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I. Motivation/Limitations

A shielding wall composed of stacked blocks inevitably has cracks between the blocks. Often the question arises as to whether small cracks can be tolerated, since to avoid cracks altogether requires either custom made blocks or a double layer. The best possible answer to this question would require detailed simulation of the detector and shield wall by a hadron cascade program with the capacity to model interactions between 250 GeV and thermal energies. What is described here is a much simpler model for estimating the effects of cracks. Various assumptions must be made which limit both the applicability and the accuracy of the estimation procedure used.

Conceptually, the dose emerging from a crack can be considered to be composed of two parts, a "high energy" part which is due to hadrons with energy greater than some tens of MeV which interact in the shield wall itself and have secondaries which emerge from the crack, and a "low energy" part which is composed of neutrons whose energy is of the order of few MeV or less which propagate from the interior "through" the crack.

The "high energy component" was previously examined[1] in a simulation of the shield wall for the STAR detector. Restrictions on the applicability of the results of Ref. [1] to other detectors are that the material distribution should not differ *too much* from that of the (rather thin) STAR detector[2] and that no "longitudinal information" exists, i.e., the model of Ref. [1] is 2-dimensional. The meaning of the last restriction is that only the worst case dose behind the shield wall (with a horizontal crack) was estimated; no information on dose behind a crack of finite length in the beam direction at a particular place in the wall was available from the model of Ref. [1].

Here we describe a series of MCNP calculations, and a model parameterization of the results of those calculations, which may be used to estimate the effects of cracks on the "low energy" component. Like the high energy estimate, the result is only 2-dimensional; the source of neutrons is always assumed to be aligned longitudinally with the crack. However, there are two significant differences between the approach taken in Ref. [1] and that described here.

(1). The calculation of Ref. [1] was an *absolute* calculation of *excess* dose, i.e., dose in excess of that behind a solid wall due to the existence of a crack. Here the objective is only a relative result, that is, the *ratio* of the low energy dose in the back of the wall (at the crack position) to the dose in front of the wall. Some independent means of estimating the dose in front of the wall is therefore required. The procedure used by Gollon[3], who assumed that the low energy dose was 85% of the CASIM entrance dose, is one possible normalization. However, the normalization is a source of uncertainty. More details regarding the Gollon procedure are given below.

(2) The actual detector is **not** simulated. Instead, what is reported here is the dose through cracks from various arrangements of Fe cylinders. Historically, this series of calculations began

with consideration of the STAR detector. This detector has a very simple distribution of material which is dominated by magnet endcaps and return yoke. The return yoke is the closest object to the shield wall, and a CASIM calculation showed a peak in the star density roughly 1m in extent in the outer region of the cylindrical yoke for a fault on the DX magnet. The approximation of the dominant source of neutrons as a collection of 1m long cylinders seemed quite reasonable for this detector. Applying the results to other detectors, however, requires some imagination. The hope is that the detector geometry might be such that the argument can be made that substituting some arrangement of cylinders for the actual geometry does not severely underestimate the actual situation. In any event, some safety factor must be allowed. The topic of safety factors is discussed in the last section of this note.

II. MCNP Geometry

The MCNP calculations were made in a geometry originally used to model one end of the 4 o'clock enclosure. Some number of Fe cylinders, usually 5 cm. in radius and 1m long in the beam direction, are placed at the nominal beam height position, about 4 ft. off the floor. The (light concrete) enclosure is about 26.8 ft wide and has a roof 11 ft. above the beam line. One of the walls, which was always assumed to be 5 ft. thick, was the subject of primary interest. "Point detectors" were placed on both sides of cracks introduced into this wall. In most runs, the calculation was "biased" toward the crack at the wall of interest which means that the sampling frequency is highest in this direction. Thus, some account of backscatter off the walls, roof etc. is still included in the calculations. Although the albedo contributions would presumably be higher in a much smaller enclosure, most detectors are in fact in much larger enclosures so that roof, opposite wall, and floor albedo should be quite small in comparison to scattering off components of the detector itself.

Only one of the cylinders was taken as the neutron source in each run. Neutrons were sampled from an evaporation spectra cut off at 10 MeV uniformly within the "source cylinder." Additional cylinders were present as objects representing other parts of the detector from which neutrons from the source scatter.

As mentioned above, most of the runs had source cylinders that were 5 cm. in radius and 1m in length. Also as mentioned above, the 1m length was motivated by the CASIM results in the STAR detector. The radius was chosen to be *of the order of* the effective attenuation length of neutrons in steel obtained in previous MCNP calculations.[4] To the extent that this is true, a single layer of cylinders representing the radially outermost part of a thicker steel volume should be the source of most of the dose incident on the shield wall. However, this is not a strong argument, and an implicit assumption exists that the fact that the MCNP calculations are normalized to some other "absolute" calculation makes the transmission results insensitive to the actual radial distribution of material. Some runs were made with a very small radius (0.1 cm.) and with a source length of 3m to test the sensitivity of the results to the model described in the next section. In no case was the material (light concrete) or the thickness (5 ft.) of the shielding wall varied. Although the model described below has the wall thickness in it, no MCNP runs have been performed to justify the thickness dependence.

III. Model Parameterization - MCNP Results

(A) *Horizontal Cracks*

The "Model" of Ref. [1], a parameterization of the high energy dose through cracks, is simply a component that behaves like punch-through. That situation, for the case of the cylinders considered here, is illustrated in Fig. 1 below.

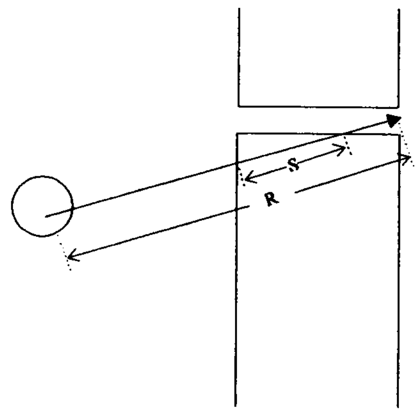

Fig. 1 Illustration of the "Direct Component"

Here called, the "direct component" (DC), the point in the back receives a dose from some point in the cylinder given by

$$(1) \qquad DC = C \times \frac{\exp(-s/\lambda)}{R^n}$$

Here, unlike in Ref. [1], the values of n and λ are regarded as (highly coupled) parameters. Also in (1) s is the length traversed in material and C is some arbitrary constant. The focus of attention has been an attempt to fit the *ratio* of exit dose to the entrance dose. At the entrance, s = 0, so the value of DC is simply C/R^n. At the exit, the "direct" contribution is some value of s averaged over the crack width. This is the procedure used to obtain the punch through in the case of high energy dose, which is done numerically. In addition to averaging over the crack, an average value of R is obtained by averaging over R0, the radius of the cylindrical source.

Now in addition to the direct dose, and for the moment assuming that no other cylinders are present, the model adds a single scattering term. Consider a small area δA = δxδy "close to" the crack. Eqn. (1), evaluated at an R between a point in the source and this point, represents the probability that a neutron reached this point. Now there is some probability P that the neutron scatters toward the back of the wall and some different probability that the neutron backscatters toward the front. In fact, **we have thus far assumed isotropy**, so that the scattering probability does not depend on direction. The contribution from this scattering in δA to the dose at the front or back is then:

$$SS(\delta A) = C\frac{\exp(-s/\lambda)}{R^n} \times P\exp(-s'/\lambda)\delta x\delta y$$

Here, s is the material traversed between the source and the center of δA, while s' refers to a line from δA to either the front or back. Again, an average is numerically performed over the width of the crack to obtain the "best" value of s'. A sum is made over the entire wall thickness in the lateral direction (X) and a distance λ on either side of the crack in Y. What is unknown is P (or some integral PδxδY). This is some arbitrary constant to be determined from the data. The single scattering term is illustrated in Fig. 2 below.

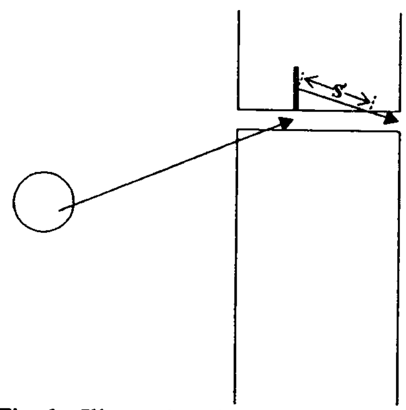

Fig. 2. Illustrating the Single Scattering Term

In fact, as illustrated in the figure, the source term is simply evaluated at the middle of the crack for all of the area elements at a given X.

Now the ratio of the back dose to the front dose is the following:

$$\text{(2)} \qquad Ratio = \frac{\dfrac{1}{R_B{}^n} + A \times SS(back)}{\dfrac{\exp(-s/\lambda)}{R_F{}^n} + A \times SS(front)}$$

where R_B is the distance from the cylindrical source to the "back" of the wall, etc. It should be understood that the values of s and R are averaged and the SS terms contain many contributions like (1) evaluated between regions close to the crack and either the back or front and therefore also contain the n and λ parameters.

In the MCNP runs it was quickly observed that if a source cylinder was not directly "in front of" the crack in the wall that the attenuation (for millimeter sized cracks) through the wall was quite large. However, if another cylinder is in line with the crack, neutrons scatter into it and the dose at the back of the wall rises substantially. The geometry is shown in Fig. 3 below:

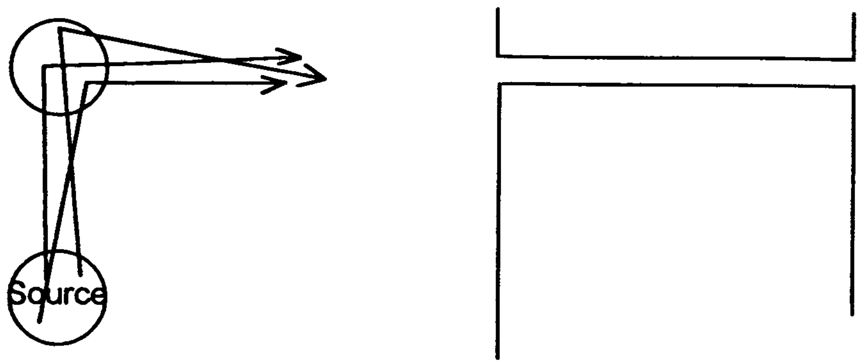

Fig. 3. Illustration of Re-Scatters.

Now the re-scatterer defines a 2-D fractional solid angle of approximately $d\omega = \mathrm{atan}(R0/D)/\pi$ where R0 is the radius of the re-scatterer and D is the distance between the centers of the two cylinders. We now introduce a third parameter, B, which is the probability that the neutron scatters in the cylinder. The total ratio then becomes

$$Ratio = \frac{\dfrac{1}{R_B{}^n} + A \times SS(back) + B \times d\omega \times \left(\dfrac{1}{R_B{}^n} + A \times SS(back)\right)_R}{\dfrac{\exp(-s/\lambda)}{R_F{}^n} + A \times SS(front) + B \times d\omega \times \left(\dfrac{1}{R_F{}^n} + A \times SS(front)\right)_R}$$

where the "R" subscript refers to re-scatterer, which means that the terms subscripted act as if the re-scatterer were the source. Finally, if three cylinders were in a row, then it would add with a probability (1-B)×B times its own dω.[5]

The table below summarizes the results to date with the parameters λ = 13.3 cm., n=1.74, A = 0.0031, B = 0.46.

Back to Front Ratio

Y (cm.)	Dis to wall (cm.)	Crack size (cm.)	Num. Re-scatterers	Y of Re-scatterers	MCNP Result	Model Result
00.0	330	0.60	0	—	6.4×10^{-02}	4.6×10^{-02}
00.0	330	0.15	0	—	1.5×10^{-02}	1.3×10^{-02}
25.0	330	0.60	0	—	2.4×10^{-04}	2.6×10^{-04}
25.0	330	0.15	0	—	5.1×10^{-05}	6.0×10^{-05}
10.0	330	0.15	0	—	5.4×10^{-05}	6.0×10^{-05}
00.0	165	0.15	0	—	6.7×10^{-03}	7.2×10^{-03}
00.0	495	0.15	0	—	2.2×10^{-02}	1.7×10^{-02}
25.0	330	0.15	1	00.0	4.4×10^{-04}	4.2×10^{-04}
50.0	330	0.15	1	00.0	2.1×10^{-04}	2.5×10^{-04}
10.0	330	0.15	1	00.0	1.1×10^{-03}	8.7×10^{-04}
00.0	330	0.15	1	10.0	1.4×10^{-02}	1.2×10^{-02}
25.0	330	0.15	2	0.00,12.5	1.6×10^{-04}	2.1×10^{-04}
50.0	330	0.15	2	0.00,25.0	8.3×10^{-05}	1.4×10^{-04}

The Y coordinate is the distance between the cylinder under consideration and the crack location.

The average deviation of 23% in the table above seems satisfactory. Note the following:

(1) The n and λ parameters are completely coupled. The n parameter must be somewhere between 1 (line source) and 2 (point source). Only the second, sixth, and seventh entries in the table above — which vary the distance to the wall for other conditions fixed — determine the "best" value for n in this geometry.

(2) Roughly "fitting" the MCNP runs effectively couples all remaining parameters. For example, if n were set to 1.6, then adjusting the other parameters would obtain a fit to the totality of MCNP runs "almost" as good as the one given above.

A few single cylinder runs were made other than those shown in the table. A single run was made with a 3m source length instead of 1m (at 3.3m from the wall and the canonical 5 cm. source radius), and no difference was seen within the ~ 4% MCNP statistics. Before adopting a 5 cm. radius, four MCNP runs had been made with an extremely small cylinder radius (0.1 cm), all for a 1m source length at 3.3m from the wall. The model fit these results with an average difference of 54%, with the worst case being a factor of 2 off (Model > MCNP calculation, crack width = 1 inch, Y = 86.3 cm. — a rather extreme case.)

(B) *Vertical Cracks*

The straightforward extension of the model to vertical cracks is illustrated in Fig. 3 below.

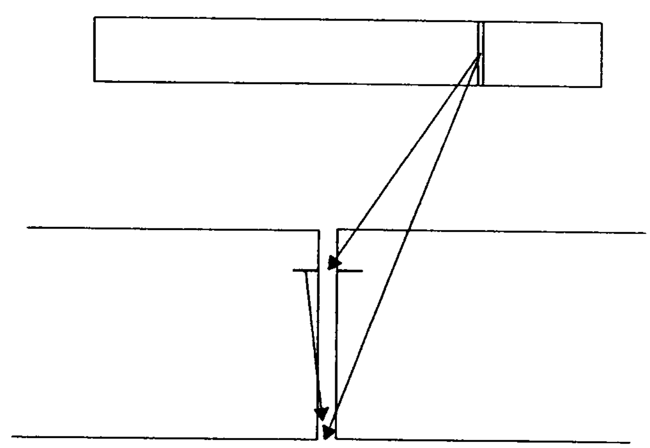

Fig. 3 Illustration of the Vertical Crack Geometry

In this case, the source cylinder is treated as a simple line, and contributions from small slices in the beam direction are simply added. Fig. 3 illustrates both the Direct Component and (a part of) the single scattering term. As in the horizontal case, the "source term" for the single scattering contribution ignores the crack as shown schematically in Fig.3.

In the case of vertical cracks, point sources are being averaged, so that the exponent that was adopted for the cylinder as a whole in the horizontal case, 1.74, must be changed to 2. As mentioned in the preceding section, the value for λ is completely coupled to n, and (for the 5 ft. thick wall under consideration), changing n from 1.74 to 2 implies a change of λ from 13.3 to about 15.5.

Note that the presence or absence of other cylinders is simply irrelevant in this case, given the limited objective; *no information is available cracks of finite length*, which was also the case in the horizontal crack geometry.

An MCNP run was made with the canoncial 1m long cylinder 330 cm. from a 0.15 cm wide vertical crack. At the back of the wall, two "point detectors" were included, one at the source elevation, and the other 60 cm. below this elevation. Within the ~ 4% MCNP statistics, both detectors gave the same 1.4×10^{-3} attenuation. With the adjusted values of n and λ the model gives 1.1×10^{-3}.

It should be clear that, if the model parameterization is taken at all seriously within the limitations of the parameters explored, that *the length of the source is a potential problem for vertical cracks*. For horizontal cracks, there is no reason to suspect sensitivity to this quantity since the first order effect of a short source would be a short expanse of dose at the back of the wall which is not being considered. For vertical cracks, on the other hand, a short source at the position of the vertical crack is clearly a hot-spot. For example, the ratio of front to back dose in the case calculated above is 4.2 higher for a source length of 15 cm. instead of 100 cm. Also, sensitivity to the distance from the source to the wall will be higher. In the next section, it will be shown that such "hot-spots" can indeed be expected to be present.

IV. Application of the Results to the PHENIX Shield Wall.

For illustrative purposes we consider the PHENIX detector together with a hypothetical shield wall which, in fact, is currently under design. An approximation of the PHENIX detector is shown in Fig. 4 below. The CASIM calculation performed[6] to determine the required shield wall thickness did not have the EmCal material shown in this figure, but it turns out that the maximum star density behind the shield wall is not effected by its presence or absence. The results of Ref. [6] is that the dose in the shield wall (at 4 times design intensity) can be approximated by:

$$Dose\,(rem) = 814\frac{e^{-S/\lambda}}{R^2}$$

At the entrance, S=0, R=7.87m. Using Ref. [3] (see also discussion in the next section), the low energy entrance dose is 85% of the above which gives 11.2 rem. At the back of the 5 ft. thick wall (of light concrete for which λ = .502m), the dose is 0.443 rem. Now the RHIC criteria for

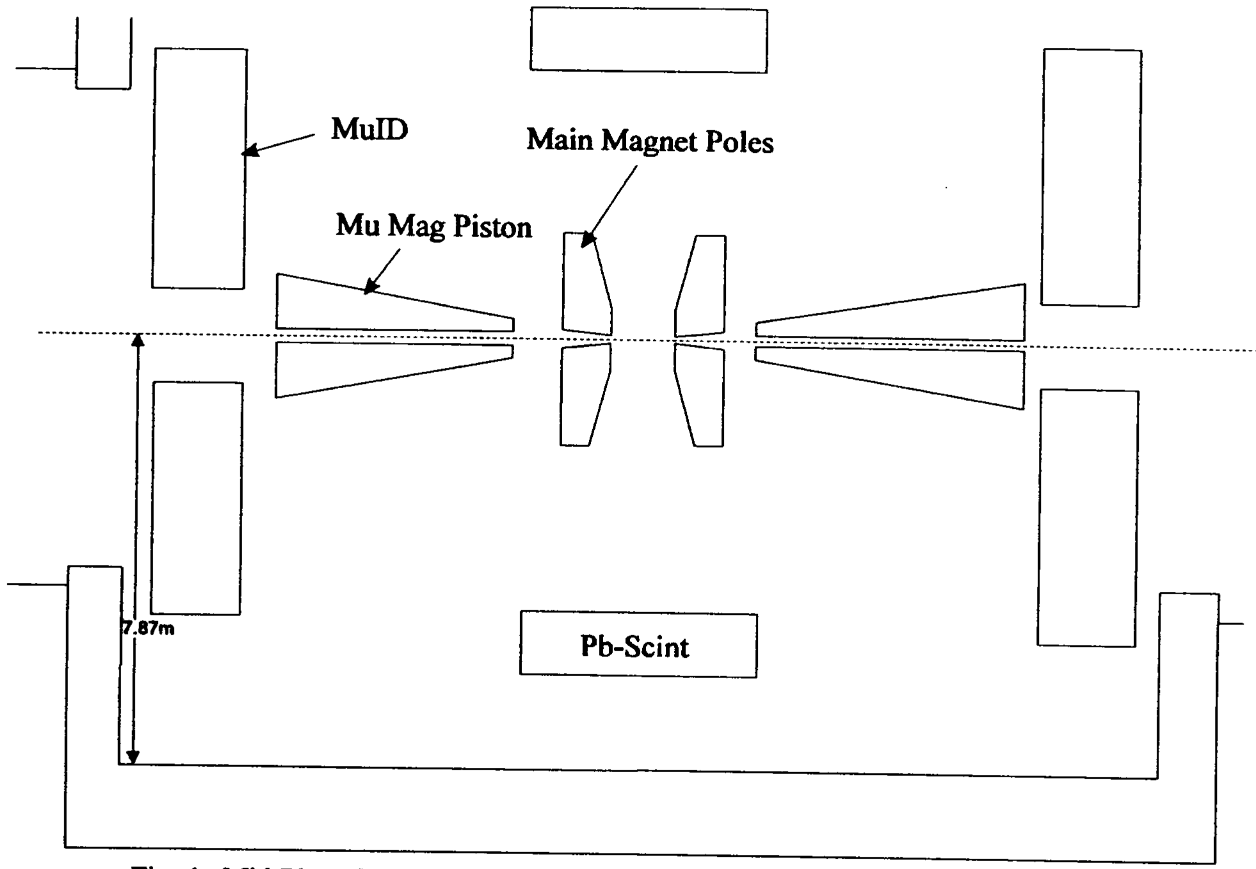

Fig. 4. Mid-Plane Schematic of the PHENIX Detector showing *Most* of the Material.

whole body exposure is 0.5 rem. In the case of the high energy cracks dose, the observation was made[1] that the excess dose was over a very small volume. However, the volume considered for numerical results was of the order of 100 cm^3, which is smaller than "whole body" but which can *conversatively* be counted as whole body exposure. In the case of the dose considered here by contrast, the values are "at a point", so the very small volume of exposure (limiting the discussion to *small* cracks) should be taken into account. Limits for exposures over small regions are higher than whole body limits. For small cracks we take the eye lens limit to whole body limit which is a factor of 3[7]. The margin for excess low energy dose due to cracks in the case of the hypothetical wall considered for PHENIX is therefore 500 mrem minus the estimate for the high energy contribution times 3.

Two specific cracks are considered here for simply for illustration; a 1/8" wide horizontal crack 5 ft. above the midplane and a similar sized vertical crack "anywhere."

(A) *Horizontal Crack*

The "high energy" contribution from Fig. 7 of Ref. [1] is 2.5 mrem. Allowing a factor of 2 for safety[1] reduces the margin for excess dose due to the low energy component to (500 - 443 - 5) × 3 = 156 mrem.

Now Fig. 4 does not look like the STAR detector on which the original concept of approximating a detector by a series of Fe cylinders was based. However, the model described here shows significant excess dose only for objects at the height of the crack considered, and since the EmCal modules are at this height and have significant mass, a partial ring of cylinders at the outer position of this device has been adopted as the neutron source. The geometry is shown below.

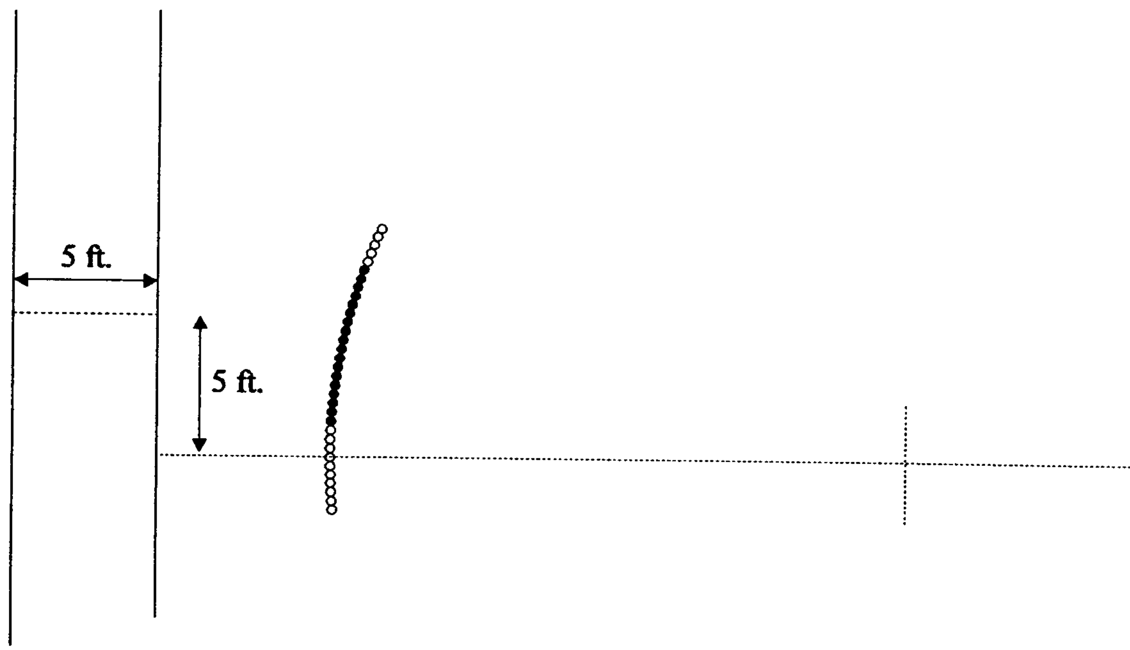

Fig. 5. Approximation for the Neutron Source.

In Fig. 5, 33 5 cm. radius cylinders are shown. The shaded 18 cylinders are a more conservative set chosen to test the sensitivity. For the 1/8" crack shown, the model[8] gives attenuation factors of 6.65×10^{-4} for the set of 33 and 1.08×10^{-3} for the set of 18. Taking 8×10^{-4} as a reasonable compromise **gives only 9 mrem, well below the 156 mrem limit**. Note however, that this example was only an illustration. A complete analysis must consider which possible sources "illuminate" which cracks. For example, the piston would be a source for all cracks within about 4 ft of the midplane. Note that the hot-spot for a horizontal crack equivalent to the vertical "short source" would be a crack short in azimuthal distance. In principle, this can happen for cracks very close to the midplane.

(B) *Vertical Crack*

Since the model shows great sensitivity to the length of the source in the case of vertical cracks, the first approach to this problem was to perform a CASIM calculation of the star density in the outer 10 cm. of the EmCal ring. The length of maximum star density here turns out to be small, about 15 cm. Referring to Fig 4, this occurs because the outermost tip of the end of the module closest to the point of beam loss is "exposed", whereas the bulk of the outer portion of the module is shielded by the material in EmCal itself.

A 15 cm long source at the "typical" distance of the cylinders shown in Fig. 5 gives an attenuation factor of 6.1×10^{-3} for a 1/8" crack which gives 68 mrem. **Note that this result is an order of magnitude higher than the 33 cylinder approximation of the horizontal crack of the same width.** Allowing 5 mrem for the high energy component[9] with its own safety factor of 2 gives a margin of 141 mrem (with the factor of 3 allowance). The 1/8 inch crack fits within the allowance with a safety factor of 2. **Note however, that this assumes that the entire low energy dose to which normalization is made is due to this very short source.** This clearly is pessimistic, and, at the time of this writing, studies are being made to determine how much contributions from other sources "washes out" this very conservative assumption.

Now in principle the argument can be made that avoiding vertical cracks located at the edges of the Pb-Scintillator EmCal would avoid the problem. However, this assumes (a) that the CASIM approximation of the geometry is correct enough, (b) that no other objects can give very narrow sources (see the approximation of the main magnet poles in Fig. 4 in conjunction with some EmCal modules being removed for some reason), and (c) that future re-arrangements of material would not introduce "short sources" in unpleasant places. Although a 1/8 inch is barely acceptable, a vertical crack this size might be difficult to achieve in practice, and 1/4 inch would leave no explicit safety factor. Whether this would be prudent is depends on the results of studies currently ongoing. It should be noted that a thicker (than 5 ft.) shield wall would provide a significantly greater margin for excess dose due to cracks. The piston (Fig. 4) is another possible (and perhaps more likely) source which, at the time of this writing, is in the process of being examined. As mentioned above, the PHENIX shield wall is just now in the design phase and the example given is simply to illustrate how application of the model might proceed. The "plan" would be to (1) use CASIM to obtain the star density in the outer regions of the most massive objects (muon piston, magnet poles and EmCal in the case of PHENIX), (2) search for the position of the worst case crack (of a given size) using the model, (3) add a safety factor of 2 (or more if the normalization is suspect as discussed in the next section), and (4) take no credit for the *actual* location of cracks relative to the worst case location found.

V. Normalization

Since the applicability of the model described here collapses if the normalization is underestimated by a sizable factor, more discussion is required of the procedure used in Ref. [3] . Dose equivalent is estimated by CASIM by assuming an "equilibrium spectrum." An equilibrium spectrum is normally considered to present after "a few" (high energy) interactions lengths in the transverse direction. For smaller transverse distances, the hadron cascade has not developed fully, which means that the ratio of low energy neutrons to high energy hadrons is smaller than exists in the equilibrium spectrum. In an equilibrium spectrum in a hydrogenous material such as soil or concrete, about 50% of the dose is due to neutrons below 20 MeV.[10]

Gollon assumes, for the purpose of estimating the low energy component of dose at the entrance of labyrinths, that the fraction of low energy neutrons is 85%, not 50%. This assumption is based on a calculation for transverse thickness of 28 cm radius of pure Fe. Below 1 MeV, Fe is known to have a "window" in the cross section which increases the low energy neutron dose. Furthermore, other calculations for "thick iron" (about 100 cm.) indicate that the low energy component is a factor of 2 greater than given by assuming a CASIM equilibrium spectrum for the dose incident on the wall.[11] Gollon adopted the "thin iron" factor since that thickness is greater than the RHIC magnet yoke thickness. Now steel is not pure Fe, so that, in reality, Gollon's assumption is *conservative* to some degree, given the total transverse thickness assumed.

Consider the PHENIX detector discussed in the last section. The Pb-Scint. was assumed to be the source for the model simply because of its obvious *location* relative to the crack being considered. In fact, according to the CASIM calculation at least, the highest star density on the entrance of the shield wall comes directly from the piston and the Pb-Scint. acts as a shield for some part of the wall. If one supposes that CASIM is correct, then the entrance dose is dominated by a source lower in elevation than the crack considered. Even though the "thick iron" enhancement could and should be applied for the piston as a source, the geometric effect would dominate, so that the estimate of the preceding section should be quite conservative. Now suppose that CASIM is wrong; that a more forward going flux of high energy hadrons than predicted by CASIM encounters the Pb-Scint., and that the neutrons coming from this module do dominate the flux on the crack entrance. In this case there are factors which go both ways relative to what was previously assumed. On the one hand, using the CASIM entrance star density (at the shield wall) which missed the Pb-Scint. is conservative. On the other hand, Pb will produce about 3.5 more evaporation neutrons than Fe. However, Pb has no "window" and scintillator (the modules are *mostly* scintillator) is a wonderful neutron degrader. It is certainly not clear how these considerations balance out, but leads one to the general conclusion that adequate safety factors are important.

In conclusion, there is no obvious reason to believe that the assumed normalization would lead to a serious underestimate of the dose in the case of the specific crack considered in the PHENIX detector. However, the simplicity of the model requires that careful attention be given to each detector to which it is applied, and understanding the "theory" behind the normalization is an integral part of that process.

VI. Proposal for Evaluation

On 06/12/96 the methodology for estimation of both the high energy component (Refs. 1,9) and the low energy component described herein was presented in overview to the AGS/RHIC Radiation Safety Committee, and to an RSC subcommittee in detail. A part of that presentation was a set of "rules" for guiding both the analysis and implementation of shield walls with cracks.

1. Cracks that exceed 3/8" must be shimmed or blocked. This restriction follows from the fact that the model is limited in applicability. High energy hadrons interactions will produce evaporation neutrons in the shield wall. If such neutrons "rattle down" cracks the equilibrium spectrum assumption (in the "high energy" contribution) would not hold. However, this is a potentially significant effect only when the crack becomes comparable to the transverse "skin depth" of neutrons which is about 1 inch in concrete. A 3/8" limitation should be conservative.

2. Estimate the "high energy contribution" as described in Refs 1,9. Treat this as whole body dose, with a safety factor of 2, and subtract from the solid wall estimated dose to obtain the allowance for the "low energy contribution."

3. Apply the model described herein to estimate the low energy contribution as follows:

(a) Experiments must be examined on an individual basis.

(b) The "equivalent whole body dose" can be treated as 3 times the model dose.

(c) For horizontal cracks, the worst case sources relative to the design position of cracks must be examined.

(d) For vertical cracks, the CASIM star density in the outer parts of massive objects facing the shield wall can be used as a (relative) neutron source. The worst case attenuation must be found if multiple sources exist.

(e) The worst case attenuation found (both horizontal and vertical) should be multiplied by a safety factor of 2.

(f) The default normalization if 85% of the worst position (in the beam direction) CASIM entrance dose without regard to crack position.

(g) The validity of the normalization must be examined. For "thick iron" sources or their equivalent additional safety factors must be applied.

VII. Safety Factors

Given the imperfect nature of the approximations being made in the estimate of the dose due to cracks, a question arose concerning safety factors. Since the concern here is for a person actually receiving excess dose, these factors, recounted here as in the 06/16/96 RSC presentation, are of various "types".

Explicit

1. The "normal" star density to dose equivalent conversion for CASIM is multiplied by 2 for :design purposes. This applies to both high and low energy contributions.

2. As mentioned above, an additional explicit safety factor of 2 applied to both high and low energy estimates.

Implicit

1. The low energy dose is assumed to come from the outer regions of the detector only. In reality, the low energy dose on the wall will also come from the interior of massive object, but these will be ***more diffuse*** on the cracks than assumed in the MCNP calculations (due to scattering) and therefore have greater attenuation than assumed. Note also that, if a "thick iron" source is present, the normalization is increased without taking credit for the fact that the neutrons from the interior are more diffuse than calculated.

2. The low energy normalization is made to the highest entrance dose without regard to position along the beam line.

"Reality"

1. The fault scenario is extreme. No fault of this magnitude has occurred in many years of Tevatron running.

2. A person is ***very unlikely*** to be immediately behind a shield wall. Occupancy near shield walls is, in fact, expected to be very low but no credit for this is taken.

Additional Considerations

1. The shielding is designed for 4 times design intensity.

2. The design criteria (500 mrem whole body for a radiation worker) is a factor of 2.5 below BNL's Administrative Control Level (1.25 rem)

References/Footnotes

1. A.J. Stevens, "Estimate of High Energy Punch-Through in Shielding Wall Cracks," AD/RHIC/RD-98, April, 1996.

2. Interestingly, the same formula used for design of the STAR shield wall, derived from CASIM calculations, applies to the PHENIX wall given the same source (the DX magnet) and the absence of the PHENIX muon identification walls. The presence of these walls shifts the worst case source for PHENIX to the beam pipe inside the hall which effectively reduces the coefficient of the formula by a factor of two. If one is considering only the worst case dose behind the shield wall, without regard to the extent of the dose profile in the beam direction, the detectors are quite "similar."

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

4. Memorandum from A.J. Stevens to S. Musolino and P. Gollon dated 03/28/94, Subject "Labyrinth Entrance Source Term." Although the direct attenuation length in steel is smaller than 5 cm., the effective attenuation length can be significantly longer due to scattering which is geometry dependent The memorandum quoted assumed a value of 11.9 for a specific geometry.

5. The model is actually slightly more sophisticated than indicated in the text. Two cylinders are always directly in line and B is given by $1\text{-}\exp(-.5\times\pi\times R0/\lambda^1)$ where the numerator in the exponential is the average chord in a cylinder of radius R0. Thus, stating that B = .46 is equivalent to λ^1 being = 12.74 cm. In considering a source cylinder and a re-scattering cylinder, a line is drawn between the centers. This line will pass through some total distance D of additional cylinders which may be present. Attenuation through these is given by $\exp(-D/\lambda^1)$.

6. A.J. Stevens, "Estimated Shielding Requirements for the PHENIX Detector," RHIC/DET Notes 13 and 13E (Erratum), December, 1994 and August, 1995.

7. BNL Radiological Controls Manual, November, 1995. Table 2-1.

8. The results were completely insensitive to variation of the number of neighbors considered as re-scatterers between 6 and 10.

9. Memorandum from A.J. Stevens to S. Musolino dated 05/08/96, subject: "High Energy Punch-Through in Vertical Shielding Wall Cracks."

10. A. Van Ginneken and M. Awschalom, "High Energy Particle Interactions in Large Targets," Vol. 1, Fermi National Accelerator Laboratory, 1975. See Figs VI-12 and VI-13 of this reference.

11. P.J. Gollon, private communication.