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An Updated Review of Soil Radioactivation Calculations for the Anti-Proton Target Area

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Abstract

The quantities of ^{3}H and ^{22}Na produced in the soil surrounding the anti-proton target station and the quantities of those radionuclides reaching the Siluria aquifer are calculated for the construction design of the target station, five variations of a proposed target and collection system, and a given scenario for the Fermilab anti-proton source. In addition, a comparision is made between the Environmental Protection Administration limits for concentrations of ^{3}H and ^{22}Na in community water supplies and the estimated concentrations due to the anti-proton target station.

Motivation

In September of 1978 Peter Gollon published calculations for soil radioactivation around the anti-proton target station.[1] In that work a particular set of anticipated operating parameters was assumed. Since that time many of these parameters have changed forcing an additional calculation to be performed. This paper presents a summary of this new work which closely follows that of Gollon.

Geometry

Five different geometries have been examined. The first is a design which might be used for normal operation. It includes, along with the construction design of the area,[2] a tungsten target, an upstream iron shield, a collection system of iron magnets, and a dump consisting of beryllium oxide, aluminum, and iron. This geometry is shown in Figure 1 and further detailed in Appendix A. Material parameters are listed in Table 1. The other four geometries are variations of the first. The second geometry examined does not include the collection system as might be done for targeting studies. The third geometry replaces the iron in the dump with concrete. This might be done to facilitate movement of the dump at some later date. The fourth and fifth geometries are possible configurations for extraction and transport studies. In the fourth the target has been

removed while in the fifth both the target and collection system are missing. Table 2 lists the different geometries in tabular form. A deviation from one of these systems should be checked by an additional calculation.

The shielding around the target area consists of a combination of iron, concrete, dense aggregate fill, and earth. The dense aggregate fill is an iron ore plus cement mix. An impervious membrane or 'bathtub' and a series of underdrains serve to collect the water containing most of the leachable radionuclides. The iron and dense aggregate fill have been placed only where deemed needed. Cross sections of both the anti-proton hall (upstream of coordinate system origin) and the target hall (downstream of coordinate system origin) are shown in Figures 2 and 3. Figure 4 prisents both a plan view and a longitudinal section of target station as well as a definition of the coordinate system.

Figures 5, 6, and 7 give details to the water collection assumptions used in this calculation. All radionuclides originating above the impervious membrane were assumed to have been collected for disposal as radioactive waste. Therefore only radionuclides produced in the regions labelled 'unprotected soil' have been used in the environmental protection calculations. This is a significant departure from the previous study mentioned above in which all radionuclides originating above the

bathtub, or in the gravel backfill but above the center of the secondary underdrain were assumed to have been collected.

Radionuclide Production

The total number of atoms of each radionuclide which are produced in the unprotected soil per year may be written as the product

$$N_i = P * S * K_i$$

where P = number of incident protons per year,

S = number of stars (hadron-nucleus interactions) produced in unprotected soil per incident proton,

and K_i = probability that an atom of the i-th radionuclide will be produced at each star.

In the more convenient units of Curies per year

$$C_i = \frac{P * S * K_i}{\tau_i * 3.7E10}$$

where τ_i = the mean life of the i-th radionuclide in seconds.

The number of protons incident per year is based on 2E13 protons per pulse and a 4 second cycle time. Furthermore, it is assumed that the accelerator will operate 44 out of every 52 weeks in a year, that each week will consist of 120 hours of actual operation, and that anti-proton physics will be run for one half of the total physics program. We thus

have about 4.8E19 protons incident per year. This is identical to the previous study although some of the assumptions have changed.

The star production in unprotected soil was calculated for the geometries and materials discussed above using a derivative of the Monte Carlo program CASIM.[3,4+5] This version of CASIM makes use of an integral estimator for star production in soil due to particles above a lower momentum limit of 0.3 GeV/c. In each run the stars produced in unprotected soil were totaled five different ways to aide in understanding the results. Figure 8 gives details to the totaling method used for all reported results and calculations. In this method each region is simply a horizontal slab.

The results of four runs, of one million stars each, for each of the first three geometries described above are listed Tables 3, 4, and 5. These runs are considered to be independent estimates of the same quantities since for each run a different random number generator seed was used. Tables 6, 7, and 8 present the mean values of the results in Tables 3, 4, and 5 respectively and their standard deviations. The standard deviations are those given by the fluctuations in the results of the four runs. The results of calculations for the fourth and fifth geometries are listed in Table 9.

Following the arguments of Gollon, values of K_i for ^3H

and ^{22}Na are chosen to be 0.075 atoms of ^{3}H per star and 0.020 atoms of ^{22}Na per star. The mean lives are calculated from the half lives of ^{3}H and ^{22}Na by divided by ln(2). This yields values of 5.58E8 seconds and 1.18E8 seconds for ^{3}H and ^{22}Na respectivily. and 1.18E8 seconds respectivily.

The quantity of the i-th radionuclide which is leached and transported to the aquifer while decaying en route is

$$m_i = C_i * f_i * \exp(-D / (v_i * \tau_i))$$

where f_i = the fraction of the i-th radionuclide leached,

D = vertical distance to the top of the aquifer in feet,

and v_i = vertical velocity in feet per year of the i-th radionuclide.

Here, f_i is taken to be 1.0 for ^{3}H and 0.2 for ^{22}Na while the velocities of H and Na are assumed to be 7.2 feet per year and 3.2 feet per year respectively.

Inserting the results in Tables 6, 7, and 8 into the above equations the quantities of ^{3}H and ^{22}Na produced in the unprotected soil, the quantities of those radionuclides reaching the Siluria aquifer and their yearly totals are calculated and listed in Tables 10, 11, and 12. Since the results in Table 9 are substantially lower than any of the other results no similar calculations are reported for these.

Upon first glance the third geometry, with concrete

substituted for the iron in the dump, seems to have the best shielding. This is caused by a flaw in the totaling method used for the calculations. The far downstream region (greater than about 32 meters downstream of the target) is not included in the calculations. Hence, with concrete, more of the hadrons escape to an uncounted region. (The total stars per incident proton jumps from about 4E-4 to 2E-1 as the iron is changed into concrete.) This and other results point out to the need for a longer dump when using concrete. Either additional concrete or iron must be added to this geometry.

To make a comparision between these totals and the Environmental Protection Administration limits for ^{3}H and ^{22}Na in drinking water supplies in the absence of all other radionuclides of 20 pCi/ml for ^{3}H and 0.2 pCi/ml for ^{22}Na the standard Fermilab model is used. It is assumed that all the activity reaching the aquifer happens to flow into a single well used by only one person. This person uses 40 gallons of water per day from this well.

Finally, for the worst case, that of the first geometry, the concentrations are calculated to be 12.2 pCi/ml of ^{3}H and 0.068 pCi/ml of ^{22}Na. Since the EPA limits are for concentrations in the absense of all other radionuclides the sum of the two above concentrations divided by their respective limits must be less than 1.0. For this case this weighted sum is calculated to be 0.95. Thus for the

assumptions given here the concentrations of H and Na radionuclides in groundwater will be below all present Federal limits.

Acknowledgments

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References

1. Peter J. Gollon, 'Soil Activation Calculations for the Anti-proton Target Area', Fermilab TM-816 (Sept., 1978).

2. Anti-proton construction drawing package, Dwg. 5-1-6b, and Dwg. 5-1-6c.

3. A. Van Ginneken, 'CASIM. Program to Simulate Hadronic Casicades in Bulk Matter', Fermilab FN-272 (Jan., 1975).

4. A. Van Ginneken, 'Integral Estimators of Radionuclide Production in Soil', Fermilab TM-856 (March 6, 1979).

5. C. V. Canada, N. V. Mokhov and A. Van Ginneken, 'Conversion of Program CASIM to CDC Cyber Computers', Fermilab TM-1009 (Oct., 1980).

Tables

1. Materials used and their parameters.

2. Geometries studied.

3. Stars produced in unprotected soil per incident proton using geometry 1.

4. Stars produced in unprotected soil per incident proton using geometry 2.

5. Stars produced in unprotected soil per incident proton using geometry 3.

6. Stars produced in unprotected soil per incident proton using geometry 1 (mean values and standard deviations).

7. Stars produced in unprotected soil per incident proton using geometry 2 (mean values and standard deviations).

8. Stars produced in unprotected soil per incident proton using geometry 3 (mean values and standard deviations).

9. Stars produced in unprotected soil per incident proton using geometries 4 and 5.

10. Radionuclide quantities produced in unprotected soil per year and radionuclide quantities reaching the Siluria per year using geometry 1.

11. Radionuclide quantities produced in unprotected soil per year and radionuclide quantities reaching the Siluria per year using geometry 2.

12. Radionuclide quantities produced in unprotected soil per year and radionuclide quantities reaching the Siluria per year using geometry 3.

Materials used and their parameters

Material	Typical Objects	Atomic Number	Atomic Weight amu	Density gm/cm^3	Critical Energy MeV
Tungsten	Target	74.00	183.85	19.30	8.70
Iron	Magnets, Dump, and Shielding	26.00	55.85	7.86	25.10
BeO	Dump Core	6.38	13.16	2.85	75.20
Dense Aggregate Fill	Shielding	23.73	50.77	3.20	25.00
Concrete	Walls	8.00	22.00	2.40	85.00
Soil	Soil	8.00	22.00	2.00	85.00
Aluminum	Dump	13.00	26.98	2.70	49.00

Geometry	Description
1	Figure 1
2	Figure 1 minus collection system
3	Figure 1 with concrete replacing iron in dump
4	Figure 1 minus target
5	Figure 1 minus target and collection system

Region	Distance to Aquifer ft	Stars (>0.3 GeV/c) in unprotected soil per incident proton using Geometry 1			
		run 1	run 2	run 3	run 4
1	62.9	2.19×10^{-3}	2.22×10^{-3}	1.70×10^{-3}	2.04×10^{-3}
2	54.7	1.34×10^{-3}	1.83×10^{-3}	1.71×10^{-3}	2.18×10^{-3}
3	46.5	1.46×10^{-3}	1.70×10^{-3}	2.29×10^{-3}	1.92×10^{-3}
4	38.3	2.16×10^{-4}	3.66×10^{-4}	2.55×10^{-4}	2.07×10^{-4}
5	17.8	2.93×10^{-5}	3.12×10^{-5}	5.94×10^{-5}	2.49×10^{-5}

Region	Distance to Aquifer ft	Stars (>0.3 GeV/c) in unprotected soil per incident proton using Geometry 2			
		run 1	run 2	run 3	run 4
1	62.9	1.40×10^{-3}	1.65×10^{-3}	3.46×10^{-3}	1.64×10^{-3}
2	54.7	4.40×10^{-4}	5.12×10^{-4}	9.79×10^{-4}	6.79×10^{-4}
3	46.5	1.04×10^{-3}	7.49×10^{-4}	9.70×10^{-4}	1.69×10^{-3}
4	38.3	1.40×10^{-4}	1.22×10^{-4}	1.14×10^{-4}	1.90×10^{-4}
5	17.8	1.73×10^{-5}	2.02×10^{-5}	3.39×10^{-5}	2.16×10^{-4}

Region	Distance to Aquifer ft	Stars (>0.3 GeV/c) in unprotected soil per incident proton using Geometry 3			
		run 1	run 2	run 3	run 4
1	62.9	1.97×10^{-3}	1.42×10^{-3}	1.41×10^{-3}	1.33×10^{-3}
2	54.7	1.51×10^{-3}	1.92×10^{-3}	2.05×10^{-3}	1.97×10^{-3}
3	46.5	1.29×10^{-3}	1.41×10^{-3}	2.27×10^{-3}	1.50×10^{-3}
4	38.3	3.53×10^{-4}	1.61×10^{-4}	4.73×10^{-4}	2.98×10^{-4}
5	17.8	1.33×10^{-5}	4.77×10^{-5}	3.63×10^{-5}	3.83×10^{-5}

Region	Stars (>0.3 GeV/c) in unprotected soil per incident proton using Geometry 1
1	$(2.04 \pm 0.20) \times 10^{-3}$
2	$(1.77 \pm 0.30) \times 10^{-3}$
3	$(1.84 \pm 0.31) \times 10^{-3}$
4	$(2.61 \pm 0.63) \times 10^{-4}$
5	$(3.62 \pm 1.36) \times 10^{-5}$

table 6

Region	Stars (>0.3 GeV/c) in unprotected soil per incident proton using Geometry 2
1	$(2.04 \pm 0.83) \times 10^{-3}$
2	$(6.53 \pm 2.07) \times 10^{-4}$
3	$(1.11 \pm 0.35) \times 10^{-3}$
4	$(1.42 \pm 0.30) \times 10^{-4}$
5	$(7.19 \pm 8.35) \times 10^{-5}$

Region	Stars (>0.3 GeV/c) in unprotected soil per incident proton using Geometry 3
1	$(1.53 \pm 0.26) \times 10^{-3}$
2	$(1.86 \pm 0.21) \times 10^{-3}$
3	$(1.62 \pm 0.34) \times 10^{-3}$
4	$(3.21 \pm 1.12) \times 10^{-4}$
5	$(3.39 \pm 1.26) \times 10^{-5}$

table 8

Region	Distance to Aquifer ft	Stars (>0.3 GeV/c) in unprotected soil per incident proton using Geometries 4 + 5	
		geometry 4 no target	geometry 5 no target and no magnets
1	62.9	1.58×10^{-6}	1.58×10^{-6}
2	54.7	1.78×10^{-5}	2.60×10^{-5}
3	46.5	4.43×10^{-6}	4.45×10^{-6}
4	38.3	4.27×10^{-7}	4.30×10^{-7}
5	17.8	9.10×10^{-9}	3.84×10^{-8}

Region	Radionuclide production using geometry 1 in Curies per year			
	^{3}H		^{22}Na	
	total	leached	total	leached
1	3.53×10^{-4}	2.16×10^{-4}	4.44×10^{-4}	4.72×10^{-7}
2	3.06×10^{-4}	1.99×10^{-4}	3.85×10^{-4}	8.11×10^{-7}
3	3.19×10^{-4}	2.21×10^{-4}	4.00×10^{-4}	1.67×10^{-6}
4	4.52×10^{-5}	3.35×10^{-5}	5.68×10^{-5}	4.68×10^{-7}
5	6.27×10^{-6}	5.45×10^{-6}	7.88×10^{-6}	3.58×10^{-7}
total	1.03×10^{-3}	6.75×10^{-4}	1.29×10^{-3}	3.78×10^{-6}

Region	Radionuclide Production using geometry 2 in Curies per year			
	^{3}H		^{22}Na	
	total	leached	total	leached
1	3.53×10^{-4}	2.16×10^{-4}	4.44×10^{-4}	4.72×10^{-7}
2	1.13×10^{-4}	7.36×10^{-5}	1.42×10^{-4}	2.99×10^{-7}
3	1.92×10^{-4}	1.33×10^{-4}	2.42×10^{-4}	1.01×10^{-6}
4	2.46×10^{-5}	1.82×10^{-5}	3.09×10^{-5}	2.55×10^{-7}
5	1.25×10^{-5}	1.08×10^{-5}	1.56×10^{-5}	7.11×10^{-7}
total	6.96×10^{-4}	4.52×10^{-4}	8.74×10^{-4}	2.74×10^{-6}

Region	Radionuclide production using geometry 3 in Curies per year			
	^{3}H		^{22}Na	
	total	leached	total	leached
1	2.65×10^{-4}	1.62×10^{-4}	3.33×10^{-4}	3.54×10^{-7}
2	3.22×10^{-4}	2.10×10^{-4}	4.05×10^{-4}	8.52×10^{-7}
3	2.81×10^{-4}	1.95×10^{-4}	3.52×10^{-4}	1.47×10^{-6}
4	5.56×10^{-5}	4.11×10^{-5}	6.98×10^{-5}	5.76×10^{-7}
5	5.87×10^{-6}	5.10×10^{-6}	7.38×10^{-6}	3.35×10^{-7}
total	9.29×10^{-4}	6.12×10^{-4}	1.17×10^{-3}	3.59×10^{-6}

Figures

1. Geometry 1.

2. Cross section thru anti-proton hall.

3. Cross section thru target hall.

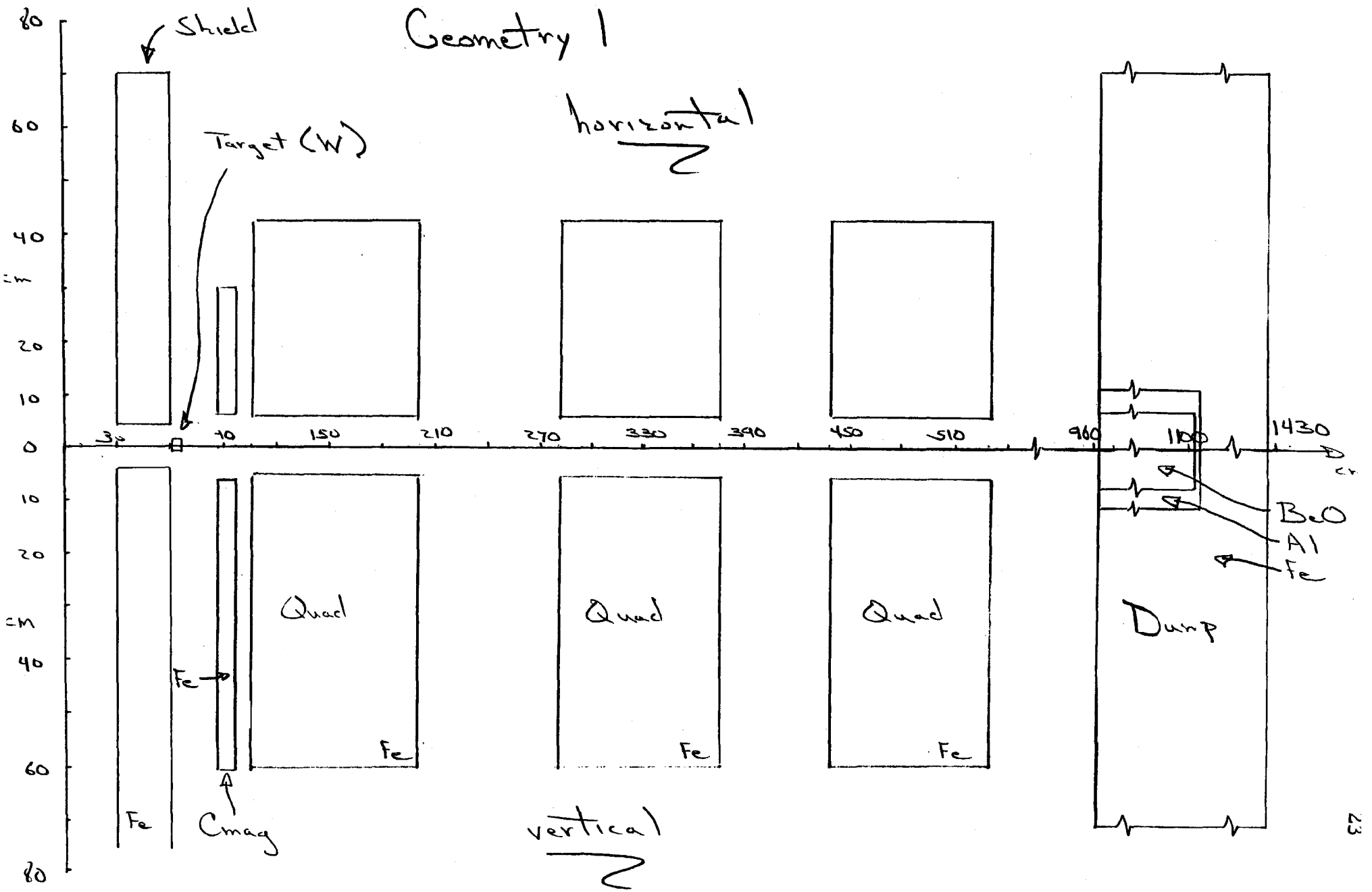
4. Plan view and longitudinal section of target station.

5. Cross section thru anti-proton hall (water collection details).

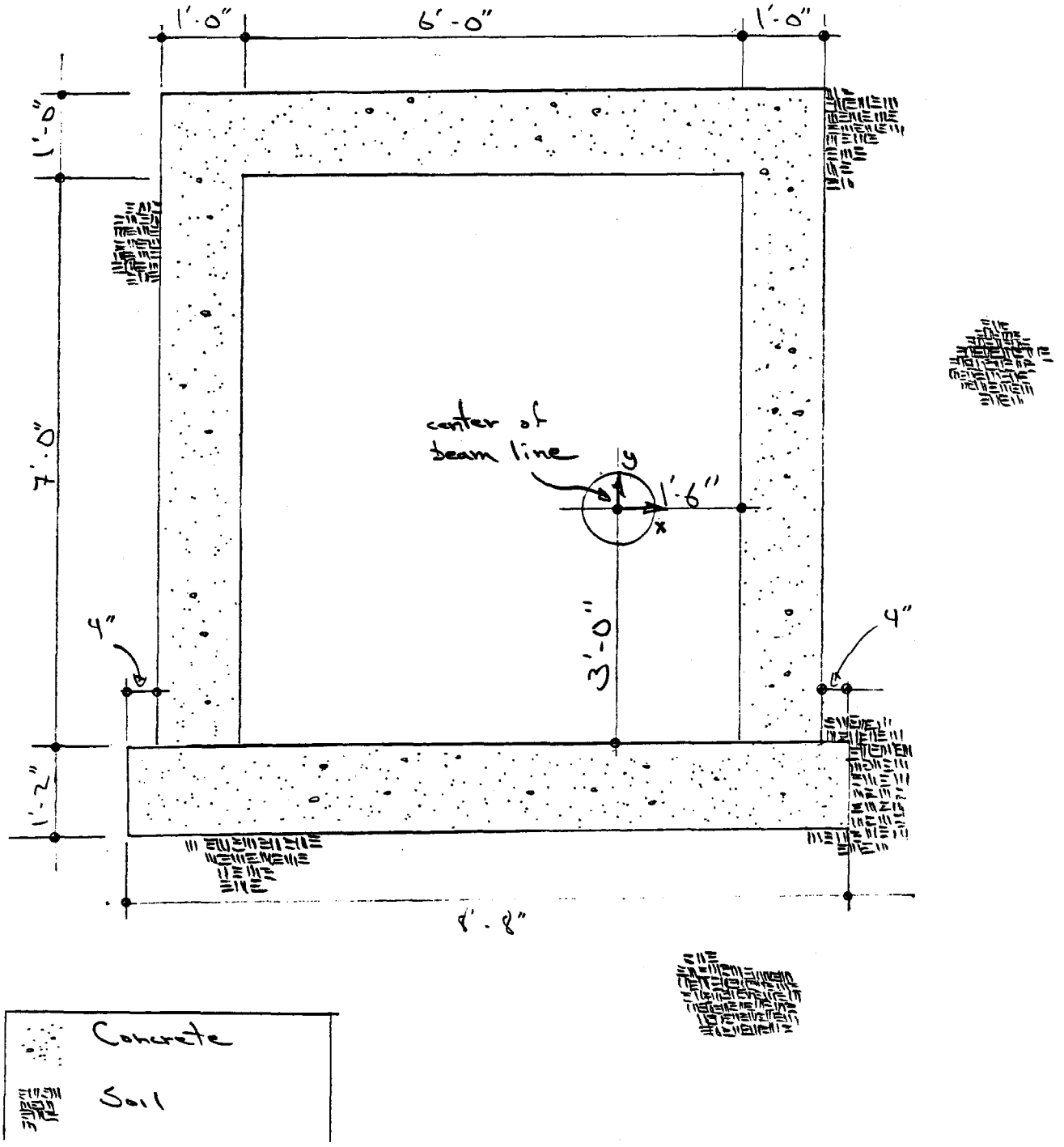
6. Cross section thru target hall (water collection details).

7. Plan view and longitudinal section of target station (water collection details).

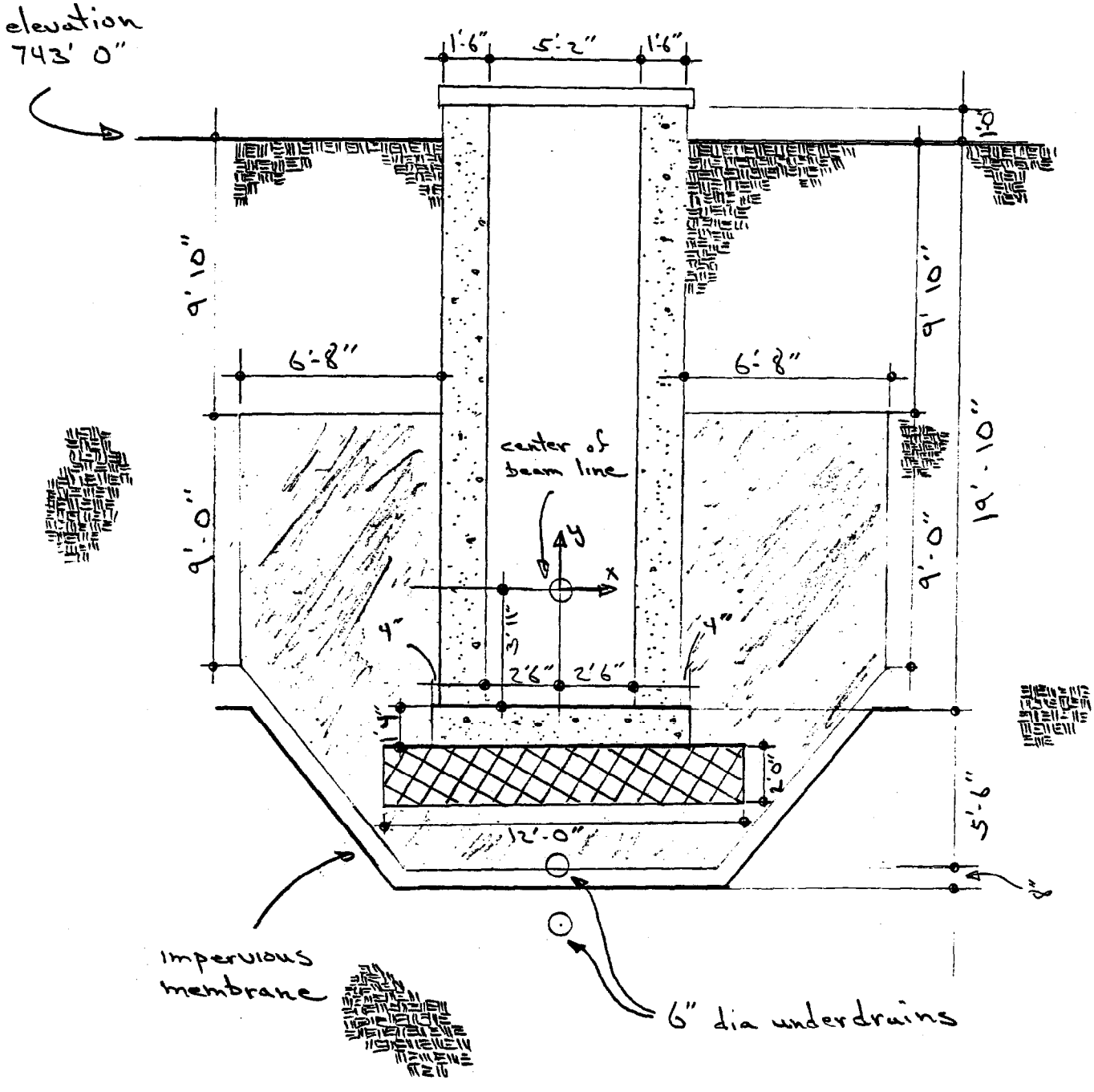
8. Cross section thru unprotected soil.


Geometry 1
Shield
Target (W)
horizontal
vertical
Quad
Quad
Quad
Dump
Fe
Fe
Fe
Fe
Cmag
BeO
Al
Fe
30
90
150
210
270
330
390
450
510
960
1100
1430
80
60
40
20
10
0
10
20
40
60
80
cm

Cross Section Thru
F Hall
looking downstream

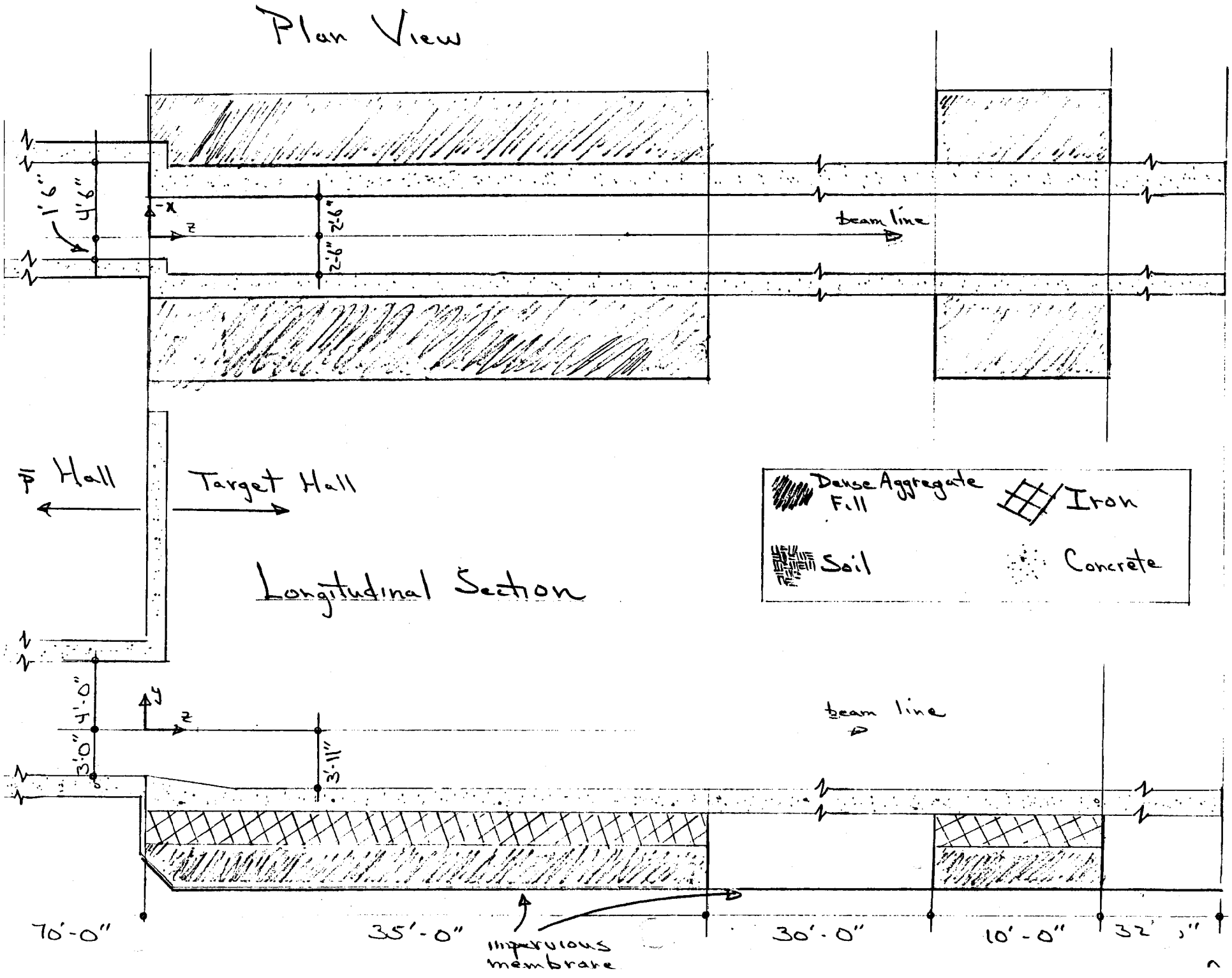


Cross Section Thru
Target Hall
looking downstream

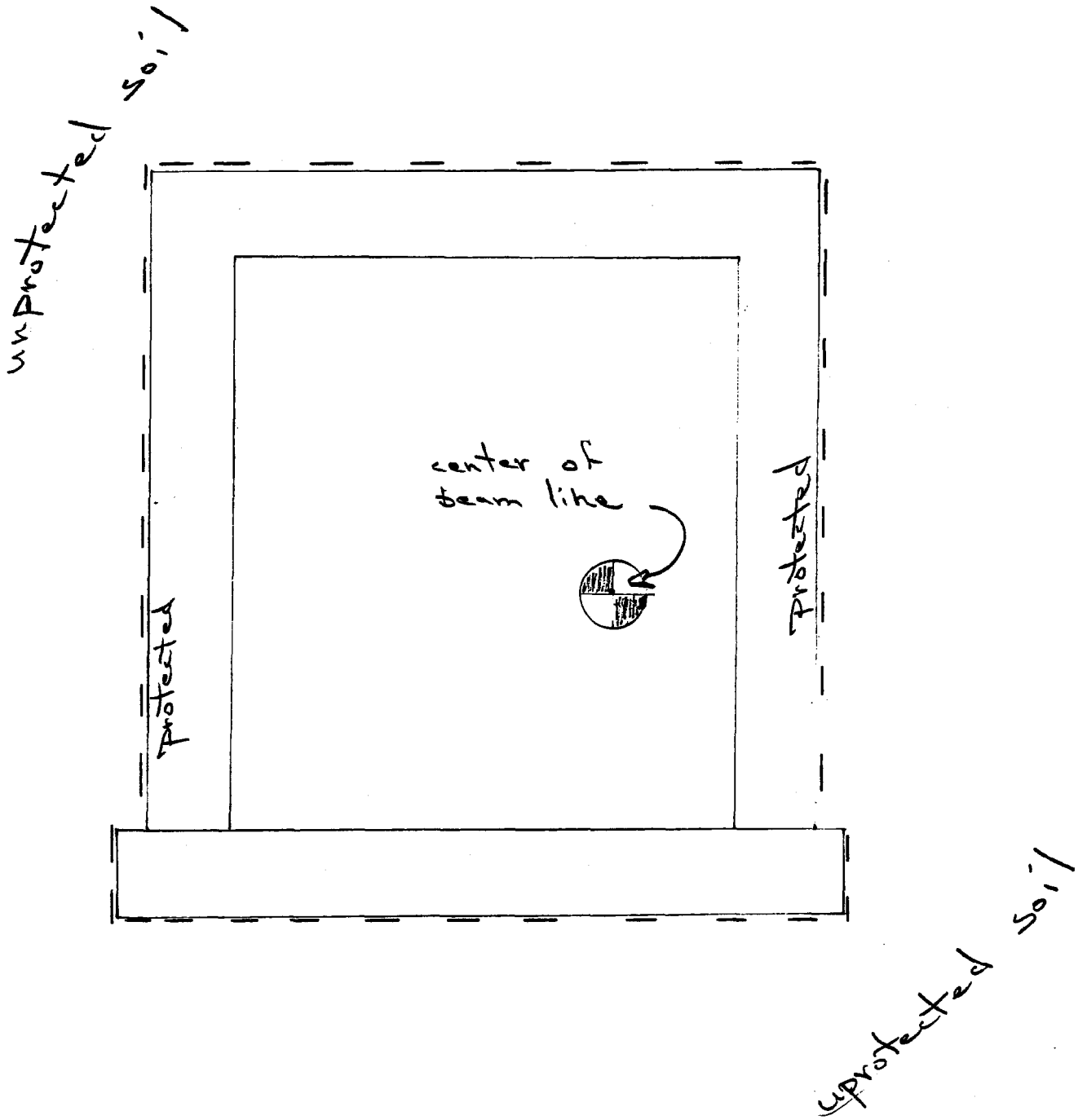


Dense Aggregate Fill	Iron
Soil	Concrete

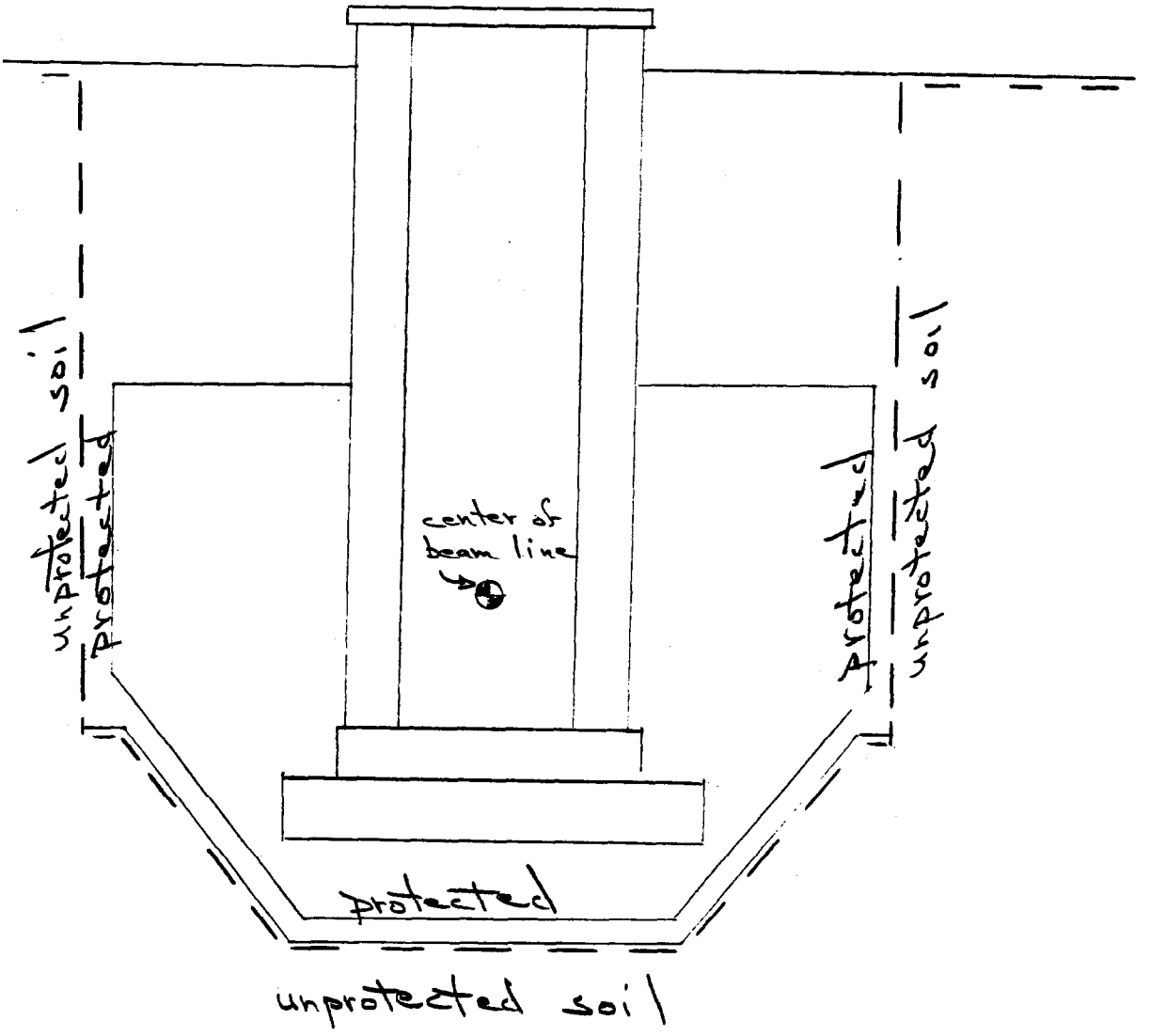
Figure 3


Plan View
1'-6"
4'-6"
-x
z
2'-6"
2'-6"
beam line
p̄ Hall
Target Hall
Dense Aggregate Fill
Iron
Soil
Concrete
Longitudinal Section
4'-0"
3'-0"
y
z
3'-11"
beam line
70'-0"
35'-0"
impervious membrane
30'-0"
10'-0"
32'

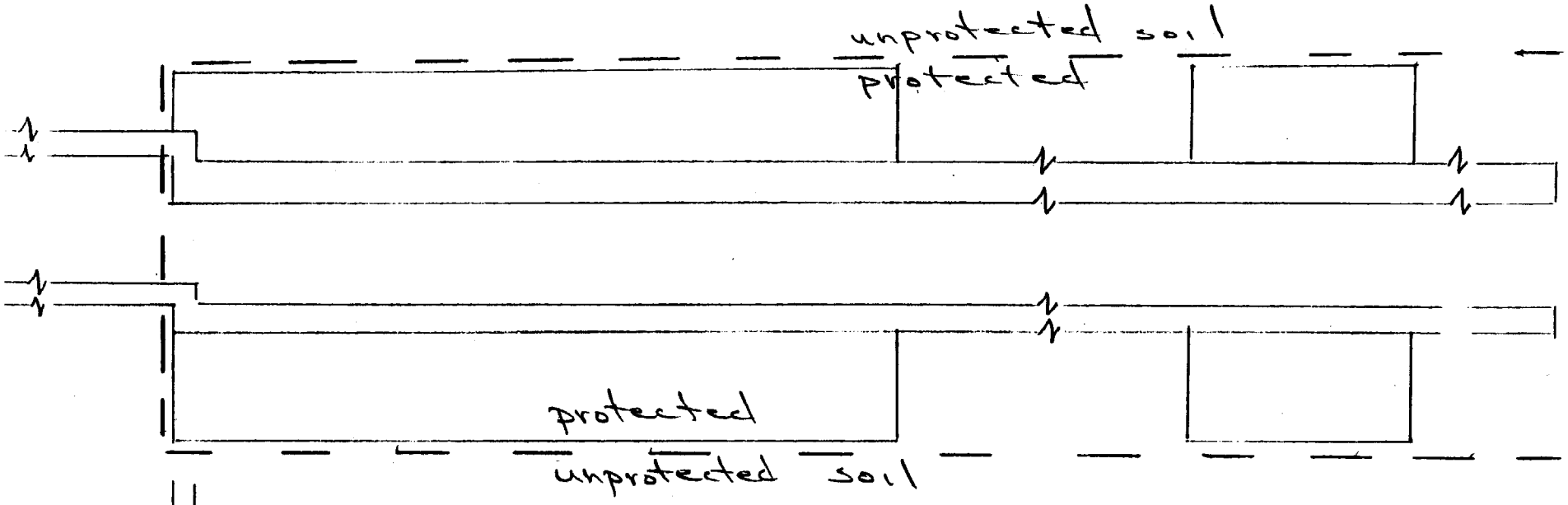
Cross Section Thru
P Hall
looking downstream

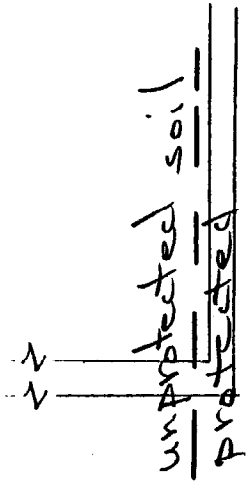


Cross Section thru
Target Hall
looking downstream

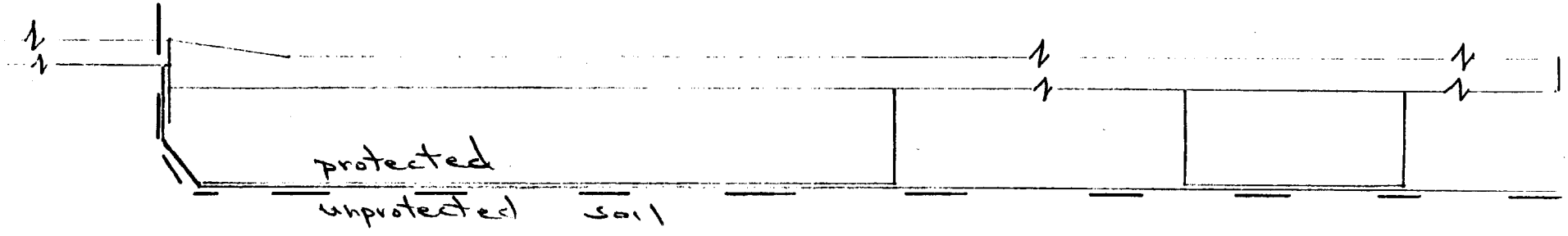


Plan View

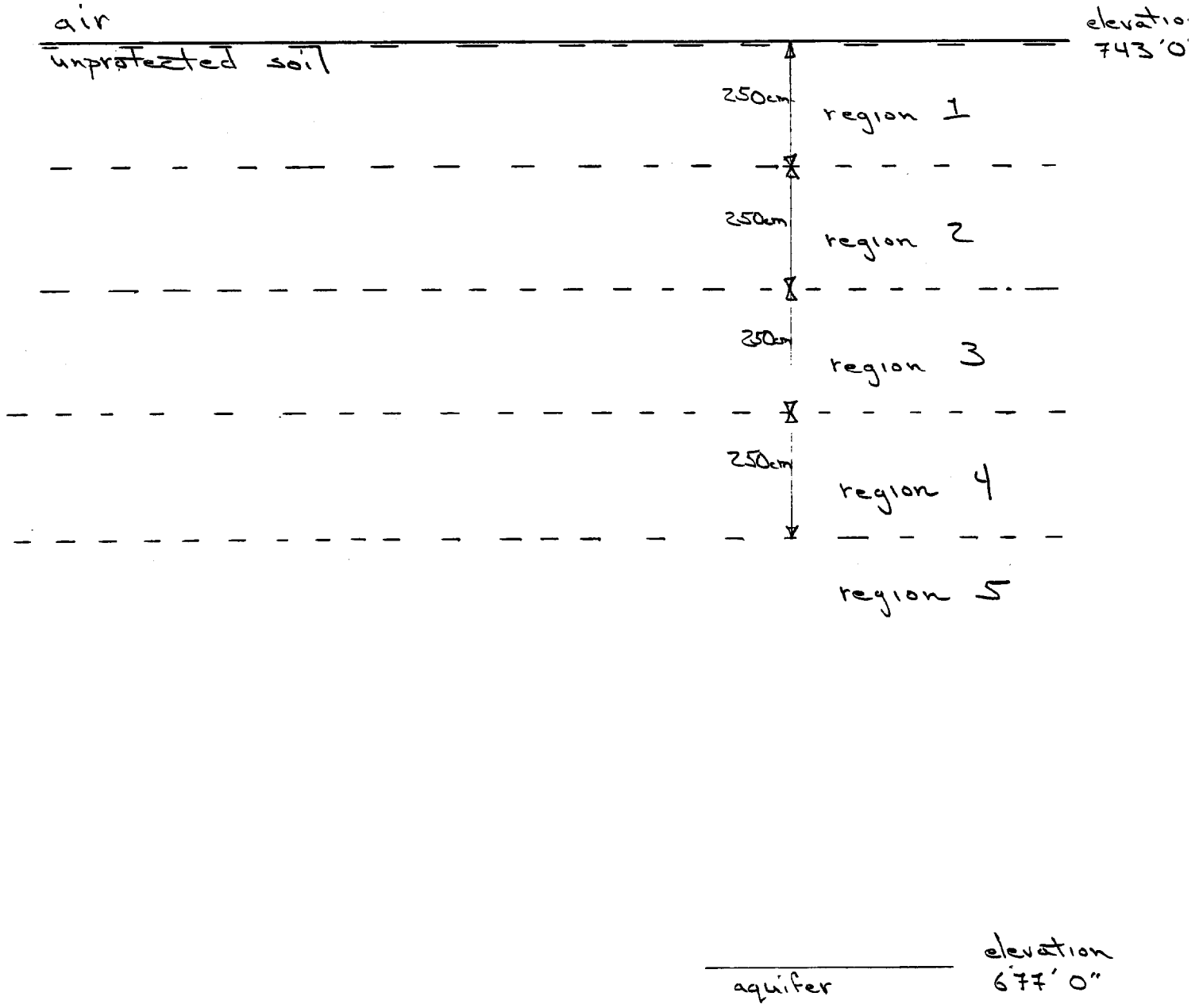




Longitudinal Section



Cross Section thru
Unprotected Soil



Appendix A

The following is a listing of the Update correction set used with the program library INTEPL in user area 93523 on the Fermilab Cyber Computer System for runs of the first geometry. It has been included to allow the the reader, if familiar with CASIM, to see the absolute details of the geometry. It is by no means an attempt at a tutorial on running CASIM and therfore will not be discussed in great detail here.

The material index, N, in subroutine HITORM is returned as an interger between 1 and 8 where 1 is tungsten, 2 is iron, 3 is beryllium oxide, 4 is dense aggregate, 5 is concrete, 6 is protected soil, 7 is aluminum, and 8 (NOUT) is unprotected soil. The region index, IREG, dimensioned five word long in subroutine HITORM is returned with the five different region numbers corresponding to the five ways of totaling the stars per incident proton. The third region index was used in the calculations.

```
*IDENT GEOM
*DELETE INTEST.211
      CALL HITORM(XA,YA,ZA,MNEW,IREG,0,DCX,DCY,DCZ,CASTEP,CBSTEP)
*DELETE INTEST.214
*DELETE HITOR.33
      ENTRY HITORM(X,Y,Z,N,IREG,IPICT,DCX,DCY,DCZ,CASTEP,CBSTEP)
*INSERT HITOR.39
C     SET UTILITY VARIABLES
C
  100 ABSX=ABS(X)
      ABSY=ABS(Y)
      RSQR=X*X+Y*Y
      R=SQRT(RSQR)
```

```
C
C     PRESET N FOR UNPROTECTED SOIL
C
      N=NOUT
C
C     TOP
C
      IF (Y-485.14) 103,103,101
  101 IF (Y-607.06) 245,245,102
  102 IREG(1)=21
      IREG(2)=6
      IREG(3)=6
      IREG(4)=8
      IREG(5)=10
      GO TO 888
C
C     UPSTREAM
C
  103 IF (Z+2133.6) 104,105,105
  104 IREG(1)=19
      IREG(2)=6
      IREG(3)=6
      IREG(4)=8
      IREG(5)=10
      GO TO 888
C
C     PRESET REGION NUMBERS 3, 4, AND 5
C
  105 IREG(3)=INT(485.14-Z)/250+1
      IF (IREG(3)-5) 107,107,106
  106 IREG(3)=5
  107 IREG(4)=INT(485.14-Z)/250+1
      IF (IREG(4)-7) 109,109,108
  108 IREG(4)=7
  109 IREG(5)=INT(485.14-Z)/250+1
      IF (IREG(5)-9) 706,706,110
  110 IREG(5)=9
C
C     UNPROTECTED SOIL
C
  706 IF (Z) 707,111,111
  707 IF (Y+127.00) 710,735,735
  710 IF (X+177.80) 720,715,715
  715 IF (X- 86.36) 725,725,730
  720 IREG(1)=6
      IREG(2)=3
      GO TO 888
  725 IREG(1)=7
      IREG(2)=3
      GO TO 888
  730 IREG(1)=8
      IREG(2)=3
```

```
      GO TO 888
  735 IF (Y+ 91.44) 740,765,765
  740 IF (X+177.80) 750,745,745
  745 IF (X- 86.36) 755,755,760
  750 IREG(1)=4
      IREG(2)=2
      GO TO 888
C
C     TARGET HALL WALLS (UPSTREAM)
C
  755 N=5
      IREG(1)=0
      IREG(2)=0
      IREG(3)=0
      IREG(4)=0
      IREG(5)=0
      GO TO 888
C
C     UNPROTECTED SOIL
C
  760 IREG(1)=5
      IREG(2)=2
      GO TO 888
C
C     VACUMM (UPSTREAM)
C
  765 IF (Y-121.92) 770,795,795
  770 IF (X+167.64) 750,775,775
  775 IF (X- 76.20) 780,780,760
  780 IF (X+137.16) 755,785,785
  785 IF (X- 45.72) 790,790,755
  790 N=0
      IREG(1)=0
      IREG(2)=0
      IREG(3)=0
      IREG(4)=0
      IREG(5)=0
      GO TO 888
C
C     UNPROTECTED SOIL
C
  795 IF (Y-152.40) 800,810,810
  800 IF (X+167.64) 750,805,805
  805 IF (X- 76.20) 755,755,760
  810 IF (X+167.64) 820,815,815
  815 IF (X- 76.20) 825,825,830
  820 IREG(1)=1
      IREG(2)=1
      GO TO 888
  825 IREG(1)=2
      IREG(2)=1
      GO TO 888
```

```
  830 IREG(1)=3
      IREG(2)=1
      GO TO 888
C
C     DOWNSTREAM
C
  111 IF (Z-3261.36) 120,120,115
  115 IREG(1)=20
      IREG(2)=6
      IREG(3)=6
      IREG(4)=8
      IREG(5)=10
      GO TO 888
C
C     PRESET REGION NUMBER 1
C
  120 IREG(1)=INT(Z/1630.68)*5+8
C
C     UNPROTECTED SOIL
C
      IF (X+350.52) 130,130,125
  125 IF (X-350.52) 160,160,145
  130 IF (Y+119.38) 140,135,135
  135 IREG(1)=IREG(1)+1
      IREG(2)=4
      GO TO 888
  140 IREG(1)=IREG(1)+3
      IREG(2)=5
      GO TO 888
  145 IF (Y+119.38) 155,150,150
  150 IREG(1)=IREG(1)+2
      IREG(2)=4
      GO TO 888
  155 IREG(1)=IREG(1)+5
      IREG(2)=5
      GO TO 888
  160 IF (Y+302.26) 165,170,170
  165 IREG(1)=IREG(1)+4
      IREG(2)=5
      GO TO 888
  170 IF (Y+119.38) 175,175,200
  175 IF (ABSX-((5.00/6.00)*Y+(30205.68/72.00))) 200,200,165
C
C     TARGET
C
  200 IF (Z-61.00) 500,500,202
  202 IF (Z-65.00) 205,205,215
  205 IF (R- 1.00) 210,210,215
  210 N=1
      IREG(1)=0
      IREG(2)=0
      IREG(3)=0
```

```
      IREG(4)=0
      IREG(5)=0
      GO TO 888
C
C     CMAG
C
  215 IF (Z- 88.798) 500,500,217
  217 IF (Z- 92.799) 220,220,250
  220 IF (ABSX-30.48) 225,225,500
  225 IF (ABSY-60.96) 230,230,500
  230 IF (ABSX-6.35) 235,235,240
  235 IF (ABSY-10.00) 245,245,240
  240 N=2
      IREG(1)=0
      IREG(2)=0
      IREG(3)=0
      IREG(4)=0
      IREG(5)=0
      GO TO 888
C
C     VACUUM
C
  245 N=0
      IREG(1)=0
      IREG(2)=0
      IREG(3)=0
      IREG(4)=0
      IREG(5)=0
      GO TO 888
C
C     Q1
C
  250 IF (Z-107.5686) 500,500,255
  255 IF (Z-202.8186) 260,260,280
  260 IF (ABSX-60.00) 265,265,500
  265 IF (ABSY-43.815) 270,270,500
  270 IF (R-5.75) 245,245,275
  275 N=2
      IREG(1)=0
      IREG(2)=0
      IREG(3)=0
      IREG(4)=0
      IREG(5)=0
      GO TO 888
C
C     Q2
C
  280 IF (Z-280.2886) 500,500,285
  285 IF (Z-375.5386) 290,290,310
  290 IF (ABSX-60.00) 295,295,500
  295 IF (ABSY-43.815) 300,300,500
  300 IF (R-5.75) 245,245,305
```

```
  305 N=2
      IREG(1)=0
      IREG(2)=0
      IREG(3)=0
      IREG(4)=0
      IREG(5)=0
      GO TO 888
C
C     Q3
C
  310 IF (Z-438.1496) 400,400,315
  315 IF (Z-533.3996) 320,320,400
  320 IF (ABSX-60.00) 325,325,500
  325 IF (ABSY-43.815) 330,330,500
  330 IF (R-5.75) 245,245,335
  335 N=2
      IREG(1)=0
      IREG(2)=0
      IREG(3)=0
      IREG(4)=0
      IREG(5)=0
      GO TO 888
C
C     DUMP
C
  400 IF (Z- 965.1996) 500,500,405
  405 IF (Z-1425.1996) 410,410,500
  410 IF (Z-(965.1996+154.46375)) 430,430,415
  415 IF (ABSX-70.00) 420,420,500
  420 IF (Y+119.38) 500,500,422
  422 IF (Y-80.62) 425,425,500
  425 N=2
      IREG(1)=0
      IREG(2)=0
      IREG(3)=0
      IREG(4)=0
      IREG(5)=0
      GO TO 888
  430 IF (Z-(965.1996+152.55875)) 450,450,435
  435 IF (ABSX-11.43) 440,440,415
  440 IF (ABSY-11.43) 445,445,415
  445 N=7
      IREG(1)=0
      IREG(2)=0
      IREG(3)=0
      IREG(4)=0
      IREG(5)=0
      GO TO 888
  450 IF (Z-(965.1996+0.15875)) 435,435,455
  455 IF (ABSX-7.62) 460,460,435
  460 IF (ABSY-7.62) 465,465,435
  465 N=3
```

```
      IREG(1)=0
      IREG(2)=0
      IREG(3)=0
      IREG(4)=0
      IREG(5)=0
      GO TO 888
C
C     TARGET HALL WALLS
C
  500 IF (Y+119.38) 535,535,505
  505 IF (ABSX-121.92) 510,510,506
  506 IF (Z-30.48) 507,507,600
  507 IF (Y-121.92) 508,508,600
  508 IF (X+167.64) 600,600,509
  509 IF (X+121.92) 515,515,600
  510 IF (Z-30.48) 511,511,513
  511 IF (Y-121.92) 512,512,515
  512 IF (X-45.72) 513,513,515
  513 IF (ABSX-72.60) 520,520,515
  515 N=5
      IREG(1)=0
      IREG(2)=0
      IREG(3)=0
      IREG(4)=0
      IREG(5)=0
      GO TO 888
C
C     CONCRETE PLUGS
C
  520 IF (Y-121.92) 527,527,525
  525 IF (Y-424.18) 526,526,245
  526 N=5
      IREG(1)=0
      IREG(2)=0
      IREG(3)=0
      IREG(4)=0
      IREG(5)=0
      GO TO 888
C
C     IRON SHIELDING
C
  527 IF (Z-30.00) 245,245,528
  528 IF (Z-60.00) 529,529,245
  529 IF (ABSX-70.00) 530,530,245
  530 IF (Y-60.62) 531,531,245
  531 IF (R-4.00) 245,245,532
  532 N=2
      IREG(1)=0
      IREG(2)=0
      IREG(3)=0
      IREG(4)=0
      IREG(5)=0
```

```
      GO TO 888
C
C     TARGET HALL FLOOR
C
  535 IF (Y+160.02) 550,550,540
  540 IF (ABSX-132.08) 545,545,600
  545 N=5
      IREG(1)=0
      IREG(2)=0
      IREG(3)=0
      IREG(4)=0
      IREG(5)=0
      GO TO 888
C
C     IRON FLOOR PLATE
C
  550 IF (Z-1066.80) 565,565,555
  555 IF (Z-1981.20) 645,645,560
  560 IF (Z-2286.00) 565,565,645
  565 IF (Y+220.98) 615,615,570
  570 IF (ABSX-182.88) 575,575,615
  575 N=2
      IREG(1)=0
      IREG(2)=0
      IREG(3)=0
      IREG(4)=0
      IREG(5)=0
      GO TO 888
C
C     DENSE AGGREGATE SHIELDING
C
  600 IF (Z-1066.80) 615,615,605
  605 IF (Z-1981.20) 645,645,610
  610 IF (Z-2286.00) 615,615,645
  615 IF (Y-185.42) 620,620,645
  620 IF (Y+88.90) 630,630,625
  625 IF (ABSX-325.12) 640,640,645
  630 IF (Y+287.02) 645,635,635
  635 IF (ABSX-((5.00/6.00)*Y+(388.62))) 640,640,645
  640 N=4
      IREG(1)=0
      IREG(2)=0
      IREG(3)=0
      IREG(4)=0
      IREG(5)=0
      GO TO 888
C
C     PROTECTED SOIL
C
  645 N=6
      IREG(1)=0
      IREG(2)=0
```

```
      IREG(3)=0
      IREG(4)=0
      IREG(5)=0
      GO TO 888
C
C     IF IN VACUUM STEP PARTICLE AND GO BACK TO CHECK AGAIN
C
  888 IF (N) 905,905,999
  905 IF (IPICT) 910,910,999
  910 X=X+DCX*CASTEP
      Y=Y+DCY*CASTEP
      Z=Z+DCZ*CASTEP
      CBSTEP=CASTEP
      GO TO 100
C
C     DONE
C
  999 CONTINUE
*DELETE EMSHW.62
   80 CALL HITORM(XB,YB,ZB,NN,IREG,0,DFX,DFY,DFZ,DR,DR)
*DELETE EMSHW.64,EMSHW.68
*DELETE EMSHW.111
      CALL HITORM(XB,YB,ZB,NL,IREG,0,DEX,DEY,DEZ,DR,DRR)
*DELETE EMSHW.114
*DELETE EDP.27
      CALL HITORM(XC,YC,ZC,NG,IREG,0,DDX,DDY,DDZ,DR,DR)
*DELETE EDP.34
*DELETE EDP.45
```

Appendix B

The following is a listing of the input deck used for one of the CASIM runs for the first geometry.

```
     1       80.0        0.1        1.0   0.1E-13   1000000         0
     1          0  295754849       0.05      0.05      15.0      15.0
     5
    21          6          6          8        10
     7
 74.00     183.85      19.30       8.70
 26.00      55.85       7.86      25.10
  6.38      13.16       2.85      75.20
 23.73      50.77       3.20      25.00
  8.00      22.00       2.40      85.00
  8.00      22.00       2.00      85.00
 13.00      26.98       2.70      49.00
```