Egress Shielding Studies for the SNS Accelerator System

J. A. Bucholz, F. X. Gallmeier, I. Popova

Oak Ridge National Laboratory
P.O. Box 2008, MS6474
Oak Ridge, TN 37830
gallmeierfz@ornl.gov

Abstract- *The radiation transport and dose levels at four egresses located in the Spallation Neutron Source (SNS) accelerator system were analyzed based on controlled and uncontrolled beam losses in the accelerator system. A six-step hybrid Monte Carlo/Discrete Ordinates approach was employed to solve these problems using the Monte Carlo code MCNPX and the discrete ordinates code DORT along with the coupling tools MTD and DTD. MCNPX served to characterize the generation and leakage of secondary radiation from the accelerator and beam line structures, whereas DORT performed the analyses of the radiation fields (neutrons and gammas) in the accelerator tunnels and walkways of the egress. The coupling tools facilitated generation of the boundary sources from one transport step to the next step. In this effort, large detailed accelerator models were built for MCNPX to properly describe the different types of linac structures, the beam transport and focusing elements (dipoles, quadrupoles, sextupoles), and the beam collimators.*

The studies confirmed that the present egress designs were adequate to attenuate the dose in the linac tunnel of up to 100 rem/hr to a level of about 0.5 mrem/hr at the egress exit during normal operation. The egress in the accumulator ring is located at the entrance of the collimator section, a section with a high beam loss rate. For this reason, a dose level in the tunnel of 400 rem/hr was estimated along with a dose level at the exit of the egress of ~3 mrem/hr, which makes it a limited occupancy radiation area.

I. INTRODUCTION AND OBJECTIVE

In the Spallation Neutron Source (SNS)[1], a 2mA, 1GeV proton beam is accelerated in a linac, bunched in an accumulator ring, and directed to a target station, where it generates neutrons for neutron scattering experiments. During normal operation, a fraction of the beam is lost in the beam tunnels, where it produces a radiation field that is safely contained by sufficient bulk shield. These bulk shields are penetrated by many holes, some of the largest of which are emergency egresses for personnel. Two of these egresses are located in the linac, one in the transfer line to the ring (HEBT), and one in the ring. These egresses are designed as a four-legged maze, the radiation attenuation of which was investigated in shielding design calculations. The objective of the study was to evaluate the doses to be expected at the exits of the egresses, and

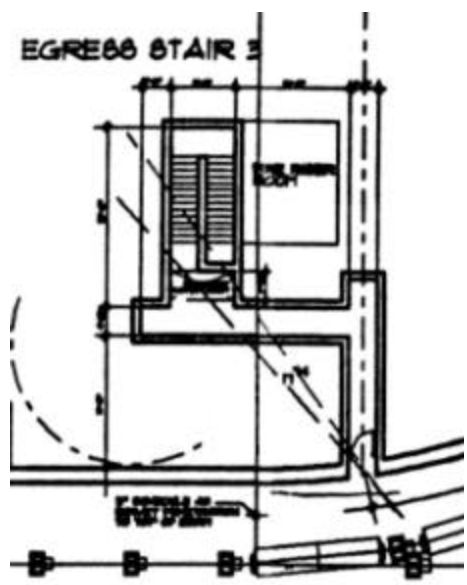

Fig. 1: Generic design of an egress in the SNS accelerator system.

to give recommendations for design changes to meet the dose requirement of below 0.25 mrem/hr for unlimited access by a non-radiological worker as given by the CFR-835 US-DOE guideline.

II. METHODOLOGY

Multi-legged penetrations through bulk shielding are among the most tedious radiation transport problems and need elaborate efforts for being solved. A combination of three-dimensional Monte Carlo analyses with the MCNPX[2] code and two-dimensional discrete ordinate analyses with the DORT[3] code has been applied that makes extensive use of the coupling tools MTD[4] and DTD[5]. The procedure is as follows:

(1) An initial MCNPX calculation tracks the modeled proton losses in the accelerator tunnel, generates the secondary radiation from the proton interactions with the accelerator structure, and transports this radiation throughout the accelerator tunnel. Besides calculating flux and dose values in the air zones of the tunnel, the code also writes a file of boundary crossing events at a user defined cylindrical surface. Because of the large-volume air zones in the accelerator tunnels (lead to long travel distances for the radiation and because of the extended sources, big MCNPX models are involved in the first part of the calculation that cover from 50 to 100 meters of accelerator structure and tunnel.

(2) The coupling code MTD creates a boundary source file for the discrete ordinates transport code DORT from the file of boundary crossing events.

(3) The DORT code performs the neutron and photon transport calculation through part of the tunnel air, the concrete walls and several meters into the earth berm in a cylindrical model. Therefore the rectangular tunnel was converted into an idealized cylindrical model conserving the absolute area of the tunnel cross section. The coupled neutron/photon HILO[6] cross sections were applied for all the DORT calculations.

(4) A second cylindrical model describes the first section of the egress, the air zone, the concrete wall and some earth berm. The DTD coupling code was used to generate a boundary source for the second DORT model from the angular flux matrix of the first DORT run.

(5) The second DORT calculation employs the boundary source obtained in (4), and performs the radiation transport in the first section. A forward biased quadrature set was used in order to give a refined description of the propagation of the radiation into the walkway.

(6) Three more sequences of DTD and DORT transport calculations make their way out and up the egress.

Performing a large fraction of the radiation transport with coupled 2D cylindrical calculations azimuthally smears out flux modulations that might occur around a circumference. These flux modulations are not considered significant, because they would normally be suppressed in the multi-bend configuration of the egress.

Neutron and gamma fluxes are folded with the flux-to-dose conversion factors distributed with the HILO cross-section library[6] to obtain equivalent dose results.

III. EGRESS MODELS

All egresses are designed as a four leg labyrinth. The first leg is perpendicular to the tunnel axis, the second leg leads upstream with regard to the beam direction, the third leg leads into a staircase, which is the final fourth leg. The cross-sectional areas and lengths of the legs are summarized in Table 1. The leg lengths are measured from the opening to the next wall, or to the exit. The first two long legs also include dead ends of 120 cm length to reduce scattering from one leg into the next. The egress in the ring differs from the generic design in that its second leg points downstream with respect to the proton beam direction rather than upstream.

For two-dimensional R-Z DORT analyses, the rectangular cross sectional areas of the legs of the egresses were converted to cylindrical areas. Some reasonable assumptions had to be made for section 3, the entrance into the staircase, and for section 4, the staircase itself. Both sections were modeled as cylinders of 2.40 m diameter, section 3 was shortened because most of its length contains the stair case shaft. All walk-way structures were assumed to be 30 cm ordinary concrete. For the first and second leg, a 30 cm thick layer of soil was included at the sides, with 100 cm and 40 cm of soil at the ends of the legs, respectively. Table 1 lists and compares the actual dimensions and the model dimensions.

Table 1: Air zone dimensions of the egress sections as given by the design drawing and as modeled in the two-dimensional DORT analyses.

Leg	Length (m)		Cross sectional area (m^2)	
	Design drawing	DORT Model	Design drawing	DORT Model
1	7.44	7.44	1.20 x 2.40	$\pi\, 0.96^2$
2	8.42	8.42	1.20 x 2.40	$\pi\, 0.96^2$
3	7.50	3.92	2.40 x 2.70	$\pi\, 1.20^2$
4	3.00	3.00	2.70 x 6.00	$\pi\, 1.20^2$

The dose levels in the egress walkways are driven by the neutron and gamma fields in the respective accelerator sections. For this reason, extensive models were used to be able to characerize the radiation fields of the linac, the HEBT, and the ring systems as part of the egress studies.

IV. BEAM LINE MODELS

A complete decription of the linac models is given in a seperate paper at this conference[7].

The HEBT model[8] describes the 99 meter-long tunnel that starts downstream of the long straight linac accelerator and exits into of the accumulator ring. The first 42 meters of the HEBT tunnel is a long straight section housing 6 pairs of quadrupole magnets and correctors, followed by a collimator, another quad/corrector pair, a second collimator, and 4 more pairs of quadrupoles and correctors. The second 57-meter section is curved over a 90-degree arc, with a beam line radius of about 36 meters. This curved section houses 8 large dipoles, with a quad/corrector pair between each dipole. The 76-cm-thick concrete walls forming the HEBT tunnel are such that, inside the tunnel is 5.2-meters wide and 5.5 meters high, with the centerline of the beam being 127 cm above the floor and 177 cm from the inside from the outer tunnel wall. The large dipole magnets have an overall length of 5.7 meters, and are comprised of two sets of lage horizontal copper windings with iron cores – one above and one below the beam line. The dipoles have a thick steel support structure on the top and bottom which run almost the full length of the dipole, as well as a thick back shielding plate facing the inner wall of the tunnel; the fourth side facing the outer wall of the tunnel is open. The smaller quadrupoles each have 4 copper coils with individual iron cores, where the planes and the windings are normal to the beam, but where the coils themselves are physically rotated 45 degrees relative to the horozontal and vertical planes. The four coils are shielded and supported by a thick external iron structure measuring 63-cm square on the outside and 77 cm in length. The correctur units downstream from the quadrupoles are smaller still and are about 41 cm square by 35 cm long. The collimators are more complex, heavily shielded, 2-meter-diameter units with an overall length of 2.6 meters. The beam enters a large-diameter hole in the 66-cm-thick upstream iron shield, then passes through a thin platinium scraper as it enters a smaller diameter hole going through a 15-cm-long water-cooled section, and 1.2-meter-long particle bed, before emerging trough the larger opening in the iron shield further downstream. Radially, the particle bed is 21.5 cm thick, with iron shielding extending beyond that to an outer radius of about 1 meter.

The accumulator ring consists of four straight sections: the injection section, the collimation section, the extraction section and the bunching section. These are connected with 90 degree curved sections. The egress in the ring is located at the beginning of the collimation section. The collimation section is to strip the halo from the beam, which is for the reason a high radiation area. A complex MCNPX geometry model[9] of all components comprising the collimator section and the adjacent curved sections has been developed for the egress dose analyses, and to address other problems. The model includes the 70-cm-thick tunnel walls surrounded by the soil. The ring tunnel is 550 cm high and 520 cm wide. The center of the proton beam line is located 177 cm from the inner sidewall and 127 cm from the floor. There are 8 dipoles and 9 quadrupole/corrector pairs (as described above) lined up in each curved section of the beam line. This equipment has been modeled using the MCNPX repeated structure capability, which allows us to describe each component in detail only once, and then to rotate and to shift the component multiple times to the needed locations. All components in the straight collimation line are modeled directly and consecutively along the proton beam. It contains one scraper/collimator, a duplet, a second collimator, a second duplet and a third collimator. Each duplet consists of a corrector and two quadrupoles. The collimators are similar to the HEBT collimators, but with larger apertures to accommodate the extended beam cross section in the ring.

V. DESCRIPTION OF THE CALCULATIONS

The radiation environment at the entrance is different for each egress, characteristic to the intensity of the proton losses, the proton energy, the source distribution and design quantities like the material composition and masses around the beam. Therefore the whole sequence of calculations has to be repeated for each egress.

5.1 Egresses 1 and 2

Egress 1 provides an exit from the linac tunnel near the end of the coupled cavity linac (CCL) section, while egress 2 an exit at the middle of the high beta superconducting linac (SCL).

As driving force for the radiation environment, a line loss of 1W/m was assumed in the LINAC models at an angle of 2.5 degrees relative to the beam centerline . For the MCNPX step of the calculation, a full CCL model[7] was employed for egress 1 with proton source energies ranging from 85 to 185 MeV, while in the 55 meter superconducting linac model (SCL) with egress 2, the proton source energies ranged from 540 to 730 MeV.

In the MCNPX calculation, the boundary crossing events for neutrons and photons were scored on a cylindrical surface with 0.60-meter radius centered at the beam axis for a 3.20-meter-long section of the geometry (only at the mantel surface of the cylinder). The first DORT calculation applied the boundary source generated from the MCNPX boundary crossing events as an internal boundary source and assumed periodic boundary conditions at the bottom and top outer boundaries of the model. This procedure was chosen to limit the length of the first DORT model to the physical size needed for coupling to the second DORT model, and to avoid the flux drop off at vacuum boundaries.

The radiation transport into the egress was performed as outlined in Sect. II.

5.2 Egress 3

Egress 3 is located at the beginning of the HEBT bend near the end of the first dipole magnet. As the driving source of radiation, a line proton beam loss of 1W/m was assumed in the beam lines in addition to 2 kW loss terms at the entrance of each collimator.

Boundary crossing events were scored in the MCNPX calculation at on a cylindrical surface with 1.25 meter radius along a 6.40-meter-long section of the beam line and the structure near the egress, and at the planes defining the beginning and the end of the 6.40-meters-long section as shown in Fig. 2. At the planes, events are only scored that are outside the cylindrical surface with 1.25 meters radius. Internal boundary sources were then constructed from these boundary-crossing events for use in a cylindrical DORT model of this tunnel section. The DORT model extended radially from 1.25 m to 4.40 m including a tunnel air zone up to radius 2.90 m, a 46-cm-thick concrete wall, and earth berm. Because of the irregular beam losses, no use could be made of periodic boundary conditions, as was done for the analyses of egress 1 and 2. Instead the axial boundary sources were explicitly modeled.

The radiation transport into the egress was performed as outlined in Sect. II.

5.3 Egresses 4

Egress 4 is located at the exit of the first bend in the accumulator ring that leads into the collimator section.

The MCNPX calculation included 1W/m proton beam line sources in the repeated dipole and quadrupole structure of the first bend and in the straight line of the collimation section. In addition, 2kW beam losses were assumed at each of the three collimators in the collimation section.

Boundary crossing events were scored in the MCNPX calculation similar to the case egress 3 but for a tunnel section approximately 10 meters long. Three coupling boundary source surfaces are positioned near the egress, outside of the beam line and structures as shown in Fig. 3. A cylindrical surface with a radius of 126 cm is limited by two planes in axial direction. This surrounds the scraper/collimator in the straight line region, the adjacent quadrupole/corrector pair, a dipole and part of the next quadrupole/corrector pair in the curved section entering the collimator section. The second and third surfaces are planes, which start from the ends of the cylinder and expand to the outer edges of the tunnel wall.

This means that the first DORT calculation also covered a tunnel section of 10 meters. The radiation transport into the egress was performed as outlined in Sect. II.

VI. RESULTS AND DISCUSSION

The dose levels in the walkways are presented in Figs. 5 to 8 for egress 4, and are representative for all egress analyses. Fig. 4 provides a good overview of the dose levels to be expected due to backscattering from the collimators, and is in good agreement with results obtained directly from the MCNPX calculaion.The equivalent dose levels at specific locations in the egresses were extracted from the plots and are summarized in Table 2. The dose at the exit of the egress scales in all cases (to first order) with the dose at the entrance. The doses at the exit of egress 3 and 4 exceed the limit of 0.25 mrem/hr because of the vicinity of the collimators. These will need further attention.

Table 2: Equivalent dose levels at specific locations in the 4 egresses of the SNS Accelerator System.

Location	Equivalent Dose (mrem/hr)			
	Egress 1	Egress 2	Egress 3	Egress 4
Entrance leg 1	40,000	50,000	100,000	400,000
Entrance leg 2	400	800	2,000	5,000
Entrance leg 3	7	10	40	200
Entrance leg 4	0.7	1	4	20
Exit egress	0.1	0.2	0.6	3

VII. REFERENCES

1. National Spallation Neutron Source Conceptual Design Report, Oak Ridge National Laboratory, NSNS/CDR-2/VI, 1997.
2. H.G. Hughes et al, „MCNPX for Neutron-Proton Transport," International Conference on Mathematics & Computation, Reactor Physics & Environmental Analysis in Nuclear Applications, Americal Nuclear Society, Madrid, Spain, September 27-30, 1999.
3. W. A. Rhoades, and R. L. Childs, „The DORT Two-Dimensional Discrete Ordinates Transport Code," Nucl. Sci. & Engr. 99, 1, pp. 88-89 (May 1988).
4. F. X. Gallmeier, and R. E. Pevey, „Creation of a Set of Interface Utilities to allow Coupled Monte carlo/Discrete Ordinates Shielding Analyses," Third International Topical Meeting on Nuclear Applications of Accelerator Technology, American Nuclear Society, Long Beach, November 14-18, 1999.
5. R. A. Lillie, „DTD: A Coupling Code for Two-Dimensional R-Z Cylindrical Geometries, Trans. Am. Nucl. Soc. 61, 381, 1990.
6. R. G. Alsmiller jr., J. M. Barnes, J. D. Drischler, „Neutron-Photon Multigroup Cross Sections for Neutron Energies less than or equal to 400 MeV (Revision 1)", ORNL- TM 9801, February 1986.
7. F. X. Gallmeier, „Calculations of operational and residual doses for the SNS linac", Fifth International Topical Meeting on Nuclear Applications of Accelerator Technology, American Nuclear Society, Reno, November 2001.
8. J. A. Buchholz, „Determination of Proton, Neutron, and Gamma Boundary Source Terms for Subsequent Egress Shielding Analyses in the SNS HEBT Tunnel", UT-Battelle, ORNL/SNS-106100200-TR0017-R00, September 2000.
9. I. I. Popova, and J. A. Bucholz, Neutron and Gamma Source Terms around the Egress Adjacent to the SNS Accumulator Ring", UT-Battelle, ORNL/SNS-106100200-TR0020, September 2000.

SNS is managed by UT-Battelle, LLC, under contract DE-AC05-00OR22725 for the U.S. Department of Energy.

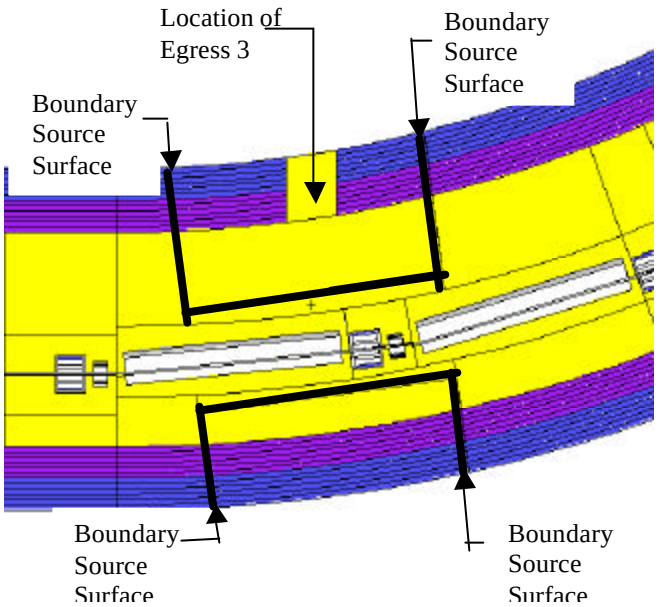

Fig. 2. Location of the boundary source in the MCNPX HEBT geometry for the dose analysis of egress 3 .

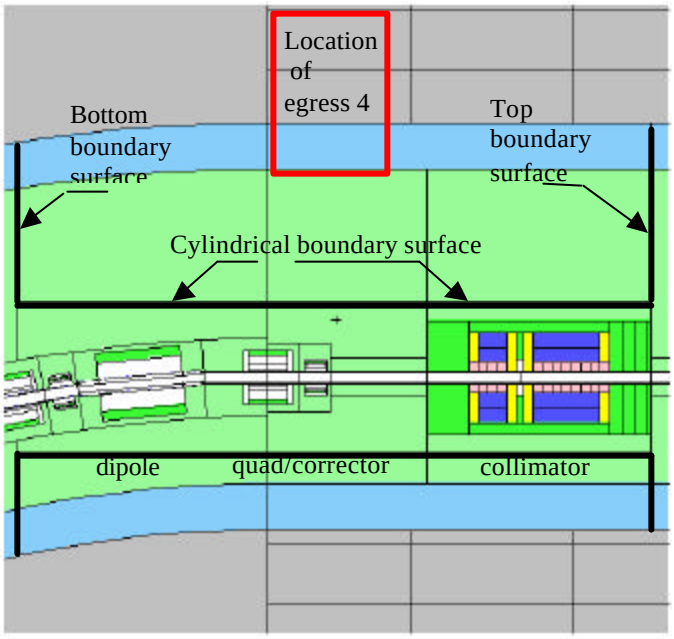

Fig. 3. Location of the boundary source in the MCNPX ring geometry for the dose analysis of egress 4 .

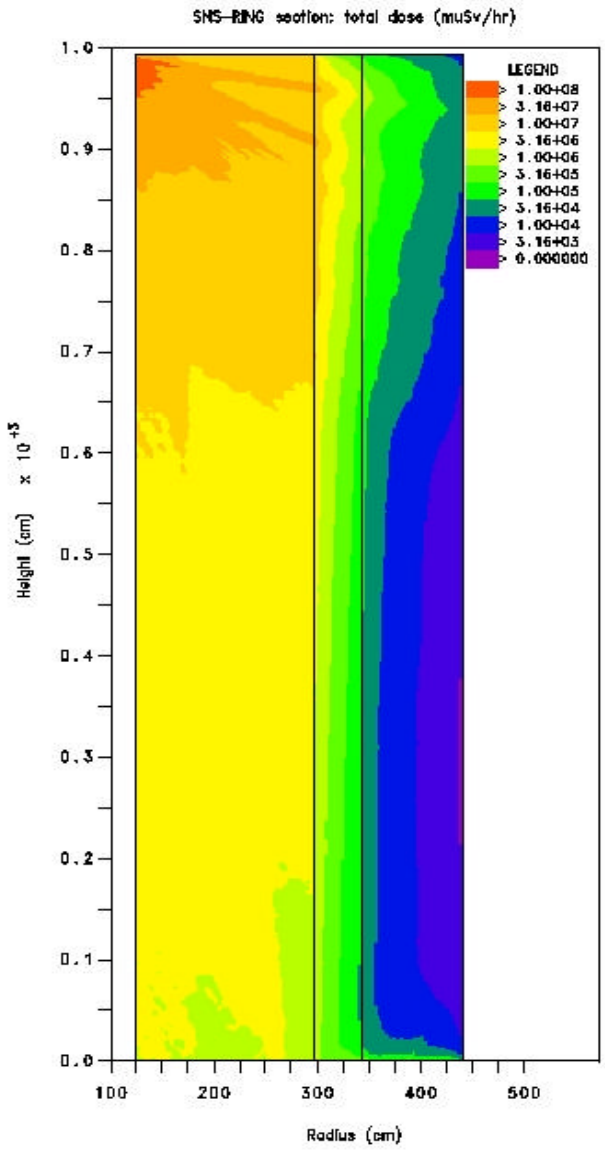

Fig. 4: Equivalent dose plot for the tunnel segment adjacent to egress 4. Material boundaries are marked with solid black lines.

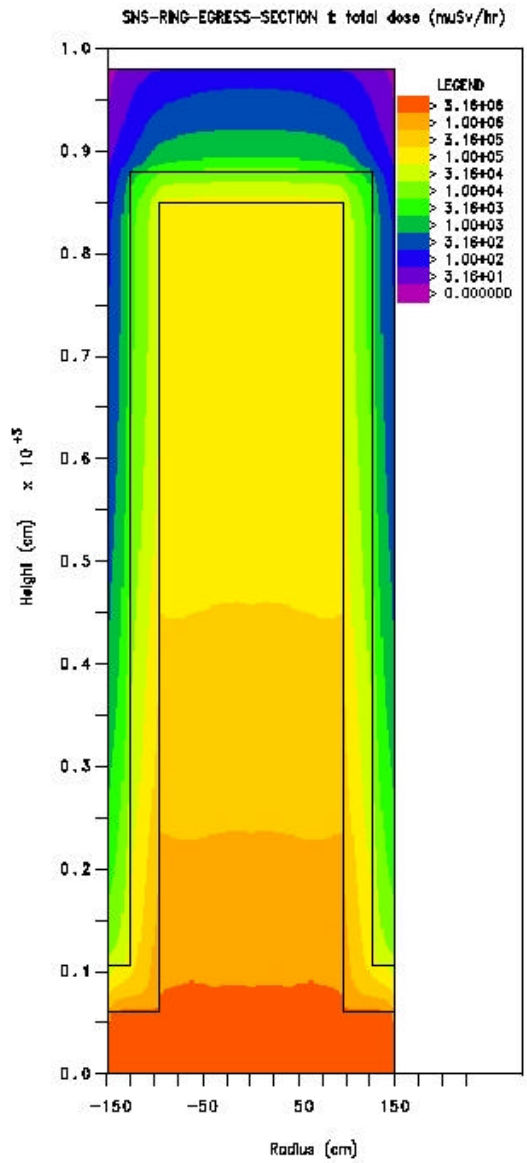

Fig. 5: Equivalent dose plot for leg 1 of egress 4. Material boundaries are marked with solid black lines.

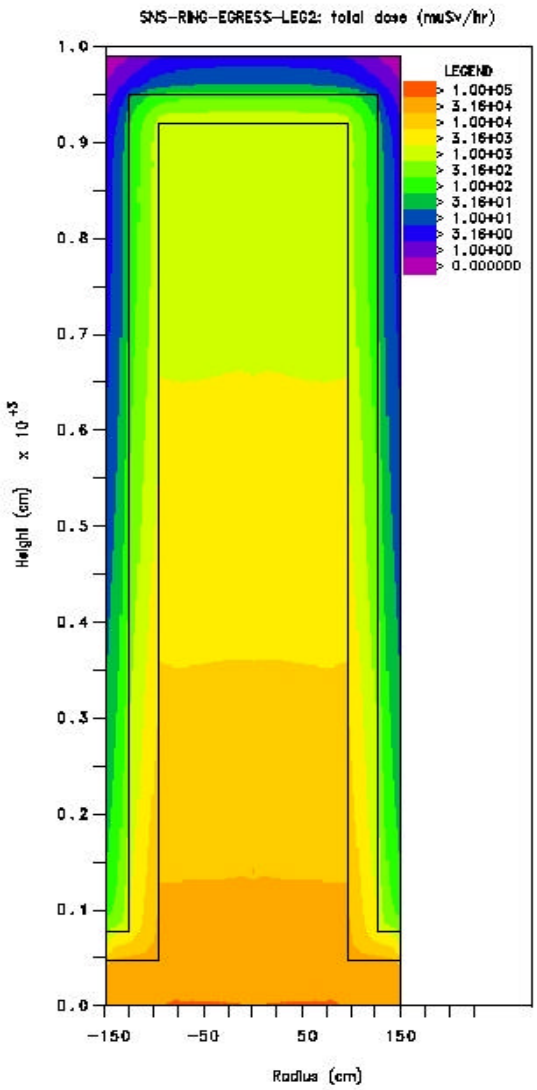

Fig. 6: Equivalent dose plot for the leg 2 of egress 4. Material boundaries are marked with solid black lines.

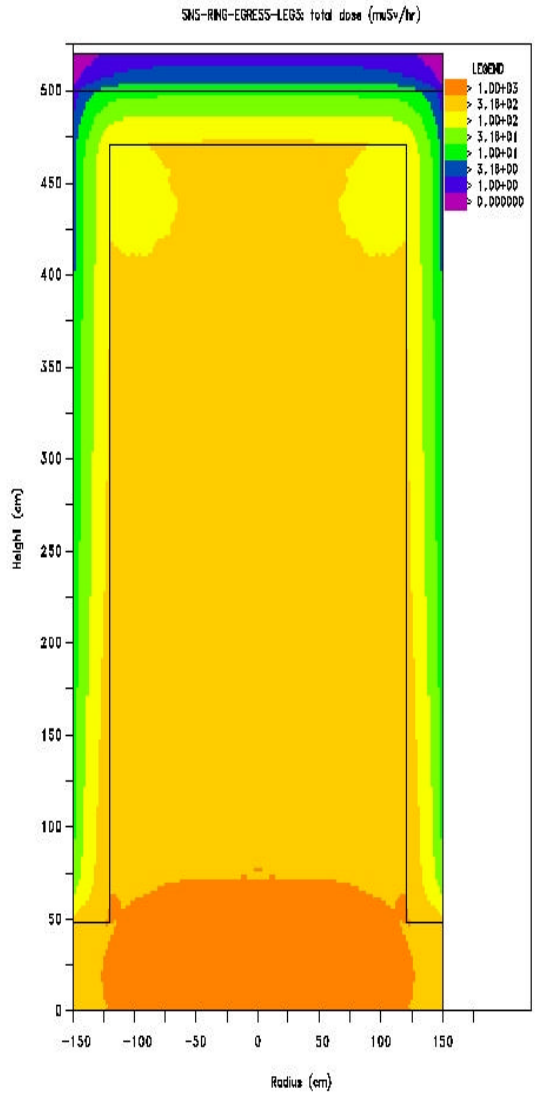

Fig. 7: Equivalent dose plot for the leg 3 of egress 4. Material boundaries are marked with solid black lines.

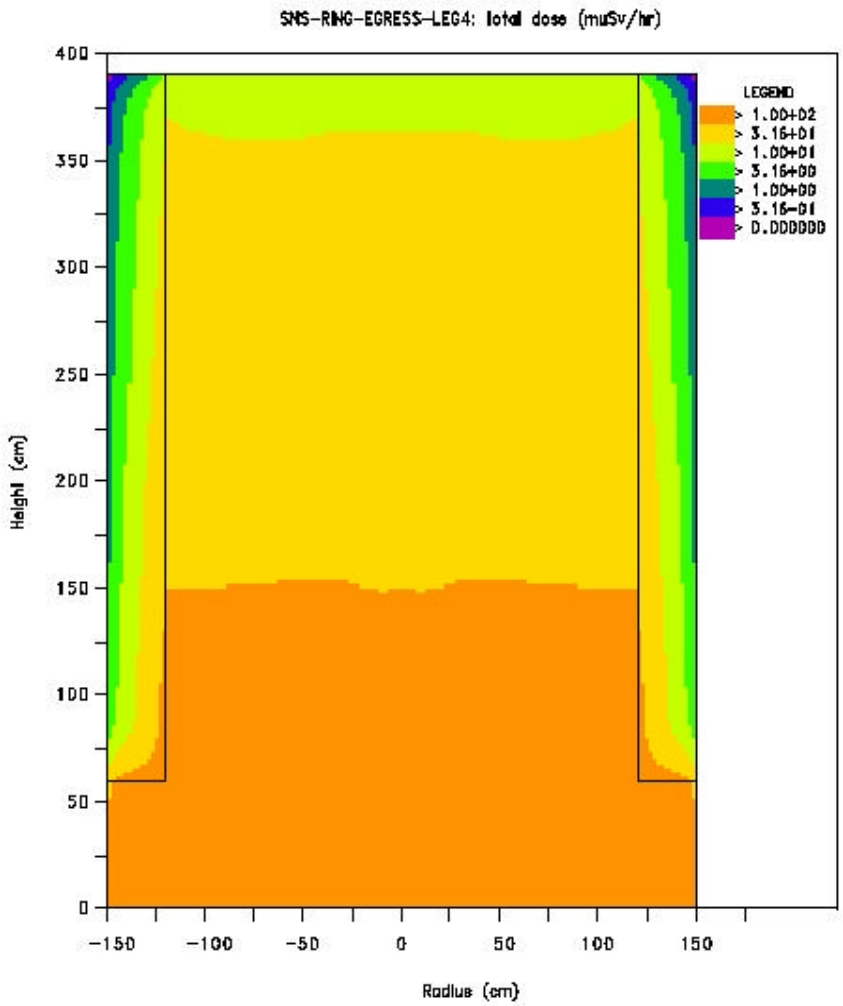

Fig. 8: Equivalent dose plot for leg4 (staircase) of egress 4. The material boundaries are marked with solid black lines.