



DOSE RATE VERIFICATION FOR SNS SPENT STRUCTURES

I. Popova¹, F.X. Gallmeier¹, S. Trotter¹ and M. Dayton¹

¹ORNL, PO box 2008, MS 6466, Oak Ridge, TN 37831-6474, US, email: popovai@ornl.gov

Residual dose rate measurements were conducted on two Spallation Neutron Source spent structures, target vessel #13 and proton beam window #5, after extraction from their service locations. These measurements were used to verify calculation methods for radionuclide inventory assessment that are typically performed for nuclear waste characterization and transportation. Neutronics analyses for predicting residual dose rates were carried out using complex and rigorous geometric models of the structures and their surroundings. Computational results were analyzed and compared to the measured dose rates.

I. INTRODUCTION

Spallation Neutron Source (SNS) target system components are exposed to a severe radiation environment. Presently, SNS is capable of operation at 1.4 MW proton beam power incident on a mercury target with a proton beam energy of 1 GeV with a pulse structure of 60 Hz repetition rate. The SNS target is liquid mercury, which is housed in a double walled steel vessel. The proton beam window (PBW) establishes the boundary between the accelerator and the target environments, through which the full beam passes before it hits the target.

Being exposed to a high-radiation environment, the target vessel and PBW module reach their end-of-life because of radiation induced material damage and pulse-induced cavitation erosion (only apply for the target vessel). The maximum allowable peak damage for steel and Inconel structures, which are materials for target vessel and PBW module, is 12 dpa. The target vessel is replaced about two or three times per year, and the PBW module (PBW) is replaced once every two or three years, which takes place during facility shut-down for maintenance.

The radionuclide inventory and dose rate prediction for the time of the transportation is provided for each spent structure that leaves the SNS site to ensure that the container/package is compliant with transportation and waste management regulations and requirements.

Analyses require complex and rigorous geometric models of the spent components and their surroundings, application of particle transport and transmutation codes and extensive data treatment. To validate these analyses and show applicability of codes and methods, measurements of dose rates from spent structures were conducted during the cool-down time for target vessel #13 and PBW module #5. Sets of neutronics analyses were carried out to calculate residual dose rates induced from each component for the time of measurement.

This work shows the final results from a comparison of calculated dose rates vs. measured dose rates for both SNS spent structures.

II. SPENT COMPONENT WASTE MANAGEMENT

All SNS spent components must be safely removed and placed in a container for temporary on-site storage. After a cool-down period, these components are ultimately transported off-site to a nuclear waste disposal site for permanent storage.

Accurate estimates of radionuclide inventory are performed to characterize and classify spent components. For each component, a bounding case is established that considers the maximum possible radionuclide inventory, based on a scenario with maximum possible irradiation exposure during its life-time. Using these data, the spent component is characterized and classified, and an appropriate container for temporary storage on-site and subsequent transport off-site is suggested. Once the container has been selected, transport calculations for the Department of Transportation (DOT) package are performed to ensure that the transport package is compliant with transportation and waste management regulations. As mentioned above, analyses for the radionuclide inventory and dose rates are performed for each off-site shipment using realistic irradiation history and actual time of the shipment. Because these analyses occur regularly, automated script systems for both target vessel and PBW assessments have been developed in order to facilitate the analyses.

Notice of Copyright

This manuscript has been authored by UT-Battelle, LLC under Contract No. DE-AC05-00OR22725 with the U.S. Department of Energy. The United States Government retains and the publisher, by accepting the article for publication, acknowledges that the United States Government retains a non-exclusive, paid-up, irrevocable, world-wide license to publish or reproduce the published form of this manuscript, or allow others to do so, for United States Government purposes. The Department of Energy will provide public access to these results of federally sponsored research in accordance with the DOE Public Access Plan (<http://energy.gov/downloads/doe-public-access-plan>).

III. METHODS

Full three-dimensional radiation transport calculations with the code MCNPX Version 2.7.0 [1] and the latest as-built target station model, including PBW model (Figure 1), are performed to simulate the radiation environment, and to calculate isotope production rates due to spallation reactions and the below-20-MeV neutron fluxes in the 63 group CINDER90 group structure for target facility areas of interest. The calculations are performed twice with two different high energy physics models - Bertini and CEM.

Isotope reaction rates and neutron fluxes are extracted from the transport calculation output and fed into the CINDER90 transmutation code [2] using the standardized ACTIVATION_SCRIPT [3] [5] to calculate the radionuclide inventory of the component. In order to obtain radionuclide inventory distributions, the component is subdivided into smaller cells. Activation calculations are performed for each cell based on cell specific isotope production rates and neutron fluxes. 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 gammas are homogeneously distributed inside each cell and have multi-group representation. The sources for both components are prepared to correspond to the time of measurement of the dose rates.

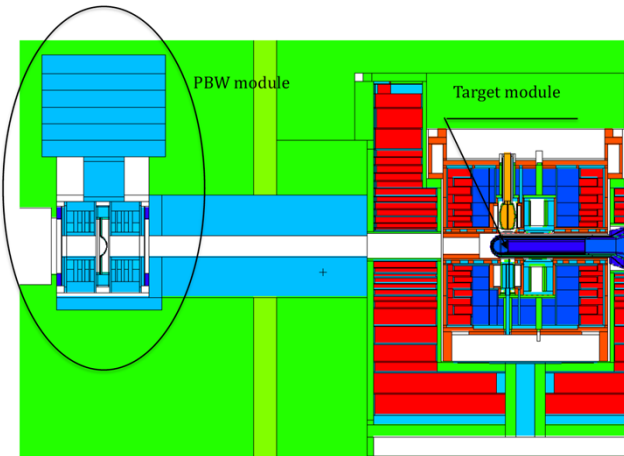


Fig. 1. MCNPX model of target station, including PBW module, vertical cross section through the beam center line.

These decay gamma source terms are then utilized in photon transport calculations for the target vessel and PBW module.

To simulate measurements, box-type volumes of $2 \times 2 \times 2 \text{ cm}^3$ at the detector positions were defined around the components at the locations of the measurements. The

sensitivity of the calculated dose rate to detector positioning was investigated.

The residual dose rate scoring in the detector volume utilizes a track-length flux tally. Dose rates are obtained by folding fluxes with SNS specific flux to dose conversion coefficients [6], which are extension of ICRP-74 [7] with Georgia Tech data above 200 MeV [8].

III. MEASUREMENTS

Remnant dose rate measurements are done using a specialized high-range radiation detection instrument, Ludlum Model 9-7 with 9-7-BH Detector, which is shown in Figure 2.



Fig. 2. Radiation detection instrumentation Ludlum Model 9-7.

According to specification, the detector range is 0.01 – 19.99 kR/hr with a resolution of 0.01 kR/h and 10% linearity. The active detector volume (ion chamber) is 7 cm^3 , 2.54-cm in diameter and 1.64-cm length. There is an acrylic cap, 0.9-cm thick in a front of the ion camera, which shifts its positioning to about 1 cm from the detector's edge. Modeling the active detector volume directly on the spent structure surface and 3 cm away from the spent structure surface brackets the actual ion chamber position and covers uncertainty in the detector placement.

The detector calibration is performed at ORNL with a Cs-137 source.

Both the spent target vessel and spent PBW module are highly irradiated, so the measurements are performed within the heavily shielded target service bay. The target vessel in the service bay is handled by a crane to position the target as required. Target vessel suspension on the crane allows the target to be perfectly aligned with its nose facing down. The remote handling equipment is used to position detectors near the spent components. The positioning accuracy is about 1 cm.

Measurements are performed by placing the detecting instrument at the component surface, at 30 cm and 100 cm from the spent target vessel surfaces at various locations. The detector placement around target vessel

#13 at 30 cm distance from the surfaces near the wide and narrow side of the target and under the target nose (detectors 17, 18, 19) is shown in Figure 3. Placement on the surface and at 100 cm distance from the surface is at the same axial locations but just at decreased/increased distance from the component surface.

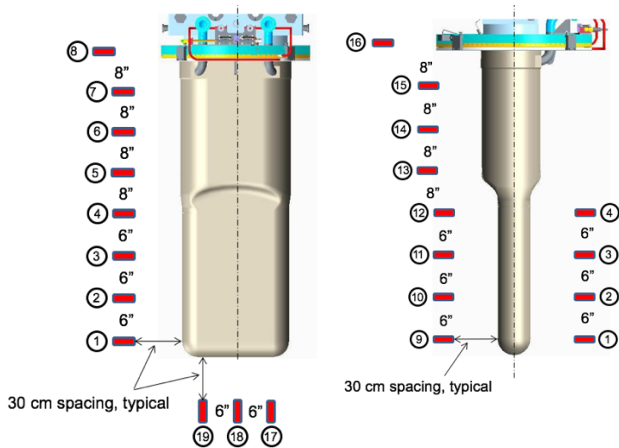


Fig. 3. Detector positioning at 30 cm from the surfaces for target vessel #13.

For PBW module dose rate measurements, detectors are positioned only at 30 cm from the surfaces. The detector placement around PBW module #5 is shown in Figure 4.

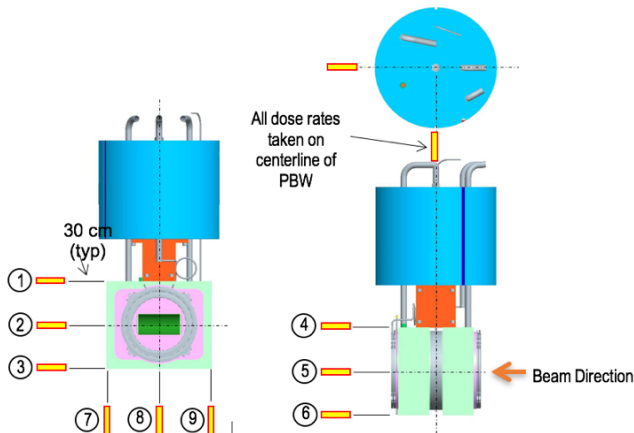


Fig. 4. Detector positioning at 30 cm distance from the surfaces for PBW module #5.

IV. GEOMETRY FOR THE COMPONENTS TRANSPORT ANALYSES

For residual dose rate assessments, the models of the target vessel and PBW module are extracted from the as-built target station model and are used for the following transport analyses to calculate remnant dose rates.

IV.A. Target Vessel

The high-energy and high-intensity proton pulses produced by the SNS accelerator strike the target vessel, which serves as a container for the target material, liquid mercury. The target vessel is made from 316L stainless steel and is located in the middle of the heavily shielded target monolith (Figure 1) during operation.

When the target vessel is ready for replacement, the mercury and cooling water are drained. Some activated mercury, assumed to be 200 g, remains dispersed in the target vessel, along with 4.16% (surface fraction of the target vessel relative to the whole loop) of 10% of the mercury radionuclide inventory (excluding mercury, gold and noble gas isotopes), which is uniformly deposited on steel piping exposed to the target mercury. For the isotope inventory and remnant dose rate analyses, this was accounted for by modeling the mercury inside the target vessel uniformly distributed at a reduced density – $1.253e-4g/cm^3$.

Figure 5 shows the calculational model for the target vessel, including detectors, reflecting their position at the surface, at 30 cm and at 100 cm from the target vessel surfaces, with horizontal and vertical cross sections through the beam center line. The target is rotated 90 degrees compared to its position in the target monolith in Figure 5, which reflect the actual orientation of the target module during measurements. for better visualization.

The stainless steel vessel is shown in blue, the dispersed mercury and plated isotopes are represented by green, and the surrounding target vessel air is represented by red. Detectors are positioned at the surface, 30 cm, and 100 cm from the target vessel surfaces along the wide and the narrow sides of the target vessel and under the target nose. Because of the uncertainty in detector position, discussed earlier, an additional set of analyses is performed with detectors shifted 3 cm away from the target vessel surface.

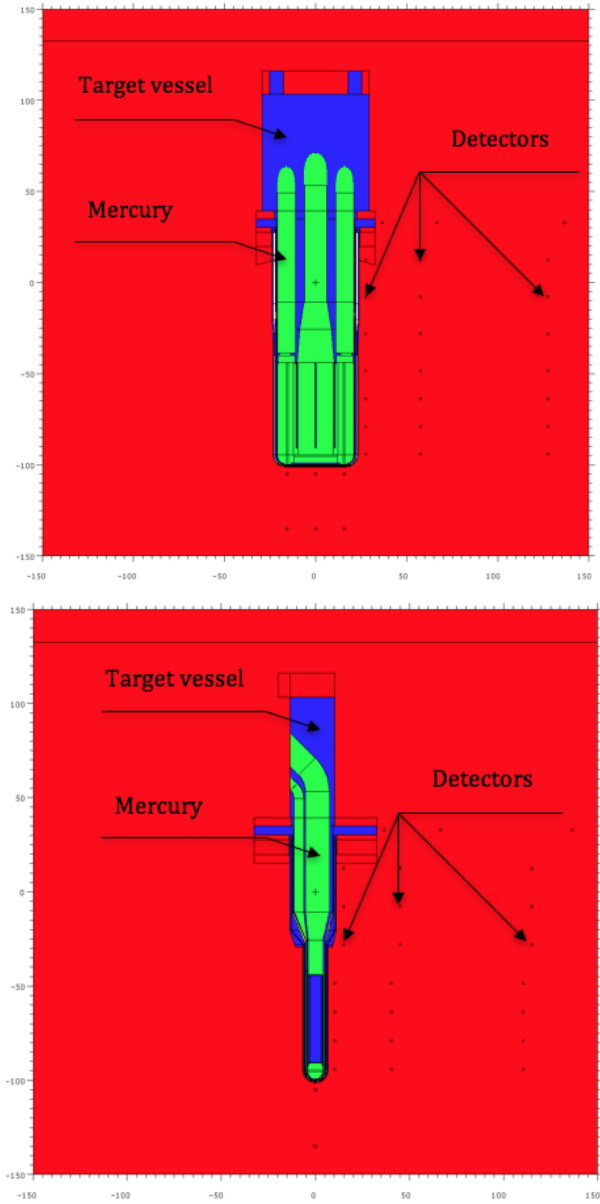


Fig. 5. MCNPX model of target vessel module, horizontal and vertical cross section through the beam center line.

IV.B. PBW

The PBW module is mounted in the target monolith approximately 2.3 meters upstream from the target. Prior to reaching the target, the full proton beam passes through the window and about 3% of the protons undergo spallation reactions in the Inconel and water of the PBW module. Thus, the PBW receives significant radiation exposure, leading to high activation in the materials.

The PBW module is comprised of an Inconel-718 window encased in a 316 stainless steel holder with a water-cooled collimator assembly. The Inconel window is

water cooled and the model consists of 2 layers, a 0.1778 cm thick upstream layer and 0.3556 cm downstream layer. The holder is attached to a steel shield plug. The module weighs 3140 kg. Water lines for cooling the assembly exit the shield plug on top and are shear-cut during PBW module removal activities. These lines, along with the interior of the water jacket, are dried with compressed air prior to removing the PBW module for disposal.

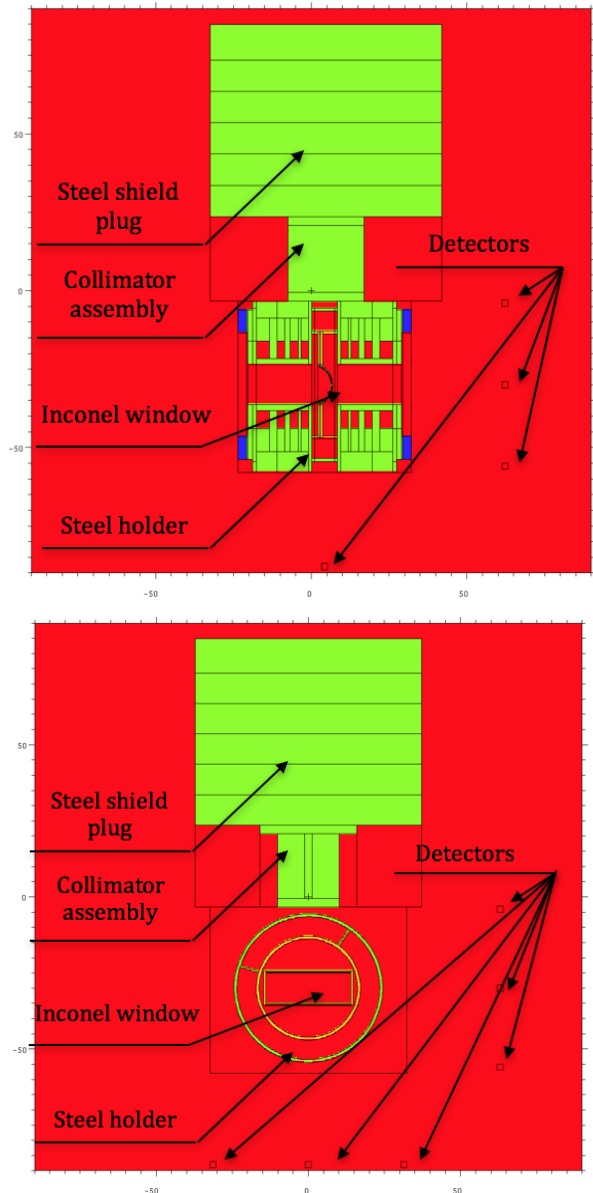


Fig. 6. MCNPX model of PBW module, vertical cross section through the beam center line and perpendicular to the beam direction.

The calculational model for the PBW module and detector positions is shown in Figure 6. Detectors are positioned 30 cm from the PBW surfaces. Green represents steel, blue represents mating surfaces of an inflatable seal, and red represents the surrounding air.

V. RESULTS AND DISCUSSIONS

Analyses for residual dose rates are performed for the time of dose rate measurements: 106 days cooling down for target #13 and 80 days cooling down for PBW module #5 after beam termination on target.

The standard deviation for most of the calculated dose rate values (MCNPX f4 tally is used) is less than 1%, excepting a few locations, where the standard deviation was slightly higher but less than 4%.

V.A. Target Vessel Analyses

Service lifetime [7] for target vessel #13 is approximately 0.50 years during which it accumulated slightly more than 2588.55 MWh proton beam at about 1GeV.

For each set of measurements (detector at the surface, 30 cm and 100 cm from the spent target vessel surfaces) four analyses were performed:

- MCNPX version 2.7 with Bertini model for high-energy particles interactions;
- MCNPX version 2.7 with CEM model for high-energy particles interactions;
- MCNPX version 2.7 with Bertini model for high-energy particles interactions, detectors are shifted 3 cm away from the target vessel surface;
- MCNPX version 2.7 with Bertini model for high-energy particles interactions, detectors are shifted 3 cm away from the target vessel surface.

The ratio of the calculated dose rate to measured dose rate is presented in Figures 7, 8 and 9 for detectors located at the surface, 30 cm from the surface, and 100 cm from the surface of the target vessel, respectively. For the measurements performed on the target vessel surface, the values for detectors 1, 2, 3 and 18 are above the detector's range.

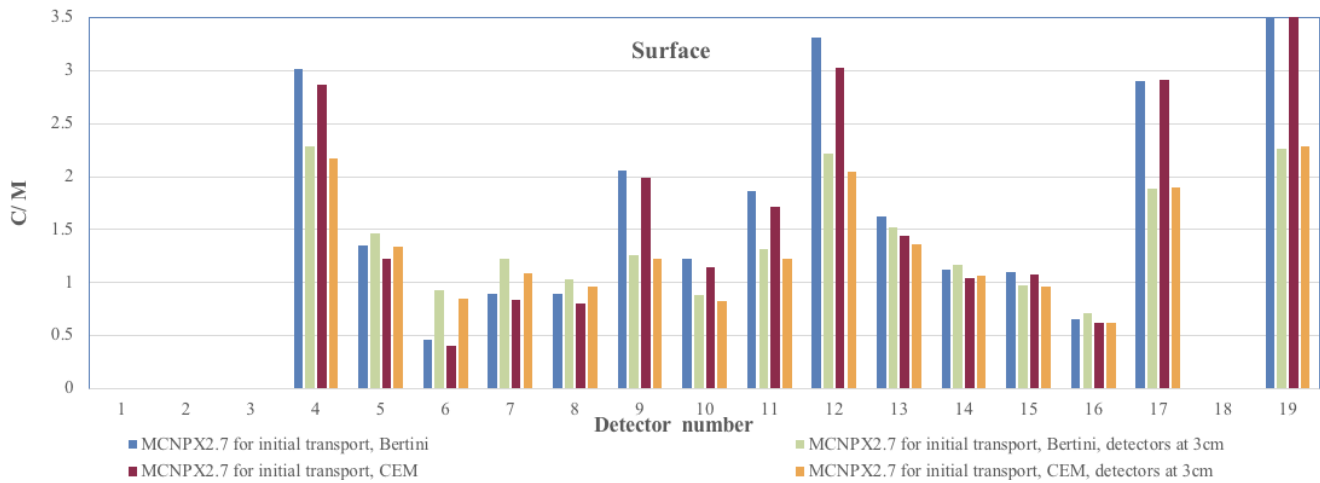


Fig. 7. Ratio of the calculated dose rate over measured dose rate (C/M), detectors at the surface.

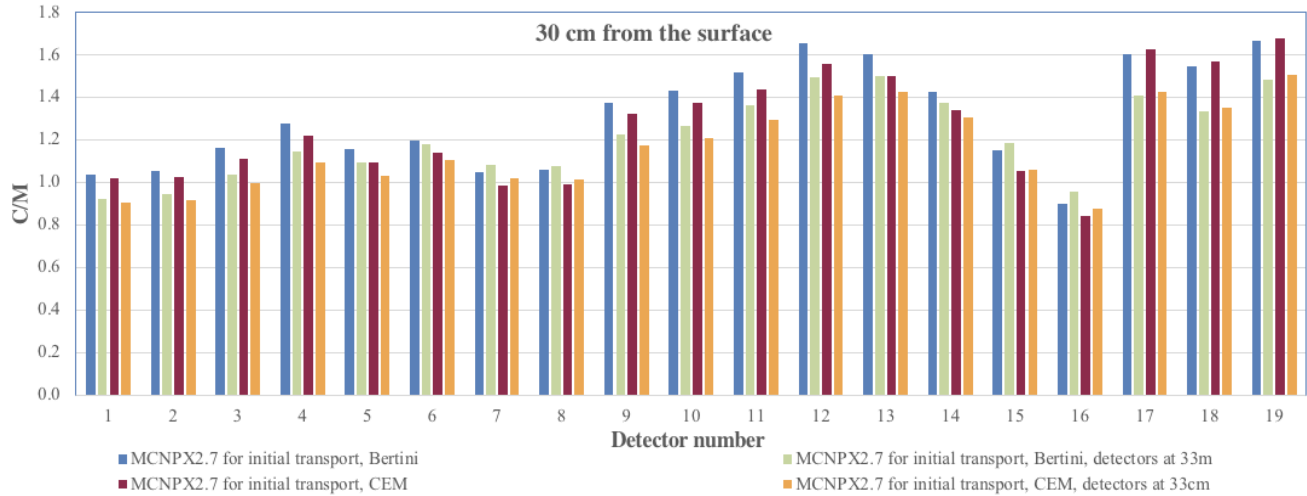


Fig. 8. Ratio of the calculated dose rate over measured dose rate (C/M), detectors at 30-cm from the surface.

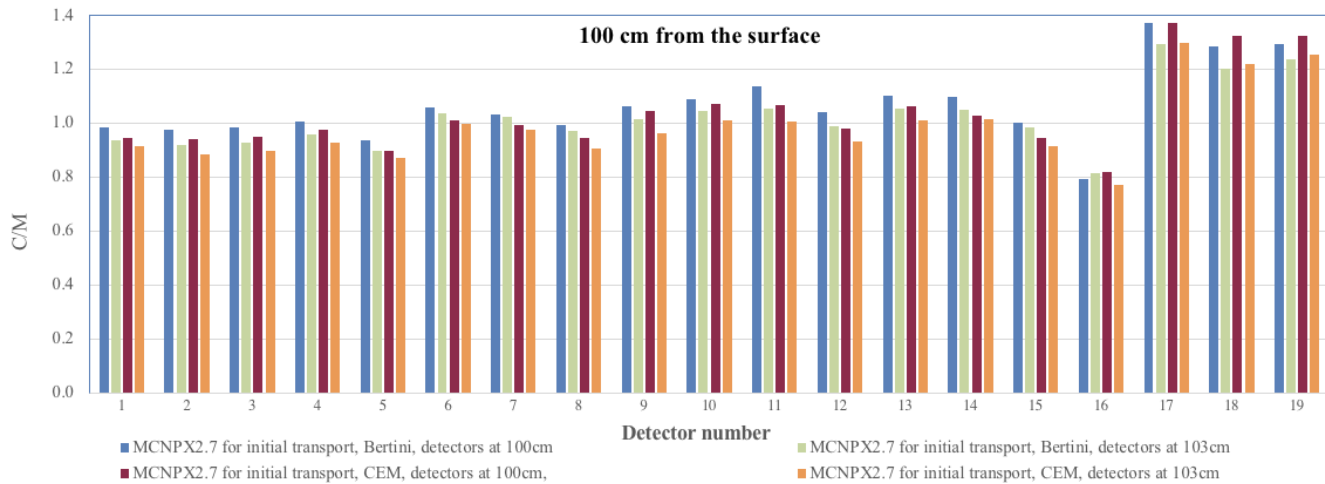


Fig. 9. Ratio of the calculated dose rate over measured dose rate (C/M), detectors at 100-cm from the surface.

The obvious observation that the further the detector location from the surface the better the consistency between measured and calculated dose rates is explained by uncertainty in the detector positioning (about 1 cm) and, as it was noticed in measurements section, the about 1 cm acrylic cup between edge of the detector and detector chamber. The comparison of measured dose rates vs calculated dose rates becomes more sensitive to this error as the detector position gets closer to the surface. This sensitivity results in greater scatter in the measurements at the surface shown in Figure 7.

From all three plots, it is clear that 3 cm shift in the detector position impacts the dose rates. For the detector location at the surface this impact is between 10% and 27%, for 30 cm from the surface is about between 4% and 13% and for 100 cm from the surface is between 2% and 6%.

Using Bertini model vs CEM model to obtain reaction rates changes dose rates between 2% and 10%. Along the target vessel, dose rates calculated with CEM-based source terms are lower compared to analyses with Bertini-based source terms. The dose rate under the target nose are related in the opposite way. The change was expected because the yield of secondary particles production and the vector of residual nuclide distribution depends on high-energy particles interaction model.

The comparison for detectors positioned at 30cm and 100cm from the surface shows that measured dose rates vs calculated dose rates are within 25% except at a few locations, where this difference is as much as 50%.

V.B. PBW Analyses

The PBW#5 module had a service lifetime [8] of approximately 2.34 years in which it accumulated about 12796 MWh proton beam energy at 1GeV proton energy.

Analyses of the dose rates were performed only for one detector position. The respective analyses for the PBW module were performed using MCNPX version 2.7 with the Bertini model for simulating the high-energy particles.

Calculated and measured dose rates (mrem/h) and the ratio of the calculated dose rate over measured dose rate (C/M) are presented in Figure 10. Most of the calculated results are quite consistent with measured data, within 20% and generally higher than measured data. There is one detector location, number 6, where the calculated dose rates differ from measured dose rates by about 40%. The detector positions at the edge of the steel holder and moving it up or down may make a large difference besides the sensitivity to detector distance.

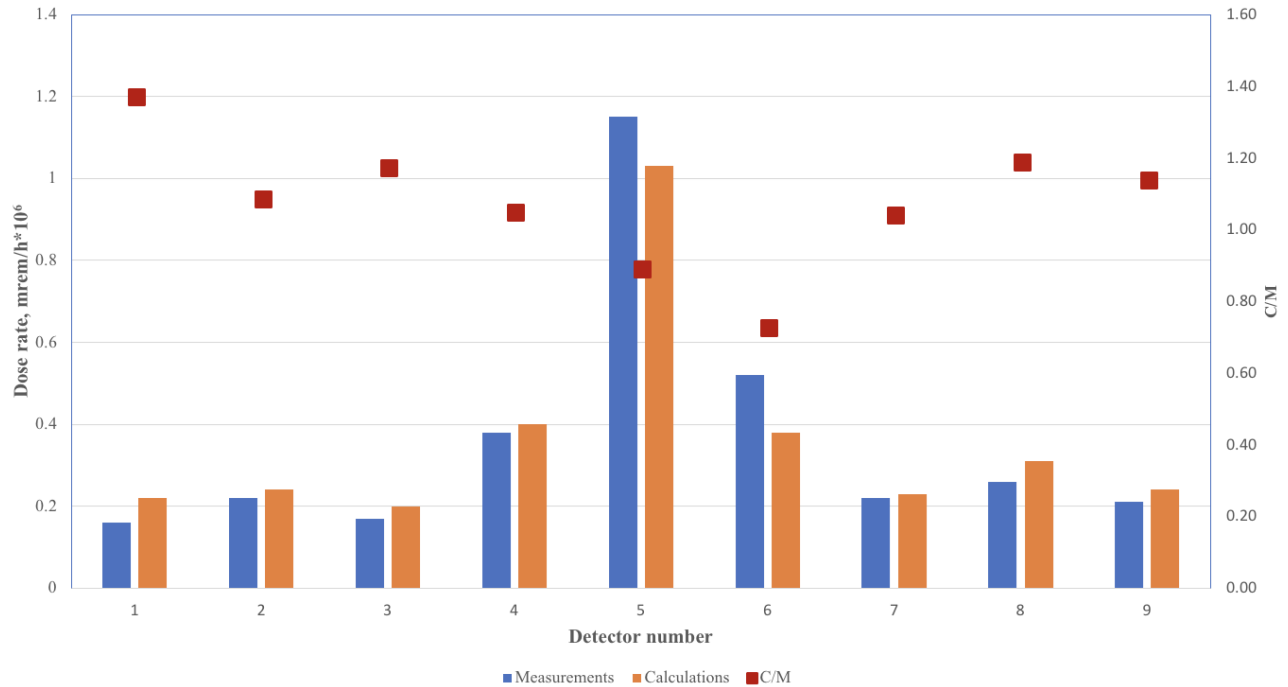


Fig. 10. Calculated and measured dose rates (mrem/h*10⁶) and ratio of the calculated dose rate over measured dose rate (C/M).

VI. CONCLUSIONS

Measurement of remnant dose rates from target vessel #13 and PBW module #5 were performed and compared to calculated dose rates. For the target vessel, two geometry modifications are introduced. The reaction rate used for each set of analyses is calculated using Bertini and CEM high-energy physics models.

The measured and calculated contact dose rates from the target vessel show large variations and, as shown above, is very sensitive to placement of the detectors. Overall, the rest of the locations show good agreement, with a difference less than 50%. Using Bertini vs CEM for obtaining reaction rated shows differences in the dose rates of between 2 and 10%.

ACKNOWLEDGMENTS

ORNL is managed by UT-Battelle, LLC, under contract DE-AC05-00OR22725 for the Energy. This research was supported by the DOE Office of Science, Basic Energy Science, Scientific User Facilities.

REFERENCES

1. D. Pellowitz, ed., "MCNPX User's Manual, Version 2.7.0," LA-CP-11-00438, Los Alamos National Laboratory, Los Alamos, New Mexico (April 2011).
2. W. B. Wilson, S.T. Cowell, T. R. England, A.C.Hayes, P. Möller, A Manual for Cinder'90 Version07.4, LA-UR-07-8412, Los Alamos National Laboratory, Los Alamos, (2007).
3. F. X. Gallmeier and M. Wohlmuther, Activation Script Version 1.0 User Guide, ORNL-TM-

2008/031, Oak Ridge National Laboratory,
August 2008

4. M. Wohlmuther and F.X. Gallmeier, User Guide for the Gamma Source Perl Script 1.0, PSI-TM-85-08-02, Paul Scherrer Institute, July 2008.
5. P. D. Ferguson, CINDER'90 for SNS Activation Studies, SNS-106100200-TR0142-R00, Oak Ridge National Laboratory, March 2006.
6. I. Popova, Flux to Dose Conversion Factors, SNS-NFDD-NSD-TR-0001-R00, Oak Ridge National Laboratory (October 2009)
7. ICRP publication 74, Conversion Coefficients for use in Radiation Protection Against External Radiation, September 1995
8. Michele R. Sutton-Ferenci, Nolan E. Hertel and Jeremy E. Sweezy, An Evaluated Set of Neutron, Proton and Photon Fluence-to-Effective-Dose Conversion Coefficients, DDN#: PPO-P00-G-DDN-X-00008