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An Approximate Method for Evaluating Neutron Punch Through in Certain Classes of Shielding Penetrations

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I. Introduction

This note describes a method for making estimates of the effect of neutron "punch through" in geometries where **transverse** penetrations exist in shielding. The primary motivation here is concern in geometries involving labyrinths. The attenuation of labyrinth formula is extremely large in the second and subsequent legs of a labyrinth[1,2] which may result in the actual dose in these legs being dominated by punch through.[3]

II. The Procedure of Van Ginneken

The method described here is essentially the inverse of a procedure described by Van Ginneken.[4] In Ref. [4], the dose equivalent at the exit of a straight penetration is calculated by using a modified version of CASIM. The procedure is illustrated by Fig. 1 which shows a sketch of the transverse projection of a tunnel geometry with a dashed penetration. The first step is to perform a CASIM calculation which **ignores the actual penetration**. As illustrated in Fig. 1, some trajectories in the hadron cascade would have exited the penetration had the "hole" actually been present. The second step[5] is then (basically) a search for such trajectories given a specific size, orientation, and length of the penetration. The dose equivalent at the exit of the penetration is then calculated from the star density at that point from such trajectories **together with the usual CASIM assumption that the dose "carried by" particles above 50 MeV (the CASIM threshold) are part of an equilibrium spectrum**. Having performed this part of the calculation, which is called the "high energy" component, three other components may be added: (1) a dose due to low energy neutrons which enter the penetration entrance, i.e., an appropriate source term for a labyrinth, (2) a term calculated from CASIM assuming the penetration does not exist, and (3) a term from low energy evaporation neutrons which come from the walls of the penetration. The basic conclusion of Ref. [4] is that the high energy component is usually the largest part of the dose. Regarding the last (evaporation) term, Ref. [4] states "In all cases studied so far this component has been negligible compared to the rest of the dose." The strategy described here is to calculate this "negligible" component and to "correct for" the missing high energy component. The advantage of this procedure is that it does not require a special version of CASIM. The disadvantage is that it is a classic case of the tail wagging the dog, which means that substantial uncertainties are introduced which are, at least qualitatively, described below.

III. General Methodology

Following Van Ginneken, the first step is to perform a CASIM calculation which ignores the penetration, but with the difference that the CASIM threshold is reduced to 10 MeV, or more accurately, .137 GeV/c which is 10 MeV for neutrons. The assumption is therefore made that 10 MeV is the appropriate threshold for nuclear excitation in soil. The next assumptions are that the source is in the worst case location along the beam direction and that the extent of the penetration in this direction is small in comparison with the star density variation. With these assumptions each star at the maximum star density along the beam direction becomes a source of evaporation neutrons.

The geometry is illustrated in Fig. 2. Referring to this sketch, the neutron flux at the penetration exit from evaporation neutrons in a small volume element *dV* near the penetration can very generally[6] be written as:

$$(1) \qquad dN = n_e \times SD \times dV \times B \times \frac{e^{-r/\lambda}}{4\pi R^2}$$

where n_e is the number of evaporation neutrons per star, *SD* is the maximum star density per incident particle at a given transverse radius, *B* is a build-up factor (which accounts for the fact that neutrons not originally within the solid angle defined by the exit can scatter into that solid angle), λ is the neutron attenuation length, and r,R are as shown in Fig. 2.

The total dose equivalent per incident at the exit is then obtained by integrating over the soil volume outside the penetration and multiplying by two factors; one (denoted C_d) which is the rem/n/cm^2 conversion factor, and the other (denoted C_f) which multiplies the dose from evaporation to correct for the "missing" high energy component. Formally at least, the dose equivalent per incident can be written as

$$(2) \qquad \text{rem/inc.} = C_d \times C_f \times \int_V dN$$

The next section discusses the parameters which enter the above equations with special emphasis on the uncertainties involved.

IV. Parameters/Uncertainties

For most of the parameters involved, we adopt the values given by Wallace.[7] For A ~ 20, appropriate for soil, Ref. [7] gives a nuclear "temperature" (T) of 4 MeV. A Maxwellian distribution ($E^{1/2} \times e^{-E/T}$) with this temperature has a peak of 2 MeV and a mean of 6 MeV. We assume parameters appropriate for a 4 MeV neutron; namely λ = 13.4 cm. in BNL soil[8] and C = 4.1×10^{-8} rem/n/cm^2.[9] Likewise from Ref. [7], we take n_e = 1.0[10,11].

The build-up factor has a detailed dependence on the physics of low energy neutron propagation in the medium (soil) under consideration. No attempt has been made to do this. It is clear that B, considered in isolation, must be greater than 1. Photons with energies of a few MeV, by analogy, have B ~ 2 in light nuclei from compton scattering.[12] However, scattering also results in a lowered neutron energy with a concomitant reduction of both λ and C_d. Since these effects, which go in the opposite direction from build-up, have been ignored, the value of B is simply taken as 1. Clearly there is a reasonably large uncertainty here. We note that a neutron transport calculation with a computer program such as MCNP might reduce this uncertainty.

Only one parameter, C_f, remains to be guesstimated. The general idea is that the equilibrium spectrum of CASIM will be assumed[13], and an energy "slice" from this spectrum will be taken to be represented by the evaporation component and used to scale to the total dose equivalent. There is a several-fold problem attempting this. First, the simple evaporation approximation adopted above undoubtedly differs significantly from the more sophisticated nuclear model on which the equilibrium spectrum is based. It is therefore difficult to say what energy interval in the equilibrium spectrum (which is changing rapidly in the few Mev region!) is represented by the dose estimated above. Secondly, even if one could pinpoint precisely the energy interval "dominated" by evaporation, it is clear that not all the dose equivalent in this region is due to evaporation. For example, lowish energy (≈ 20 MeV) nucleons created by the intra-nuclear cascade lose energy (primarily by scattering from hydrogen) and degrade into the "few MeV" region. **The assumption made here is that *most* of the energy between 0.5 MeV and 10 MeV is represented by the evaporation component estimated here**. For the definition of "most" we make the crudest estimate possible, namely 0.75 which is midway between the minimum and maximum possible values of that term. The value of C_f guesstimated from this assumption and Ref [13] is 2.78.

V. Evaluation

To perform the evaluation of Eqn. (2) a simple Fortran program was written which assumes beam loss in a tunnel of some radius R_t. The user must supply two subroutines and appropriate input parameters.

The subroutines are RVSZHOLE(Z,R) and SDVSR(R,SD). In rvszhole, the input is Z, the (positive) distance along the penetration as measured from the exit (the point of interest), and the output is R the radial distance from the loss point (tunnel center) to the point at Z in the lateral center of the penetration. In SDVSR, the input is the value of R returned from RVSZHOLE, and the output is the (maximum) star density at this R value. A default version of SDVSR is available which used a Moyer Model parameterization of the star density; to wit $SD = (A\times e^{-d/L})/R^2$ where A is some coefficient, L some attenuation length, and $d=R-R_t$. If this option is chosen, A and L are also parameters read in. All distances are in units of cm.

The input parameters are a flag which specifies whether the penetration is circular or rectangular, the lateral dimension(s) and depth of the penetration, and two of the parameters (n_e and λ) discussed above.

The integration is approximated by a numerical summation using bin widths of 1 cm in the direction(s) transverse to the penetration and ~ 10 cm along the penetration. The summation in the lateral direction is terminated when the local contribution is 5% of the contribution of the innermost lateral bin.

VI. Comparison with Calculations of Van Ginneken

Two calculations have been made to compare the results of this procedure with the more sophisticated procedure described in Ref. [4]. The first case, which represents a typical survey shaft in the RHIC tunnel, is sketched in Fig. 3. A 100 GeV/c proton beam is incident on a solid Fe cylinder of radius 10 cm. where R_t is 188 cm. The comparison of the high energy component of Van Ginneken[14] with the approximation made here is as follows:

Van Ginneken	4.49×10^{-15} rem/p
Approximation	1.87×10^{-15} rem/p

In a second calculation, a culvert geometry discussed in Ref. [4] and sketched in Fig. 4 was compared. In this geometry, an 8 GeV proton beam is incident on a 7 cm. Fe plug in a 154 cm. tunnel. The culvert is a rectangular geometry with dimensions 2 ft. (in Fig. 4) by 11.7 ft. in the beam direction. In this case, the results are:

Van Ginneken	3.0×10^{-18} rem/p
Approximation	1.5×10^{-18} rem/p
Data	3.8×10^{-18} rem/p

VII. Discussion of Results

It is quite gratifying that the approximation is lower by only a factor of ~ 2 from a far more sophisticated calculation in two geometries which are quite different in every respect and whose results span 3 orders of magnitude. Although it is tempting to simply assign a build-up factor of 2 to eliminate this difference, the uncertainties described in section IV do not permit such an ad hoc correction in this author's opinion. A perhaps more justified "correction" would be to simply assert that the star density along the walls of a penetration, when coupled with the geometry (size, depth) of the penetration, is directly proportional to the punch through component of the dose at the exit. This assertion would be roughly equivalent to the original ansatz of Van Ginneken and Awschalom wherein the star density above 50 MeV was assumed to be directly proportional to the dose as calculated by a more sophisticated method.

The range of applicability of the approximation is not entirely clear and caution should be exercised. For example, if the angle of a straight penetration with respect to the radial vector (0.659 radian in Fig. 3) becomes small, the approximation may seriously underestimate the actual punch through, as the high energy (>50 MeV) component may constitute a larger fraction of the total dose than is assumed in the equilibrium spectrum. Similarly, if the size of the penetration becomes comparable to or smaller than the assumed attenuation length λ then the sensitivity to this uncertain quantity increases considerably. The approximation as described, perhaps multplied by 2, would appear to be applicable to either transverse straight penetrations of the types shown in Figs. 3 or 4, or the *last leg* of a labyrinth.

Acknowledgement

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References/Footnotes

1. P. Gollon and M. Awschalom, "Design of Penetrations in Hadron Shields," in Proc. Internat. Congress on Protection against Accelerator and Space Radiation, CERN report CERN 71-16, Vol. 2, p. 697 (1971).

2. G. Stevenson, "Neutron Attenuation in Labyrinths at High-Energy Proton Accelerators," CERN TIS-RP/182/CF (1987).

3. J. D. Cossairt, J.G. Couch, A.J. Elwyn and W.S. Freeman, Health Physics **49** 907 (1965). This reference reports measurements in labyrinth ducts at FNAL which have been used by several authors (see references in [2] above) in the development of formula. The data in the third and fourth legs of the labyrinth are substantially higher than the parameterization given in Ref. [1] The speculation is sometimes made that punch through accounts for this fact.

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

5. The discussion in the text is considerably simplified from the actual procedure described in [4].

6. M. Barbier, "Induced Radioactivity," North Holland, p. 44 (1969).

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

8. Fig. 10 of Ref. [7] gives a half-value thickness of ~2 3/4 inches for concrete ($\rho = 2.4$ g/cm^3). This gives an attenuation length of 13.4 cm. with the assumption that BNL soil has $\rho = 1.8$ g/cm^3.

9. G. R. Stevenson, "Dose Equivalent per Star in Hadron Cascade Calculations," CERN TIS-RP/173 (1986).

10. Wallace, Table 5. This table has $n_e = 1.0$ from the lowest energy considered (50 MeV) to 200 MeV followed by a slow increase to 1.5 at the highest energy considered of 2 GeV.

11. Since the star creation threshold has been lowered to 10 MeV, some (additional) uncertainty exists as to the value of n_e between 10 and 50 MeV. One author (M. P. Guthrie, ORNL-TM-3119, 1970) calculates a mean value for evaporation nucleons (including protons) of 1.5 at E=20 MeV for A = 55.9. Assuming that n_e goes linearly from zero at 10 MeV to 1 at 30 MeV in soil, a CASIM calculation at 100 GeV incident energy (section VI in the text) gave $n_e = 0.88$ with the 10 MeV threshold and 1.03 with the normal 50 MeV threshold. The error induced by ignoring the energy dependence is likely to be less than 10% therefore, which is clearly negligible when compared to other uncertainties.

12. Barbier, p. 77.

13. A. Van Ginneken and M. Awschalom, "High Energy Particle Interactions in Large Targets," Fermilab, Batavia (1975). Figs. VI.12 and VI. 13 give (among other quantities) the Maximum Dose Equivalent in concrete (for an assumed equilibrium spectrum) as a function of the fraction of hadrons below a specific energy for 30 and 1000 GeV respectively. If the fraction of the total dose equivalent in some interval around 1 MeV is considered, the dependence on incident energy is remarkably small and is ignored.

14. A. Van Ginneken, private communication. As mentioned in section II, other components are added to obtain the total dose which is 9×10^{-15} rem/p.

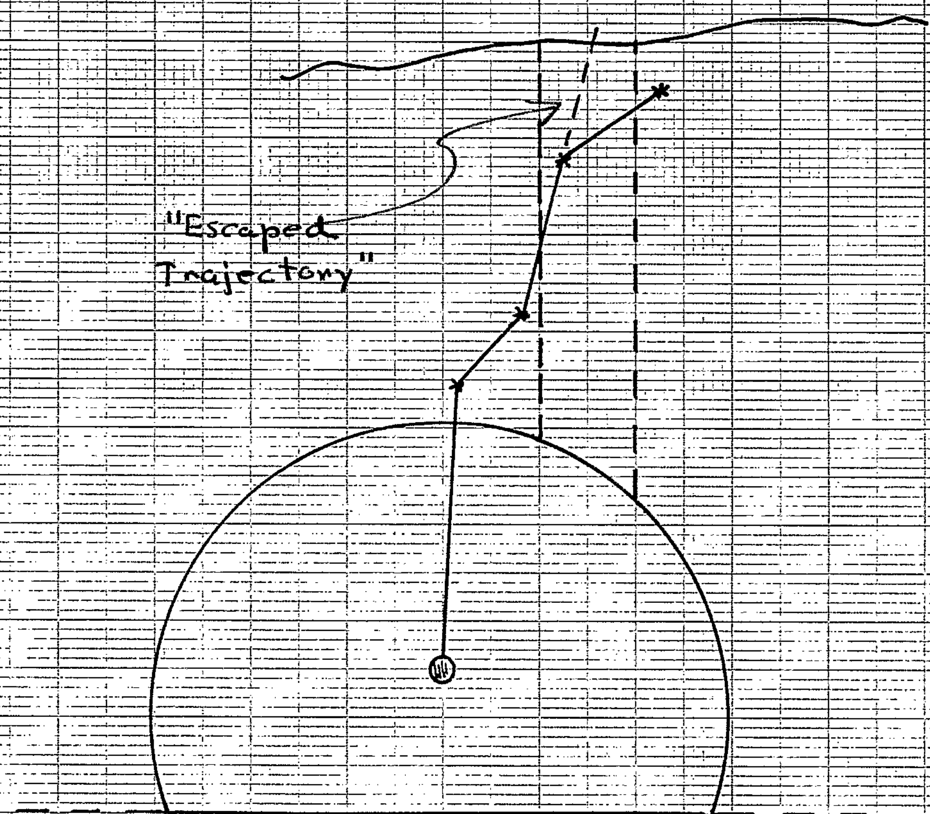

Fig. 1 Illustration of the Transverse Projection of a cascade in a Tunnel geometry.

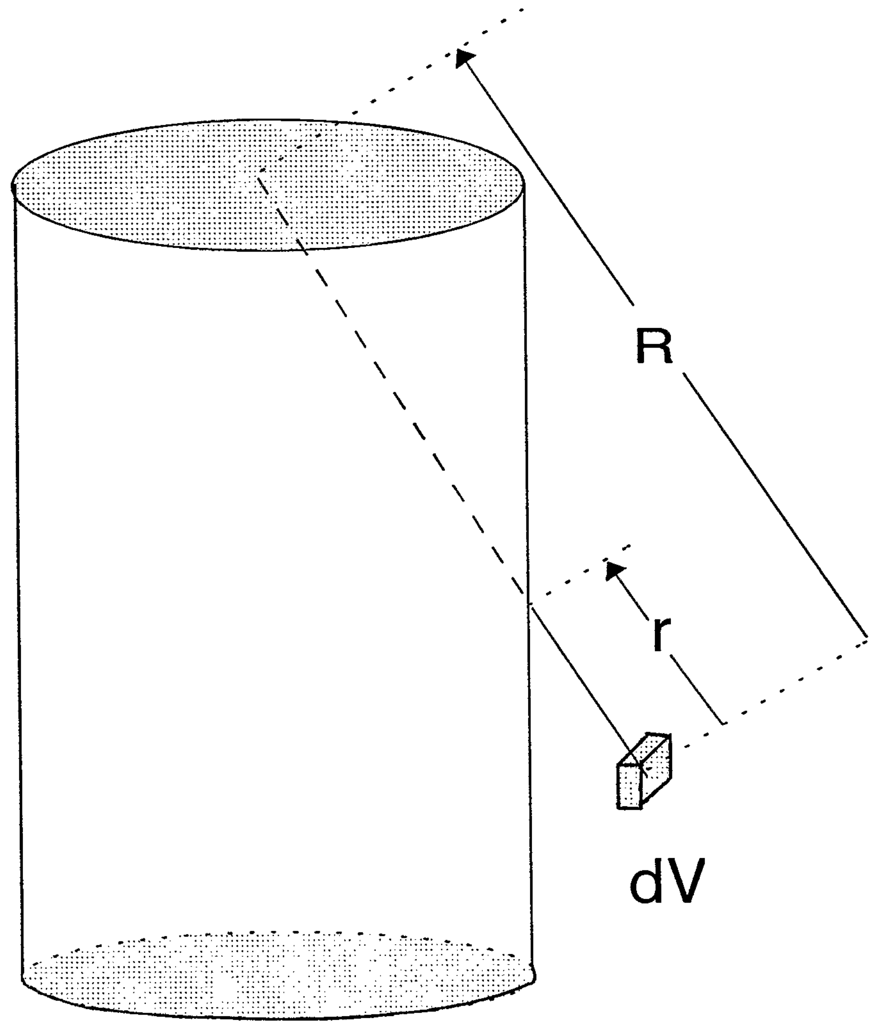

Fig. 2. Illustration of Evaporation Contribution

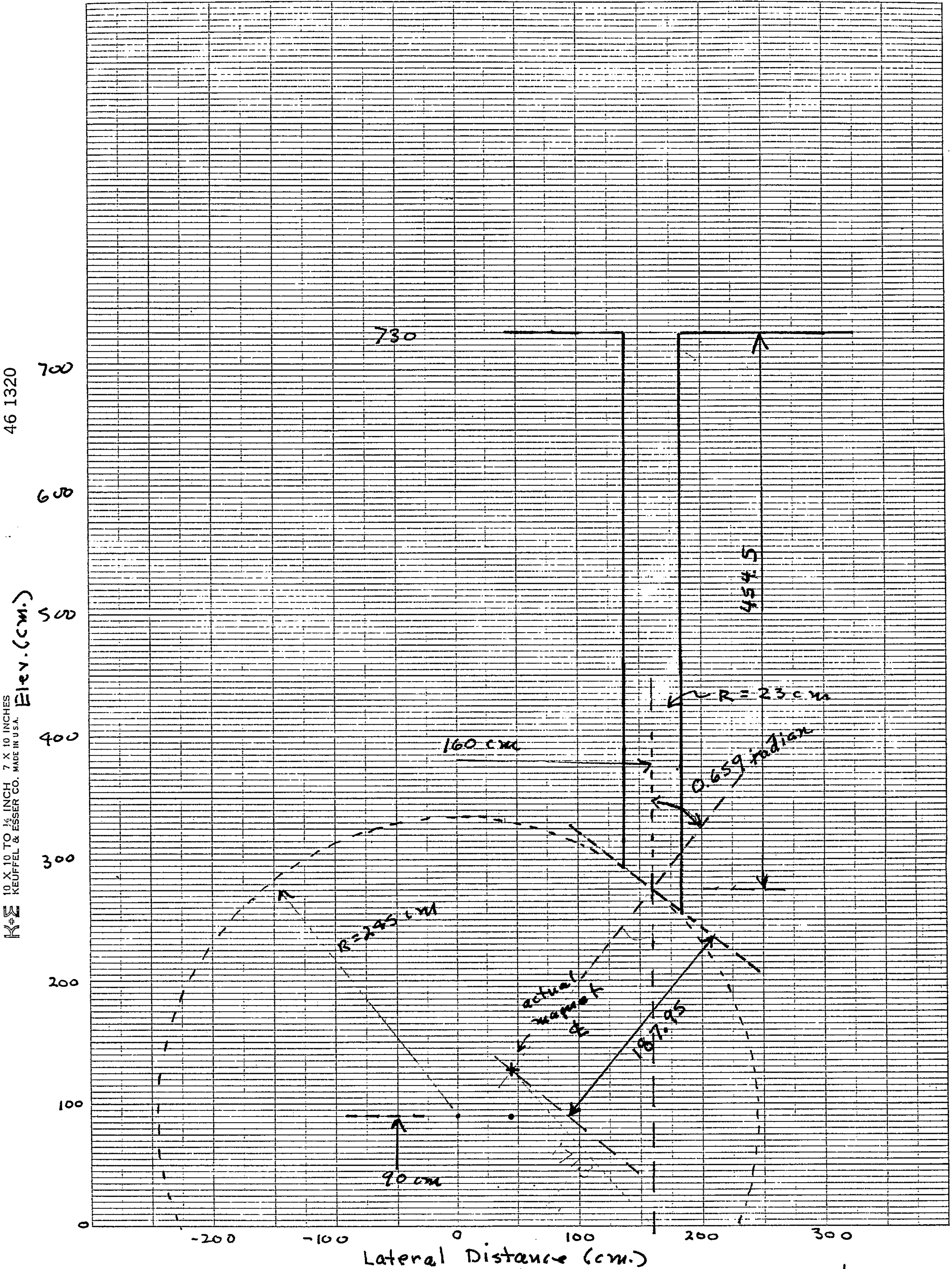

Fig. 3. The RHIC Survey Shaft Geometry

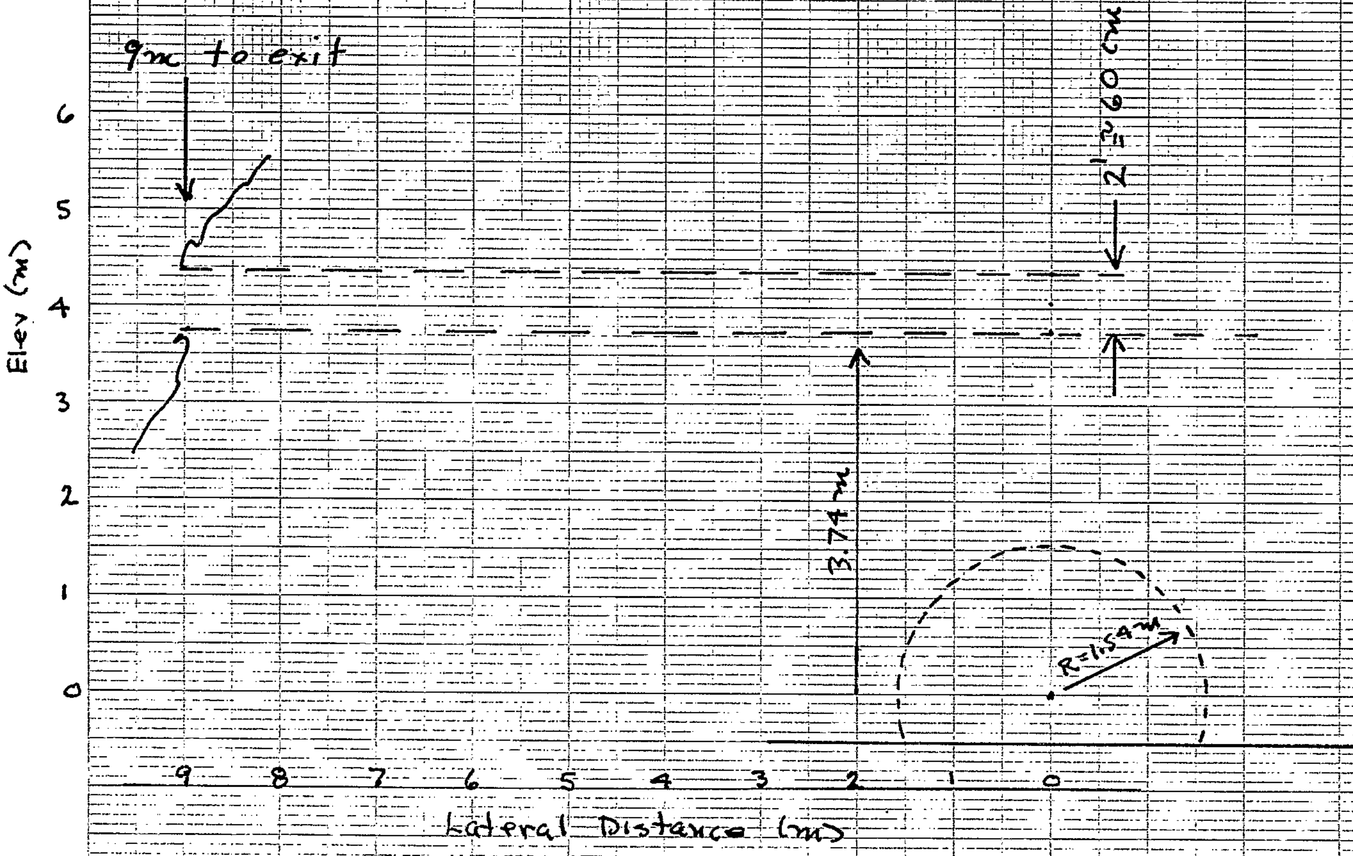

Fig. 4. Sketch of the Culvert Approximation