Analyses to support waste disposition of SNS Inner Reflector Plug

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Abstract

The Spallation Neutron Source Inner Reflector Plug (IRP) is scheduled for replacement. It reached end of life-time because of moderator neutron poison and decoupler burn-out, which is used for shaping neutron pulses. 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 size, which requires removal in segments. In order to support the disposal of spent IRP, waste characterization analyses are performed. These analyses include an accurate estimate of the radionuclide inventory and the residual dose rate. Using this data, the package class is determined for the segment and appropriate containers for temporary storage and subsequent transport are assigned. Analyses are performed in four steps: a radiation transport analysis of the radiation environment for producing the flux and isotope production information using MCNPX, a multi-cell transmutation analysis based n CINDER90, the generation of decay gamma source terms, and the gamma transport analyses of the decay gammas arriving at residual dose rates again using MCNPX. . Due to the complexity of the geometry of the lower segment, transport analyses for the residual dose rate require elaborate work for the source terms definition.[1]

Introduction

The Spallation Neutron Source (SNS) in Oak Ridge, Tennessee, is an accelerator driven neutron scattering facility for materials research. Presently the SNS operates at 1.4 MW proton beam power incident on a mercury target with proton beam energy of 1 GeV and 60 Hz repetition rate. The SNS consists of an accelerator facility, target facility, and a world-class suite of neutron scattering instruments.

Some components of the facility are scheduled for replacement because they reach their end-of-life due to radiation induced material damage or burn-up, or because of mechanical failure, or as the result of design improvements. These components must be safely removed, placed in a container for temporary on-site storage, and are ultimately transported off-site to an approved radioactive waste disposal site.

The Inner Reflector Plug (IRP) is a central component of the SNS target monolith, which houses the mercury target and moderators. As a central component, it is exposed to high-level radiation fields during routine operation and builds up significant radioactivity. The IRP assembly contains shielding, 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. The lifetime of the IRP was by calculations estimated to be about 40,000 MWh of proton energy delivered to the target. The IRP will be extracted from the target monolith during facility maintenance period, and split into three segments. Each segment will be characterized and subsequently disposed separately.

Accurate estimates of the radionuclide inventory, as well as the radiation fields and respective dose rates of the spent IRP, were performed in order to characterize and classify each segment. These estimates support decisions in choosing the appropriate storage and transport package/container.

Methods and codes

Neutronics analyses are performed to support spent IRP disposition. Full three-dimensional radiation transport calculations, using the state-of-the-art code MCNPX Version 2.7.0 [1] [5] and the latest as-built target station model, are performed to simulate the radiation environment of the IRP, and to calculate isotope production rates due to spallation reactions and the below-20-MeV neutron fluxes in areas of interest originating from a 1 GeV proton beam delivered into a mercury target.

Isotope reaction rates and neutron fluxes are fed into the CINDER90 code [2] [6] using the standardized ACTIVATION_SCRIPT [3] to calculate the IRP radionuclide inventory. Irradiation history was assumed to fit 40,443 MWh of proton energy delivered the target, which were distributed over 11 years, as illustrated in Table 1.

In order to obtain radionuclide inventory decay gamma sources distributions in the segments, the segments were subdivided into finer cells for each of which activation calculations were performed based on cell specific isotope production rates and neutron fluxes.

Table 1: Irradiation history of IRP

Period, days	Delivered energy, MWh	Period, days	Delivered energy, MWh
730	3749.28	124	2410.56
248	1964.16	57	0
117	0	124	2470.08
248	2380.8	60	0
117	0	124	2470.08
248	3571.2	57	0
117	0	120	2499.84
248	4047.36	63	0
117	0	120	2499.84
124	2232	62	0
60	0	120	2499.84
124	2232	62	0
57	0	90	1998
124	2410.56	2	0
60	0	30	1008

Then, to obtain integral isotope inventory and decay gammas, the post-processing code ALLCODE is used. This code is part of CINDER90 package and accumulates quantities from all material regions.

Decay gamma sources for a defined history of build-up and decay are extracted from each cell and compiled to a source term in MCNPX language by running the GAMMA_SOURCE_SCRIPT [4]. The decay gamma source is prepared for tentative transport dates to the waste disposal facility. For upper and middle segments, analyses are performed for 100 days, 185 days and 365 days cooling down after beam termination. For the lower segment, analyses are performed for 100 days of cool down after the beam termination. The source is utilized in photon transport calculations for each IRP segment. For analyses of the residual dose rates, next-event point and ring detectors were applied, as well as dose rate mesh tallies to allow for dose rate contours in and around the segments geometries.

Geometry

The IRP with segmentation for waste disposal is shown in Figure 1. The IRP is cylindrical, approximately 454-cm tall and 100-cm in diameter.

The SNS as-built target station model is a CAD type model that details the target module; cylindrical inner reflector plug including moderators, beryllium and steel reflectors; the cylindrical outer plug; and the proton beam window assembly. A full three-dimensional model was developed for transport analyses to simulate proton interactions on the proton beam window and target, and secondary radiation fields in the IRP environment. A vertical cut of the target station transport analyses model containing the IRP is shown in Figure 2. The target station model consists of the proton beam window assembly, IRP, outer reflector plug and target module. The IRP, outer reflector plug and target module are surrounded by the shielding monolith.

Figure 1: SNS IRP extracted from the target station

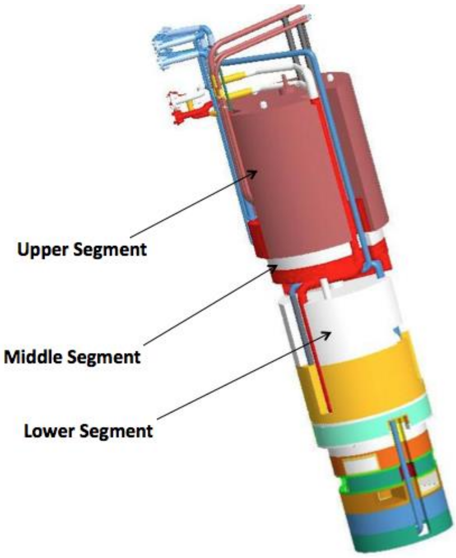
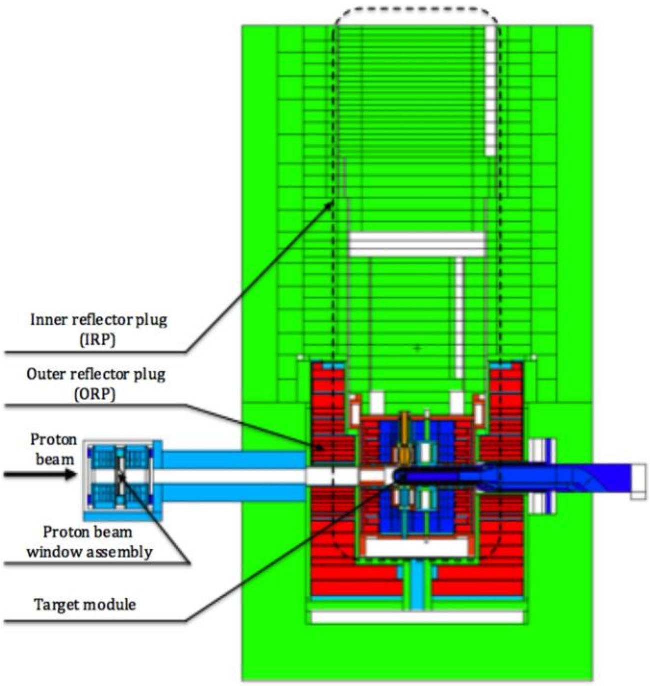


Figure 2: Vertical cross section through the beam central line of the target station model



The IRP model for residual gamma transport was extracted from target monolith model and divided, according to the drawings, into three segments, each of which is going to be disposed separately. Analyses were performed for each component.

Results

The obtained residual nuclide inventories and dose rates around the segments will enable characterisation of the IRP segments for waste disposal, and selection of an appropriate container/package for off-site transport to ensure compliance with Department of Transportation (DOT) regulations.

The residual dose rates 100 hours after shutdown are shown in the Table 2 for upper, middle and lower segments. The upper and middle segments are significantly cooler (about 3 orders of magnitude in the dose rates) compared to the lower segment. The lower segment is located in the proximity of the beam hitting the mercury target and exposed high levels of the radiation.

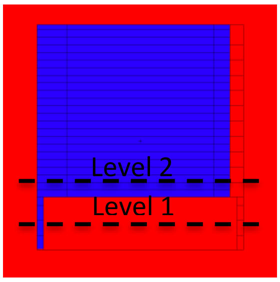
Table 2: Residual shutdown dose rates (mrem/h) at specified locations around the IRP upper, middle and lower segments after 100 hours cool down

Location	Upper segment	Middle segment	Lower segment
0 ft from the bottom	3.31E+02	3.59E+03	1.37E+06
1 ft from the bottom	2.46E+02	1.73E+03	9.50E+05
3 ft from the bottom	8.77E+01	5.12E+02	2.69E+05
10 ft from the bottom	7.10E+00	6.57E+01	2.90E+04
25 ft from the bottom	9.83E-01	1.13E+01	5.69E+03
50 ft from the bottom	2.31E-01	2.88E+00	1.19E+03
125 ft from the bottom	3.60E-02	4.45E-01	3.36E+02
0 ft from the side	1.70E+02	2.13E+03	6.76E+06
1 ft from the side	6.54E+01	5.60E+02	2.25E+06
3 ft from the side	1.93E+01	1.53E+02	7.19E+05
10 ft from the side	2.86E+00	2.22E+01	1.01E+05
25 ft from the side	5.46E-01	4.09E+00	1.81E+04
50 ft from the side	1.44E-01	1.08E+00	4.70E+03
125 ft from the side	2.37E-02	1.79E-01	7.60E+02

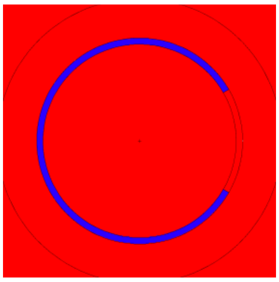
Upper segment

The IRP upper segment transport analyses model is comprised of stainless steel and is shown in Figure 3, which depicts 4 cross sections of the segment. Red color represents the air and blue color represent the steel of the upper IRP segment. Stainless steel 316/53 with density 7.95 g/cm is used for transport and activation analyses.

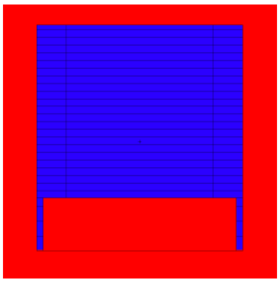
Figure 3: IRP upper section transport analyses model



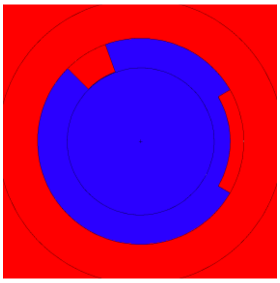
Vertical cross section through the beam centerline



Horizontal cross section at level 1



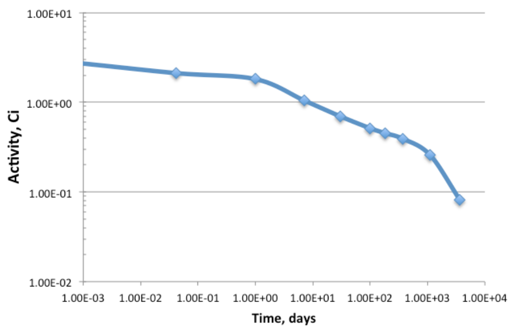
Vertical cross section perpendicular the beam centerline



Horizontal cross section at level 2

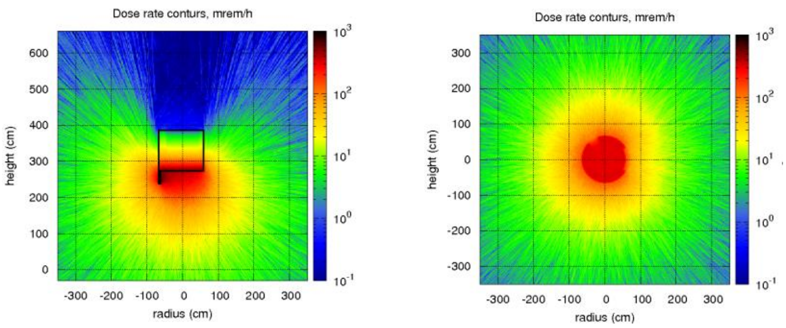
The activity vs time after shutdown in the IRP upper section is shown in Figure 4.

Figure 4: Activity (Ci) in the IRP upper segment during cool down



Dose rate contours for the spent IRP upper segment after 100 days cool down are presented at Figure 5 in vertical cross section and in horizontal cross section at about 47 cm from the bottom edge of the IRP upper section.

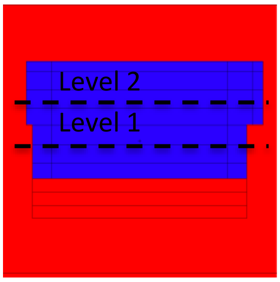
Figure 5: Dose rate contours in and around the IRP upper segment after 100 days, vertical cross section along the beam centreline and horizontal cross section at about 47 cm from the IRP upper segment bottom.



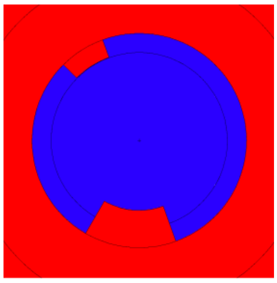
Middle segment

The IRP middle segment transport analyses model is comprised of stainless steel shield plug and is shown in Figure 6, which contains 4 cross sections of the segment. Red color represents the air and blue color represent the steel of the upper IRP segment. Stainless steel 316/53 with density 7.95 g/cm is used for transport and activation analyses.

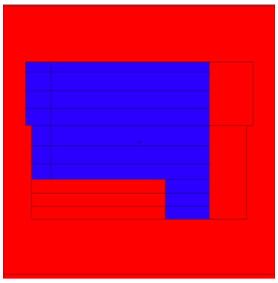
Figure 6: IRP middle section transport analyses model



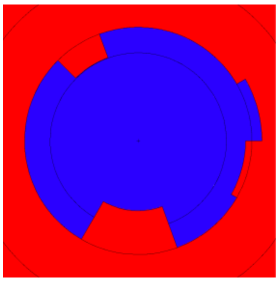
Vertical cross section through the beam centerline



Horizontal cross section at level 1



Vertical cross section perpendicular the beam centerline



Horizontal cross section at level 2

Activity in the IRP middle segment during the cool down after beam termination is shown in Figure 7. Dose rate contours for the spent IRP middle segment after 100 days cool down are presented at Figure 8 in vertical cross section and in horizontal cross section at about 30 cm from the bottom edge of the IRP upper segment.

Figure 7: Activity (Ci) vs time after beam termination in the IRP middle segment during cool down

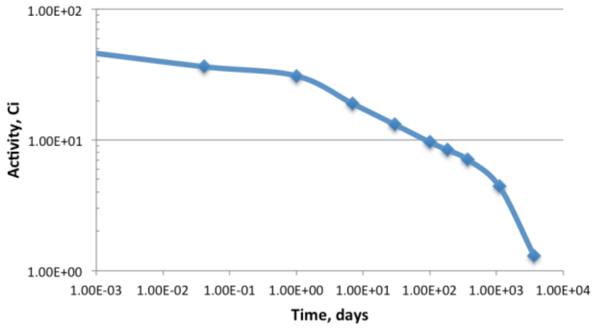
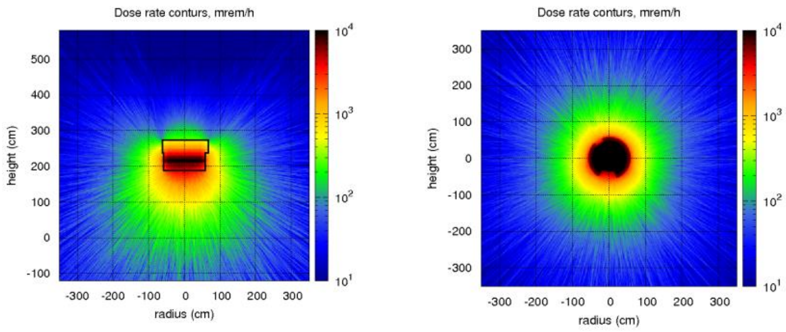


Figure 8: Dose rate contours in and around the IRP middle segment after 100 days, vertical cross section along the beam centreline and horizontal cross section at about 30 cm from the IRP upper segment bottom.



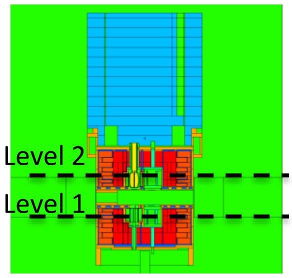
Lower segment

The IRP lower segment transport analyses model is shown in Figure 9, which contains 4 cross sections of the segment. The IRP lower segment is a reflector plug, which has shielding attached on the top. The plug material is beryllium (red color in Figure 9), extending radially to 32 cm , and followed by stainless steel 304 (orange color), extending radially to 47.6 cm. The reflector plug is enclosed in an aluminium hull (yellow color), extending radially to 49.5 cm (yellow color). The reflector has an opening for the target vessel and houses 4 moderators, two moderators are located above the opening for the target and two moderators are located below opening for the target. Moderator vessels are comprised from aluminium, two are wrapped partially with cadmium, and have a gadolinium plate for pulse shaping,. The moderator vessels are fed by liquid water and hydrogen through invar piping. The shielding above the reflector plug is made of stainless steel 316 (blue color).

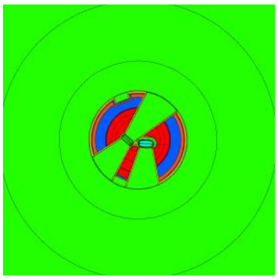
Due to the complexity of the lower segment geometry and large amount of segment cells, transport analyses for the residual dose rate require elaborate work for the decay source terms definition. The cells that contribute less than a fraction of 10^{-4} times compered to the total source strength were omitted. The rest of the cells were split into two source decks to meet MCNPX restriction for the maximum cell numbers in the source description. The description of the moderator cells was altered manually to reflect the universe structure used for the moderators geometry modelling. Two transport analyses utilising the prepared source decks were performed, and results were combined.

Activity in the IRP lower segment during the cool down after beam termination is shown in Figure 10. The activation is mostly dominated by steel components. Beryllium reflector has a long living activation, after 10 years of decay, activity decreases only only to half of the initial activity.

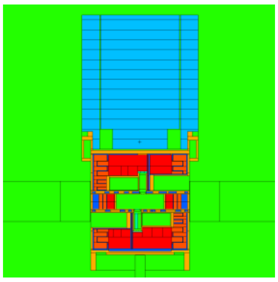
Figure 9: IRP lower segment transport analyses model



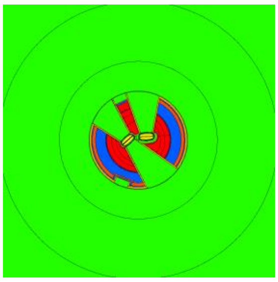
Vertical cross section through the beam centerline



Horizontal cross section at level 1

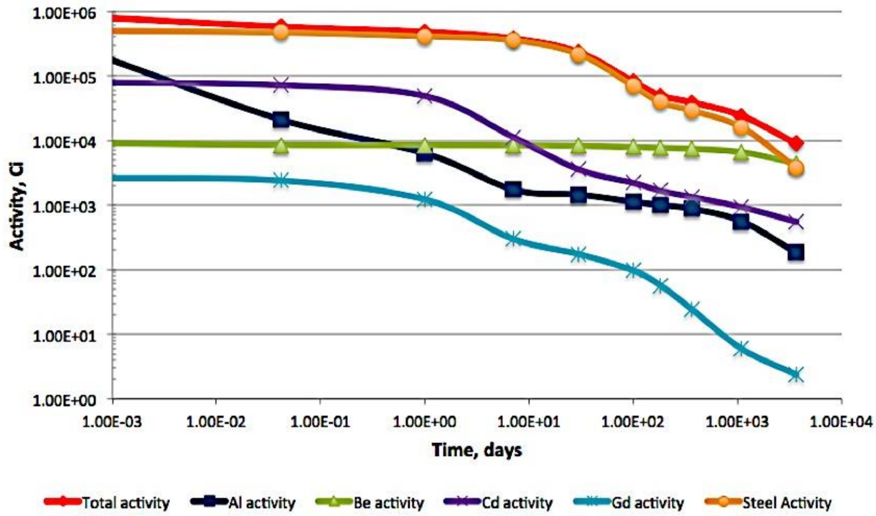


Vertical cross section perpendicular the beam centerline



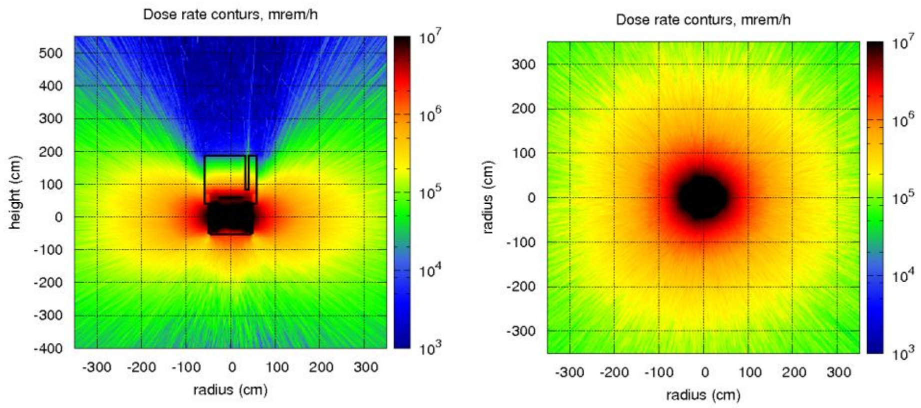
Horizontal cross section at level 2

Figure 10: Activity (Ci) in the IRP lower segment in the components materials and total during cool down



Dose rate contours for the spent IRP middle section after 100 days cool down are presented at Figure 8 in vertical cross section and in horizontal cross section at the beam centerline.

Figure 11: Dose rate contours in and around the IRP lower section after 100 days, vertical cross section along the beam centreline and horizontal cross section through the beam centerline.



Acknowledgements

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