LANSCE Isotope Production Facility—
Access Shaft Shielding Calculations

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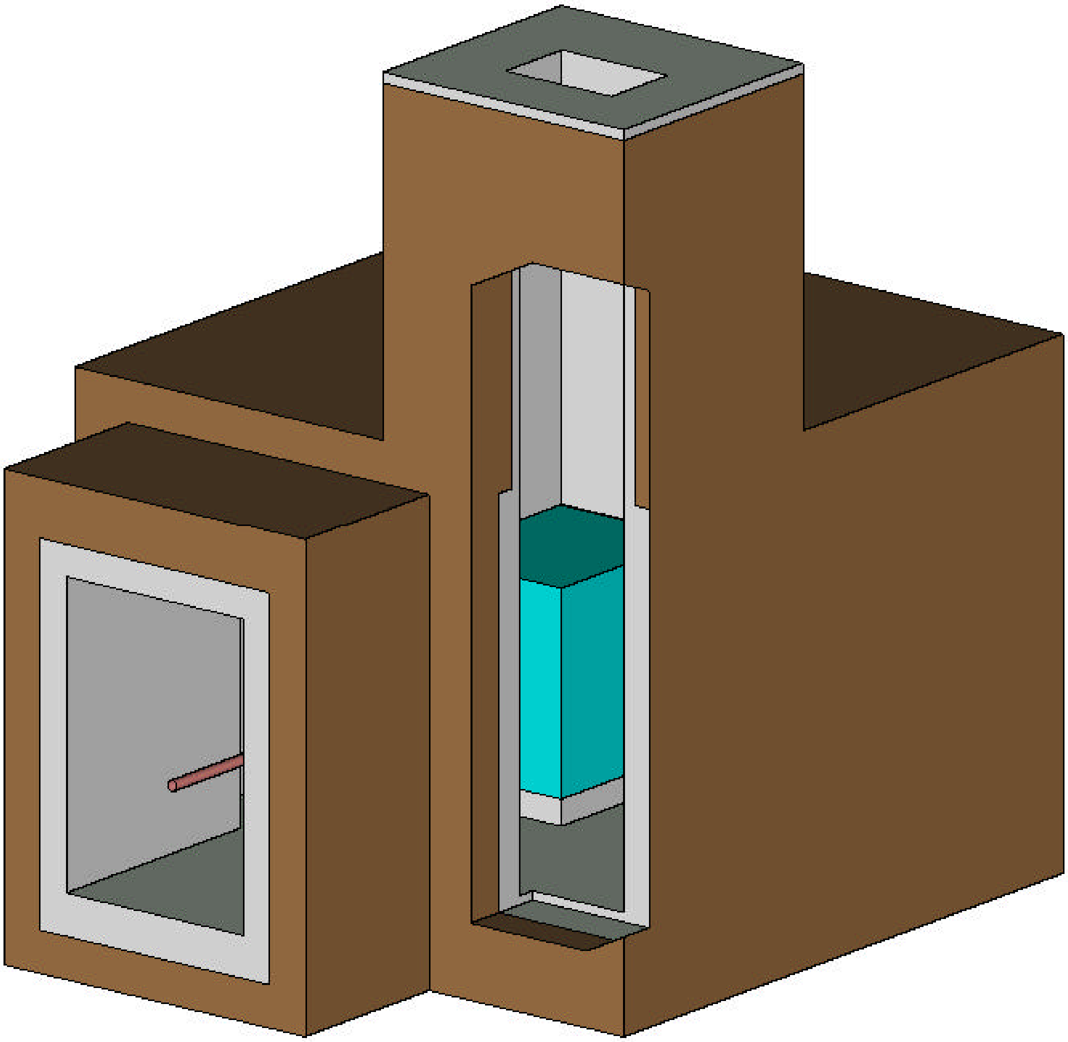

Figure 1. Three-dimensional view of the access shaft model. A section of the corner that includes the shaft has been removed to show the interior structures. Ordinary concrete is light gray, Magnetite concrete surrounding the target is light blue, the beam pipe is light red, and the surrounding earth is brown. The picture does not show the 2 foot thick concrete plug as the top of the shaft that was included in the calculation.

Introduction

The LANSCE Isotope Production Facility[1] (IPF) will consist of a branch of the LANSCE main beam line leading through the IPF tunnel to the production target. A support room above the target room contains a hot cell and other equipment. An access shaft, through which equipment may be raised or lowered, connects the target and support rooms. When the beam is in operation, this shaft is closed at the top by a plug. We assume a 2 foot thick plug made of ordinary concrete. Workers may carry out activities in the support room if the dose they receive from a beam spill accident in the tunnel or target room is below acceptable limits.

We present here the results of Monte Carlo radiation transport calculations of the flow of radiation, resulting from a beam spill, up the shaft and through the plug. The model predicts a dose equivalent rate (DER) of 4.4 REM/hour in the support room air space just above the shaft.

Model

The model includes a section of the beam tunnel adjacent to the target room, the target room itself, and the access shaft. The stairwell between the target and support rooms, considered in previous calculations, is not included. Because the shaft and stairwell are located at diagonally opposite corners of the target room, any effect on the radiation flow in the other should be small. Further, omission of the stairwell is a conservative assumption in that with radiation not escaping through the lower stairwell door, the DER within the target room and shaft would be larger than with the stairwell in place.

Figure 1 is a three dimensional view of the model. The access shaft extends to the floor level of the support room; a section of the upper floor is included. We did not model the inner details of the target. All structures within the inner SEG steel block were deleted; a solid block of SEG steel comprises the inner target. The outer magnetite concrete layer of the target contains penetrations by the beam line, the beam line cooling jacket, and the coolant return line. Water filled the cooling jacket and coolant lines. Other penetrations, such as the vertical isotope access pipe, are not included.

Figure 2 shows the floor plan of the model. The walls, ceiling, and floor are composed of ordinary concrete. The air in the access shaft, target room, and tunnel is at a density appropriate to a 7,000 feet altitude. Appendix A lists the MCNP and LAHET material descriptions.

The lower floor is 2 feet thick. The section of the upper support room floor included is 6 inches thick. The walls of the tunnel and target room are 18 inches thick. The ceiling is 18 inches thick in the tunnel and 2 feet thick in the target room. The shaft walls are 8 inches thick, enclosing a 4 by 6 foot air space that extends through the target room ceiling to the 2 foot plug capping the shaft. The plug thickness includes the 6 inch support room floor layer. The outer layer of the model, except where the tunnel is cut and the top of and around the shaft, is 2 feet (slightly thicker on top of the tunnel) of dirt. The dirt thicknesses surrounding the shaft were determined by the reuse of existing surfaces in the definition of those earth cells.

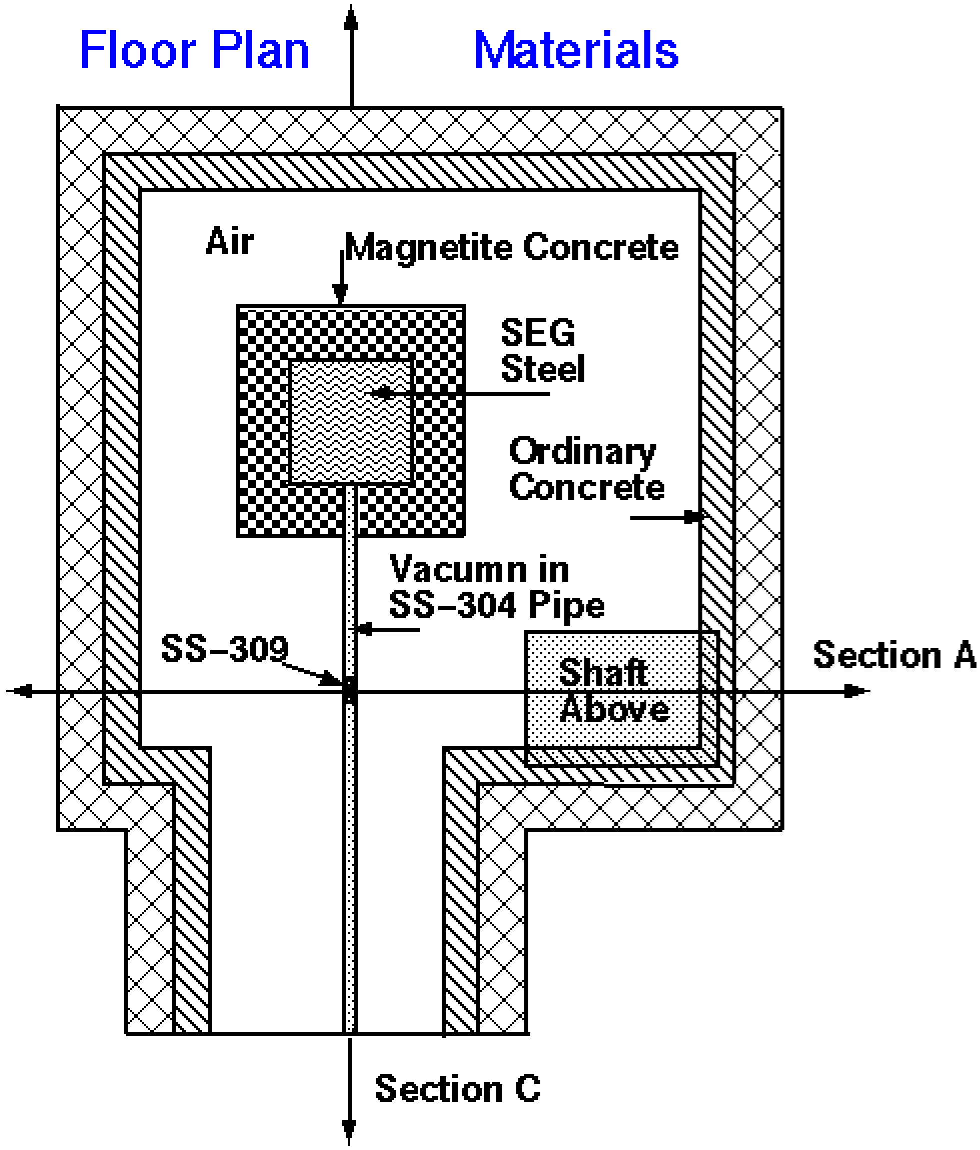

Figure 2. Floor plan of the target room showing the shaft location. The hatch patterns represent the same materials in all subsequent Figures.

Figure 3 gives some dimensions in the floor plan view. Figure 4 gives dimensions in the vertical sections through the target along the beam line. Figure 5 is a section perpendicular to the beam line passing through the shaft; the detail at the top of the shaft is enlarged in Figure 6. The locations of these sections in the floor plan are shown in Figure 2. Figure 7 is a cross section of the shaft (the location of this section is noted in Figure 6). Figure 7 also shows the position of the shaft relative to the target room walls.

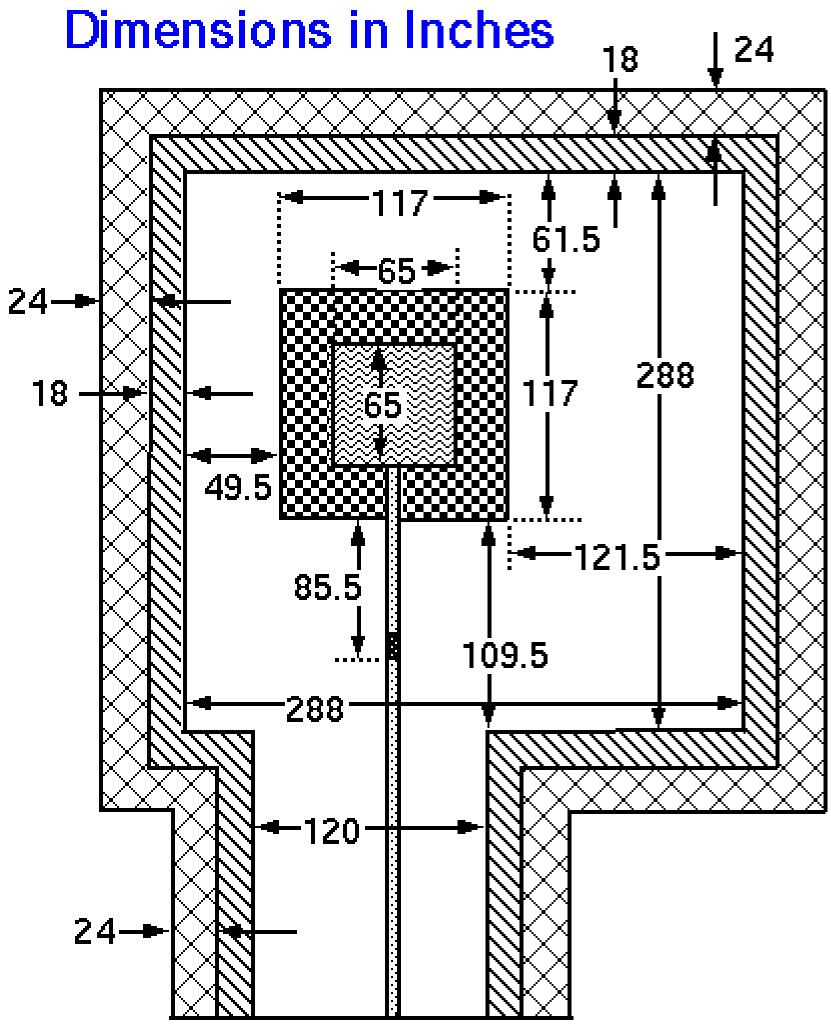

Figure 3. Floor plan of the target room showing dimensions in inches.

Beam Spills

The beam line is a 0.210801 cm thick 304 stainless steel pipe with 7.4092 cm outside radius containing vacuum at 1.5×10^{-12} g cm^{-3}. A beam spill is simulated by replacing a foot long section of the vacuum with a 304 stainless steel plug. The upstream end of the plug lies in the plane bisecting the 4 foot cross section of the shaft. The spill results from a pencil beam of 100 MeV protons, at the center of the tube, impinging on the plug. The scaling factors for the tallies assume a 1 milliAmp beam.

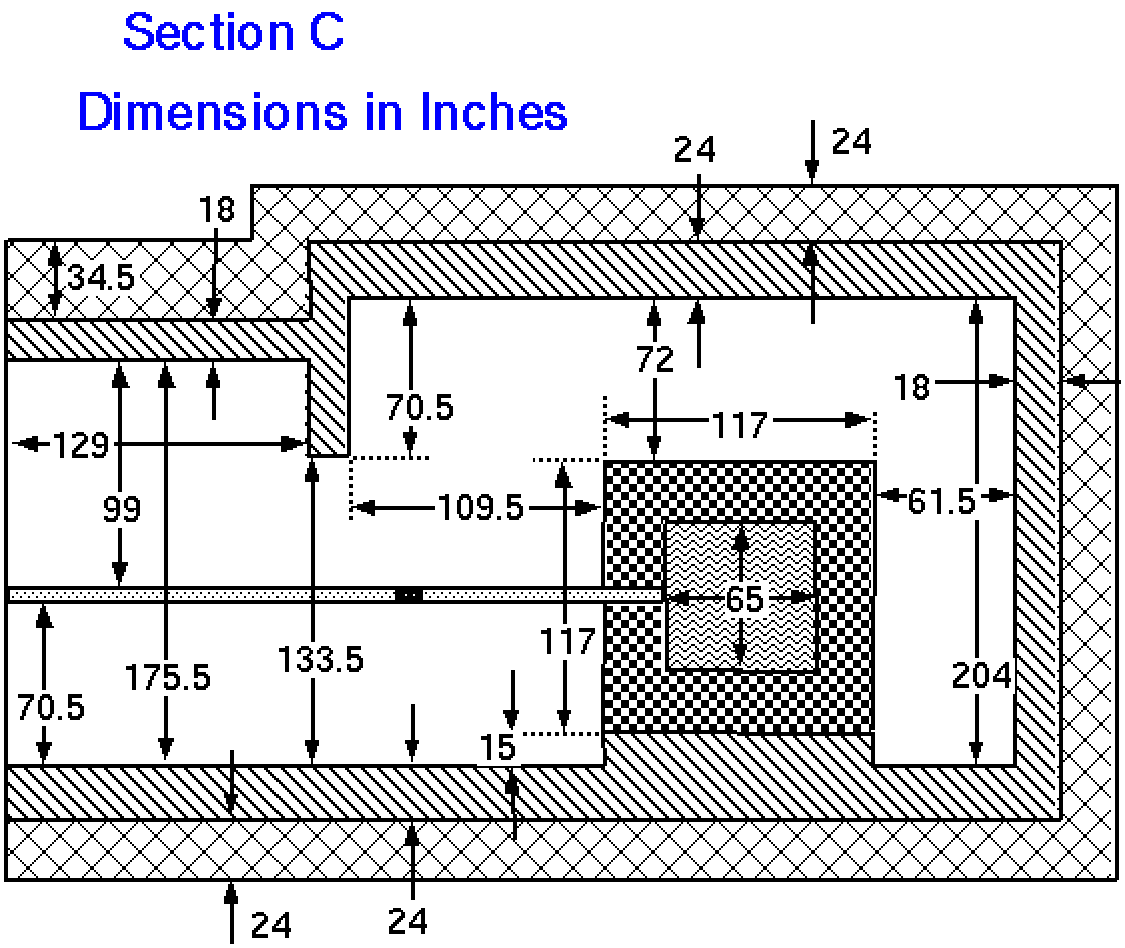

Figure 4. Section C through the target room showing dimensions in inches.

Importance Splitting

We used importance splitting to maximize the particle population reaching the top of the shaft. When a Monte Carlo particle enters a cell of higher importance, it may be split into 2 (or more) particles, thereby increasing the particle population in that cell and decreasing the variance of tallies. (The splitting process reduces the weight of the daughter particles in a manner that preserves the correct result.)

The model incorporates 13 layers of importances from the beam spill to the top of the shaft. The importance increases towards the top by a factor of 2 from layer to layer. Within each layer, the importance decreases by a factor of 2 from the target room, shaft, and tunnel into the walls, floor, and ceiling, and by a further factor of 2 from the concrete shell into the surrounding earth. Nowhere does the importance across a surface vary by more than a factor of 2. Neutron and photon importances are equal and the same for MCNP and LAHET. The importances are independent of energy.

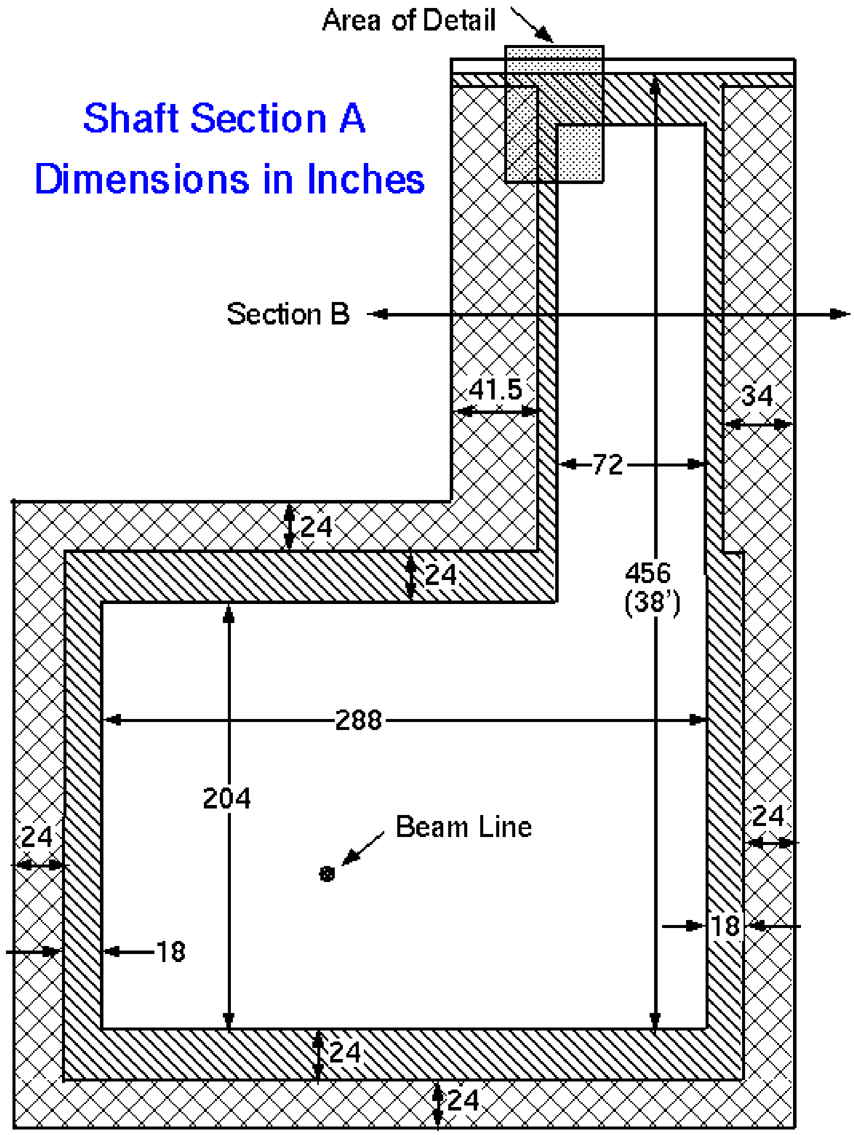

Figure 5. Section A through the shaft and target room showing dimensions in inches.

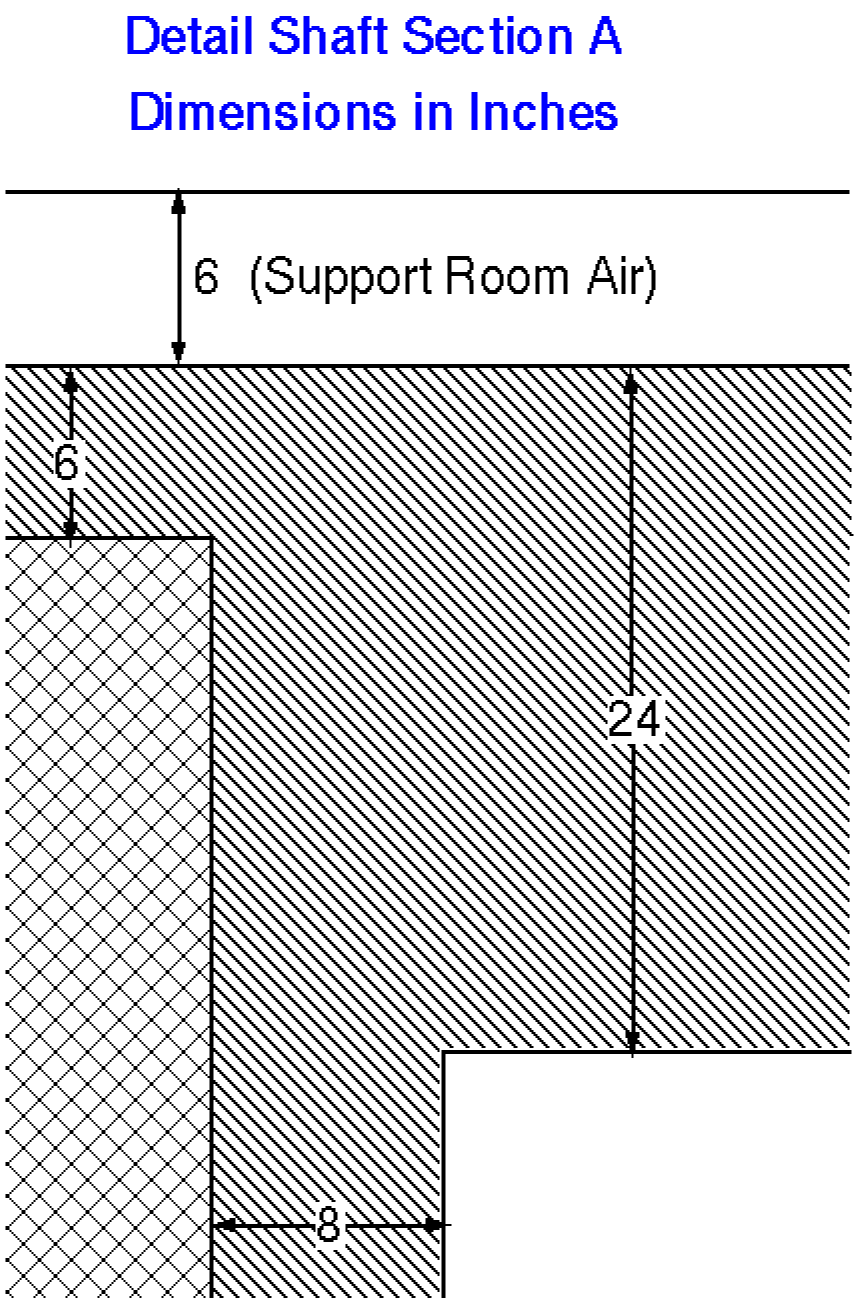

Figure 6. Detail of Figure 5, enlarging the top of the shaft, showing dimensions in inches.

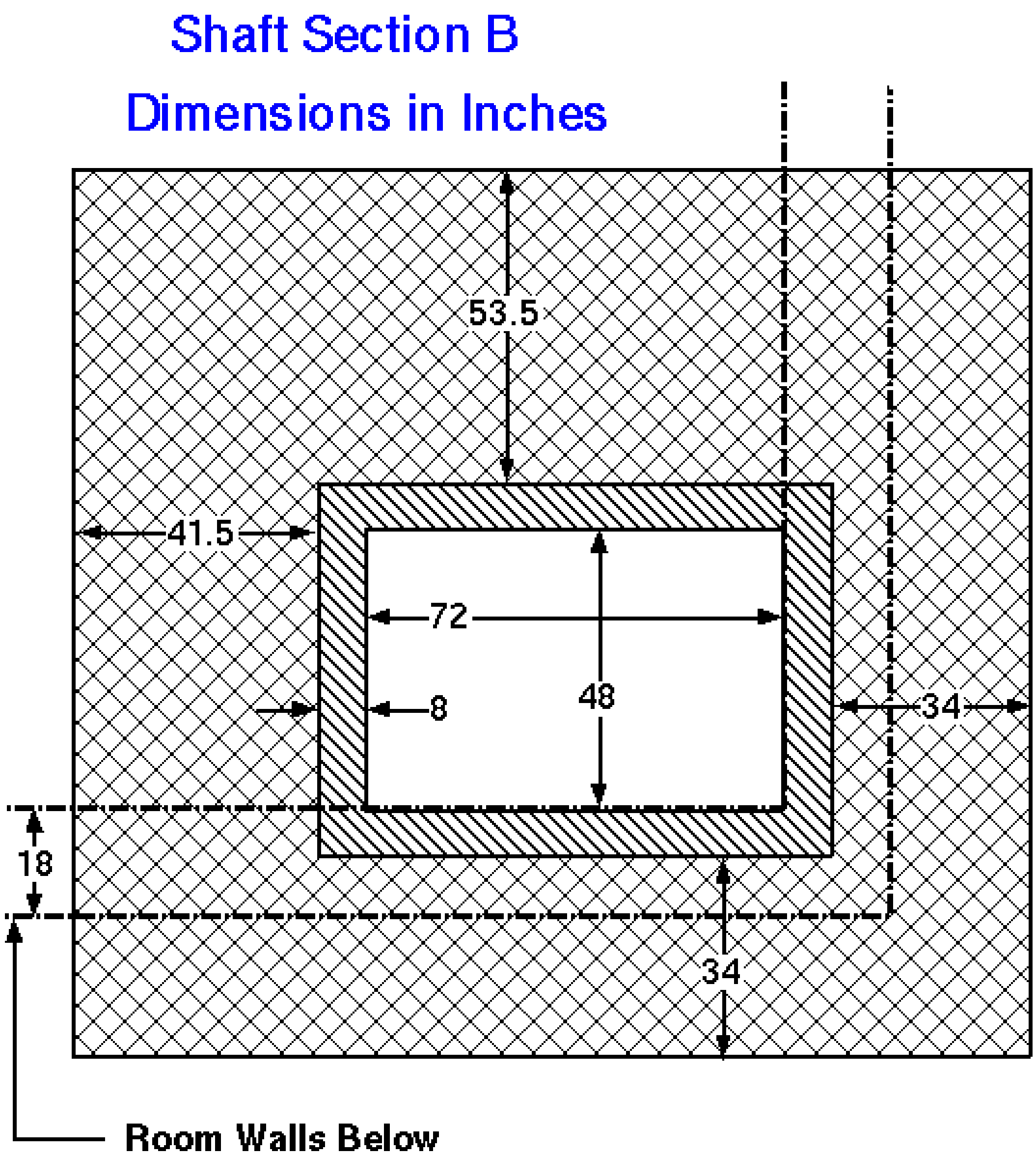

Figure 7. Section B through the shaft showing dimensions in inches.

Calculations

The methods in and use of the LAHET Code System (LCS)[2] and MCNP[3] are well documented in Progress Reports on activities for the IPF by Bill Wilson (T–2) and others[4]. All physics options for the LCS codes were as described in those Reports. Our work used LAHET version 2.83[5] and MCNP version 4B.

In brief, LAHET calculates the transport of protons, high energy (³ 20 MeV) neutrons, and a number of nuclear particles. A log of events is written to a history file that is processed to obtain tallies for the high energy neutron contribution to the Dose Equivalent Rate (DER) and a low energy neutron and photon source for MCNP. Transport of those particles by MCNP yields the remainder of the neutron DER and the photon DER.

Monte Carlo accuracy increases with, among other factors, the number of particles followed. A preliminary calculation showed that following 10,000,000 proton histories would result in an acceptable variance (£ 0.10) for the low energy neutron tallies at the top of the shaft; the results presented here are based on 10,000,000 proton histories. The MCNP run used the full history file written by LAHET.

Table 1 summarizes the codes run and their input and output files. Those files will be stored on the Common File System (CFS). In the Table, HE and LE stand for High Energy and Low Energy (above and below 20 MeV), respectively.

Table 1. Input and Output Files Stored on CFS

Code	Function	Input File	Output File
LAHET	Proton and HE Neutron Transport	`inhshaft`	`outhshaft`
HTAPE	HE Neutron Tallies	`intshaft`	`outtshaft`
PHT	Makes Photon Source for MCNP	`inph`	`outphshaft`
MCNP	LE Neutron and Photon Transport	`inpshaft`	`outpshaft`

Dose Equivalent Rate Tallies

The Dose Equivalent Rate (DER) was tallied at a number of volumes in the target room and access shaft. The DER was also tallied at a few surfaces near the top of the shaft. Figure 8 and Figure 9 show the positions of the tally volumes; the position of the tally surfaces are noted on Figure 9. The volumes in the target room extend the 109.5 inches from the front wall of the room to the plane defined by the front surface of the target shield (see Figure 3 and Figure 4). The volumes in the shaft extend across the air space in the shaft (the cross section for those volumes within the concrete of the plug is the same).

Appendix B lists the dose response functions by which neutron and photon fluxes are converted to DERs.

We list the Monte Carlo variance ("Var") in the Tables along with the tallied DERs. The variance is a measure of the statistical uncertainty of the answer. A widely accepted rule of thumb for Monte Carlo calculations is that a variance less than 0.1 is adequate and the true answer then lies within plus or minus the variance times the tally of the tallied DER. Variances larger than 0.5 indicate only a small number of particles reached the tally position; much credence cannot be given to the tallied DER.

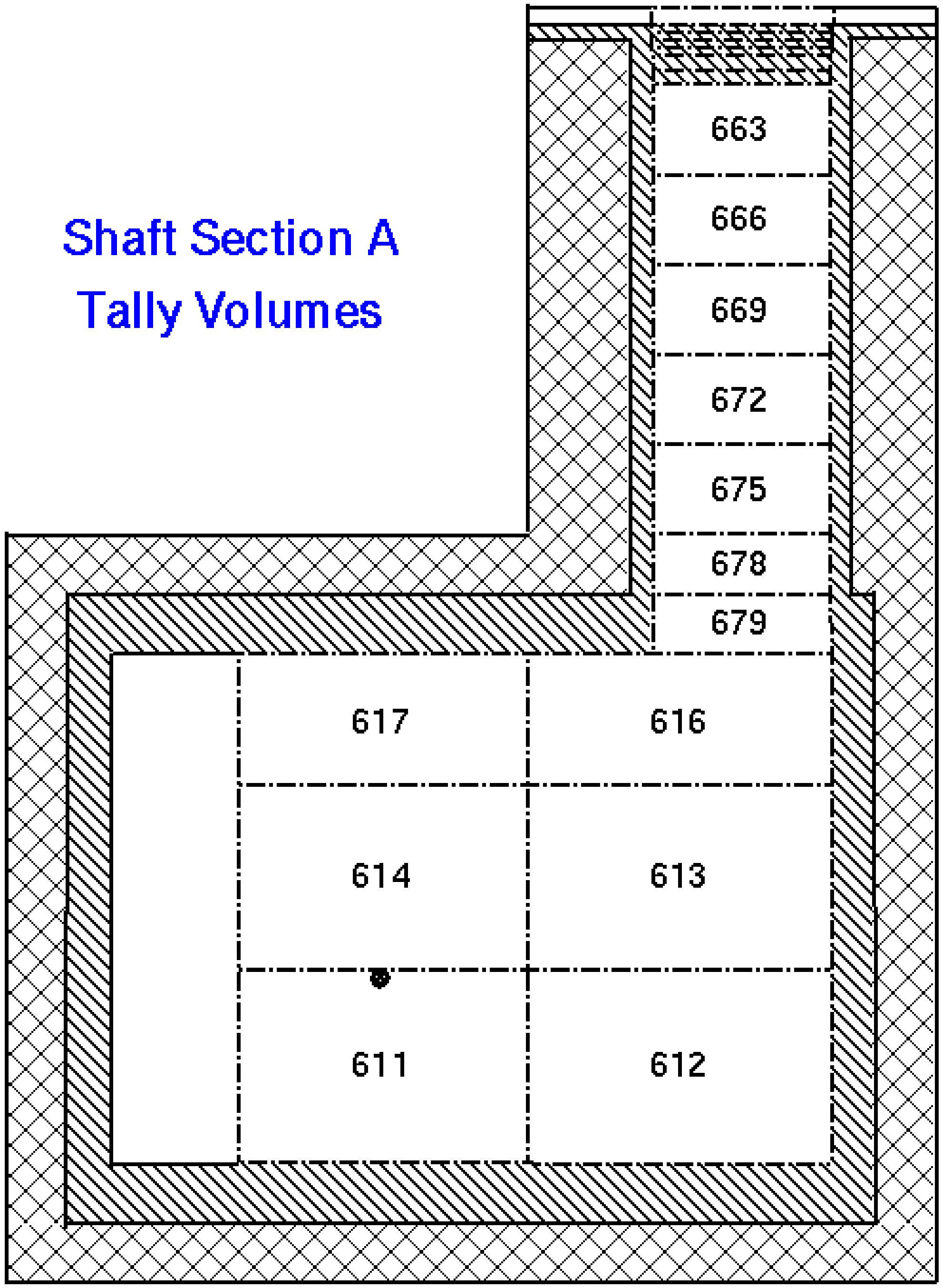

Figure 8. Section A through the target room and shaft showing the volumes in which the DER was tallied.

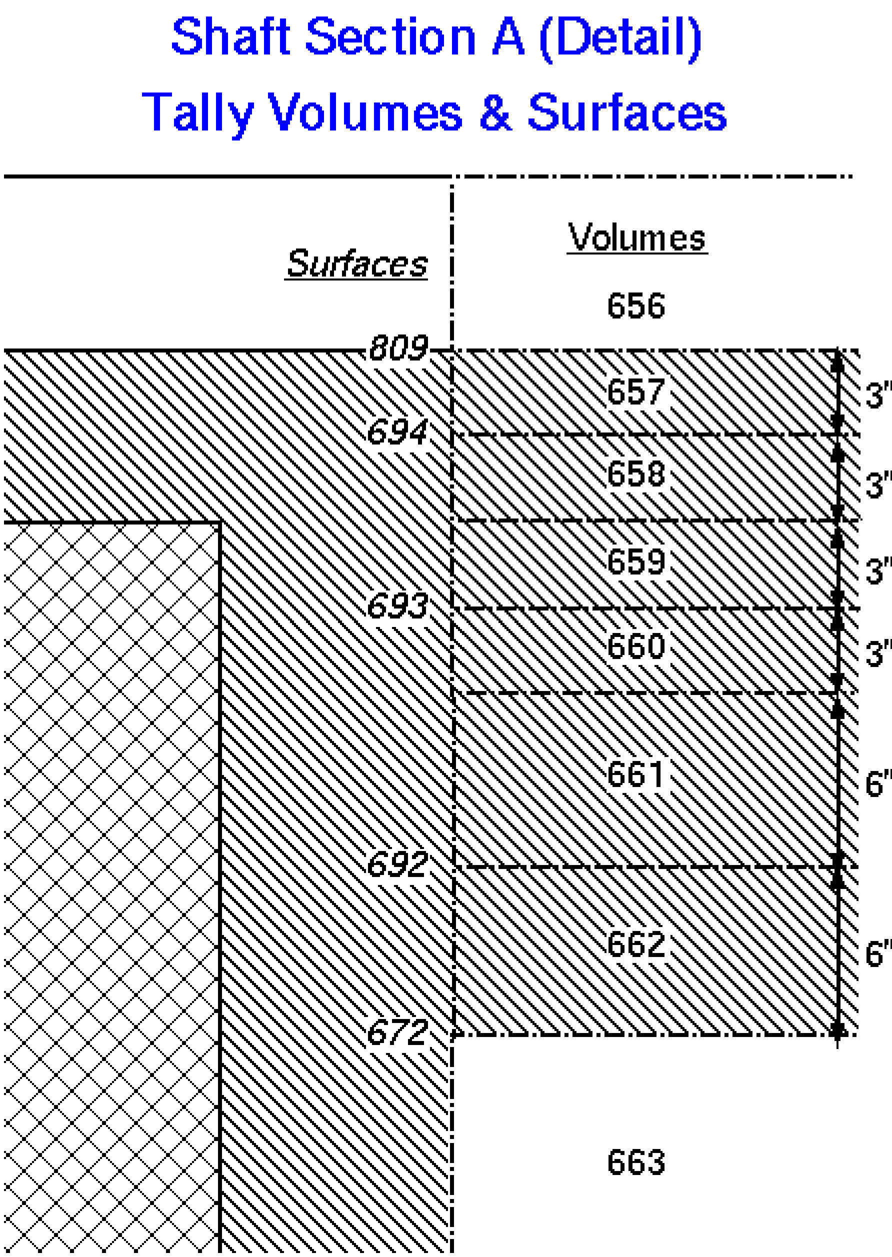

Figure 9. Detail of Section A through the top of the shaft showing the volumes and surfaces where the DER was tallied.

Results

Dose Equivalent Rates

Table 2 and Table 3 list the neutron and photon DERs in the target room and access shaft tally volumes and surfaces, respectively. Table 4 and Table 5 give the relative contributions of low and high energy neutrons and photons to the total DER for volumes and surfaces, respectively. Figure 10 and Figure 11 display the total DER throughout sections of the target room and shaft.

Table 2 . Dose Equivalent Rates in Volumes in the Target Room and Access Shaft.

	Neutrons					Photons		Total
	£ 20 MeV DER		> 20 MeV DER		Total DER	DER		DER
Volume	REM/hour	Var	REM/hour	Var	REM/hour	REM/hour	Var	REM/hour
611	558000	0.002	58300	0.004	616000	12600	0.002	629000
614	439000	0.002	46100	0.005	485000	9730	0.002	495000
617	152000	0.003	7680	0.012	160000	3140	0.004	163000
612	133000	0.004	6940	0.013	140000	2740	0.004	143000
613	124000	0.004	6580	0.014	131000	2630	0.004	134000
616	90500	0.004	3440	0.020	94000	1960	0.005	96000
679	48400	0.010	0.0008	0.720	48400	1190	0.009	49600
678	29600	0.011	0.01	0.529	29600	768	0.010	30400
675	15600	0.013	311	0.098	15900	444	0.010	16400
672	6200	0.014	45.5	0.123	6240	229	0.011	6470
669	3300	0.018	15.4	0.164	3320	142	0.012	3460
666	2040	0.022	7.46	0.231	2050	98.4	0.014	2150
663	1470	0.026	5.51	0.282	1480	79.9	0.014	1560
662	904	0.034	3.01	0.336	907	73.1	0.014	980
661	213	0.048	1.60	0.334	215	35.0	0.016	250
660	68.7	0.060	0.93	0.333	69.6	16.6	0.018	86.2
659	33.8	0.066	0.61	0.317	34.4	9.82	0.020	44.2
658	16.5	0.074	0.41	0.309	16.9	5.57	0.021	22.5
657	6.69	0.083	0.28	0.300	6.97	2.93	0.022	9.89
656	2.42	0.100	0.21	0.297	2.63	1.77	0.024	4.40

The DER decreases from the spill location and into the shaft. Just below the shaft plug, the DER is 1,560 REM/hour. The 2 foot plug diminishes the DER in the air volume above the plug to 4.4 REM/hour.

All low energy neutron and photon tallies have acceptable variances. The variances for the high energy neutrons in the shaft are somewhat larger. The high energy neutrons, however, contribute a small fraction of the total DER; the uncertainty in the total DER is dominated by the variance of the low energy neutrons and photons.

Table 3 . Dose Equivalent Rates Across Surfaces Near the Top of the Access Shaft.

	Neutrons					Photons		Total
	£ 20 MeV DER		> 20 MeV DER		Total DER	DER		DER
Surface	REM/hour	Var	REM/hour	Var	REM/hour	REM/hour	Var	REM/hour
692	404	0.043	2.12	0.339	406	52.3	0.015	458
693	47.0	0.064	0.75	0.331	47.8	12.7	0.019	60.5
694	10.8	0.077	0.32	0.305	11.1	4.05	0.022	15.1
672	229	0.029	0.76	0.288	229	17.3	0.012	247
809	0.61	0.094	0.05	0.261	0.66	0.53	0.019	1.19

Surfaces 692, 693, and 694 extend no further than across the airspace in the shaft. The DER on these surfaces is approximately the geometric mean of the DERs in the volumes on either side of the surface, thus showing consistency between the 2 sets of tallies. The tallies on surfaces 672 and 809 are averaged over the full cross section of the hatch model, including air, concrete, and earth. The ratio of the perpendicular cross section of the air space to the total cross section (see Figure 7) is 0.14. Dividing the DER on these 2 surfaces by the ratio gives a value that is 1.3 times the geometric mean of the DERs in the neighboring volumes. These 2 tallies show that the bulk, but not all, of the radiation flows through the shaft's air space.

Table 4. Fractional Contributions by Particle Type and Energy Range to the Dose Equivalent Rates in Tally Volumes in the Target Room and Access Shaft.

	Neutrons		Photons
Cell	£ 20 MeV	> 20 MeV	
611	0.89	0.093	0.02
614	0.89	0.093	0.02
617	0.93	0.047	0.02
612	0.93	0.049	0.02
613	0.93	0.049	0.02
616	0.94	0.036	0.02
679	0.98	0	0.02
678	0.97	0	0.02
675	0.95	0.019	0.03
672	0.96	0.007	0.04
669	0.95	0.004	0.04
666	0.95	0.003	0.04
663	0.94	0.004	0.05
662	0.92	0.003	0.07
661	0.85	0.006	0.14
660	0.80	0.011	0.19
659	0.76	0.014	0.22
658	0.73	0.018	0.25
657	0.68	0.028	0.30
656	0.55	0.048	0.40

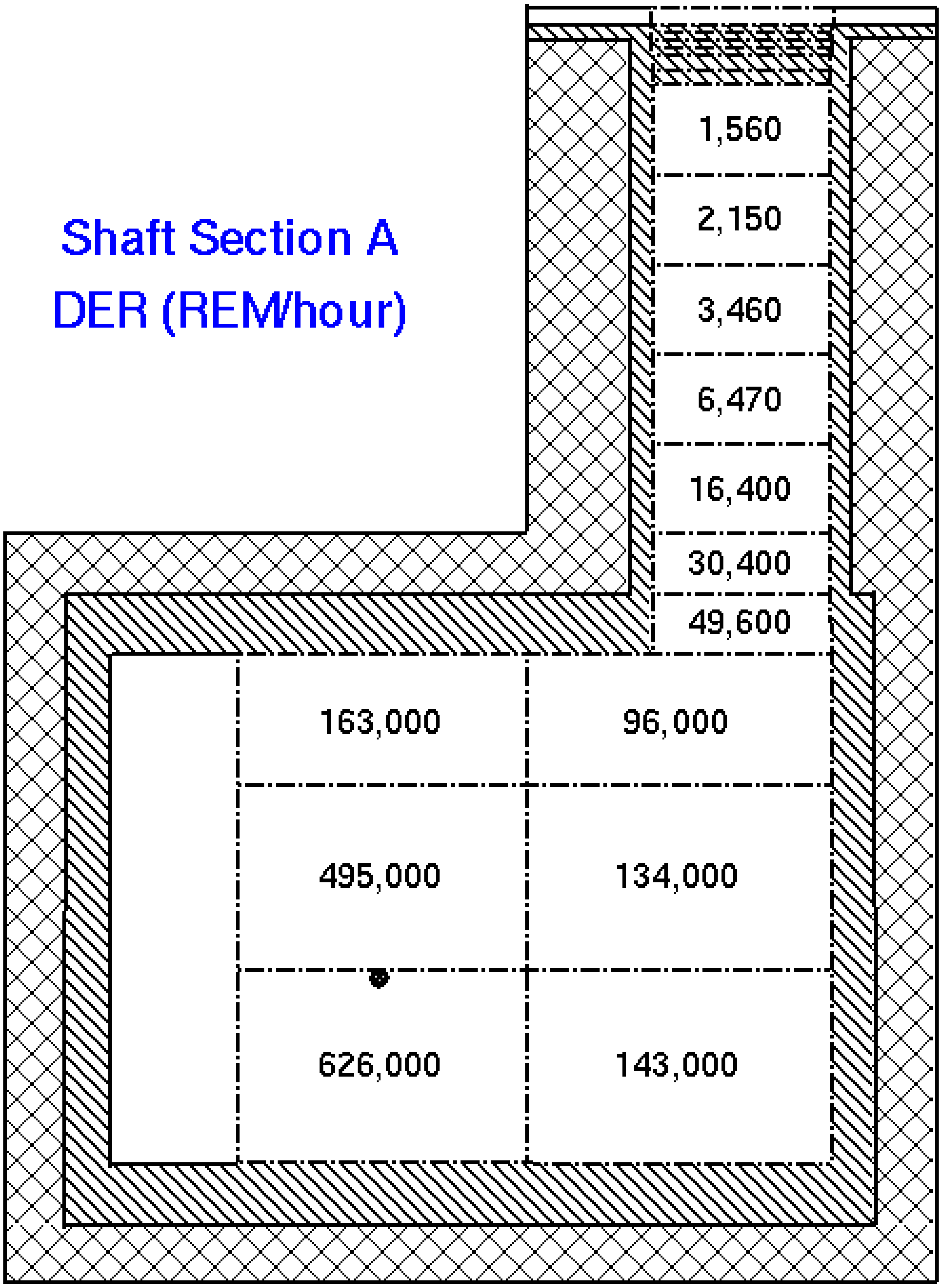

Figure 10. Dose Equivalent Rate, in REM/hour, at various volumes in section A of the target room and access shaft.

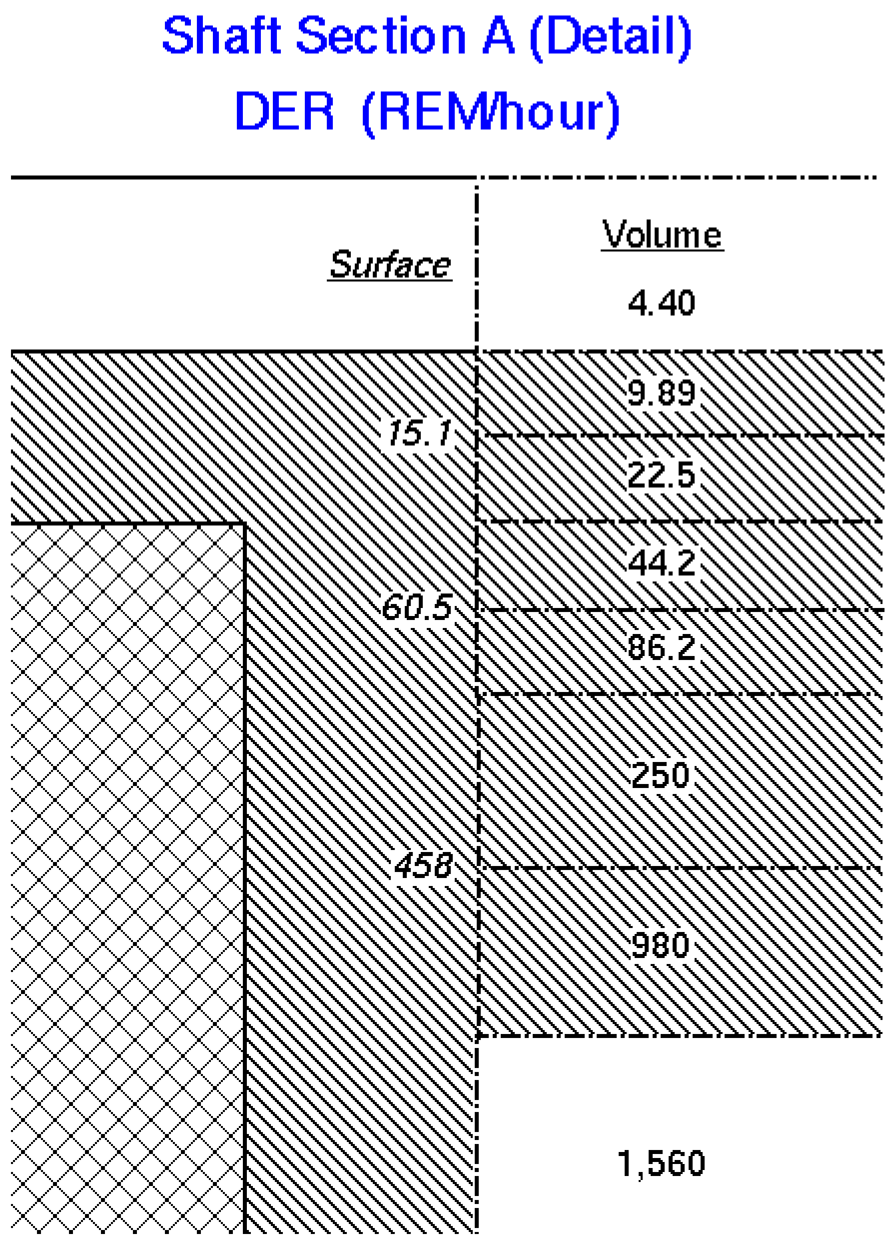

Figure 11. Dose Equivalent Rate, in REM/hour, in volumes and across surfaces near the top of the access shaft.

Table 5. Fractional Contributions by Particle Type and Energy Range to the Dose Equivalent Rates in Tally Surfaces Near the Top of the Access Shaft.

	Neutrons		Photons
Cell	**£ 20 MeV**	**> 20 MeV**	
692	0.88	0.005	0.11
693	0.78	0.012	0.21
694	0.71	0.021	0.27
672	0.93	0.003	0.07
809	0.51	0.042	0.45

APPENDIX A. Material Definitions

Following are the material definitions used in MCNP and LAHET. In the MCNP definition, the nuclide identifier ZZZAAA is followed by the atomic fraction of that constituent. Here ZZZ is the atomic number and AAA is the atomic mass. When AAA is 0, MCNP uses the naturally occurring isotopes of the element. S(a, b) cross sections are used for the H component of light water in those materials—concrete and sediment—containing water. The LAHET definition starts with a line giving the density of hydrogen (^1H) in atoms per cubic Angstrom, the number of other nuclides, and the number of nuclides for which neutron elastic scattering is used. For each additional nuclide, the atomic number, atomic mass, density (atoms per cubic Angstrom) and neutron elastic scattering table position follow.

Magnetite Concrete

Total Atom Density: 7.97855E-02 a b^{-1} cm^{-1}
Total Mass Density : 3.534000 g cm^{-3}

MCNP

```
 1001     6.57085E-03  1002     9.85776E-07
 8016     4.39628E-02 12000     8.17638E-04
13027     1.85249E-03 14000     1.95121E-03
16032     9.39055E-05 20000     3.77148E-03
22000     2.41493E-03 23000     1.30036E-04
24000     6.94906E-05 25055     7.67306E-05
26000     1.80730E-02
```

LAHET

```
6.57085E-03,37,33/
 1,  2,9.85776E-07, 1/ 8, 16,4.38573E-02,12/ 8, 17,1.75851E-05,13/
 8, 18,8.79256E-05,14/12, 24,6.45852E-04,16/12, 25,8.17638E-05,17/
12, 26,9.00219E-05,18/13, 27,1.85249E-03,19/14, 28,1.79960E-03,20/
14, 29,9.11215E-05,21/14, 30,6.04875E-05,22/16, 32,8.92290E-05,24/
16, 33,7.04291E-07,25/16, 34,3.95342E-06,26/16, 36,1.87811E-08,27/
20, 40,3.65611E-03,28/20, 44,7.86730E-05,29/22, 46,1.93194E-04,30/
22, 47,1.76290E-04,31/22, 48,1.78222E-03,32/22, 49,1.32821E-04,33/
22, 50,1.30406E-04,34/23, 50,3.25090E-07,35/23, 51,1.29711E-04,36/
24, 50,3.02284E-06,37/24, 52,5.82261E-05,38/24, 53,6.60160E-06,39/
24, 54,1.63998E-06,40/25, 55,7.67306E-05,41/26, 54,1.05185E-03,42/
26, 56,1.65910E-02,43/26, 57,3.79533E-04,44/26, 58,5.06044E-05,45/
20, 42,2.44015E-05, 0/20, 43,5.09150E-06, 0/20, 46,1.50859E-07, 0/
20, 48,7.05266E-06, 0/
```

Air

Total Atom Density: 4.08660E-05 a b^{-1} cm^{-1}
Total Mass Density : 9.872400E-04 g cm^{-3}

MCNP

```
  1001     1.75967E-10  1002     2.63992E-14
  2003     1.50545E-16  2004     1.07532E-10
  6012     5.98744E-09  6013     6.65947E-11
  7014     3.19374E-05  7015     1.18607E-07
  8016     8.61191E-06 16032     1.34301E-13
 18000     1.91724E-07 36078     8.18517E-14
 36080     5.26189E-13 36082     2.71279E-12
 36083     2.68941E-12 36084     1.33302E-11
 36086     4.04581E-12 54000     1.79399E-12
```

LAHET

```
1.75967E-10,32,12/
 1,  2,2.63992E-14, 1/ 2,  3,1.50545E-16, 3/ 6, 12,5.98744E-09, 9/
 6, 13,6.65947E-11,10/ 7, 14,3.19374E-05,11/ 8, 16,8.59124E-06,12/
 8, 17,3.44476E-09,13/ 8, 18,1.72238E-08,14/16, 32,1.27613E-13,24/
16, 33,1.00726E-15,25/16, 34,5.65407E-15,26/16, 36,2.68602E-17,27/
18, 36,6.46110E-10, 0/18, 38,1.20786E-10, 0/18, 40,1.90957E-07, 0/
36, 78,8.18517E-14, 0/36, 80,5.26189E-13, 0/36, 82,2.71279E-12, 0/
36, 83,2.68941E-12, 0/36, 84,1.33302E-11, 0/36, 86,4.04581E-12, 0/
54,124,1.79399E-15, 0/54,126,1.61459E-15, 0/54,128,3.42652E-14, 0/
54,129,4.73613E-13, 0/54,130,7.35536E-14, 0/54,131,3.80326E-13, 0/
54,132,4.82583E-13, 0/54,134,1.86575E-13, 0/54,136,1.59665E-13, 0/
 2,  4,1.07532E-10, 0/ 7, 15,1.18607E-07, 0/
```

Ordinary Concrete

Total Atom Density: 7.49809E-02 a b^{-1} cm^{-1}
Total Mass Density : 2.339000 g cm^{-3}

MCNP

```
  1001     7.76555E-03  1002     1.16501E-06
  8016     4.38499E-02 11023     1.04778E-03
 12000     1.48662E-04 13027     2.38815E-03
 14000     1.58026E-02 16032     5.63433E-05
 19000     6.93104E-04 20000     2.91501E-03
 26000     3.12719E-04
```

LAHET

```
7.76554E-03,29,22/
 1,  2,1.16501E-06, 1/ 8, 16,4.37446E-02,12/ 8, 17,1.75399E-05,13/
 8, 18,8.76997E-05,14/11, 23,1.04778E-03,15/12, 24,1.17428E-04,16/
12, 25,1.48662E-05,17/12, 26,1.63677E-05,18/13, 27,2.38815E-03,19/
14, 28,1.45747E-02,20/14, 29,7.37980E-04,21/14, 30,4.89880E-04,22/
16, 32,5.35373E-05,24/16, 33,4.22574E-07,25/16, 34,2.37205E-06,26/
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26, 58,8.75612E-07,45/19, 39,6.46375E-04, 0/19, 40,8.10931E-08, 0/
19, 41,4.66472E-05, 0/20, 42,1.88601E-05, 0/20, 43,3.93526E-06, 0/
20, 46,1.16600E-07, 0/20, 48,5.45106E-06, 0/
```

Stainless Steel 304 (SS-304)

Total Atom Density: 8.76287E-02 a b^{-1} cm^{-1}
Total Mass Density : 7.944000 g cm^{-3}

MCNP

```
 6012     3.15129E-04  6013     3.50500E-06
14000     1.70334E-03 15031     6.95027E-05
16032     4.47591E-05 24000     1.74810E-02
25055     1.74157E-03 26000     5.81184E-02
28000     8.15145E-03
```

LAHET

```
 .00000E+00,24,24/
 6, 12,3.15129E-04, 9/ 6, 13,3.50500E-06,10/14, 28,1.57099E-03,20/
14, 29,7.95460E-05,21/14, 30,5.28036E-05,22/15, 31,6.95027E-05,23/
16, 32,4.25301E-05,24/16, 33,3.35693E-07,25/16, 34,1.88436E-06,26/
16, 36,8.95182E-09,27/24, 50,7.60424E-04,37/24, 52,1.46473E-02,38/
24, 53,1.66070E-03,39/24, 54,4.12552E-04,40/25, 55,1.74157E-03,41/
26, 54,3.38249E-03,42/26, 56,5.33527E-02,43/26, 57,1.22049E-03,44/
26, 58,1.62732E-04,45/28, 58,5.56500E-03,46/28, 60,2.12753E-03,48/
28, 61,9.21114E-05,49/28, 62,2.92637E-04,50/28, 64,7.41782E-05,51/
```

Average Sediment

Total Atom Density: 2.33206E-02 a b^{-1} cm^{-1}
Source: CRC Handbook

MCNP

```
 1001     2.16060E-03  1002     3.24139E-07
 6012     3.18949E-03  6013     3.54748E-05
 8016     1.11268E-03 11023     1.91546E-04
12000     5.71632E-04 13027     3.22987E-03
14000     9.65725E-03 15031     1.31523E-05
16032     5.25206E-05 19000     2.52734E-04
20000     6.86371E-04 22000     1.07614E-04
26000     2.05936E-03
```

LAHET

```
2.16060E-03,37,30/
 1,  2,3.24139E-07, 1/ 6, 12,3.18949E-03, 9/ 6, 13,3.54748E-05,10/
 8, 16,1.11001E-03,12/ 8, 17,4.45072E-07,13/ 8, 18,2.22536E-06,14/
11, 23,1.91546E-04,15/12, 24,4.51532E-04,16/12, 25,5.71631E-05,17/
12, 26,6.29366E-05,18/13, 27,3.22987E-03,19/14, 28,8.90687E-03,20/
14, 29,4.50993E-04,21/14, 30,2.99374E-04,22/15, 31,1.31523E-05,23/
16, 32,4.99050E-05,24/16, 33,3.93904E-07,25/16, 34,2.21112E-06,26/
16, 36,1.05041E-08,27/20, 40,6.65374E-04,28/20, 44,1.43177E-05,29/
22, 46,8.60911E-06,30/22, 47,7.85581E-06,31/22, 48,7.94191E-05,32/
22, 49,5.91876E-06,33/22, 50,5.81115E-06,34/26, 54,1.19855E-04,42/
26, 56,1.89049E-03,43/26, 57,4.32465E-05,44/26, 58,5.76620E-06,45/
19, 39,2.35695E-04, 0/19, 40,2.95698E-08, 0/19, 41,1.70095E-05, 0/
20, 42,4.44082E-06, 0/20, 43,9.26600E-07, 0/20, 46,2.74548E-08, 0/
20, 48,1.28351E-06, 0/
```

Vacuum

Total Mass Density : 1.5E-12 g cm^{-3}

MCNP

```
 1001     1.20334E-07  1002     3.60779E-11
 2003     6.29819E-13  2004     5.97028E-07
 6012     1.73421E-01  6013     2.09014E-03
 7014     6.20346E-01  7015     2.46784E-03
 8016     1.91047E-01 18000     1.06238E-02
36078     8.84688E-09 36080     5.83296E-08
36082     3.08236E-07 36083     3.09313E-07
36084     1.55156E-06 36086     4.82130E-07
54000     3.26719E-07
```

LAHET

```
1.80501E-19,28, 8/
 1,  2,5.41169E-23, 1/ 2,  3,9.44729E-25, 3/ 6, 12,2.60132E-13, 9/
 6, 13,3.13521E-15,10/ 7, 14,9.30520E-13,11/ 8, 16,2.85883E-13,12/
 8, 17,1.14628E-16,13/ 8, 18,5.73141E-16,14/18, 36,5.37033E-17, 0/
18, 38,1.00395E-17, 0/18, 40,1.58720E-14, 0/36, 78,1.32703E-20, 0/
36, 80,8.74945E-20, 0/36, 82,4.62354E-19, 0/36, 83,4.63970E-19, 0/
36, 84,2.32734E-18, 0/36, 86,7.23195E-19, 0/54,124,4.90079E-22, 0/
54,126,4.41071E-22, 0/54,128,9.36051E-21, 0/54,129,1.29381E-19, 0/
54,130,2.00932E-20, 0/54,131,1.03897E-19, 0/54,132,1.31831E-19, 0/
54,134,5.09682E-20, 0/54,136,4.36170E-20, 0/ 2,  4,8.95543E-19, 0/
 7, 15,3.70176E-15, 0/
```

SEG Steel Blocks

Total Mass Density : 7.5146 g cm^{-3}
Source: Shield block 255S201 quality control checklist (Jeff Bull)

MCNP

```
 6012     4.64518E-04  6013     5.16657E-06
13027     7.20074E-05 14000     2.42207E-04
15031     3.51854E-05 24050     9.96649E-06
24052     1.91975E-04 24053     2.17659E-05
24054     5.40711E-06 25055     1.12921E-04
26054     4.64326E-03 26056     7.32389E-02
26057     1.67540E-03 26058     2.23386E-04
28058     1.67589E-04 28060     6.40702E-05
28061     2.77391E-06 28062     8.81273E-06
28064     2.23386E-06 29063     2.37718E-04
29065     1.05954E-04 42000     9.00093E-07
```

LAHET

```
 .00000E+00,30,30/
 6, 12,4.64518E-04, 9/ 6, 13,5.16657E-06,10/13, 27,7.20074E-05,19/
14, 28,2.23387E-04,20/14, 29,1.13111E-05,21/14, 30,7.50842E-06,22/
15, 31,3.51854E-05,23/24, 50,9.96649E-06,37/24, 52,1.91975E-04,38/
24, 53,2.17659E-05,39/24, 54,5.40711E-06,40/25, 55,1.12921E-04,41/
26, 54,4.64326E-03,42/26, 56,7.32389E-02,43/26, 57,1.67540E-03,44/
26, 58,2.23386E-04,45/28, 58,1.67589E-04,46/28, 60,6.40702E-05,48/
28, 61,2.77391E-06,49/28, 62,8.81273E-06,50/28, 64,2.23386E-06,51/
```

```
29, 63,2.37718E-04,52/29, 65,1.05954E-04,54/42, 92,1.33574E-07,61/
42, 94,8.32586E-08,62/42, 95,1.43295E-07,63/42, 96,1.50135E-07,64/
42, 97,8.59589E-08,65/42, 98,2.17192E-07,66/42,100,8.66789E-08,67/
1.80501E-19,28, 8/
```

Natural H20

Total Mass Density :   1.00000 g cm^{-3}

MCNP

```
1001     1.9997       1002     3.0000E-04
8016     1
```

LAHET

```
6.68446E-02, 4, 4/
 1,  2,1.00282E-05, 1/ 8, 16,3.33471E-02,12/ 8, 17,1.33709E-05,13/
 8, 18,6.68547E-05,14/
```

APPENDIX B. Dose Response Functions

Table 6. Neutron Dose Response Function

Neutron Energy E (MeV)	DF (E) (REM/hr)/(n/cm^2/s)
1.0e-11	3.68e-6
1.00e-7	3.68e-6
2.50e-7	3.92e-6
5.00e-7	4.28e-6
1.00e-6	4.46e-6
1.00e-5	4.46e-6
2.50e-5	4.43e-6
5.00e-5	4.37e-6
1.00e-4	4.31e-6
2.50e-4	4.07e-6
5.00e-4	3.87e-6
1.00e-3	3.68e-6
2.50e-3	3.78e-6
5.00e-3	4.32e-6
1.00e-2	6.12e-6
2.00e-2	9.00e-6
5.00e-2	1.80e-5
1.00e-1	2.88e-5
2.00e-1	4.68e-5
5.00e-1	9.00e-5
1.00e+0	1.08e-4
2.00e+0	1.26e-4
5.00e+0	1.44e-4
2.00e+2	1.44e-4

Table 7. Photon Dose Response Function

Neutron Energy E (MeV)	DF (E) (REM/hr)/(n/cm^2/s)
5.00E-3	5.87E-7
3.00E-2	5.87E-7
5.00E-2	2.82E-7
7.00E-2	2.66E-7
1.00E-1	2.77E-7
1.50E-1	3.83E-7
2.00E-1	5.18E-7
2.50E-1	6.20E-7
3.00E-1	7.56E-7
3.50E-1	8.66E-7
4.00E-1	9.77E-7
4.50E-1	1.07E-6
5.00E-1	1.17E-6
5.50E-1	1.26E-6
6.00E-1	1.36E-6
6.50E-1	1.45E-6
7.00E-1	1.53E-6
8.00E-1	1.69E-6
1.00E+0	2.00E-6
1.40E+0	2.50E-6
1.80E+0	3.00E-6
2.20E+0	3.40E-6
2.60E+0	3.79E-6
2.80E+0	4.00E-6
3.25E+0	4.40E-6
3.75E+0	4.82E-6
4.25E+0	5.23E-6
4.75E+0	5.62E-6
5.00E+0	5.81E-6
5.25E+0	6.00E-6
5.75E+0	6.38E-6
6.25E+0	6.75E-6
6.75E+0	7.11E-6
7.50E+0	7.66E-6
9.00E+0	8.76E-6
1.10E+1	1.02E-5
1.30E+1	1.18E-5
1.50E+1	1.33E-5
3.00E+1	2.34E-5

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