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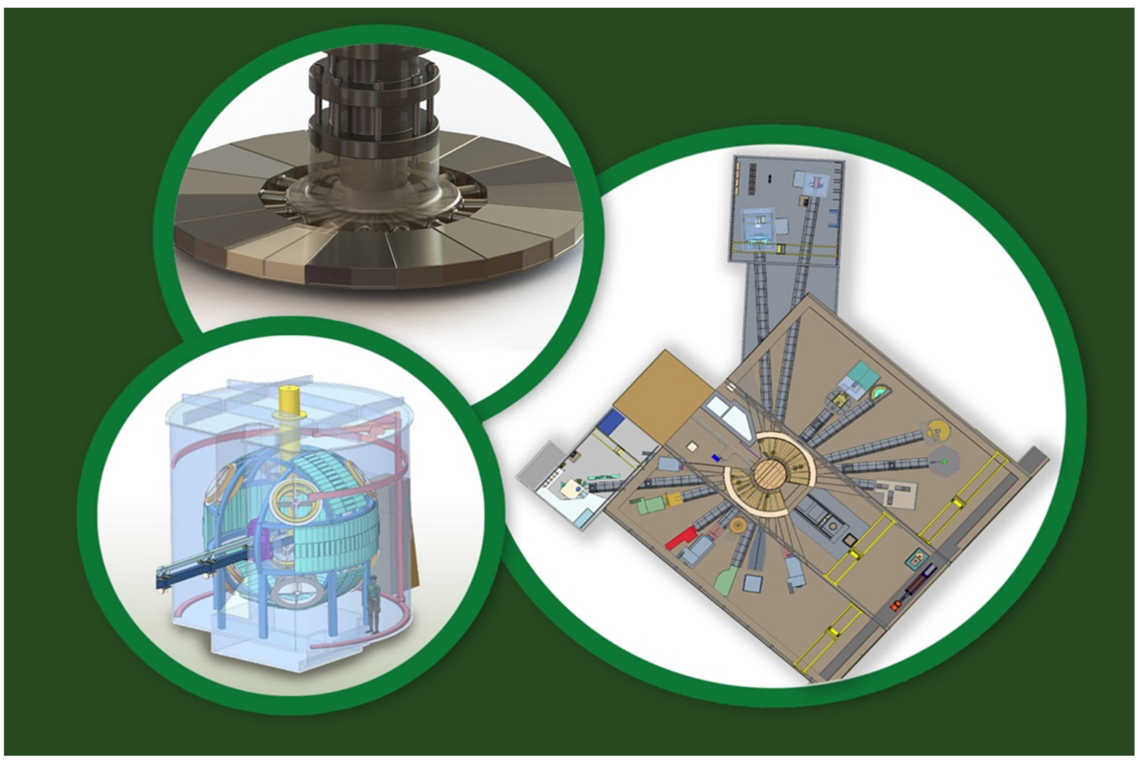
ORNL/TM-2024/3338

Oak Ridge National Laboratory Proton Beam Window In Situ Neutronics Analysis for the Preliminary Design for the Second Target Station



Kristel Ghoos

February 2024

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Second Target Station Project

Proton Beam Window In Situ Neutronics Analysis for the Preliminary Design for the Second Target Station

Kristel Ghoos

February 2024

Prepared by
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Oak Ridge, TN 37831
managed by
UT-Battelle LLC
for the
US DEPARTMENT OF ENERGY
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Proton Beam Window In Situ Neutronics Analysis for the Preliminary Design for the Second Target Station

LABORATORY ORNL	DIVISION/GROUP Second Target Station (STS) Project	CALC NO. S03120100-TRT10013
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	REV 0	REV 1	REV 2	REV 3
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Task Leader				
Level III Manager				
Checked By				
Lead Engineer				

CONTENTS

LIST OF FIGURES

ABBREVIATIONS

ORNL	Oak Ridge National Laboratory
PBT	Proton Beam Tube
PBW	Proton Beam Window
SNS	Spallation Neutron Source
STS	Second Target Station

1 SCOPE

These analyses provide estimates for the residual dose rates for various geometric configurations related to proton beam window (PBW) removal and replacement maintenance events. This information will be used to plan a remote handling strategy for the replacement and maintenance of the PBW. The 5 and 100 mrem/h dose rate contour lines are of specific interest as they classify radiation areas (between 5 and 100 mrem/h) and high radiation areas (>100 mrem/h).

The purpose of this analysis is to obtain estimates for the dose rates for five PBW maintenance events:

- The first configuration requires access inside the monolith and underneath the upper most shield block. There is a need to evaluate whether hands-on maintenance operations can be performed at the top of the PBW shielding. All components will remain in their operational location, except the top shield block will be removed. This analysis is performed for a decay time of 1 week.
- In the second configuration, the upstream PBW shield blocks are removed and there is a straight line of sight from the PBW out of the monolith into the target drive room. All remaining monolith components remain in their operational position. This analysis is performed for a decay time of 1 week.
- For the third configuration, the upstream PBW shield blocks and and the replaceable part of the PBW assembly are removed from their operational position in the monolith. All remaining monolith components remain in their operational position. This analysis is performed for a decay time of 2 weeks.
- For the fourth configuration, all PBW shield blocks and the replaceable part of the PBW assembly are removed from their operational position in the monolith. All remaining monolith components remain in their operational position. This analysis is performed for a decay time of 4 weeks.
- For the fifth configuration, all PBW shield blocks and the full PBW assembly are removed from their operational position in the monolith. All remaining monolith components remain in their operational position. This analysis is performed for a decay time of 4 weeks.

This is in response to a Neutronics Task Orders 85, 87, and 153 (https://ornl.sharepoint.com/sites/sts/targetsystems/Shared%20Documents/Forms/AllItems.aspx?id=%2Fsites%2Fsts%2Ftargetsystems%2FShared%20Documents%2FS%2E03%2E01%20Management%20%26%20System%20Integration%2FNeutronics%5Fplanning%2FNeutronics%20Task%20Orders).

2 ACCEPTANCE CRITERIA

Not applicable.

3 ASSUMPTIONS AND LIMITATIONS

Cobalt content in stainless steel materials is chosen at 0.2% (conservative). There is no assumed cobalt impurity in carbon steel.

For the decay times analyzed in this study, the activation source from water is negligible and not considered.

The decay gamma sources are calculated based on a facility lifetime of 40 years of operation. The PBW assumes 3 years of operation. Each operational year is broken down as 2500 hr beam on target, 1880 hr beam off, 2500 hr beam on target, 1880 hr beam off.

4 METHODOLOGY AND MODELS

The methodology outlined by T. McClanahan [1] is followed.

This model is taken from the STS master model with the skeleton as of November 6th, 2023 (Rev. 3, 2023-10-10). The proton beam window (PBW) assembly and its shielding has been updated for this analysis based on SpaceClaim file "PBW-Shine-In-Situ-October-24-2023_Rev2.scdoc". A vertical cross-section view through the most important parts of the model is shown in Figure 1. The model consists of:

- master skeleton Rev. 3, 2023-10-10, including the proton beam tube (PBT), the core vessel, the target drive room,
- the zitti target 3.5 V4.0, as detailed in [1],
- the moderator assembly, downloaded from Devel branch 2023-11-6,
- the proton beam window (PBW) assembly, Rev. 2, 2023-11-22,
- the target viewing periscope (TVP), Rev. 0, 2022-07-11.

The core vessel and target station shielding is slightly adjusted in the immediate surroundings of the PBW assembly and shielding to represent the goemetry in SpaceClaim file "PBW-Shine-In-Situ-October-24-2023_Rev2.scdoc". The gaps between the shielding blocks above the PBW and the target station shielding are 20 mm. The accelerator, downstream utilities, instrument halls, and high bay, are not modeled.

A discussion on materials, proton source, variance reduction, physics options, tally details, transmutation and post-processing is available in [1]. A short summary and additional comments for this analysis are listed here:

- Materials include maximal impurity concentrations from STS material specifications. Noteworthy is the 0.2% Co-59 in all stainless steels.

- Proton source `qd60_sampled_source_d_0300_cm_source_arrays.txt` has been used. This sources starts just before the PBW (located at X= -268 cm).
- The surrogate neutron source that is used to generate weight window parameters for the neutron flux calculation includes a point source at the location of the PBW. The tally of interest for this analysis covers the PBW assembly, the shielding above it, and the target station shielding in the surrounding area.
- The AARE package with CINDER2008 is used for the activation calculations and source generation.
- For the residual dose rate calculations, module `mcnp/mcnp6.2mod_20231115` is used. Weight-windows are generated using advantg 3.2.0.
- The plots have been made using the RTPlotter suite (python) developed by Joel Risner. Only results with a statistical precision <10% are shown.

The activation source for this work is split into 5 parts, i.e. 5 different `sdef`s, illustrated with different colors in Figures 2 and 3 :

- the part of the PBW assembly that will be replaced every 3 years (light blue),
- the irreplaceable part of the PBW assembly (dark blue),
- the shielding above the PBW (green),
- the PBT (magenta),
- a part of the target station shielding surrounding the PBW area (orange).

A lifetime of 40 years of operation is assumed for each of these components, except the replaceable part of the PBW assembly, which assumes 3 years of operation. One operational year is broken down as 2500 hr beam on target ,1880 beam off, 2500 hr beam on, 1880 beam off. In this analysis, a decay time of 1 week after the last beam on target is used for analysis 1 and 2. A decay time of 2 weeks is taken for analysis 3. A decay time of 4 weeks is taken for analysis 4 and 5.

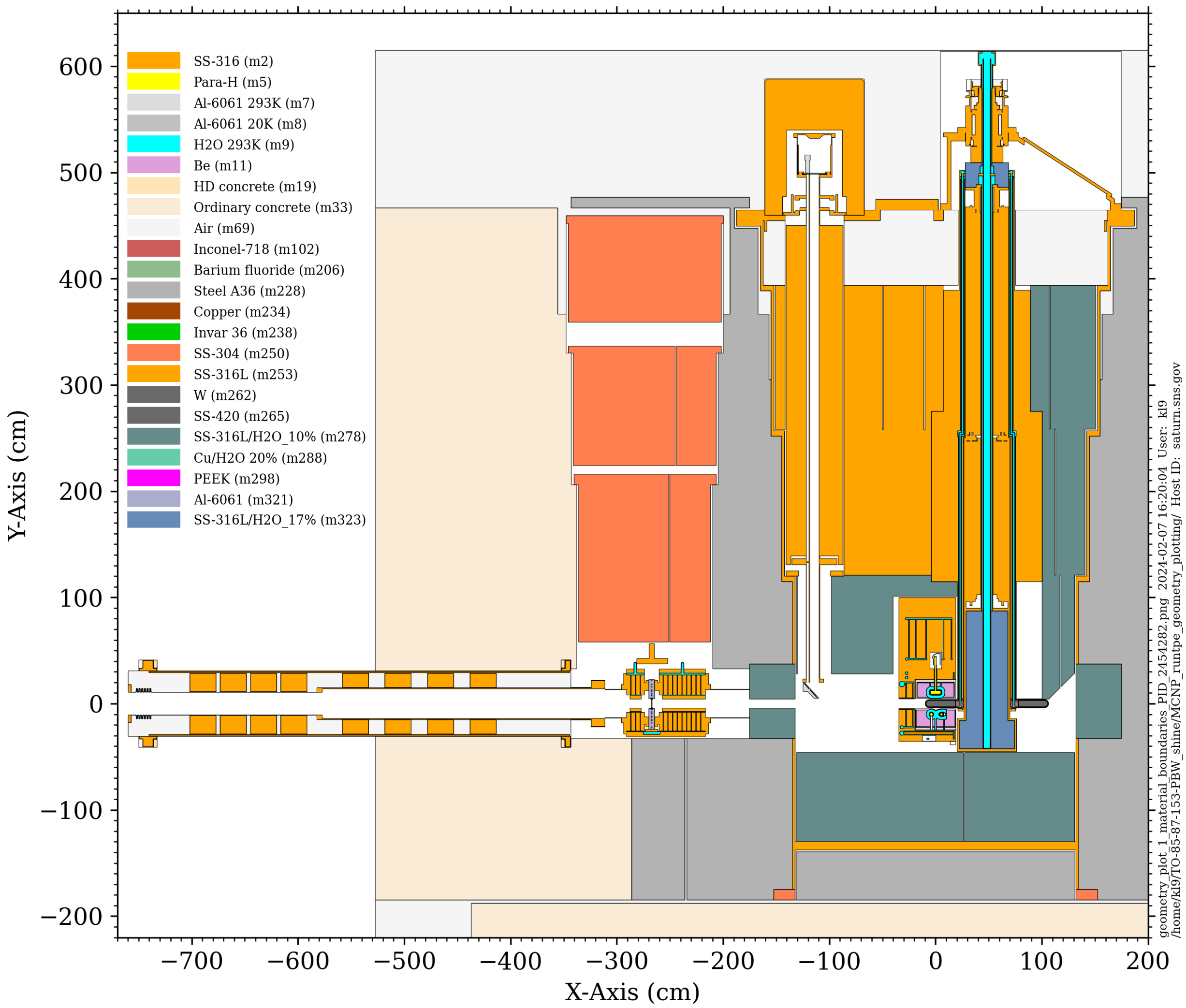

Figure 1. Overview of geometry and materials in the STS model used to calculate neutron fluxes and spallation products .

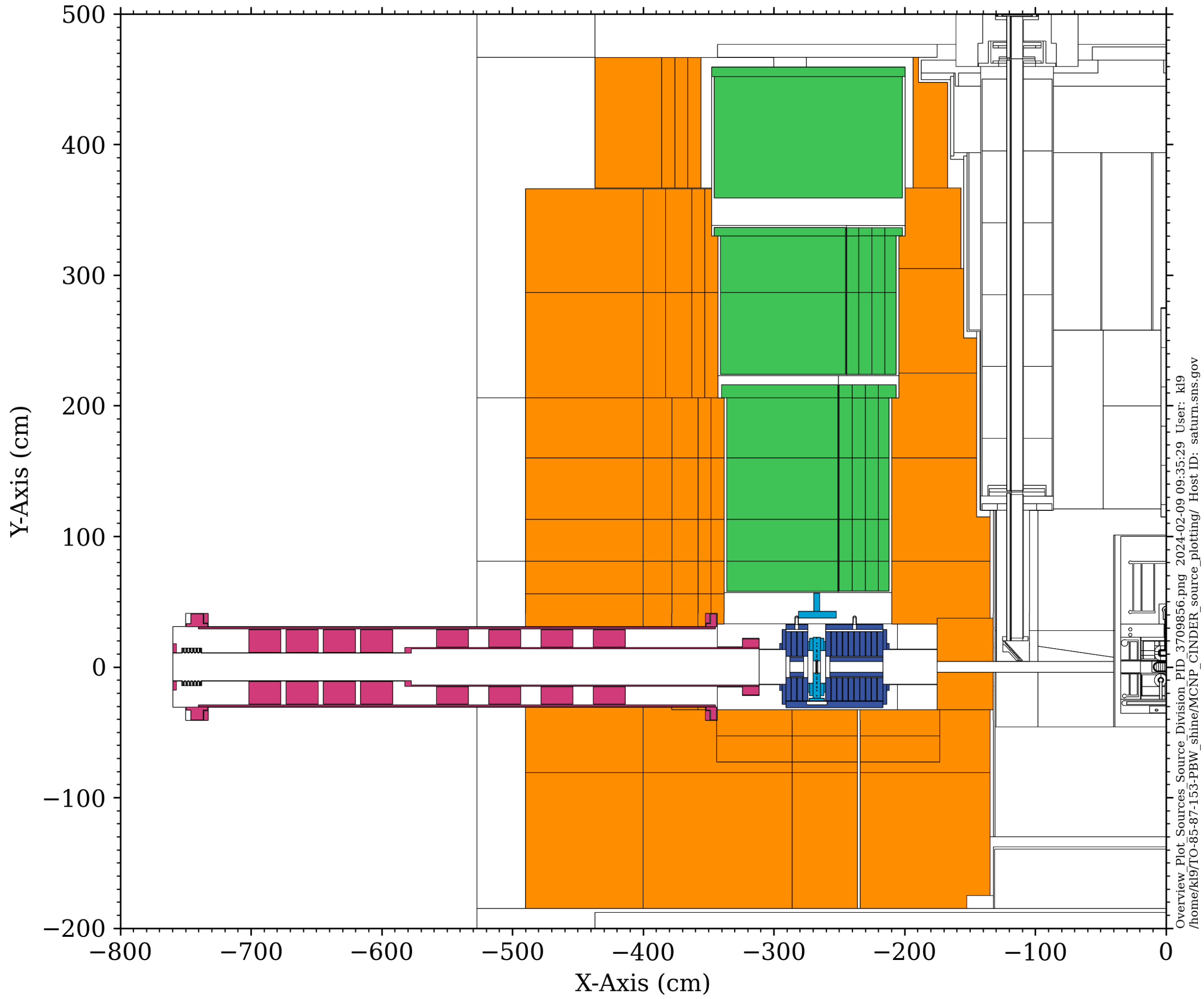

Figure 2. Vertical cut (Z = 0 cm) through the geometry indicating the area in which the activation source terms are calculated. The light blue, dark blue, green, magenta, and orange colors indicate respectively the replaceable part of the PBW, the irreplacable part of the PBW, the shielding above the PBW, the PBT, and the target station shielding around the PBW.

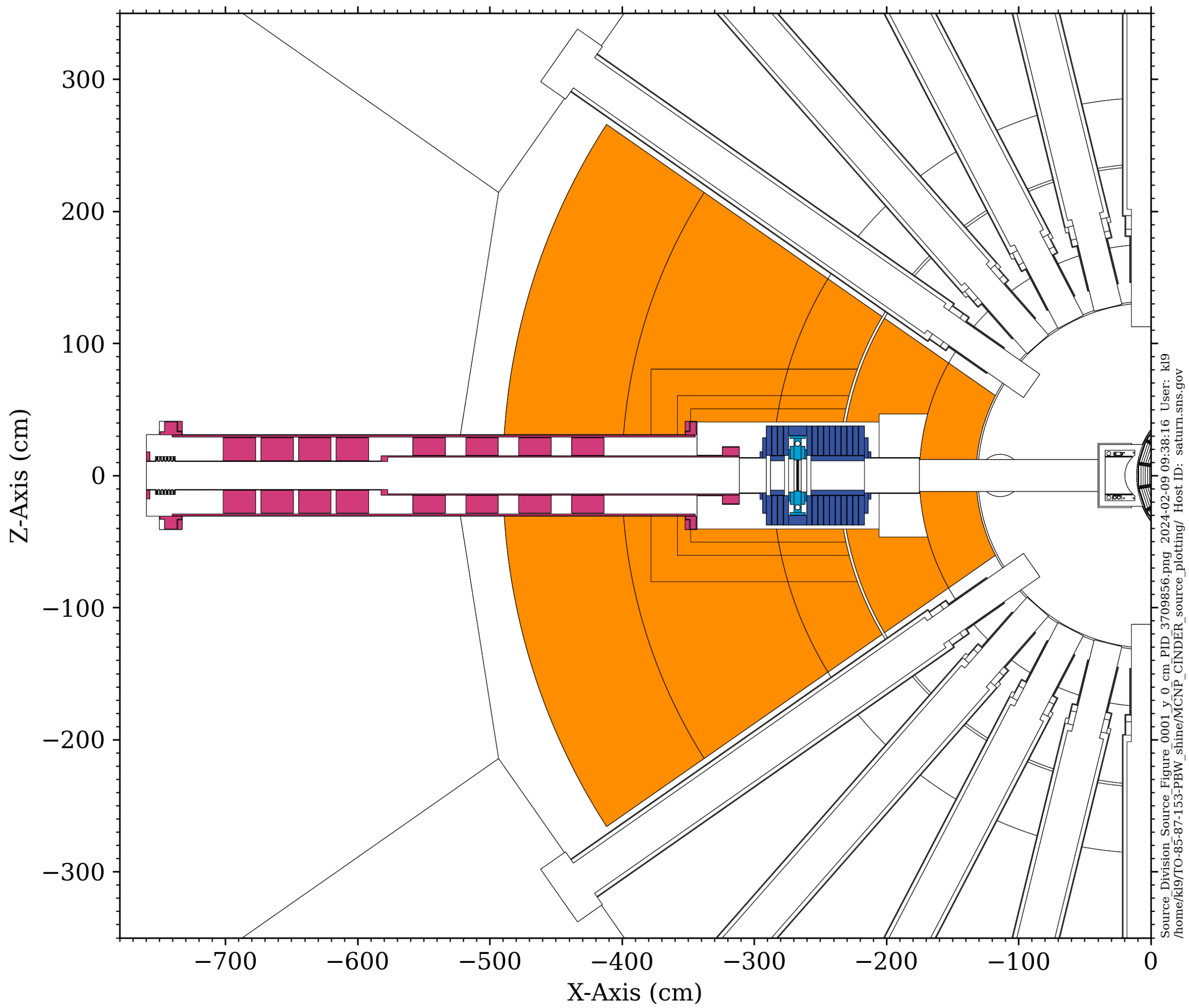

Figure 3. Horizontal cut (Y = 0 cm) through the geometry indicating the area in which the activation source terms are calculated. The light blue, dark blue, magenta, and orange colors indicate respectively the replaceable part of the PBW, the irreplacable part of the PBW, the PBT, and the target station shielding around the PBW.

5 ANALYSIS AND RESULTS

5.1 ACTIVATION SOURCE

Figures 4, 5 and 6 give an overview of the gamma source intensity after 1 week. The source with the highest intensity is the PBW assembly itself, specifically the cooled shielding downstream of the PBW. Spallation reactions occur in the PBW, causing many secondary particles and reactions, especially downstream of the PBW. Another large source is the section of the target station shielding closest to the proton beam between the PBW and the target. The target-moderator area provides the largest neutron source. Gamma sources in the schielding will thus generally be larger in closer proximity to the target and moderators. Gamma source intensity quickly decreases with increasing shielding, which can be clearly seen from the scale in Figure 4, which covers 10 orders of magnitude.

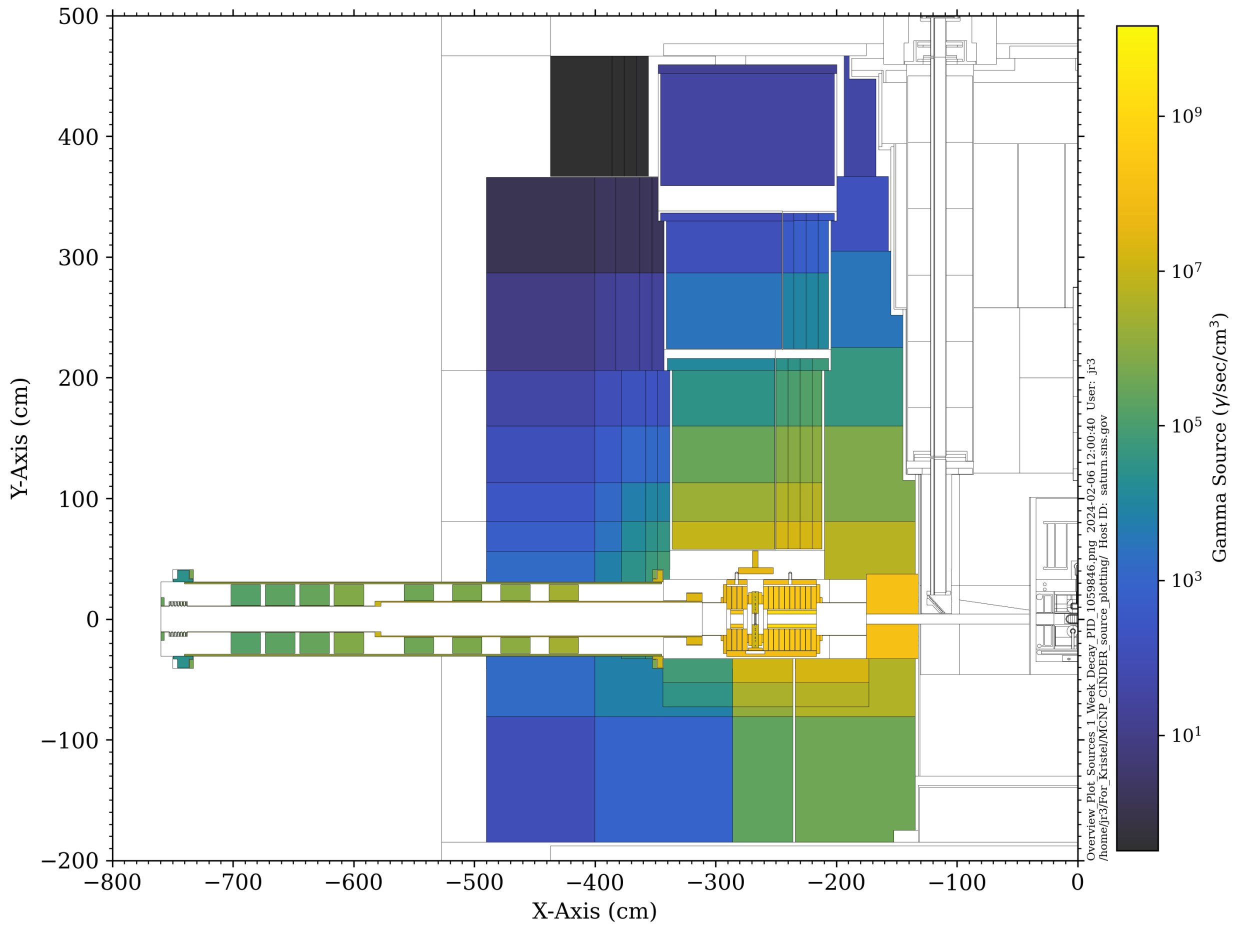

Figure 4. Vertical cross section view (Z = 0 cm) of the 1 week decay gamma source intensity for the PBW assembly, its shielding, its immediate surroundings, and the PBT.

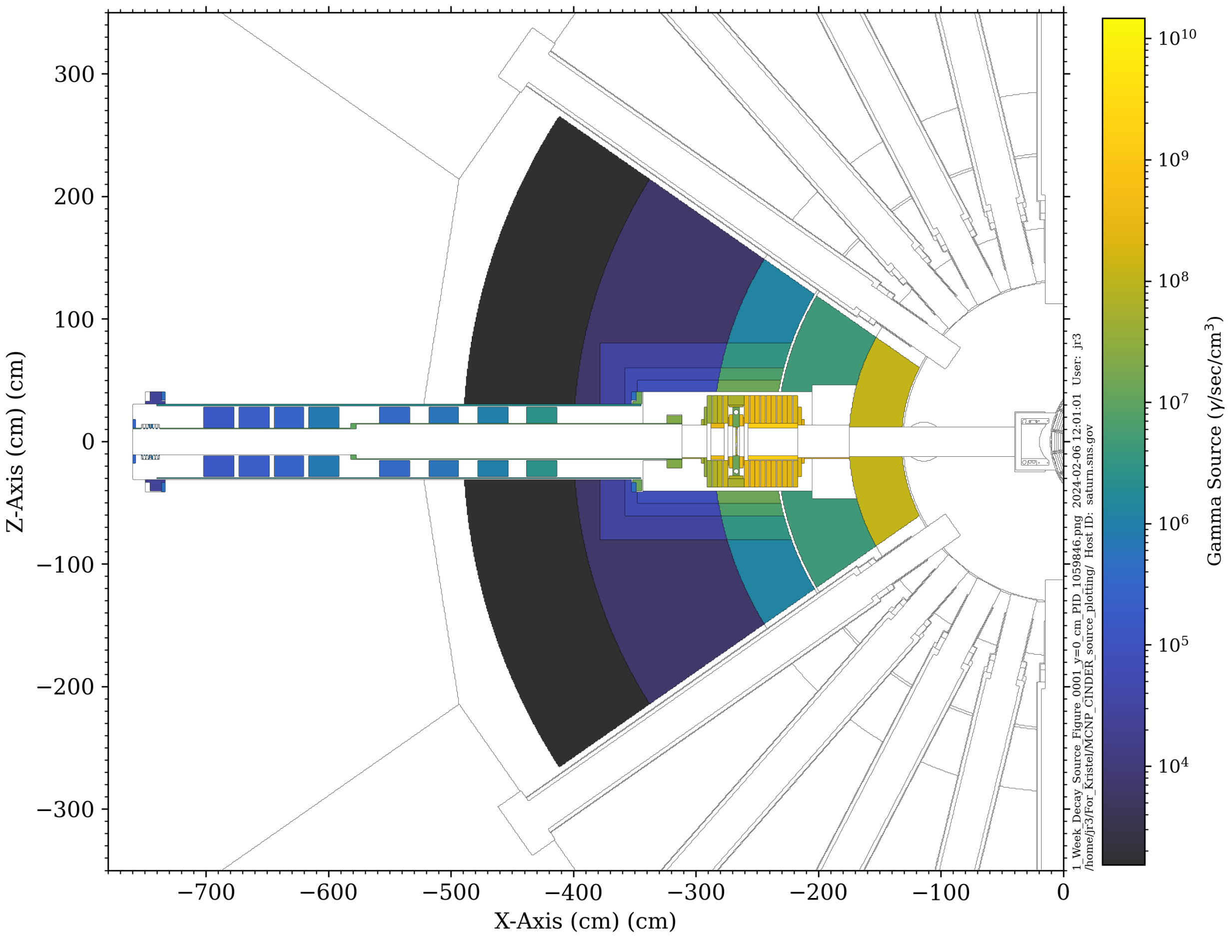

Figure 5. Horizontal cross section view (Y = 0 cm) of the 1 week decay gamma source intensity for the PBW assembly, its shielding, its immediate surroundings, and the PBT.

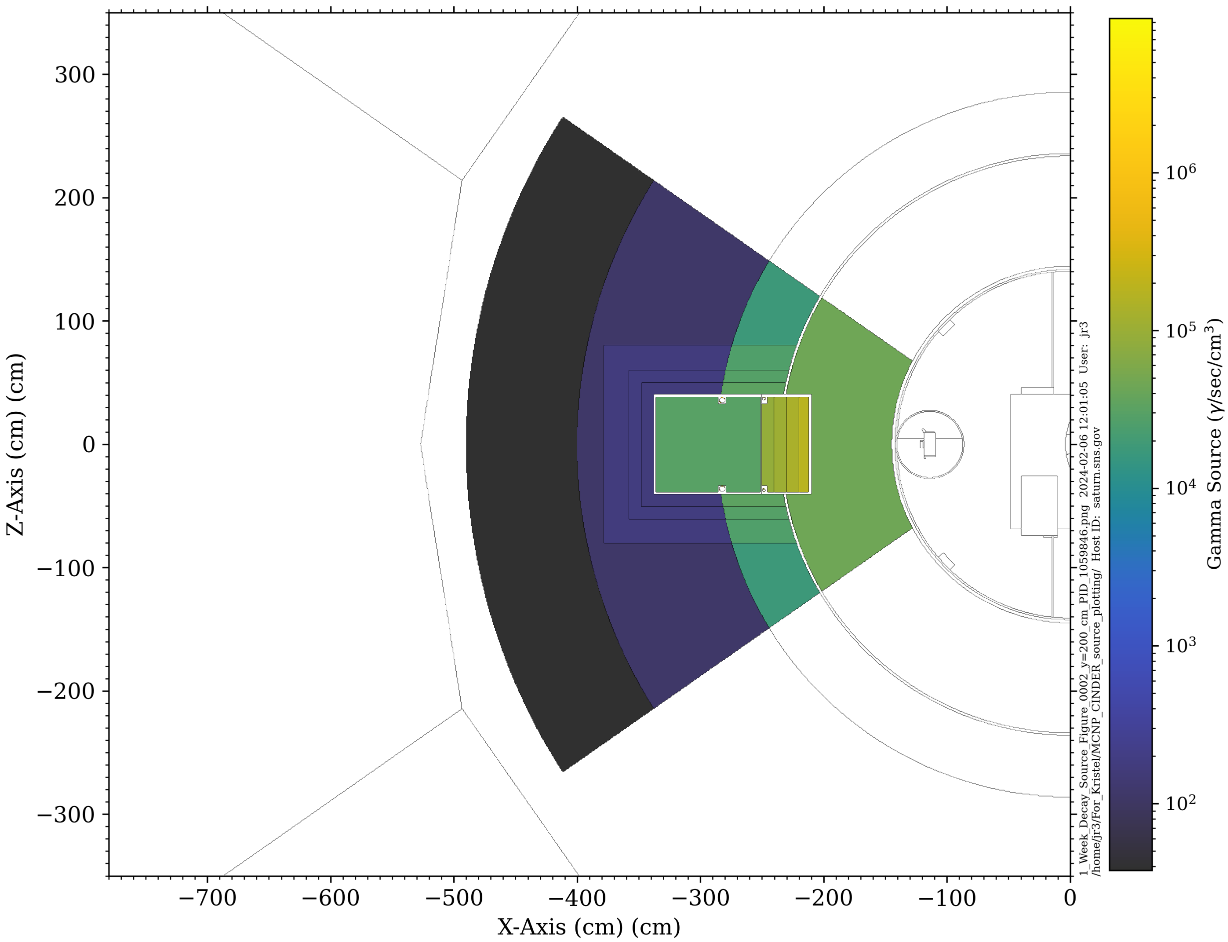

Figure 6. Horizontal cross section view (Y = 200 cm) of the 1 week decay gamma source intensity for the PBW assembly, its shielding, its immediate surroundings, and the PBT.

5.2 ANALYSIS 1: UPPER SHIELD BLOCK REMOVED, DECAY TIME OF 1 WEEK

Figure 7 shows the geometry (left) and dose rates (right) in a vertical cut of the geometry for the first analysis. In this configuration, the upper PBW shield block is removed such that the water joints are accessible. The dose rates after 1 week of decay at the level of the water joints, just above the PBW shield blocks is less than 1 mrem/h. This can be more clearly seen in Figure 8, which shows the dose rates in a horizontal cut at Y=350 cm. The largest dose rates are present on the right side of the hole, which is the side closest to the target. The specific shape of the dose rate contours is influenced by the segmentation of the activation source that was chosen for this analysis. The PBW shield block on the upstream side has no segmentation along the proton beam direction, thus the activation source which in reality is larger on the downstream side of the shield block and lower on the upstream side of the shield block is approximated as the average across the block. This influences the shape of the dose rate contours, but will not change the order of magnitude of the dose rates. As the dose rates are well below 5 mrem/h, no further effort has been invested into refining this result.

Figure 9 shows the 100 mrem/h and 0.25 mrem/h dose rate contour lines for each of the following gamma sources seperately: the replaceable component of the PBW assembly (light blue), the irreplaceable component of the PBW assembly (dark blue), the PBW shielding (green), the target station shielding (orange), and the PBT (magenta). The color used for the contour line indicates from which source it originates. For example the green contour line indicating 0.25 mrem/h (left plot) in the area above the PBW shielding indicates that this contribution originates from the source coming from the PBW shielding (also colored in green). Looking at the other 0.25 mrem/h contours, none of which extend up to the level of the water joints (around Y = 350 cm), we conclude that all other sources are either well-shielded or very small. The main radiation source for this configuration is thus the PBW shielding. It is noteworthy to point out that the PBW shielding in this model is stainless steel A304, which contains a 0.2% Cobalt impurity, while the target station shielding consists of carbon steel A36, which does not have a cobalt impurity modeled. Adding a 0.05% Cobalt impurity to the target station shielding increases the gamma source intensity after 1 week of decay time by 30 to 80 % (location dependent). The corresponding increase in dose rates has not been evaluated as it is not expected to change the conclusion of this analysis.

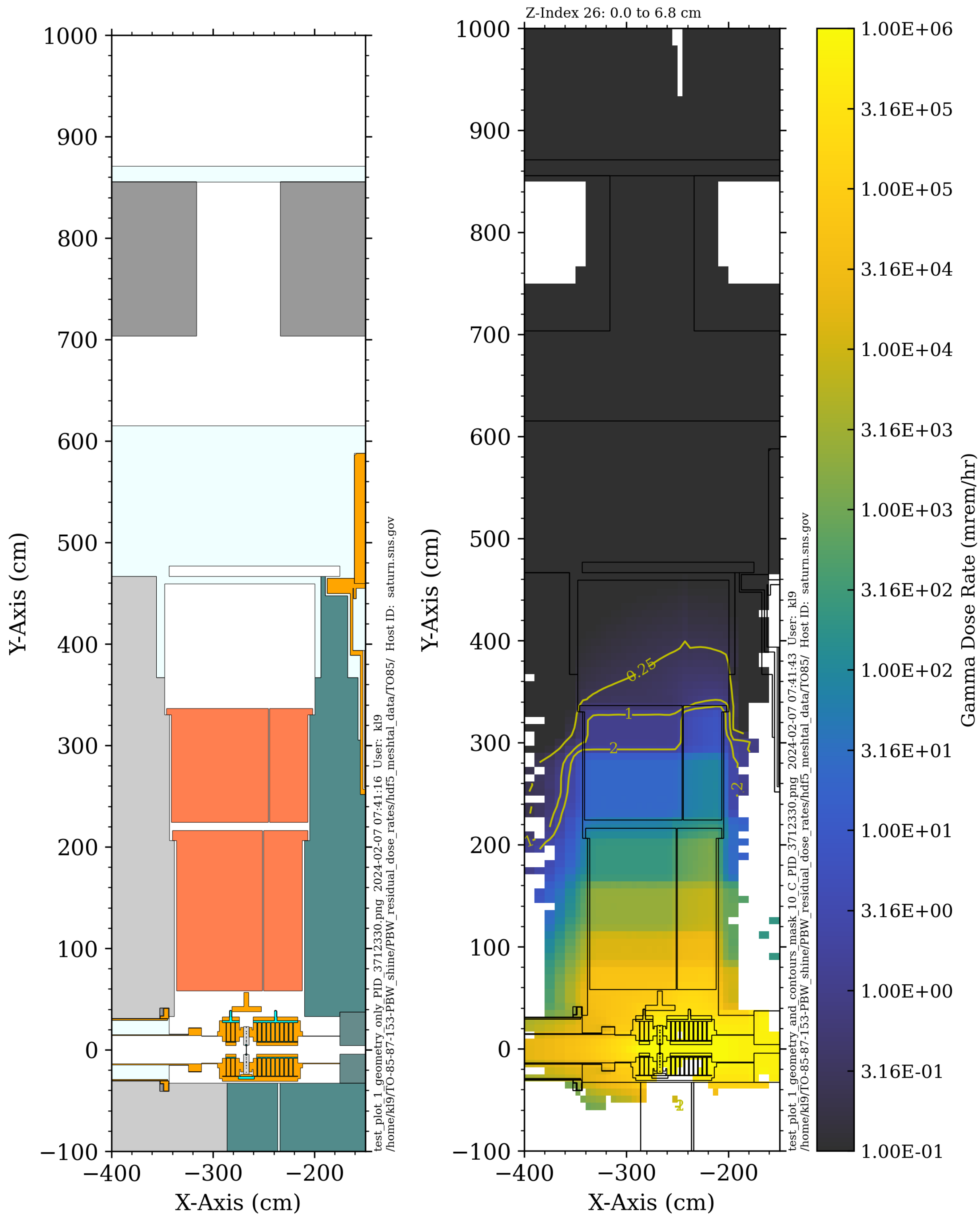

Figure 7. Geometry (left) and dose rates (right) in a vertical cut (Z = 0 cm) through the PBW area for analysis 1. The yellow lines indicate the 0.25, 1 and 2 mrem/h total dose rate contours.

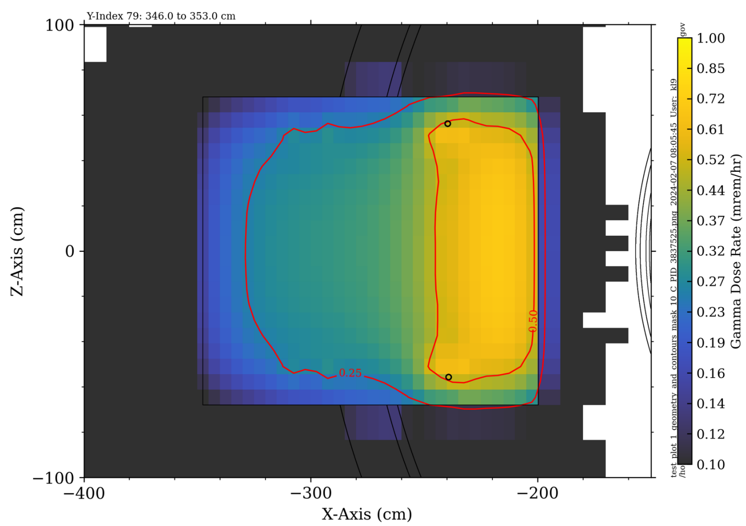

Figure 8. Dose rates in a horizontal cut above the PBW shielding at Y = 350 cm for analysis 1. The red lines indicate the 0.25 and 0.5 mrem/h total dose rate contours.

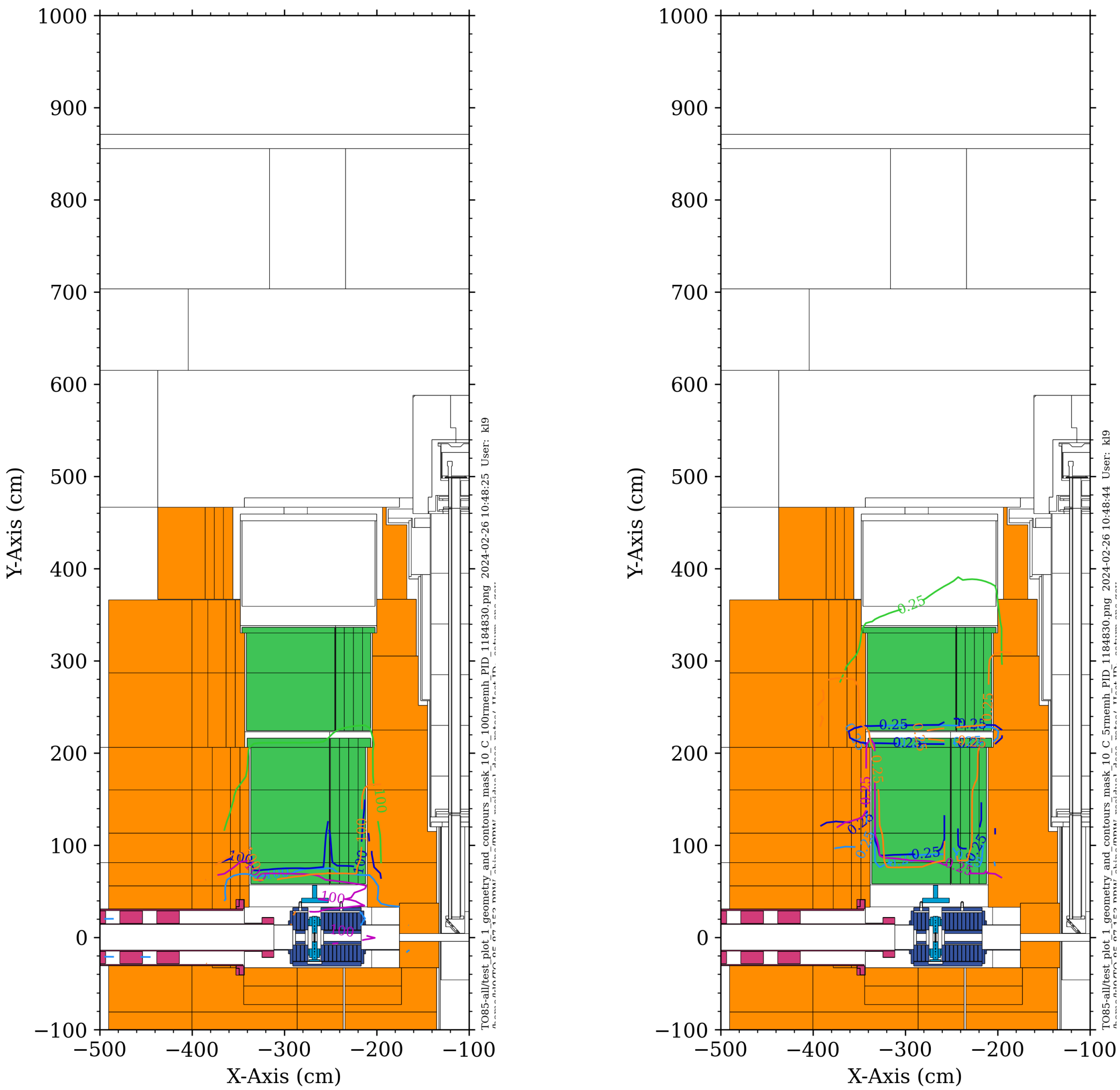

Figure 9. Dose rate contour lines for 100 mrem/h (left) and 0.25 mrem/h (right) for each of the gamma sources seperately (analysis 1). The color used for the contour line indicates from which source it originates: light blue for the replaceable component of the PBW assembly, dark blue for the irreplaceable component of the PBW assembly, green for the PBW shielding, orange for the target station shielding, and magenta for the PBT.

5.3 ANALYSIS 2: UPSTREAM SHIELD BLOCKS REMOVED, DECAY TIME OF 1 WEEK

In the second analysis, the upstream shield blocks have been removed, while the PBW assembly remains in place. The decay time is 1 week. Figure 10 shows the geometry (left) and dose rates (right) in the vertical cross-section through the middle of the geometry. The dose rates at the target drive room reach more than 500 mrem/h in the hole in the floor, while at the high bay floor level, the dose rates reach 150 mrem/h. Figure 11 zooms in on the upper part of the geometry, starting at the target drive room floor level, where radiation workers could be expected to enter for the maintenance operations. Approximate distances in the air from the 5 mrem/h contour line to beginning of the opening of the PBW shielding (dotted line) are indicated. Figure 12 shows the dose rates in two horizontal cross-sections, at Y = 500 cm in the target drive room, and at Y = 900 cm in the high bay, with indications of the approximate distance of the 5 mrem/h contour to the hole in the floor. Away from the hole in the target drive room floor, the dose rates decrease quickly, as can be seen from the 100 mrem/h and 200 mrem/h contour lines that are close to each other. To reach 5 mrem/h, a person needs to stand 100 cm or more away from the hole, depending on the heigth and exact location. At the high bay floor level, the dose rates still reach 150 mrem/h. Radiation is very collimated: just 20 cm away from the hole, the dose rates have decreased to less than 5 mrem/h.

Figure 13 shows the 100 mrem/h (left) and 5 mrem/h (right) dose rate contour lines for each of the gamma sources seperately: the replaceable component of the PBW assembly (light blue), the irreplaceable component of the PBW assembly (dark blue), the PBW shielding (green), the target station shielding (orange), and the PBT (magenta). The color used for the contour line indicates from which source it originates (similar to Similar to Figure 9). The main contributor to the dose rates is the irreplaceable component of the PBW assembly, as can be seen from the dark blue lines which extend the furthest in the geometry, followed by the replaceable component of the PBW assembly, the PBT, and the PBW shielding. The target station shielding contibrutes the least.

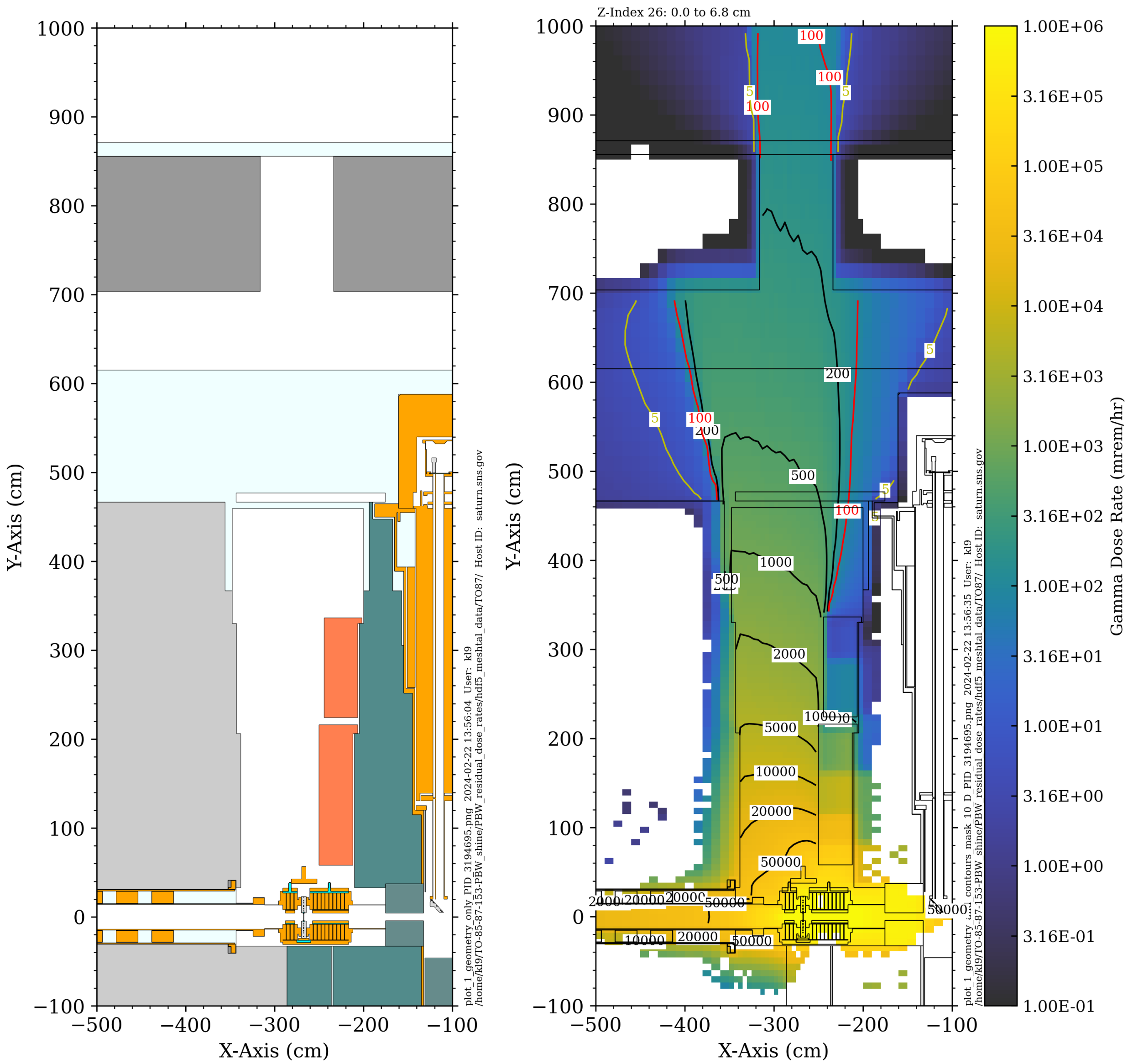

Figure 10. Geometry (left) and dose rates (right) in a vertical cut (Z = 0 cm) through the PBW area for analysis 2. The yellow and red lines indicate the 5 and 100 mrem/h contours.

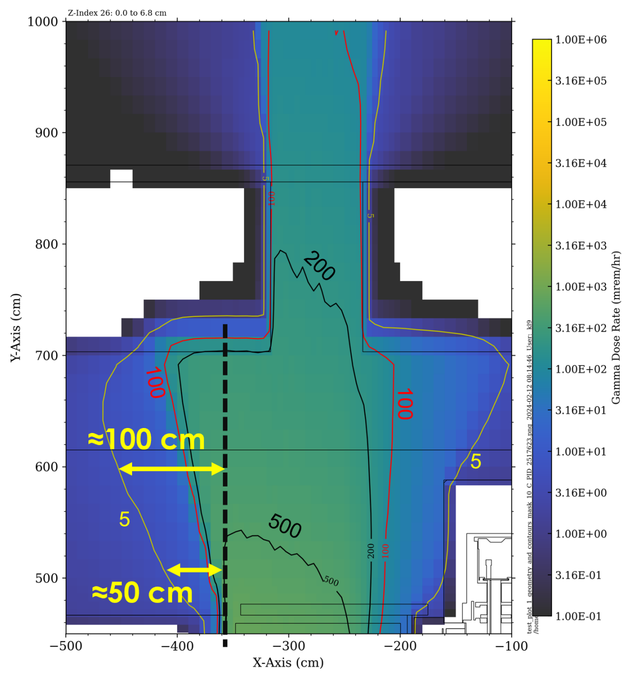

Figure 11. Dose rates in a vertical cut (Z = 0 cm) focused on the target drive room and high bay area above the PBW hole (analysis 2). The yellow and red lines indicate the 5 and 100 mrem/h contours. The approximate distance of the 5 mrem/h contour to the edge of the hole in the target drive room floor is indicated at Y = 500 cm and Y = 600 cm.

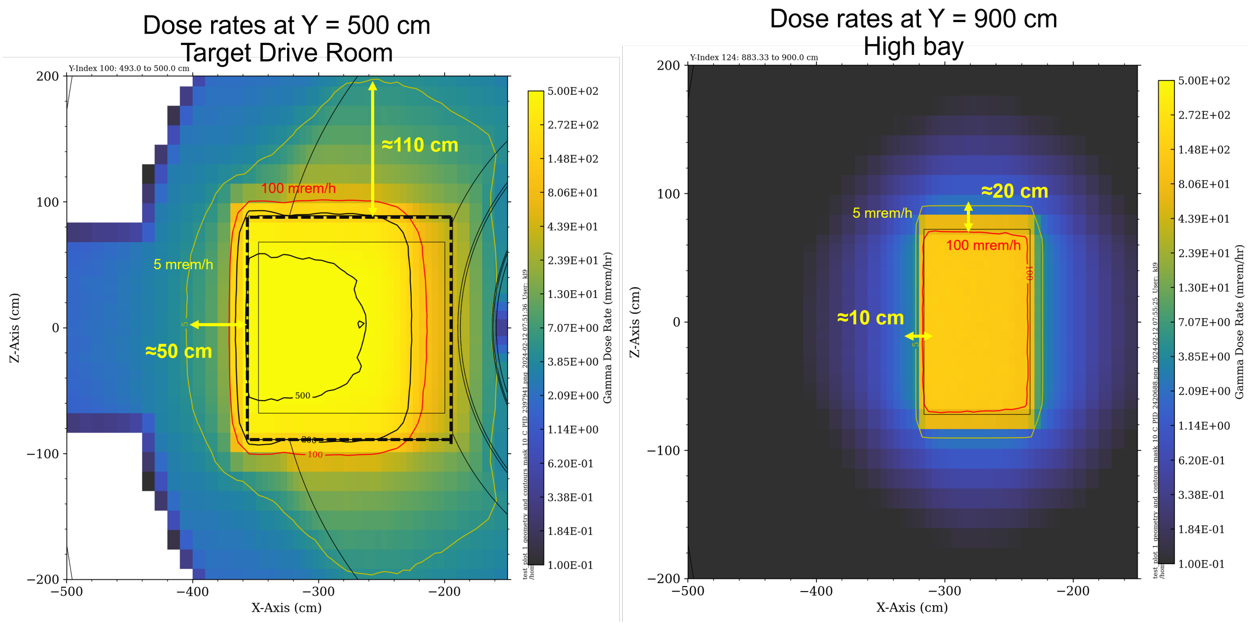

Figure 12. Dose rates in a horizontal cut in the target drive room (Y = 500 cm, left) and high bay (Y = 900 cm, right) above the PBW hole (analysis 2). The yellow and red lines indicate the 5 and 100 mrem/h contours. The approximate distance of the 5 mrem/h contour to the edge of the hole is indicated in the X and Z direction.

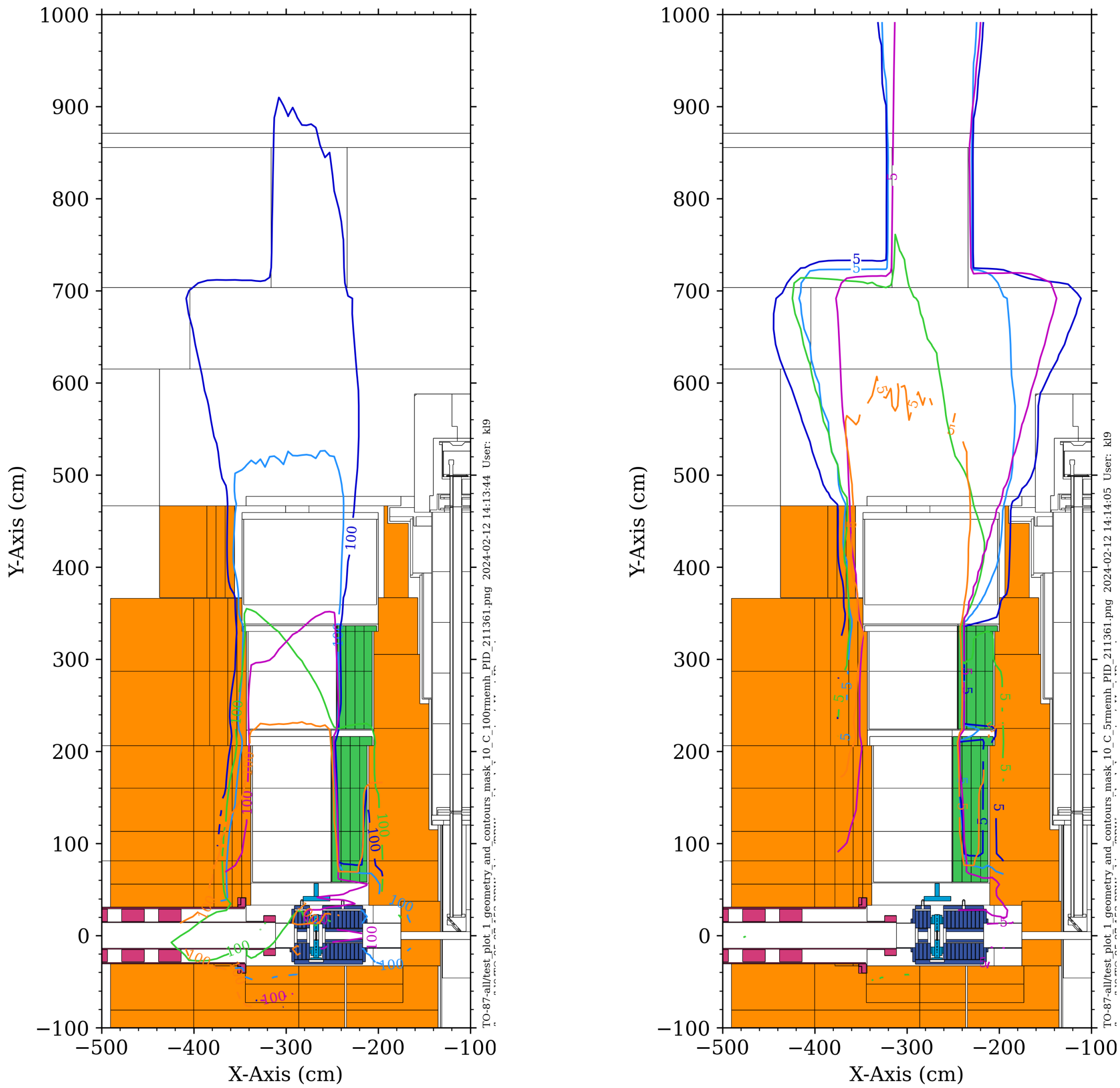

Figure 13. Dose rate contour lines for 100 mrem/h (left) and 5 mrem/h (right) for each of the gamma sources seperately (analysis 2). The color used for the contour line indicates from which source it originates: light blue for the replaceable component of the PBW assembly, dark blue for the irreplaceable component of the PBW assembly, green for the PBW shielding, orange for the target station shielding, and magenta for the PBT.

5.4 ANALYSIS 3: UPSTREAM SHIELD BLOCKS AND PBW REMOVED, DECAY TIME OF 2 WEEKS.

In the third analysis, the upstream shield blocks and the replaceable component of the PBW assembly are removed. The decay time is 2 weeks. Figure 14 shows the geometry (left) and dose rates (right) in the vertical cross-section through the middle of the geometry. The dose rates at the target drive room reach approximately 1000 mrem/h in the hole in the floor, while at the high bay floor level, the dose rates reach 200 mrem/h. Figure 15 zooms in on the upper part of the geometry, starting at the target drive room floor level. Approximate distances from the 5 mrem/h contour line to the hole of the PBW shielding are indicated. Figure 16 shows the dose rates in two horizontal cross-sections, at Y = 500 cm, in the target drive room, and at Y = 900 cm in the high bay, with indications of the approximate distance of the 5 mrem/h contour to the hole in the floor. In general, the dose rates are slightly higher than those in analysis 2. While removing part of the PBW assembly removes a gamma source, it also decreases the amount of shielding for the downstream components of the PBW assembly, where the largest source is located. The source intensity in the irreplaceable part of the PBW assembly (stainless steel) is only 5-10% lower with 2 weeks of decay time than with 1 week of decay time. We conclude that removing part of the PBW assembly increases the dose rates because the dominant gamma source is less well shielded.

More details on the contributions of the sources to the dose rates can be observed in Figure 17, which shows the 100 mrem/h (left) and 5 mrem/h (right) contour lines for each of the gamma sources seperately. The color used for the contour line indicates from which source it originates (similar to Figures 9 and 13). The main contributor to the dose rates is the irreplaceable component of the PBW assembly, as can be seen from the dark blue lines which extend the furthest in the geometry, followed by the PBT, and the PBW shielding. The target station shielding contibrutes the least.

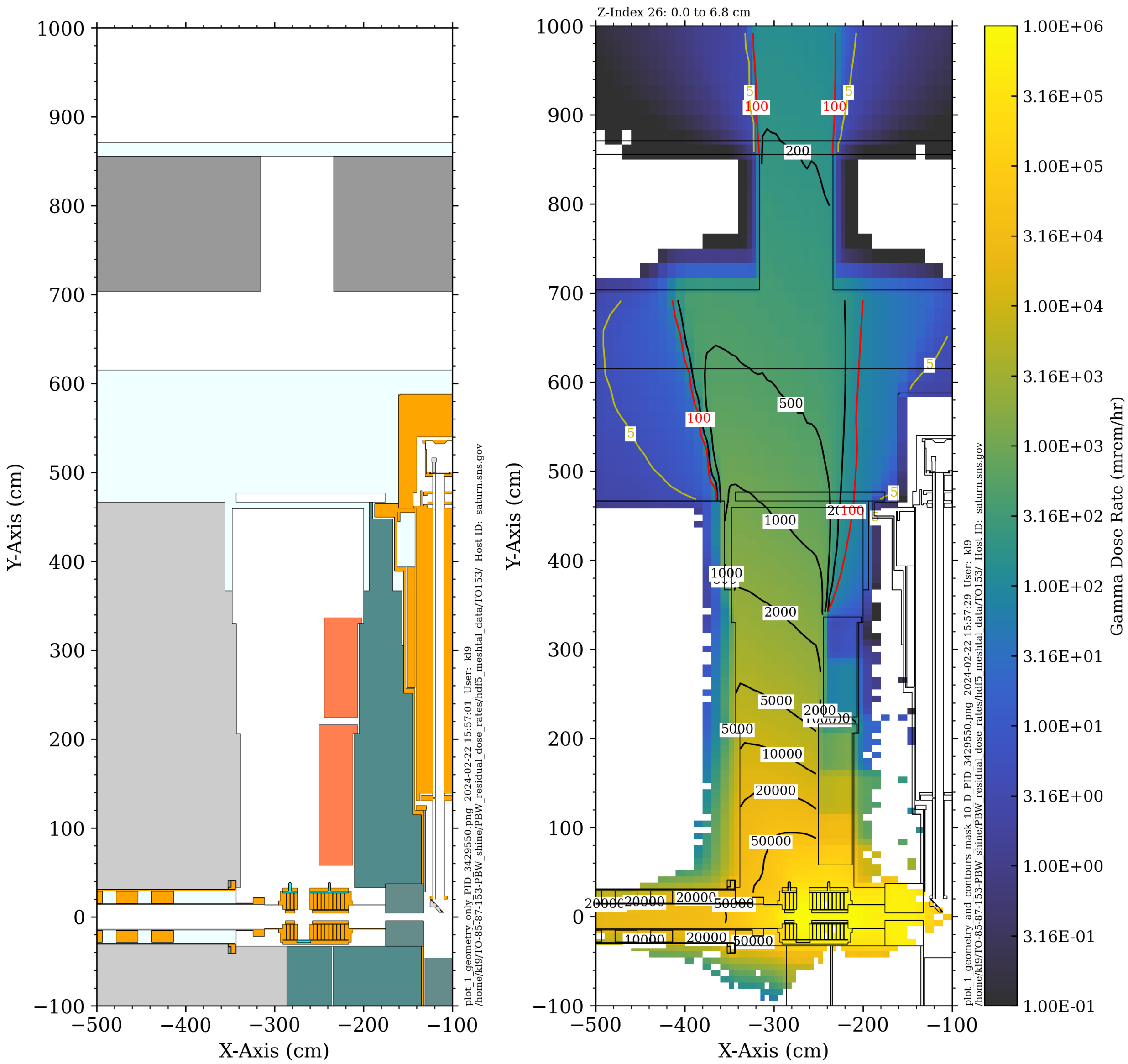

Figure 14. Geometry (left) and dose rates (right) in a vertical cut (Z = 0 cm) through the PBW area for analysis 3. The yellow and red lines indicate the 5 and 100 mrem/h contours.

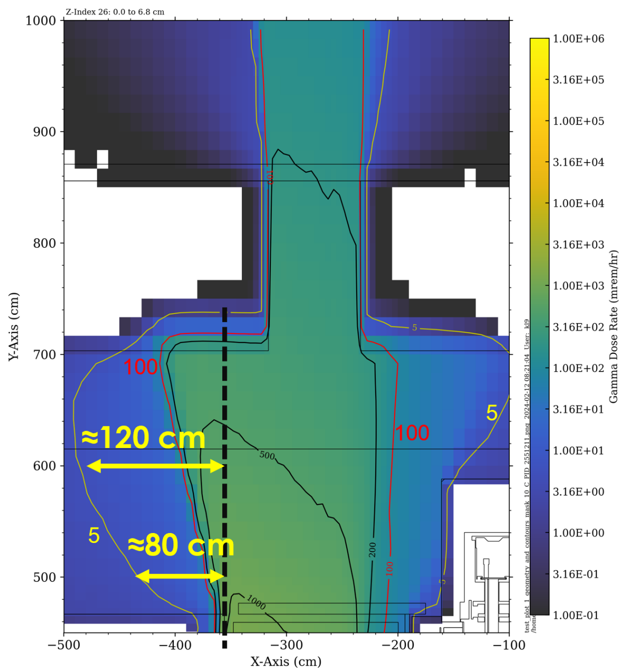

Figure 15. Dose rates in a vertical cut (Z = 0 cm) focused on the target drive room and high bay area above the PBW hole (analysis 3). The yellow and red lines indicate the 5 and 100 mrem/h contours. The approximate distance of the 5 mrem/h contour to the edge of the hole in the target drive room floor is indicated at Y = 500 cm and Y = 600 cm.

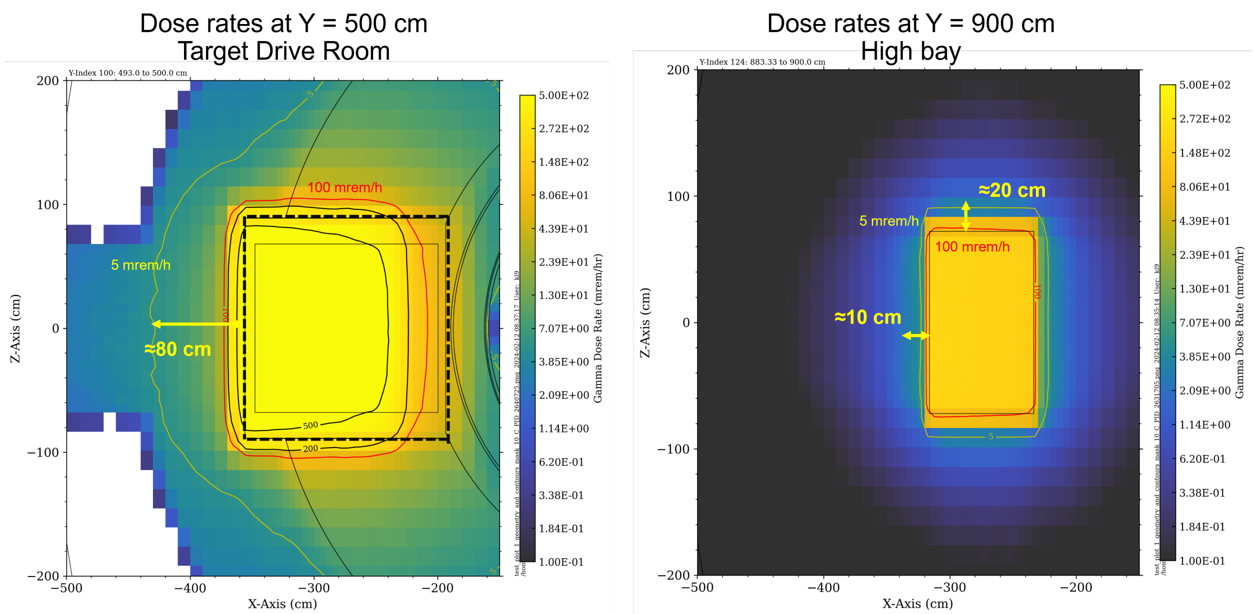

Figure 16. Dose rates in a horizontal cut in the target drive room (Y = 500 cm, left) and high bay (Y = 900 cm, right) above the PBW hole (analysis 3). The yellow and red lines indicate the 5 and 100 mrem/h contours. The approximate distance of the 5 mrem/h contour to the edge of the hole is indicated in the X direction.

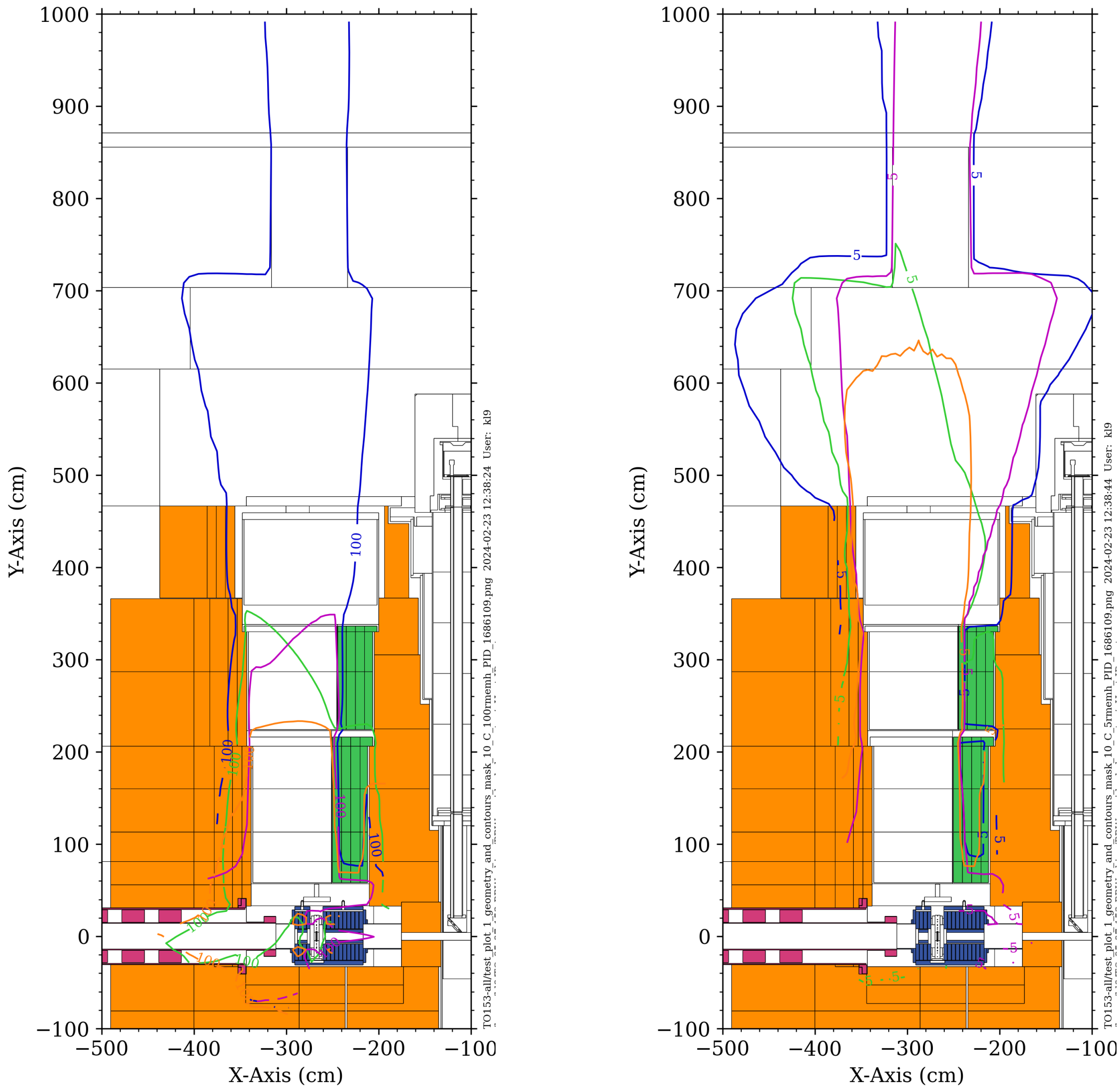

Figure 17. Dose rate contour lines for 100 mrem/h (left) and 5 mrem/h (right) for each of the gamma sources seperately (analysis 3). The color used for the contour line indicates from which source it originates: dark blue for the irreplaceable component of the PBW assembly, green for the PBW shielding, orange for the target station shielding, and magenta for the PBT.

5.5 ANALYSIS 4: ALL SHIELD BLOCKS AND PBW REMOVED, DECAY TIME OF 4 WEEKS.

In the fourth analysis, all PBW shield blocks and the replaceable component of the PBW assembly are removed. The decay time is 4 weeks. Figure 18 shows the geometry (left) and dose rates (right) in the vertical cross-section through the middle of the geometry. The dose rates at the target drive room reach approximately 1500 mrem/h in the hole in the floor, while at the high bay floor level, the dose rates reach 400 mrem/h. Figure 16 shows the dose rates in two horizontal cross-sections, at Y = 500 cm, in the target drive room with indications of the approximate distance of the 5 mrem/h contour to the hole in the floor. With all the PBW shielding removed, the streaming path is much larger than in analysis 3. This explains the higher dose rates. The longer decay time has a very limited effect on the results, because the source intensity in the irreplaceable part of the PBW assembly (stainless steel) is only 10% lower with 4 weeks of decay time than with 2 weeks of decay time. Figure 20 shows the 100 mrem/h (left) and 5 mrem/h (right) contour lines for each of the gamma sources seperately, which confirms the irreplaceable part of the PBW as the dominant source.

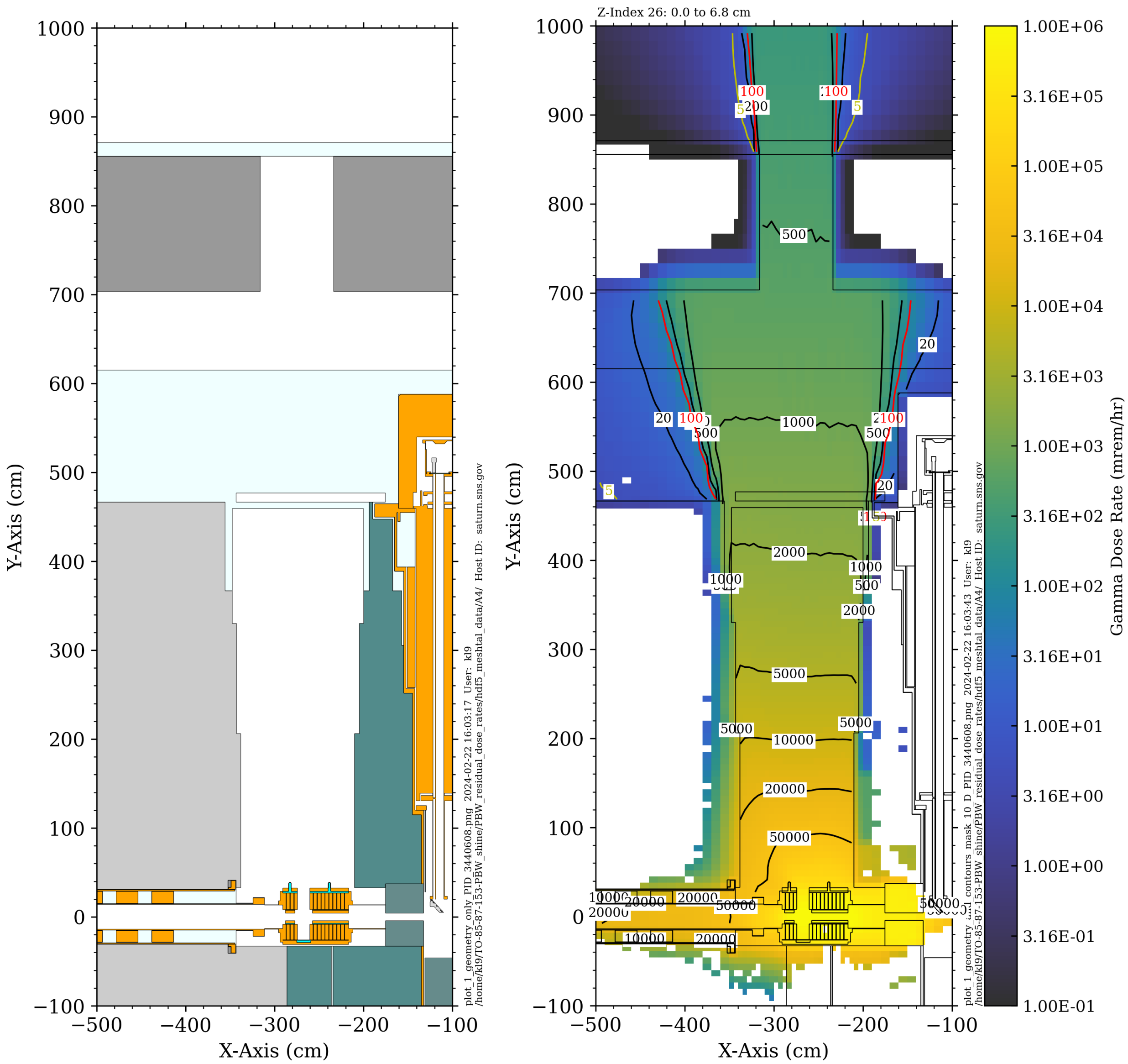

Figure 18. Geometry (left) and dose rates (right) in a vertical cut (Z = 0 cm) through the PBW area for analysis 4. The yellow and red lines indicate the 5 and 100 mrem/h contours.

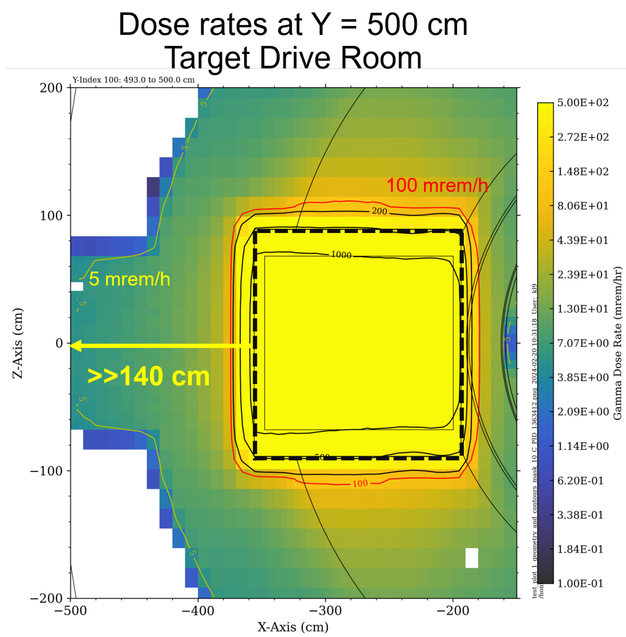

Figure 19. Dose rates in a horizontal cut in the target drive room (Y = 500 cm) above the PBW hole (analysis 4). The yellow and red lines indicate the 5 and 100 mrem/h contours. Most of the 5 mrem/h contour is outside of the tallied area, with a distance >140 cm to the hole

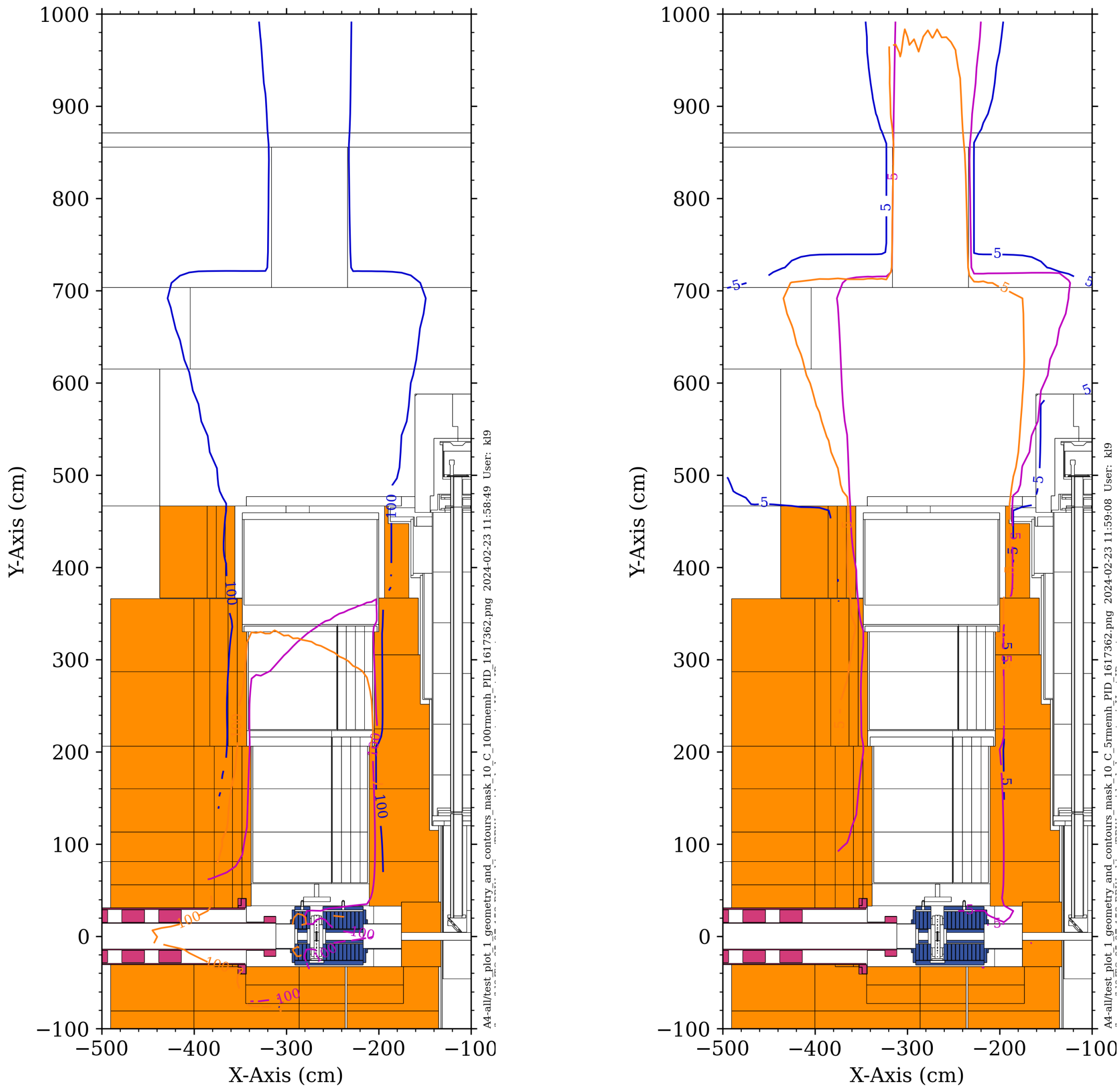

Figure 20. Dose rate contour lines for 100 mrem/h (left) and 5 mrem/h (right) for each of the gamma sources seperately (analysis 4). The color used for the contour line indicates from which source it originates: dark blue for the irreplaceable component of the PBW assembly, orange for the target station shielding, and magenta for the PBT.

5.6 ANALYSIS 5: FULL PBW ASSEMBLY AND SHIELD BLOCKS REMOVED, DECAY TIME OF 4 WEEKS.

In the fifth analysis, the full PBW assembly and PBW shield blocks are removed. The decay time is 4 weeks. The only remaining sources are from the PBT and the target station shielding. Figure 21 shows the geometry (left) and dose rates (right) in the vertical cross-section through the middle of the geometry. The dose rates at the target drive room reach approximately 150 mrem/h in the hole in the floor, while at the high bay floor level, the dose rates reach 35 mrem/h. Figure 16 shows the dose rates in two horizontal cross-sections, at Y = 500 cm, in the target drive room with indications of the approximate distance of the 5 mrem/h contour to the hole in the floor. Figure 23 shows the 100 mrem/h (left) and 5 mrem/h (right) contour lines for each of the gamma sources (PBT and target station shielding) seperately.

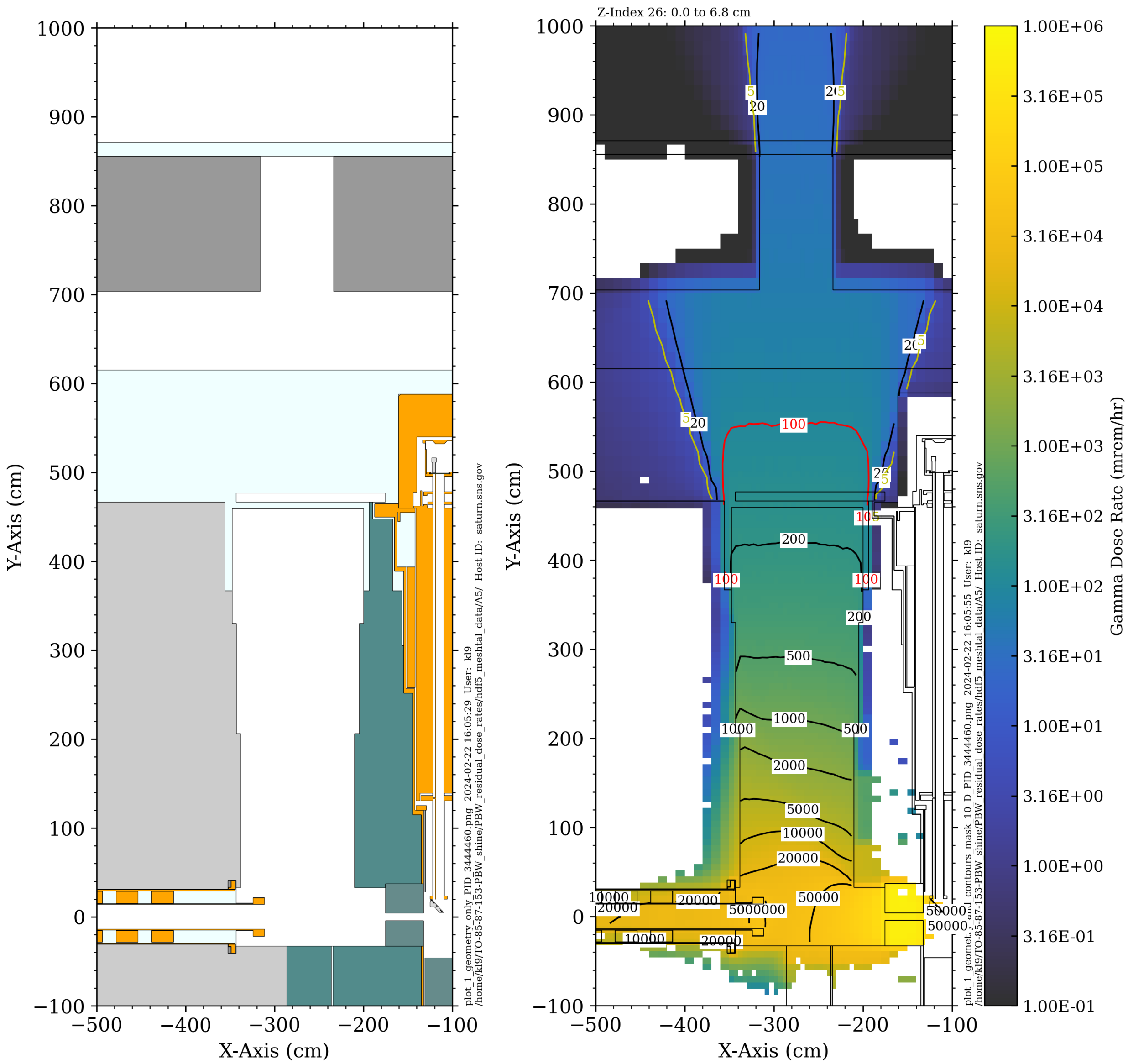

Figure 21. Geometry (left) and dose rates (right) in a vertical cut (Z = 0 cm) through the PBW area for analysis 5. The yellow and red lines indicate the 5 and 100 mrem/h contours.

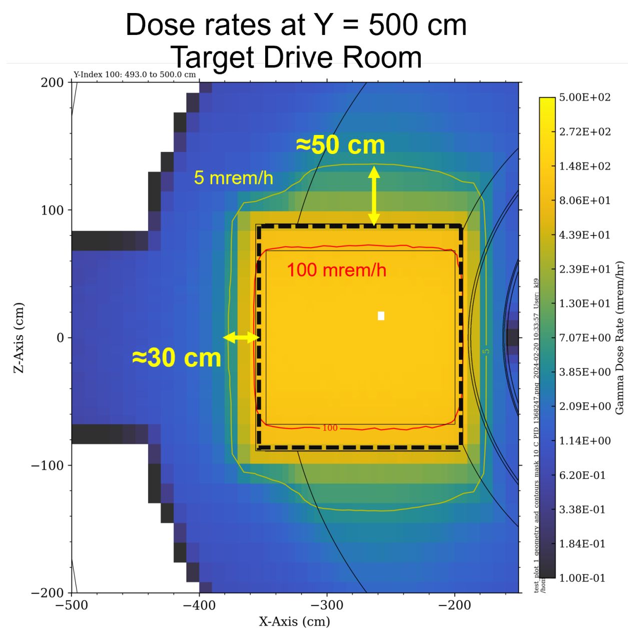

Figure 22. Dose rates in a horizontal cut in the target drive room (Y = 500 cm) above the PBW hole (analysis 5). The yellow and red lines indicate the 5 and 100 mrem/h contours. The approximate distance of the 5 mrem/h contour to the edge of the hole is indicated in the X and Z direction.

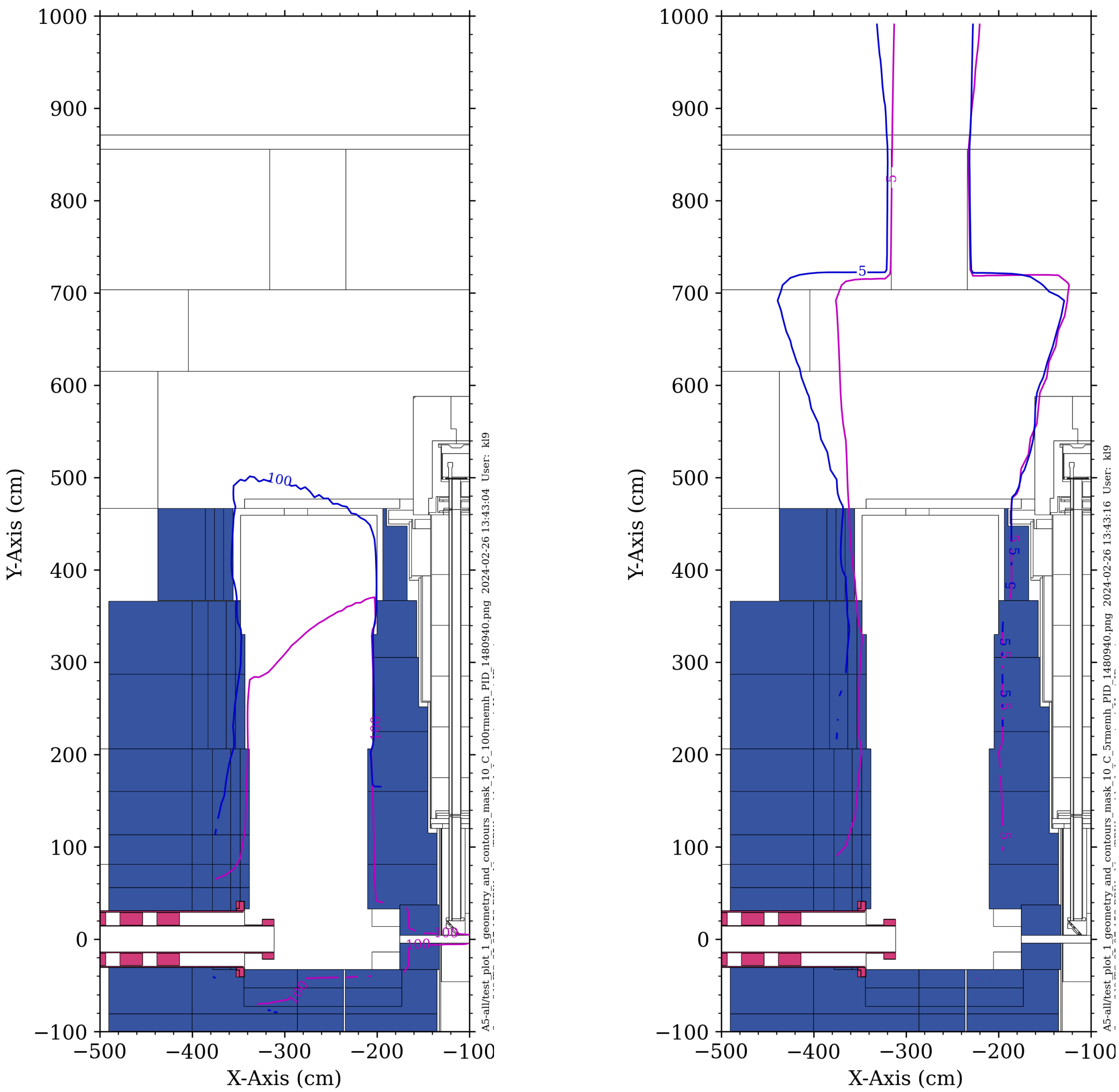

Figure 23. Dose rate contour lines for 100 mrem/h (left) and 5 mrem/h (right) for each of the gamma sources seperately (analysis 4). The color used for the contour line indicates from which source it originates: dark blue for the target station shielding, and magenta for the PBT.

6 CONCLUSIONS

The residual dose rates are calculated for several configurations related to proton beam window (PBW) removal and replacement maintenance events. The results will be used for planning of the related remote handling tasks.

The dose rates are evaluated for five configurations:

- In the first configuration, the upper PBW shield block is removed. With a decay time of 1 week, the dose rates remain below 5 mrem/h in the area where the waterjoints are accessible.
- In the second configuration, the upper PBW shield block and the upstream PBW shield blocks are removed. With a decay time of 1 week, the dose rates reach 800 mrem/h at the target drive room floor level. Away from the hole with a straight line of sight form the activated PBW assembly components, the dose rates decrease quickly. The 5 mrem/h contour line extends 100 cm or more from the edge of the hole. At the high bay floor level, dose rates reach 150 mrem/h. Radiation is very collimated: only 20 cm away from the hole, the dose rates decrease to 5 mrem/h.
- In the third configuration, the upper PBW shield block, the upstream PBW shield blocks and the replaceable part of the PBW assembly removed. With a decay time of 2 weeks, the dose rates reach 1000 mrem/h at the target drive room floor level. The 5 mrem/h contour line extends further in the geometry than in the previous configuration (120 cm or more, depending on the location in the target drive room). The dose rates at the high bay floor reach 200 mrem/h.
- In the fourth configuration, all PBW shield blocks and the replaceable part of the PBW assembly removed. With a decay time of 4 weeks, the dose rates reach 1500 mrem/h at the target drive room floor level. The 5 mrem/h contour in the target drive room extends more than 140 cm in all directions. At the high bay floor level, the dose rates reach 400 mrem/h.
- In the fifth configuration, all PBW shield blocks and the full PBW assembly removed. With a decay time of 4 weeks, the dose rates at the target drive room level and high bay floor level are 150 mrem/h and 35 mrem/h respectively.

The most intense gamma source, which is the dominant contibutor in configuration 2, 3, and 4, is the cooled part of the PBW assembly located downstream of the PBW. This component consists of stainless steel, which assumes a 0.2% cobalt impurity. The source intensity for this component decreases slowly: 5-10% from 1 week to 2 weeks of decay time, and approximately 10% from 2 weeks to 4 weeks of decay time.

7 ACKNOWLEDGEMENTS

The author would like to thank Tucker McClanahan, Lukas Zavorka, Joel Risner, and Igor Remec for the support with this work.

8 REFERENCES

[1] T. McClanahan, “Methodology to generate decay gamma sources for the full second target station target assembly,” Tech. Rep. S03120100-TRT10012, ORNL/TM-2023/3215, Oak Ridge National Laboratory, December 2023.

APPENDIX A. COMPUTER HARDWARE AND SOFTWARE

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All simulations have been performed on the STS clusters Kryo and Saturn. The following modules have been loaded.

- For the weight-window generation used in the calculation of neutron fluxes and spallation products: `advantg/advantg3.2.1`
- For the particle transport calculation of neutron fluxes and spallation products: `mcnp/mcnp6.2mod_20231005`
- For the activation calculation: `cinder/2008`
- For the weight-window generation used in the calculation of the residual dose rates: Advantg version 3.2.0-HILO has been used from `/home/t25/Tools/ADVANTG/3.2.0-HILO/advantg.rc`
- For the particle transport calculation of residual dose rates: `mcnp/mcnp6.2mod_20231115`

Many of the plots are generated using the RTPlotter Python suite of tools developed by of Joel Risner.

APPENDIX B. LOCATION OF COMPUTATIONAL INPUT AND OUTPUT FILES

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On saturn:

```
sts_archive/0-Task-Orders/TO-85_S.03.10_2023-02-20_PBW_SHINE_IN-SITU_WATER_JOINTS
sts_archive/0-Task-Orders/TO-87_S.03.10_2023-02-20_PBW_SHINE_IN-SITU
sts_archive/0-Task-Orders/TO-153_S.03.10_2023-02-20_PBW_SHINE_IN-SITU_POST_PBW_REMOVAL
```

The MCNP calculation for the neutron fluxes and the CINDER activation calculation are the same for all analyses. These are archived with TO-85. Analysis 4 and 5 do not have a separate task order number and are archived with TO-153. All plotting scripts are archived with TO-87.

APPENDIX C. SHORT COMPARISON BETWEEN MCNP AND ADVANTG RESULTS

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The dose rate results obtained using Advantg provide a good first estimate in for the residual dose rate analyses. Figures 24, 25, and 26 show a vertical cross-section of the dose rate results obtained with Advantg (left) and MCNP (middle) as well as a plot of the residual error (RE) on the MCNP result (right). The contour lines in each dose rate plot are chosen at the same values to make a quick comparison easy. The RE plot shows the areas where the MCNP results are converged in blue (0-5% RE) and, less converged in red (5-10% RE). Results with more than 10% RE are shown in white. In the statistically converged zones in the PBW area, the MCNP and Advantg results give very similar results. No effort was made to evaluate the discretization errors on the Advantg results. In future iterations, it can be considered to use Advantg results to provide a first estimate for the dose rates, before running the computationally more demanding MCNP runs.

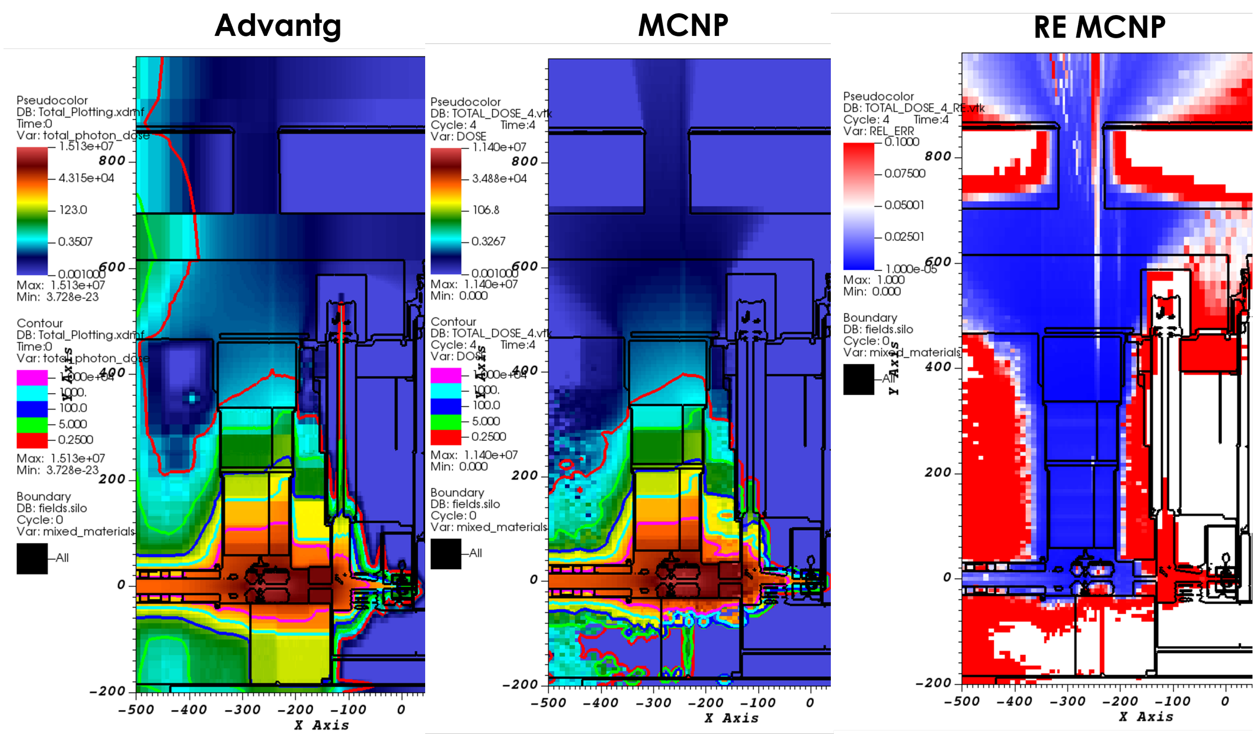

Figure 24. Comparison of dose rates (mrem/h) obtained with Advantg and MCNP for analysis 1. These plots show a vertical cross section through the geometry of the dose rates calculated with Advantg (left), with MCNP (middle), and the relative error of the MCNP result (right).

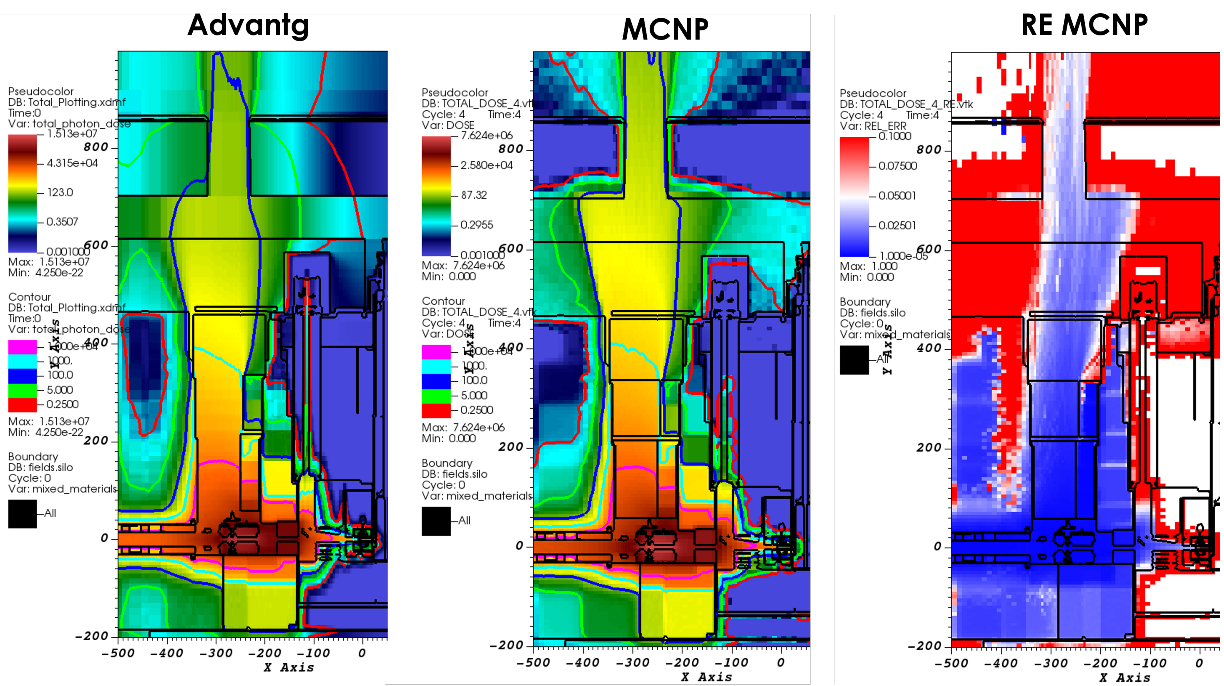

Figure 25. Comparison of dose rates (mrem/h) obtained with Advantg and MCNP for analysis 2. These plots show a vertical cross section through the geometry of the dose rates calculated with Advantg (left), with MCNP (middle), and the relative error of the MCNP result (right).

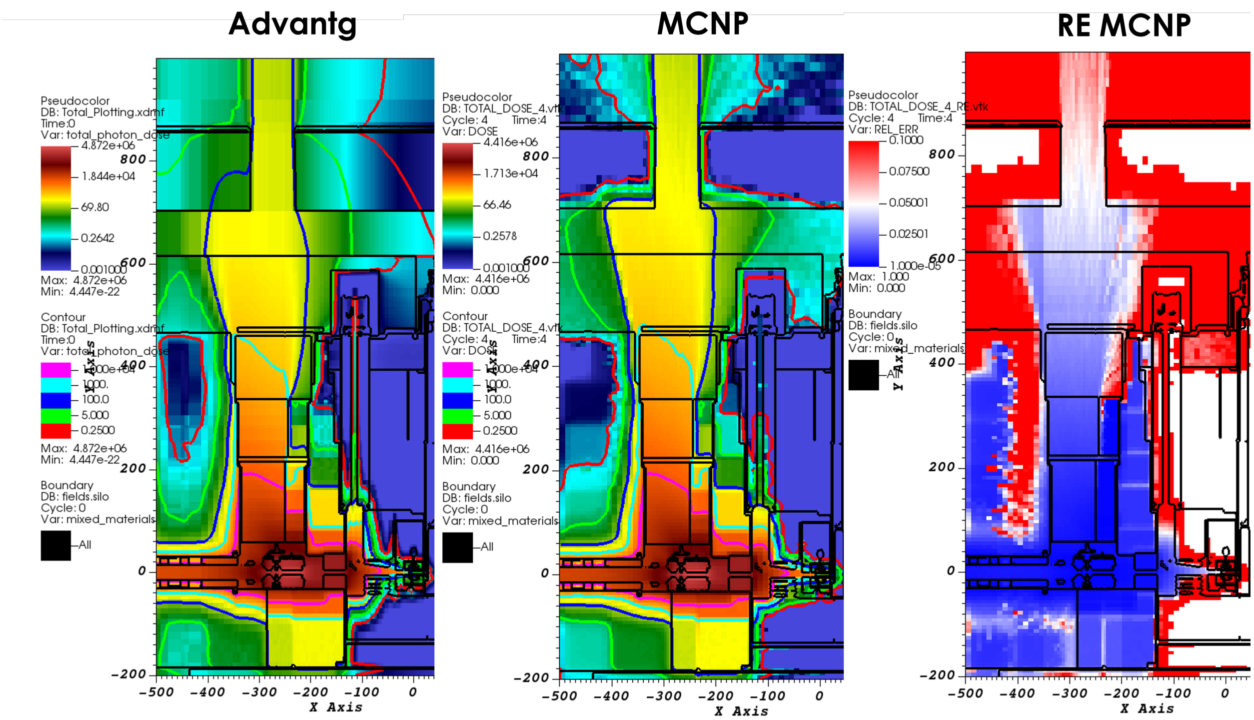

Figure 26. Comparison of dose rates (mrem/h) obtained with Advantg and MCNP for analysis 3. These plots show a vertical cross section through the geometry of the dose rates calculated with Advantg (left), with MCNP (middle), and the relative error of the MCNP result (right).

APPENDIX D. RESIDUAL DOSE RATES FROM MONOLITH COMPONENTS

APPENDIX D. RESIDUAL DOSE RATES FROM MONOLITH COMPONENTS

For analysis 2, the residual dose rates have been evaluated from the activation sources in the moderator reflector assembly (MRA), the target viewing periscope (TVP), core vessel, and some of the target components (wheel, drive, stave, shaft). All these sources have a negligible contribution to the total dose rates in the area of interest for this analysis. Therefore, they have not been taken into account. The source terms have been generated by Tucker McClanahan and Lukas Zavorka as part of other neutronics task orders related to remote handling operations of the MRA removal, target segment removal, and target drive room operations. For the target wedges and staves, 10 years of operation is assumed. For the moderator reflector assembly (MRA) and the the target viewing periscope (TVP), respectively 6 years and 4 years of operation is assumed.

For the MRA and the TVP, results have been calculated with both Advantg and MCNP. Figures 27 and 28 show a vertical cross-section of the dose rate results obtained with Advantg (left) and MCNP (middle) as well as a plot of the relative error (RE) on the MCNP result (right). The contour lines in each dose rate plot are chosen at the same values to make a quick comparison easy. The RE plot shows the areas where the MCNP results are converged in blue (0-5% RE) and, less converged in red (5-10% RE). Results with more than 10% RE are shown in white. In the statistically converged zones in the PBW area, the MCNP and Advantg results give very similar results. For the core vessel and the target, the dose rates have only been calculated with Advantg.

For analysis 2, the dose rate close to the PBW exceeds 50 rem/h. At the target drive room floor level, dose rates above 500 mrem/h are reached. Having these numbers in mind, it is clear that the contributions of the monolith components are negligible. Dose rates close to the PBW are around 5 mrem/h, while at the target drive room floor level 0.25 mrem/h is hardly reached. We conclude that the activated monolith components do not contribute significantly to the dose rates in the PBW area for the evaluated configurations.

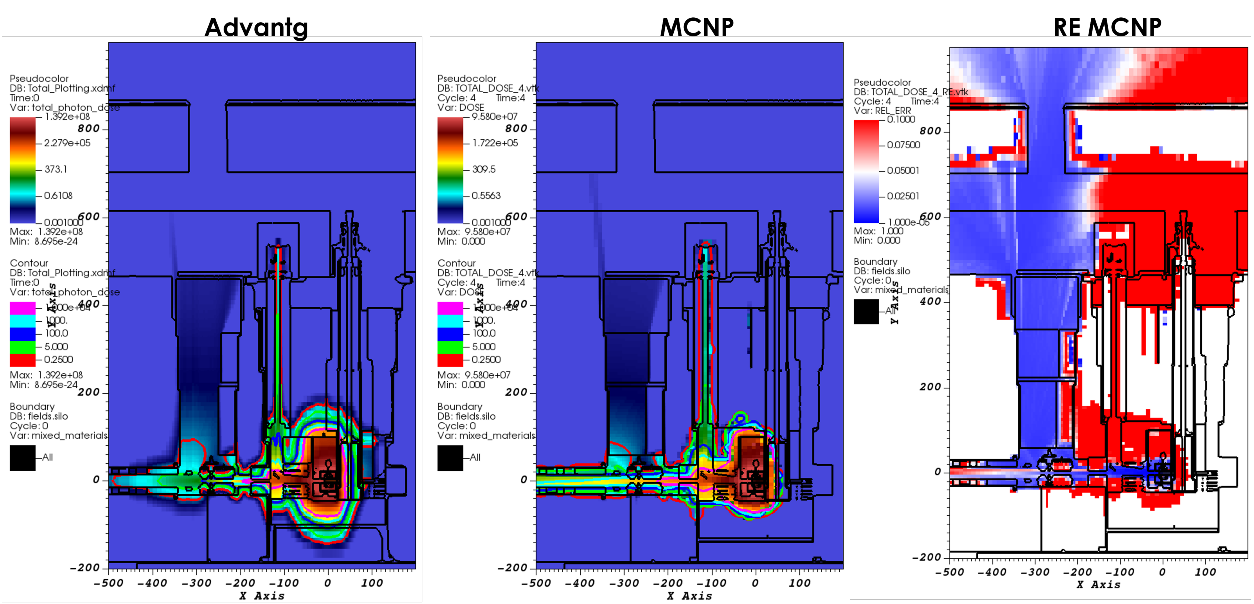

Figure 27. Dose rate (mrem/h) from the activated MRA. The left plot shows the result with Advantg, the middle plot with MCNP, and the right plot showns the relative error of the MCNP result.

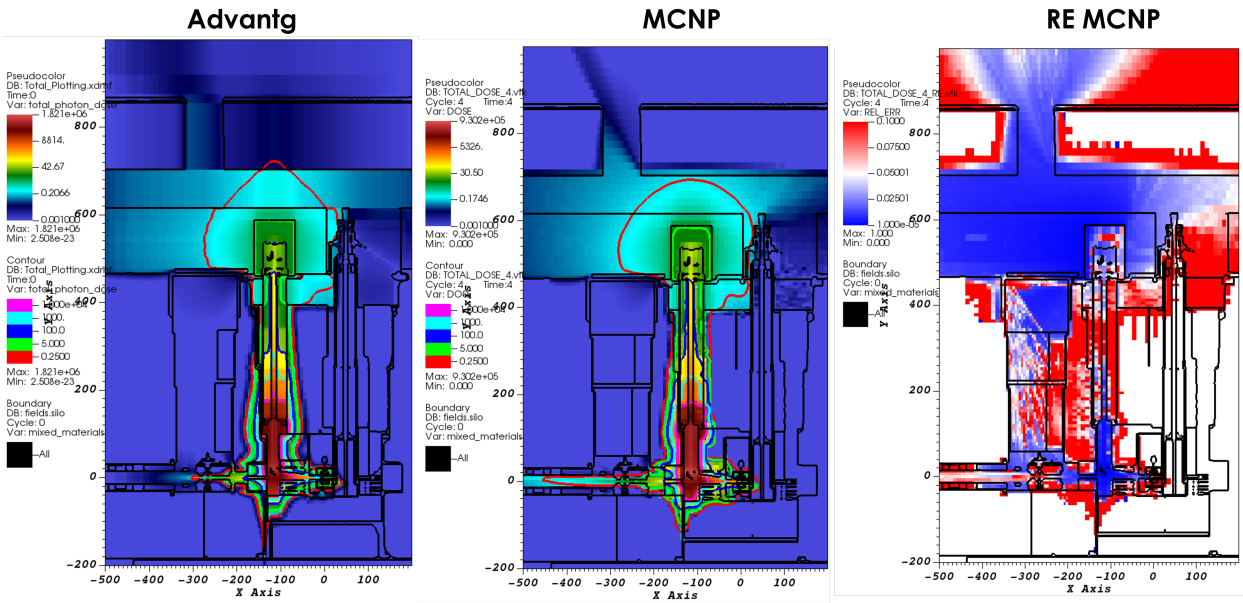

Figure 28. Dose rate (mrem/h) from the activated TVP. The left plot shows the result with Advantg, the middle plot with MCNP, and the right plot showns the relative error of the MCNP result.

For the target, the simulation was run for a subset of the activation sources from . This subset includes the sources with the highest gamma source intensities in the wheel, staves, and shaft. As seen in Figure 30

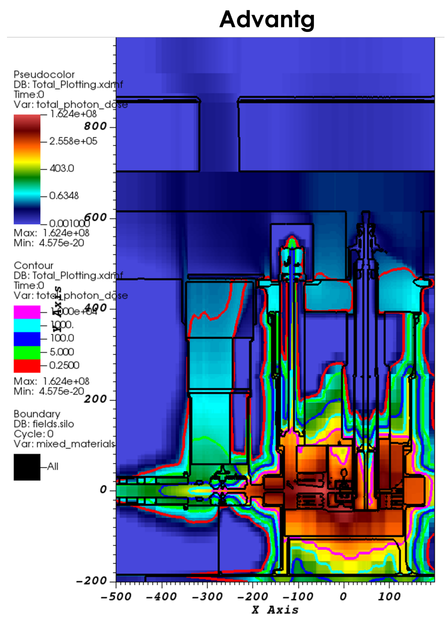

Figure 29. Dose rate (mrem/h) from the activated core vessel. This result was obtained with Advantg.

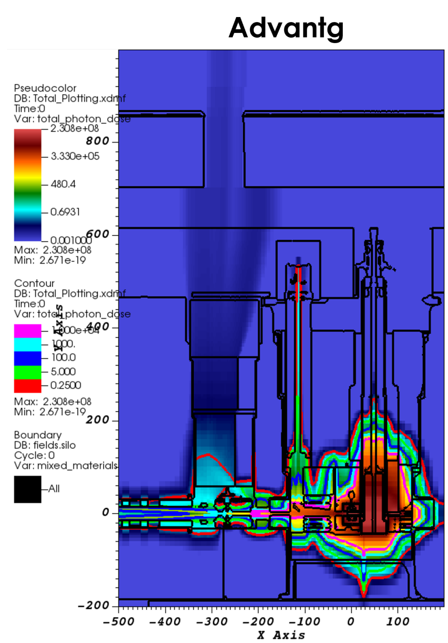

Figure 30. Dose rate (mrem/h) from the largest sources of the activated target. This result was obtained with Advantg.

The largest streaming path from the monolith components to the PBW area is present in analysis 5, where the full PBW assembly and its shielding is removed. The dose rate is evaluated for two source terms: the source from the target wedges that contributes the most to the dose rate in the PBW area (Figure 31), and similarly the source from the core vessel that contributes the most in the area of interest (Figure 32). For simplicity, the source term is taken for 1 week of decay, which is conservative considering the actual decay time of 4 weeks. The main objective of this analysis is to confirm that the dose rates from the monolith components are significantly lower than those from the target station shielding and the PBT. At the target drive room floor level, the dose rate from the target station shielding and the PBT is approximately 150 mrem/h. At this location, the largest contributor from the target source provides less than 0.25 mrem/h and the largest contributor from the core vessel source provides less than 5 mrem/h. We conclude that for the purposes of this analysis, the sources from the monolith components can be neglected.

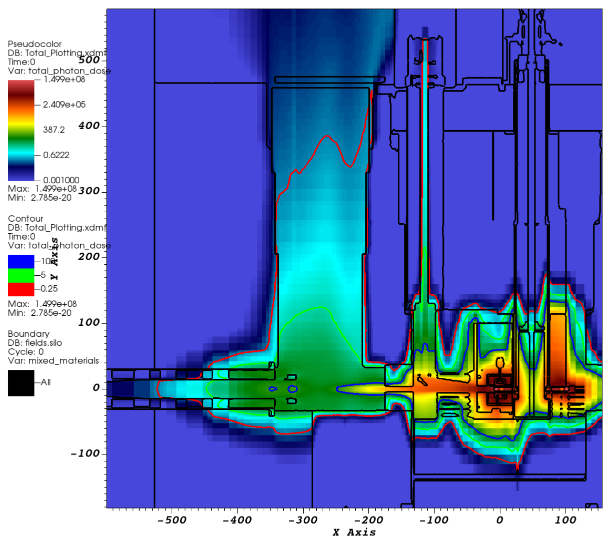

Figure 31. Dose rate (mrem/h) from the largest dose rate contributor from the activated target.

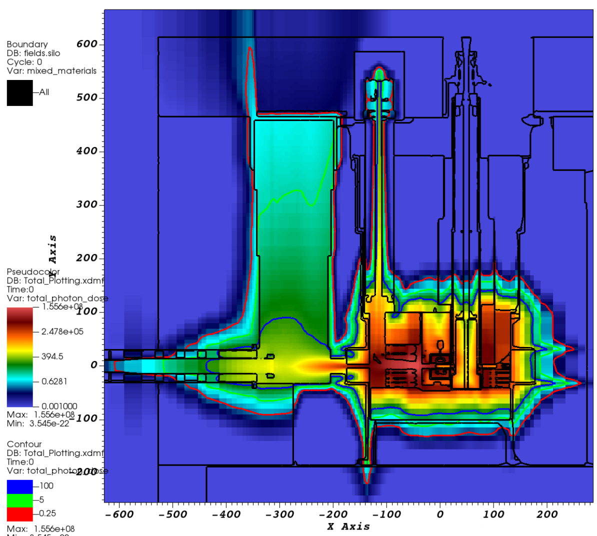

Figure 32. Dose rate (mrem/h) from the largest dose rate contributor from the activated core vessel.