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Analyses of Dose Rates for Second Inner Reflector Plug Replacement at Spallation Neutron Source

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OAK RIDGE National Laboratory

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Neutron Science Directorate

ANALYSES OF DOSE RATES FOR SECOND INNER REFLECTOR PLUG REPLACEMENT AT SPALLATION NEUTRON SOURCE

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ABBREVIATIONS

ORNL	Oak Ridge National Laboratory
SNS	Spallation Neutron Source
IRP	Inner Reflector Plug
ORP	Outer Reflector Plug
MCNP6	Monte Carlo N-Particle
AARE	Activation in Accelerator Radiation Environments
PBW	proton beam window
ALARA	as low as reasonably achievable
mrem/h	(milli roentgen equivalent man)/hour
rem/h	(roentgen equivalent man)/hour

ABSTRACT

The Inner Reflector Plug (IRP) is a central component of the Spallation Neutron Source (SNS) target monolith, which houses the liquid mercury target and four liter-sized neutron moderator units. It is exposed to high-level radiation fields during routine operation and builds up significant activity. The IRP needs to be replaced due to moderator neutron poison and decoupler burn-out, which is used for shaping neutron pulses. The first IRP exchange took place in March 2018 and next one, which is IRP2, is planned to be replaced during the facility maintenance period at the end of December 2025, beginning of January 2026.

The replacement of IRP is a complex task due to its location in the area receiving high irradiation, being under significant amount of shielding, and its size requiring removal in segments. For planning the replacement workflow to help to reduce radiation exposure to workers dose rates for each stage of extraction/replacement operation are predicted.

1. INTRODUCTION

Oak Ridge National Laboratory (ORNL) operates the Spallation Neutron Source (SNS), which converts a 1.8 MW proton beam of 1.3 GeV energy and sub-micro-second pulse width incident on a mercury target into a neutron source at 60 Hz repetition rate.

The Inner Reflector Plug (IRP) is a central component of the SNS target monolith, which houses the mercury target and moderators. It is situated in the middle of the target monolith in the shaft, from which it can be removed. As a central component, it is exposed to high-level radiation fields during operation and builds up significant radioactivity. The IRP assembly contains four moderators and a beryllium reflector. The IRP needs to be replaced due to the burn out of neutron poisons used in some of the moderators for shaping narrow neutron pulses for use in neutron scattering. Next replacement, which is removal of IRP2 and placement of IRP3 will take place during the facility maintenance period in the end of December 2025, beginning of January 2026. IRP1 was successfully replaced with IRP2 during facility maintenance period that started in January 2018.

The replacement of an IRP represented a critical operation demanding significant planning for a variety of activities one of which is radiological planning. This document reflects predicted residual dose rates during each stage of removal/exchange process.

2. REPLACEMENT OPERATION

IRP2 will be split into 3 segments during the replacement from the monolith shaft, and each segment will be extracted separately and due to expected high residual radiation levels, they are going to be extracted directly into a storage cask and will be disposed separately. Replacement starts with IRP2 shielding removal from the shaft to open the access to IRP2.To support operational needs the residual dose rate distributions are calculated for each stage, and the peak values are identified.

The IRP2 removal/exchange stages that require dose rates analyses to support radiological planning will include:

- The shaft open with the IRP2 middle section inside,
- Water supply pipe and L-blocks cutting,
- Removal operations of middle and lower IRP2 segments,

- Empty IRP shaft with and without inspection tools,
- Placing fresh IRP3

After shielding removal from the shaft to open IRP2 the shielded adapter plate will be installed on the shaft opening to provide technician shielding and cask alignment, and then actual IRP2 replacement starts. Timeline for removal/exchange operation is presented in Table 1.

Table 1. Removal/exchange tentative timeline.

Beam off	11/25/25	Days from beam off
Remove upper segment cask and move to storage position	12/9/25	14
Install middle cask, lift middle segment, secure, and store cask	12/10/25	15
Install lower cask in SDER and shielded door support frame	12/16/25	21
Lower cask removed	12/18/25	23
Install IRP-3 IRP module	12/30/25	35

Each stage described in timeline table was carefully analyzed to predict the dose rates distributions besides removing the IRP2 upper section, which does not produce significant radiation. Between lower cask removal and installation of IRP3 inspection tooling will be installed temporarily and this stage was analyzed.

3. METHODS

Neutronics analyses for the residual dose rates during the IRP2 replacement are performed in 3 steps. As a first step reaction rates in the IRP2 vicinity are calculated with particles transport code MCNP6.2 [2], which simulates the generation of secondary radiation fields due to the impact of proton beams the mercury target and transport of secondary particles through the target monolith. The source term for these analyses is an SNS nominal beam that is directed to the target.

Into the lifetime of IRP2 fell an upgrade of the SNS accelerator facility. Proton Power Upgrade (PPU) [2] involved upgrading the SNS accelerator complex, to double its proton beam power capability from 1.4 to 2.8 MW at an increase of the proton beam energy from 1 GeV to 1.3 GeV.

Two source terms were used for the transport analyses - pre-PPU and post PPU. Pre-PPU source term describes a 1GeV proton energy beam [4], the post-PPU source term gives the 1.3GeV proton energy beam[5]. The primary beam transport analyses were performed on a per one proton basis.

A further complication for the activation of the permanent monolith components making up the shaft is the fact that the cooling medium of the IRPs and the ORP was changed from light water to heavy water with the insertion of IRP2. Two transport analyses were performed for pre-PPU conditions one with light-water cooling and the second with heavy-water cooling. Each part of IRP and surrounding shaft area were subdivided to several cells, for which reaction rates and fluxes below 20 MeV are collected. The geometry subdivision is performed to use geometry splitting to provide particle population control toward the outside the shielding and to obtain convergence of calculational results. The sub-division allows as well to describe sources for residual doses with better spatial resolution.

As the second step, the decay gamma sources in the activated material are calculated. The activation script (Activation in Accelerator Radiation Environments – AARE) [6] as interface between transport code MCNP6.2 and transmutation code CINDER2008 [7] reads the isotope production rates and neutron fluxes, which are resulting from the MCNP6.2 calculations for each IRP and surrounding IRP cells, and executes the CINDER2008 code to obtain the time dependence of the isotope buildup and decay including decay gamma spectra according to the operational scenario. The analyses assume the last day of beam on target of November 25, 2025, with total beam energy deposited to the IRP2 of 42.444 GWh since IRP2 was put in operation in May 2018. Analyses for the target monolith cells around the IRP shaft assume operation time since facility start-up in April 2006.

The beam operation history is taken from SNS logbooks and deposited beam energy is averaged over 380.36 days for first 10.4 years of operation in first 10 steps and followed by various time steps for the remainder of the IRP1 service time. The deposited beam energy by time-period and cumulative energy is presented in Table 2 for the IRP1 service time.

Table 2. Beam history during IRP1 service time

Time, Days	Energy per Period, GWh	Cumulative Energy, GWh	Time, Days (continue)	Energy per Period, GWh (continue)	Cumulative Energy, GWh (continue)
380.36	3.909	3.909	2.5	0.070	39.303
380.36	3.909	7.818	3.01	0.072	39.375
380.36	3.909	11.727	2.59	0.073	39.448
380.36	3.909	15.636	2.66	0.063	39.510
380.36	3.909	19.544	3.02	0.086	39.596
380.36	3.909	23.453	2.67	0.062	39.658
380.36	3.909	27.362	3.02	0.082	39.740
380.36	3.909	31.271	2.67	0.076	39.816
380.36	3.909	35.180	3.01	0.069	39.885
380.36	3.909	39.089	2.66	0.072	39.958
27	0.000	39.089	2.54	0.073	40.030
2.33	0.002	39.091	2.94	0.068	40.098
1.76	0.032	39.123	2.94	0.075	40.173
2.96	0.053	39.175	2.94	0.070	40.243
	0.000	39.175	5.45	0.149	40.392
3.26	0.057	39.232	1.78	0.050	40.442

The deposited beam energy by time-period and cumulative energy is presented in Table 3 for the IRP2 service time. The beam operation history is taken from SNS logbooks till the end of May 2025 and for time frame from May 2025 to November 25, 2025 the beam power history was modeled with the assumption that 3.550GWh proton power beam on the target will be deposited and total deposited energy during the lifetime of IRP2 is 42.404GWh.

Table 3. Beam history during IRP2 service time.

1.0GeV energy incoming proton			1.3GeV energy incoming proton beam		
Time, Days	Energy per Period, GWh	Cumulative Energy, GWh	Time, Days	Energy per Period, GWh	Cumulative Energy, GWh
144	0	0	322	0.000	30.448
83	1.988	1.988	146	4.346	34.794
19	0.000	1.988	61	0.000	34.794
83	2.233	4.220	7	0.174	34.968
61	0.000	4.220	7	0.247	35.215
65	1.830	6.051	7	0.248	35.463
92	0.000	6.051	7	0.157	35.619
64	1.383	7.434	7	0.255	35.875
16	0.000	7.434	7	0.255	36.130
22	0.481	7.915	7	0.240	36.370
30	0.000	7.915	7	0.190	36.560
111	2.967	10.882	7	0.262	36.822
44	0.000	10.882	7	0.236	37.058
95	2.671	13.553	7	0.112	37.170
43	0.000	13.553	7	0.286	37.456
101	2.840	16.393	7	0.278	37.734
72	0.000	16.393	7	0.264	37.998
83	2.275	18.667	7	0.284	38.282
10	0.000	18.667	4	0.169	38.451
162	3.186	21.854	7	0.220	38.671
75	0.000	21.854	6	0.216	38.887
68	1.932	23.786	75	0.000	38.887
64	0.000	23.786	7	0.172	39.059
84	2.258	26.043	7	0.247	39.306
113	0.000	26.043	7	0.247	39.553
98	2.650	28.694	7	0.157	39.710
90	0.000	28.694	7	0.255	39.965
72	1.755	30.448	7	0.254	40.219
			7	0.239	40.458
			7	0.190	40.648
			7	0.257	40.905
			7	0.228	41.133
			7	0.113	41.246
			7	0.286	41.531
			7	0.278	41.809
			7	0.292	42.101
			7	0.302	42.404

To obtain decay gamma sources during transmutation analyses, it was necessary to develop a workflow due to the complex and large geometry - there are more than 600 source cells - and due to the various initial transport calculations source terms. The target monolith was exposed to the radiation environment from facility start up and exposed to 1GeV and later 1.3GeV incoming beam energy. In addition, the light water that cools the IRP and ORP was changed to heavy water after IRP1 replacement. To reflect it an workflow that includes multiple steps was developed. Transmutation code CINDER2008 has a capability of conducting an analysis with an inventory information from a previous analysis and that this capability was used to string together the assessment of inventories of the IRP2 components from the 1 GeV and 1.3 GeV source terms, and the assessment with the two source terms and the cases with two different coolants in both the IRPs and ORP.

Transmutation analyses for the target monolith are performed to the end of IRP1 operation cycle as summarized in Table 2, and results of analyses are stored in a binary file (*alldnz*) that gives the atom densities of all nuclides present initially or produced in the time intervals of the calculation for each cell. Then transmutation analyses are performed using the results from the transport analyses for IRP2 for timeline of operation at 1GeV. Then *alldnz* files for previous analyses for target monolith were copied into each of new cell with name *dnz* and input file for each monolith cell changed to used monolith isotope inventory by the beginning of the IRP2 cervices. Then transmutation analyses were performed again. Same procedure was applied to do final transmutation analyses. First analyses are performed for all cells from the time when facility started to operate at 1.3GeV (Table 3), then *alldnz* files from previous analyses are copied in to present analyses as *dnz* files and input files are changed. Then final transmutation analyses are performed for each cell.

As the third step, decay gammas spectra in the multi-group structure and gamma power for the time step corresponding to cooling down time for replacement stage are extracted for each cell and are fed back to MCNP6.2 input file to be used as source terms for residual gamma dose rate estimations during each stage of the removal. As photo neutrons can be generated from the beryllium reflector and heavy-water at a energy threshold of 1.67 MeV, decay gamma sources for energies of 1.33MeV and higher for the defined history of build-up and decay are extracted and compiled to a source term and describing the gamma source distribution of the IRP lower segment to account for photo-nuclear reactions. Main source of gammas at these energies is produced from Co-56m at 1.77 and 2.60 MeV. As it is not expected that neutrons will be the main contributors to the total dose rates during the IRP extraction, the neutron contribution was only calculated for the IRP2 loaded in the cask.

The radiation fields are calculated using the mesh tally feature in Cartesian coordinates for the vertical view, and in planar views at the top of the shaft as parts of the IRP2 are removed. The thickness of a mesh-tally slice is 0.20 m, and the mesh size is 10 × 10 cm. This report shows decay gamma dose rates that result from multiplying the energy-dependent gamma fluxes by photon flux-to-dose coefficients [8].

4. GEOMETRY

A schematic overall view of the target monolith is presented in Figure 1 [9]. The target monolith, which is about 510-cm in radius, houses steel shielding, the Outer Reflector Plug (ORP), and the IRP, which is inserted into the shaft with shielding on the top of it. One of the assumptions that was made for the analyses that the IRP1 and IRP2 have similar geometry and IRP1 model is used in the calculations. Both IRP have the same materials, and the differences are mostly in openings through the shielding for the piping. The monolith material is stainless steel 316-53 with a density of 7.95g/cm^3. Its isotopic composition is given in Table 4. The ORP is fabricated of blocks of stainless steel 304 with density 8.03g/cm^3 stacked in a stainless steel 316-53 housing and cooled by heavy water with density 1.099987g/cm^3.

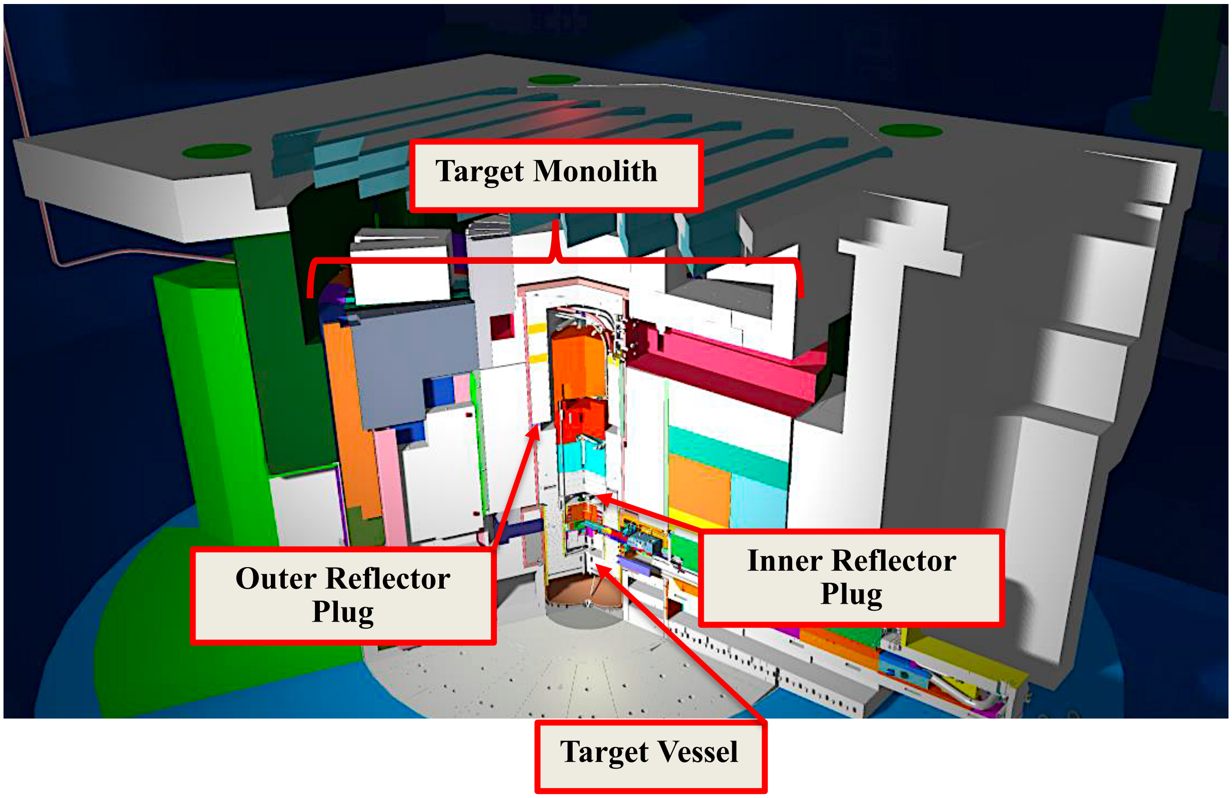


Figure 1. Schematic overall view of target monolith, vertical view.

Table 4. Isotope composition for SS-316-53and SS-304.

SS-316-53		SS-304	
Isotope	Weight %	Isotope	Weight %
C	0.03	C	0.015
N	0.16	Mn	1
Mo	2.6	Si	0.5
Cr	17.9	P	0.023
Ni	10.8	S	0.015
Fe	68.51	Cr	19
Co	0.1	Ni	10
		Fe	69
		Co	0.1

The IRP is shown in Figure 2, with segmentation for the waste disposal. The IRP assembly including shield plugs is cylindrical in shape and about 454-cm in height. IRP segments with the dimensions are shown in Figure 3. Both Figures 2 and 3 are taken from the M. Dayton presentation at SNS for IRP1 replacement. Upper and middle segments both are stainless steel 316 shielding.

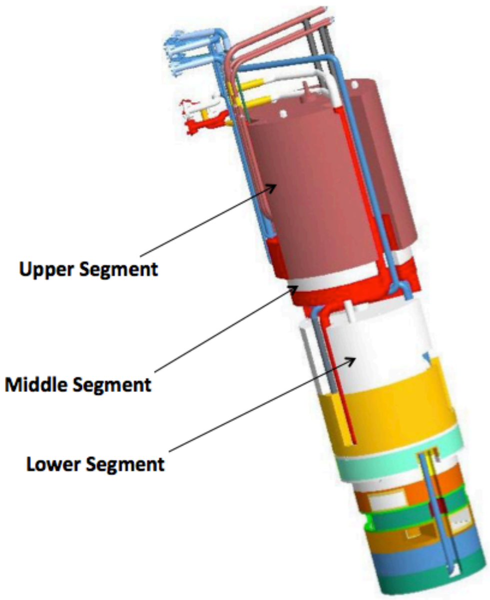


Figure 2. Schematic overall view of IRP extracted from the shaft with segmentation.

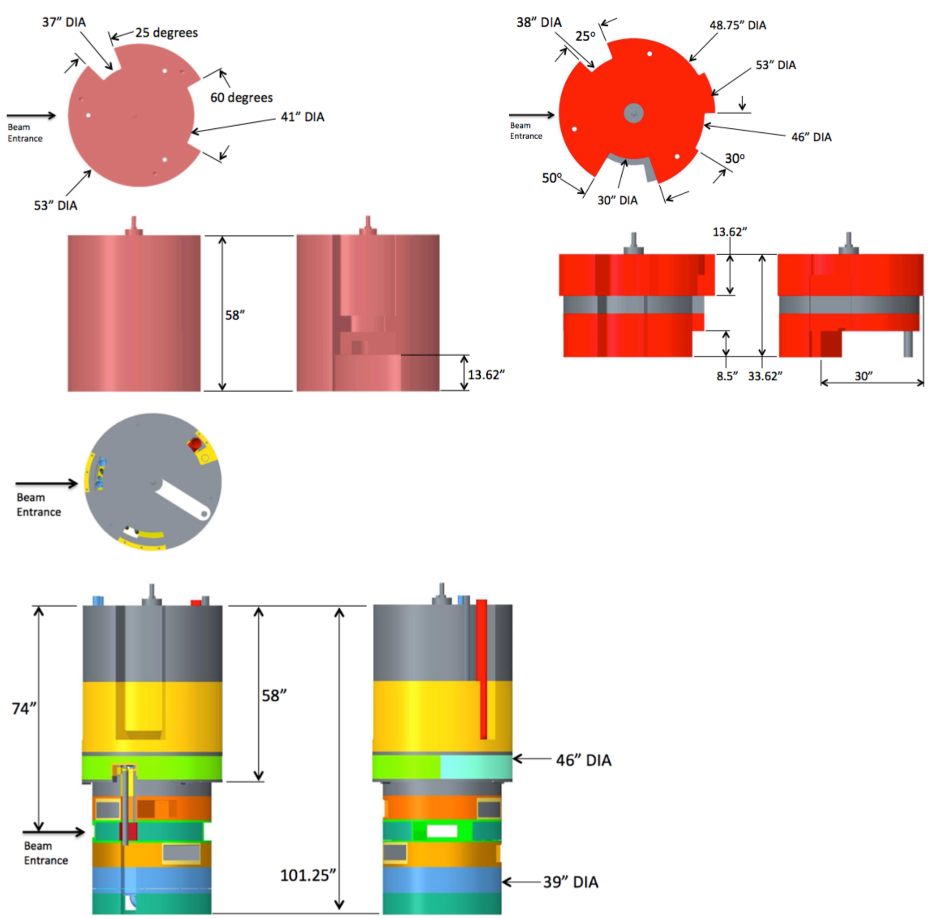


Figure 3. IRP segment with the dimensions (inches). Top row from left to right: top segment, middle segment. Bottom row - lower segment, Dimensions are in inches.

In the preparation for the IRP replacement the shielding above the shaft is removed to provide access to IRP2. Then a shielded adapter plate is installed see Figure 4 (courtesy of R. Schultz), which is a 5-cm thick A36 steel plate with an attached shielding collar. The collar is a cylinder ring of 6.1 cm height, 21.59-cm radial thickness of lead enclosed by 1.28-cm thick steel and an outside radius is 110.49 cm.

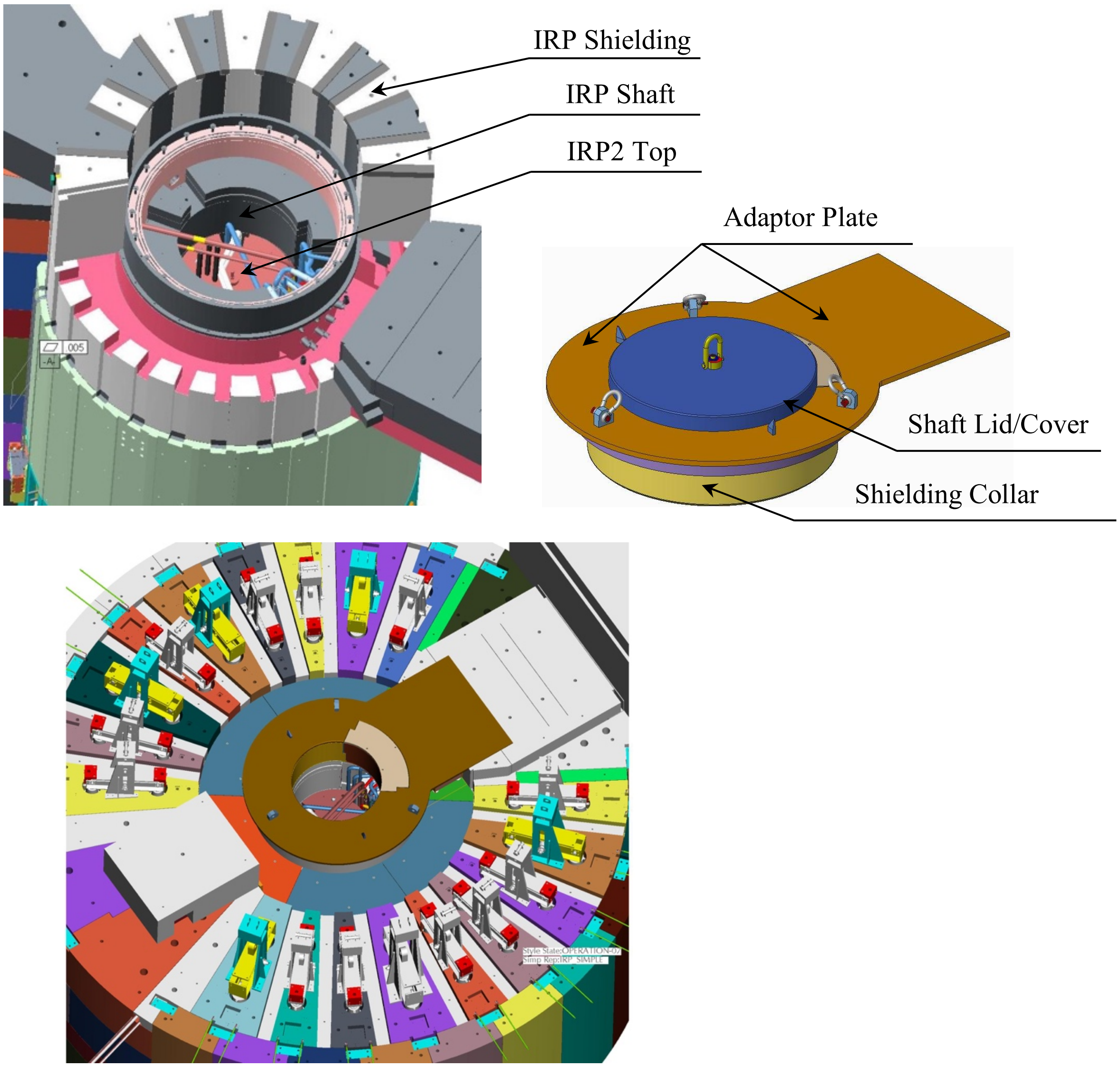


Figure 4. View of the target monolith with removed top shielding with open IRP shaft (top row left) from the top, shielded adapter plate with cover (top row right), target monolith with installed shielded adapter plate.

The target monolith model in MCNP6 geometry language was taken from older analyses [10], extended with the upper part of the monolith shielding and modified to the needs of the present analyses. The geometry model of target monolith is presented in Figure 5 in vertical cross section through beam center line and in vertical cross section perpendicular to the beam center line though the target nose. The material zones in the plots are color-coded. Zones, that do not have color are neutronically black areas. This model was used in prompt fluxes and reaction rates, for followed up the residual dose rates analyses the area above the monolith was extended with adaptor plate and was filled with the materials.

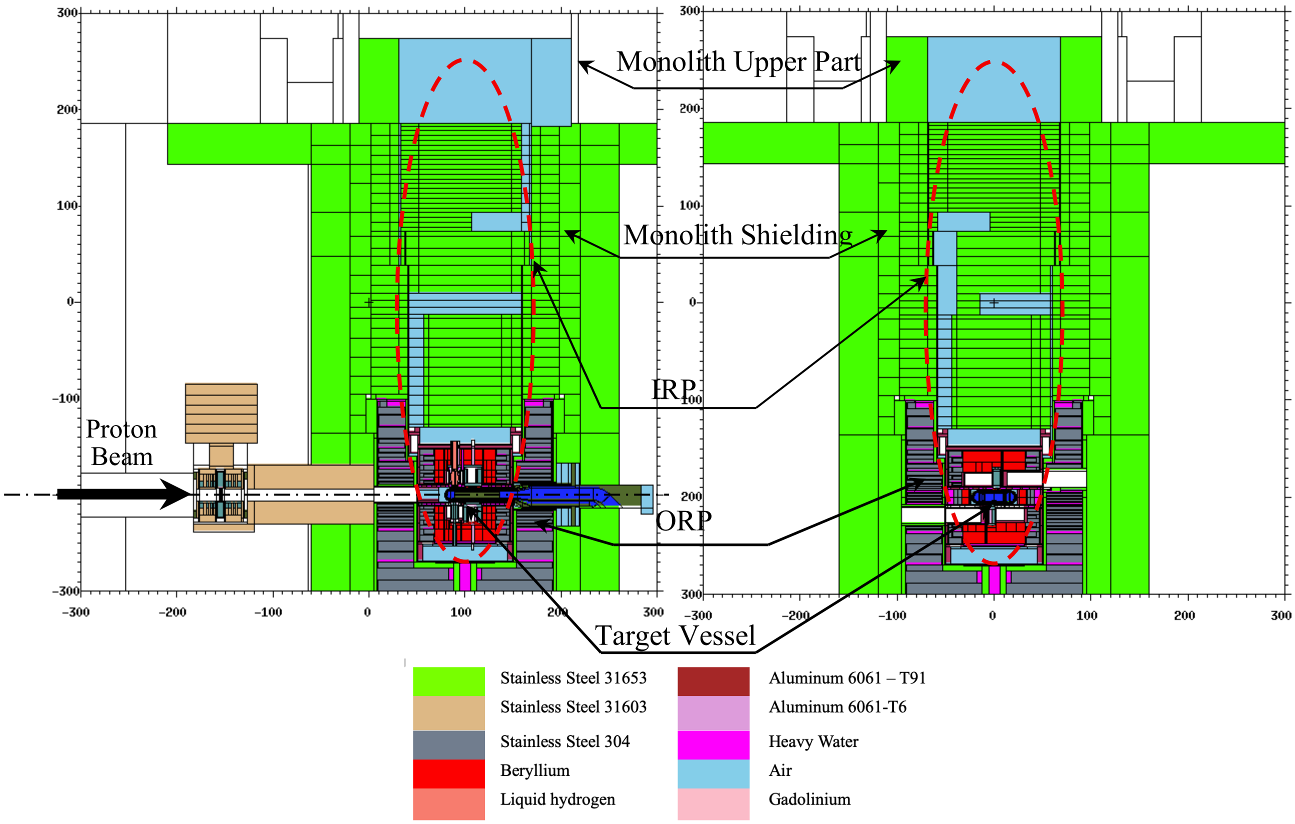


Figure 5. MCNP6 target monolith calculational model in vertical cross section through beam center line, and transverse cross section perpendicular to the beam center line dimensions are given in cm.

A zoomed-out view of the lower segment inside the monolith is shown in Figure 6. The lower IRP segment has a steel shielding on the top and the IRP itself is surrounded by aluminum casing (aluminum 6061-T91) with density of 2.7g/cm^3. For the material composition see Table 5.

Table 5. Isotope composition of aluminum and beryllium.

Aluminum		Beryllium	
Isotope	Weight %	Isotope	Weight %
AL	97.15	Be	98.5
Mg	1	BeO(alpha)	0.98
Si	0.6	AL	0.50.1
Fe	0.5	C	0.0230.15
Cu	0.3	Fe	0.13
Cr	0.2	Mg	0.08
Mn	0.1	Si	0.06
Ti	0.1		
Zn	0.05		

The IRP contains 4 moderators surrounded by beryllium reflector with density of 1.829g/cm^3 (Table 5) and heavy water-cooled stainless-steel shielding. Moderators' casings are made from the aluminum (two of them equipped with a central gadolinium plate) and are loaded with flowing liquid hydrogen or water during operation. For IRP replacement operation target vessel with liquid mercury will be extracted. Water and hydrogen is planned to be drained.

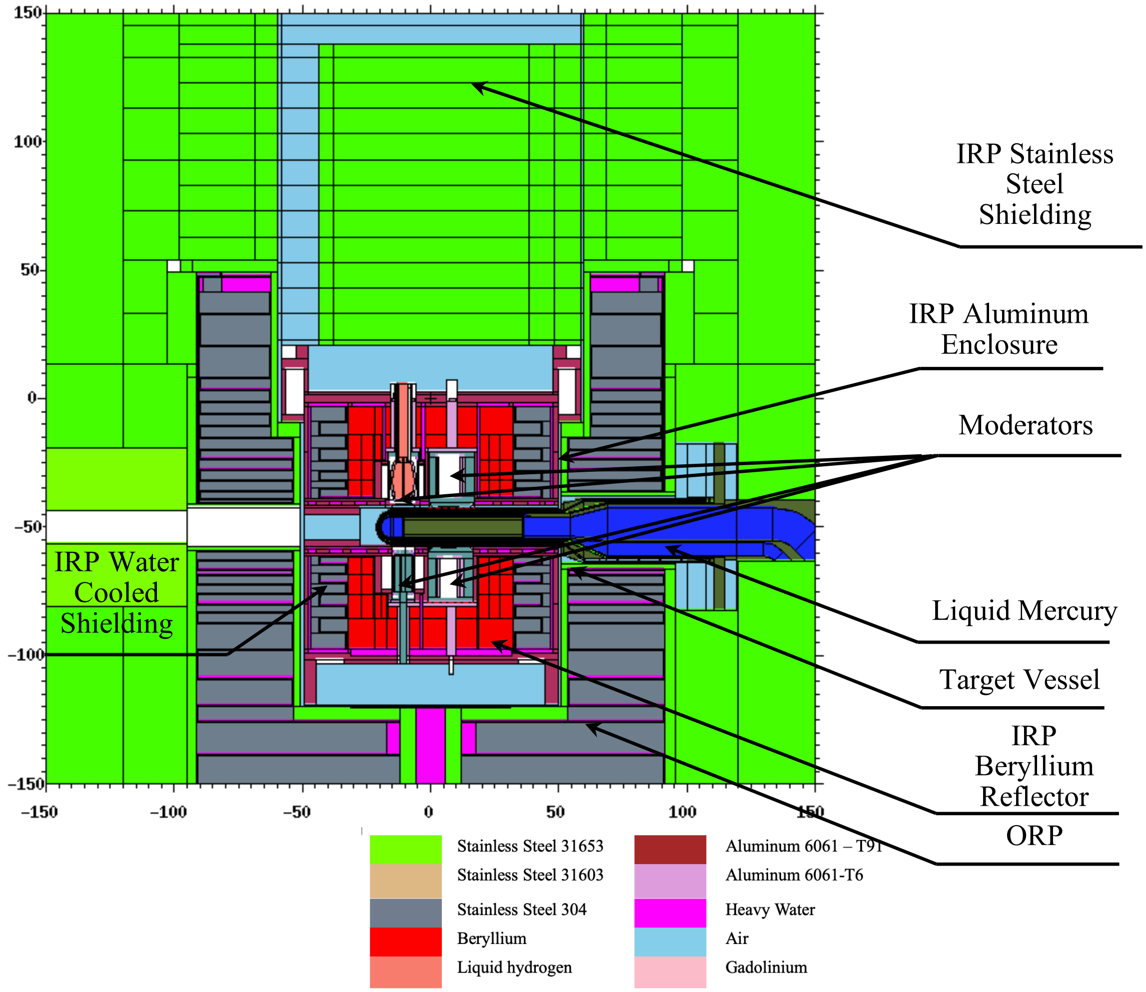


Figure 6. MCNP6 IRP calculational model in vertical cross section through the beam center line, dimensions are given in cm.

5. REPLACEMENT OF IRP2

Extraction/replacement operation of the IRP2 is performed in stages as describe above. Analyses are starting with stage when shielding above the IRP2 shaft is removed, the top IRP2 shielding segment is removed, and shielded adapter plate is placed on the top of the shaft. Each following stage will be described below by calculational MCNP6 model and dose rate map. The geometry is overlaid in white colors on top of the dose rate map in the presented plots.

The decay of the gamma sources over time of the target monolith and IRP2 lower segment is presented in Figure 7.

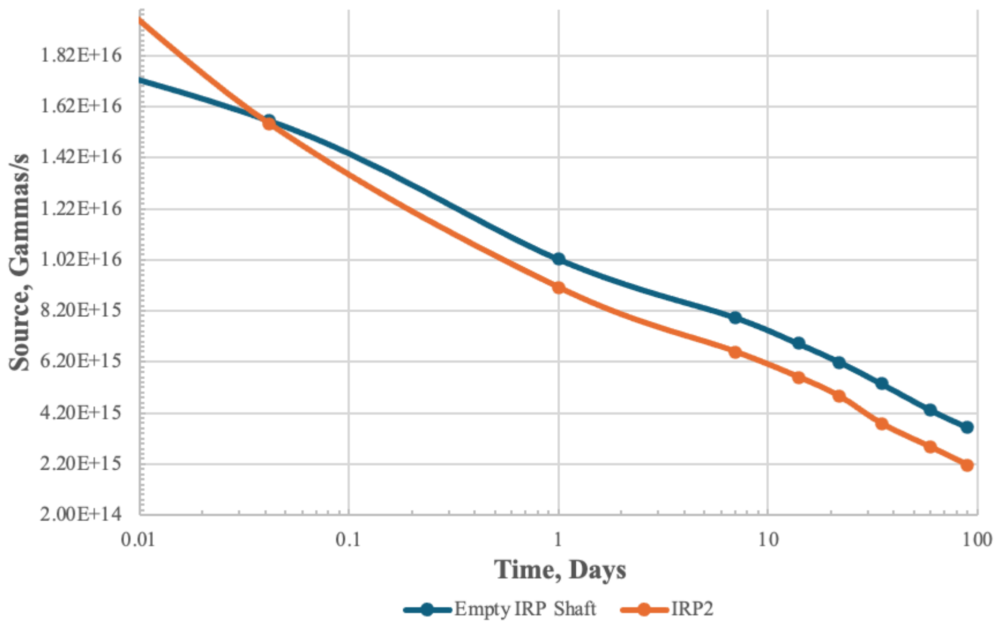


Figure 7. Gamma sources from target monolith and IRP2 after beam termination. Time is in logarithmic scale.

Figure 8 show gamma sources from the target monolith and IRP2 in time-period between 10 and 90 days after the beam termination. Between day 10 and day 90 sources decay with about factor of 3, and during the foreseen replacement operation, which is between day 14 and day 35 the sources reduce as a factor of 1.3 for the target monolith and factor of 1.5 for the IRP2 lower segment.

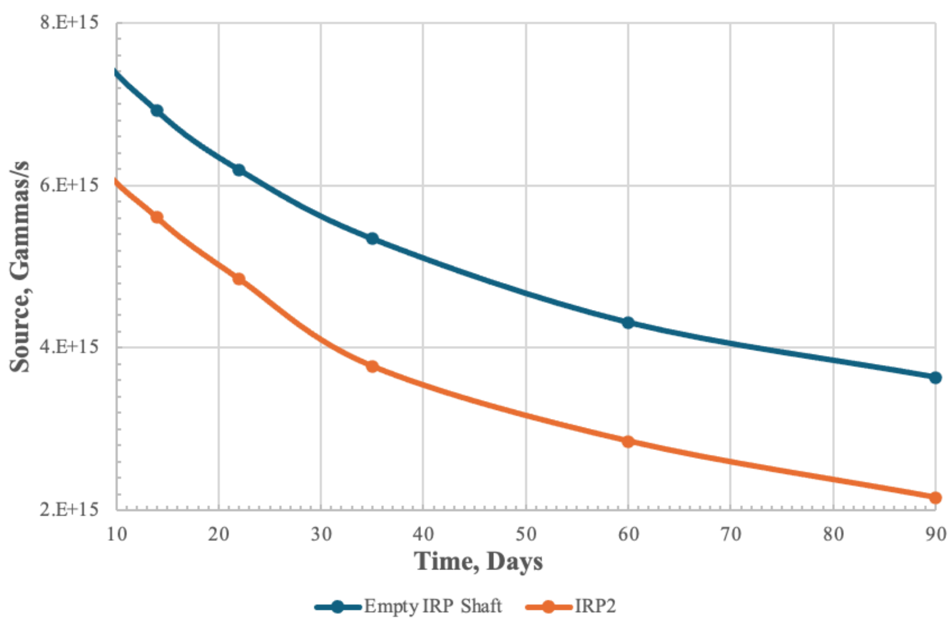


Figure 8. Gamma sourced from target monolith and IRP2 in decay time-period from 10 to 90 days.

5.1 IRP2 MIDDLE SEGMENT EXTRACTION

IRP2 middle segment will be removed in about 14 days after beam termination. Four sets of analyses are performed:

- open shaft with lower and middle IRP2 segments sitting in the shaft, heavy water is not drained,
- middle segment container placed on adaptor plate and middle segment partially lifted, heavy water is drained,
- middle segment inside the container that is on the top of the adaptor plate, heavy water is drained,
- container with the middle segment is removed, open shaft with IRP lower segment resting in shaft.

Vertical cross sections through the beam centerline and perpendicular to the beam centerline are shown in Figure 9.

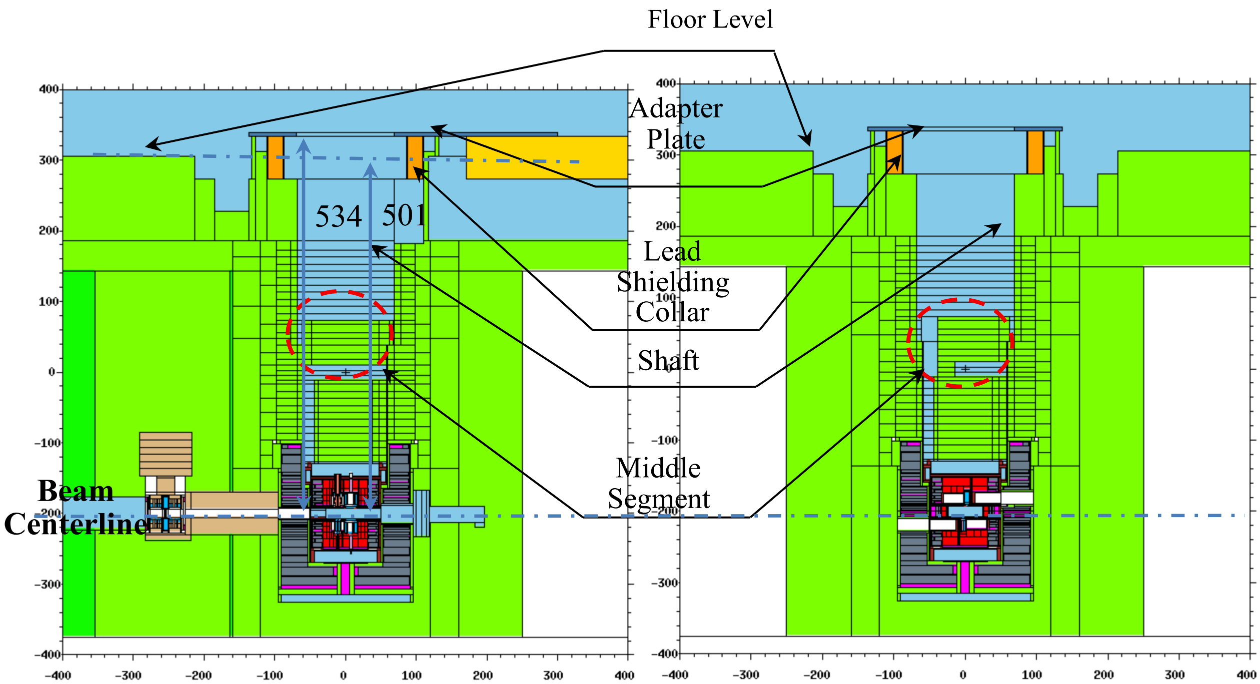


Figure 9. Vertical cross section through the beam centerline (left) and vertical cross section perpendicular to the beam centerline (right).

Gamma source terms and residual dose rates through target monolith corresponding to the time of 14 days after the beam termination and middle and lower IRP segments in the shaft are shown in Figure 10.

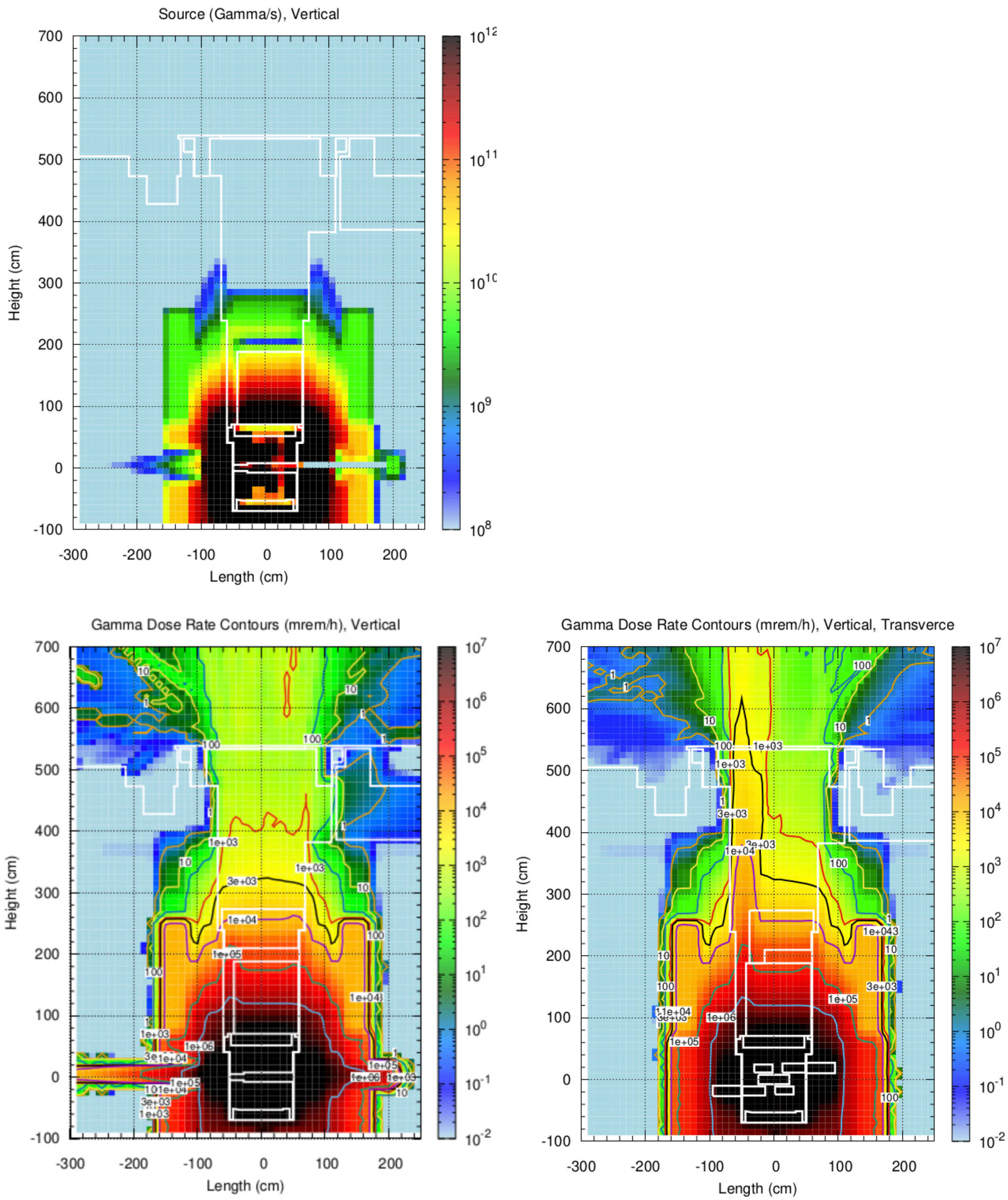


Figure 10. Gamma sources and residual dose rates through the target monolith with lower and middle segments inside the shaft 14 days after beam termination. Top row: gamma sources in vertical cross section through the beam center line. Bottom row shows residual dose rates in vertical cross section: through the beam centerline (left) and perpendicular to the beam centerline (right)

Residual dose rates through target monolith corresponding to the time of 14 days after the beam termination in horizontal cross section and in vertical cross section through the upper part of the shaft are shown in Figure 11.

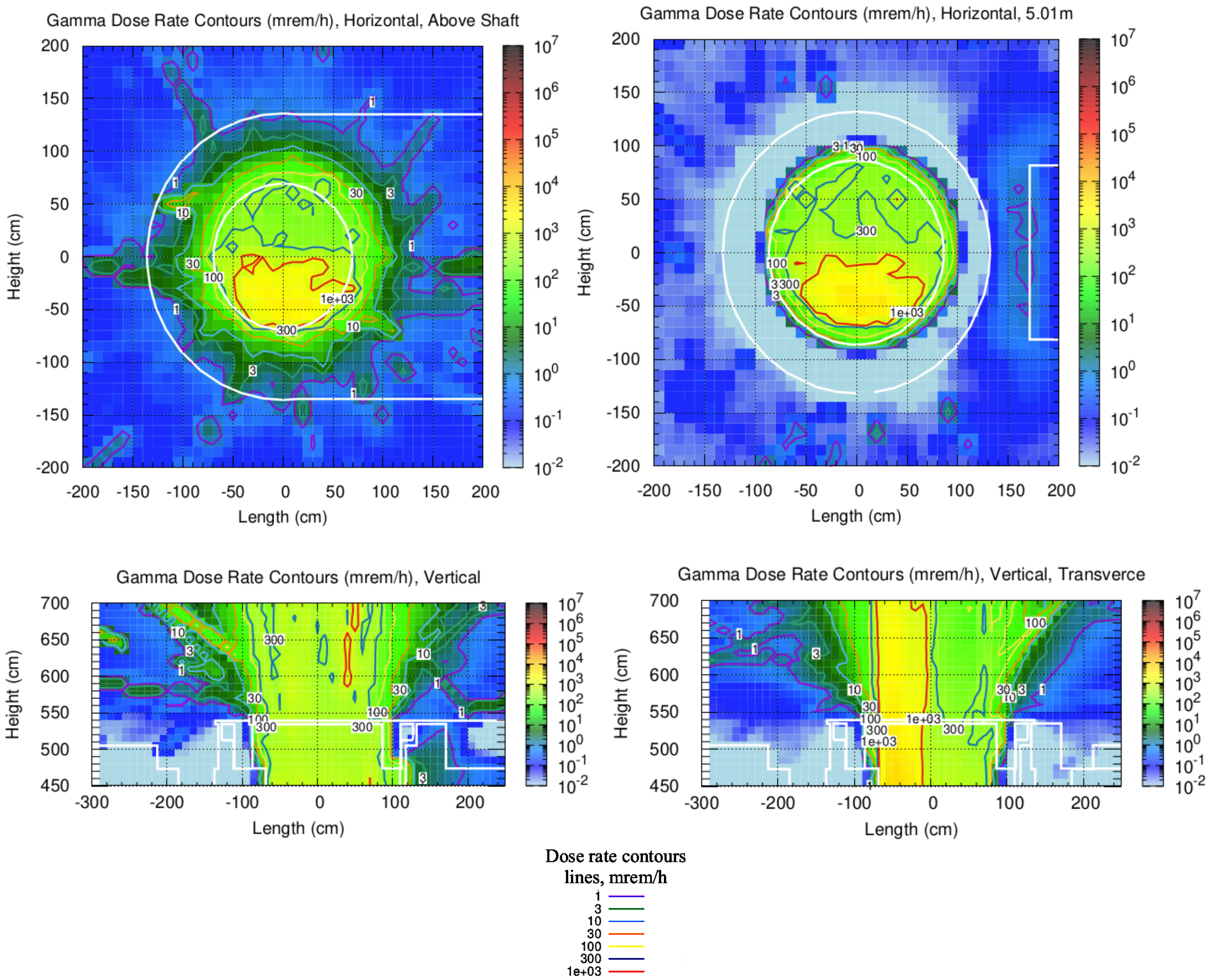


Figure 11. Residual dose rates through the target monolith with lower and middle segments inside the shaft 14 days after beam termination. Top row: horizontal cross section above the shaft(left) and through the shaft at 501-cm distance from the beam centerline. Bottom row vertical cross section: through the beam centerline (left) and perpendicular to the beam centerline (right).

Analyses of calculation show that the dose rates above the shaft opening are unto 2000 mrem/h and the dose rate on the floors are up to 3 mrem/h outside the adaptor plate.

Dose rates in vertical cross section through the beam centerline and in vertical cross section perpendicular to the beam centerline with the container for the middle segment installed on the adaptor plate, and for the middle segment partially lifted are shown Figure 12. Bottom of the middle section is at 480-cm distance from the beam centerline.

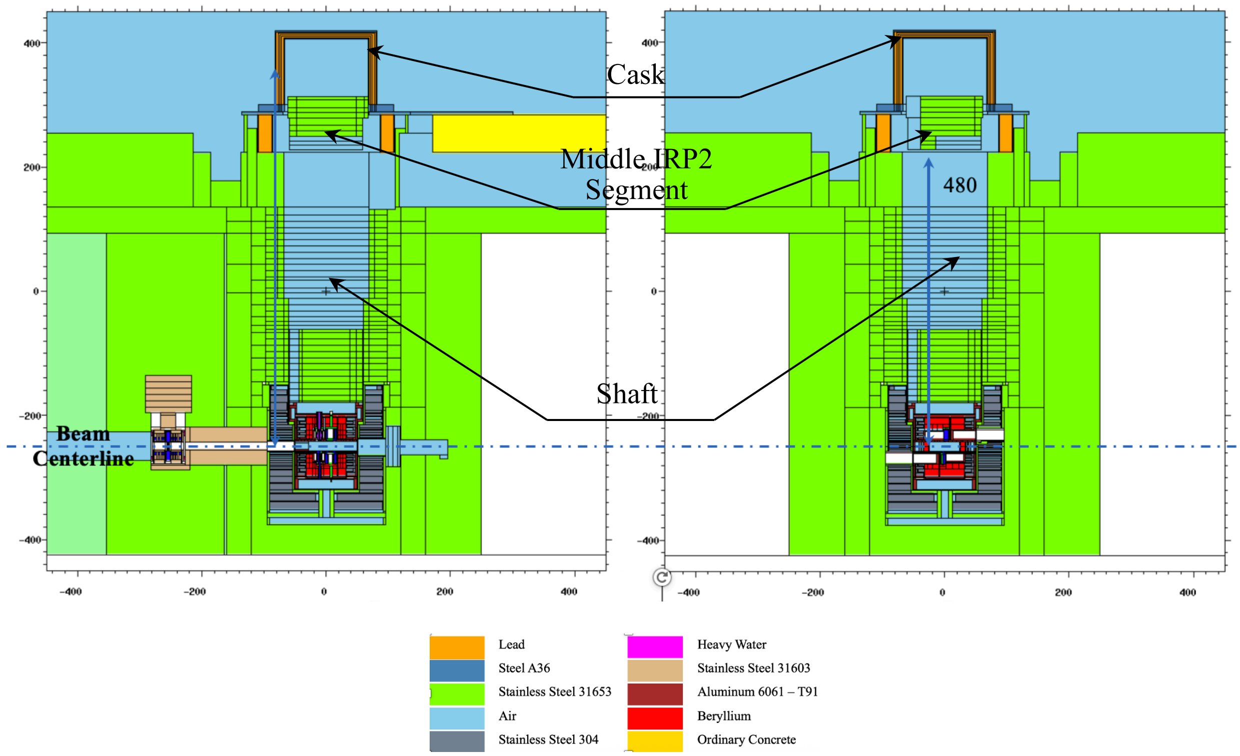


Figure 12. Vertical cross section through the monolith with middle segment cask installed and middle section in transition to the cask through the beam centerline (left) and vertical cross section perpendicular to the beam centerline (right).

Gamma source terms and residual dose rates through target the monolith corresponding to the time of 14 days after the beam termination with middle section partially lifted to the container installed on the adaptor plate are shown in Figure 13.

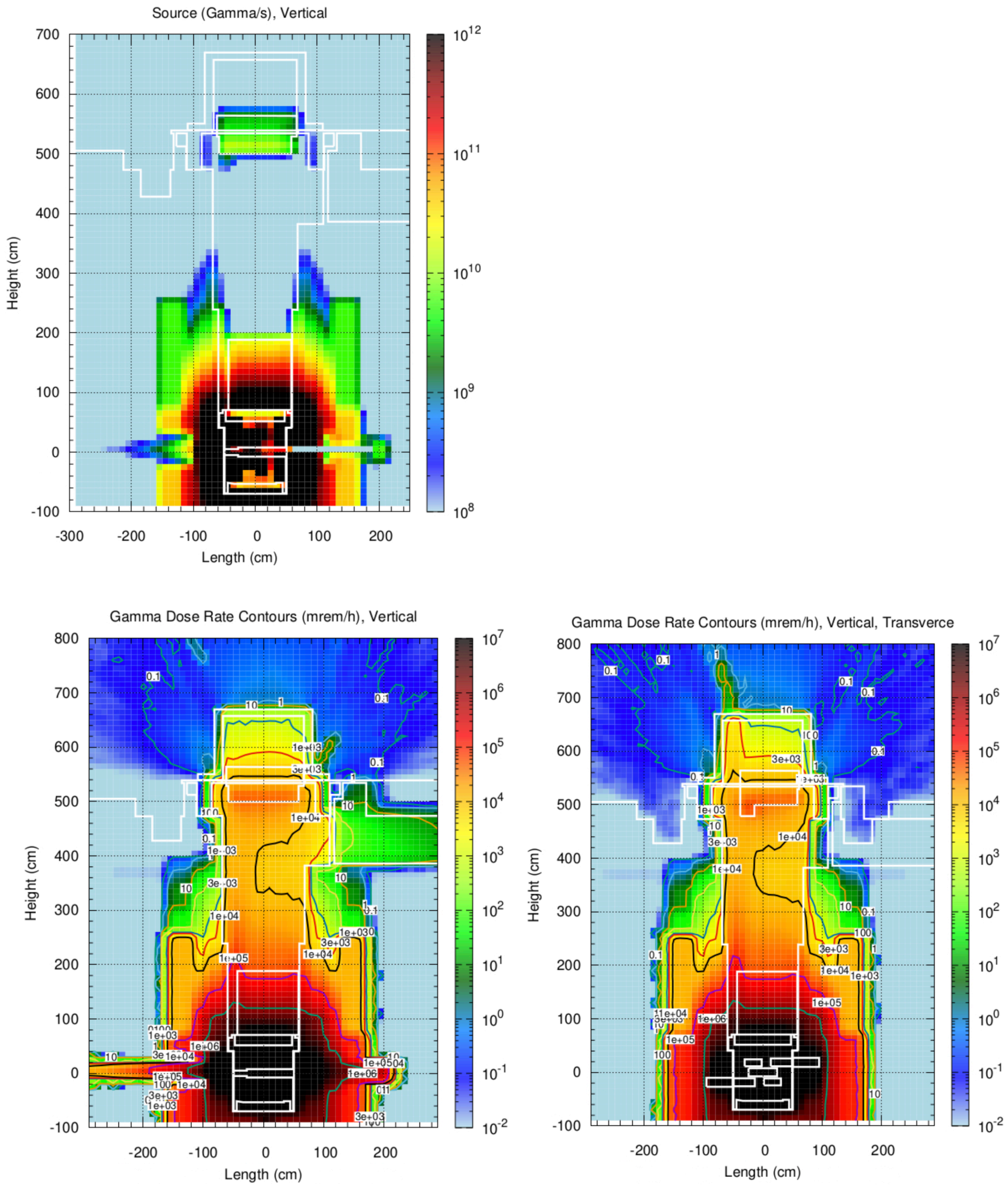


Figure 13. Gamma sources and residual dose rates through the target monolith with lower section on the place and middle segment partially lifted to the cask 14 days after beam termination. Top row: gamma sources in vertical cross section through the beam center line. Bottom row shows residual dose rates in vertical cross section: through the beam centerline (left) and perpendicular to the beam centerline (right)

Residual dose rates through target monolith corresponding to the time of 14 days after the beam termination in horizontal cross section in vertical cross section through the upper part of the shaft with partially lifted middle section and container installed on the shaft are shown in Figure 14.

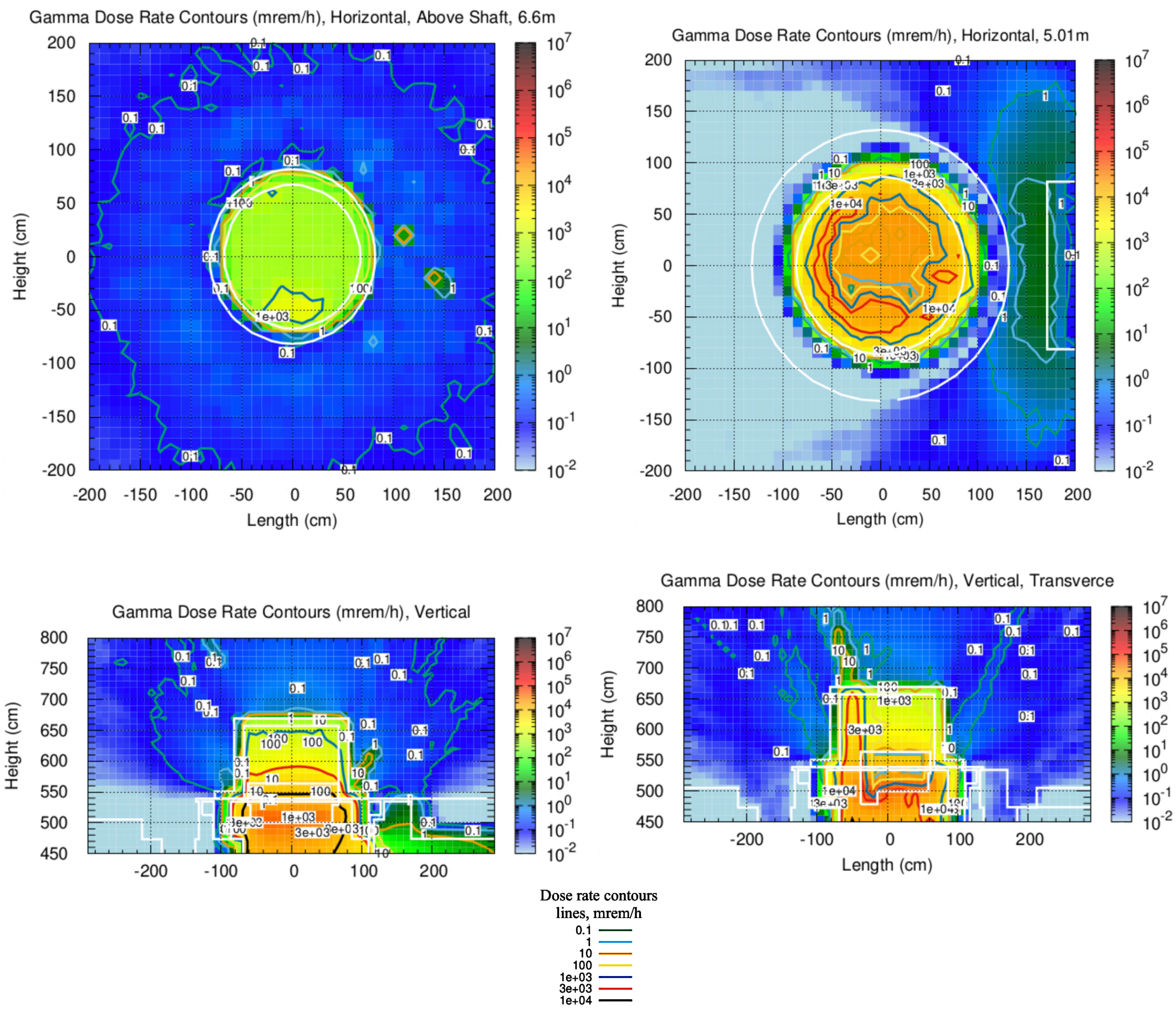


Figure 14. Residual dose rates through the target monolith middle segments partially lifted to container installed on the adaptor plate 14 days after beam termination. Top row: horizontal cross section above the shaft(left) and through the shaft at 501-cm distance from the beam centerline. Bottom row vertical cross section: through the beam centerline (left) and perpendicular to the beam centerline (right).

Analyses of the results show that the highest dose rate is near downstream container corner sitting on the adapter plate and about 10 mrem/h. On the floor, outside the shaft, dose rates overall lower than 1mrem/h outside of the adaptor plate.

Next analyses are performed for the IRP2 middle section fully lifted to container that is installed on the adapter plate. Vertical cross section through the beam centerline and vertical cross section perpendicular to the beam centerline with described configuration are shown in Figure 15.

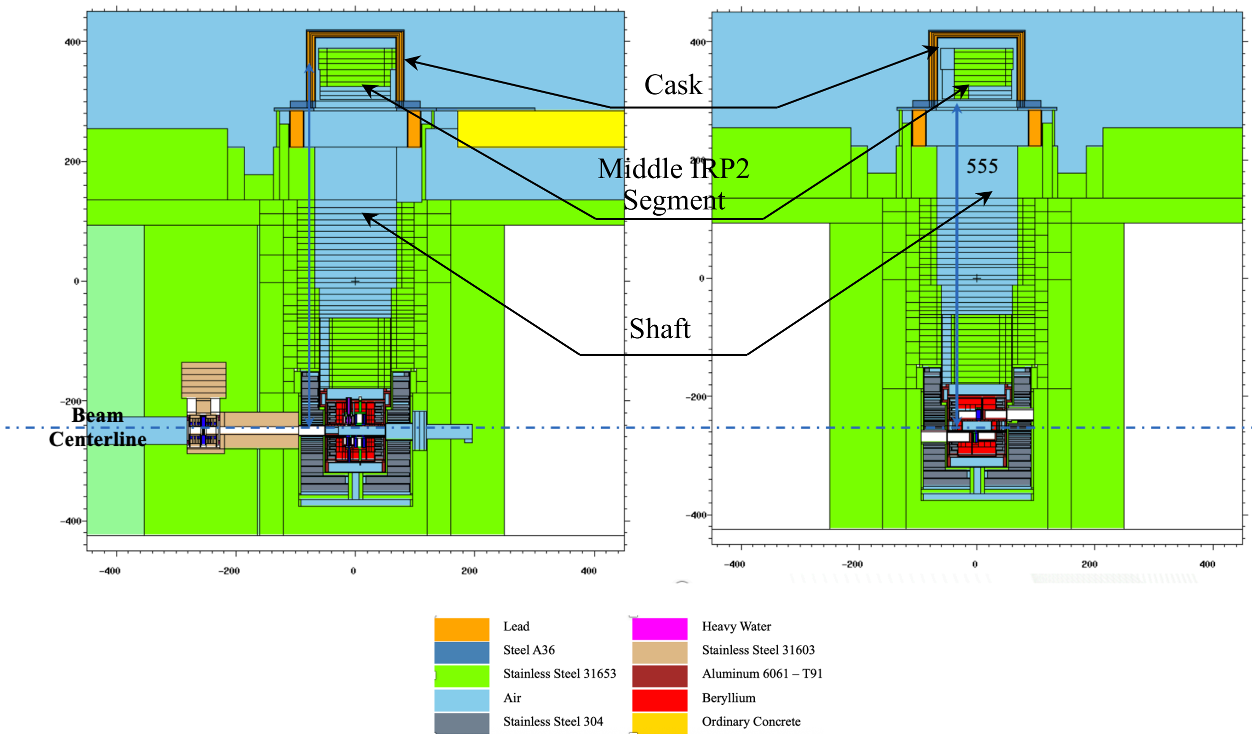


Figure 15. Vertical cross section through the monolith with middle segment inside the cask installed on the adaptor plate through the beam centerline (left) and vertical cross section perpendicular to the beam centerline (right).

Gamma source terms and residual dose rates through target the monolith corresponding to the time of 14 days after the beam termination with middle section fully lifted to container installed on the adapter plate are shown in Figure 16.

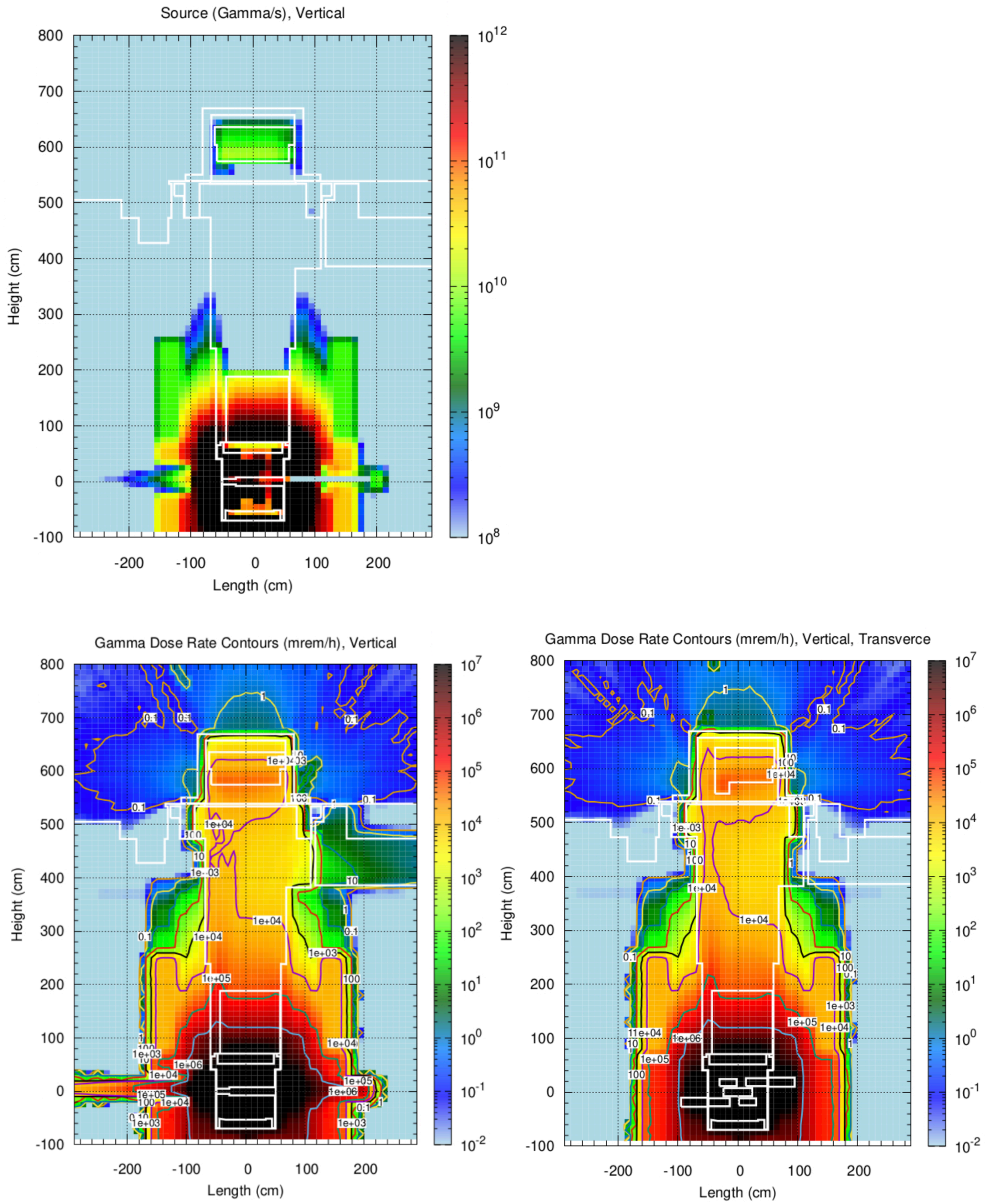


Figure 16. Gamma sources and residual dose rates through the target monolith with middle segment fully lifted to the cask installed on the adaptor plate 14 days after beam termination. Top row: gamma sources in vertical cross section through the beam center line. Bottom row shows residual dose rates in vertical cross section: through the beam centerline (left) and perpendicular to the beam centerline (right).

Residual dose rates through target monolith corresponding to the time of 14 days after the beam termination in horizontal cross section in vertical cross section through the upper part of the shaft with fully lifted middle section and container installed on the adapter plate are shown in Figure 17.

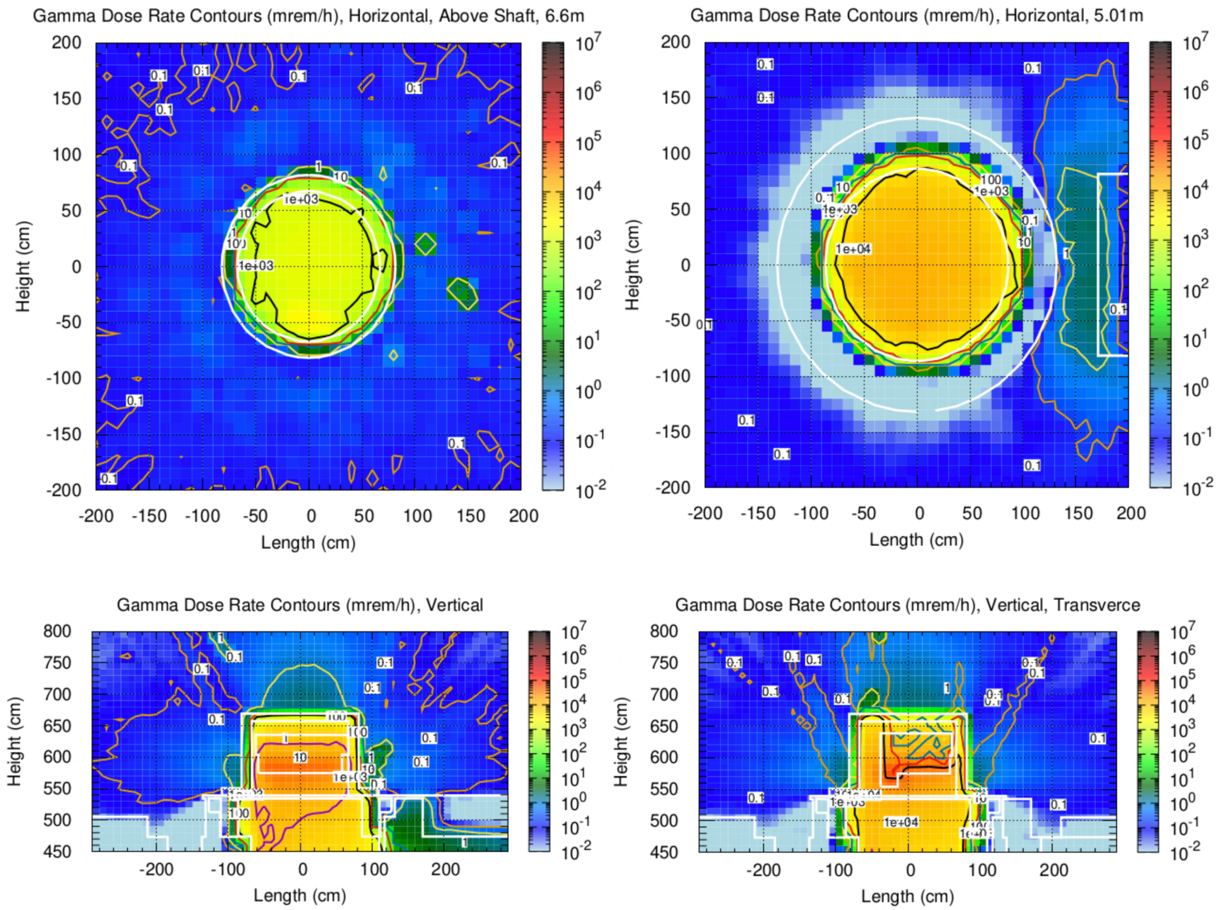


Figure 17. Residual dose rates through the target monolith middle segments fully lifted to container installed on the adapter plate 14 days after beam termination. Top row: horizontal cross section above the shaft(left) and through the shaft at 501-cm distance from the beam centerline. Bottom row vertical cross section: through the beam centerline (left) and perpendicular to the beam centerline (right).

Analyses of the results show dose rates are about couple mrem/h on the container surfaces. Dose rates on the floor outside of the adapter plate are below 1 mrem/h.

Vertical cross section through the beam centerline and vertical cross section perpendicular to the beam centerline with open shaft containing IRP2 lower segment are shown in in Figure 18.

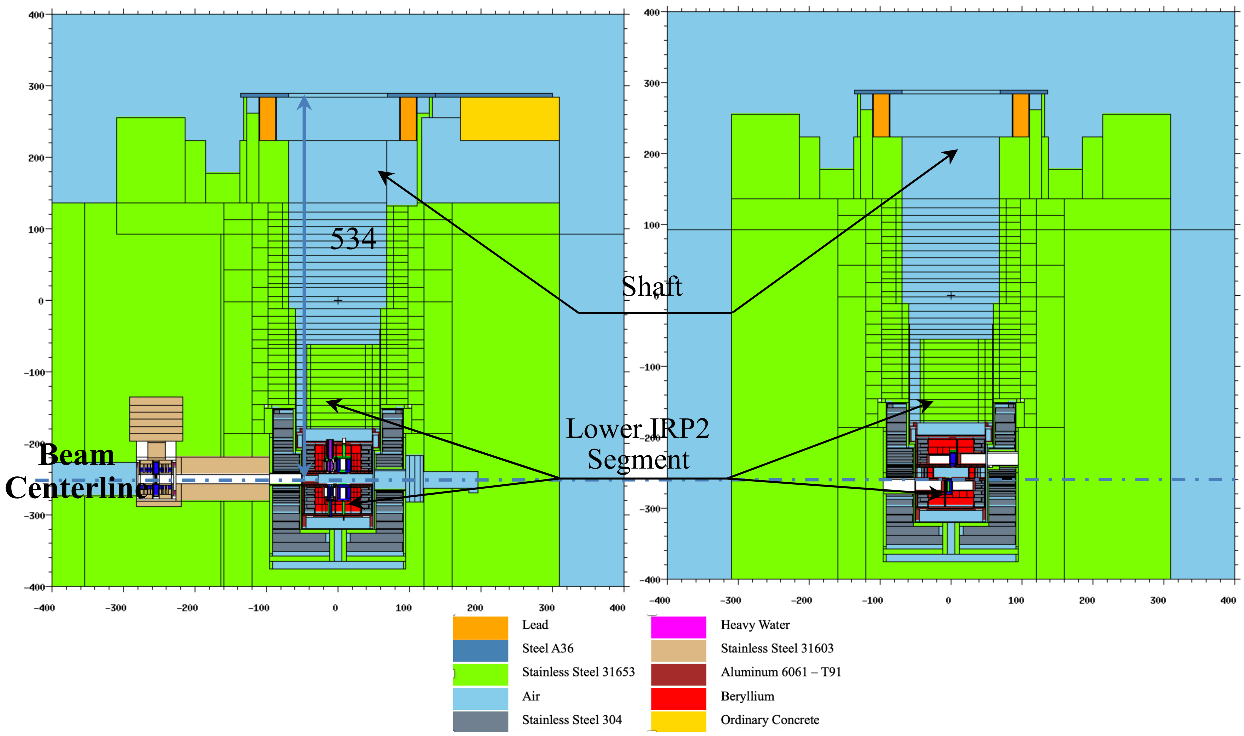


Figure 18. Vertical cross section through the monolith with open shaft containing lower segment through the beam centerline (left) and vertical cross section perpendicular to the beam centerline (right).

Following sets of analyses are performed to evaluate the dose rated for the configuration shown in Figure 18:
- IRP/ORP are both drained, no water,
- IRP/ORP are with water,
- neutron dose rates from IRP2 lower segment inside the shaft

To evaluate impact of the heavy water inside IRP/ORP analyses are performed for heavy water not drained in the system and heavy water drained from the system (dry system). The impact of the presence of heavy water is shown in Figure 19, and it shows that presence of the heavy water reduces residual gamma doses by about 10% as it acts as an additional shielding.

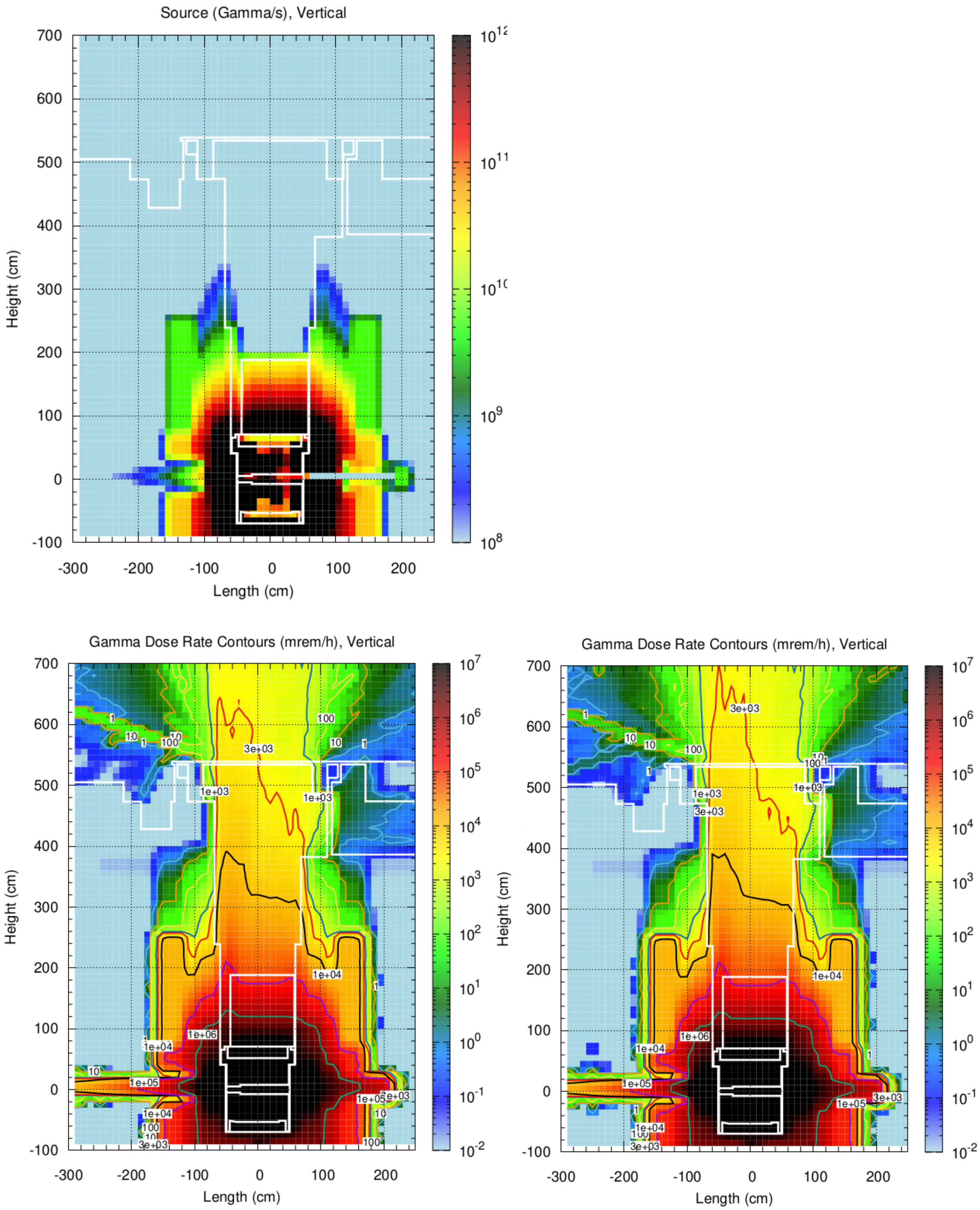


Figure 19. Gamma sources and residual dose rates through the target monolith with lower segment inside the open shaft in vertical cross section through the beam center line. Top row: gamma sources. Bottom row shows residual dose: heavy water in the system (left) heavy water is drained from the system (right)

Residual dose rates through target monolith corresponding to the time of 14 days after beam termination in horizontal cross section and in vertical cross section through the upper part of the shaft housing heavy-water-drained lower segment are shown in Figure 20.

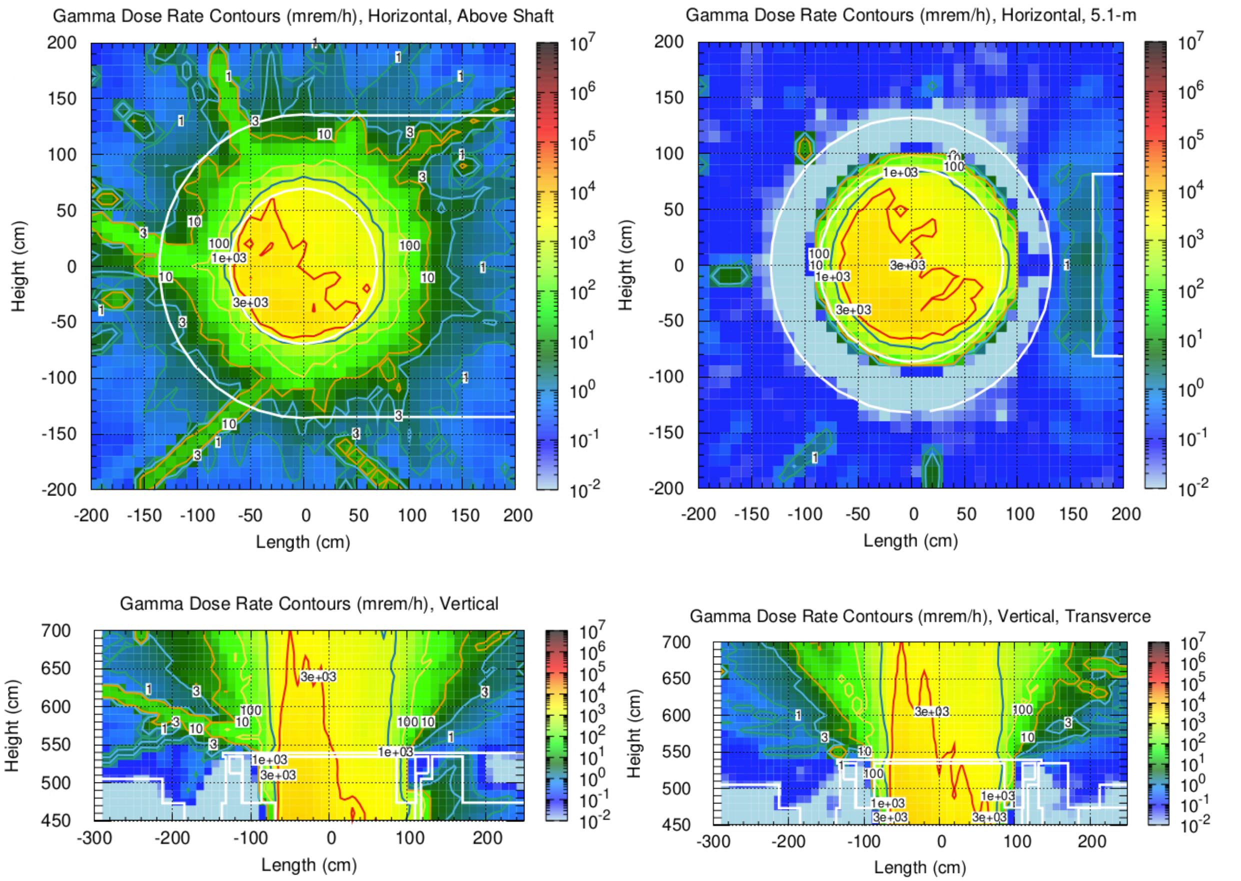


Figure 20. Residual dose rates through the target with open shaft containing lower segment. Top row: horizontal cross section above the shaft(left) and through the shaft at 501-cm distance from the beam centerline. Bottom row vertical cross section: through the beam centerline (left) and perpendicular to the beam centerline (right).

Analyses of the calculations show that the dose rates above the shaft opening are up to 5000 mrem/h and on the floor, outside the adaptor plate, dose rates are up to 10 mrem/h.

Residual neutron dose rates 14 days after the beam termination through the target monolith with lower segment inside the open shaft in vertical cross section through the beam centerline and perpendicular to the beam centerline are shown in Figure 21.

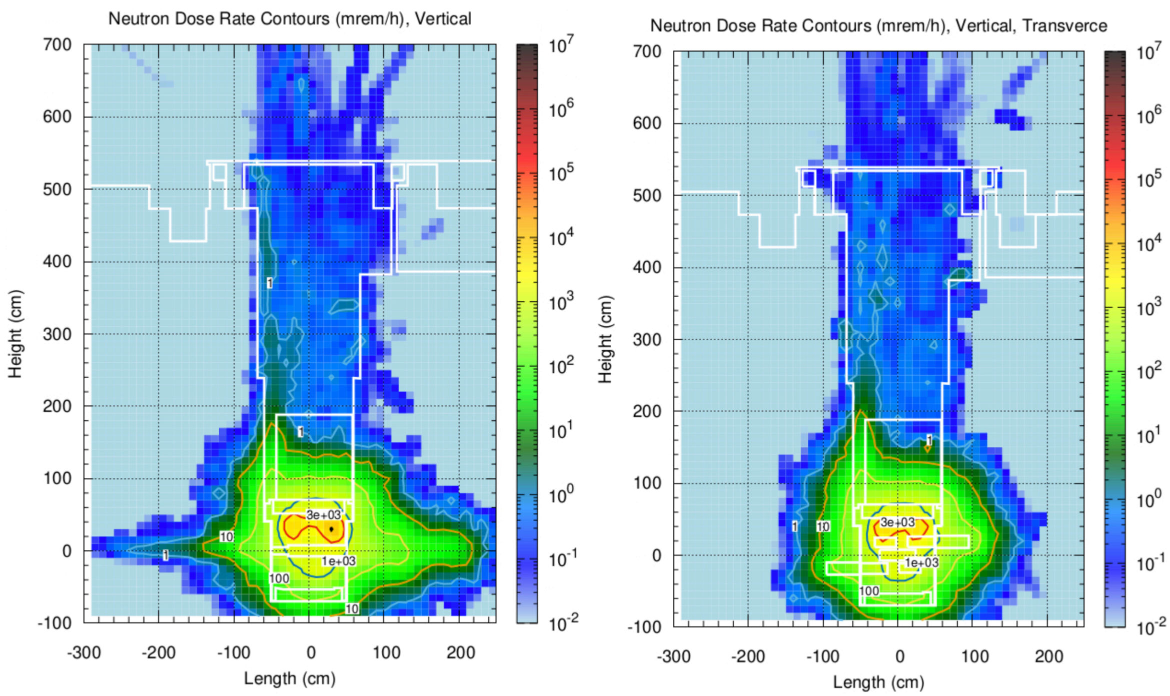


Figure 21. Residual neutron dose rates 14 days after the beam termination through the target monolith with lower segment inside the open shaft in vertical cross section through the beam centerline (left) perpendicular to the beam centerline (right)

The residual neutron dose rated are a couple orders of magnitude lower that the gamma dose rates and are not an issue for the replacement operation. Neutron dose rates at the level of the shaft opening are up to 1 mrem/h, neutron doses on the IRP2 lower segment surfaces are up to 1000 mrem/h.

5.2 IRP2 LOWER SEGMENT L-BLOCKS EXTRACTION

The IRP2 lower segment has 3 so-called L-blocks that are located between middle and lower segments (see Figure 22) and they supporting the weight of the middle section are instrumental to the mechanical stability of whole IRP2. All 3 L-blocks are planned to be cut out and deposited separately from the IRP2 lower segment, and for planning the deposition the residual dose rates from the L-blocks were calculated for 14 days of decay. The L-blocks are not part of the IRP2 model in the initial transport analyses. Their activities and gamma sources were scaled by weight ratios from the results obtained from the top layer of IRP2 lower segment shielding as depicted in Figure 24.

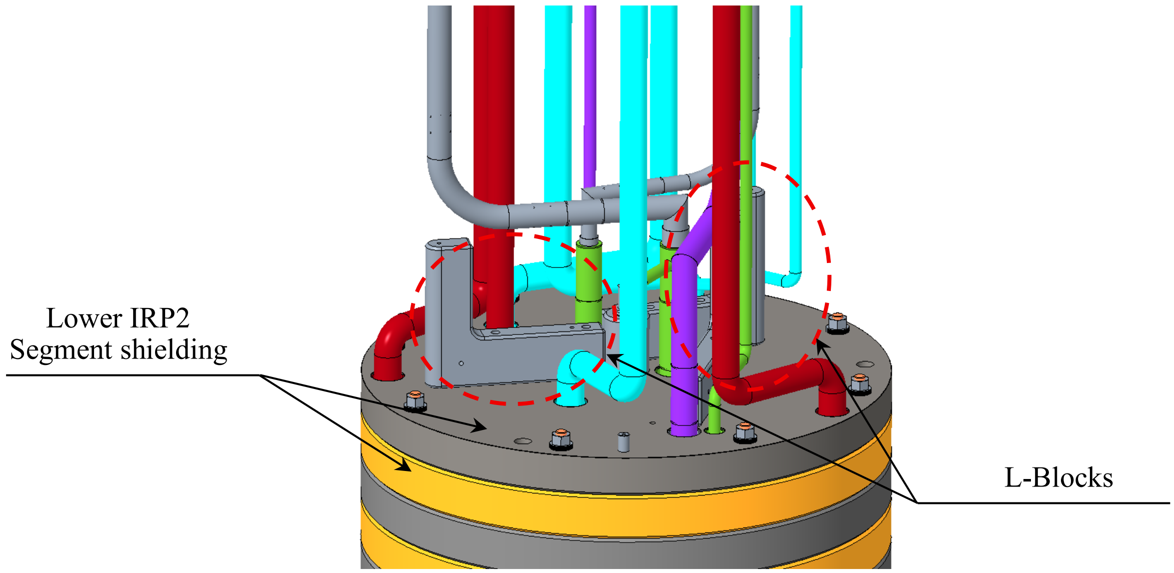


Figure 22. Top part of the IRP2 lower segment shielding with l-Blocks and piping.

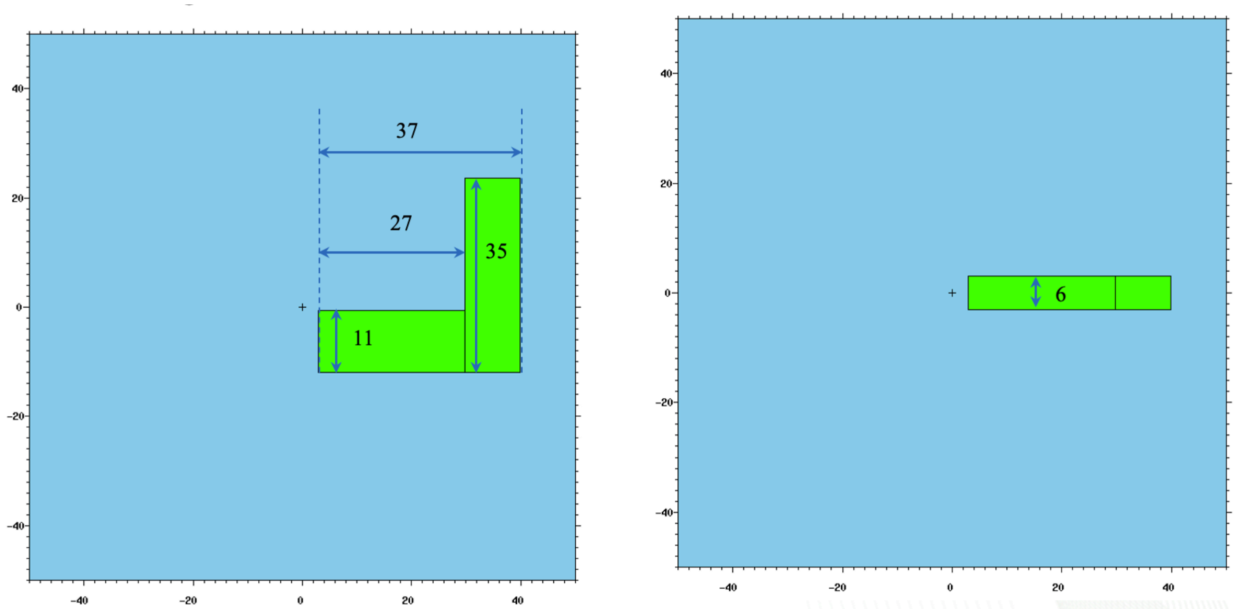


Figure 23. MCNP6 geometry model of L-block in vertical (left) and horizontal cross section (right). Dimensions are in centimeters.

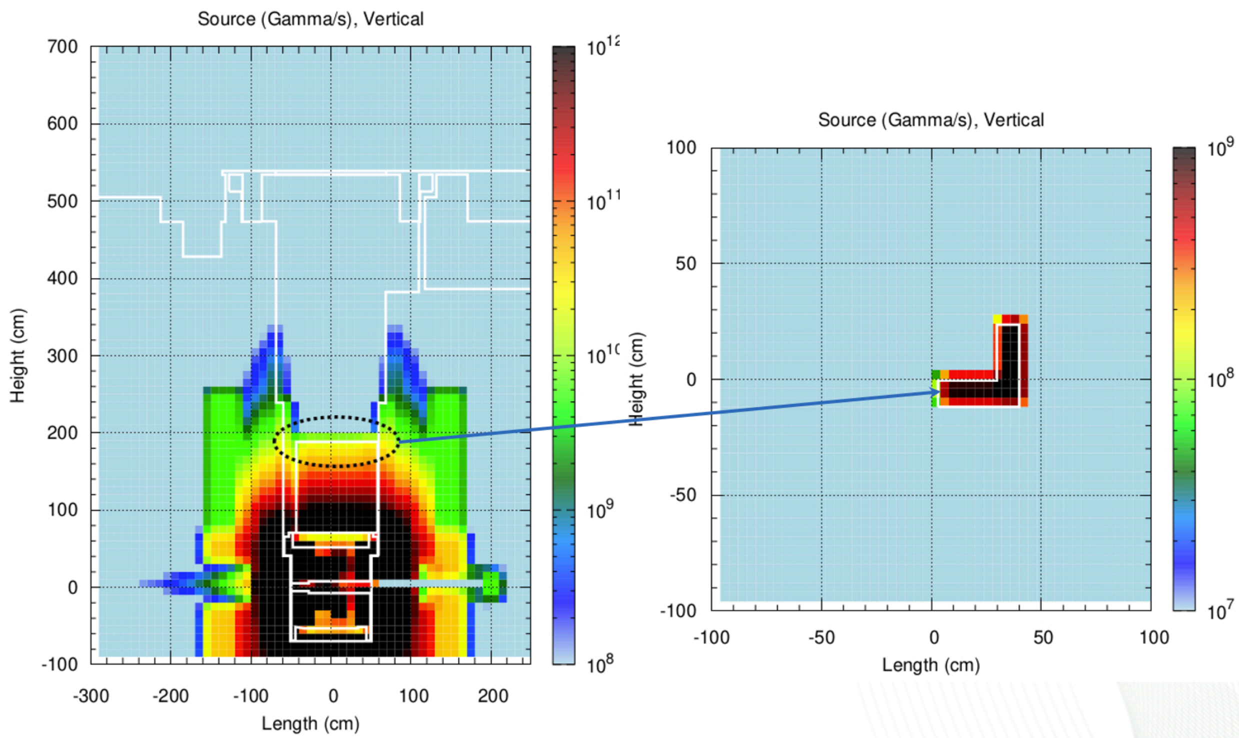


Figure 24. Source preparation for residual radiation from L-block.

The calculated dose rates are presented in Figure 25 in vertical, transverse and horizontal cross section.

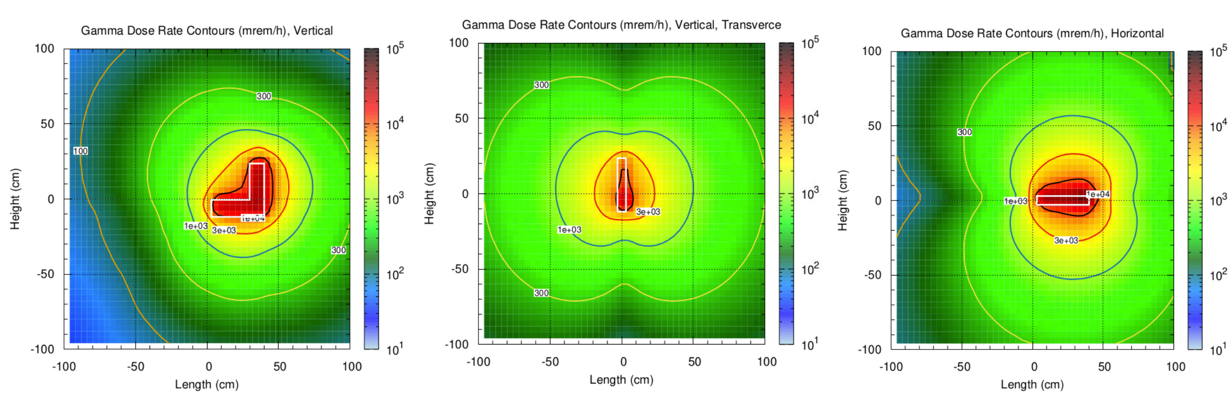


Figure 25. Residual gamma dose rates in vicinity of L-Block in vertical (left), transverse (middle) and horizontal cross section (right), 22 days after beam termination. Dimensions are in centimeters.

Analyses show that 14 days after beam termination, the dose rates are about 1000 rem/h at 30-cm distance from the surfaces of an L-block.

5.3 IRP2 LOWER SEGMENT EXTRACTION

The IRP2 lower segment will be removed in about 22 days after the beam termination. Two sets of analyses are performed:

- lower segment container placed on the top of the adaptor plate and lower segment is partially lifted,

- lower segment container placed on the top of the adaptor plate and lower segment is fully lifted inside the container.

Vertical cross section through the beam centerline and vertical cross section perpendicular to the beam centerline with lower segment container placed on the top of the adaptor plate and lower segment is partially lifted are shown in Figure 26.

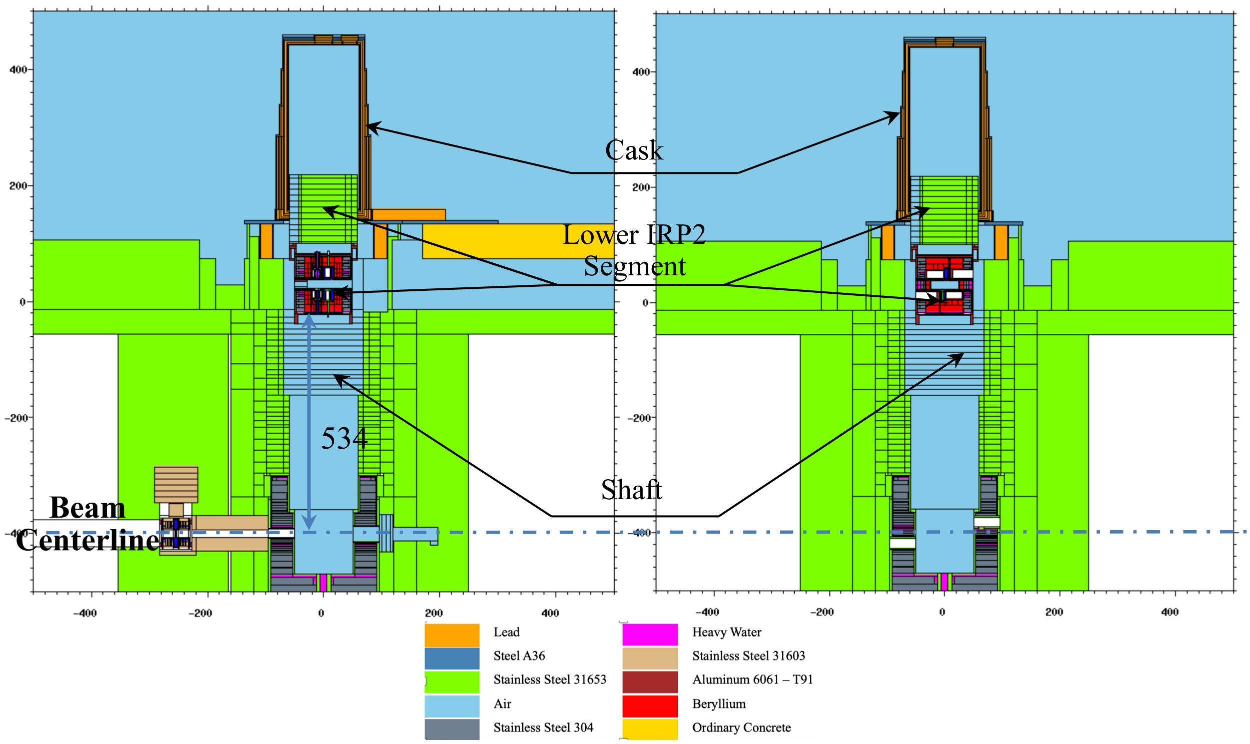


Figure 26. Vertical cross section through the monolith with cask installed and lower segment is partially lifted to the cask: through the beam centerline (left) and vertical cross section perpendicular to the beam centerline (right).

Gamma source terms and residual dose rates through target the monolith corresponding to the time of 22 days after the beam termination with the IRP2 cask installed on the adaptor plate and the lower segment partially lifted are shown in Figure 27.

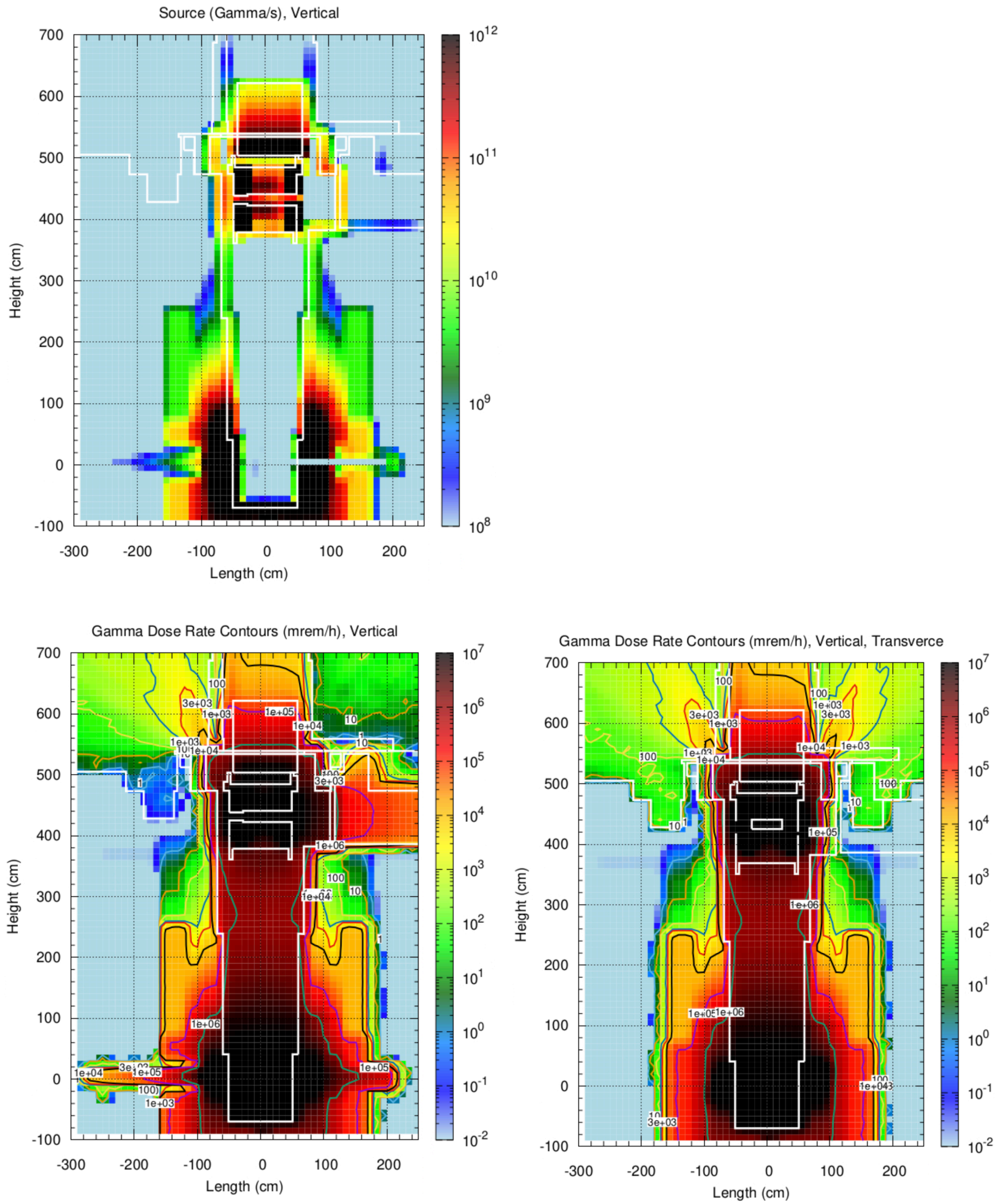


Figure 27. Gamma sources and residual dose rates through the target monolith with cask installed on the adaptor plate and lower segment partially lifted into the cask 22 days after beam termination. Top row: gamma sources in vertical cross section through the beam center line. Bottom row shows residual dose rates in vertical cross section: through the beam centerline (left) and perpendicular to the beam centerline (right)

Residual dose rates through target monolith corresponding to the time of 22 days after the beam termination in horizontal cross section and in vertical cross section through the upper part of the shaft with partially lifted lower segment into the cask installed on the adapter plate are shown in Figure 28.

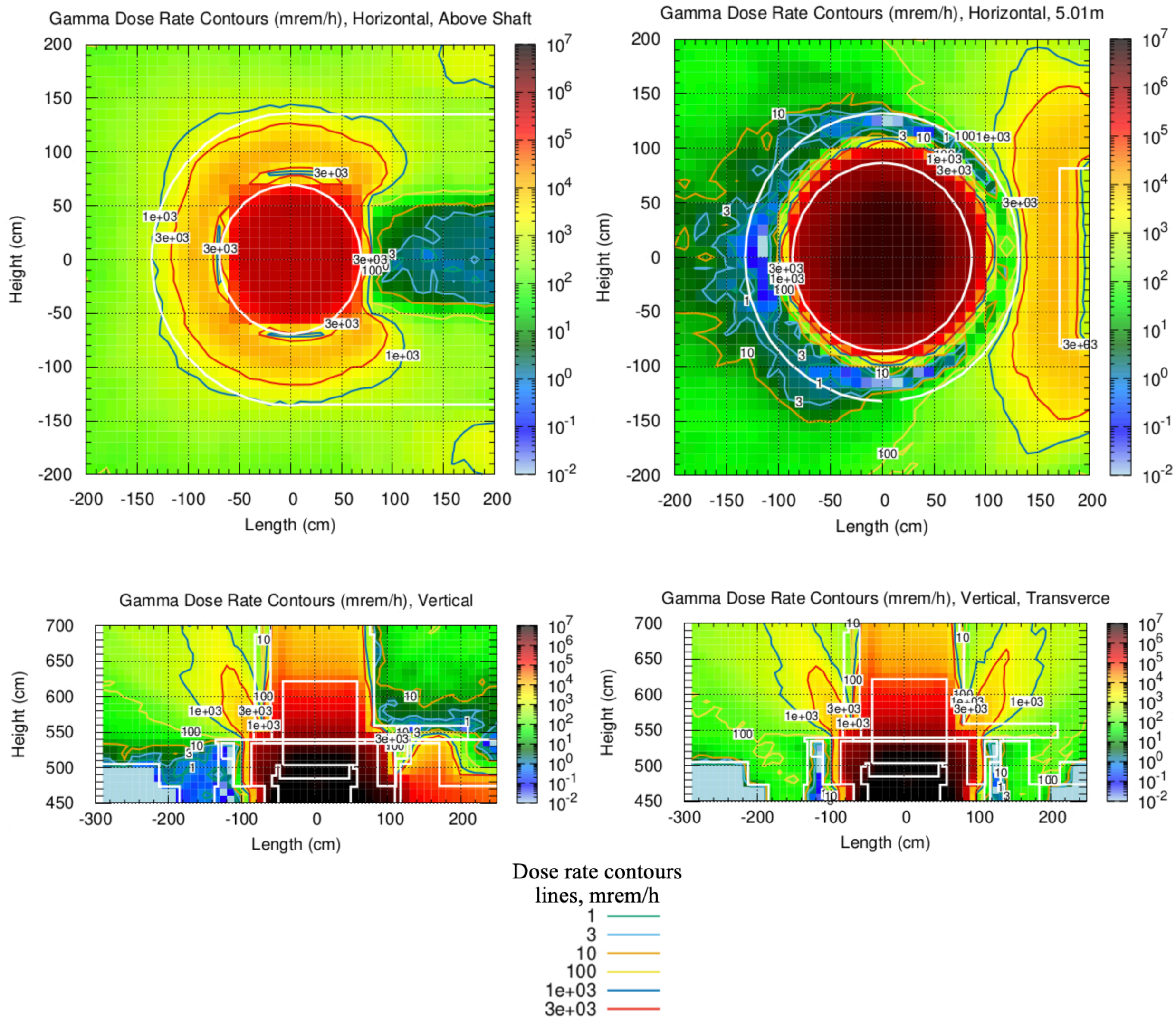


Figure 28. Residual dose rates through the target monolith with cask installed and IRP2 lower segment partially lifted into the cask 22 days after beam termination. Top row: horizontal cross section above the shaft(left) and through the shaft at 501-cm distance from the beam centerline. Bottom row vertical cross section: through the beam centerline (left) and perpendicular to the beam centerline (right).

Dose rates on the cask side are upto 3000 mrem/h, dose rates on the floor outside the adaptor plate are upto 1000 mrem/h. The dose rate spike between cask bottom and adaptor plate is due to radiation leackage from the IRP2 lower segment throught the adaptor plate.

Vertical cross section through the beam centerline and vertical cross section perpendicular to the beam centerline with cask placed on the top of the adaptor plate and lower segment is fully lifted into cask are shown in Figure 29.

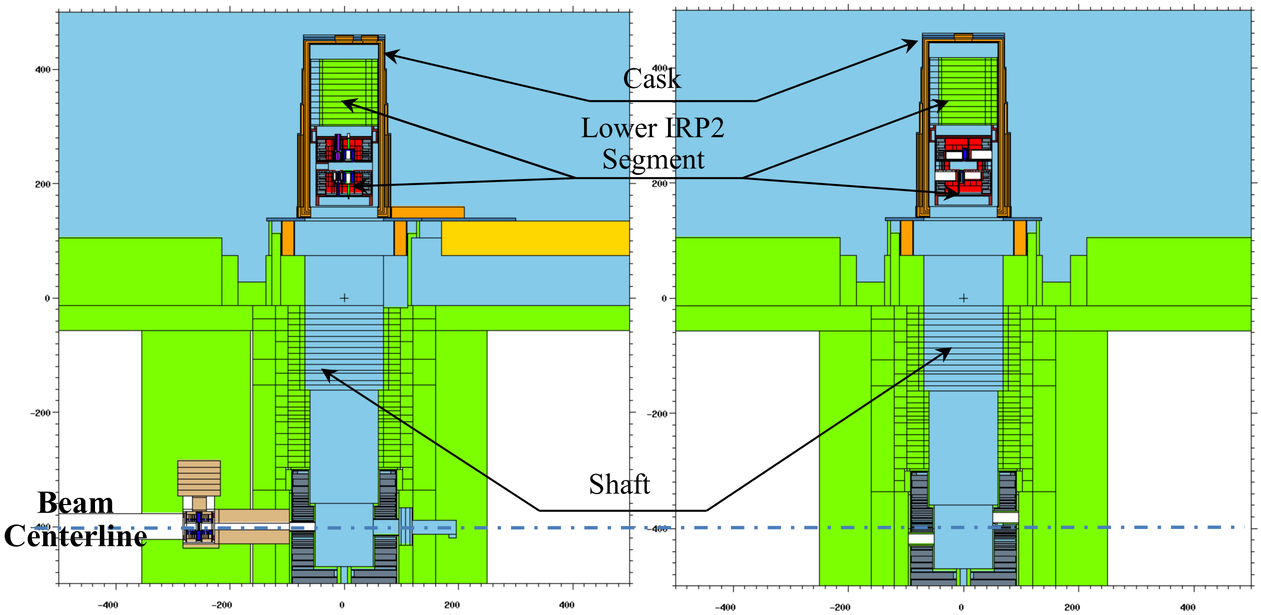


Figure 29. Vertical cross section through the monolith with cask installed and IRP2 lower segment fully lifted into the cask 22 days after beam termination: through the beam centerline (left) and vertical cross section perpendicular to the beam centerline (right).

Gamma source terms and residual dose rates through target the monolith corresponding to the time of 22 days after the beam termination with lower segment fully lifted to the container installed on the adaptor plate are shown in Figure 30.

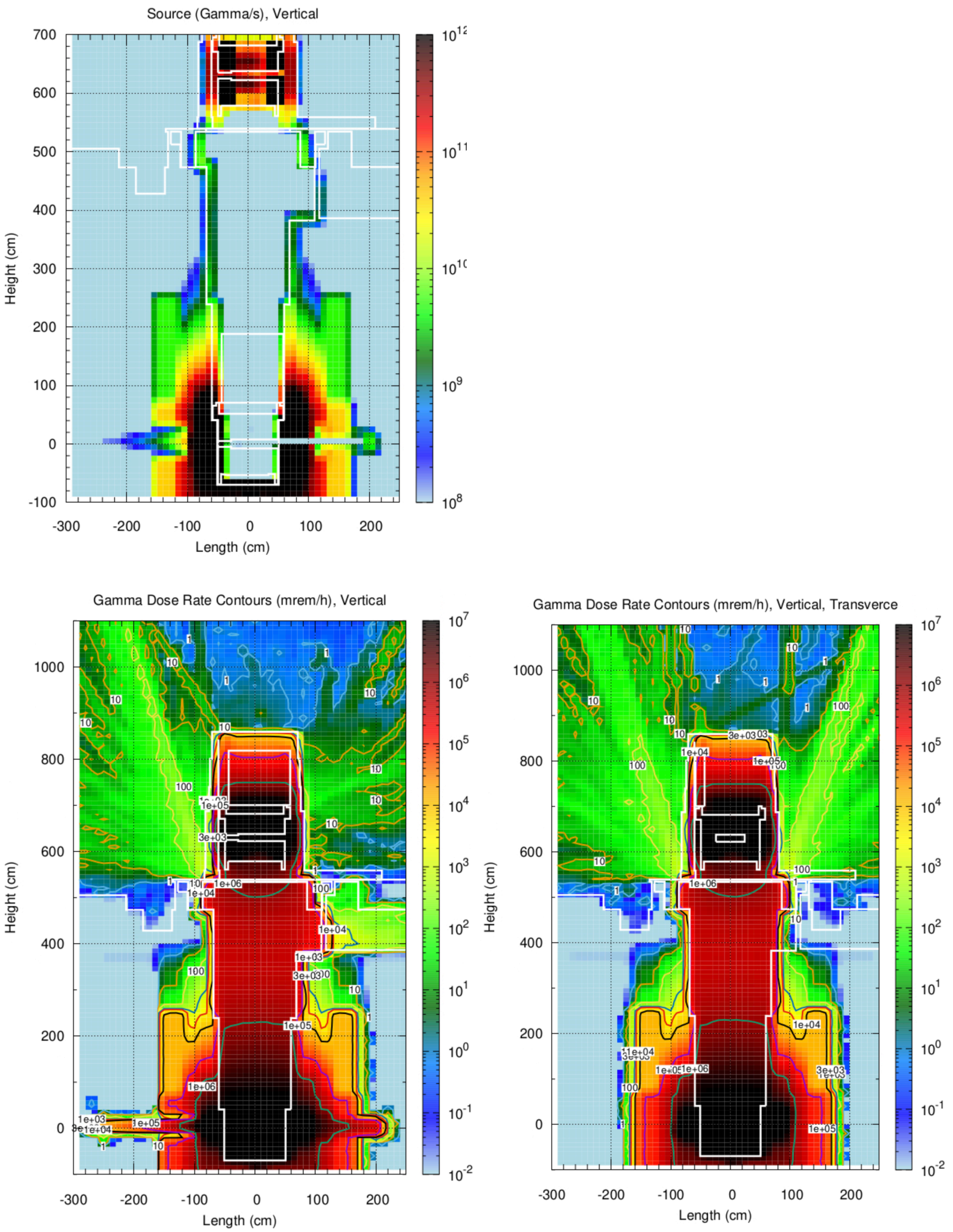


Figure 30. Gamma sources and residual dose rates through the target monolith with cask installed and IRP2 lower segment fully lifted into the cask 22 days after beam termination. Top row: gamma sources in vertical cross section through the beam center line. Bottom row shows residual dose rates in vertical cross section: through the beam centerline (left) and perpendicular to the beam centerline (right)

Residual dose rates through target monolith corresponding to the time of 22 days after the beam termination in horizontal cross section and in vertical cross section through the upper part of the shaft with fully lifted IRP2 lower section into the cask installed on the adaptor plate are shown in Figure 31.

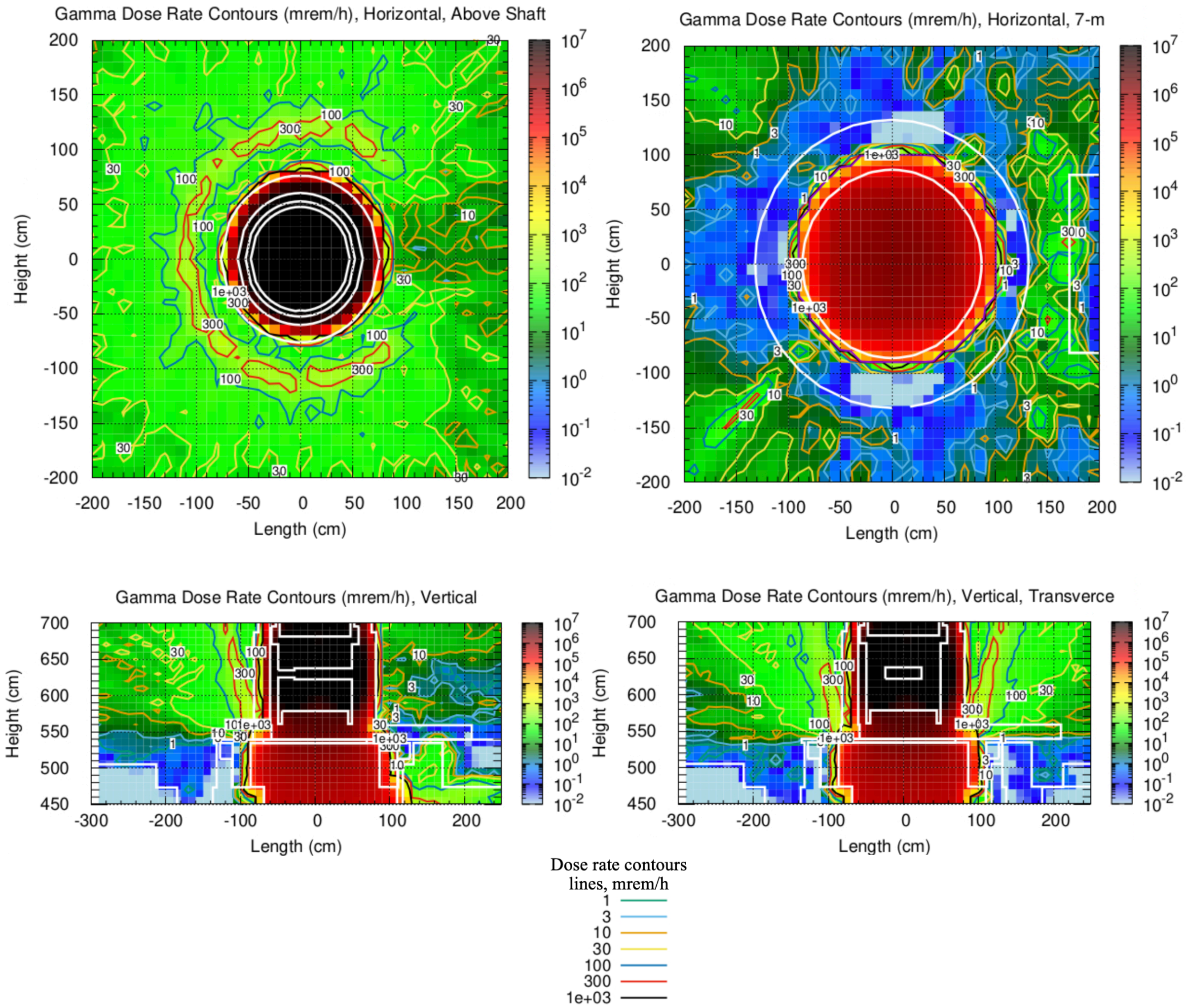


Figure 31. Residual dose rates through the target monolith with cask installed and IRP2 lower segment fully lifted into the cask 22 days after beam termination. Top row: horizontal cross section above the shaft(left) and through the shaft at 501-cm distance from the beam centerline. Bottom row vertical cross section: through the beam centerline (left) and perpendicular to the beam centerline (right).

Analyses of the dose rate map show that the dose rates on the cask side are up to 300 mrem/h due to radiation leack through the adaptor plate. Dose rates on the floor, outside the adaptor plate are up to 100 mrem/h.

5.4 IRP2 EMPTY SHAFT

IRP2 lower segment will be removed in about 22 days after the beam termination, and it will leave an empty shaft in the target monolith. Two sets of analyses are performed:
- open empty shaft,
- empty shaft covered by plate.

Geometry for all listed above sets in vertical cross section through the beam centerline and vertical cross section perpendicular to the beam centerline with empty open shaft are shown in Figure 26.

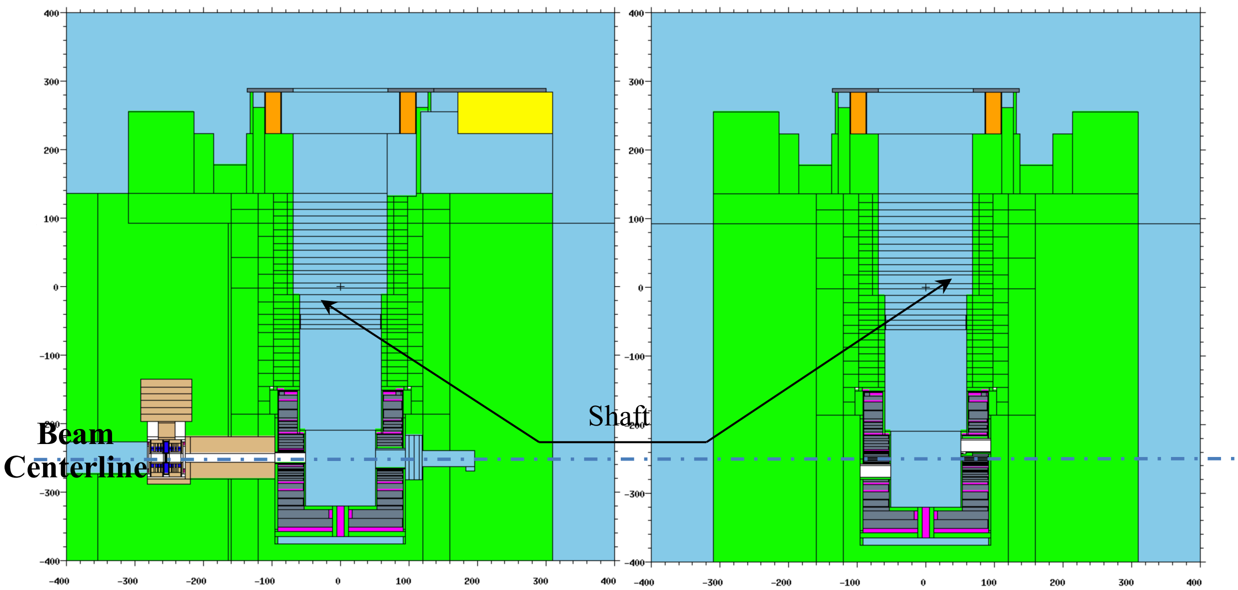


Figure 32. Vertical cross section through the monolith with empty shaft: through the beam centerline (left) and vertical cross section perpendicular to the beam centerline (right).

Gamma source terms and residual dose rates through target monolith with empty open shaft corresponding to 22 days after the beam termination are shown in Figure 33.

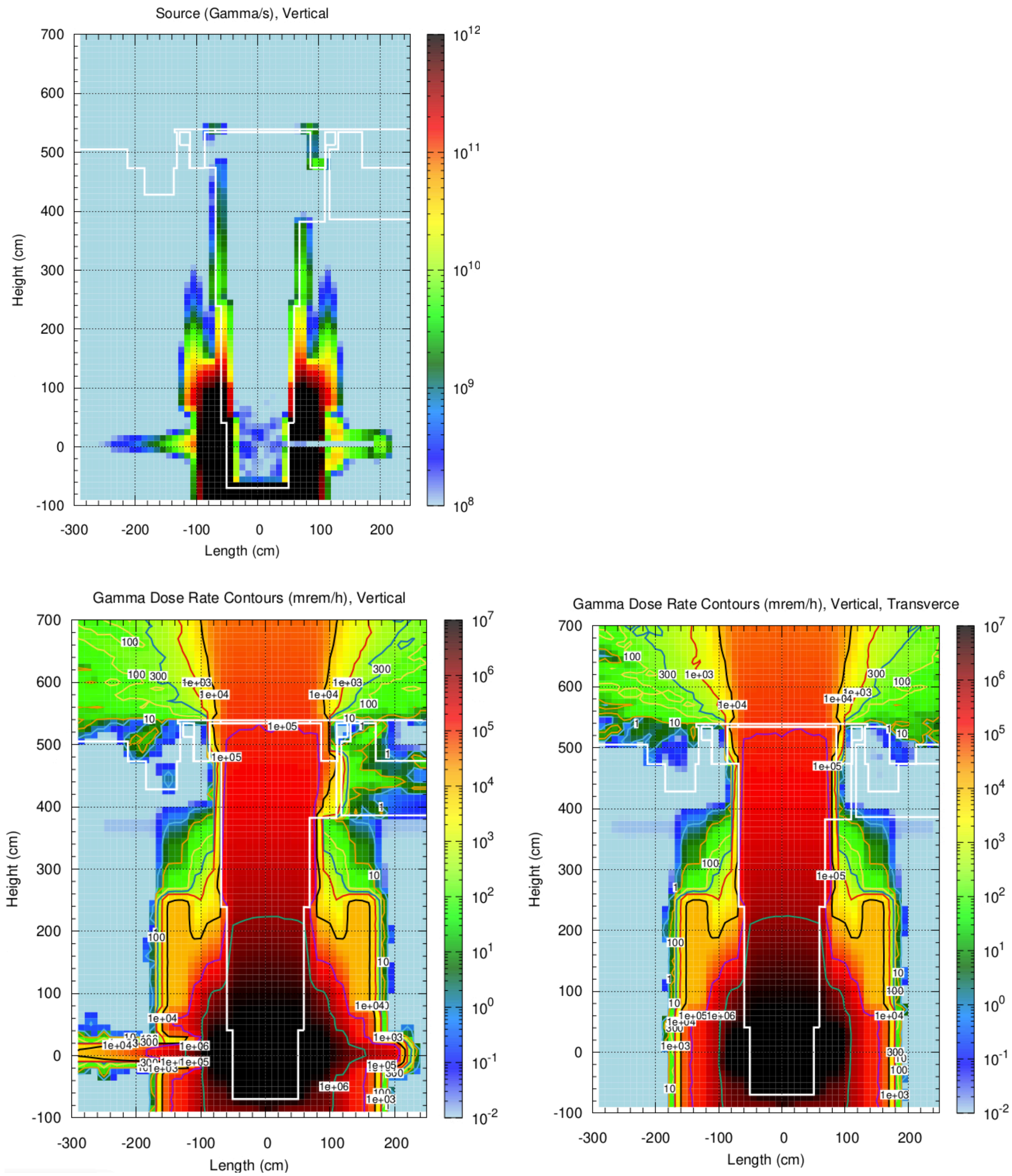


Figure 33. Gamma sources and residual dose rates through the target monolith with open empty shaft 22 days after beam termination. Top row: gamma sources in vertical cross section through the beam center line. Bottom row shows residual dose rates in vertical cross section: through the beam centerline (left) and perpendicular to the beam centerline (right)

Residual dose rates in horizontal cross section in vertical cross section through the upper part of the shaft through target monolith corresponding with empty open shaft 22 days after the beam termination are shown in Figure 34.

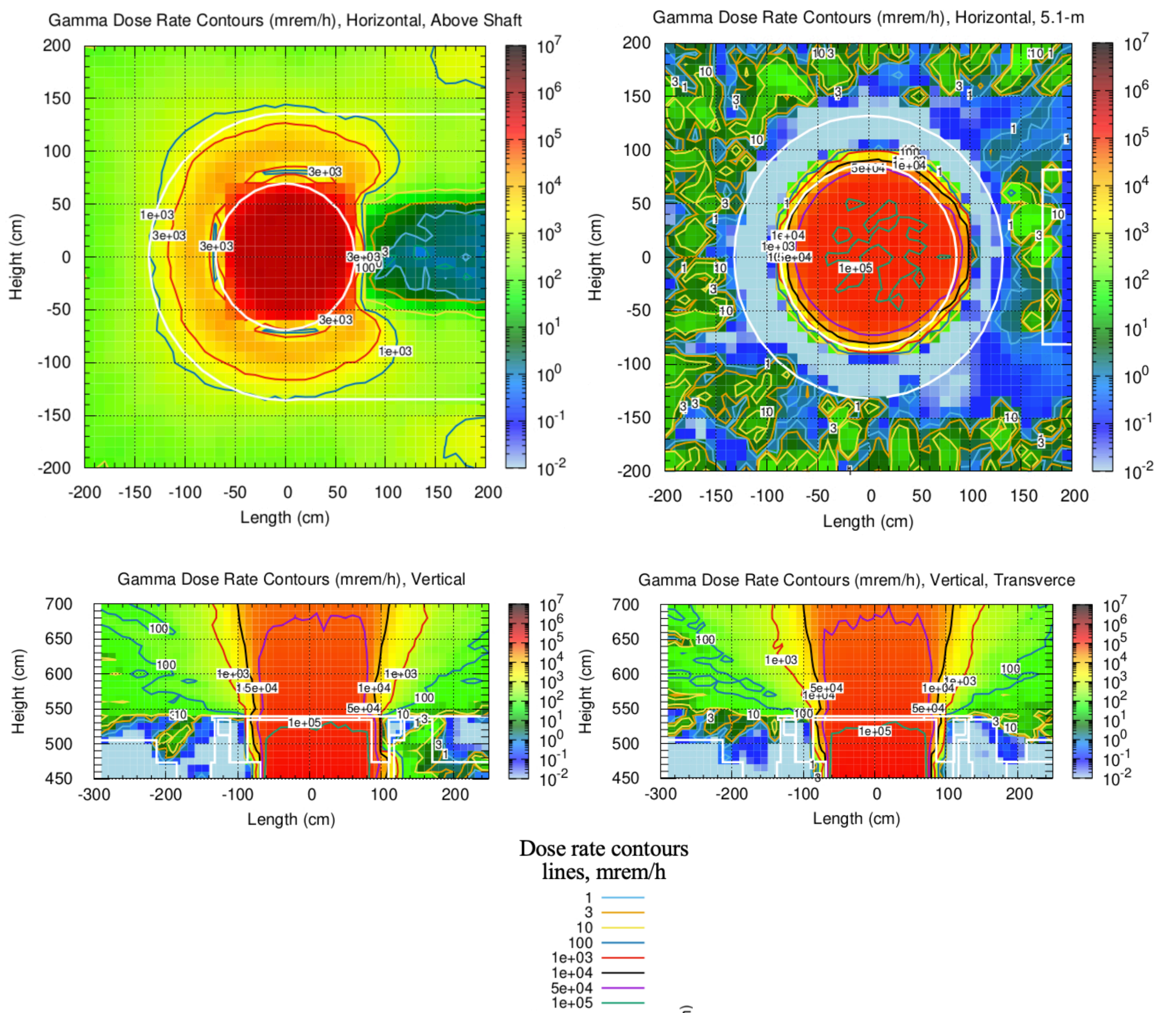


Figure 34. Residual dose rates through the target monolith with open and empty shaft 22 days after beam termination. Top row: horizontal cross section above the shaft(left) and through the shaft at 501-cm distance from the beam centerline. Bottom row vertical cross section: through the beam centerline (left) and perpendicular to the beam centerline (right).

Analyses of the results show that the dose rates above the shaft opening are up to 90000 mrem/h. On the monolith floor, outside the adaptor plate, dose rates are up to 500 mrem/h.

Dose rates inside the target monolith shaft in vertical cross section on a larger dose rate scale are shown in Figure 35. Dose rates inside the shaft are extremally high peaking above 1e7 mrem/h.

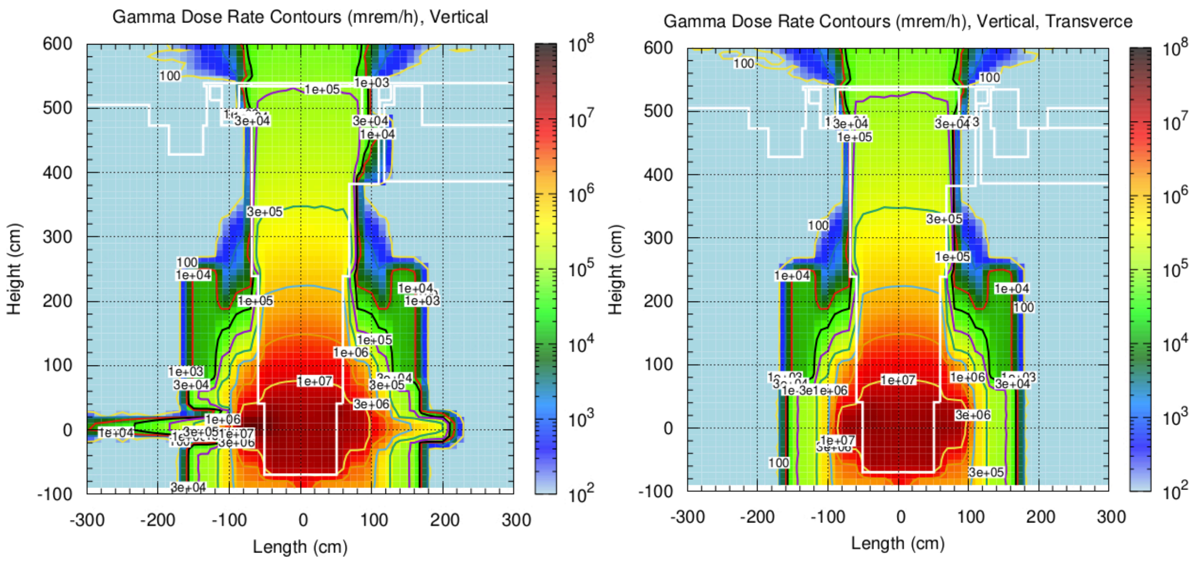


Figure 35. Residual dose rates through the target monolith with open and empty shaft 22 days after beam termination in vertical cross section through the beam centerline (left) and perpendicular to the beam centerline (right)

Additional analyses are performed to see radiation propagation in the air in the target building up to 50-m distance from the center of the target. Dose rates are presented in Figure 38 and Figure 39.

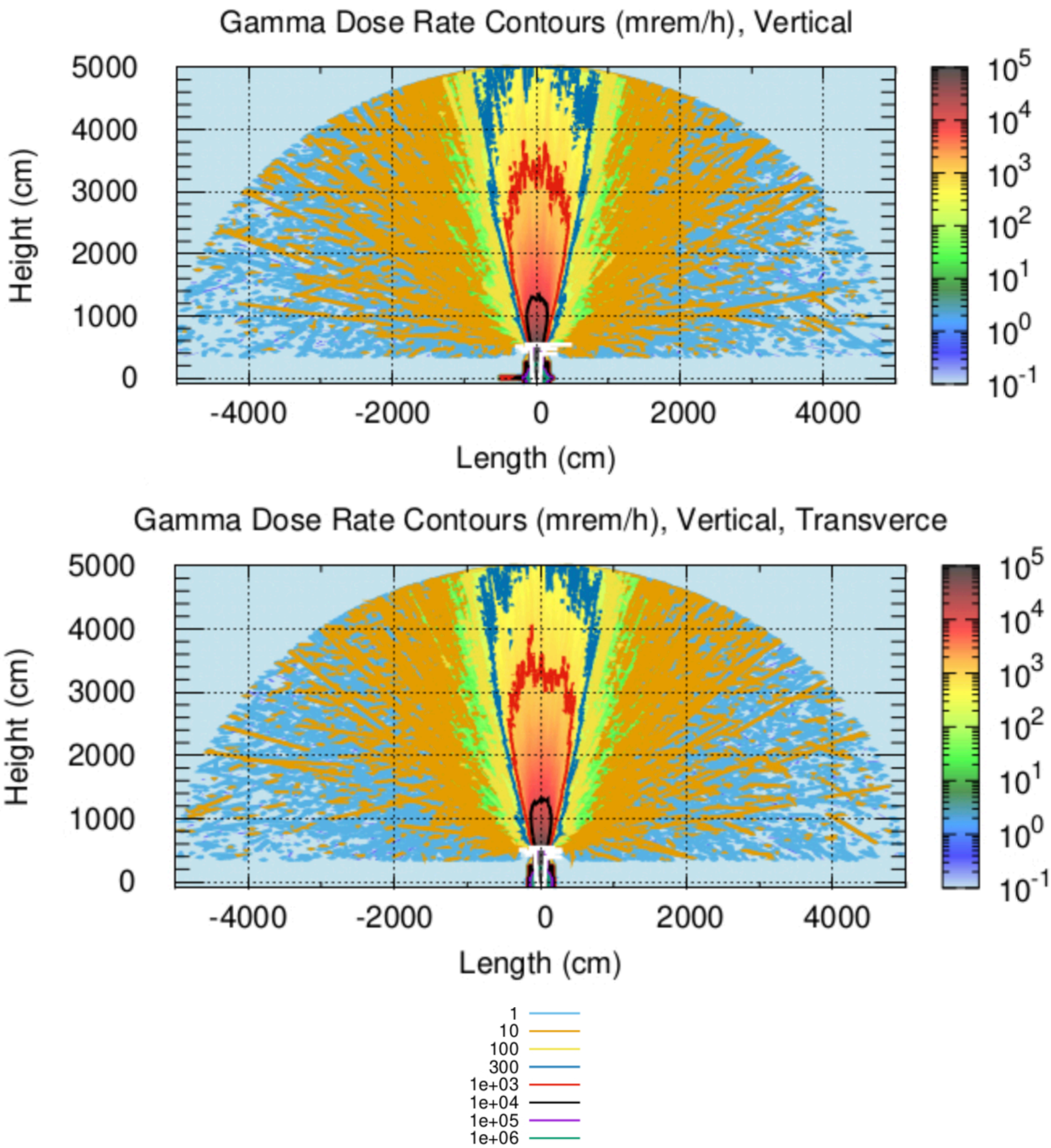


Figure 36. Residual dose rates through the target monolith with open shaft in vertical cross section through the beam centerline (left) and perpendicular to the beam centerline (right) to the distance 50-meters from the shaft.

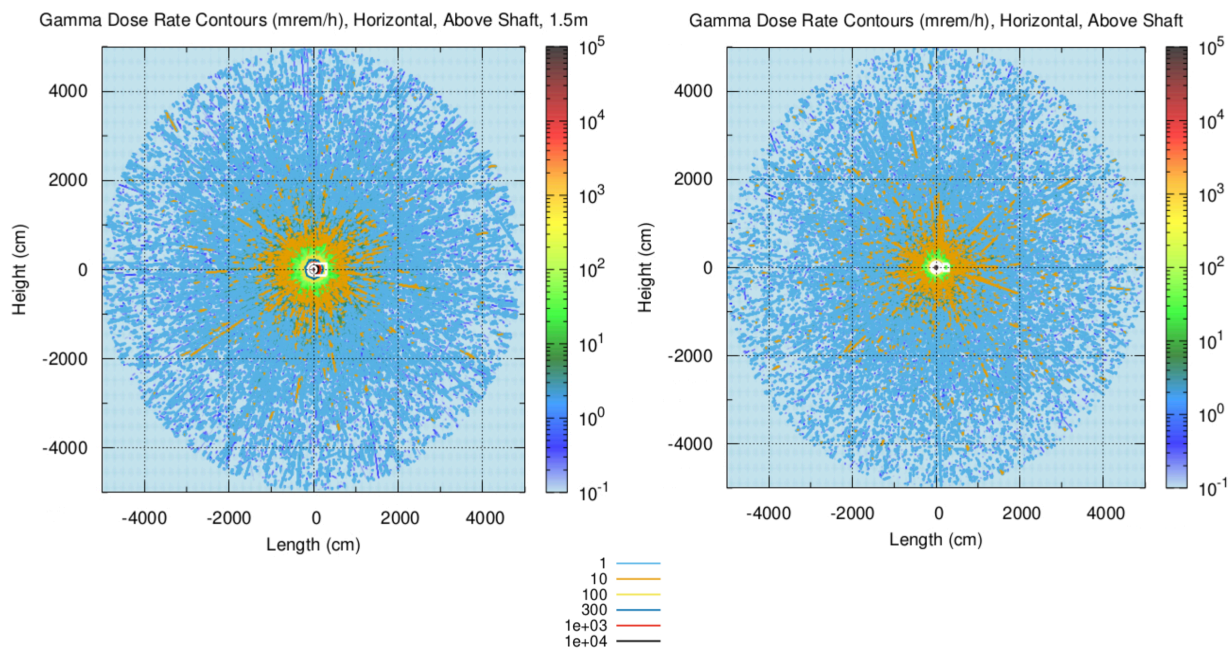


Figure 37. Residual dose rates through the target monolith with shaft in horizontal cross section at 1.5-m distance from the top of the shaft (left) and the top of the shaft (right)

Comparison of the dose rates from the empty shaft for IRP2 replacement versus IRP1 replacement is performed to estimate the radiation field difference. Figure 38 shows comparison of the predicted dose rates from the open empty shafts for these two cases. Results are shown in vertical cross section through the beam centerline. For IRP1 dose rates are averaged azimuthally and shown for 30 days after the beam termination and the dose rates for IRP2 replacement are in Cartesian geometry and are shown for 22 days after the beam termination. Target monolith to the time of IRP1 replacement received about 40.443 GWh and about 82.88GWh for the replacement time of IRP2.

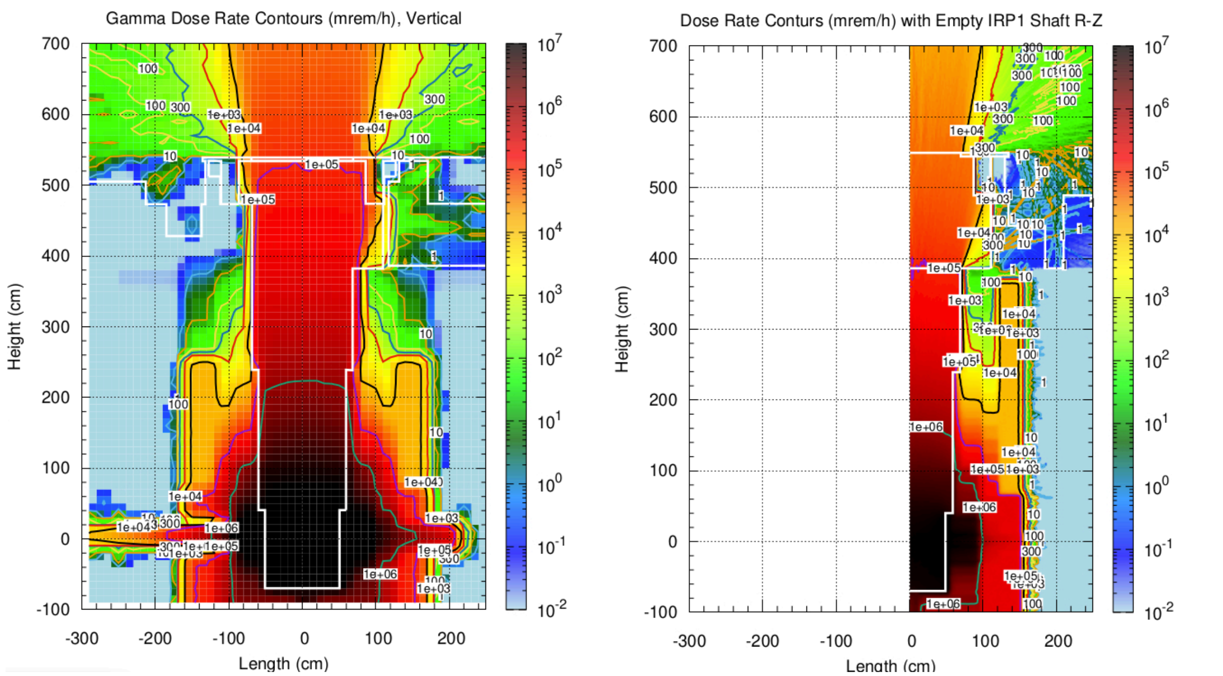


Figure 38. Residual dose rates through the target monolith with open and empty shaft. during the IRP2 replacement (left) vs IRP1 replacement (right).

Residual dose rates through target monolith in vertical cross section through the upper part of the shaft and in horizontal cross section are shown in Figure 39.

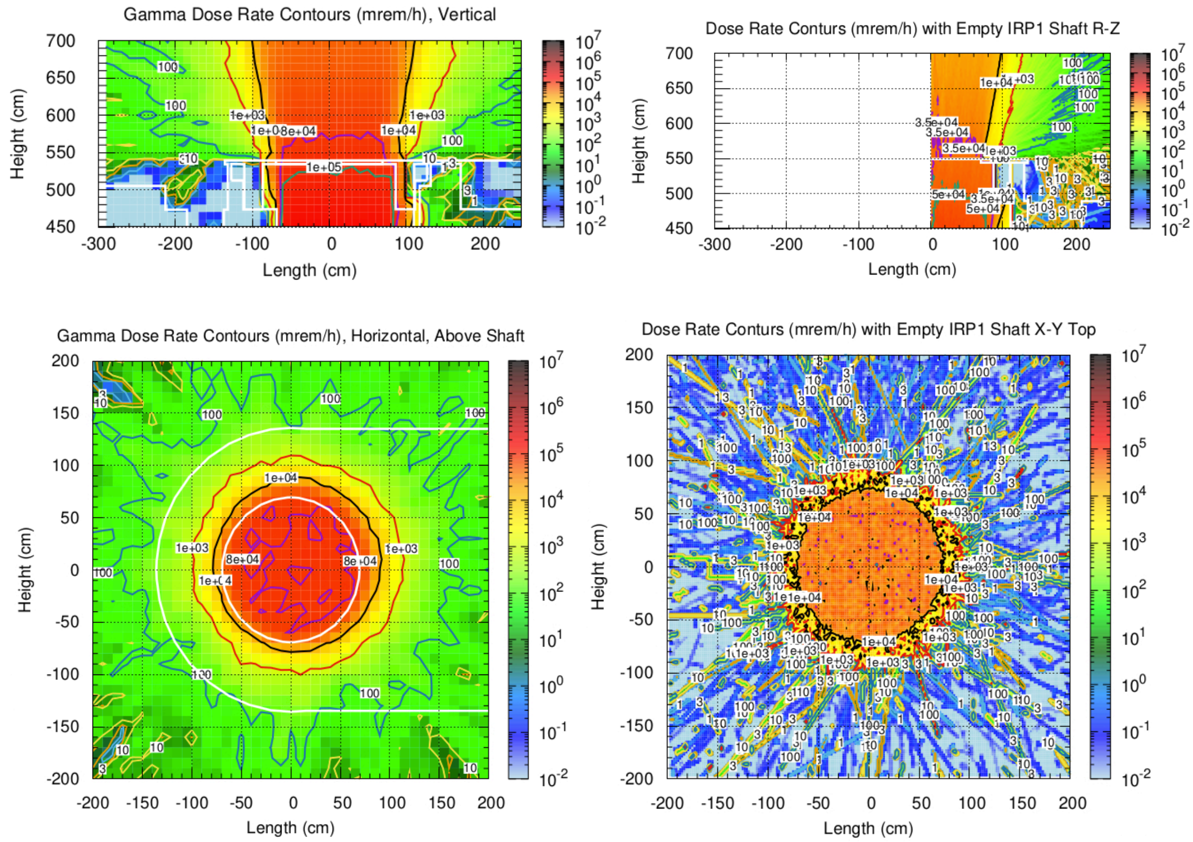


Figure 39. Residual dose rates through the target monolith with open and empty shaft during the IRP2 replacement (left column) vs IRP1 replacement (right column). From top to bottom: vertical cross section through the beam centerline, horizontal cross section above the shaft.

Dose rates above the shaft at 570-cm distance from the beam centerline at the shaft opening is up to 9000mrem/h for IRP2 replacement and 35000mrem/h for IRP1 replacement, which is for IRP2 about a factor of 2.75 higher than for IRP1. This difference comes about the longer exposure to high power beam of the target monolith, the higher post-PPU proton beam energy during the last run cycles, and the higher post-PPU power levels.

Due to very high shine of radiation from the shaft, the shaft will be closed with 25.4-cm thick steel (A36) cover plate, 91-cm in diameter as shown in Figure 40. The cover plate is placed over the opening in the adaptor plate; the center part of the cover plate that drops inside the adapter plate is 30.5-cm thick.

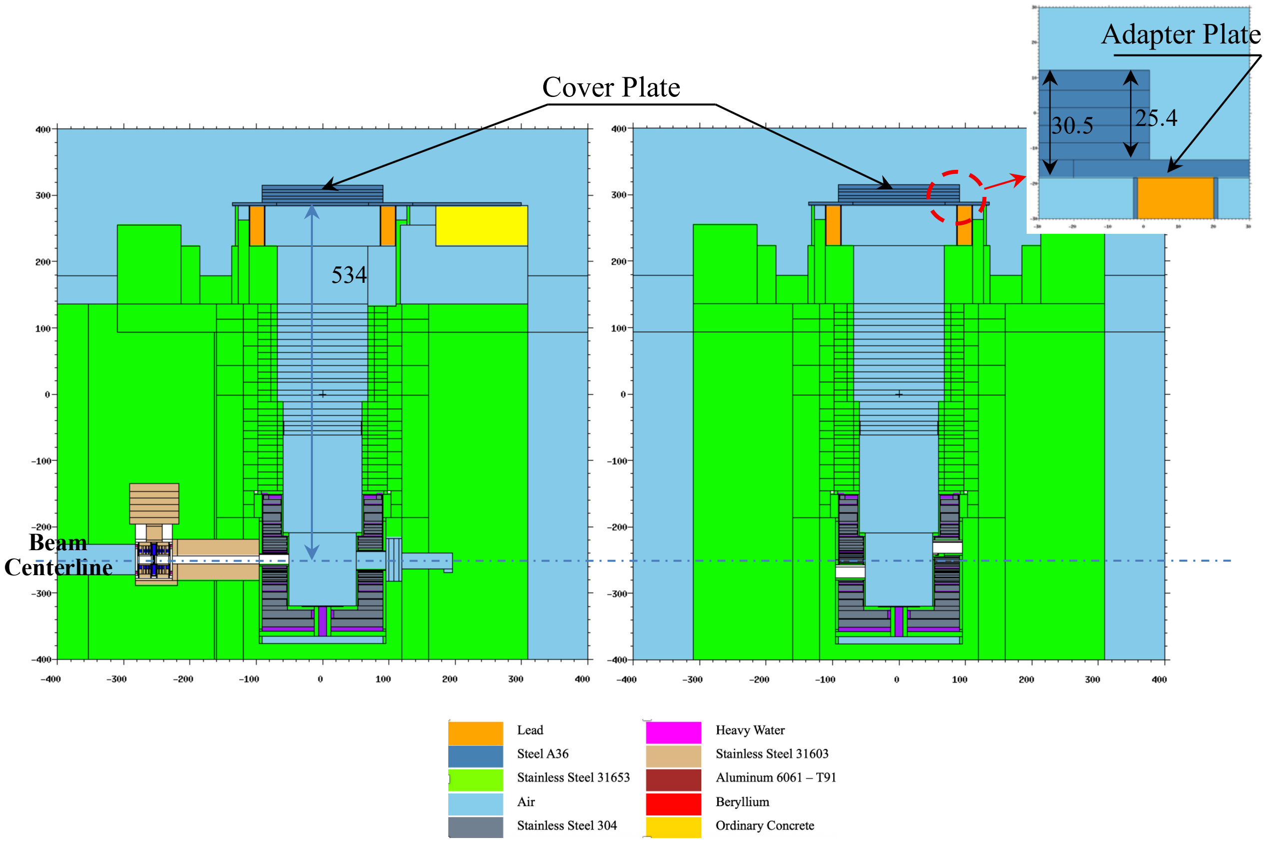


Figure 40. Vertical cross section through the monolith with empty shaft and cover plate installed: through the beam centerline (left) and vertical cross section perpendicular to the beam centerline (right).

Residual dose rates through target the monolith with empty shaft with cover plate on top of the adaptor plate 22 days after the beam termination is shown in Figure 41.

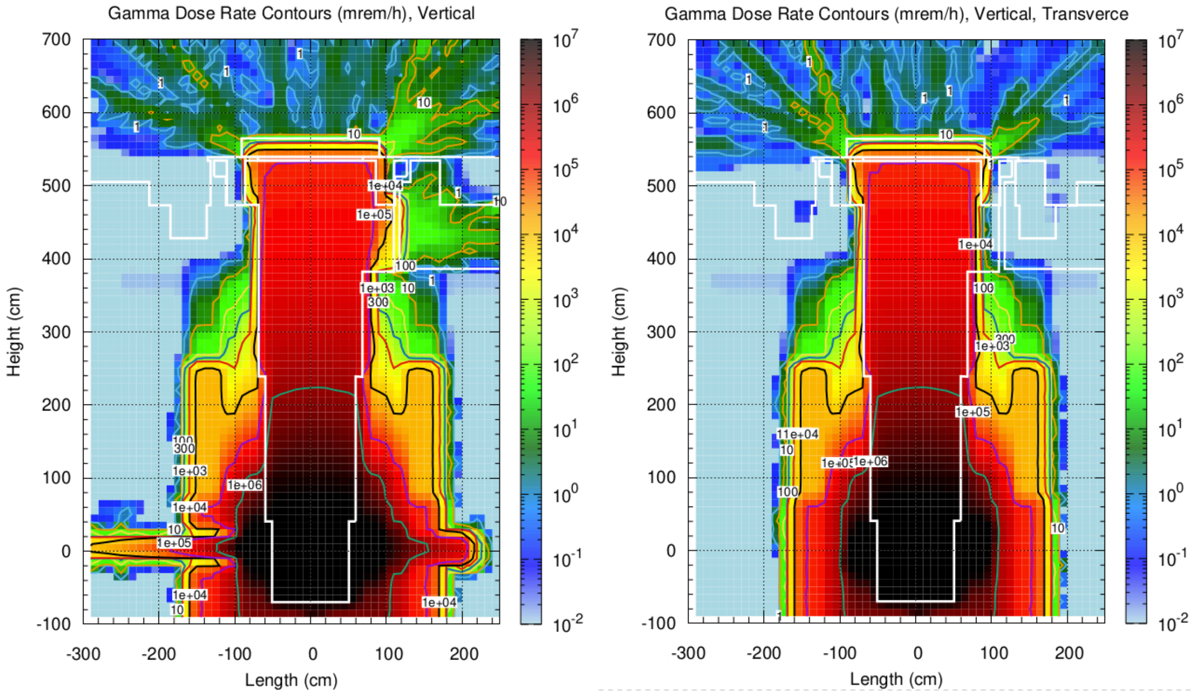


Figure 41. Residual dose rates through the target monolith with empty shaft covered with steel plate 22 days after beam termination in vertical cross section through the beam center line (left) and perpendicular to the beam centerline (right)

Residual dose rates through the target monolith in horizontal cross section and in vertical cross section through the upper part of the shaft housing are shown in. Figure 42.

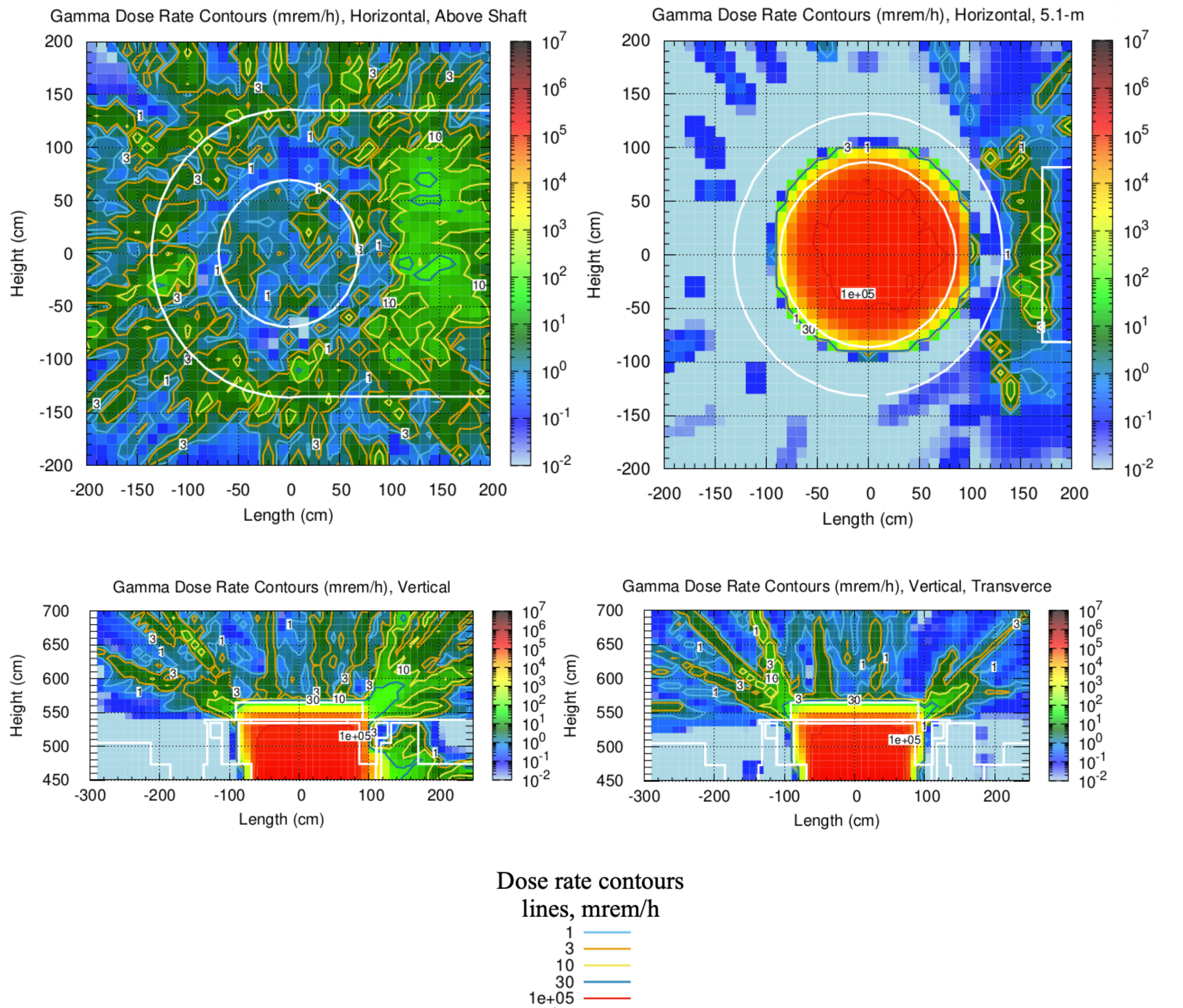


Figure 42. Residual dose rates through the target with empty shaft covered with steel plate 22 days after beam termination. Top row: horizontal cross section above the shaft(left) and through the shaft at 501-cm distance from the beam centerline. Bottom row vertical cross section: through the beam centerline (left) and perpendicular to the beam centerline (right).

Dose rates over the cover plate are overall couple mrem/h. Hot spot is on the transition plate downstream the adaptor plate and the dose rates are up to 30 mrem/h. The cover place reduces radiation streaming from the shaft about 4 orders of magnitude.

5.5 IRP2 EMPTY SHAFT WITH INSPECTION TOOL

During the IRP2 replacement the shaft in the monolith will be inspected using so called inspection tool, which is made from stainless steel (SS316) and will be inserted all the way inside into the shaft. To support inspection process the dose rates from the shaft with inserted inspection tool are analyzed. Geometry in vertical cross section through the beam centerline and vertical cross section perpendicular to the beam centerline with empty open shaft are shown in Figure 43.

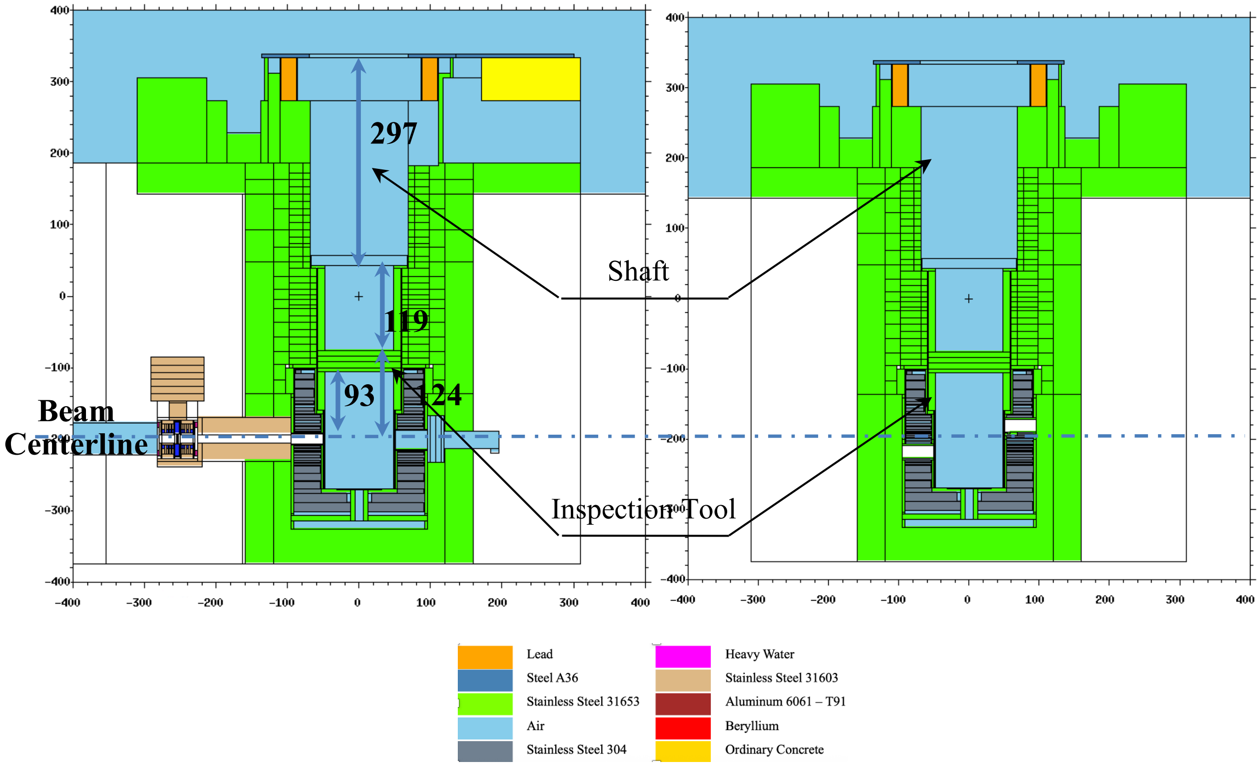


Figure 43. Vertical cross section through the monolith with inspection tool installed to the shaft: through the beam centerline (left) and vertical cross section perpendicular to the beam centerline (right). Dimensions are given in centimeters.

Residual dose rates through target the monolith corresponding to the time of 22 days after the beam termination with empty open shaft are shown in Figure 44.

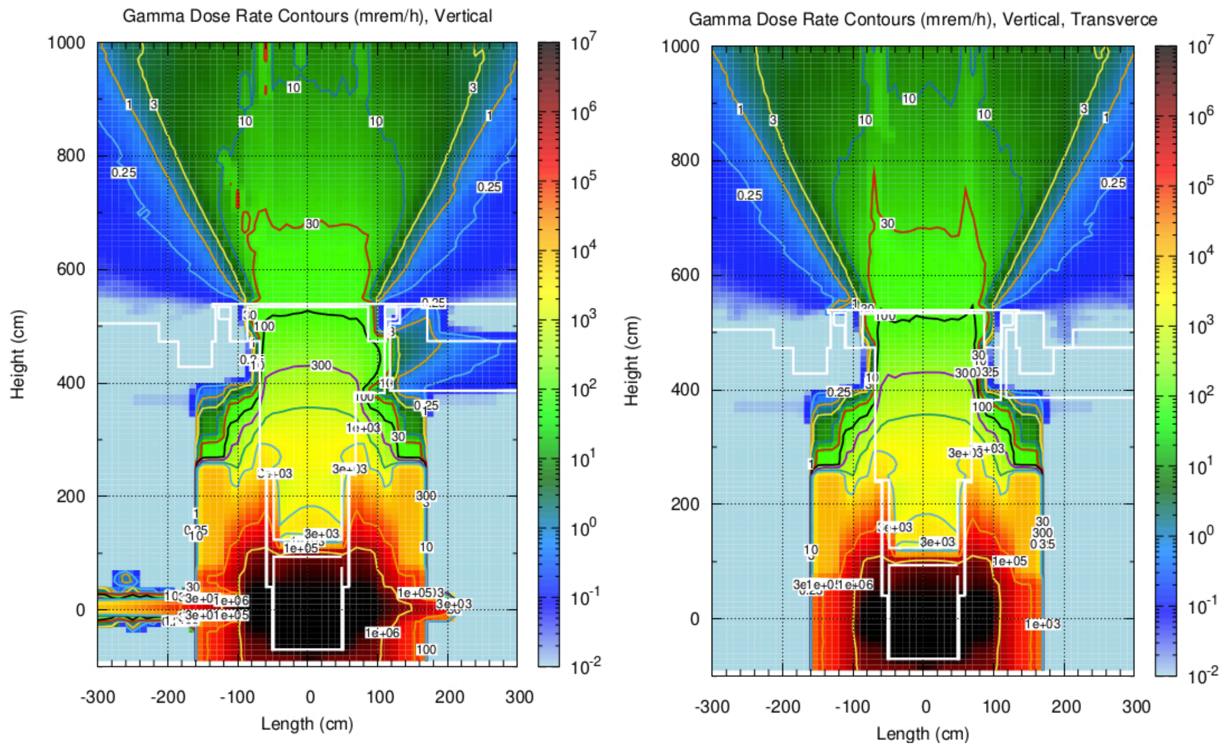
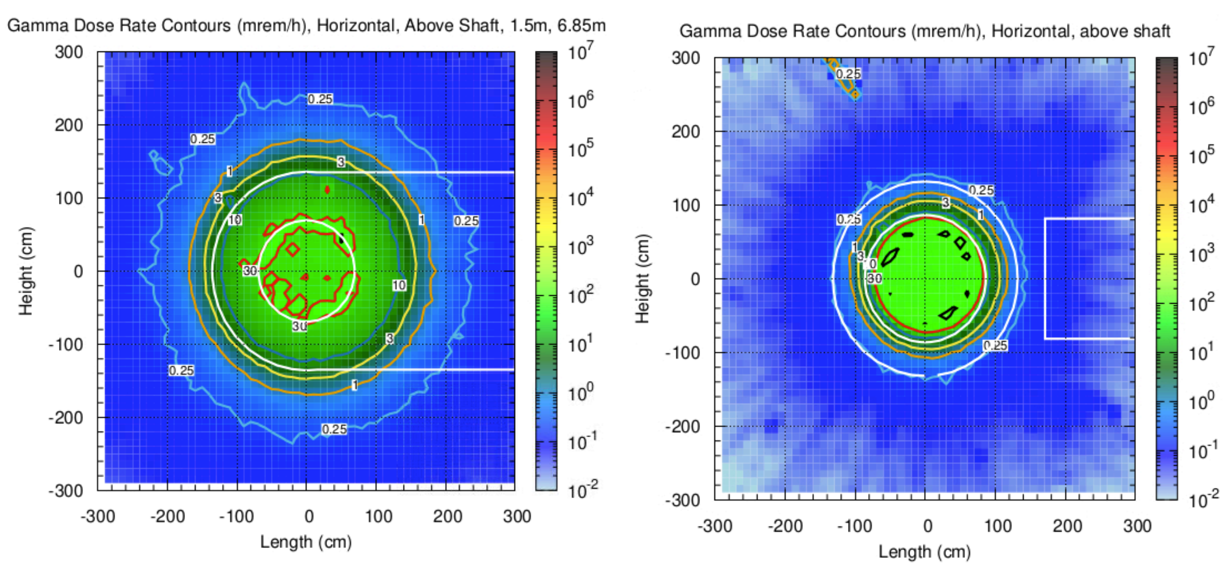


Figure 44. Residual dose rates through the target monolith with inspection tool installed to the shaft 22 days after beam termination in vertical cross section through the beam center line (left) and perpendicular to the beam centerline (right).

Residual dose rates through target monolith in horizontal cross section and in vertical cross section through the upper part of the shaft housing corresponding to the time of 22 days after the beam termination are shown in Figure 45.



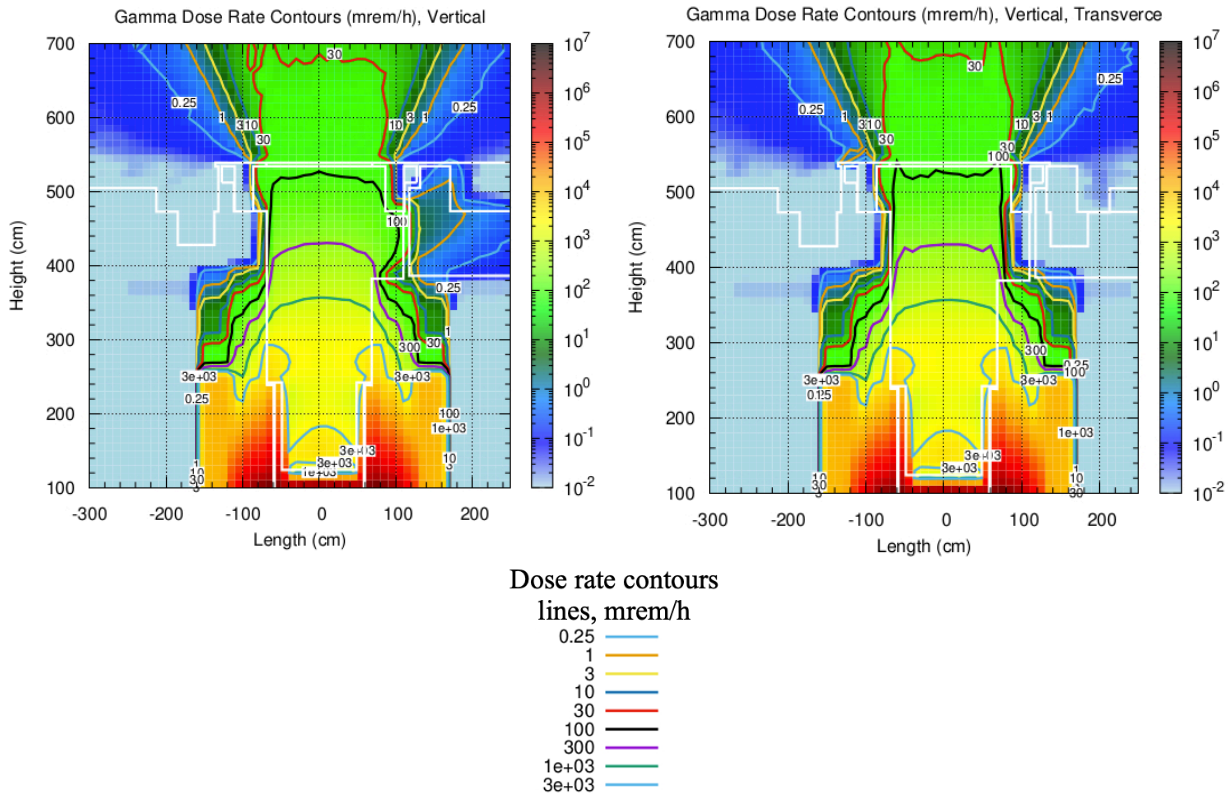


Figure 45. Residual dose rates through the target with inspection tool inserted into the shaft 22 days after beam termination. Top row: horizontal cross section above the shaft(left) and through the shaft at 501-cm distance from the beam centerline. Bottom row vertical cross section: through the beam centerline (left) and perpendicular to the beam centerline (right).

Analyses of the results show that the dose rates above the shaft are up to 100mrem/h. Dose rates on the floor at 1.50-m distance from the center of the opening in the adaptor plate are about 1mrem/h and below, the dose rates on the horizontal part of the inspection tool are up to 3000 mrem/.

5.6 NEW IRP3 INSTALLED

New IRP3 is planned to be installed about 35 days after the beam termination. Vertical cross section through the monolith with IRP3 installed is shown in Figure 46.

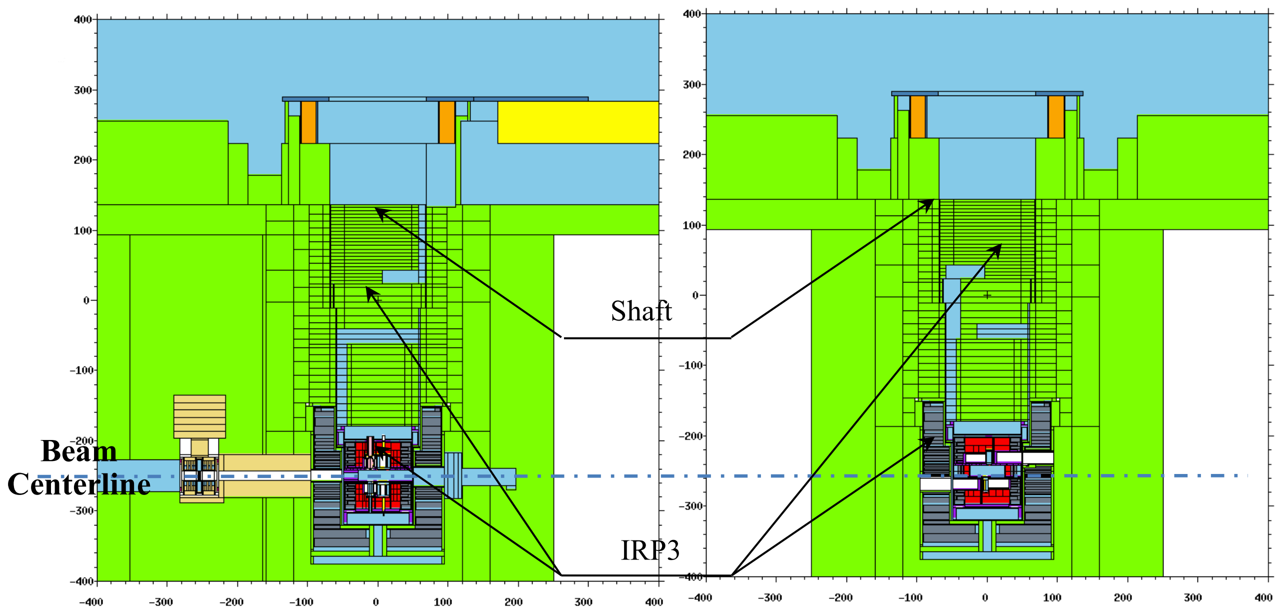


Figure 46. Vertical cross section through the monolith with new IRP3 installed to the shaft: through the beam centerline (left) and vertical cross section perpendicular to the beam centerline (right).

Residual dose rates through target the monolith corresponding to the time of 35 days after the beam termination with IRP3 installed are shown in Figure 47.

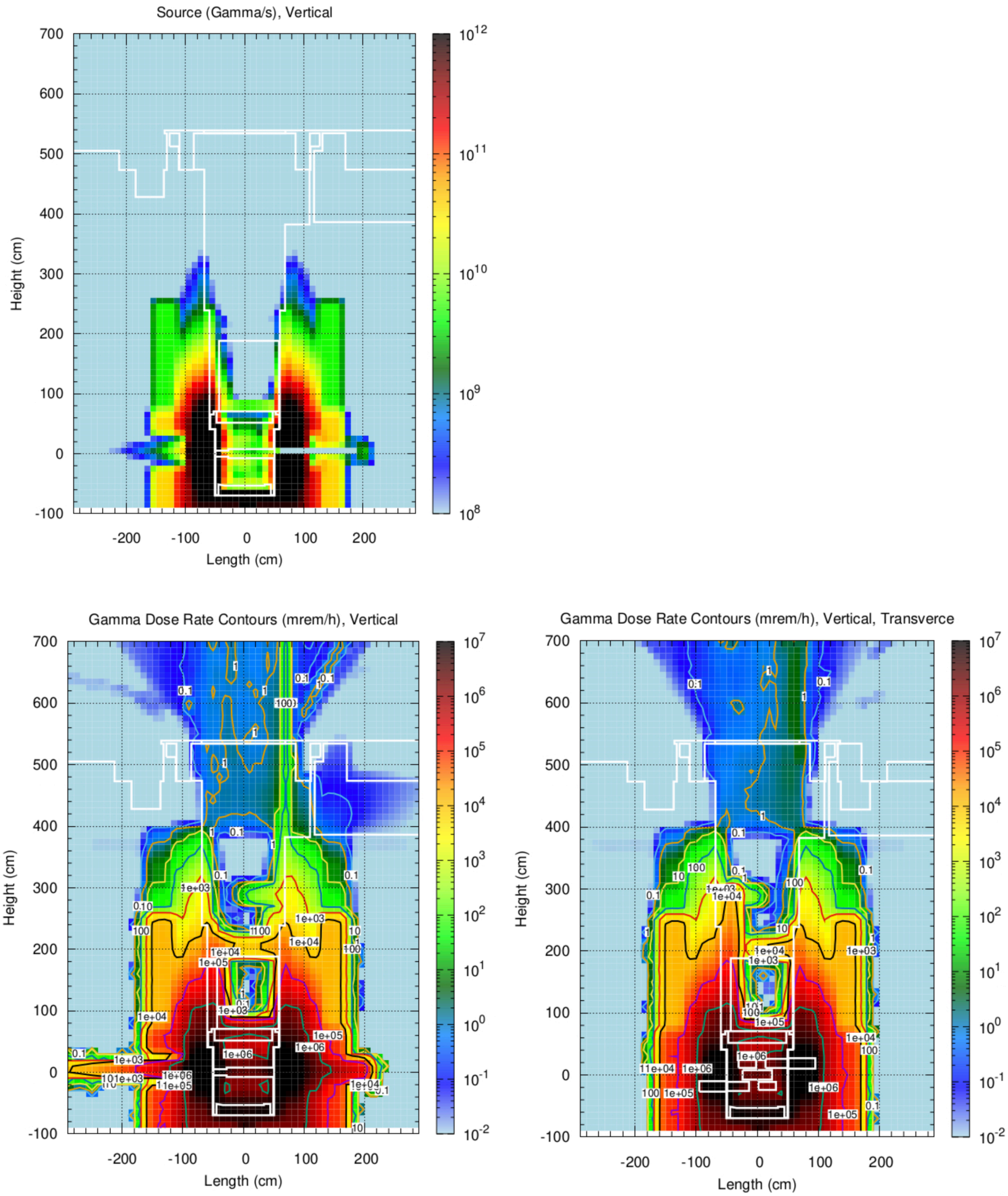


Figure 47. Gamma sources and residual dose rates through the target monolith with IRP3 installed into the shaft 35 days after beam termination. Top row: gamma sources in vertical cross section through the beam center line. Bottom row shows residual dose rates in vertical cross section: through the beam centerline (left) and perpendicular to the beam centerline (right).

Residual dose rates through target monolith corresponding to the time of 35 days after the beam termination in horizontal cross section and in vertical cross section through the upper part of the shaft housing are shown in Figure 48.

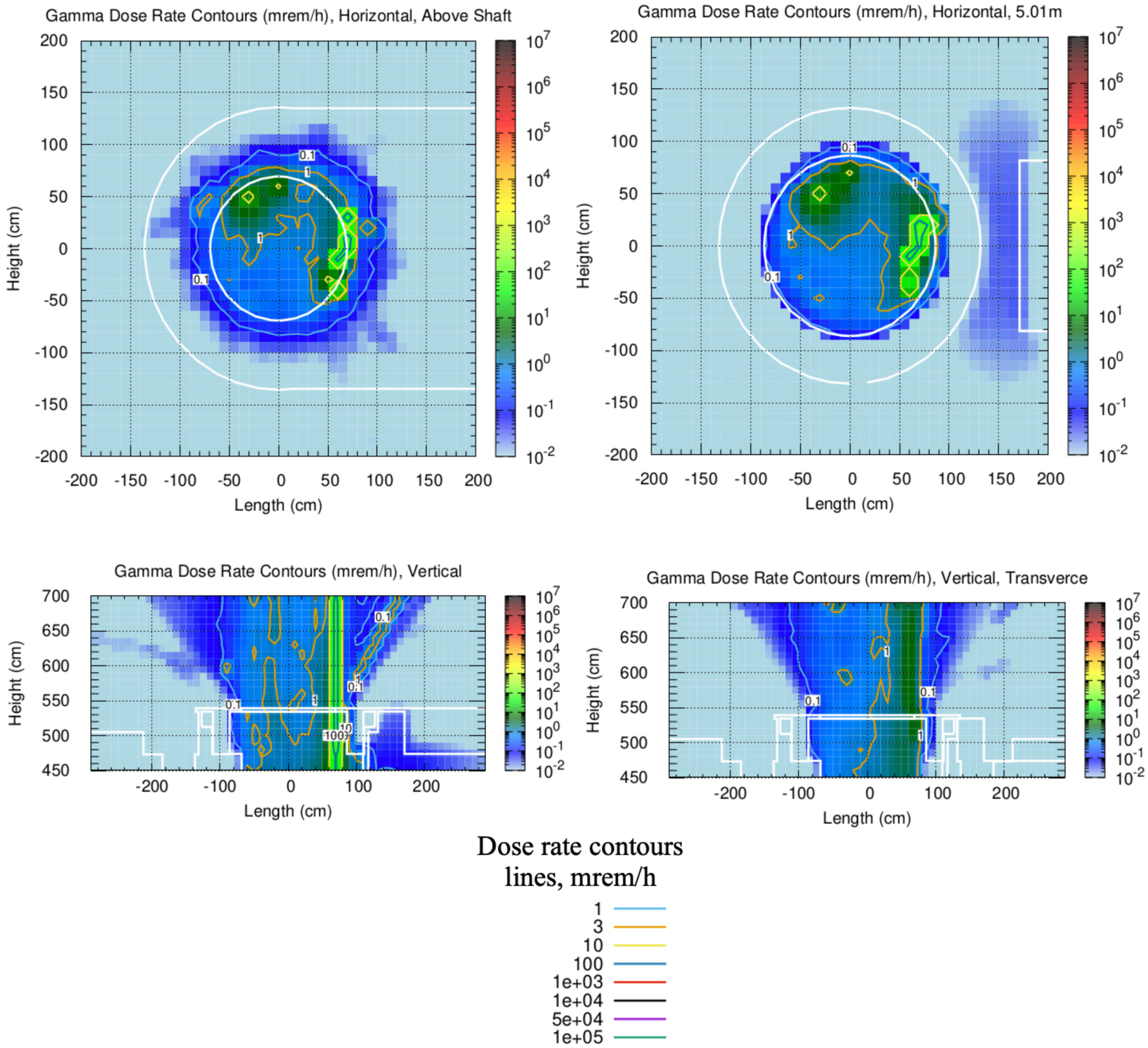


Figure 48. Residual dose rates through the target IRP3 installed to the shaft 35 days after beam termination. Top row: horizontal cross section above the shaft(left) and through the shaft at 501-cm distance from the beam centerline. Bottom row vertical cross section: through the beam centerline (left) and perpendicular to the beam centerline (right).

Analyses of the results show that the dose rates above the shaft opening peak at 100 mrem/h due to radiation streaming through the pipe chase in the upper shielding segment. At locations without interfering chases, the highest dose rate drops to single-digit mrem/h. On the floor, outside the shaft perimeter, outside of the adaptor plate, dose rates are under 0.1mrem/h.

6. CONCLUSIONS

Neutronics analyses to evaluate the residual dose rates to support work planning from radiation-protection point of view during the replacement stages for IRP2 are performed. Results are reported in a form of dose rates maps with reporting the highest expected dose rates for all foreseen steps of the IRP2 replacement scenario.

7. REFERENCES

[1] National Spallation Neutron Source Conceptual Design Report, Oak Ridge National Laboratory, NSNS/CDR-2/VI, 1997.

[2] C J. Werner, ed., "MCNP User's Manual, Code Version 6.2 " LA-UR-17-29981, Los Alamos, New Mexico, October 2017.

[3] Conceptual Design Report Proton Power Upgrade Project, ORNL/TM-12016/672, Oak Ridge National Laboratory, Oak Ridge, Tennessee (August 2017)

[4] F. X. Gallmeier and D. Raparia, Proton Beam Profiles at the Target and at the Beam Dumps of the SNS, Fourth International Topical Meeting on Nuclear Applications of Accelerator Technology, Washington, D.C., November 12-15, 2000, American Nuclear Society, p. 240-245, (2000).

[5] F. X. Gallmeier, SNS Beamline Shielding Source Terms for Beams with 1.3 GeV Incident Proton Energy, SNS-107030700-DA0007-R00 (Oak Ridge, TN: Oak Ridge National Laboratory, April 2019).

[6] F. X. Gallmeier, M. Wohlmuther, AARE_ACTIVATION SCRIPT VERSION 2.0 USER GUIDE, ORNL/TM-2018/1036, Oak Ridge National Laboratory, Oak Ridge, TN, July 2018

[7] I. Popova, An updated Manual of CINDER2008 Codes and Data in the AARE package, Oak Ridge National Laboratory, ORNL/TM-2018/926, December 2018.

[8] I. I. Popova, Flux to Dose Conversion Factors, SNS-NFDD-NSD-TR0002-R02, Oak Ridge National Laboratory, Oak Ridge, Tennessee, (August 2012).

[9] B. Rimmer, The Spallation Neutron Source Target Design and Operating experience, A&T Seminar, CERN, September 2013.

[10] I. I. Popova, Impact on Activation and Dose Rates for Target Vessel Waste Handling due to Change Beam from 1GeV to 1.3GeV, SNS-106050200-DA10005-R00 (Oak Ridge, TN: Oak Ridge National Laboratory, April 2025.