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Radiation Environment for the Replacement Scenario of the Activated SNS Core Vessel Inserts

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Abstract

The core vessel inserts are the most target-near beam-shaping components in the neutron beam lines of the Spallation Neutron Source (SNS), and start at about 1 meter distance from the target center. These core vessel inserts will be replaced at component failure, when new needs of beam tailoring arise, or when plugged beam lines will be opened and the dummy inserts (plugs) will be removed. For these replacement scenarios, the activation of the inserts and the radiation field due to radioactive decay in the inserts were calculated, including cask designs for the enclosure of the activated components, using the MCNPX transport code and the ORIHET95 activation tool. After 30 years of operation at 5000 hours per year and one week of cool-down, we calculate activity levels of the inserts that range from 150 to 700 Curies. Steel casks with wall thicknesses of up to 0.36 m will have to be provided for shielding against the decay-gamma radiation.

1. Introduction

The Spallation Neutron Source (SNS)[1] under construction at the Oak Ridge National Laboratory will be a world-class neutron-scattering facility. A high-current beam of 1-GeV protons generated in a linac and an accumulator ring[2] will direct 1.4 MW of power onto a liquid mercury target with 60 Hz pulse repetition rate for production of pulsed high-intensity neutron beams. The neutrons generated in the target will be moderated in four supercritical H_2 and H_2O moderators located on top and on bottom of the flat mercury target and scattered into the neutron beam lines.

Beam shaping elements are positioned as close as possible to the moderators to allow a large solid angle of the thermal neutron leakage to be accepted by neutron guides and directed to the sample positions. The most target near components of the neutron beam lines are the core vessel inserts that extend radially from 1 to 2 meters from the target monolith axis, followed by the shutter inserts located in the beam line shutters. The core vessel inserts also serve an important containment function for mercury vapor that might accumulate in the core vessel at target failures. Hence all the core vessel inserts are flanged to the core vessel and are equipped with beam windows at both ends: near to the target and far from the target. Unused uninstrumented beam lines will be closed of with a solid beam plug at place of the core vessel inserts to confine the radiation as deep in the target monolith as possible. All core vessel inserts are replaceable to provide provisions for new needs of beam tailoring, but also to be able to exchange inserts with failures of the neutron guides and/or the mercury containment function. Also, uninstrumented beam lines will eventually be opened up and be equipped with real inserts instead of plugs. In all the instances the inserts will be extracted through the opened shutter shaft, pulled by a remote handling tool, and lifted into an shielding cask.

Information about the activation levels of the core vessel and shutter inserts was requested for replacement planning. This not only encompases the knowledge of the insert activation but also the shutter and shutter shaft activation and the residual radiation field shining up through the opened shutter shaft including adequate shielding. Deep penetration particle transport calculations were performed to obtain isotope production rates, followd by buildup and decay analyses of radionuclides in the structural material. The resulting radionuclide inventories allow us to evaluate the decay-gamma sources that are fed into gamma transport analyses of various replacement scenarios, including cask design. Here we report on activation of the core vessel inserts and cask design as the first steps of a complex investigation that was recently completed for the inner plug and proton beam window assembly replacement.[3]

2. Geometry models

A MCNPX target monolith model was created based on the SNS target station model, which served for numerous neutronics calculations, i.e. for the optimization of the moderator design[4] and the neutron beam characterizations[5]. The target station model describes the target near environment extending about 5 meters in diameter and 2 meters in height. It includes in detail the target, inner and outer plug, moderators and the proton beam window assembly located about 2 meters upstream from the target. The core vessel as well as the backend of the target was coarsely described in the target station model to include albedo effects to the particle transport in the detailed regions.

The target station model was extended to the target monolith model to a diameter of 10.2 meters and a height of 6.6 meters as shown in Fig. 1. The target station model underwent a rigorous clean-up and modularization before its extension, which allows now for an easy update and change-out of model components. Modular means that a component uses a defined pool of MCNPX surface and cell numbers and the component reacts on a single MCNPX transformation card. The new features of the target monolith model, the details of the core vessel and neutron beam line shutters are also added in a modular way. The beam lines were grouped in 6 sections of three beam lines being served from the same moderator face. For each section, a core vessel region and a shutter region was defined. Each core vessel region contains three core vessel insert openings, and the core vessel inserts such that the core vessel inserts are modular by themselves. Each shutter section contains three shutter shafts housing the modularly moving shutters. Each shutter is equipped with a shutter insert opening and the corresponding modular shutter insert, and tungsten insert for improving its shielding function. Depending on the shutter position, shutter travel gaps form on top or on bottom of the shutter (see Fig. 1b). For the present study all shutters were assumed to be closed with the tungsten insert at beam elevation because the neutron backscattering from the tungsten inserts was thought to increase the activation of the core vessel inserts and would therefore be the conservative case. All core vessel and shutter inserts were modeled according to design drawings[6] and reflect the 1st –day-operations configuration. This means that the beam lines 7,8,10,14,15,16 will be uninstrumented and as such be closed with solid plugs.

Furthermore, models of steel transport casks housing the activated core vessel inserts were developed for single and multi beam line inserts as shown in Fig. 2. Advantage was taken from the modular structure of the target monolith model, which allowed quickly extracting and implementing the appropriate core vessel inserts into the cask geometry. Cask shielding performance was studied with the activated core vessel inserts # 8, 9, 10, 11.

3. Methodology of the Analyses

The typical calculation sequence follows. First, an MCNPX[7] calculation simulating the particle interactions of the primary protons and their progenies throughout the target monolith was performed. This calculation provided neutron fluxes throughout the core vessel insert regions, as well as nuclide production rates due to high-energy particles. Second, a calculation with ORIHET95[8] was performed to determine the activation of the materials and the resulting gamma-ray emission rates. Third, the gamma-ray sources were put in the MCNPX model of the shielding cask configurations and the transport of the gamma rays throughout the configuration was calculated, yielding dose rates at desired locations by folding the gamma fluxes with flux-to-dose conversion coefficients based on ANSI-6.1.1.[9]

All the transport calculations were performed with the MCNPX code version 2.4.0[10]. This code was modified by extending the mesh-based weight window description and weight window generator to all particle types and to the physics model regime, and by implementing an isotope production tally[11]. The first modification allows the effective use and optimization of the variance reduction methods Russian roulette and splitting without having to subdivide the geometry to zones of suitable width. The second enhancement provides isotope production rates from the physics model regime (high energy particles) directly in the MCNPX output rather than going the original route of generating and post-processing a high energy history file. Typical CPU times of the first step of calculation (protons on target) were 10000-20000 minutes on a cluster of 1GHz Pentium-III machines using a LINUX operating system.

For the calculation of neutron fluxes and high energy isotope production rates, the geometry typically extended up to 10.2 meters in diameter and 6.6 meters in height. Typically large parts of the geometries consisted of steel shielding. Neutron flux and isotope production data are required for all the core vessel inserts. Variance reduction methods were heavily used to maintain a particle population throughout the zones of interest. A weight window scheme was set up with using cylindrical meshes with 10 cm radial spacing, typically 20-30 cm axial spacing and 8 azimuthal segments, which reflected the beam line sections, a proton beam window section and a target shielding section. The weight window mesh is overlaid on the geometry. Energy-wise the weight windows were structured into 8 coarse neutron groups, 5 proton groups and 4 groups for all other hadrons and mesons appearing in the calculation. This variance reduction scheme was developed with the shutter activation calculation in mind. For the gamma transport calculations of the cask configurations the shield wall was built of 3 cm thick onion type shells, which were used to define importance regions for a geometrical Russian roulette/splitting scheme. The importance parameters were optimized based on the changes of populations from short "first shot" MCNPX runs

The neutron fluxes for the calculation of the isotope production rates in the core vessel inserts were calculated with a track-length estimator averaged over cell volumes. The mesh tally was applied for scoring the dose rates in and around the shielding casks. Mesh tallies significantly slow down the calculations. For this reason we backed off from getting three-dimensional dose rate maps in geometries, but choose instead to obtain some two-dimensional dose rate slices through critical cuts of geometry.

The buildup and decay of the radioactive isotopes was calculated with the ORIHET95 code as laid out by Odano et. al.[12]. The preparation of the isotope production rates from neutron fluxes, activation cross sections[13], and direct isotope production rate contributions from the spallation reactions is well automated by scripts, as well as the extraction and formatting of the decay gamma sources for the gamma transport calculations. The isotope production rates, and hence the resulting decay gamma production rates, are cell-averaged quantities.

4. Results

The integral activity of the core vessel inserts was calculated assuming 30 years of operation for 5000 hours per year at the design-basis power level of 2 MW. The decay of the activity levels with time is plotted in Fig. 3 for the multi beam line inserts. Typically, the activity levels drop to one-half of the initial values within a day of decay time, but do not decrease much further within a month.

The integral 1-week-decay activities of all core vessel inserts (CVI) are listed in Table 1 together with the specific activity per unit mass. The integral activities range from 150 Curies to 965 Curies, the specific activities range from 0.308 mCurie/g to 0.882 mCurie/g. In both cases the extreme values were found to be for CVI-18 and CVI-4, respectively. Generally the multi core vessel inserts have about twice the mass and twice the activity of a single insert. Inserts at forward-directed beam lines (with respect to the incident proton direction) are exposed to more radiation and show about a factor of two higher activities. Many additional factors may influence the activity level, i.e. the material composition of neutron guides, the moderator face viewed, beam line decoupling with neutron absorbers, and may explain the range of the activity found. CVI-4 may show the highest activity levels because it is uniquely exposed to a larger solid angle from neutrons from its moderator than all other inserts.

Cask design studies were performed using CVI-9 and CVI-10, which are, because of their most forward location, the hottest inserts. CVSI-9 is a real insert, whereas CVSI-10 is a plug. For this reason the distribution of the activity was thought to be different. Similarly, CVI-8, a plug, and CVI-11, a real insert were picked as multi beam line insert representatives for the cask design. CVI-4, the hottest multi insert, is larger than all inserts and needs therefore special consideration. Its specific activity, which will drive the cask dimensions, is only slightly higher than CVI-11's. Dose profiles were calculated for horizontal and vertical sections at the beam center-line. The dose profiles look very similar for all cases investigated regardless of the presence of beam line penetration. A typical dose profile for CVI-11 in vertical direction is presented in Fig. 4. The dose rate at the target-near insert nose of about 10^7 mrem/h is attenuated by 36 cm of steel to about 1 mrem/h. At the target-far end of the insert a wall thickness of 24 cm steel is sufficient to contain the decay gamma flux.

5. Conclusion and Outlook

Neutronics calculations characterizing the radiation fields for the scenario of replacing a core vessel insert have been started. As first subtask, the activity buildup in the core vessel inserts was investigated and a cask design proposed. As next step, the radiation fields during operation will be extended throughout the shutter region to the outer edge of the target monolith. This will require more effort optimizing the variance reduction scheme of the Monte Carlo transport part, because isotope production rates will have to be calculated in large volumes throughout the shutter and the shaft.

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Table 1: Activity of core vessel inserts after 30 years of target operation at 2 MW and after one week of decay.

CVI	Type	Moderator	Activity (Curie)	Activity per unit mass (mCurie/gram)
1	multi	Top upstream decoupled liquid H_2	303	0.321
2	single		203	0.448
3	single		167	0.339
4	multi	Top downstream coupled liquid H_2	965	0.882
5	single		186	0.399
6	single		210	0.360
7	single	Bottom upstream decoupled H_2O	289	0.459
8	multi		672	0.661
9	single		345	0.684
10	single	Top upstream decoupled liquid H_2	390	0.622
11	multi		708	0.856
12	single		288	0.565
13	single	Bottom downstream coupled liquid H_2	178	0.392
14	multi		335	0.343
15	single		158	0.257
16	multi	Top upstream decoupled liquid H_2	276	0.286
17	single		197	0.405
18	single		149	0.308

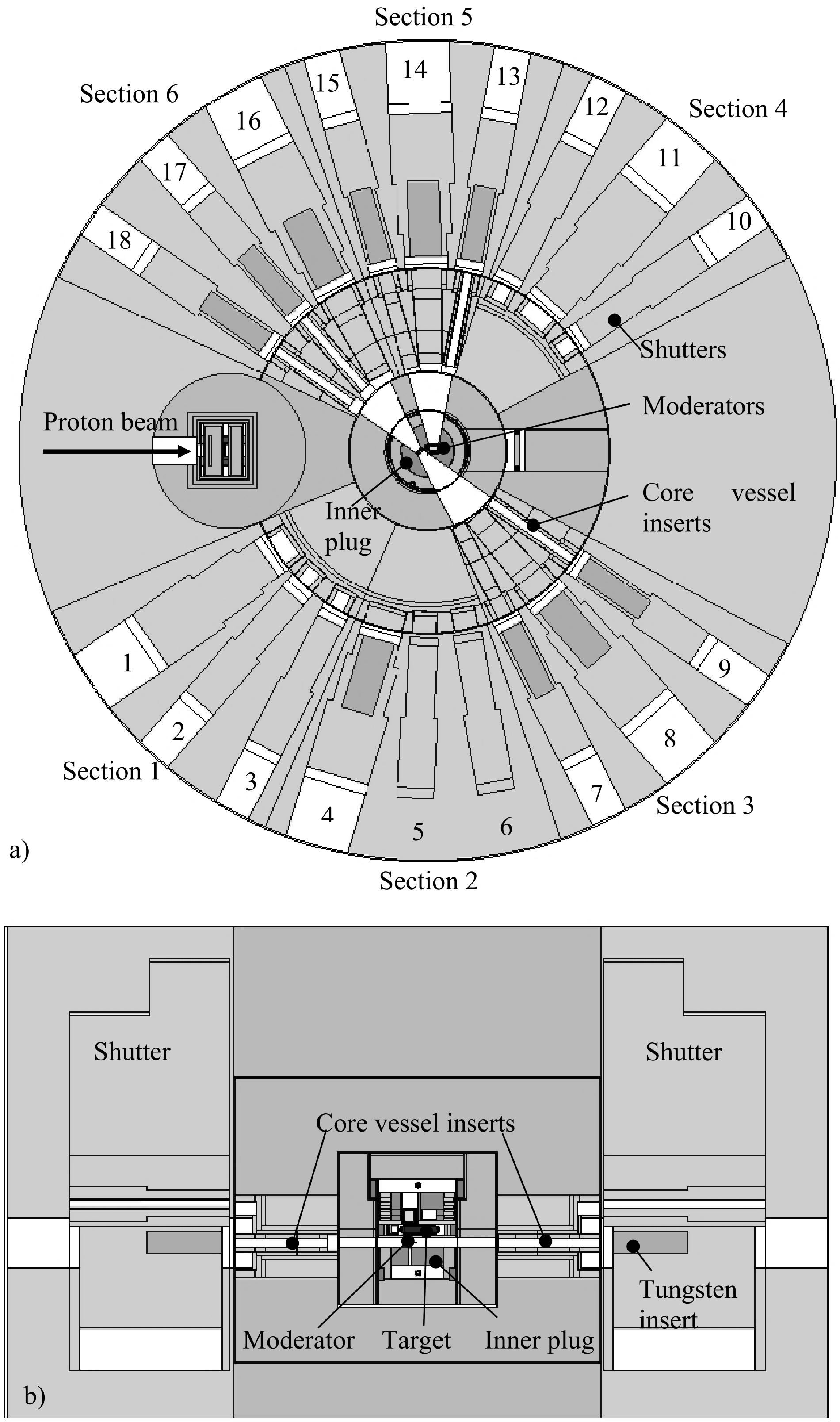

Figure 1: MCNPX model of SNS Target monolith: a) horizontal cut through the elevation of the moderators at the bottom of the target; b) vertical cut through beam lines 1 and 9. The target monolith diameter is about 10 meters.

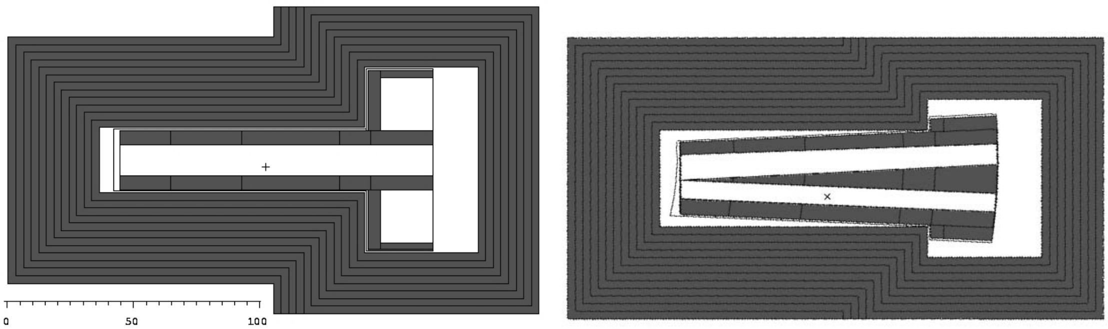

Figure 2: Vertical and horizontal cut through CVI-11 enclosed in a transport cask.

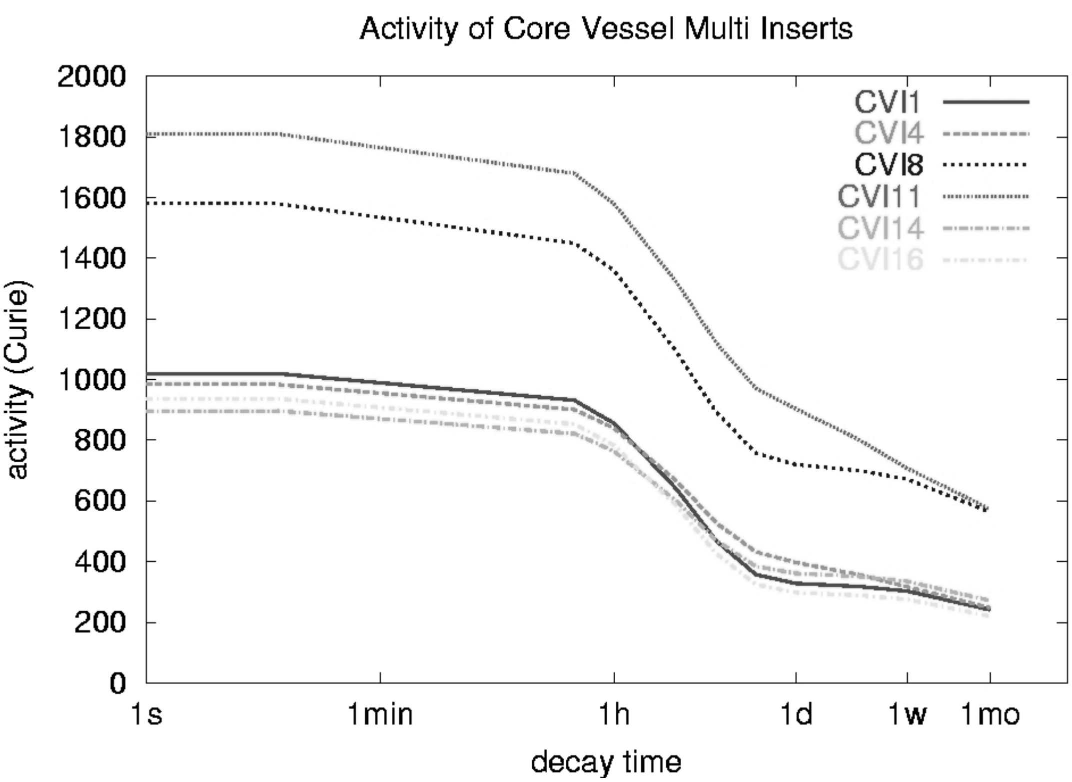

Figure 3: Decay of activity of multi-beam-line core vessel inserts after 30 years of target operation at 2 MW power for 5000 hours per year.

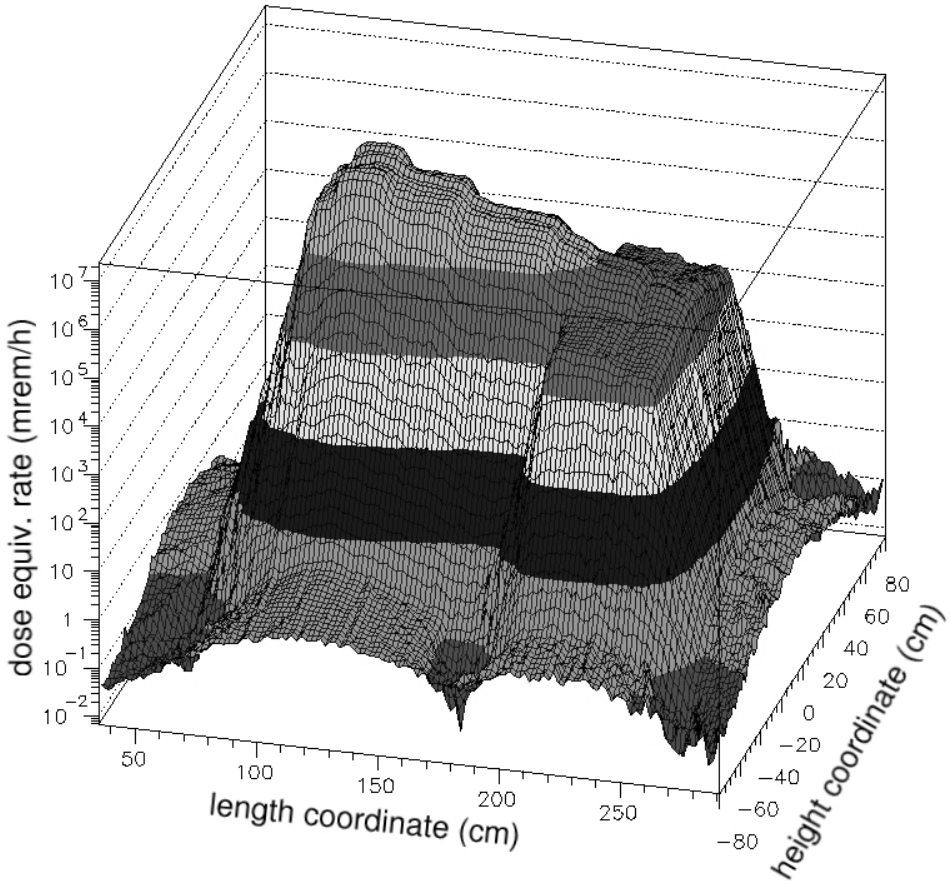

Figure 4: Dose equivalent rates in the central vertical plane of CVI-11 in a cask.