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Estimation of Neutron Punch-Through in Circular Shielding Penetrations

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I. Introduction

This note describes a method for estimating neutron "punch-through" at the exit of circular penetrations in earth shielding berms. The geometry of a proto-typical penetration is sketched in Fig. 1. The method consists of two basic steps. First a high-energy hadron cascade star density calculation is made using CASIM which ignores the presence of the hole. The stars at the maximum of the cascade in the beam direction (or the actual beam direction position of the hole if the beam loss location is known) surrounding the hole are then considered a source of evaporation neutrons. The dose at the center of the exit of the penetration from these neutrons is estimated using a parameterization of MCNP[1] calculations which is described below. Finally a correction is made to account for the "missing" high energy component of the dose. It is important to realize that the exit dose due to particles present at the entrance of the penetration is **not** considered; other methods, e.g., first-leg labyrinth formula, may be employed to estimate this component which is briefly discussed in Section V below. A preliminary version of the method described here was presented in a previous note.[2]

II. MCNP Calculations

The geometry of the calculation is shown in Fig. 2. A hole exists in earth of radius R_h. A small element dV is a source of evaporation neutrons which cause some dose equivalent at the center of the exit of the hole which is the point $Z = R_\perp = 0$ in Fig. 2. The MCNP program was used to calculate the dose equivalent at this point from rings at constant $R_\perp$, and Z values of extent $\Delta R_\perp = 1$ cm. and $\Delta Z = 2$ cm. The neutron source function was a Maxwellian distribution with a mean "temperature" of 4 MeV with a high energy cut off at 10 MeV. This distribution had been adapted from Wallace[3] and used in the earlier work.[2]

The geometric parameters which specify the location of a ring are the $R_\perp$ and Z values and the hole radius R_h. These values are measured to the center of the 1 by 2 cm. rings. The results from the MCNP runs are shown in Table I below. In this table, the transverse distance shown is the distance measured from the hole radius $s_\perp = R_\perp - R_h$. As shown in the table, the hole radius ranged from 10 to 70 cm, the longitudinal distance from the hole entrance from 31 to 469 cm, and the transverse distance into the earth berm from 1.5 to 45.5 cm.

Each MCNP run was made with 15,000 primary neutrons. The statistical error on the results shown was in the 1% — 12% range.

Table I. MCNP Runs

Hole Radius R_h (cm.)	Transverse Distance $s_\perp$ (cm)	Longitudinal Distance z (cm)	Dose Equivalent at $z = R_\perp = 0$ (rem/neutron)
50	5.5	31	1.4×10^{-12}
50	10.5	31	1.1×10^{-12}
50	15.5	31	8.5×10^{-13}
50	5.5	250	7.4×10^{-14}
50	10.5	250	5.5×10^{-14}
50	15.5	250	4.2×10^{-14}
50	5.5	469	9.7×10^{-15}
50	10.5	469	7.4×10^{-15}
50	15.5	469	5.3×10^{-15}
40	15.5	250	3.5×10^{-14}
30	25.5	250	1.7×10^{-14}
20	35.5	250	6.5×10^{-15}
10	45.5	250	9.5×10^{-16}
20	5.5	31	3.2×10^{-12}
20	10.5	31	2.4×10^{-12}
20	5.5	250	2.5×10^{-14}
20	10.5	250	1.7×10^{-14}
20	5.5	469	1.9×10^{-15}
30	1.5	200	1.4×10^{-13}
30	7.5	200	7.7×10^{-14}
30	1.5	400	1.6×10^{-14}
30	7.5	400	6.9×10^{-15}
70	1.5	200	1.7×10^{-13}
70	7.5	200	1.2×10^{-13}
70	1.5	400	3.8×10^{-14}
70	7.5	400	2.3×10^{-14}

III. Parameterization of MCNP Results

As a first step in obtaining an approximate parameterization of the MCNP results, the first 9 runs shown in Table I were repeated with the hole "filled in", i.e., with same $R_\perp$ and Z values as these runs but with R_h set to zero. For this situation the dose equivalent per neutron D was parameterized as:

$$D(no-hole) = B \times (4 \times 10^{-8}) \times \frac{e^{-R/\lambda}}{4\pi R^2}$$

where B is the "build up factor", 4×10^{-8} is the dose equivalent in mrem for a neutron in the few MeV range, and λ is the absorption length in BNL soil.[4] The build up factor parameterizes all re-scattering processes which contribute to the dose. Since a part of the MCNP output is the direct dose, the absorption length and build up factor are readily decoupled. A λ value of 12.5 cm. is an excellent fit to all the runs. For R ~ 260 cm. or less, a value of B of $e^{.048R}$ fits the data reasonably well.[5] In the absence of a hole then, the following approximation is obtained.

$$D(no-hole) = \frac{10^{-8}}{\pi R^2} e^{-R/\lambda(Eff)} \ with\ \lambda(Eff) = 31.25cm.$$

With the introduction of the hole, the first order approximation of the dose becomes

$$D = \frac{10^{-8}}{\pi R^2} e^{-S/\lambda(Eff)}$$

i.e., the above expression with S replacing R in the exponential term (see Fig. 2). The first 9 MCNP runs shown in Table I did not fit such a simple expression well. In particular, rings close to the hole radius with a small value of $S_\perp$ but a large value of S (in comparison to λ(Eff) of 31.25 cm.) gave rise to a much larger exit dose than given by this expression. For this reason a second term was sought which conceptually represents a contribution from a "hot spot" ring at the hole radius. The final expression is the following:

(1) $$D = \frac{10^{-8}}{R^2} \left\{ e^{-S/\lambda(Eff)} + \left(1 - e^{-KR_h/\sqrt{R_h^2 + Z^2}}\right) \times e^{-S_\perp/\lambda(Eff)} \right\}$$

In this expression the first term is simply the first order term given above. The second term - with $S_\perp$ rather than S in the exponential - represents the "hot spot". The coefficient of this term is constructed to go to zero at $R_h = 0$ as it must. It is also constructed to remain finite as R_h becomes large and the difference between s and $s_\perp$ becomes small. The z dependence should be regarded as strictly empirical. Given the form of the expression, the only free parameter is K.

A rough "fit" to K was made by testing the expression against the first 18 entries in Table I with the result that K =5 was adopted. [The spirit of the "fit" is that 5 appears better than 1 or 10.] With this value for K Eqn. (1) above was compared to the entries in Table I. The rms deviation for all the entries is a factor of 1.41 with a worst case of 2.20. The worst case comparison is the 13th entry in Table I which is the largest value of $s_\perp$. The last 8 entries in the table, which were not used in obtaining the fit, also have an rms deviation from Eqn. (1) of a factor of 1.41. The parameterization is regarded as satisfactory over the range of parameters which was investigated.

IV. Combining with CASIM

The procedure for estimating the punch-through at the center of the exit of a circular penetration is the following. First a CASIM run is made with the threshold momentum at 0.137 GeV/c (10 MeV neutron)[6] in a geometry which, in fact, ignores the existence of the penetration. The implicit assumption here, which is also made by Van Ginneken,[7] is that the penetration does not have a large effect on the development of the hadron cascade. The result of this step is the star density, *SD*, as a function of the transverse radius R_{Tr} shown in Fig. 1. Unless the relationship between the loss source position and the penetration in the beam direction is known, the evaluation should be at the beam direction position where the star density is maximum. The penetration of radius R_h is surrounded by volume elements dV specified by z and $R_\perp$. The dose equivalent **due to neutrons below 10 MeV** (the energy cut-off in the MCNP calculations) at the center of the exit is then given by:

$$Exit\ Dose\ per\ primary\ = n_e \times \int_V D \times SD \times dV$$

where n_e is the number of evaporation neutrons per star and D is Eqn. (1) in the preceding section. The integration is performed by a small Fortran program called DOSEXIT. This program has two subroutines, RVSZHOLE(z,rtoz,d) and SDVSR(rtoz,d,sd). The user must supply a different RVSZHOLE for each geometry. Given a value of z (see Fig. 1), this subroutine returns rtoz, the R_{Tr} value at z, and d, the transverse distance in soil to the point at z in the center of the penetration. Again, the actual presence of the hole is ignored here. The subroutine SDVSR returns the star density sd specified by the values of rtoz and d. A default SDVSR exists which parameterizes the star density in the form:[8]

$$SD = A \times \frac{e^{-d/\Lambda}}{R_{Tr}^2}$$

where the values of A and Λ are supplied by the user.

The DOSEXIT program assumes a value of 0.8 for the average number of evaporation neutrons per interaction in soil.[9] After performing the integration, DOSEXIT **multiplies the result by a factor of 1.72**. This is an attempt to correct for the "missing" dose above 10 MeV by assuming an equilibrium spectrum. The correction factor is taken from a "standard" deep penetration CASIM calculation.[10]

V. Comparison with CASIM Calculations

In Ref. [2] a comparison was made between the earlier version of the dose equivalent estimate and two calculations made by Van Ginneken. The first of these is shown in Fig. 3 of Ref. [1]. It is a circular survey shaft in the RHIC tunnel of radius 23 cm. and length 454 cm.[11] The calculation of Van Ginneken[12] for this geometry gave a total dose estimate, which is composed of four components, of 9×10^{-15} rem/p. Slightly more than half of this total (5×10^{-15} rem/p) comes from the "high energy" part of the Van Ginneken calculation which should be comparable with the estimate made here of the punch-through. Of the remaining components, one is a CASIM result at the position of the penetration exit where the penetration has been ignored (which contributes 1.5×10^{-15}), and the remaining two are low-energy components which traverse the entire penetration.

The DOSEXIT program gives 1.4×10^{-14} rem/p for this geometry, which is higher than the comparable component of Van Ginneken by a factor of 2.8. It should be remembered, however, that the MCNP parameterization has an error of about 40%. When this is coupled with the considerable uncertainties in the number of evaporation neutrons per star and the 1.72 correction factor, the agreement is not too bad (and fortunately on the more conservative "high side").

It is instructive at this point to consider the other components which must be added to the punch-through. Following Van Ginneken, the CASIM contribution in the absence of a penetration must be added,[13] which is of course the same. For the low energy component, the procedure currently followed at RHIC is to apply a first-leg labyrinth formula to 85% of the dose equivalent deduced from the CASIM star density (assuming an equilibrium spectrum) at the penetration entrance. The justification of this procedure is given elsewhere.[14] This entrance term turns out to be 2.2×10^{-11} rem/p. If the (source off-axis) labyrinth formula of Goebel is applied (see Ref. [14]) a reduction of 9×10^{-4} is obtained which gives a low energy contribution of 2×10^{-14} rem/p. This result is higher than the punch-through estimate and **is about a order of magnitude larger than Van Ginneken's estimate of the same quantity**. This discrepancy — in a component not addressed in a detailed way either here or in the procedure of Van Ginneken — is larger than the difference in the punch-through estimates by a considerable amount.

The second comparison in Ref [2] was with a rectangular culvert at FNAL whose full width opening is 2 ft. by 11.7 ft. The geometry is shown in Fig. 4 of Ref. [2] and the proton beam energy is 8 GeV. It is by no means obvious that the DOSEXIT program can be applied to a rectangular geometry. We have done so by running DOSEXIT twice; first taking the hole radius to be the half-width of the smaller rectangular dimension, and secondly taking it to be the larger. The result is taken to be the geometric mean of the two runs which differ by about an order of magnitude! A change to DOSEXIT was also necessary. The value of λ(Eff) was changed from 31.25 cm. to 25.1 cm. because of the difference in soil density between FNAL and BNL. The result was 6.8×10^{-18} rem/p which compares to Van Ginneken's estimate of 3.0×10^{-18} rem/p and a measured value of 3.8×10^{-18} rem/p. The result is quite satisfactory, especially considering possible uncertainty in the source term, but the procedure used is not well justified. In this case, no entrance term exists.

VI. Discussion

The result obtained here is much higher ($\sim\times 5$) than obtained in Ref. [1] since the build-up factor was not properly taken into account in that work.[15] The result of the MCNP parameterization agrees reasonably with other methods of estimation, but is clearly restricted to penetrations with radii less than ~ 70 cm. Extrapolation beyond penetration lengths of greater than 5m is also problematical, but in many geometries the total result should not be overly-sensitive to such an extrapolation.

Although one rectangular geometry was treated with the methodology described here, the satisfactory result obtained has not been justified.

Finally, the punch-through estimate is generally smaller than the estimates that have been made (at RHIC) of the dose equivalent due to neutrons impinging on the penetration entrance from the beam loss "target". An order of magnitude discrepancy exists between different methods of estimating this quantity.

References/Footnotes

1. MCNP refers to the MCNP4 code distributed by the Radiation Shielding Information Center (RISC) at Oak Ridge National Laboratory. MCNP4 was developed at Los Alamos National Laboratory.

2. A.J. Stevens, "An Approximate Method for Evaluating Punch Through in Shielding Penetrations", AD/RHIC/RD-65 (1994).

3. R. Wallace, Nucl. Inst. Meth. **18/19** p. 405 (1962).

4. BNL soil was assumed to be 66.7% (atomic fraction) ${}_8O^{16}$ with the remainder natural Si. The density was taken as 1.8 g/cc.

5. "Reasonably well" means better than a factor of 2 over the range indicated. It should be noted that sources near Z = 0 and sources which have a large attenuation in soil are both unimportant in this case. The latter are unimportant because sources close to the edge of the hole dominate the dose. The former are not important because the cascade stars, which are the source of the evaporation neutrons, fall off exponentially in the direction transverse to the beam line (see Fig. 1). This rapid fall-off means that points close to the exit of the penetration (Z=0) contribute very little to the total dose, although this is known only "after the fact" by examining the contributions from various parts of the penetration wall.

6. In practice, multiplying the standard threshold (0.3 GeV/c) star density by a factor of 1.8 seems to work well.

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

8. In this expression — for reasons that are primarily historical — R_{Tr} is in meters and Λ in cm.

9. A. Van Ginneken, private communication. This differs slightly from the 1.0 value which was assumed in Ref [1].

10. A. Van Ginneken and M. Awschalom, "High Energy Particle Interactions in Large Targets," Volume 1, Fermi National Accelerator Laboratory, Batavia Illinois (1975). The fraction of Maximum Dose Equivalent below 10 MeV from Fig. VI.12 or VI.13 of this reference is 0.58.

11. In this calculation the source is a 100 GeV/c proton beam on a solid steel target of 10 cm. radius. This gives higher dose estimates than are canonically assumed for RHIC faults by a factor of about 2.3. The difference is that a scraping loss is assumed in making RHIC fault estimates; in such a loss a considerable amount of energy "escapes" down the beam pipe with the result that the star density distribution in space has a much lower maximum, but extends much further in the beam direction. For the numbers reported here, the solid target was assumed for direct comparison.

12. Memorandum from A. Van Ginneken to A.J. Stevens dated October 21, 1992.

13. The DOSEXIT program explicitly subtracts the "no-hole" result so that the dose estimate is the incremental dose due to the existence of the hole.

14. P. J. Gollon, "Shielding of Multi-Leg Penetrations into the RHIC Collider," AD/RHIC/RD-76 (1994). Some crude MCNP calculations coupled with an assumption of 2.5 evaporation neutrons per star give results which agree with Gollon's estimate. The latter are documented in a memorandum from Stevens to Gollon dated 03/03/94.

15. Although the build-up factor was ignored (set to 1) in Ref [2] explicitly, some account of re-scattering was implicitly considered by taking the evaporation contribution to represent a slice of the equilibrium spectrum rather than the spectrum from 10 MeV to thermal. However, this accounting clearly underestimated the effect of "build-up".

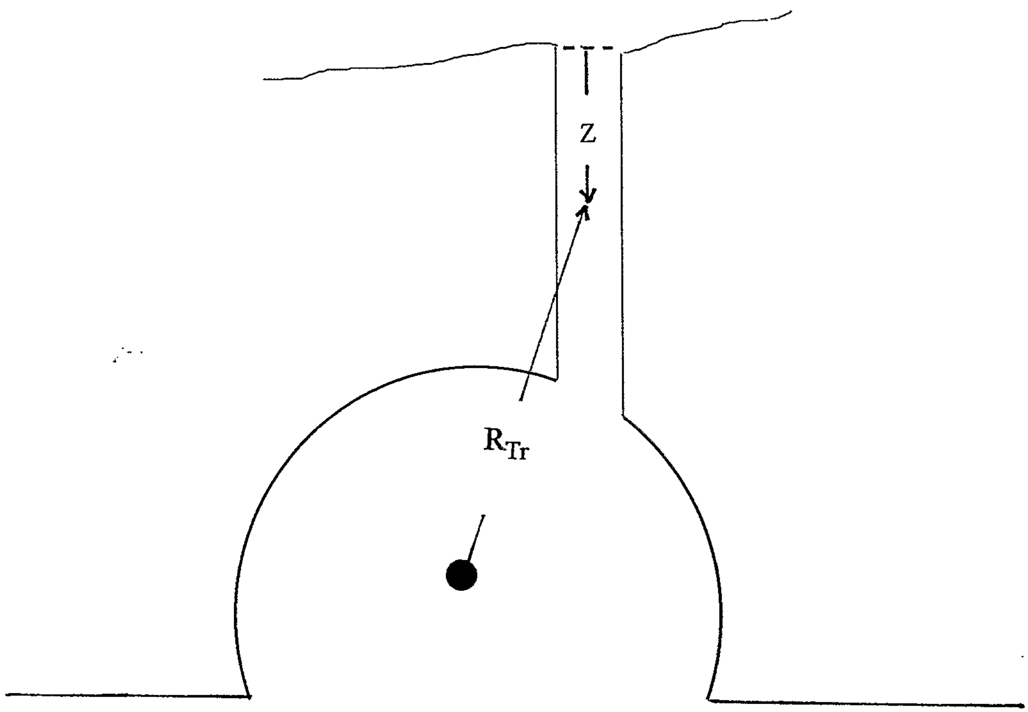

Fig. 1 Prototypical Tunnel Cross Section with Penetration.

A point is indicated in the center of the penetration which is a distance Z from the exit of the penetration and a transverse distance R_{Tr} from a magnet which is a source of beam loss.

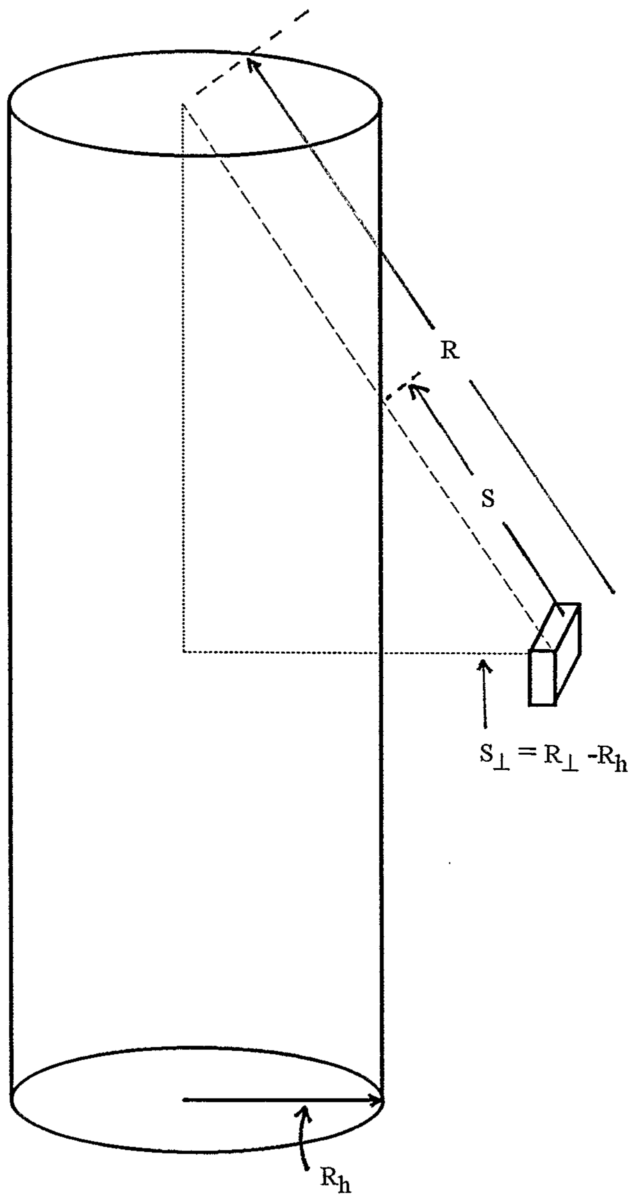

Fig. 2 Illustrative Sketch of the Geometry