Shielding Calculations For The SNS Proton Beam Transport System

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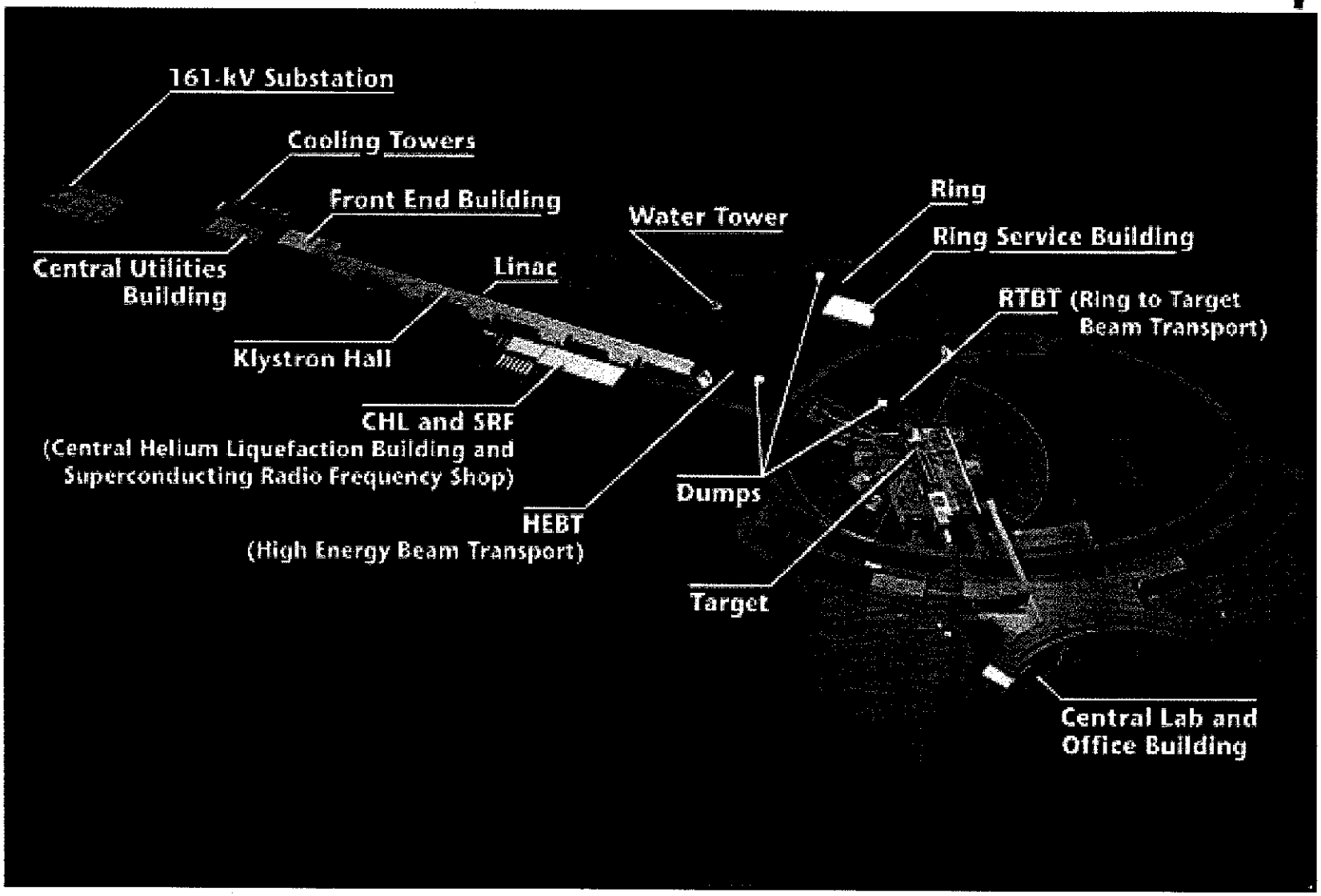
The SNS Neutronics, Shielding & Activation Analyses Focused On One Key Objective

- **Generate the required neutronics, shielding and activation design data so that key decisions can be made as to the baseline geometry and materials for the design of the *complete* SNS facility.**
- **The analyses need to address:**
  - **> Normal operation,**
  - **> Credible fault scenarios, and**
  - **> Shutdown/maintenance conditions.**

The Spallation Neutron Source Project



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The SNS Baseline Technical Design Parameters

Proton beam power on target	2.0 MW
Proton beam energy on target	1.0 GeV
Average proton beam current on target	2.0 mA
Pulse repetition rate	60 Hz
Peak ion source H- front end current	52 mA
Front-end and linac length	332 m
Drift tube linac (DTL) output energy	87 MeV
Number of DTL 402.5-MHz, 2.5-MW klystrons	6
Coupled cavity linac (CCL) output energy	186 MeV
Number of CCL 805-MHz, 5.0-MW klystrons	4
Number of SRF Cryomodules	26
Medium beta cryomodules	11
High beta cryomodules	15
Number of SRF 805-MHz, 0.4-MW klystrons	92
Linac beam duty factor	6.0 %

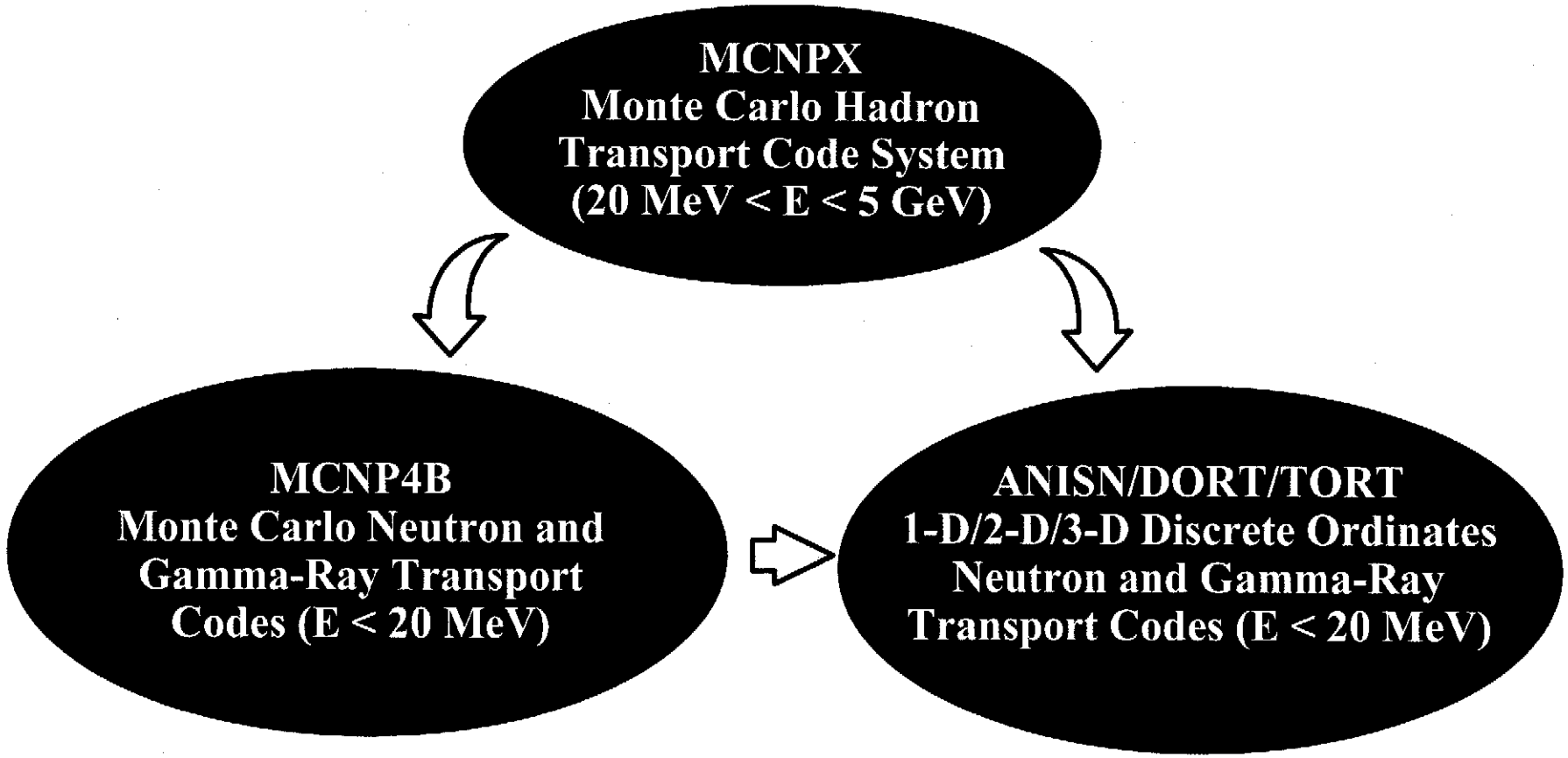
The SNS Baseline Technical Design Parameters

HEBT length	170 m
Accumulator ring circumference	248.0 m
Ring orbit rotation time	945 ns
Number of injected turns	1060
Ring fill time	1.0 ms
Ring beam extraction gap	250 ns
RTBT length	162 m
Protons per pulse on target	2.08E+14
Protons per second on target	1.25E+16
Proton pulse width on target	695 ns
Target material	Hg
Number of ambient/cold moderators	1/3
Number of neutron beam shutters	18
Number of neutron beam lines	24
Initial number of instruments	10

Primary Computational Tools Utilized

- The MCNPX code system
  - > High energy (E>20 MeV) hadron transport (protons, charged pions, muons, neutrons, etc.)
  - > Electron, positron, and photon transport
  - > Low energy (E<20 MeV) neutron & photon transport
  - > ENDF/B-VI cross-section data (20 MeV or 150 MeV cutoff)
- The DOORS v3.2 code system (ANISN, DORT & TORT)
  - > Multi-dimensional discrete-ordinates codes
  - > ENDF/B-V and ENDF/B-VI cross-section data
  - > HILO2K, DABL69, BUGL96 libraries
- The ORIHET95 depletion and isotope production code
  - > Nuclide library data - Table of Isotopes, 7th edition
  - > Gamma-ray library data - Darmstadt Gamma-Ray Atlas
  - > Coupling to CINDER90 nuclide and gamma-ray libraries

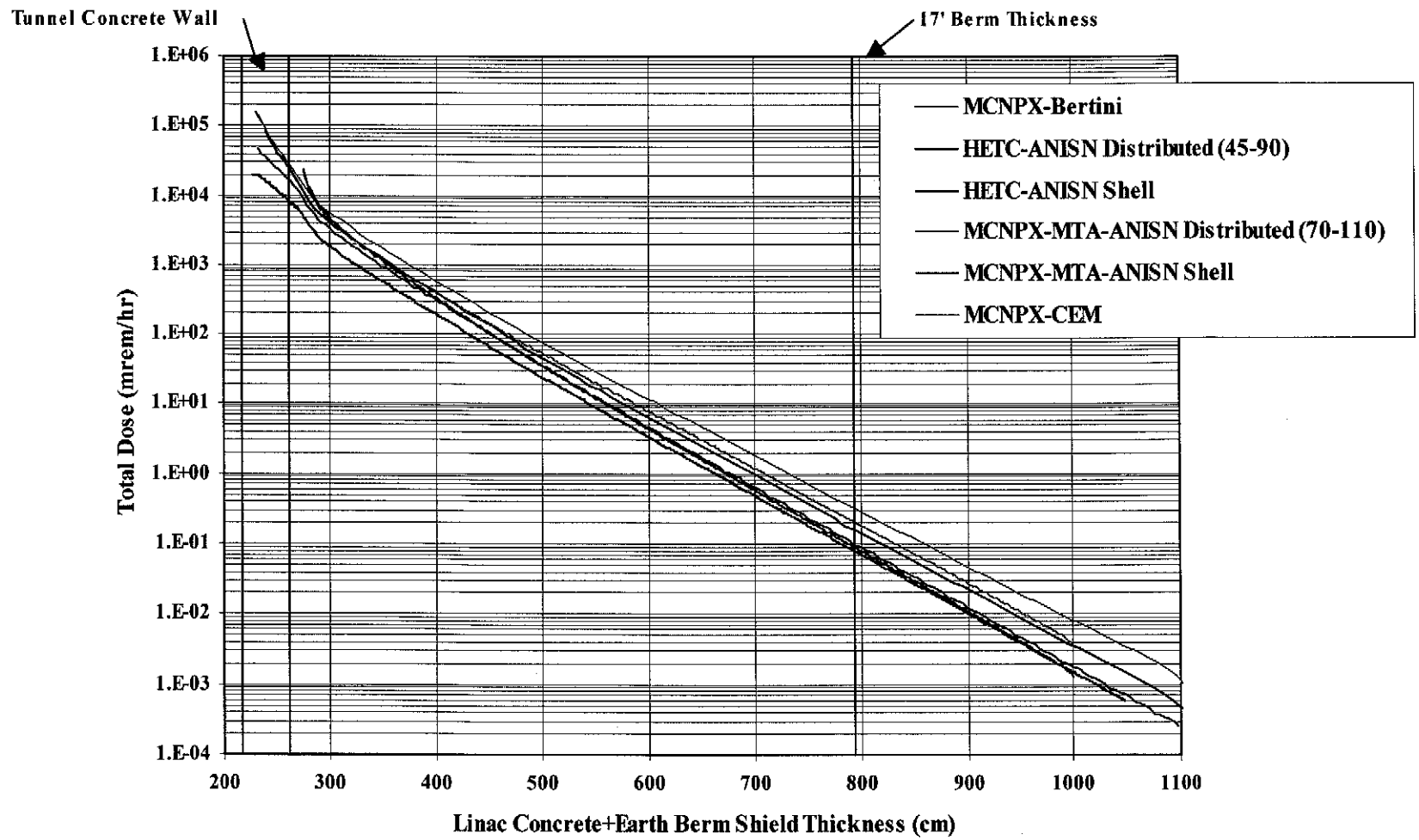
To Meet Project Schedule Timelines, A Combination Of Monte Carlo And Discrete Ordinates Codes Are Needed For The Complete Radiation Transport Analysis Of The SNS



A Suite Of Monte Carlo To Discrete Ordinates Coupling Codes Were Developed

- MTA – Monte Carlo To ANISN
  - > Generates input for ANISN 1-D Discrete Ordinates code
  - > Sources for planar, cylindrical, or spherical modes
- MTD – Monte Carlo To DORT
  - > Generates input for DORT 2-D Discrete Ordinates code
  - > Sources for x-y planar or r-z cylindrical modes
- MTT – Monte Carlo To TORT
  - > Generates input for TORT 3-D Discrete Ordinates code
  - > Sources for x-y-z planar or r-Θ-z cylindrical modes
- Generate distributed isotropic volume sources or directional flux shell sources
- Utilize the newly developed HILO2K library
  - > Maximum neutron energy of 2 GeV
  - > Improved energy and angular resolution of high energy production data
  - > Increased the number of nuclides in library

Comparison of Monte Carlo and Coupled Monte-Carlo/Discrete Ordinates Calculations of the SNS Linac Shield Berm



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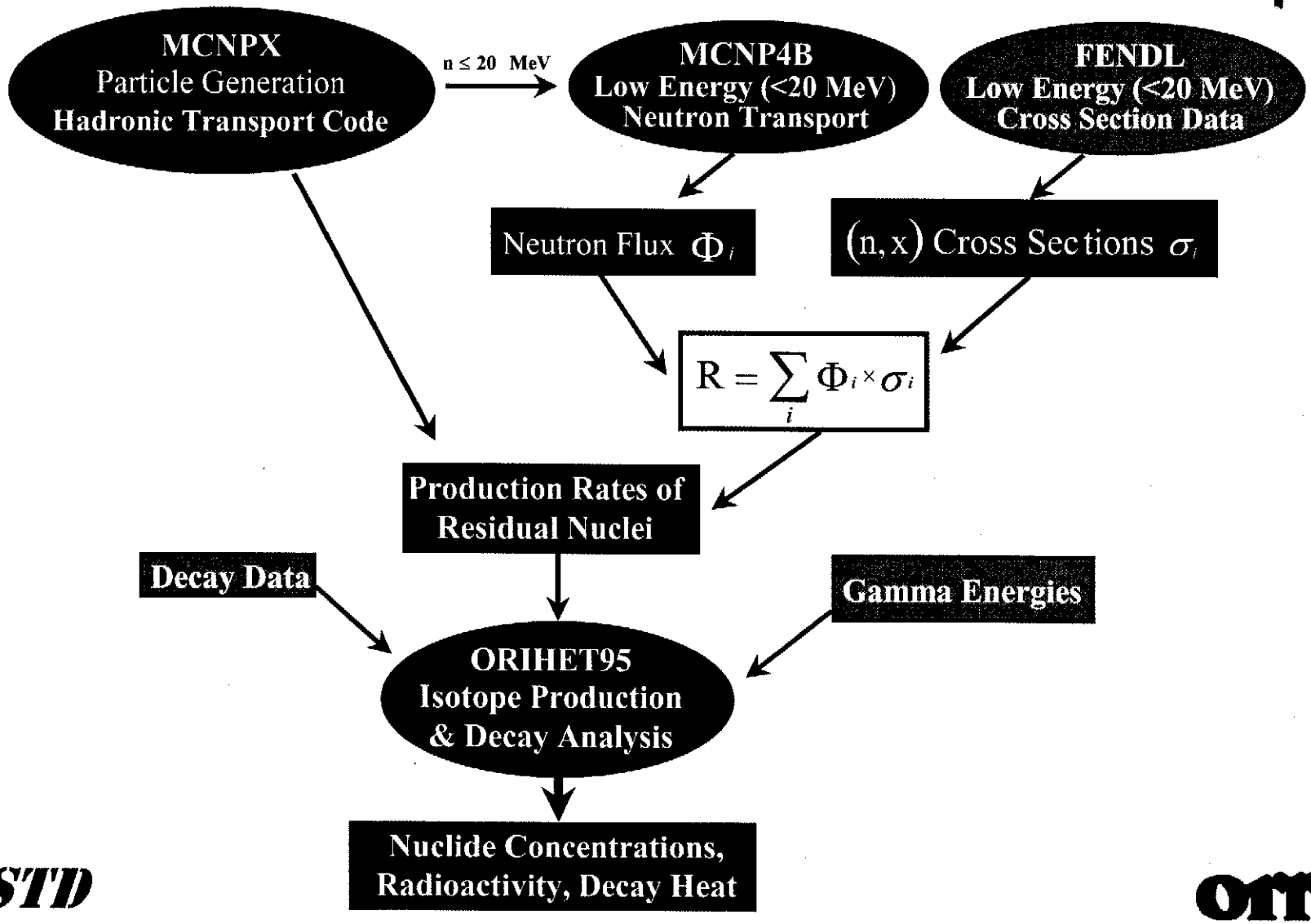
Flow Diagram Of The ORNL Activation Analysis System (AAS)



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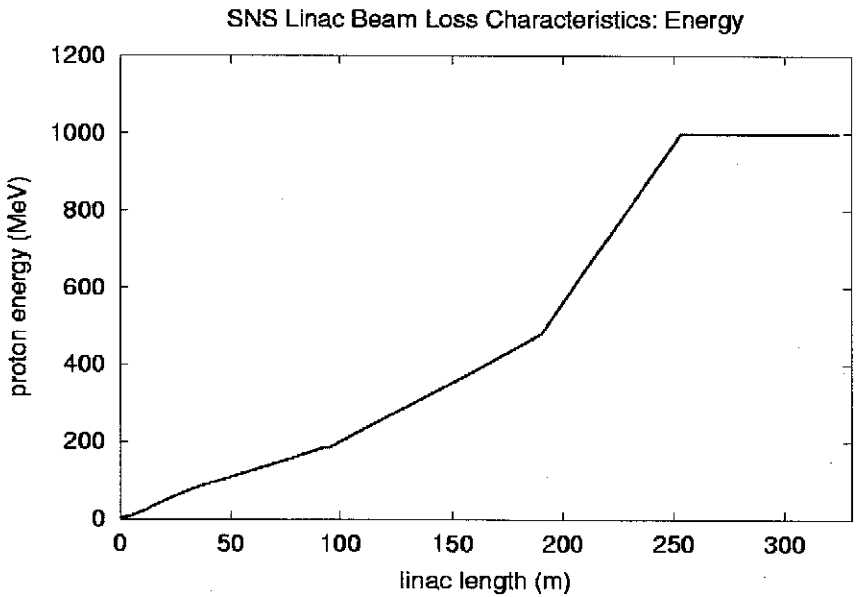
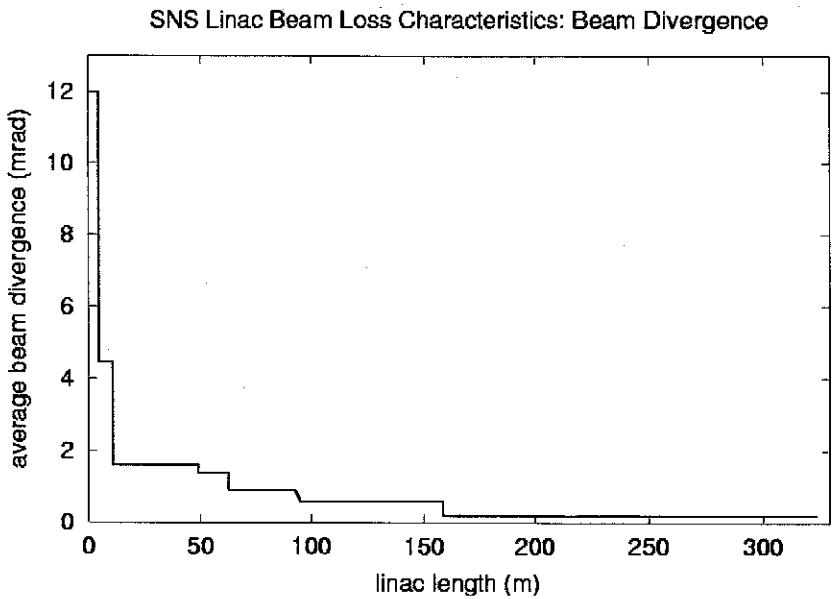
Example Analyses Performed To Support The Design Of The SNS Accelerator System

- Operational and residual doses for the linac
- Full beam loss accident in the HEBT arc
- HEBT shield labyrinth design calculations
- Ring collimator section skyshine analysis
- Personnel and truck egress design studies
- Target/PBW back-streaming into the RTBT

The SNS Linac Beam Energy And Beam Divergence Characteristics As A Function Of Linac Length



N. Catlan-Lasheras, et.al., "Accelerator Physics Model Expected Beam Losses Along the SNS Accelerator Facility During Normal Operation," SNS/AP Technical Note 07, UT-Bettelle, LLC, Oak Ridge, TN (March, 2001)



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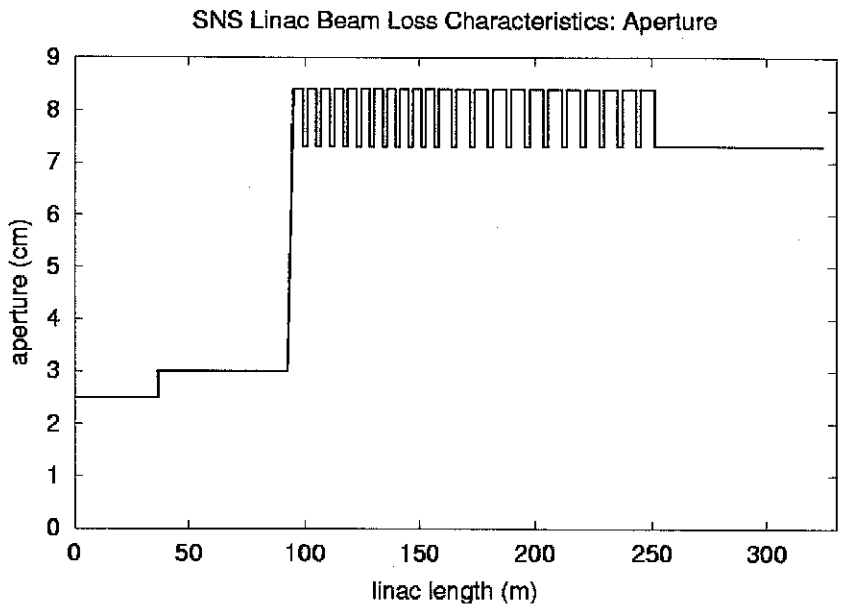
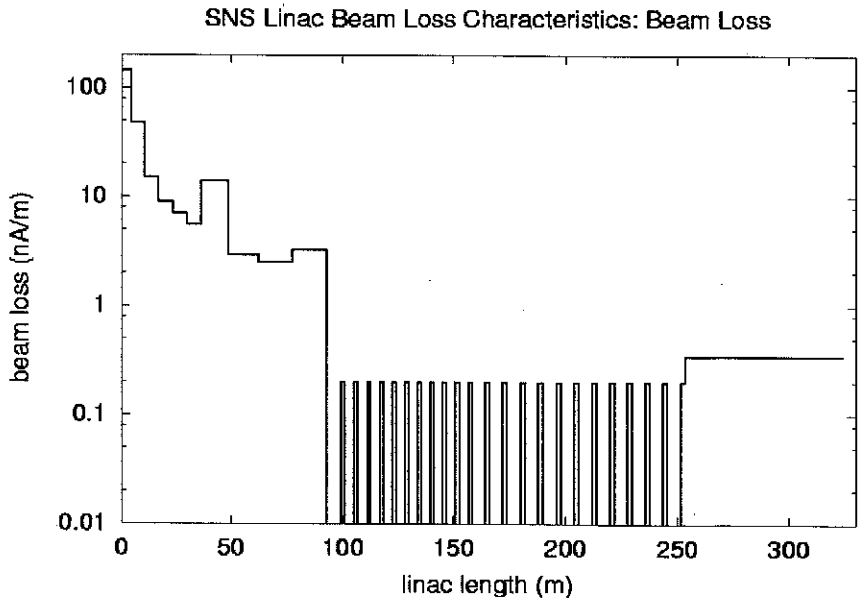
The SNS Linac Aperture And Beam Loss Characteristics As A Function Of Linac Length





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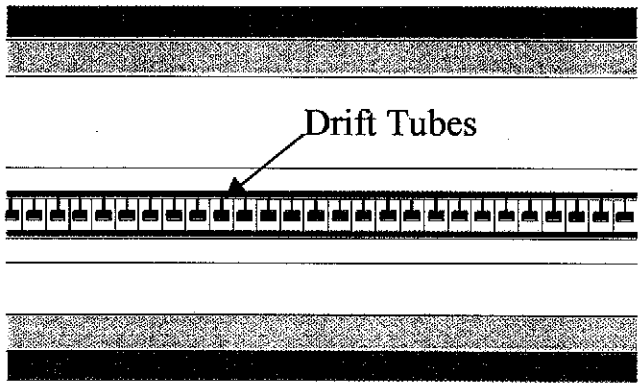
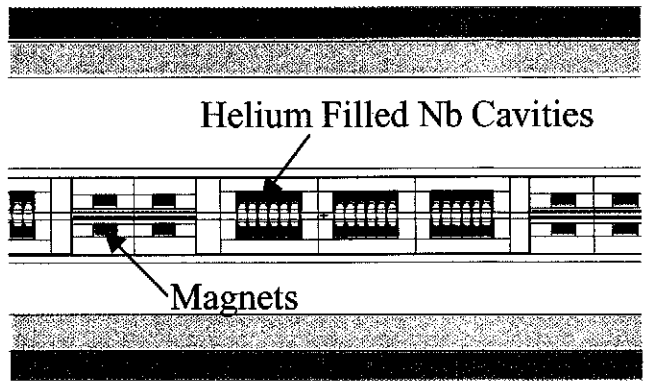
MCNPX Models of the SNS Linac

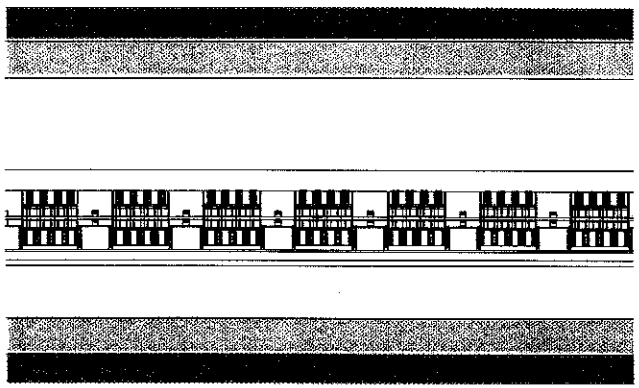
DTL Model



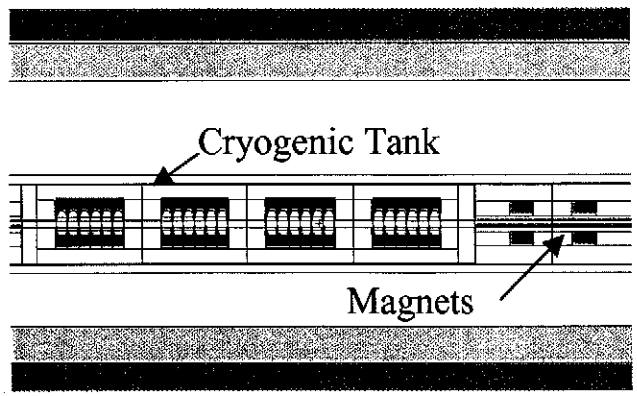
Low Beta SCL Model



CCL Model

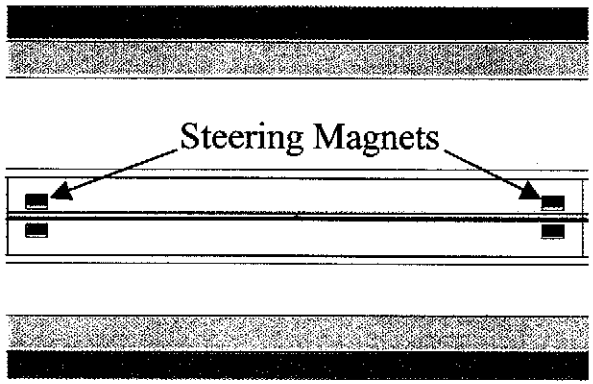


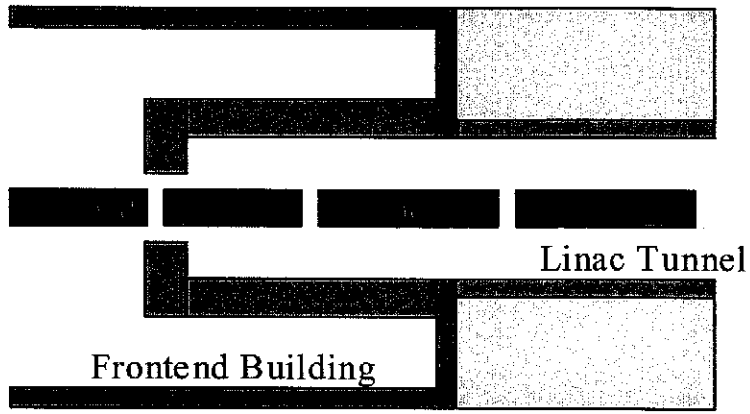
High Beta SCL Model



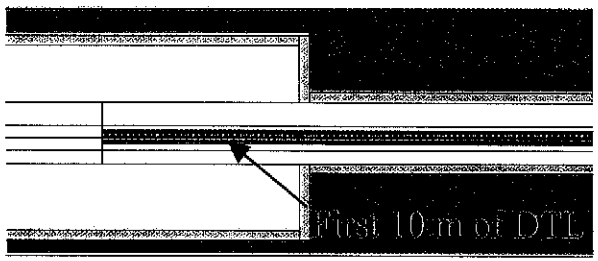
MCNPX Models of the SNS Linac

Spare SCL Period



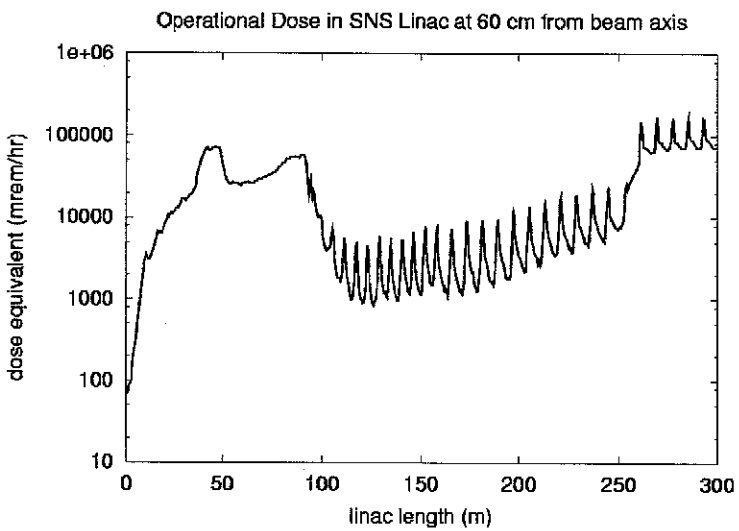


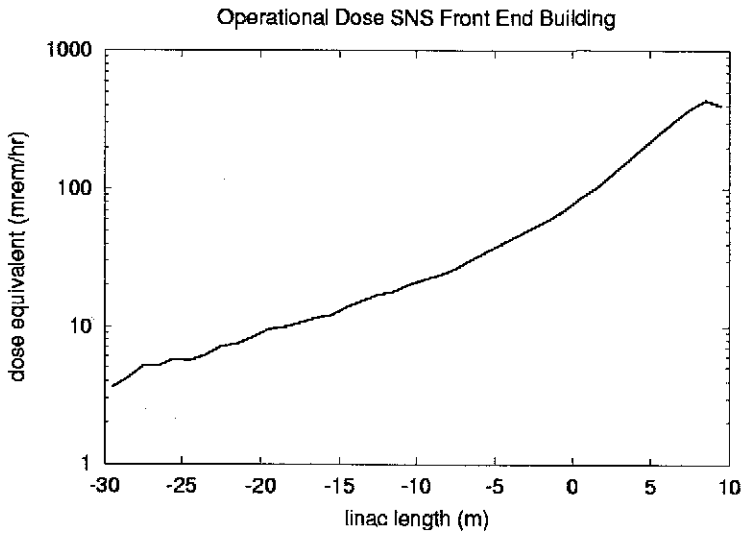
Front End Building

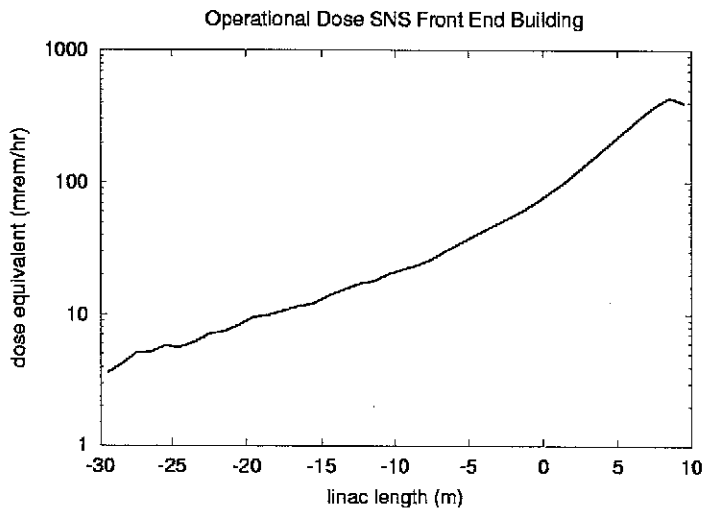


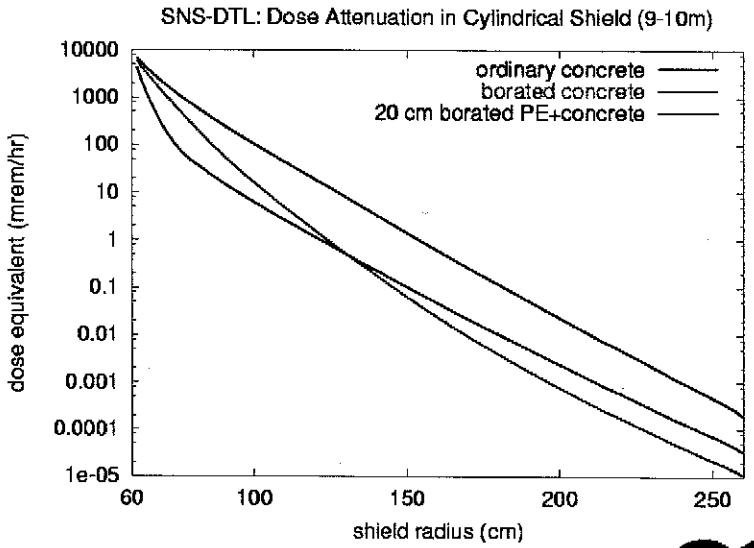
Schematic Diagram of the Front-end building and linac tunnel model used to determine additional shield requirements in this area. Concrete structures are colored in grey, and soil is light brown.

Operational Dose In The SNS Linac And Front End Building Due To Anticipated Beam Losses









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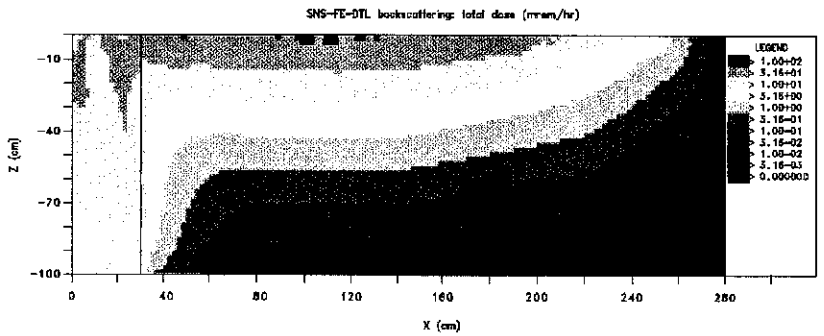
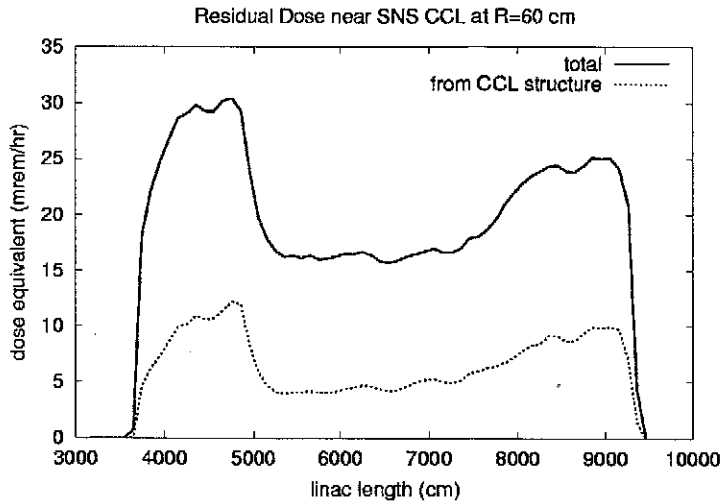
Front End Building Shield Design And Residual Doses In The SNS Linac Due To Anticipated Beam Losses (1 Foot Distance, 30 years Operation, 1 hour Decay)

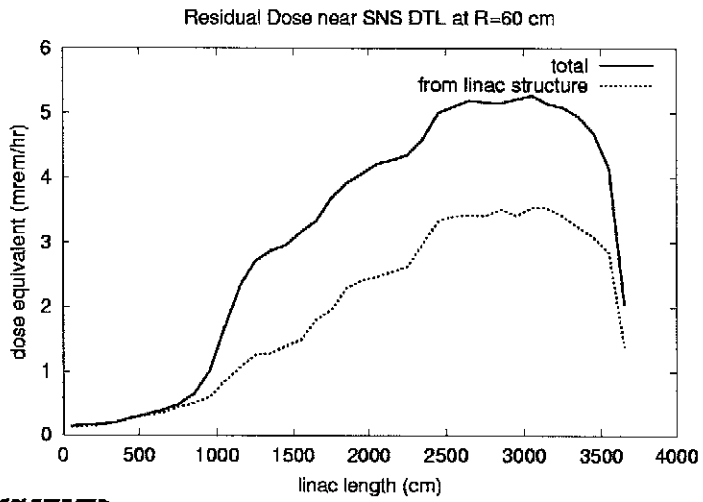
Dose Contour Through DTL Shield Wall

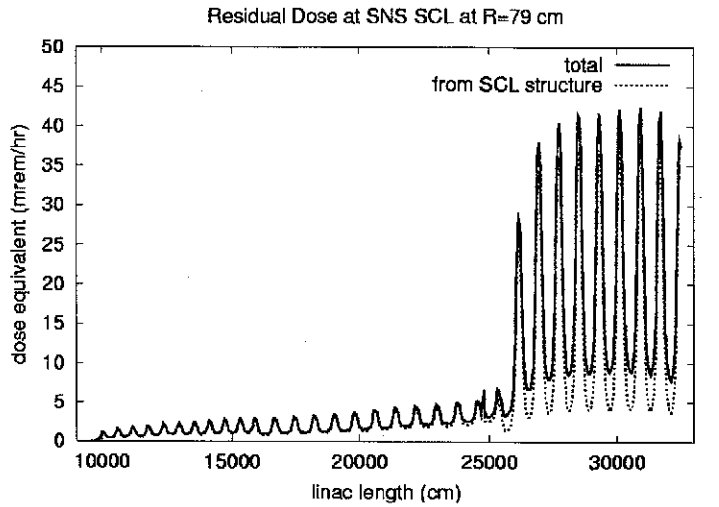


~80-cm-thick Concrete shield required

~10 mrem/hr at the beamline penetration







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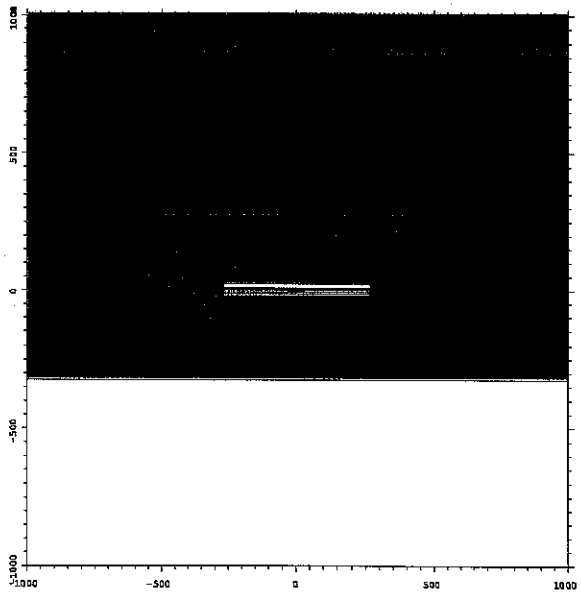
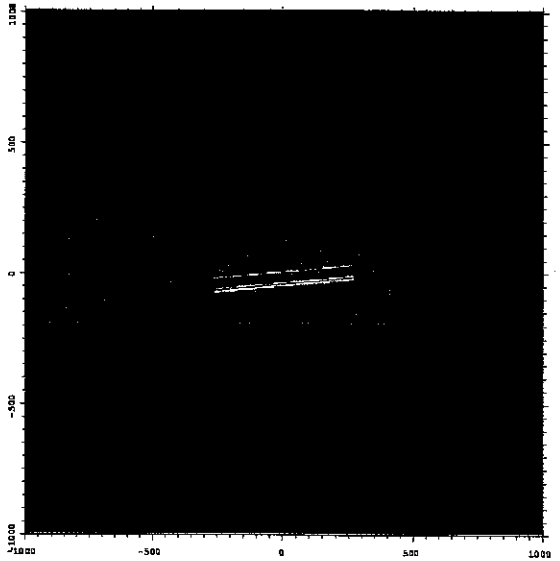
MCNPX Model For The HEBT Dipole Magnet Failure Analysis

Elevation Cut



Plan Cut



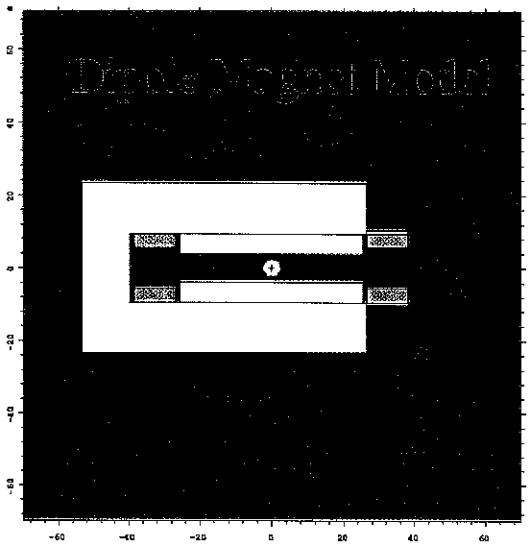
Legend

Blue = soil

Magenta = concrete

Green = air

Yellow = dipole



Analysis Assumptions

1st HEBT Dipole Failure

Full 2 MW Beam loss hits the Tunnel wall or the 2nd Dipole

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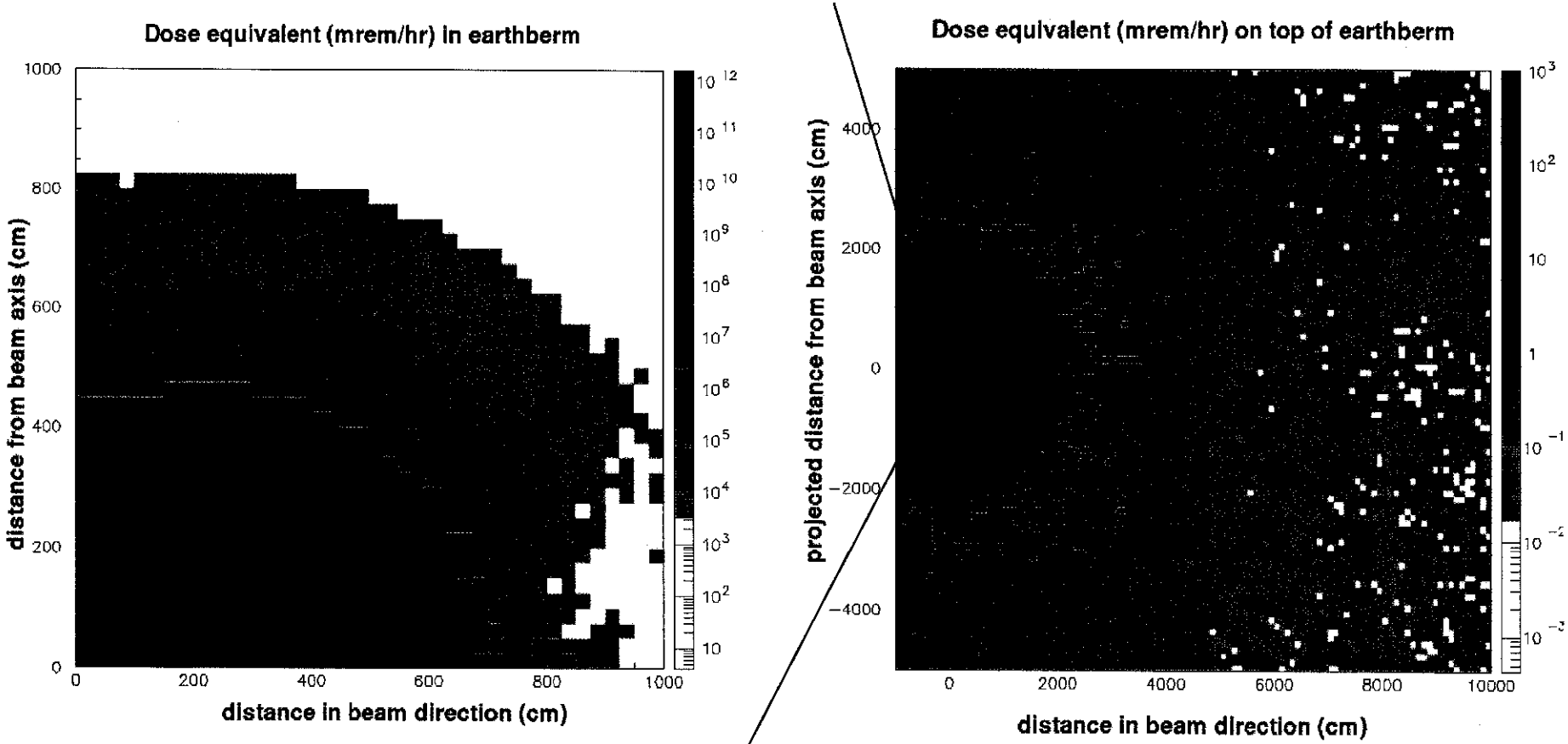
Dose Contours In And On Top Of The Earth Berm For A Full Beam Loss In The HEBT Arc With The Proton Beam Hitting The Tunnel Concrete Wall And The Earthberm

Peak ~1 Rem/hr



Dose level exceeding the 20 mrem/hr level has a radius of about 10 meters.

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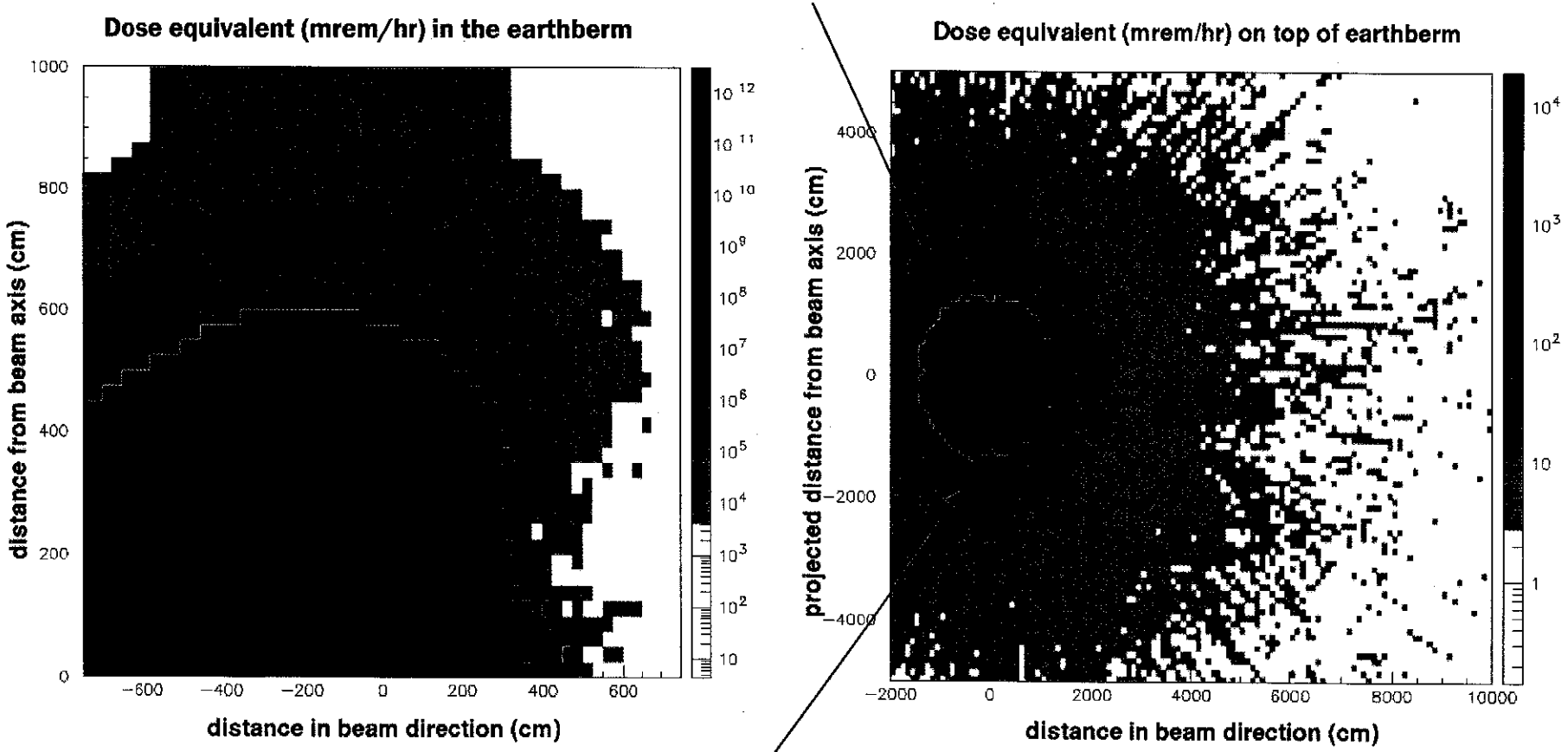
Dose Contours In And On Top Of The Earth Berm For A Full Beam Loss In The HEBT Arc With The Proton Beam Hitting A HEBT Dipole

Peak ~20 Rem/hr



Dose level exceeding the 20 mrem/hr level has a radius of about 16 meters

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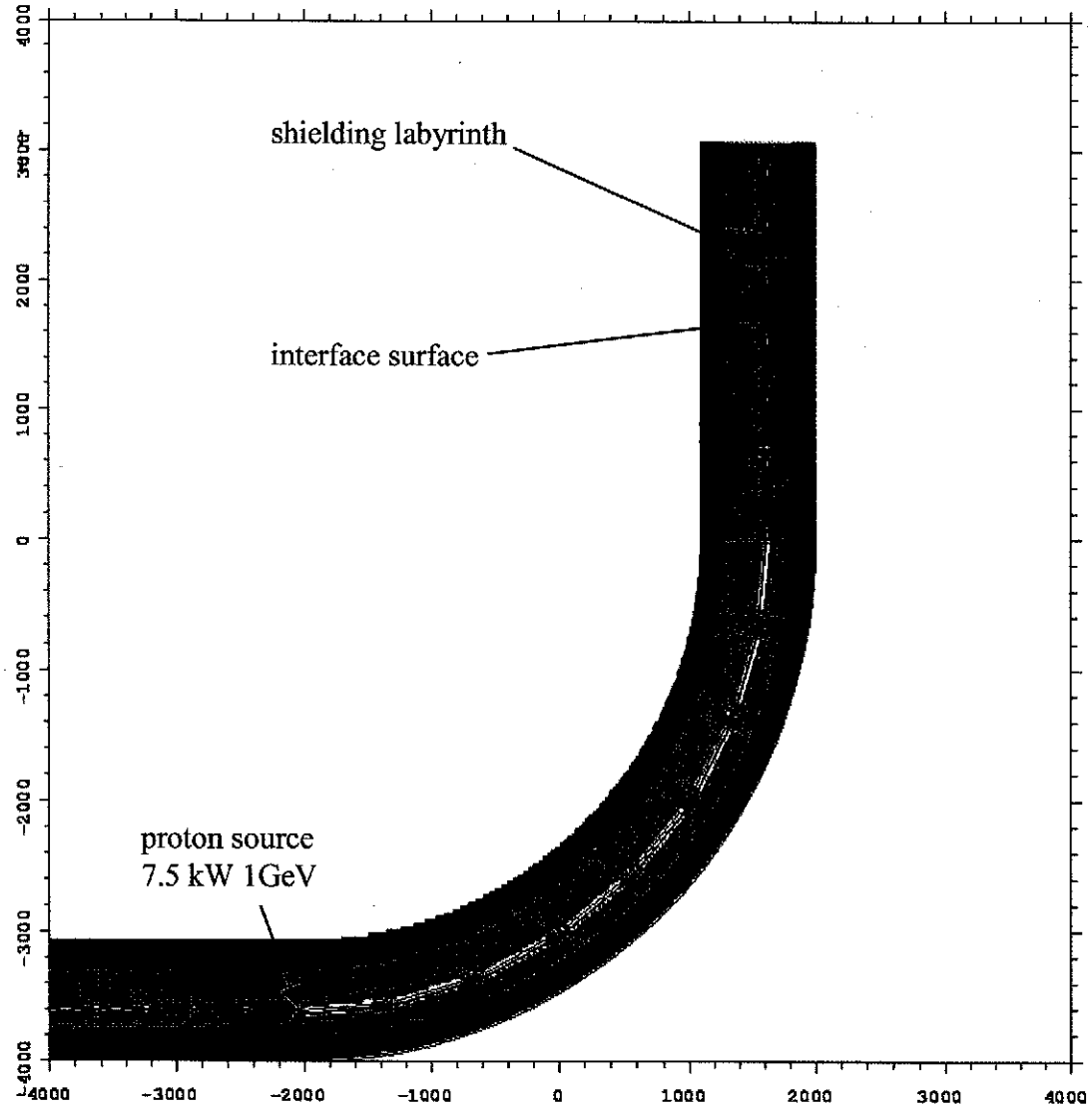
The MCNPX HEBT Shield Labyrinth Model



Requirement

Access to the Ring during linac beam tuning operations

Worst-case scenario

Full tuning beam with 1 GeV beam energy and 7.5 kW beam power is assumed to impinge on the front face of the first HEBT dipole.

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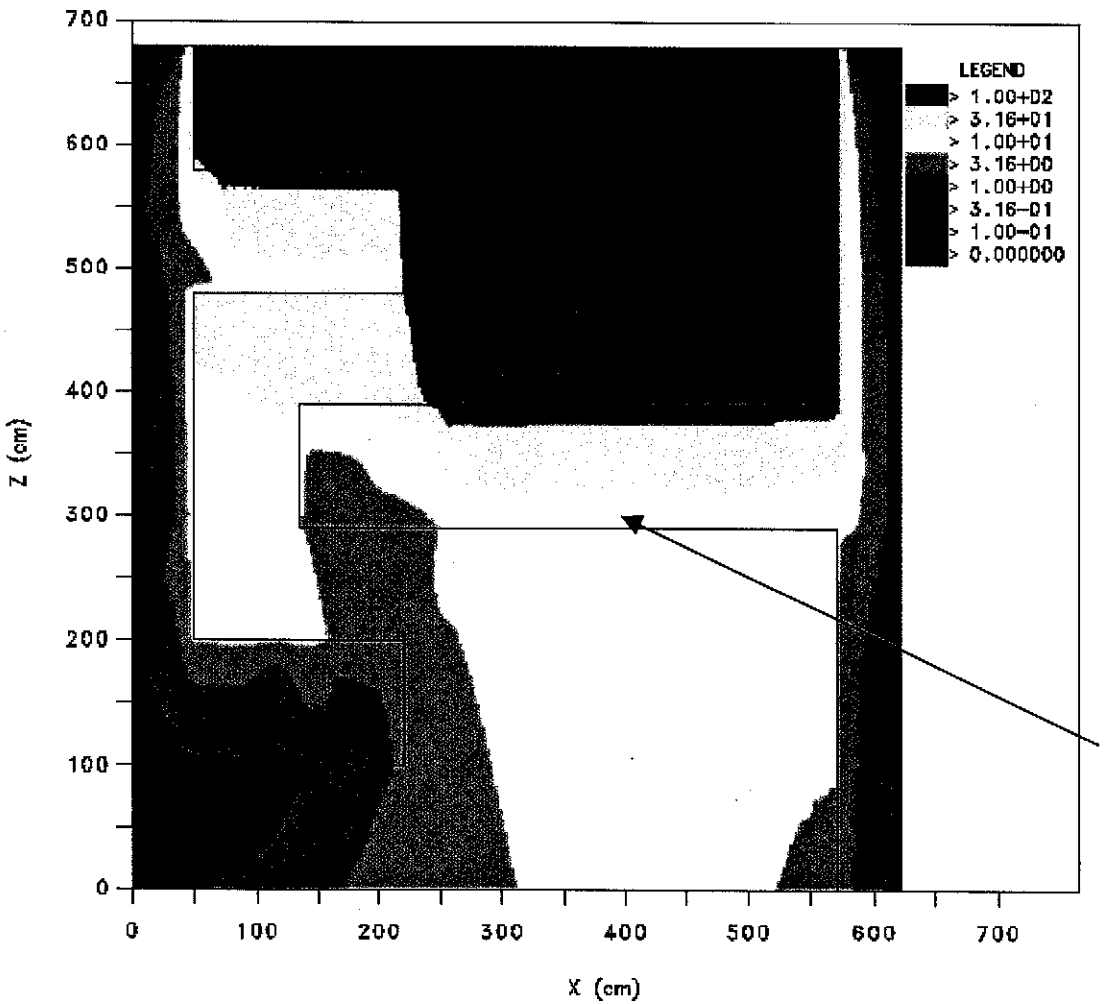
Dose Equivalent Contours For A Shield Labyrinth With 1 Meter Thick Walls Calculated With DORT



Dose through the 1-m-thick Shield wall is too high for Workers in the Ring.

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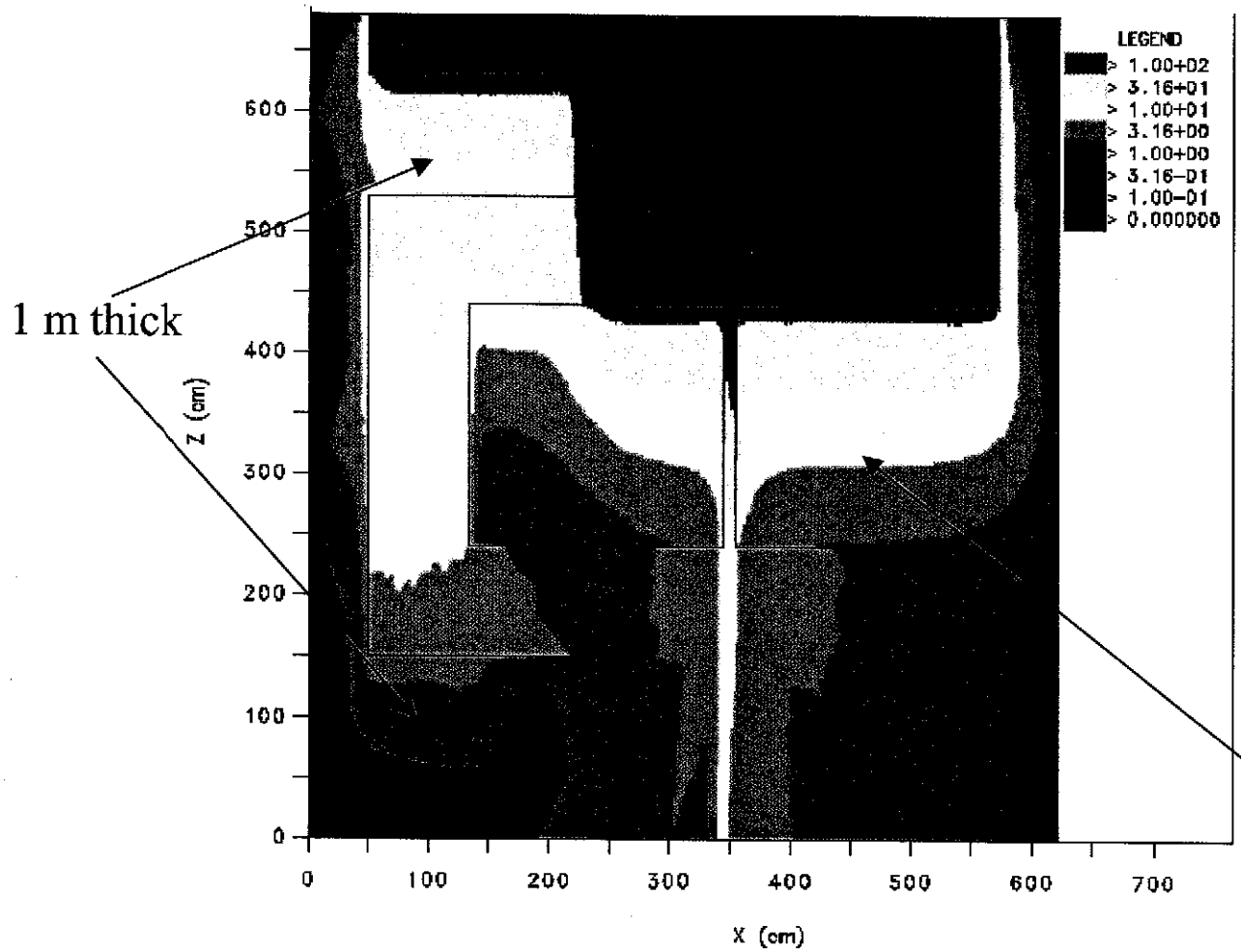
Dose Equivalent Contours For A Shield Labyrinth With 1-Meter Thick Walls For The Outer Walls And A 2-Meter Thick Inner Wall



Design Results

1 – 3 mrem/hr dose rate through the wall

~30 mrem/hr dose rate through the beam line slit

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Skyshine Dose Estimates Due To Normal Beam Losses In The Ring Collimator Section Based On Hand Calculations

Assumptions

100 mrem/hr on top of the berm

Covers a 5 x 30 meter area

5000 hours of operation per year

NOTE: Annual doses based on 5000 hours

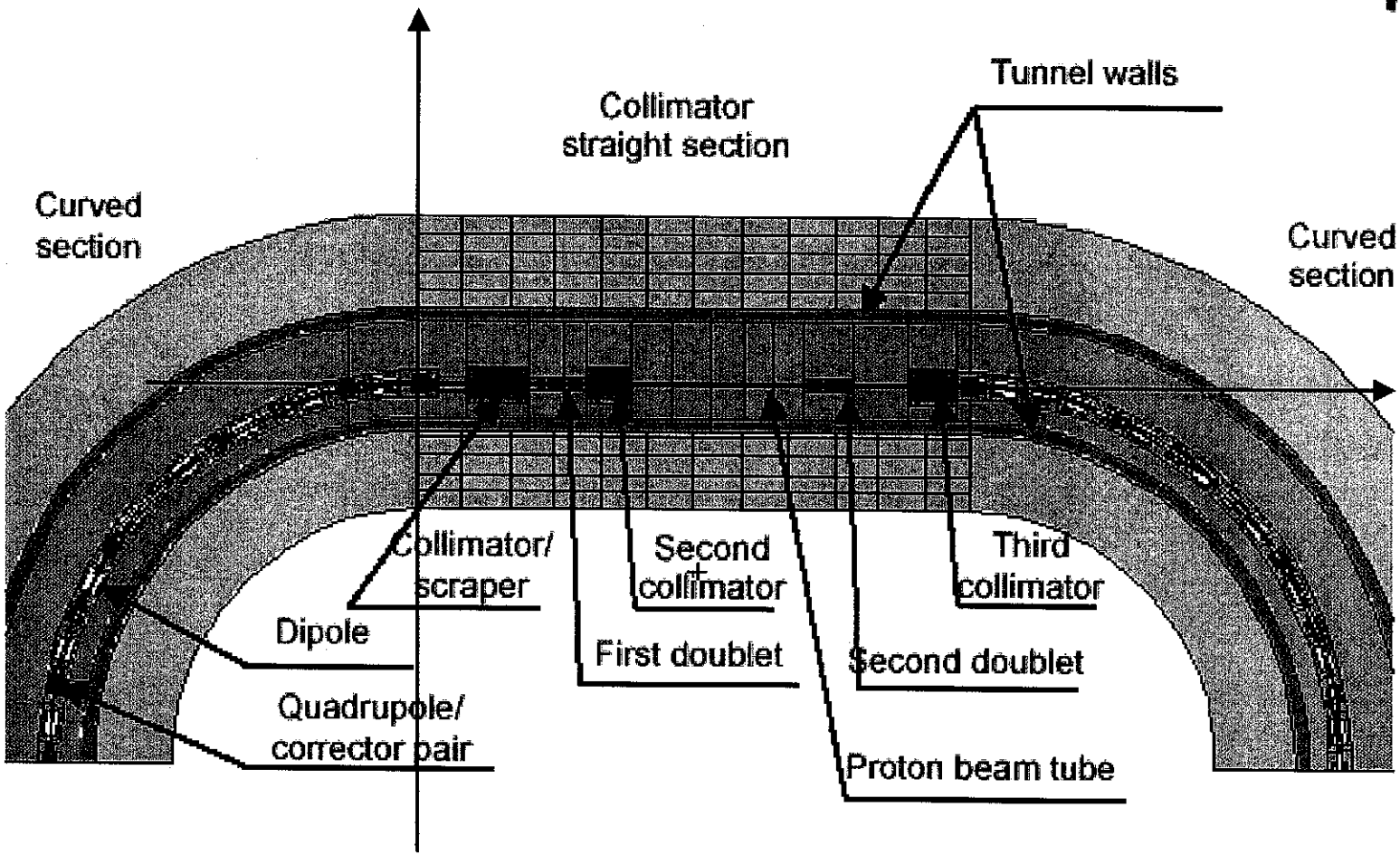
Sullivan's Hand Formula

Location	Distance (m)	Dose rate (mrem/h)	Annual dose (mrem)
Target Building	200	0.0188	94
CLO building	350	0.0048	24
Site boundary	1400	$5.2\ 10^{-5}$	0.26

Moritz's Hand Formula

Location	Distance (m)	Dose rate (mrem/h)	Annual dose (mrem)
Target Building	200	0.0264	132
CLO building	350	0.0078	39
Site boundary	1400	$8.2\ 10^{-5}$	0.41

MCNPX Model Of The Extended Ring Collimator Section (Red Lines Defining the Geometry's Origin)



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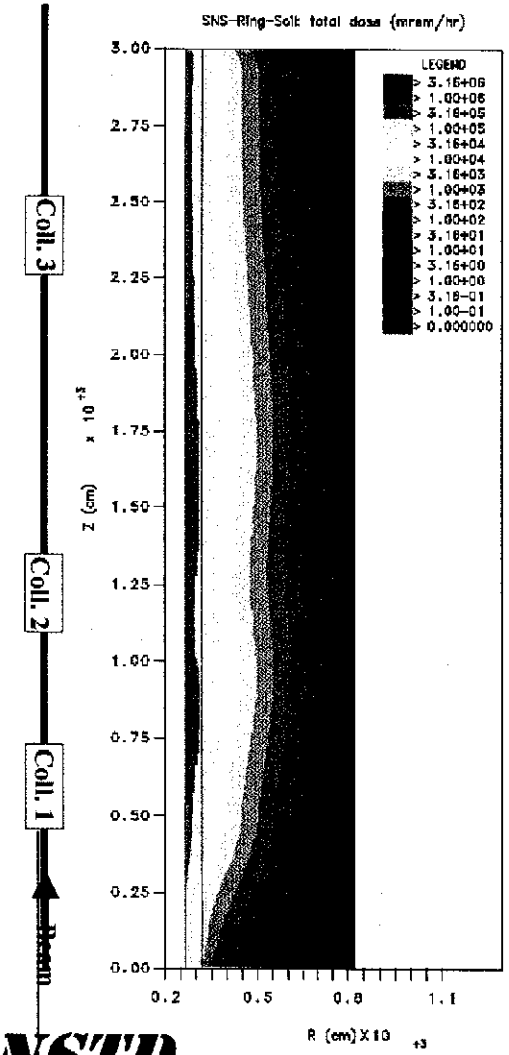
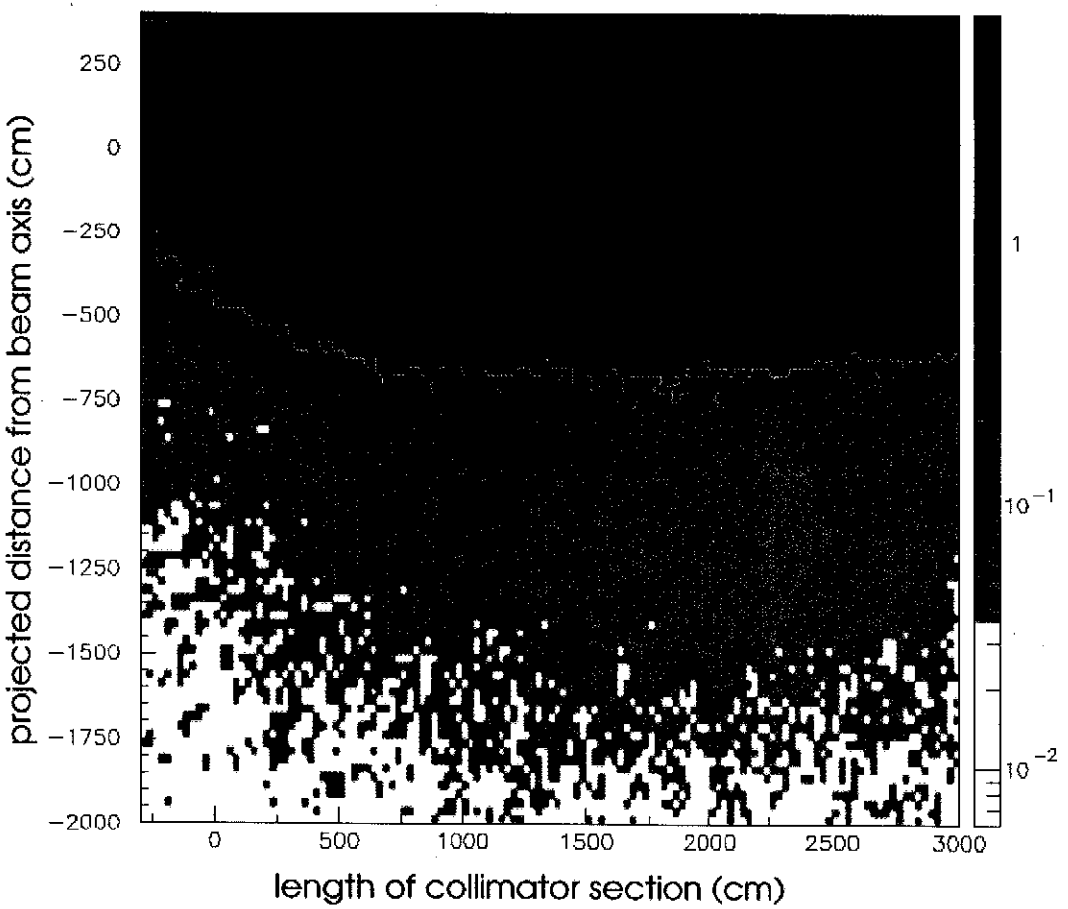
Skyshine From Operational Proton Beam Losses In The SNS Ring Collimator Section

Dose equivalent (mrem/h) contours in the soil on top of the ring collimator section tunnel



Dose Equivalent (mrem/hr) COntours on Top of Earthberm



Peak ~7 mrem/hr after 5 meters of soil

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Skyshine Dose Estimates Due To Normal Beam Losses In The Ring Collimator Section Based On Transport Calculations

Sensitivity of Maximum Calculated Dose Rate Levels
on Top of the Earth Berm Due to Soil Density Effects

Soil type	Dose equivalent (mrem/h)
Generic soil ρ=1.75 g/cm^3	5
Tennessee soil ρ=1.61 g/cm^3	20
Tennessee soil ρ=1.76 g/cm^3	8

Conclusions

Hand calculations yielded 94 to 132, 24 to 39, and 0.26 to 41 mrem at the Target building, CLO building, and Site boundary, respectively

- 100 mrem/hr over a 5 m by 30 m area for 5000 hours operation

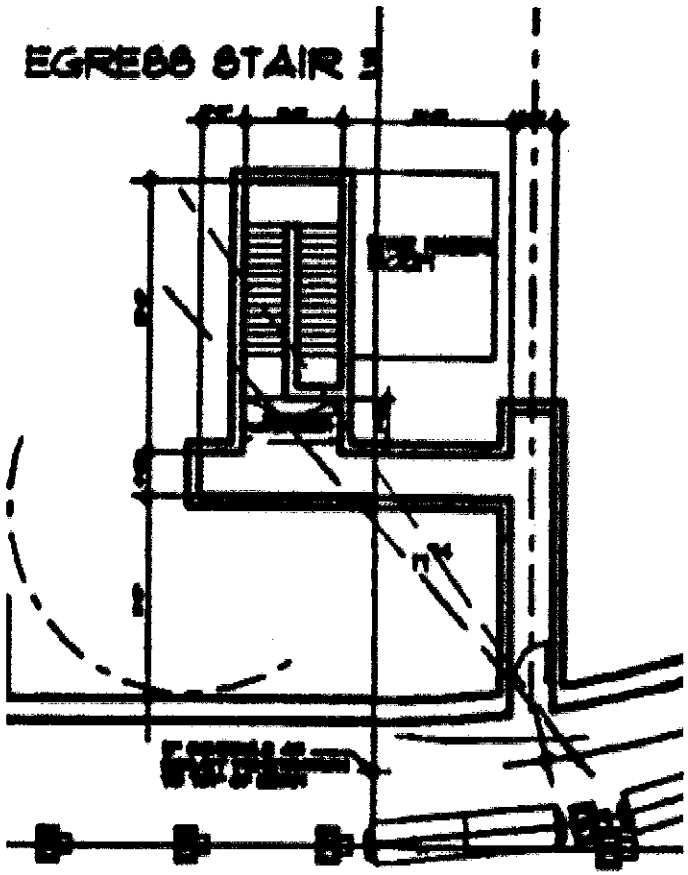
Two Transport calculations yielded 5 to 20 mrem/hr on top of the berm over the collimator section depending on the soil density assumption

- Peak area illuminated was approximately 6 m by 20 m

Previous benchmark analyses of the calculated dose rate on top of the 5-m-thick berm indicated a factor of 4 uncertainty

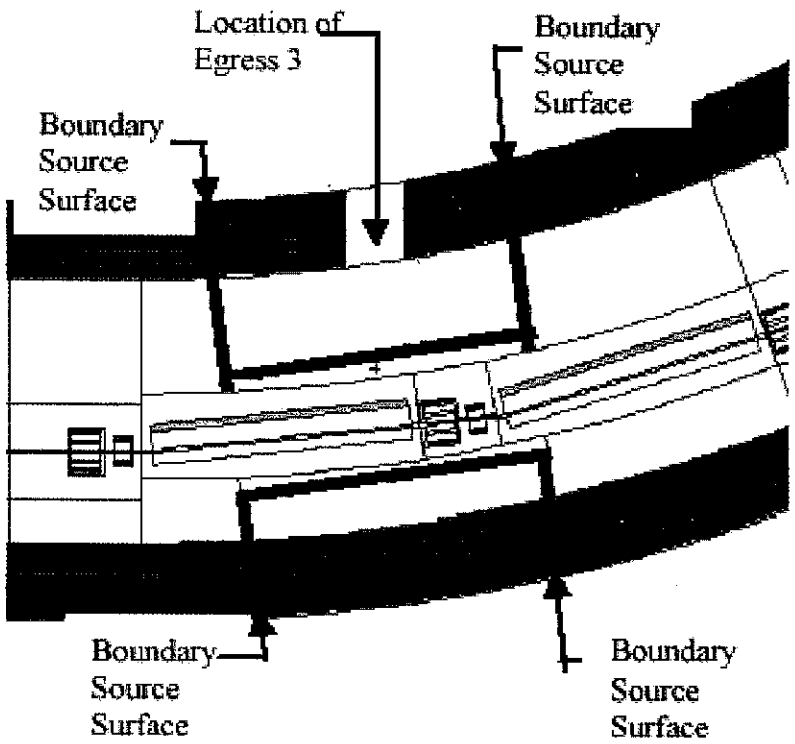
Consequently, the initial 100 mrem/hr dose rate assumption is not unreasonable and represents a conservative upper bound for determining the skyshine estimates

Generic Design Of An Egress In The SNS Accelerator System

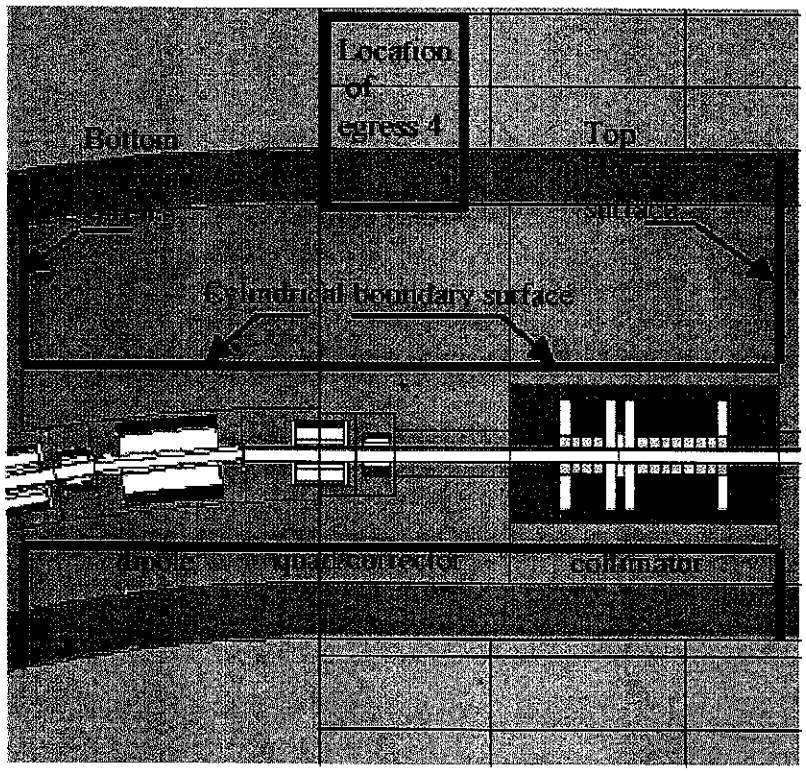


Leg	Length (m)		Cross sectional area (m^2)	
	Design drawing	DORT Model	Design drawing	DORT Model
1	7.44	7.44	1.20 x 2.40	π 0.96^2
2	8.42	8.42	1.20 x 2.40	π 0.96^2
3	7.50	3.92	2.40 x 2.70	π 1.20^2
4	3.00	3.00	2.70 x 6.00	π 1.20^2

Location Of The Boundary Sources In The MCNPX HEBT Geometry For The Dose Analysis Of Egress 3 And Egress 4



Boundary Source for Egress 3



Boundary Source for Egress 4

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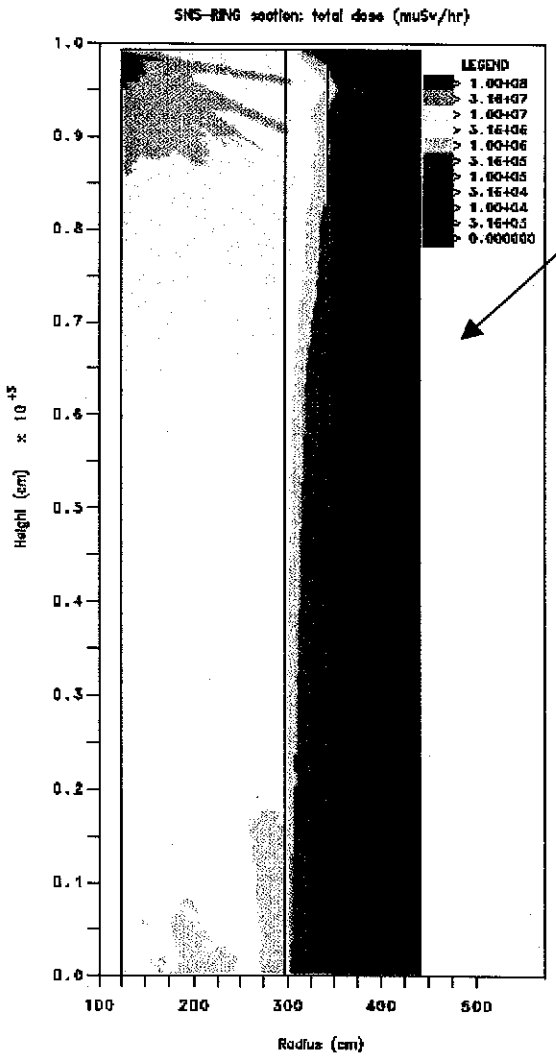
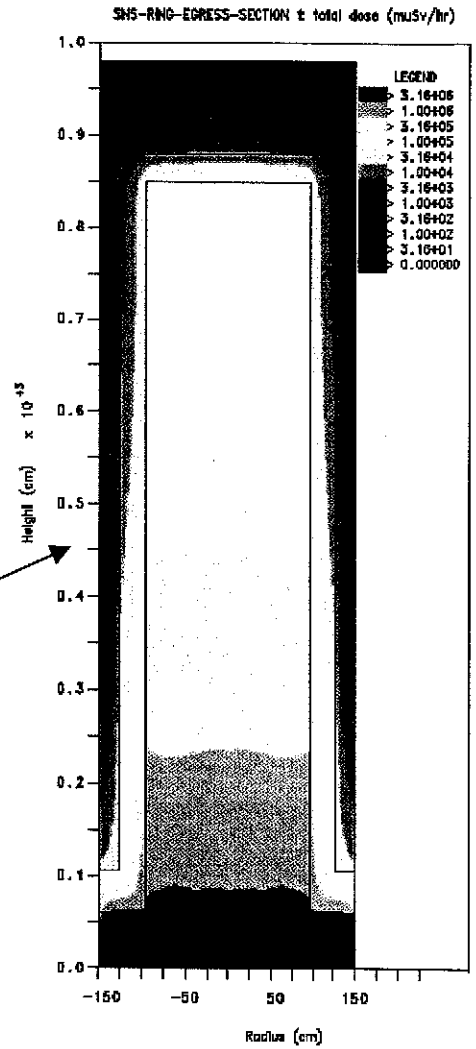
Equivalent Dose Plots For The Tunnel Segment Adjacent To Egress 4 And The First Leg Of Egress Four



Tunnel Segment

1st Leg



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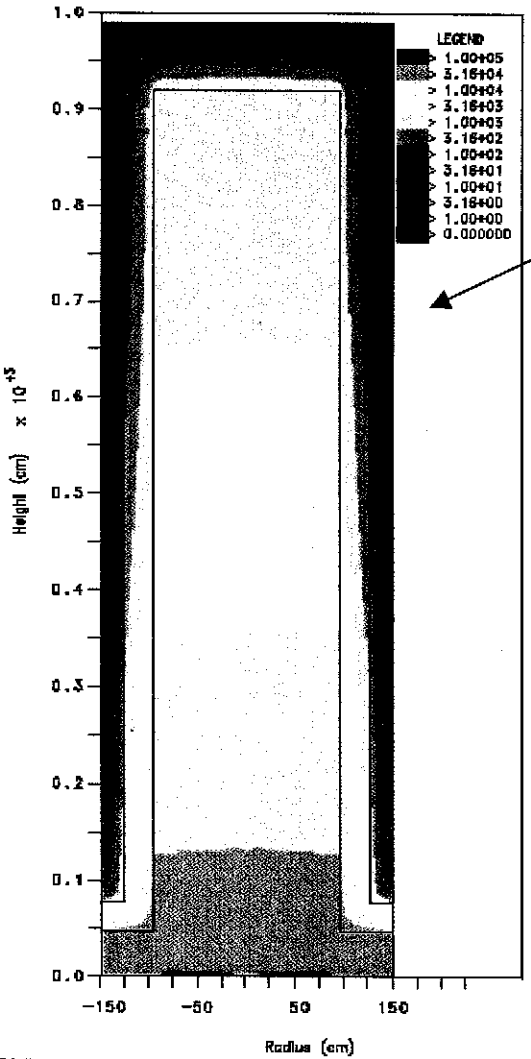
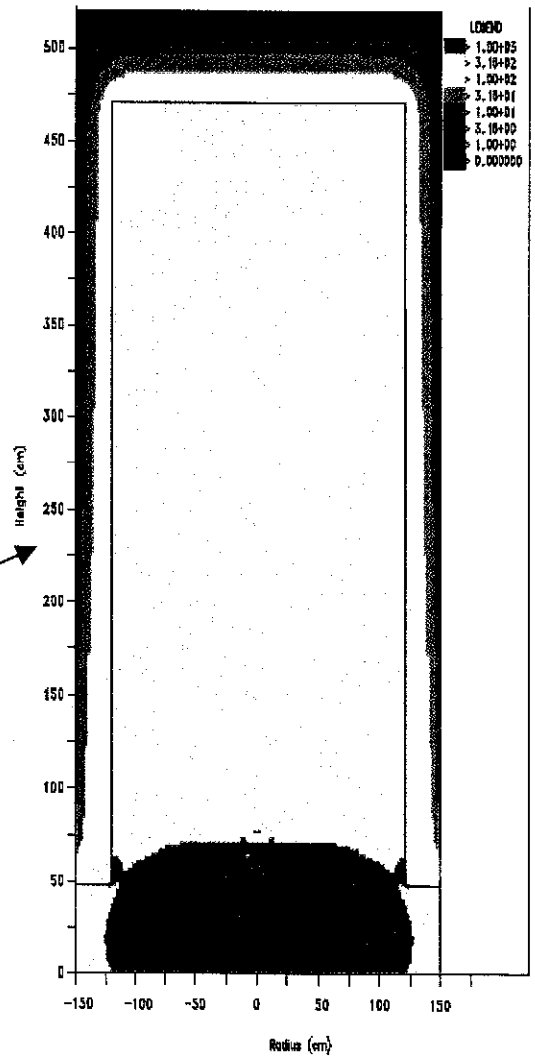
Equivalent Dose Plots For The Second And Third Legs Of Egress Four



2nd Leg

3rd Leg



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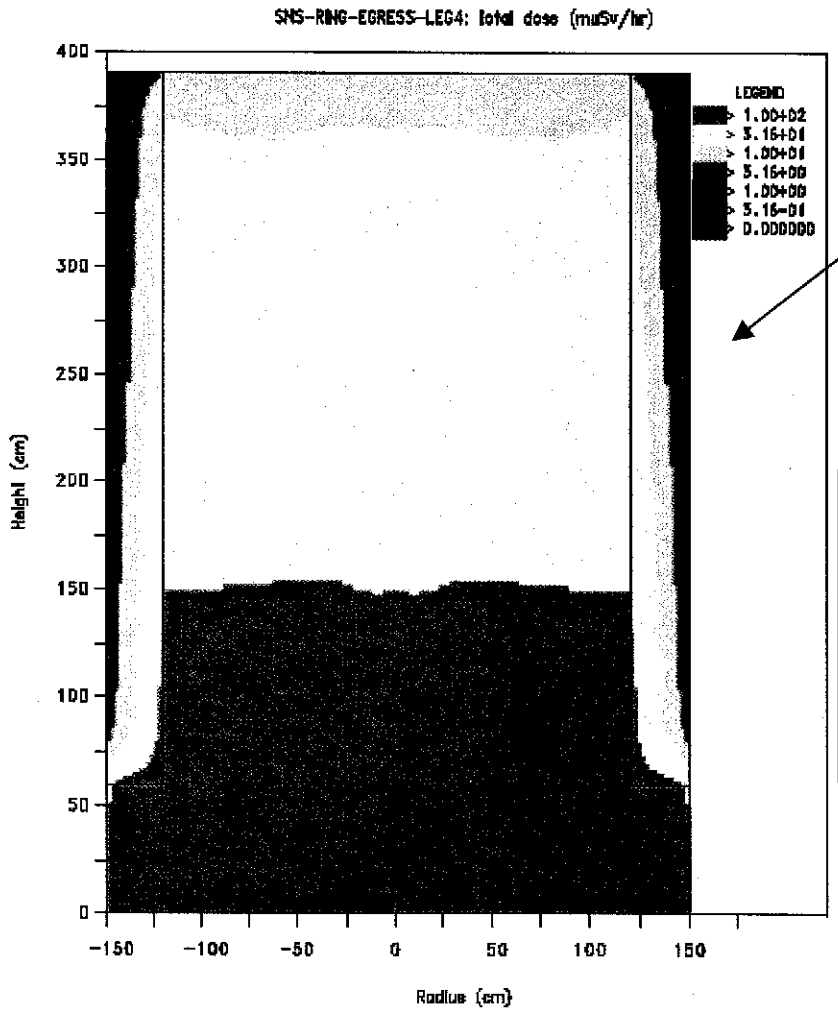
Equivalent Dose Plots For The Fourth Leg Of Egress Four And The Summary Dose Table



4th Leg
(Staircase)

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

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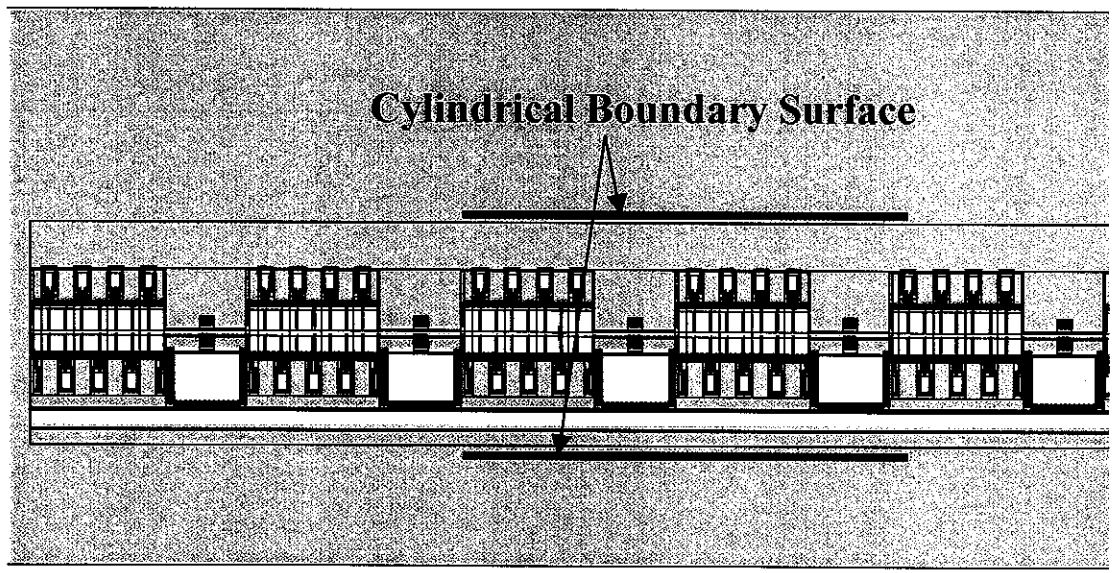
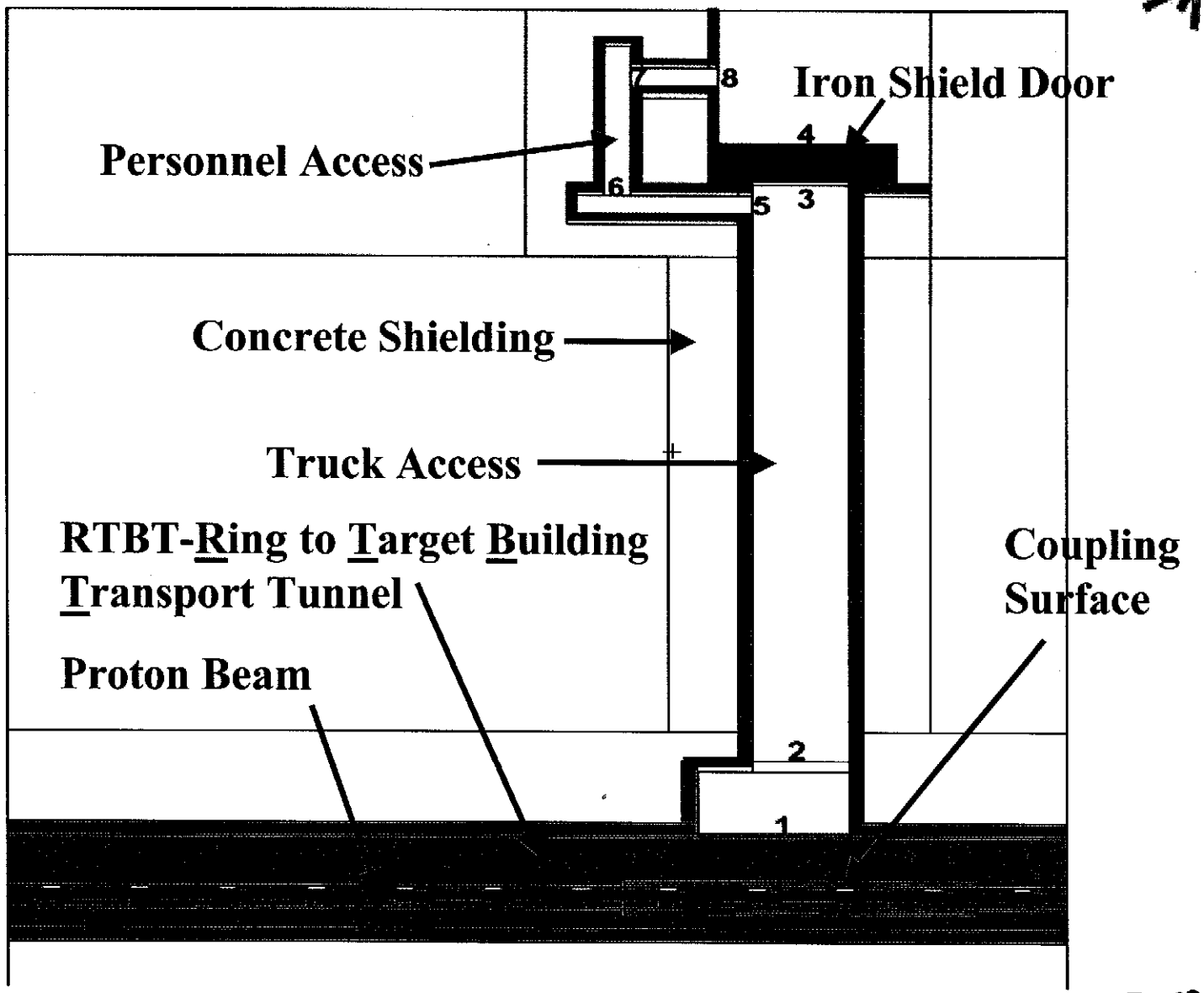
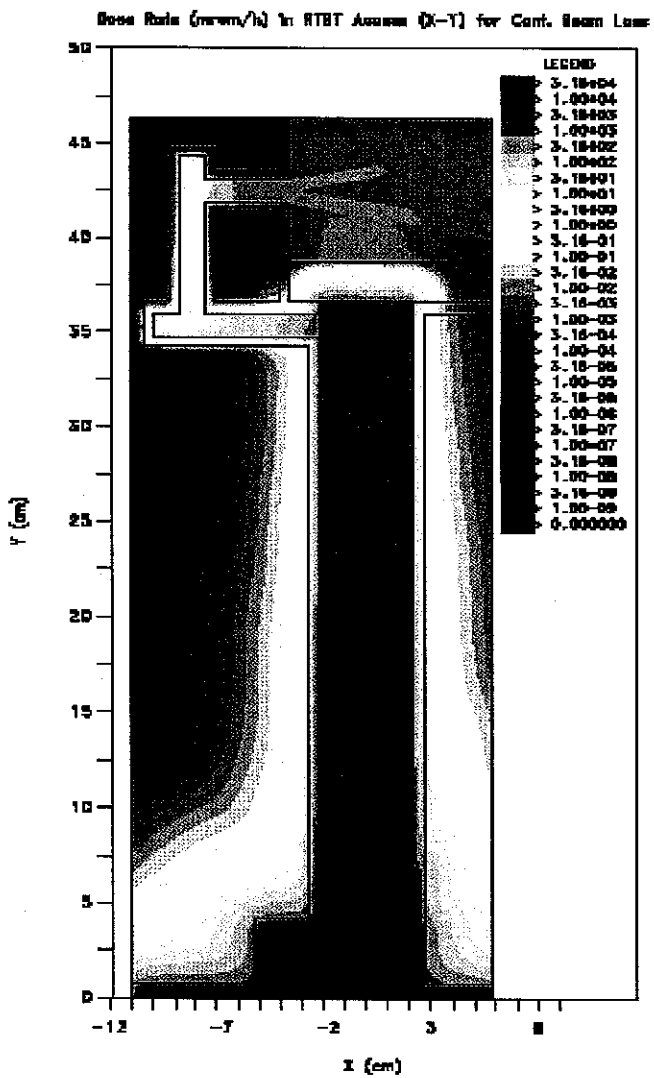
The Boundary Source For The Dose Analysis Of The Earth Berm Was Taken At A 3.20 Meter Cylinder Surface in the MCNPX Calculation of the Coupled Cavity LINAC



Plan View Of The RTBT Truck and Personnel Egress



Dose Rate In The RTBT Truck Access Due To 1 W/m Normal Operational Line Losses



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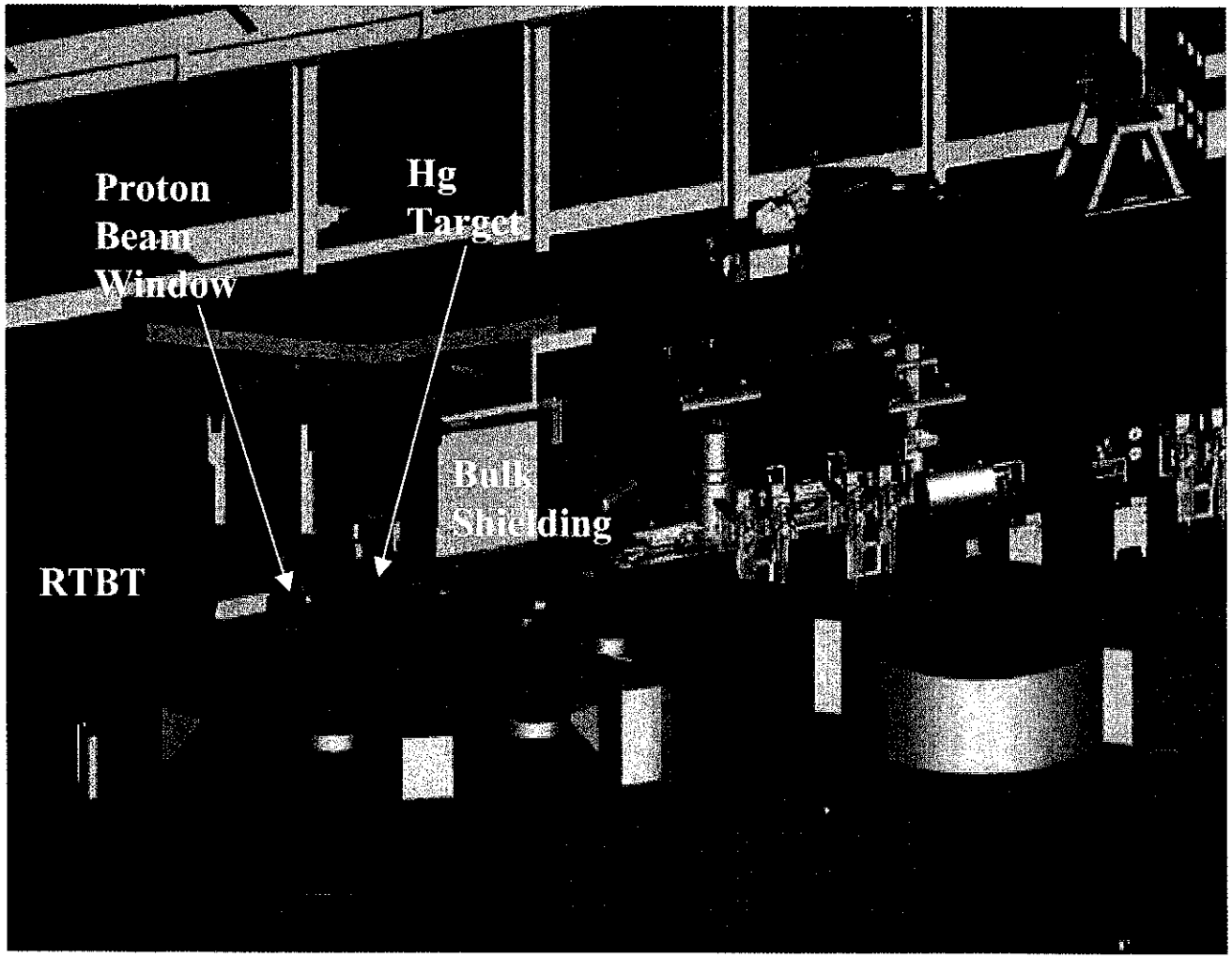
Dose (mrem/hr) In The RTBT Truck & Personnel Egress

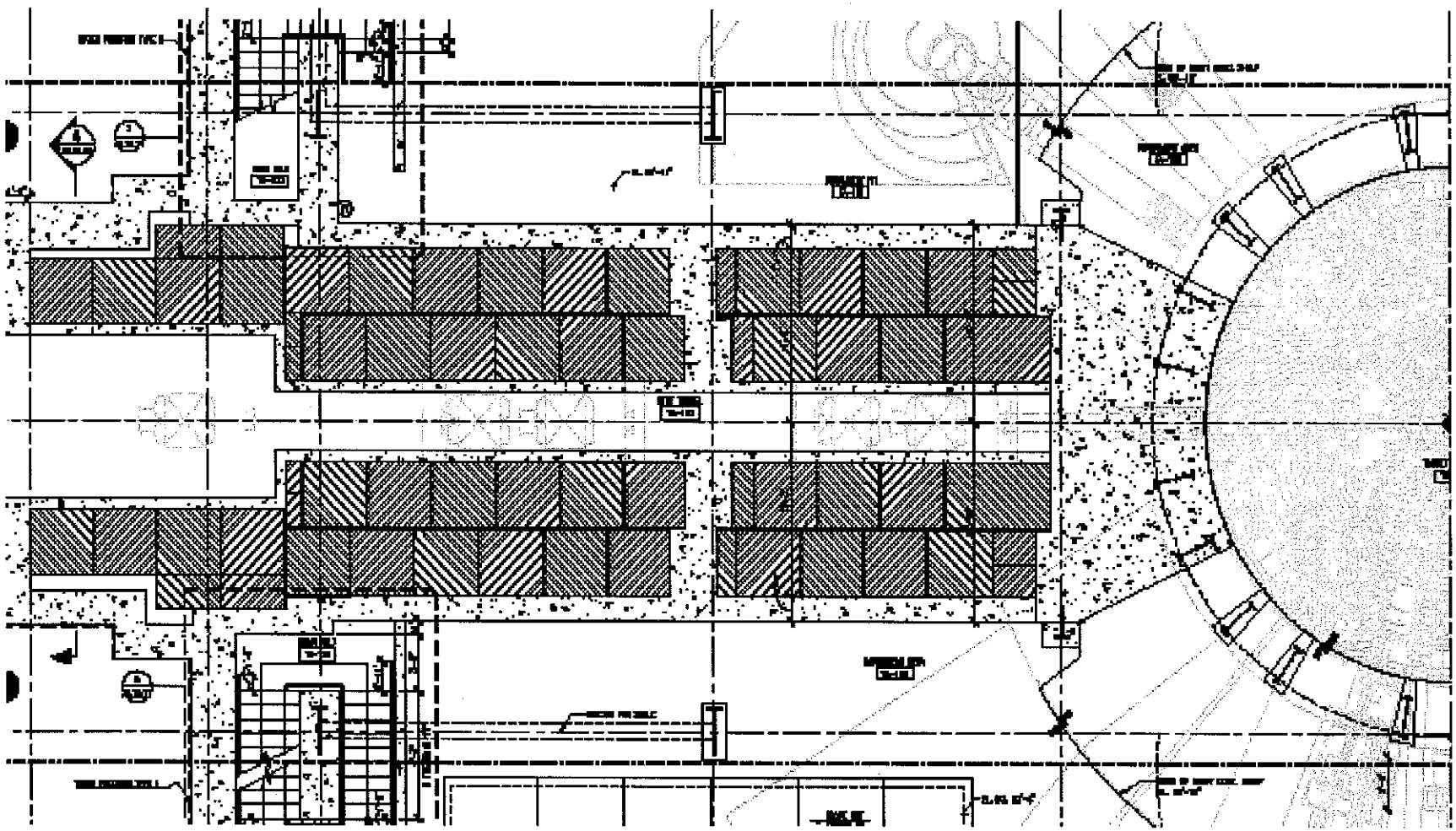
Location	MCNPX	DORT
1	6.74+4 (0.5) [a]	3.2+4 - 1.0+5
2	2.06+4 (0.7)	1.0+4 - 3.2+4
3	5.82+2 (4.0)	1.0+2 – 1.0+3
4	1.03-1 (31)	3.2-3 - 3.5-2
5	4.26+2 (32)	1.0+2 - 3.2+2
6	2.67 (23)	1.0 - 3.2
7	2.78-2 (68)	1.0-2 - 3.2-2
8	1.70-2 (75)	1.0-3 - 3.2-3

[a] 6.74+4 read as 6.74×10^4 : no.'s in ( ) = Monte Carlo percent fractional standard deviations

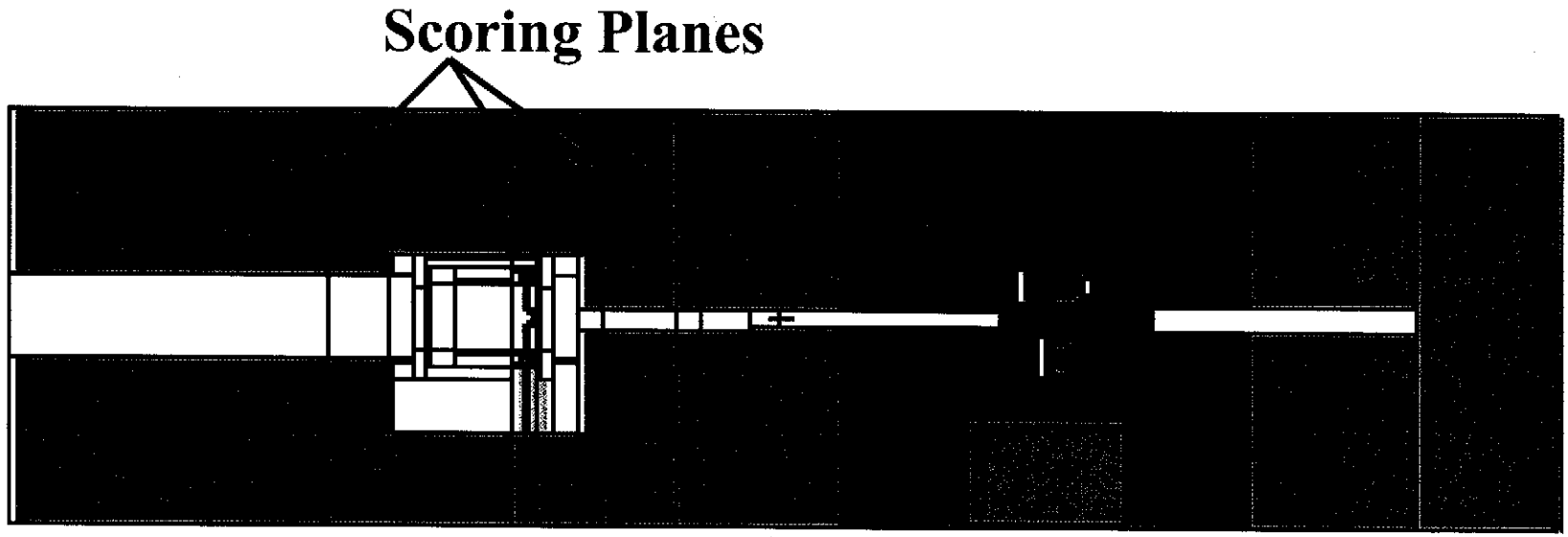
The Spallation Neutron Source
High Power Target Station



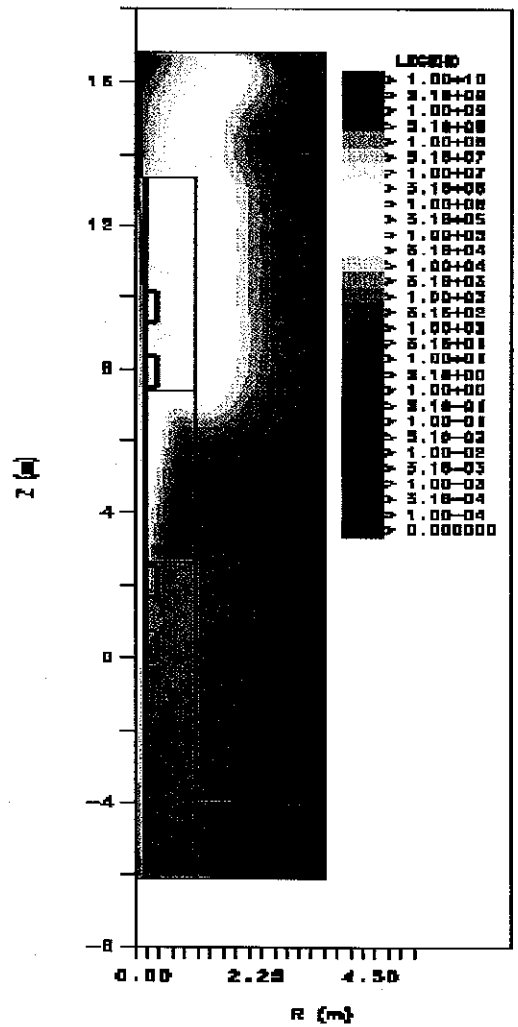
Plan Drawing Of The RTBT Tunnel Section Inside The Target Building



X-Z Slice Through A Trimmed MCNPX Geometry For The Target Monolith



Dose Rate In The RTBT Due To Radiation Back-Scattering From the Target



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The SNS Neutronics And Shielding Design Team Possesses Unique Skills and Tools For Performing Detailed Radiation Transport Design Analyses Of An Accelerator Driven Facility

- Specifically, the team has performed almost all analyses for the SNS involving:
  - > Neutronic performance, energy deposition distributions, material damage and activation, and shielding design
- Project schedule and specific design engineering constraints/problems typically dictated coupling Monte Carlo to Discrete Ordinates to meet design milestones
  - > Developed the new HILO2k library
  - > Developed a suite of Monte Carlo to Discrete Ordinates coupling codes
  - > Developed the Activation Analysis System for performing activation analyses
- The design team successfully utilized the strengths of the two methods to compliment each other and meet the project design milestones; addressing many design issues that were not readily solvable with any one specific method
  - > Operational and residual doses for the linac
  - > HEBT shield labyrinth design calculations
  - > Ring collimator section skyshine analysis
  - > Detailed analyses of the linac, HEBT, ring, and RTBT shield berm penetrations
  - > Back-scattering off of the target and proton beam window into the Ring to Target Beam Transport (RTBT) tunnel
  - > Streaming through the target monolith shutter gate "travel voids"
  - > Curved neutron beamlines and neutron beam benders