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Comparison of CASIM with the LAHET Code System

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I. Introduction

The CASIM Monte Carlo Program[1] has been used for shielding calculations at RHIC. In the most common application, the "star density" is calculated at some (usually transverse) depth in some medium assumed to have a few per cent water by weight (soil or concrete). In cases where the location of the source is not known, the maximum star density in the beam direction is used to evaluate the adequacy of the transverse shielding. The star density is related to dose[2] by assuming an "equilibrium spectrum" of neutrons down to thermal energy. CASIM has been used extensively in this manner at both FNAL and the AGS without, to this author's knowledge, any significant deviation from prompt radiation measurements.[3]

In some instances however, primarily due to a lack of any reasonable alternative, CASIM results have been used in a manner which is less well justified. Three applications are of particular concern among those performed to date for RHIC. All multi-leg penetrations at RHIC (labyrinths, vents and the like) were analyzed by Gollon[4] using the assumption that the appropriate entrance dose for such penetrations was 85% of the entrance dose given by CASIM. This was intended to represent the fraction of the dose below ~10 MeV. This author used the same assumption in estimating the dose exiting from straight penetrations[5] and through cracks in shielding walls.[6] Since CASIM does not transport neutrons below ~50 MeV correctly, and since the ansatz for creation of evaporation neutrons in CASIM is very crude, this assumption is suspect.

Recently this author obtained access to the Monte Carlo codes which comprise the LAHET Code System (LCS)[7] in order to explore the validity of these assumptions. This code also has "weaknesses" which are discussed in the next section. Two important points should be kept in mind when considering the comparisons between CASIM and LCS which are described below:

(1) Although the statement was made above that 85% of the CASIM maximum entrance dose was used as a part of penetration calculations, in fact *twice* this number was used. This is because the RHIC Project has assumed that the neutron quality factor will someday be doubled, and estimates have been made with *doubled quality factor at 4 times the design intensity*. In the comparisons in this note, the *standard* star density to dose conversion constants have been used.

(2) The comparisons in this note are in the context of the specific geometries considered. No such thing as a "general" comparison exists.

II. LCS

The LAHET Code System in principle "does everything." A simplified sketch of the system (appropriate to the comparison in this note[8]) is shown in Fig. 1. LAHET proper transports hadrons above some threshold kinetic energy which is in the range of 0.1 to 1 Mev except for neutrons, where the threshold is 20 MeV. During the transport, two files are created, one containing information about the cascade for all hadrons other than neutrons and another containing all neutrons below 20 MeV. The latter file is passed to MCNP[9,10] for transport through the geometry being considered. As shown in the figure, one can obtain output for either all particles or only low energy neutrons. However, if one uses the HTAPE code, the output obtainable is restricted to flux (or dose) across specified surfaces whereas MCNP allows a variety of sophisticated variance reduction techniques. In the geometries considered here, dose is dominated by low energy neutrons (see next section), so the tools in MCNP can be employed. The estimation of dose is described below in connection with the various calculations made.

Although MCNP is probably the best low energy neutron code in existence, LCS has two deficiencies in comparison to CASIM.

(1) The high energy code in LAHET[11] is suspect. In fact, some people caution against using LAHET for energies above the 3-5 GeV range. According to Tony Gabriel,[12] the *first order effect* of the deficiency is that, at energies in the 100 GeV range, LAHET overestimates hadronic energy and underestimates electromagnetic energy (π^0's). This leads to an overestimate of low energy neutrons, *exactly the opposite* of the concern with respect to the use of CASIM mentioned above. However, Tony's estimate (or perhaps guesstimate) is that at 100 GeV in a *thin iron* geometry[13] low energy neutrons are overestimated only by of order 10%. By contrast, ignoring the heavy target problem,[3] the parameters of the CASIM model were fixed by data at 20 GeV and subsequently "tuned" to fit data in the few 100 GeV range, precisely those of interest to RHIC.

(2) The second deficiency relates to statistical precision. The price one pays for "doing everything" is the computer time and disk space needed to do it.[14] Here this author, being a *novice* to LCS, is on somewhat shaky ground. One of the quantities in the MCNP output file is the range of weights which are encountered in its input file (the neutrons on the NEUTP file in Fig. 1). For the calculations described below *this range was less than 1 order of magnitude*. This is in stark contrast to CASIM where the hadron weights range from $\sim 10^2$ to the (user specified) cutoff which may be 10^{-9} or so. It seems clear that LCS is "almost analog" in the high energy part, *which makes it unsuitable for doing the deep penetration calculations for which CASIM is optimized by design*. As will be indicated in the following sections of this note, this observation will influence the *interpretation* of some of the LCS results.

(3) LCS has no provision for calculations where an external magnetic field is present. One can , in principle, "make corrections" for the absence of magnetic field by using programs such as CASIM to scale LCS results. The influence of fields on the maximum star density in previous CASIM calculations done in relation to RHIC has been modest, typically ~1.4 or less. However, making such a correction must clearly be considered on a case-by-case basis.

III. RHIC Tunnel Geometry

The first comparison is a near duplication of an earlier CASIM calculation[15] on which many results have been based, namely loss in a geometry resembling the RHIC tunnel. A material distribution which approximates a single ring of a few magnets — specifically quad, drift, dipole, drift, quad — is placed in the center of a circular tunnel of radius 250 cm., and beam loss occurs on the beam pipe in the first quadrupole. The magnetic field is ignored. The material distribution is given in detail in Appendix A. Outside the tunnel, although for only a total of 90 cm. in this case, is "soil." In this specific calculation, the soil was quite "dry," consisting of a mixture of 4% H_2O and 96% SiO_2 which is only 1.2% water by weight. The density is taken to be 1.8 g/cc. A "0 importance" region exists outside of R = 340 cm., so that transport ceases for particles exiting this radius.

The comparison is for 100 GeV/c protons. In CASIM, the usual assumption of loss (forced interactions) across the length of the first quadrupole was made, which was approximated in LCS by averaging only two points, one 1/3 of the distance along the 1.13m length of the first quad, and the second 2/3 of the distance.

In the first set of calculations made with LCS, the neutron flux across cylindrical surfaces at R = 250 cm., 280 cm., 310 cm., and 340 cm. were made, and converted to dose by using the conversion factors given by Stevenson.[16] The comparison between this dose estimate and the CASIM star density dose estimate on the plane defining the tunnel wall is shown in Fig. 2. The LAHET curve in this figure was made by averaging 2 runs of 100 primaries at each of the two incident locations on the first quadrupole. Note that this magnet starts at a Z (beam direction) coordinate of 212 cm. rather than 0. Although the statistics are low in this case, the runs agreed well with one another (about 3% difference near the maximum) and the smooth Z dependence also indicates that the statistical precision is adequate. One notes the following characteristics of this comparison:

(1) *The Z dependence is dramatically different, especially in the backwards direction where CASIM underestimates the LCS dose by over 3 orders of magnitude.*

(2) *The maximum dose is greater in LCS than LAHET by a factor of* 4.3.

For comparison, Fig. 2 also shows LCS dose in a geometry where the soil is removed. Neutrons crossing the surface at 250 cm. simply "disappear" into the 0 importance region. Although the Z dependence difference remains dramatic, the difference in the maximum dose is very small, indicating that **the difference in the maximum dose between the two codes is dominated by albedo from the tunnel wall.**

Note that the LCS neutron dose is being compared to the CASIM total dose. For comparison, so-called "edits" were made for pions and protons. The maximum LCS dose from these on the tunnel wall was 4% (flux about 1.2%) of the neutron dose. Also, the low energy dose, defined here at the 20 MeV MCNP threshold, was 90% of the total neutron dose.

Fig. 3 compares the maximum dose in Z as a function of radius through the thin soil shield of this calculation. The difference grows progressively smaller at depths of 30 and 60 cm. into the soil and, at 90 cm., which is the end of the calculation, the CASIM dose is slightly higher. **At the last point there is no albedo from greater radii**, which explains the dramatic change in the last 30 cm. It should be noted that this is, in general, a more appropriate geometry for estimating dose to a person, who is far more likely to be behind a shield wall in a nearly empty hall than sandwiched between two shielding blocks.

As mentioned in the introduction, the motivation for these calculations was concern about the entrance dose assumptions used as a component in estimations for penetrations. In the penetrations considered by Gollon, and to a lesser extent in the evaluation of straight penetrations, at least "local albedo" should be excluded; the neutrons going radially inward at the tunnel wall in the geometry considered here is not relevant.

To explore this question, one of the methods available in MCNP for calculating dose, namely "point detectors," was used to estimate the (low energy) dose in a geometry changed such that 1/4 of the soil in azimuth was removed. Detectors (points in space) were positioned as indicated in Fig. 4 at various Z locations. Several runs were again made with 100 protons per run with the following result:

$$\text{max. rem/p (soil side)} = 3.77 \pm .50 \times 10^{-11}$$

$$\text{max. rem/p (open side)} = 1.70 \pm .06 \times 10^{-11}$$

The error here is simply the rms. estimator of σ from the multiple runs. The result on the soil side is excellent agreement with the total neutron dose of 4.3×10^{-11} rem/p obtained from the procedure above. The ratio of the open side to 85% of the CASIM maximum is the best estimate of the underestimate (according to LCS) of the low energy entrance dose in this very large opening:

$$\frac{1.7 \times 10^{-11}}{.85 \times 9.91 \times 10^{-12}} = 2.0$$

Now the openings considered by Gollon (vents and labyrinths) are certainly smaller than this, so one expects a larger underestimate, perhaps (crudely) in the range 2.5 to 3. The openings of straight penetrations smaller yet, so an underestimate in the 3 - 3.5 range (say) is expected, and cracks have essentially no opening so the full 4.3 factor might be expected to apply. However, this is over-simplified, and in any event, the real interest is in the dose at the **exit** of penetrations, not the entrance, which LCS can be used to calculate.

In the remainder of this note, examples of penetration calculations using LCS are made and compared to the results of previous estimates.

IV. A Straight Penetration

The second comparison calculation was a straight penetration. The geometry is shown in Fig. 5. This geometry was chosen because it had been calculated by A. Van Ginneken at FNAL using a special version of CASIM written for such penetrations.[17] The geometry is identical except for the magnet geometry (the assumed loss mechanism of the proton beam "target") which is, in this case, virtually identical[18] to that described in the last section.

Such geometries have been estimated at RHIC in the context of a conceptual model which assumes that the dose at the exit is composed of three parts: (1) the dose in the absence of the penetration, (2) the low energy component computed from assuming 85% of the CASIM entrance dose and applying the first labyrinth formula of Goebel,[4] and (3) a component from the DOSEXIT program.[5] The last component is intended to represent the dose (called neutron punch-through) from "high energy" interactions in the soil near the penetration which "escapes" because of the penetration. The second two components of this method, i.e., the *excess* dose components, total 1.88×10^{-14} rem/p (1.30 from the low energy part and 0.58 from DOSEXIT)[19] for this geometry.

Although LCS in principle contains all the dose, this author is convinced that the dose in the absence of the penetration is not contained in the LCS estimate because of the limited statistics of the runs and the absence of deep penetration biasing for the high energy particles. An occasional high energy particle might well make a "deepish" penetration, but that is very unlikely in the small statistics considered here, and would appear as a "jump" in the comparison of multiple runs characteristic of bad sampling. The LCS result will be interpreted as excess dose due to the penetration although this may be slightly conservative.

The two point detectors in Fig. 5 are positioned 1 ft. above the opening[20] and at a point 3 ft. above the opening and 2 ft. off to the side, which is intended to simulate the position of a person standing beside the opening. At this point in the series of calculations described here, the decision was made to change the soil to have a more conventional water content, namely 5% H_2O by weight.

A series of LCS runs were made with 100 protons per run varying the interaction point between the two positions as described above and the location (in Z) of the point detectors. Within the (limited) statistical precision, no difference could be seen between the two interaction points, and very little difference between the Z locations of the detectors, which were at 300, 400, and 500 cm. The worst case (by a small amount) was for Z = 400 where the point detector above the opening gave:

$$\text{dose at opening} = 2.64 \pm .50 \times 10^{-14} \text{ rem/proton.}$$

where, again, the error is simply the results from the simple rms. comparison of multiple runs. This is only a factor of 1.40 ±0.26 higher than the estimate made by the "usual" method. Although the entrance dose is higher in the LCS case by about a factor of 3, the attenuation is greater than that obtained by using the first-leg labyrinth formula.

For comparison, a few runs were made with the detector at Z = 400 with the dry soil (1.2% water) assumption. In this case the result changed to $3.16 \pm .48 \times 10^{-14}$ rem/proton

The fairest description of the results for the point detector off to the side is that the dose at this point is small. The multiple runs at 100 protons per gave results which varied over 2 orders of magnitude, which is characteristic of bad statistics. An average of 12 runs (where both the two interaction locations and the detector locations at 300 cm. and 400 cm. are combined) gives the following simple average and rms. deviation:

$$\text{dose at side} = 1.38 \pm 1.90 \times 10^{-6} \text{ rem/p.}$$

If one is optimistic, one could take the 2 standard deviation value from these runs and assert that the dose off to the side is less than 1/50 of the dose over the penetration with 95% confidence. Such a claim would not be well justified. However, the results do justify the claim that the assumption that has been made to date, namely that the dose to the side of a "typical" penetration is less than 1/10 of the exit dose, is conservative.

Before leaving this section, the comparison of the method of Van Ginneken and the RHIC method (Ref. [5]) should be noted. For the geometry of Fig. 5, but with different targeting assumptions, Van Ginneken obtained (for the excess dose) 7.5×10^{-15} rem/p vs. the RHIC method of 3.4×10^{-14}, **differing by a factor of 4.5.**

V. Multileg Penetration: Vent Calculation

The vent calculated is shown in Fig. 6. The dose was calculated at the three points indicated in the upper right hand side of the figure. The point in the middle (labeled point #1) is the nominal exit dose. The points on either side are 2 ft away from the side of the vent and 3 ft. above the berm. These are intended to simulate the position of the middle of the body of a person standing next to the vent.

The first series of LCS runs were for the same magnet simulation as in the comparisons described above where the magnets are positioned on the magnet center line closest to the vent opening shown in Fig. 6. A later set of runs added the second ring to the simulation, although the source of interactions was still the closest to the vent opening, to see if the presence of a second ring could be detected. No difference was seen and the results were combined.

As in the case of the straight penetration, multiple runs (with 200 interacting protons per run in this case) were made with the Z location of the vent changed to find the worst case position. The final result for the points shown in Fig. 6 are given in the following table.

Table 1 Results of Vent Calculation - See Fig. 6

Location	rem/100 GeV/c proton
#1	$1.91 \pm .41 \times 10^{-14}$
#2	$6.8 \pm 6.5 \times 10^{-16}$
#3	$1.2 \pm 1.0 \times 10^{-15}$

This vent corresponds to Gollon's[22] vent V-7. His result (with a small adjustment[22] and divided by 2 to remove the neutron quality factor enhancement) is 3.85×10^{-15} rem/p. The LCS result is higher by a factor of 5.0 ± 1.0. The entrance dose is a factor of 3.5 higher than taken by Gollon. The result is consistent with the difference in the exit dose being solely due to the difference in the input dose, but cannot exclude the possibility that the attenuation is less in the LCS result than estimated by Gollon. Note that this would be the opposite of the observation in the straight penetration case.

The results on the points off to either side suffer from "bad sampling". The nominal estimates correspond to an excess dose at these positions of 15 mrem for position #2 and 27 mrem for position #3 for the canonical fault of 2.24×10^{13} 100 GeV nucleons.

If one interprets the LCS result as the "excess" and adds the estimated no-hole dose from the CASIM calculation in Ref. [15], position #2 gives 83 mrem for the sum. If one further multiplies this by 2 in anticipation of an increased neutron quality factor, the 166 mrem/fault at this position slightly exceeds the RHIC criteria of 160 mrem in a low occupancy area. However, the error is large. Given the likelihood (see Section II above) that LCS overestimates low energy neutrons and the small probability that a vent would actually be in the worst case location relative to a source, this appears to be more of an awkward numerical result than a real problem. It should also be noted that if one takes the CASIM beam-direction seriously (as for example, Fig. 2), then adding the maximum LCS dose to the maximum CASIM dose is an overestimate since these occur at different positions.

VI. Multileg Penetration: Labyrinth Calculation

The labyrinth modeled, one view of which is shown in Fig. 7, is the main access labyrinth leading into Bldg. 1005.[23] Point detectors were placed at the end of each leg as indicated in the Figure. Calculations were made both with and without the cul-de-sac (which actually does exist) shown at the end of the second leg. Without belaboring details, the results (for the calculations including the cul-de-sac) are shown in Table 2.

Table 2. Results of LCS Calculation of Bldg. 1005 Labyrinth

Location	rem/proton
Entrance	$2.90 \pm .08 \times 10^{-11}$
End of First Leg	$1.62 \pm .10 \times 10^{-12}$
End of Second Leg	$2.67 \pm .19 \times 10^{-14}$
End of Labyrinth	$5.37 \pm .62 \times 10^{-16}$

The final result, $5.37 \pm .62 \times 10^{-16}$ rem/p, is **considerably larger** than Gollon's Labyrinth P-8 estimate. The entrance dose is higher by a familiar factor, 3.8, but the overall attenuation from the numbers in Table 2 is 1.85×10^{-5} in contrast to 5.39×10^{-6} estimated by Gollon, so that the total disagreement is a factor of 13!

It is not entirely clear how to decompose Gollon's attenuation result, since he combines two empirical formula (Tesch and Goebel) and multiplies the overall Tesch result by a "source geometry reduction factor" of 0.25 which is supposed to account for the fact that the design basis faults being considered are not point sources. Also, Gollon accounts for the cul-de-sac by multiplying the second leg by 0.75. In the LCS runs where the cul-de-sac was eliminated, the effect (which has dubious statistical significance) was in the third leg.[24] I have applied the source reduction factor to leg1 and left the cul-de-sac reduction where Gollon has it in comparing the attenuation factors leg by leg in Table 3.

Table 3 Attenuation by Leg in the Labyrinth

Leg	Attenuation (LCS)	Attenuation (Gollon)
1	5.59×10^{-2}	2.02×10^{-2}
2	1.68×10^{-2}	1.69×10^{-2}
3	1.58×10^{-2}	2.01×10^{-2}

Most of the difference in attenuation, especially when considering the statistical error, is in the first leg. There are two obvious candidates for this discrepancy, although the following is somewhat speculative. First, the 0.25 source reduction factor is probably simply inappropriate, at least in the comparison being made, since we are approximating loss on a short quadrupole (113 cm) by only two points about 40 cm apart. Secondly, hadrons >20 Mev will interact in the walls of the first leg and "feed" low energy neutrons into the labyrinth. This is precisely the mechanism calculated in the case of straight penetrations by the DOSEXIT program, but ignored by Gollon. Both of these effects may well be larger in this very large opening than in the significantly smaller vent considered in the preceding section.

The actual dose at the end of this labyrinth given by the LCS calculation is 12 mrem, which is not a problem since the end of the third leg is within a radiation area.

VI. Short Remarks on Cracks in Shielding Walls

It was mentioned in Section III above that the underestimate of entrance dose by using the prescription of Gollon would be largest in the case of cracks. However, this would be true only in a tunnel such as that considered here. In a large hall housing an experiment, "backwall" albedo would certainly be less. More relevant is the fact that the approximation of dose through cracks described in Ref. [6] has many *conservative* components.

At the time of this writing, LCS has been used to calculate the dose through cracks in the STAR shield wall.[25] The result is that the dose estimate through cracks is much *lower* than the estimate made using the approximations of Ref. [6]. As mentioned above, however, the geometry of each experiment must be considered in such calculations.

VI. Summary/Conclusions

The LAHET Code System (LCS) was compared to CASIM at 100 GeV/c in a geometry which assumes beam loss over a short distance on a quadrupole beam pipe in the RHIC tunnel. The motivation for the comparisons was concern that the low energy neutron entrance dose, which is used as a part of dose estimates through various penetrations, may have been underestimated by using the CASIM entrance dose in such a geometry. The LCS estimate is, indeed, greater than that used by Gollon[4] by a factor of typically 3.

LCS is believed suitable for performing complete calculations, to the end of whatever penetration is being considered, subject to interpreting the result of the calculation as *excess* dose due to the existence of the penetration. Although LCS in principle calculates the total dose, limited computing resources lead to an undersampling of deeply penetrating "high energy" particles in material. Since CASIM has been shown to be an accurate tool for this type of calculation, LCS and CASIM nicely complement one another.

Three calculations of excess dose through penetrations were made using LCS. The first of these was a straight penetration representing one of the RHIC survey shafts. The LCS result was only slightly higher than the previous estimate. Although the entrance dose is much higher than had been assumed, the attenuation was greater than had been estimated by a first-leg labyrinth formula and a "punch-through" component has been conventionally added to the excess dose. Dose at the side of the penetration was nominally lower than had previously estimated.

The second and third LCS calculation were for one of the vents and labyrinths calculated by Gollon. These differ from the straight penetration both in the size of the openings and in the fact that the primary neutron source "points directly" at the first leg of these penetrations. The dose at the exit of the vent was a factor of ~5 higher than Gollon's estimate, and the dose at the exit of the (3-leg) labyrinth a factor of ~13 higher. The vent has a significantly smaller opening than the labyrinth.

The implications of this comparison are varied. The exits of straight-through penetrations are blocked from access by barricades and posting. Since the excess dose to the side of such penetrations is calculated to be at least as small (and very likely smaller) than had been assumed, no action beyond that already planned is needed. To first approximation, the vents are in a similar situation since the caps over vent exits have been regarded as inaccessible. However, the implication of the estimate of Gollon being a factor of 4-5 low on the adequacy of the vent cap as a barrier should be examined. It should be noted that the factor of 2 allowance for the possibility of an increased neutron quality factor may be decisive here. Whether this allowance should continue to be made, in contrast to having a plan to deal with such an increase *should it occur*, seems to this author to be a legitimate question. Finally, the order of magnitude difference between the labyrinth estimate of Gollon and the LCS calculation is a serious discrepancy. A review of all personnel labyrinths (the implication of fault dose being considerably higher than previously estimated and whether remediative action is required) would seem to be in order.

References/Footnotes

1. A. Van Ginneken, "CASIM; Program to Simulate Hadron Cascades in Bulk Matter," Fermilab FN-272 (1975). For the modifications to CASIM for heavy ion transport see A.J. Stevens, "Maximum Energy Deposition Densities in the Internal Dump." AD/RHIC/RD-41 (1992).

2. The term "dose" in this document is shorthand for dose equivalent.

3. A very modest exception to this statement were measurements at the AGS of dose from a 24 GeV proton beam on a platinum target, wherein CASIM underestimated the maximum dose exterior to > 10 ft. of heavy concrete shield by a factor of slightly over 2. The location of the maximum dose also disagreed with the measurements, being predicted to occur at about 75° with respect to the target by CASIM whereas the measurement showed a maximum at ~ 90°. At least some of this discrepancy is related to a well known deficiency of CASIM, namely that the model used in particle production overestimates energy in the forward direction (and consequently underestimates energy in the transverse direction) for heavy targets. This comparison is documented in a memorandum from A.J. Stevens to D. Beavis dated 12/04/91, Subj.: "Comparison of CASIM Calculation with D-line Radiation Level Measurement."

4. P.J. Gollon, "Shielding of Multi-Leg Penetrations into the RHIC Collider," AD/RHIC/RD-76 (1994).

5. J.R. Preisig and A.J. Stevens, "Estimation of Neutron Punch-Through in Circular Shielding Penetrations," AD/RHIC/RD-81, November, 1994.

6. A.J. Stevens, "Approximation for Low Energy Dose Through Cracks in Shielding Walls," RHIC/DET Note 21, June, 1996.

7. R.E. Prael and H. Lichtenstein, "User Guide to LCS: The LAHET Code System," Los Alamos National Laboratory Report LA-UR-89-3014, September, 1989.

8. Neither the electromagnetic transport in LCS nor muons are considered here, although both exist within the code system.

9. Actually, a code called HMCNP (version 4a) was used for the results reported here. This is identical to the same version of MCNP except that the neutron "source" has been created by LAHET instead of by the user.

10. Judith F. Briemeister, Ed., "MCNP - A General Monte Carlo N-Particle Transport Code Version 4A," LA-12625-M, November 1993.

11. The "Bertini Model" was used as described in ORNL Report CCC-178, "HETC Monte Carlo High-Energy Nucleon-Meson Transport Code," August, 1977.

12. T.A. Gabriel, ORNL, Private Communication.

13. Thin iron means transverse thickness of approximately 10 cm. For thick (~1m) iron, the overestimate would be much higher. The calculations here (Section III) are thin iron.

14. The files shown in Fig. 1, particularly the histp file, which is needed even if only low energy neutrons are being transported, are *huge* in the geometries considered here, typically 40MB for only 100 incident protons at 100 GeV.

15. A.J. Stevens, "Radiation Field in the Vicinity of the Collider Center," AD/RHIC/RD-77, October, 1994.

16. G.R. Stevenson, "Dose Equivalent per Star in Hadron Cascade Calculations," (Appendix A) CERN Divisional Report TIS-RP/173, May, 1986.

17. A. Van Ginneken, "Calculation of Radiation Dose Around Shielding Penetrations," FN-571, 1991.

18. To save disk space and computer time, the last quadrupole in the string described in Section III was deleted. The geometry was thus shortened to ~15m. Again, the source of interactions is the first quadrupole which begins at Z = 212 cm., and is 113 cm. long.

19. This estimate was made using approximations that are usually made in calculating the entrance dose and running the dosexit approximation. Using the actual entrance dose calculated in Section II scaled up by R^2 would have come closer to the LCS result.

20. Use of the DOSEXIT program demands this because of numerical problems if the detector is exactly at the exit.

21. This is simply the number of nucleons corresponding to 1/2 the Au beam at 4 times design intensity. The design fault is half the beam on a single magnet at most locations.

22. Ref [4] takes the diameter of the vent to be 48 inches instead of the 46 inches in Fig. 6. In fact the vent is defined by a corregated surface with slightly varying diameter. For the purposes of this comparison, Gollon's result has been scaled down by 17%.

23. The labyrinth which was calculated has since been modified by blocking off a substantial portion of the end of the first leg to eliminate a punch-through problem described in Ref. [15].

Although not shown in the sketch, the walls, ceiling etc. of the tunnel enclosure are included in the calculation.

24. The total attenuation was lower in the results quoted in the text by a factor of 0.78 when compared to runs made without the cul-de-sac. The agreement with the factor used by Gollon may be fortuitious.

25. A.J. Stevens, "Estimation of Dose Through Cracks in the STAR Shield Wall," RHIC/DET Note to be published.

Appendix A Materials Used in the LCS Calculations

All the calculations described in the text assumed a source due to interacting protons which are parallel to the tunnel direction on the beam pipe "within" a quadrupole. Except for the beam pipe, which extends for the length of the geometry, the material in a magnet is simply assumed to be a radial distribution along its magnetic length. The radial regions are shown in the table below.

Table A-1 Radial Material Distribution in the Magnets

Region	Inner Radius (cm.)	Outer Radius (cm.)	Material Description
1	0.000	3.645	Vacuum
2	3.645	3.825	Beam pipe, Steel#2
3	3.825	4.000	He Region
4	4.000	5.000	Coil
5	5.000	6.000	Spacer
6	6.000	13.50	Yoke, Steel #1
7	13.50	29.40	Vacuum
8	29.40	30.00	Cryo. Vessel wall, Steel#3

The materials are defined in the table below in terms of their density and atomic fraction. In addition to those used in the magnets, soil and concrete are included.

Table A-2 Material Composition

Material Description	Density (g/cc)	Composition
Steel#1	7.7	.9985 Fe, .0003 O, .0012 Mn
Steel#2	7.7	.71 Fe, .18Cr, .10 Ni, .01 Mn
Steel#3	7.7	.96 Fe, .04 C
He Region (*)	.12	.9 Be, .1 H
Coil	6.6	.95 Cu, .045 C, .005 H
Spacer	2.7	.67 O, .33 Si
Soil (**)	1.8	.617 O .283 Si, .1 H
Concrete	2.35	.5833 O, .1937 Si, .17 H, .032 Ca .021 Al

(*) Cross sections for He were not conveniently available. Since this region is so small, the approximation as shown was used.

(**) Except as noted in text.

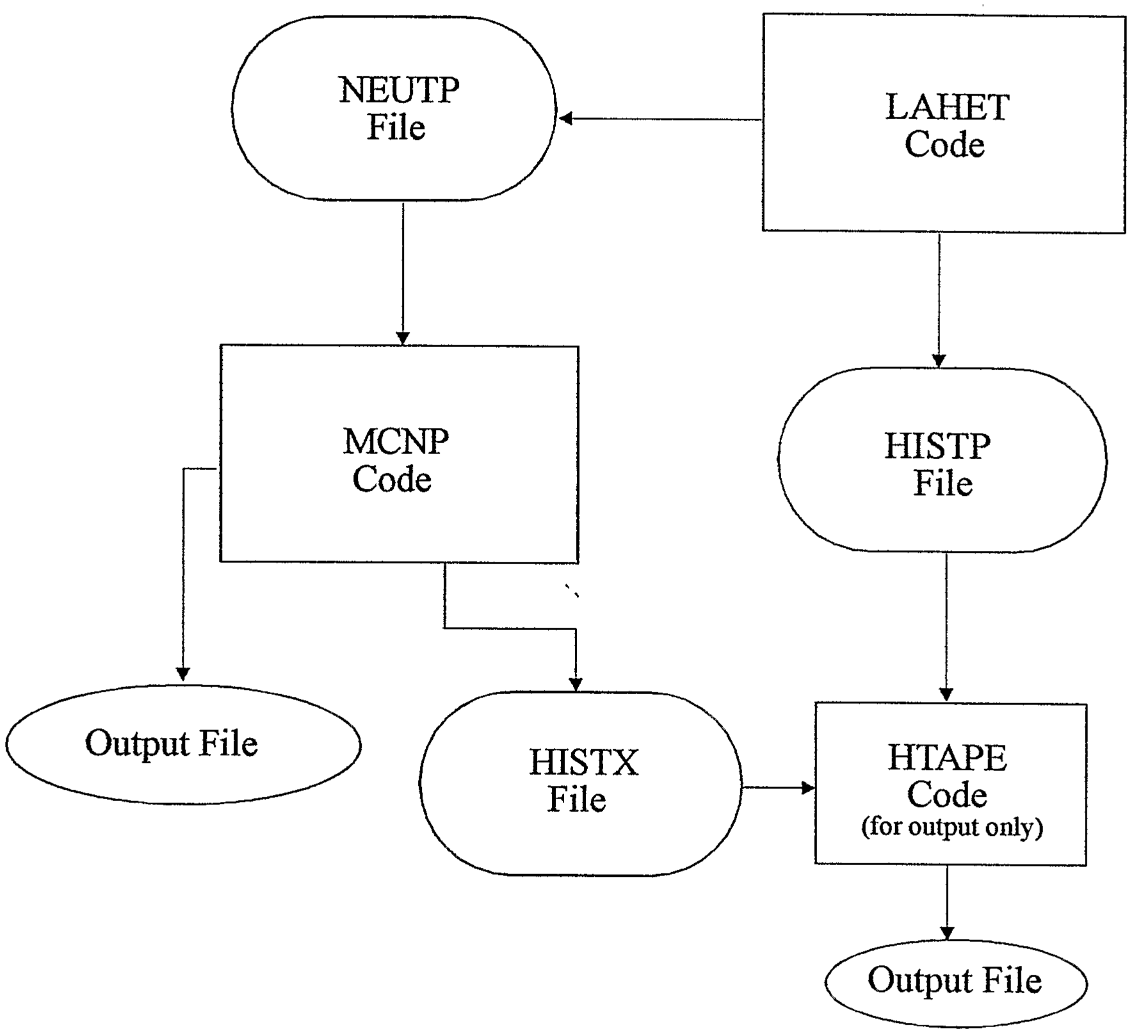

Fig. 1. Simplified Block Drawing of LCS. The Electromagnetic Components are not Shown.

Rem/proton at R=2.5m

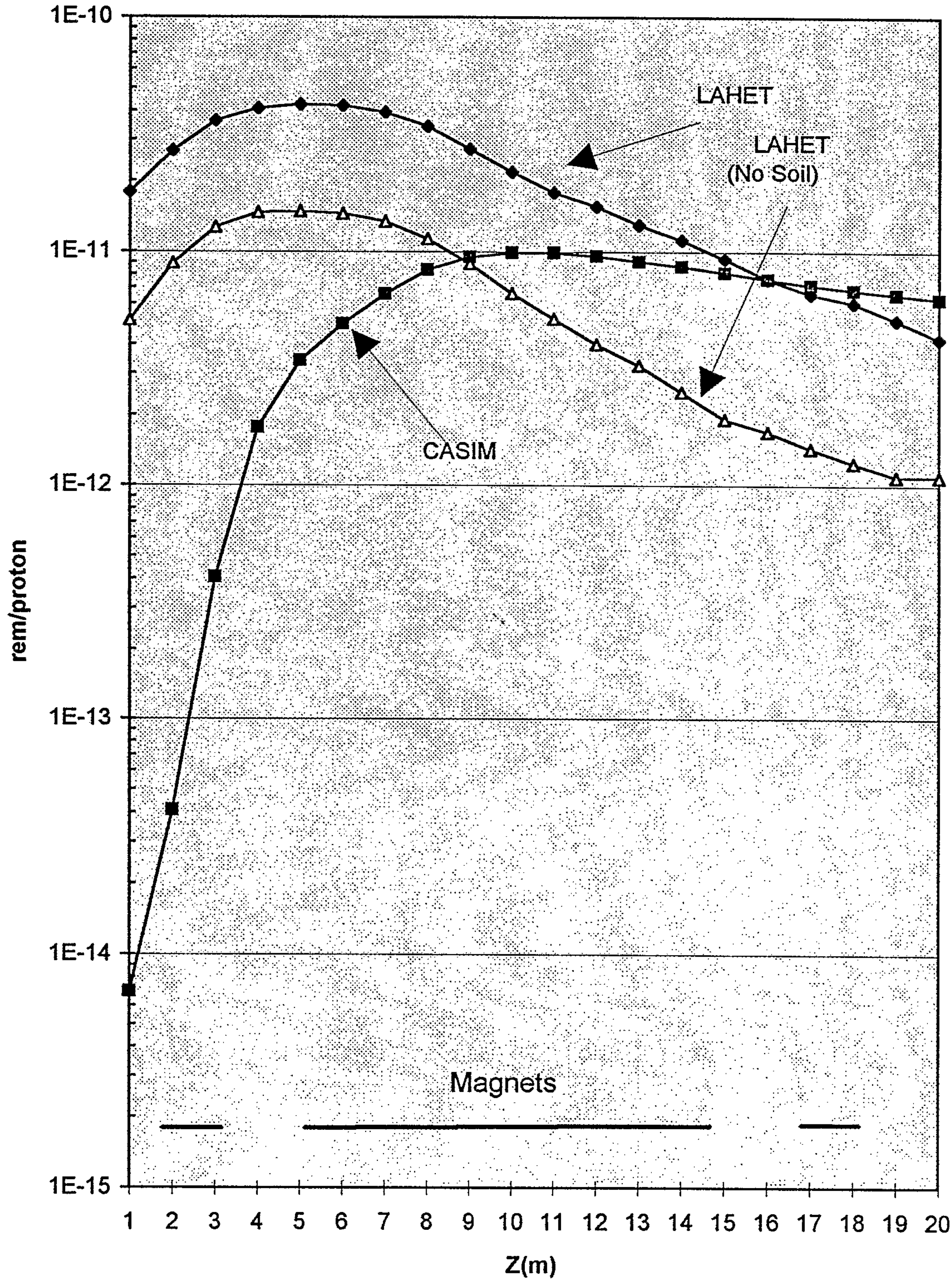

Fig. 2

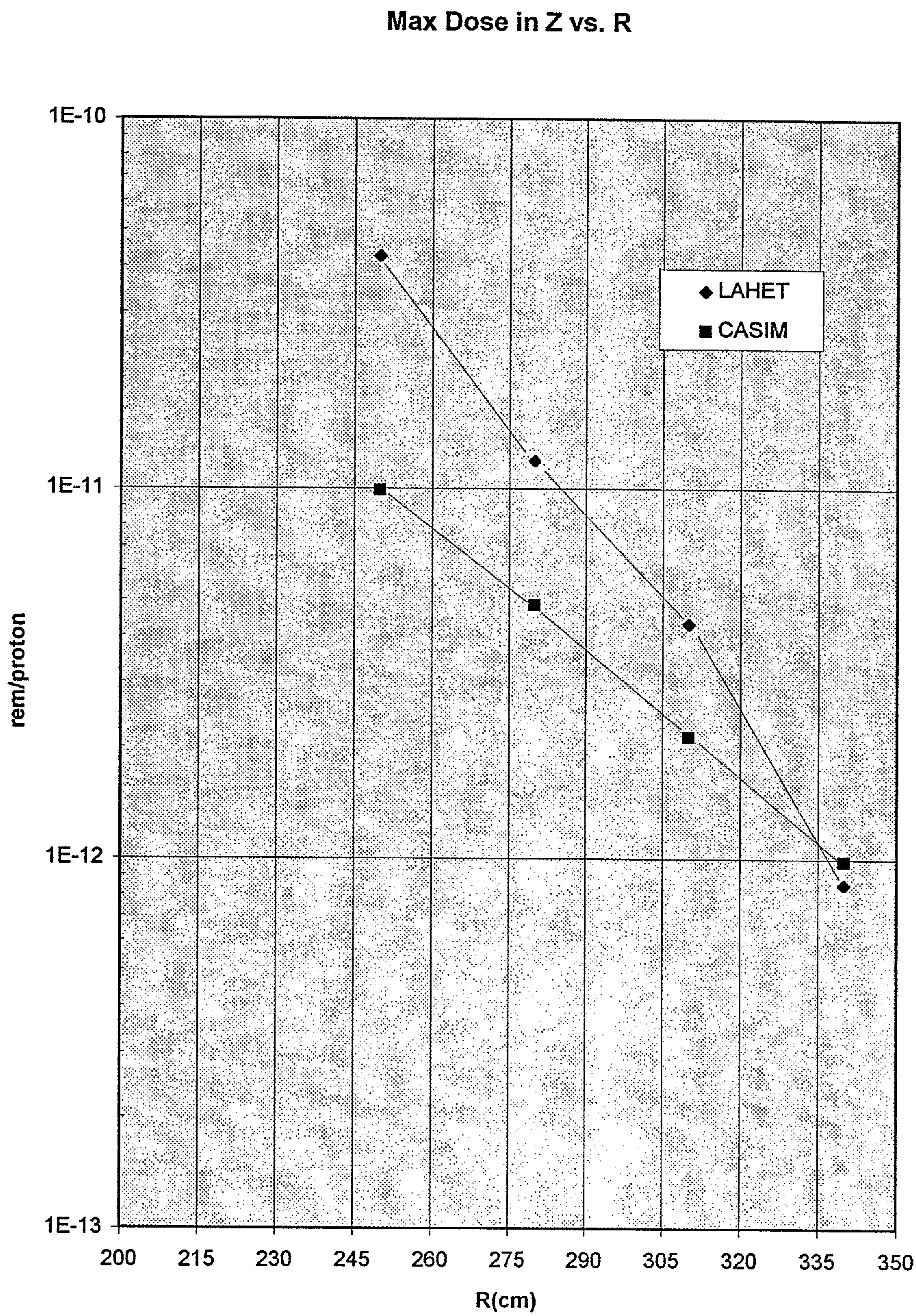
Max Dose in Z vs. R
1E-10
1E-11
1E-12
1E-13
rem/proton
LAHET
CASIM
200
215
230
245
260
275
290
305
320
335
350
R(cm)

Fig. 3.

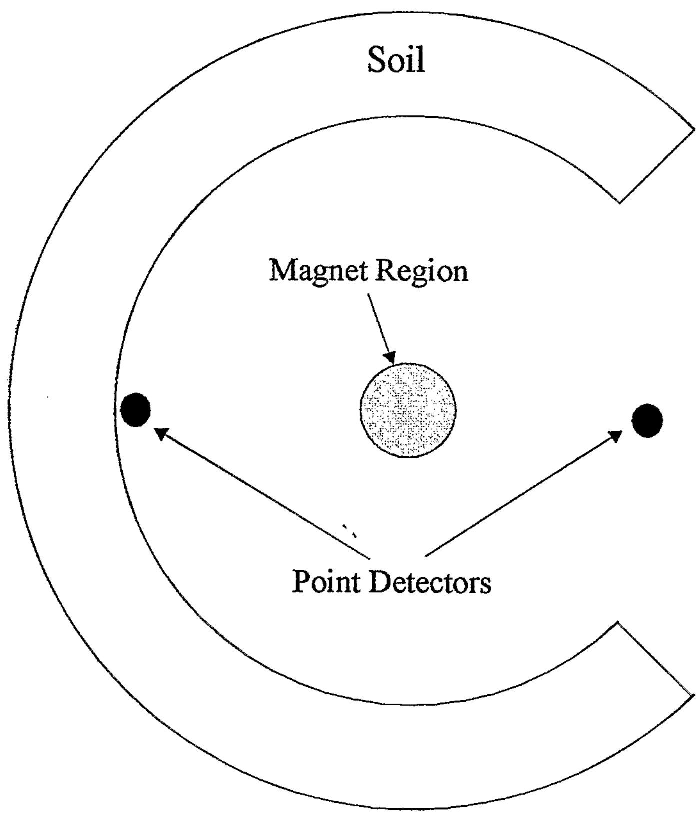

Fig. 4 Illustration of Calculation To Eliminate Local Albedo

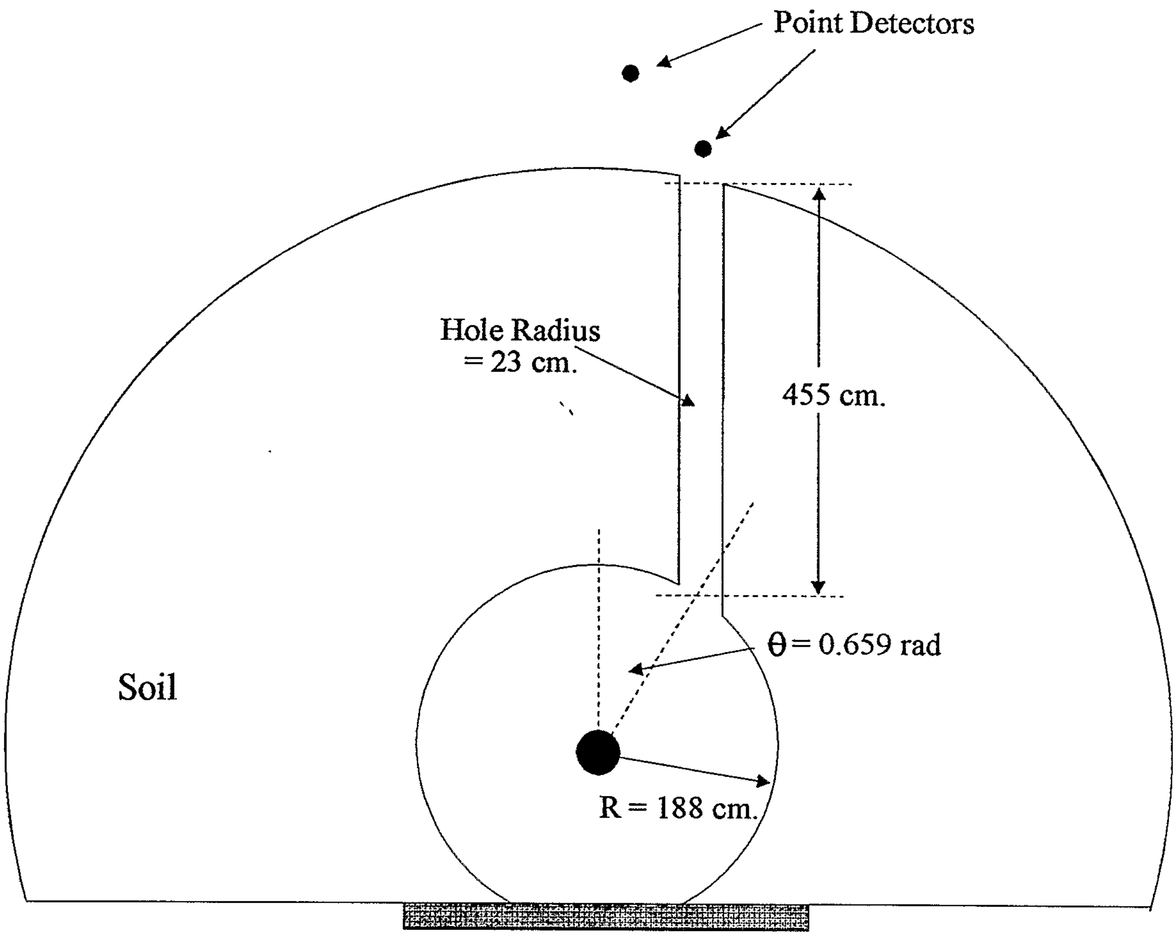

Fig. 5. The Straight Penetration Geometry

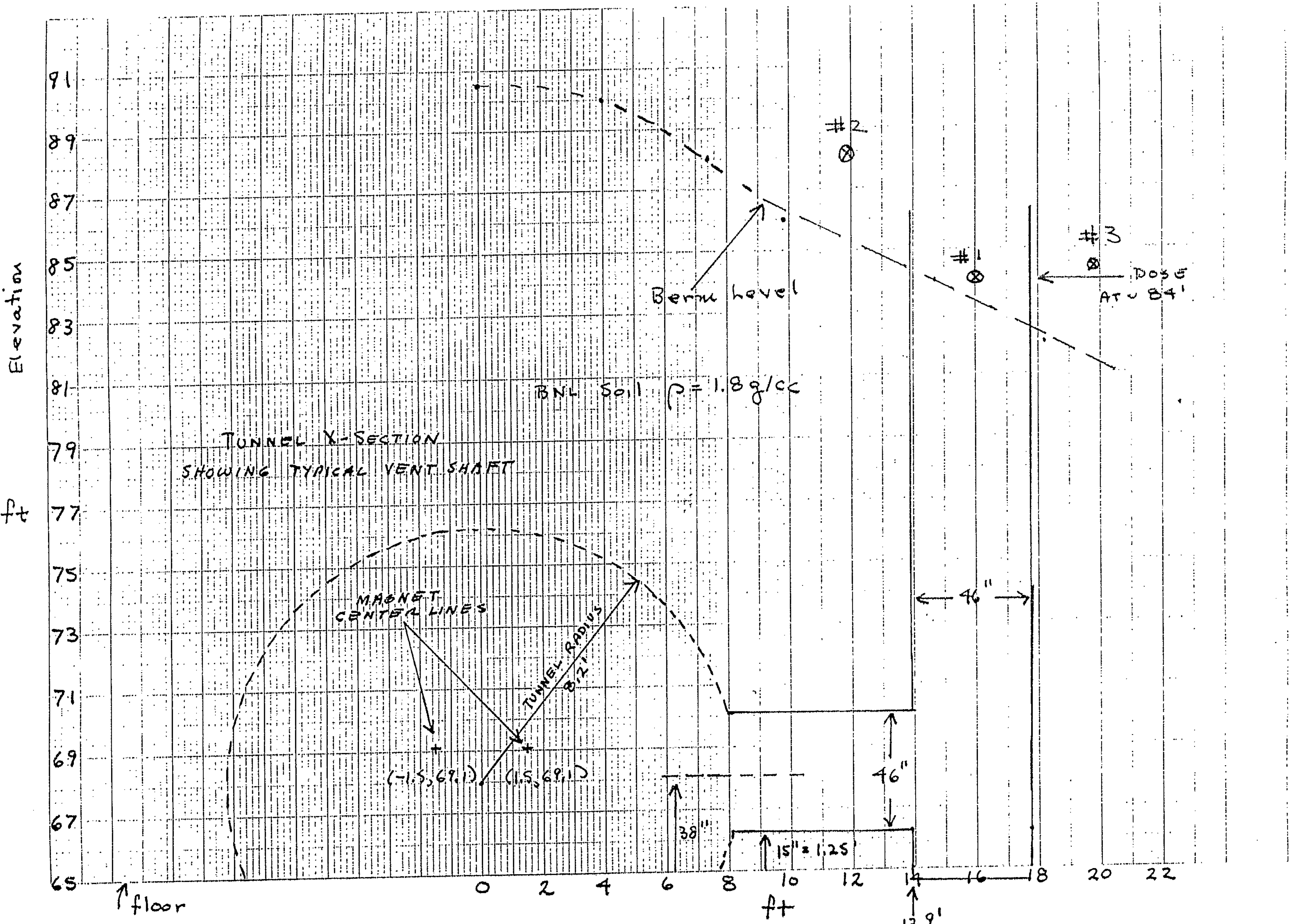

Fig. 6 Sketch of Vent Cross-Section

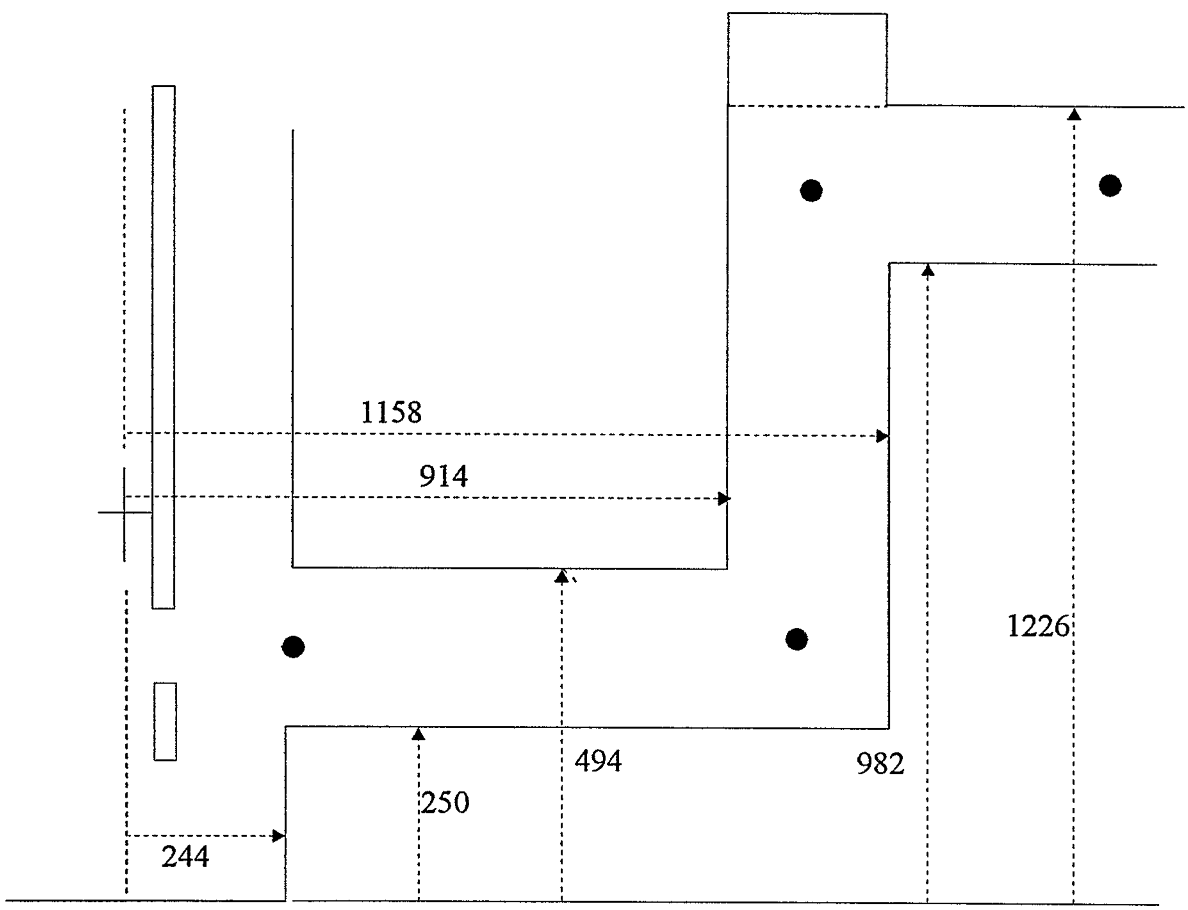

Fig. 7 Top View of Labyrinth Calculation. Point detectors (dark circles) exist at the entrance and at the end of each leg.