03
^{28}Si	4.5474E-03	9.5671E-03
^{29}Si	2.3927E-04	4.8602E-04
^{30}Si	1.6334E-04	3.2076E-04
^{31}P	1.4800E-04	2.8125E-04
^{32}S	1.4017E-04	2.5805E-04
^{33}S	1.1413E-06	2.0374E-06
^{34}S	6.6631E-06	1.1546E-05
^{36}S	1.6601E-08	2.7167E-08
^{46}Ti	3.1355E-04	4.0162E-04
^{47}Ti	2.8891E-04	3.6219E-04
^{48}Ti	2.9235E-03	3.5887E-03
^{49}Ti	2.1902E-04	2.6336E-04
^{50}Ti	2.1398E-04	2.5217E-04
^{50}Cr	8.9735E-03	1.0575E-02
^{52}Cr	1.7996E-01	2.0393E-01
^{53}Cr	2.0798E-02	2.3124E-02
^{54}Cr	5.2748E-03	5.7559E-03
^{55}Mn	4.9500E-03	5.3033E-03
^{54}Fe	2.7942E-03	3.0490E-03
^{56}Fe	4.5485E-02	4.7863E-02
^{57}Fe	1.0692E-03	1.1054E-03

Table D.13 – continued from previous page

Nuclide	Mass Fraction	Atom Fraction
^{58}Fe	1.4479E-04	1.4710E-04
^{59}Co	9.8990E-03	9.8866E-03
^{58}Ni	3.8975E-01	3.9596E-01
^{60}Ni	1.5530E-01	1.5252E-01
^{61}Ni	6.8635E-03	6.6301E-03
^{62}Ni	2.2242E-02	2.1140E-02
^{64}Ni	5.8473E-03	5.3837E-03
^{93}Nb	3.6500E-02	2.3124E-02
^{92}Mo	1.2734E-02	8.1553E-03
^{94}Mo	8.1309E-03	5.0964E-03
^{95}Mo	1.4156E-02	8.7792E-03
^{96}Mo	1.5007E-02	9.2099E-03
^{97}Mo	8.6907E-03	5.2786E-03
^{98}Mo	2.2217E-02	1.3357E-02
^{100}Mo	9.0630E-03	5.3393E-03
Density (g/cm^3)	8.44	

Table D.14. 17-4 PH condition A SS Material Definition

Nuclide	Mass Fraction	Atom Fraction
^{0}C	3.5000E-04	1.6103E-03
^{28}Si	4.5934E-03	9.0733E-03
^{29}Si	2.4169E-04	4.6093E-04
^{30}Si	1.6500E-04	3.0420E-04
^{31}P	2.0001E-04	3.5684E-04
^{32}S	1.4207E-04	2.4556E-04
^{33}S	1.1568E-06	1.9389E-06
^{34}S	6.7533E-06	1.0987E-05

Table D.14 – continued from previous page

Nuclide	Mass Fraction	Atom Fraction
^{36}S	1.6825E-08	2.5851E-08
^{50}Cr	6.8033E-03	7.5274E-03
^{52}Cr	1.3643E-01	1.4516E-01
^{53}Cr	1.5768E-02	1.6460E-02
^{54}Cr	3.9991E-03	4.0972E-03
^{55}Mn	5.0001E-03	5.0296E-03
^{54}Fe	4.1850E-02	4.2876E-02
^{56}Fe	6.8126E-01	6.7307E-01
^{57}Fe	1.6015E-02	1.5544E-02
^{58}Fe	2.1686E-03	2.0686E-03
^{59}Co	2.0001E-03	1.8755E-03
^{58}Ni	2.6880E-02	2.5639E-02
^{60}Ni	1.0711E-02	9.8763E-03
^{61}Ni	4.7336E-04	4.2931E-04
^{62}Ni	1.5340E-03	1.3688E-03
^{64}Ni	4.0327E-04	3.4860E-04
^{63}Cu	2.7392E-02	2.4055E-02
^{65}Cu	1.2609E-02	1.0732E-02
^{93}Nb	3.0001E-03	1.7845E-03
Density (g/cm^3)	7.78	

Table D.15. SS-304 Material Definition

Nuclide	Mass Fraction	Atom Fraction
^{0}C	7.9073E-04	3.5937E-03
^{28}Si	9.1866E-03	1.7924E-02
^{29}Si	4.8336E-04	9.1058E-04
^{30}Si	3.2999E-04	6.0097E-04

Table D.15 – continued from previous page

Nuclide	Mass Fraction	Atom Fraction
^{31}P	4.5000E-04	7.9307E-04
^{32}S	2.8415E-04	4.8514E-04
^{33}S	2.3136E-06	3.8304E-06
^{34}S	1.3507E-05	2.1706E-05
^{36}S	3.3651E-08	5.1072E-08
^{50}Cr	8.3474E-03	9.1231E-03
^{52}Cr	1.6740E-01	1.7593E-01
^{53}Cr	1.9347E-02	1.9949E-02
^{54}Cr	4.9067E-03	4.9657E-03
^{55}Mn	2.0000E-02	1.9872E-02
^{54}Fe	3.7060E-02	3.7505E-02
^{56}Fe	6.0329E-01	5.8876E-01
^{57}Fe	1.4182E-02	1.3597E-02
^{58}Fe	1.9204E-03	1.8095E-03
^{59}Co	2.0000E-03	1.8525E-03
^{58}Ni	7.3917E-02	6.9646E-02
^{60}Ni	2.9454E-02	2.6828E-02
^{61}Ni	1.3017E-03	1.1662E-03
^{62}Ni	4.2183E-03	3.7183E-03
^{64}Ni	1.1090E-03	9.4696E-04
Density (g/cm^3)	8.0	

Table D.16. SS-316 Material Definition

Nuclide	Mass Fraction	Atom Fraction
^{0}C	7.9073E-04	3.6489E-03
^{28}Si	9.1866E-03	1.8200E-02
^{29}Si	4.8336E-04	9.2456E-04

Table D.16 – continued from previous page

Nuclide	Mass Fraction	Atom Fraction
^{30}Si	3.2999E-04	6.1020E-04
^{31}P	4.5000E-04	8.0525E-04
^{32}S	2.8415E-04	4.9259E-04
^{33}S	2.3136E-06	3.8892E-06
^{34}S	1.3507E-05	2.2040E-05
^{36}S	3.3651E-08	5.1857E-08
^{50}Cr	7.5126E-03	8.3368E-03
^{52}Cr	1.5066E-01	1.6077E-01
^{53}Cr	1.7412E-02	1.8229E-02
^{54}Cr	4.4161E-03	4.5378E-03
^{55}Mn	2.0000E-02	2.0178E-02
^{54}Fe	3.4802E-02	3.5761E-02
^{56}Fe	5.6653E-01	5.6137E-01
^{57}Fe	1.3318E-02	1.2965E-02
^{58}Fe	1.8034E-03	1.7253E-03
^{59}Co	2.0000E-03	1.8810E-03
^{58}Ni	9.4077E-02	9.0002E-02
^{60}Ni	3.7486E-02	3.4668E-02
^{61}Ni	1.6567E-03	1.5070E-03
^{62}Ni	5.3688E-03	4.8051E-03
^{64}Ni	1.4114E-03	1.2237E-03
^{92}Mo	4.2448E-03	2.5599E-03
^{94}Mo	2.7103E-03	1.5997E-03
^{95}Mo	4.7187E-03	2.7558E-03
^{96}Mo	5.0023E-03	2.8910E-03
^{97}Mo	2.8970E-03	1.6569E-03
^{98}Mo	7.4059E-03	4.1926E-03
^{100}Mo	3.0210E-03	1.6760E-03
Density (g/cm^3)	8.0	

Table D.17. SS-316L Material Definition

Nuclide	Mass Fraction	Atom Fraction
^{0}C	2.9652E-04	1.3708E-03
^{28}Si	9.1866E-03	1.8232E-02
^{29}Si	4.8336E-04	9.2621E-04
^{30}Si	3.2999E-04	6.1129E-04
^{31}P	4.5000E-04	8.0669E-04
^{32}S	2.8415E-04	4.9347E-04
^{33}S	2.3136E-06	3.8962E-06
^{34}S	1.3507E-05	2.2079E-05
^{36}S	3.3651E-08	5.1949E-08
^{50}Cr	7.5126E-03	8.3517E-03
^{52}Cr	1.5066E-01	1.6106E-01
^{53}Cr	1.7412E-02	1.8262E-02
^{54}Cr	4.4161E-03	4.5459E-03
^{55}Mn	2.0000E-02	2.0214E-02
^{54}Fe	3.4830E-02	3.5854E-02
^{56}Fe	5.6699E-01	5.6283E-01
^{57}Fe	1.3328E-02	1.2998E-02
^{58}Fe	1.8049E-03	1.7299E-03
^{59}Co	2.0000E-03	1.8843E-03
^{58}Ni	9.4077E-02	9.0163E-02
^{60}Ni	3.7486E-02	3.4730E-02
^{61}Ni	1.6567E-03	1.5097E-03
^{62}Ni	5.3688E-03	4.8137E-03
^{64}Ni	1.4114E-03	1.2259E-03
^{92}Mo	4.2448E-03	2.5645E-03
^{94}Mo	2.7103E-03	1.6026E-03
^{95}Mo	4.7187E-03	2.7607E-03
^{96}Mo	5.0023E-03	2.8961E-03

Table D.17 – continued from previous page

Nuclide	Mass Fraction	Atom Fraction
^{97}Mo	2.8970E-03	1.6599E-03
^{98}Mo	7.4059E-03	4.2001E-03
^{100}Mo	3.0210E-03	1.6790E-03
Density (g/cm^3)	8.0	

Table D.18. Ta max impurities Material Definition

Nuclide	Mass Fraction	Atom Fraction
^{1}H	1.4999E-05	2.6692E-03
^{2}H	3.4474E-09	3.0698E-07
^{0}C	9.8854E-05	1.4761E-03
^{14}N	9.9622E-05	1.2760E-03
^{15}N	3.8987E-07	4.6615E-06
^{16}O	1.4961E-04	1.6776E-03
^{17}O	6.0569E-08	6.3904E-07
^{28}Si	4.5938E-05	2.9450E-04
^{29}Si	2.4171E-06	1.4961E-05
^{30}Si	1.6501E-06	9.8735E-06
^{46}Ti	7.9210E-06	3.0915E-05
^{47}Ti	7.2986E-06	2.7880E-05
^{48}Ti	7.3854E-05	2.7625E-04
^{49}Ti	5.5328E-06	2.0273E-05
^{50}Ti	5.4055E-06	1.9411E-05
^{54}Fe	5.6463E-06	1.8774E-05
^{56}Fe	9.1913E-05	2.9471E-04
^{57}Fe	2.1606E-06	6.8062E-06
^{58}Fe	2.9257E-07	9.0576E-07
^{58}Ni	6.7206E-05	2.0805E-04

Table D.18 – continued from previous page

Nuclide	Mass Fraction	Atom Fraction
^{60}Ni	2.6779E-05	8.0140E-05
^{61}Ni	1.1835E-06	3.4837E-06
^{62}Ni	3.8353E-06	1.1107E-05
^{64}Ni	1.0083E-06	2.8289E-06
^{93}Nb	1.0001E-03	1.9307E-03
^{92}Mo	2.8302E-05	5.5230E-05
^{94}Mo	1.8071E-05	3.4514E-05
^{95}Mo	3.1462E-05	5.9456E-05
^{96}Mo	3.3353E-05	6.2373E-05
^{97}Mo	1.9315E-05	3.5748E-05
^{98}Mo	4.9378E-05	9.0454E-05
^{100}Mo	2.0142E-05	3.6159E-05
^{181}Ta	9.9759E-01	9.8878E-01
^{180}W	5.8736E-07	5.8541E-07
^{182}W	1.3115E-04	1.2928E-04
^{183}W	7.1211E-05	6.9810E-05
^{184}W	1.5331E-04	1.4947E-04
^{186}W	1.4380E-04	1.3869E-04
Density (g/cm^3)	16.65	

Table D.19. W max impurities Material Definition

Nuclide	Mass Fraction	Atom Fraction
^{0}C	9.8843E-05	1.5059E-03
^{14}N	9.9611E-05	1.3017E-03
^{15}N	3.8982E-07	4.7555E-06
^{16}O	9.9730E-05	1.1409E-03
^{17}O	4.0374E-08	4.3461E-07

Table D.19 – continued from previous page

Nuclide	Mass Fraction	Atom Fraction
^{28}Si	9.1867E-05	6.0087E-04
^{29}Si	4.8336E-06	3.0525E-05
^{30}Si	3.2999E-06	2.0146E-05
^{54}Fe	5.6456E-06	1.9153E-05
^{56}Fe	9.1903E-05	3.0065E-04
^{57}Fe	2.1604E-06	6.9435E-06
^{58}Fe	2.9254E-07	9.2402E-07
^{58}Ni	6.7198E-05	2.1225E-04
^{60}Ni	2.6776E-05	8.1756E-05
^{61}Ni	1.1834E-06	3.5540E-06
^{62}Ni	3.8348E-06	1.1331E-05
^{64}Ni	1.0082E-06	2.8859E-06
^{180}W	1.1739E-03	1.1937E-03
^{182}W	2.6211E-01	2.6361E-01
^{183}W	1.4232E-01	1.4235E-01
^{184}W	3.0640E-01	3.0480E-01
^{186}W	2.8739E-01	2.8281E-01
Density (g/cm^3)	19.25	

Table D.20. Steel 1018 Material Definition

Nuclide	Mass Fraction	Atom Fraction
^{0}C	2.0000E-03	9.2240E-03
^{31}P	4.0001E-04	7.1539E-04
^{32}S	4.7357E-04	8.2051E-04
^{33}S	3.8560E-06	6.4783E-06
^{34}S	2.2511E-05	3.6711E-05
^{36}S	5.6085E-08	8.6379E-08

Table D.20 – continued from previous page

Nuclide	Mass Fraction	Atom Fraction
^{55}Mn	9.0003E-03	9.0750E-03
^{54}Fe	5.5784E-02	5.7288E-02
^{56}Fe	9.0808E-01	8.9930E-01
^{57}Fe	2.1347E-02	2.0769E-02
^{58}Fe	2.8906E-03	2.7639E-03
Density (g/cm^3)	7.87	

Table D.21. Al ASTM B247-M-20 Material Definition

Nuclide	Mass Fraction	Atom Fraction
^{24}Mg	9.3540E-03	1.0623E-02
^{25}Mg	1.2336E-03	1.3449E-03
^{26}Mg	1.4124E-03	1.4807E-03
^{27}Al	9.6000E-01	9.6919E-01
^{28}Si	7.3493E-03	7.1557E-03
^{29}Si	3.8669E-04	3.6352E-04
^{30}Si	2.6399E-04	2.3991E-04
^{46}Ti	1.1880E-04	7.0422E-05
^{47}Ti	1.0947E-04	6.3511E-05
^{48}Ti	1.1077E-03	6.2930E-04
^{49}Ti	8.2983E-05	4.6181E-05
^{50}Ti	8.1073E-05	4.4217E-05
^{50}Cr	1.4608E-04	7.9670E-05
^{52}Cr	2.9295E-03	1.5364E-03
^{53}Cr	3.3858E-04	1.7421E-04
^{54}Cr	8.5868E-05	4.3365E-05
^{55}Mn	1.5000E-03	7.4374E-04
^{54}Fe	3.9519E-04	1.9957E-04

Table D.21 – continued from previous page

Nuclide	Mass Fraction	Atom Fraction
^{56}Fe	6.4331E-03	3.1329E-03
^{57}Fe	1.5123E-04	7.2354E-05
^{58}Fe	2.0478E-05	9.6286E-06
^{63}Cu	2.7392E-03	1.1857E-03
^{65}Cu	1.2608E-03	5.2896E-04
^{64}Zn	1.1794E-03	5.0254E-04
^{66}Zn	7.0491E-04	2.9126E-04
^{67}Zn	1.0493E-04	4.2707E-05
^{68}Zn	4.9390E-04	1.9807E-04
^{70}Zn	1.6864E-05	6.5695E-06
Density (g/cm^3)	2.7	

Table D.22. Graphite Material Definition

Nuclide	Mass Fraction	Atom Fraction
^{10}B	1.8431E-07	2.2109E-07
^{11}B	8.1569E-07	8.8991E-07
^{0}C	1.0000E+00	1.0000E+00
Density (g/cm^3)	1.7	

Table D.23. Copper Chromium Zirconium Material Definition

Nuclide	Mass Fraction	Atom Fraction
^{28}Si	9.1867E-04	2.0801E-03
^{29}Si	4.8336E-05	1.0567E-04
^{30}Si	3.2999E-05	6.9741E-05
^{50}Cr	5.0084E-04	6.3523E-04

Table D.23 – continued from previous page

Nuclide	**Mass Fraction**	**Atom Fraction**
^{52}Cr	1.0044E-02	1.2250E-02
^{53}Cr	1.1608E-03	1.3890E-03
^{54}Cr	2.9440E-04	3.4576E-04
^{54}Fe	4.5164E-05	5.3042E-05
^{56}Fe	7.3521E-04	8.3265E-04
^{57}Fe	1.7283E-05	1.9229E-05
^{58}Fe	2.3404E-06	2.5591E-06
^{63}Cu	6.7329E-01	6.7776E-01
^{65}Cu	3.0991E-01	3.0237E-01
^{90}Zr	1.5212E-03	1.0718E-03
^{91}Zr	3.3543E-04	2.3374E-04
^{92}Zr	5.1834E-04	3.5728E-04
^{94}Zr	5.3673E-04	3.6207E-04
^{96}Zr	8.8314E-05	5.8332E-05
Density (g/cm^3)	8.89	

Table D.24. PPE Type Oil Material Definition

Nuclide	**Mass Fraction**	**Atom Fraction**
^{1}H	6.7097E-02	4.7053E-01
^{2}H	1.5422E-05	5.4118E-05
^{0}C	7.9974E-01	4.7059E-01
^{16}O	1.3280E-01	5.8681E-02
^{17}O	3.4380E-04	1.4294E-04
Density (g/cm^3)	1.166	

Table D.25. EPDM Material Definition

Nuclide	Mass Fraction	Atom Fraction
^{1}H	1.4111E-01	6.6190E-01
^{2}H	3.2435E-05	7.6127E-05
^{0}C	8.5886E-01	3.3803E-01
Density (g/cm^3)	0.9	

Table D.26. Steel 1040 ASTM A830 Material Definition

Nuclide	Mass Fraction	Atom Fraction
^{0}C	4.4000E-03	2.0123E-02
^{31}P	3.0001E-04	5.3206E-04
^{32}S	2.8415E-04	4.8819E-04
^{33}S	2.3136E-06	3.8545E-06
^{34}S	1.3507E-05	2.1843E-05
^{36}S	3.3651E-08	5.1394E-08
^{55}Mn	9.0003E-03	8.9991E-03
^{54}Fe	5.5665E-02	5.6688E-02
^{56}Fe	9.0565E-01	8.8939E-01
^{57}Fe	2.1301E-02	2.0551E-02
^{58}Fe	2.8845E-03	2.7350E-03
^{59}Co	5.0000E-04	4.6604E-04
Density (g/cm^3)	7.85	

Table D.27. Steel 4130 ASTM A829 Material Definition

Nuclide	Mass Fraction	Atom Fraction
^{0}C	3.3000E-03	1.5104E-02

Table D.27 – continued from previous page

Nuclide	Mass Fraction	Atom Fraction
^{28}Si	3.2154E-03	6.3180E-03
^{29}Si	1.6918E-04	3.2096E-04
^{30}Si	1.1550E-04	2.1183E-04
^{31}P	3.0001E-04	5.3246E-04
^{32}S	3.7886E-04	6.5140E-04
^{33}S	3.0848E-06	5.1432E-06
^{34}S	1.8009E-05	2.9145E-05
^{36}S	4.4868E-08	6.8576E-08
^{50}Cr	4.5912E-04	5.0532E-04
^{52}Cr	9.2073E-03	9.7446E-03
^{53}Cr	1.0641E-03	1.1050E-03
^{54}Cr	2.6988E-04	2.7505E-04
^{55}Mn	6.0002E-03	6.0039E-03
^{54}Fe	5.4931E-02	5.5983E-02
^{56}Fe	8.9370E-01	8.7832E-01
^{57}Fe	2.1020E-02	2.0296E-02
^{58}Fe	2.8464E-03	2.7010E-03
^{92}Mo	3.5374E-04	2.1158E-04
^{94}Mo	2.2586E-04	1.3222E-04
^{95}Mo	3.9323E-04	2.2777E-04
^{96}Mo	4.1686E-04	2.3894E-04
^{97}Mo	2.4141E-04	1.3695E-04
^{98}Mo	6.1716E-04	3.4652E-04
^{100}Mo	2.5175E-04	1.3852E-04
^{59}Co	5.0000E-04	4.6639E-04
Density (g/cm^3)	7.85	

Table D.28. Steel 4340 ASTM A829 Material Definition

Nuclide	Mass Fraction	Atom Fraction
^{0}C	4.3000E-03	1.9635E-02
^{28}Si	3.2154E-03	6.3034E-03
^{29}Si	1.6918E-04	3.2022E-04
^{30}Si	1.1550E-04	2.1134E-04
^{31}P	3.0001E-04	5.3122E-04
^{32}S	3.7886E-04	6.4990E-04
^{33}S	3.0848E-06	5.1313E-06
^{34}S	1.8009E-05	2.9078E-05
^{36}S	4.4868E-08	6.8418E-08
^{50}Cr	3.7565E-04	4.1249E-04
^{52}Cr	7.5332E-03	7.9545E-03
^{53}Cr	8.7065E-04	9.0197E-04
^{54}Cr	2.2081E-04	2.2452E-04
^{55}Mn	8.0003E-03	7.9867E-03
^{54}Fe	5.3661E-02	5.4562E-02
^{56}Fe	8.7402E-01	8.5699E-01
^{57}Fe	2.0534E-02	1.9780E-02
^{58}Fe	2.7806E-03	2.6324E-03
^{59}Co	5.0003E-04	4.6534E-04
^{58}Ni	1.3440E-02	1.2723E-02
^{60}Ni	5.3554E-03	4.9009E-03
^{61}Ni	2.3668E-04	2.1304E-04
^{62}Ni	7.6699E-04	6.7926E-04
^{64}Ni	2.0164E-04	1.7299E-04
^{92}Mo	4.2449E-04	2.5331E-04
^{94}Mo	2.7103E-04	1.5830E-04
^{95}Mo	4.7187E-04	2.7269E-04
^{96}Mo	5.0023E-04	2.8607E-04

Table D.28 – continued from previous page

Nuclide	Mass Fraction	Atom Fraction
^{97}Mo	2.8970E-04	1.6396E-04
^{98}Mo	7.4059E-04	4.1487E-04
^{100}Mo	3.0211E-04	1.6584E-04
Density (g/cm^3)	7.85	

Table D.29. Steel 8620 ASTM A829 Material Definition

Nuclide	Mass Fraction	Atom Fraction
^{0}C	2.3000E-03	1.0572E-02
^{28}Si	3.2154E-03	6.3449E-03
^{29}Si	1.6918E-04	3.2233E-04
^{30}Si	1.1550E-04	2.1273E-04
^{31}P	3.0001E-04	5.3473E-04
^{32}S	3.7886E-04	6.5418E-04
^{33}S	3.0848E-06	5.1651E-06
^{34}S	1.8009E-05	2.9269E-05
^{36}S	4.4868E-08	6.8868E-08
^{50}Cr	2.5043E-04	2.7680E-04
^{52}Cr	5.0221E-03	5.3379E-03
^{53}Cr	5.8044E-04	6.0527E-04
^{54}Cr	1.4721E-04	1.5067E-04
^{55}Mn	9.0003E-03	9.0442E-03
^{54}Fe	5.4649E-02	5.5932E-02
^{56}Fe	8.9011E-01	8.7851E-01
^{57}Fe	2.0912E-02	2.0277E-02
^{58}Fe	2.8318E-03	2.6985E-03
^{59}Co	5.0003E-04	4.6841E-04
^{58}Ni	4.7040E-03	4.4824E-03

Table D.29 – continued from previous page

Nuclide	**Mass Fraction**	**Atom Fraction**
^{60}Ni	1.8744E-03	1.7266E-03
^{61}Ni	8.2838E-05	7.5055E-05
^{62}Ni	2.6845E-04	2.3931E-04
^{64}Ni	7.0573E-05	6.0945E-05
^{92}Mo	3.5374E-04	2.1248E-04
^{94}Mo	2.2586E-04	1.3278E-04
^{95}Mo	3.9323E-04	2.2874E-04
^{96}Mo	4.1686E-04	2.3996E-04
^{97}Mo	2.4141E-04	1.3753E-04
^{98}Mo	6.1716E-04	3.4800E-04
^{100}Mo	2.5175E-04	1.3911E-04
Density (g/cm^3)	7.85	

Table D.30. Steel 9310 AMS 6265R Material Definition

Nuclide	**Mass Fraction**	**Atom Fraction**
^{10}B	1.8432E-06	1.0210E-05
^{11}B	8.1572E-06	4.1096E-05
^{0}C	1.3000E-03	6.0032E-03
^{28}Si	3.2154E-03	6.3747E-03
^{29}Si	1.6918E-04	3.2384E-04
^{30}Si	1.1550E-04	2.1373E-04
^{31}P	1.5001E-04	2.6862E-04
^{32}S	1.4207E-04	2.4647E-04
^{33}S	1.1568E-06	1.9460E-06
^{34}S	6.7533E-06	1.1027E-05
^{36}S	1.6825E-08	2.5946E-08
^{50}Cr	5.8434E-04	6.4890E-04

Table D.30 – continued from previous page

Nuclide	Mass Fraction	Atom Fraction
^{52}Cr	1.1718E-02	1.2514E-02
^{53}Cr	1.3544E-03	1.4189E-03
^{54}Cr	3.4348E-04	3.5320E-04
^{55}Mn	7.0002E-03	7.0674E-03
^{54}Fe	5.2667E-02	5.4156E-02
^{56}Fe	8.5784E-01	8.5063E-01
^{57}Fe	2.0154E-02	1.9633E-02
^{58}Fe	2.7291E-03	2.6128E-03
^{59}Co	5.0003E-04	4.7061E-04
^{58}Ni	2.3520E-02	2.2517E-02
^{60}Ni	9.3719E-03	8.6735E-03
^{61}Ni	4.1419E-04	3.7703E-04
^{62}Ni	1.3422E-03	1.2021E-03
^{64}Ni	3.5286E-04	3.0615E-04
^{63}Cu	2.3968E-03	2.1125E-03
^{65}Cu	1.1033E-03	9.4247E-04
^{92}Mo	2.1224E-04	1.2809E-04
^{94}Mo	1.3552E-04	8.0044E-05
^{95}Mo	2.3594E-04	1.3789E-04
^{96}Mo	2.5012E-04	1.4465E-04
^{97}Mo	1.4485E-04	8.2905E-05
^{98}Mo	3.7029E-04	2.0978E-04
^{100}Mo	1.5105E-04	8.3859E-05
Density (g/cm^3)	7.85	

Table D.31. Silicon Carbide Material Definition

Nuclide	Mass Fraction	Atom Fraction
^{0}C	2.9955E-01	4.9999E-01
^{28}Si	6.4348E-01	4.6112E-01
^{29}Si	3.3857E-02	2.3425E-02
^{30}Si	2.3114E-02	1.5460E-02
Density (g/cm^3)	3.21	

Table D.32. Corning 7980 fused silica Material Definition

Nuclide	Mass Fraction	Atom Fraction
^{16}O	5.3112E-01	6.6499E-01
^{17}O	1.4432E-03	1.7003E-03
^{28}Si	4.2942E-01	3.0739E-01
^{29}Si	2.2594E-02	1.5615E-02
^{30}Si	1.5425E-02	1.0306E-02
Density (g/cm^3)	2.2	

Table D.33. Invar 20K Material Definition

Nuclide	Mass Fraction	Atom Fraction
^{0}C	1.4827E-03	6.9470E-03
^{28}Si	3.6748E-03	7.3922E-03
^{29}Si	1.9335E-04	3.7553E-04
^{30}Si	1.3200E-04	2.4784E-04
^{31}P	2.5001E-04	4.5426E-04
^{32}S	2.3679E-04	4.1680E-04
^{33}S	1.9280E-06	3.2909E-06

Table D.33 – continued from previous page

Nuclide	Mass Fraction	Atom Fraction
^{34}S	1.1255E-05	1.8648E-05
^{36}S	2.8043E-08	4.3879E-08
^{50}Cr	1.0435E-04	1.1758E-04
^{52}Cr	2.0926E-03	2.2673E-03
^{53}Cr	2.4185E-04	2.5710E-04
^{54}Cr	6.1337E-05	6.3997E-05
^{55}Mn	6.0002E-03	6.1466E-03
^{54}Fe	3.5031E-02	3.6550E-02
^{56}Fe	5.7025E-01	5.7375E-01
^{57}Fe	1.3405E-02	1.3251E-02
^{58}Fe	1.8153E-03	1.7634E-03
^{59}Co	5.0002E-03	4.7749E-03
^{58}Ni	2.4192E-01	2.3500E-01
^{60}Ni	9.6397E-02	9.0522E-02
^{61}Ni	4.2603E-03	3.9349E-03
^{62}Ni	1.3806E-02	1.2546E-02
^{64}Ni	3.6295E-03	3.1952E-03
Density (g/cm^3)	8.051	

Table D.34. Al-6061 20K Material Definition

Nuclide	Mass Fraction	Atom Fraction
^{24}Mg	9.3540E-03	1.0623E-02
^{25}Mg	1.2336E-03	1.3449E-03
^{26}Mg	1.4124E-03	1.4807E-03
^{27}Al	9.6000E-01	9.6919E-01
^{28}Si	7.3493E-03	7.1557E-03
^{29}Si	3.8669E-04	3.6352E-04

Table D.34 – continued from previous page

Nuclide	Mass Fraction	Atom Fraction
^{30}Si	2.6399E-04	2.3991E-04
^{46}Ti	1.1880E-04	7.0422E-05
^{47}Ti	1.0947E-04	6.3511E-05
^{48}Ti	1.1077E-03	6.2930E-04
^{49}Ti	8.2983E-05	4.6181E-05
^{50}Ti	8.1073E-05	4.4217E-05
^{50}Cr	1.4608E-04	7.9670E-05
^{52}Cr	2.9295E-03	1.5364E-03
^{53}Cr	3.3858E-04	1.7421E-04
^{54}Cr	8.5868E-05	4.3365E-05
^{55}Mn	1.5000E-03	7.4374E-04
^{54}Fe	3.9519E-04	1.9957E-04
^{56}Fe	6.4331E-03	3.1329E-03
^{57}Fe	1.5123E-04	7.2354E-05
^{58}Fe	2.0478E-05	9.6286E-06
^{63}Cu	2.7392E-03	1.1857E-03
^{65}Cu	1.2608E-03	5.2896E-04
^{64}Zn	1.1794E-03	5.0254E-04
^{66}Zn	7.0491E-04	2.9126E-04
^{67}Zn	1.0493E-04	4.2707E-05
^{68}Zn	4.9390E-04	1.9807E-04
^{70}Zn	1.6864E-05	6.5695E-06
Density (g/cm^3)	2.7	

Table D.35. SS-416 Material Definition

Nuclide	Mass Fraction	Atom Fraction
^{0}C	1.5000E-03	6.7882E-03

Table D.35 – continued from previous page

Nuclide	Mass Fraction	Atom Fraction
^{28}Si	9.1869E-03	1.7849E-02
^{29}Si	4.8338E-04	9.0673E-04
^{30}Si	3.3000E-04	5.9842E-04
^{31}P	6.0002E-04	1.0529E-03
^{32}S	1.4207E-03	2.4153E-03
^{33}S	1.1568E-05	1.9070E-05
^{34}S	6.7533E-05	1.0807E-04
^{36}S	1.6825E-07	2.5427E-07
^{50}Cr	5.8433E-03	6.3591E-03
^{52}Cr	1.1718E-01	1.2263E-01
^{53}Cr	1.3543E-02	1.3905E-02
^{54}Cr	3.4348E-03	3.4613E-03
^{55}Mn	1.2500E-02	1.2368E-02
^{54}Fe	4.6965E-02	4.7327E-02
^{56}Fe	7.6452E-01	7.4293E-01
^{57}Fe	1.7972E-02	1.7157E-02
^{58}Fe	2.4337E-03	2.2833E-03
^{59}Co	2.0001E-03	1.8447E-03
Density (g/cm^3)	7.7	

Table D.36. N2 Material Definition

Nuclide	Mass Fraction	Atom Fraction
^{14}N	9.9610E-01	9.9636E-01
^{15}N	3.8982E-03	3.6400E-03
Density (g/cm^3)	0.0035418	

APPENDIX E. DOSE CONVERSION FACTORS

APPENDIX E. DOSE CONVERSION FACTORS

Table E.1. Photon flux to dose conversion factors [16]

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

Table E.2. Neutron flux to dose conversion factors [16]

Energy (MeV)	**DCF (mrem hr^{-1} (n/cm^2/sec)$^{-1}$)**
1.0000E-09	1.8864E-03
1.0000E-08	2.3580E-03
2.5000E-08	2.7360E-03
1.0000E-07	3.5820E-03
2.0000E-07	4.0320E-03
5.0000E-07	4.6080E-03
1.0000E-06	4.9680E-03
2.0000E-06	5.2200E-03
5.0000E-06	5.4000E-03
1.0000E-05	5.4360E-03
2.0000E-05	5.4360E-03
5.0000E-05	5.3280E-03
1.0000E-04	5.2560E-03
2.0000E-04	5.1840E-03
5.0000E-04	5.1120E-03
1.0000E-03	5.1120E-03
2.0000E-03	5.1840E-03
5.0000E-03	5.6520E-03
1.0000E-02	6.5880E-03
2.0000E-02	8.5680E-03
3.0000E-02	1.0440E-02
5.0000E-02	1.3860E-02
7.0000E-02	1.6992E-02
1.0000E-01	2.1528E-02
1.5000E-01	2.8872E-02
2.0000E-01	3.5640E-02
3.0000E-01	4.7880E-02

Table E.2 – continued from previous page

Energy (MeV)	DCF (mrem hr^{-1} (n/cm^2/sec)$^{-1}$)
5.0000E-01	6.7680E-02
7.0000E-01	8.3160E-02
9.0000E-01	9.6120E-02
1.0000E+00	1.0152E-01
1.2000E+00	1.1160E-01
2.0000E+00	1.3788E-01
3.0000E+00	1.5552E-01
4.0000E+00	1.6488E-01
5.0000E+00	1.7064E-01
6.0000E+00	1.7388E-01
7.0000E+00	1.7640E-01
8.0000E+00	1.7784E-01
9.0000E+00	1.7892E-01
1.0000E+01	1.7964E-01
1.2000E+01	1.7964E-01
1.4000E+01	1.7856E-01
1.5000E+01	1.7784E-01
1.6000E+01	1.7676E-01
1.8000E+01	1.7496E-01
2.0000E+01	1.7280E-01
3.0000E+01	1.6488E-01
5.0000E+01	1.5732E-01
7.5000E+01	1.5444E-01
1.0000E+02	1.5444E-01
1.3000E+02	1.5552E-01
1.5000E+02	1.5768E-01
1.8000E+02	1.6020E-01
2.0000E+02	1.7028E-01
5.0000E+02	2.2680E-01

Table E.2 – continued from previous page

Energy (MeV)	**DCF (mrem hr^{-1} (n/cm^2/sec)$^{-1}$)**
1.0000E+03	3.4920E-01
2.0000E+03	5.0724E-01

APPENDIX F. DOSE RATE FIGURES

APPENDIX F. DOSE RATE FIGURES

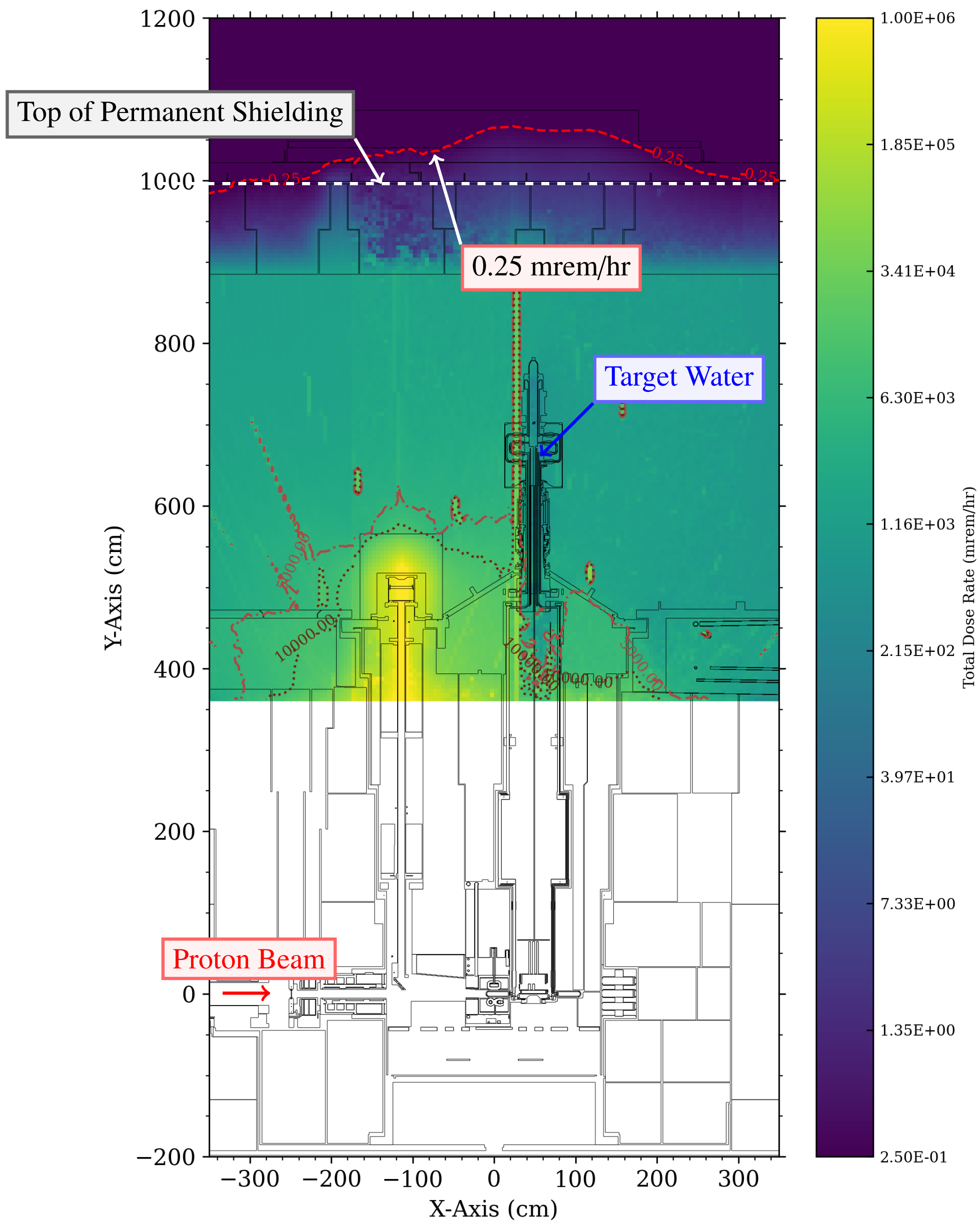

Figure F.1. Cross section view 0.51 cm off the proton beam of the beam-on-target source only total effective dose rates in the target drive room and through the target drive room ceiling.

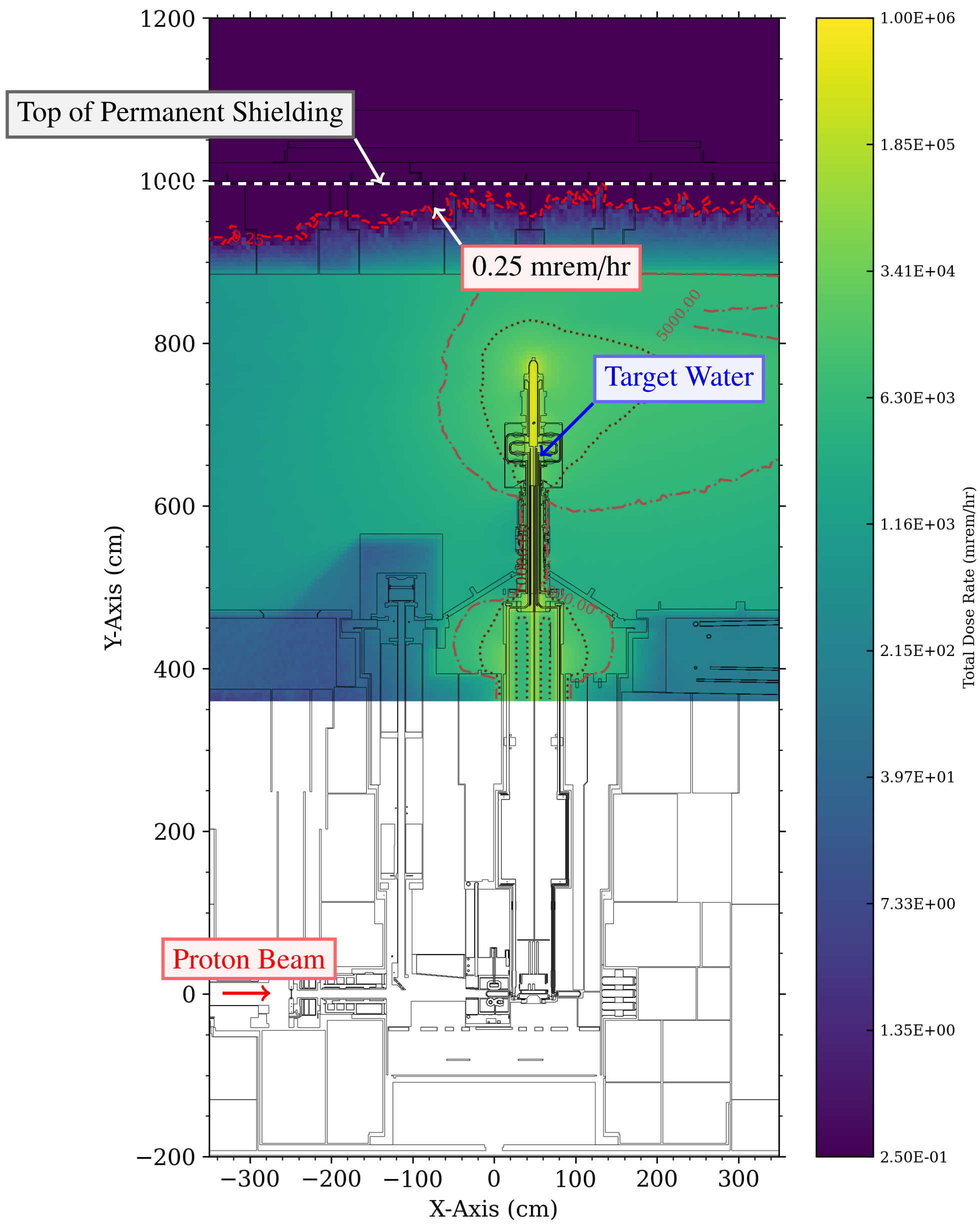

Figure F.2. Cross section view 0.51 cm off the proton beam of the water neutron and photon sources only total effective dose rates in the target drive room and through the target drive room ceiling.