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Shielding Design at Fermilab; Calculations and Measurements*

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ABSTRACT

The development of the Fermilab accelerator complex during the past two decades from its original concept as the "200 BeV accelerator" to that of the present Tevatron, designed to operate at energies as high as 1 TeV, has required a coincidental refinement and development in methods of shielding design. In this paper I describe these methods as used by the radiation protection staff of Fermilab. This description will review experimental measurements which substantiate these techniques in realistic situations. Along the way, observations will be stated which likely are applicable to other proton accelerators in the multi-hundred GeV energy region, including larger ones yet to be constructed.

INTRODUCTION

The experience of most accelerator health physicists is that the shielding design of accelerators, particularly large ones, must be done with great care. This is because the addition of shielding to an initially undershielded accelerator is generally quite difficult or costly while overconservatism at the design stage squanders resources which, in this era of rather Spartan budgets, could be used more productively. I will emphasize the design of shielding to contain the prompt radiation. Other topics such as radioactivation are quite important but do not present particularly unusual problems at high energy accelerators.

One, obviously, must have a set of shielding design criteria. Practical experience by the author has shown that accelerator designers compare notes and will very quickly detect inconsistencies in criteria. At Fermilab, the radiation policy guide (called the Fermilab Radiation Guide) gives such criteria in the form of allowable dose equivalent rates for a hierarchy of occupancy levels and access control procedures.

Figure 1 illustrates schematically a typical situation encountered in which an incident beam of protons or a secondary beam of hadrons (particles subject to the strong interaction such as pions) derived from a target interact with a material object which could be a beam dump, the pole pieces of a beam transport magnet (usually by accident!), some element of instrumentation which intercepts the beam, residual gas, or a target. These particle interactions produce a hadronic cascade or shower which must be understood to determine the dimensions and composition of the shield.

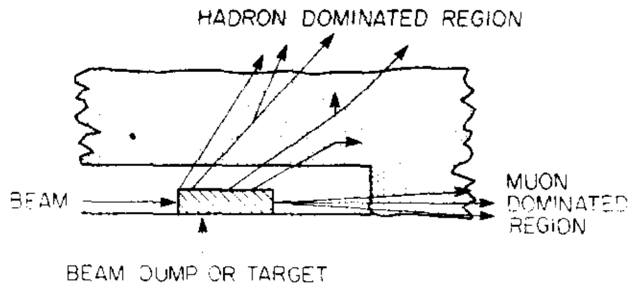


Figure 1.The general situation involved in the design of shielding. An incident hadron beam is shown to strike an object and produce a forward-peaked cone of muons which determines the longitudinal shield dimensions. The lateral shielding dimensions are determined primarily by neutrons of a wide range of energies produced in the hadronic cascade.

A good general description of the physical mechanisms involved in the development of such a cascade is given in Accelerator Health Physics by Patterson and Thomas (1). While the secondary particle yields and energy flow near the initial interactions of the beam particles are strongly peaked along the direction of the incoming beam, the development of the radiation field in the shield by the hadronic cascade processes determines the lateral shielding profile necessary to achieve a desired dose equivalent per incident particle. Thus a first ingredient of the shielding design is to establish the profile of lateral shielding against hadrons (principally neutrons) which will achieve a desired dose equivalent rate. A second ingredient in practical situations is to be able to successfully design penetrations through the lateral hadron shield for personnel access and for equipment such as cables and water pipes.

At the high proton energies presently available, the forward-peaked distribution of secondary particles contains large numbers of high energy muons from the decay of the pions and kaons as well as from direct processes. These muons behave in matter essentially as heavy electrons and so must be ranged out since they are not, to first order, attenuated by nuclear interactions. The range of these muons in soil is quite large (e.g.,700 meters at 400 GeV) making the longitudinal shield dimensions a third concern.

LATERAL SHIELDING AGAINST HADRONS

Monte-Carlo Estimates of Absorbed Dose

The complexities of following the hadronic cascade are most amenable to study by using the Monte-Carlo technique. Several programs to do such simulations have been developed at the various laboratories. Andy Van Ginneken of Fermilab has developed a very versatile program, CASIM, for this purpose (2). Comparison has been made with programs developed elsewhere and with experimental data with quite satisfactory results (3). A particular advantage to using CASIM, aside from the availability of its author for consultation, is its flexibility in handling complex geometries, multiple material media, and magnetic fields. By modifying a FORTRAN subroutine, one can specify the geometry to the degree of detail desired, often limited by one's patience in programming. Normally the Hagedorn-Ranft thermodynamical particle production model is used. (Other models have been checked by Van Ginneken). The principal output is the density of "stars" (high energy nuclear interactions) per incident hadron (protons or pions may be chosen) or the density of energy deposition per incident hadron. Conversion factors provided by Van Ginneken are used to convert to absorbed dose or dose equivalent because the program is optimized by having a momentum threshold of 0.3 GeV/c (a kinetic energy of 47 MeV for nucleons). These conversion factors were derived by matching the high energy spectrum calculated by this program with spectra extending to lower energies calculated by others. Conversion factors are also available to estimate production of specific radionuclides and residual dose rates in the shield. The accuracy of this program has been verified experimentally at 400 GeV to be better than ± 20 % for situations involving small (roughly table-top size) geometries for energy deposition in targets (4) and for radioactivation (5).

The accuracy of this code for predicting absorbed doses external to thick shields has been tested for the proton beam energy domain of 350 to 800 GeV (6,7). The quantity absorbed dose was chosen because it is a purely physical quantity, in principal readily measured. Two examples are given for illustration. Figure 2 shows the geometry of a study made at 350 GeV. In this case the beam of protons struck the iron plug in a Gaussian spot about 10 mm X 10 mm FWHM producing an hadronic cascade resulting in detectable radiation at the surface 662 cm above the enclosure.

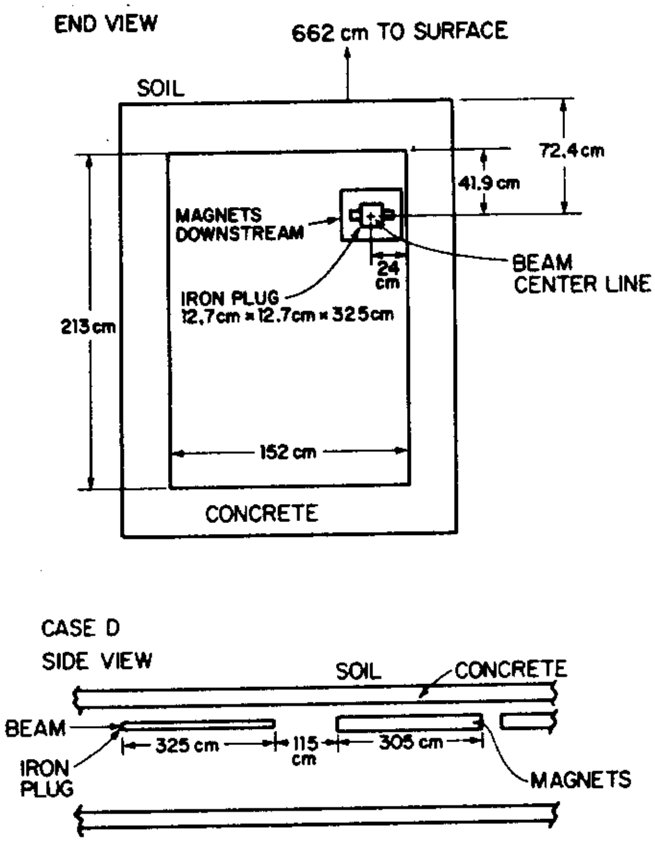


Figure 2. Two views of the geometry used in a test at 350 GeV in which an incident proton beam struck an iron block in an underground enclosure and produced a radiation field measurable above the surface.

Figure 3 shows the cylindrically symmetric model used in the Monte-Carlo calculations.

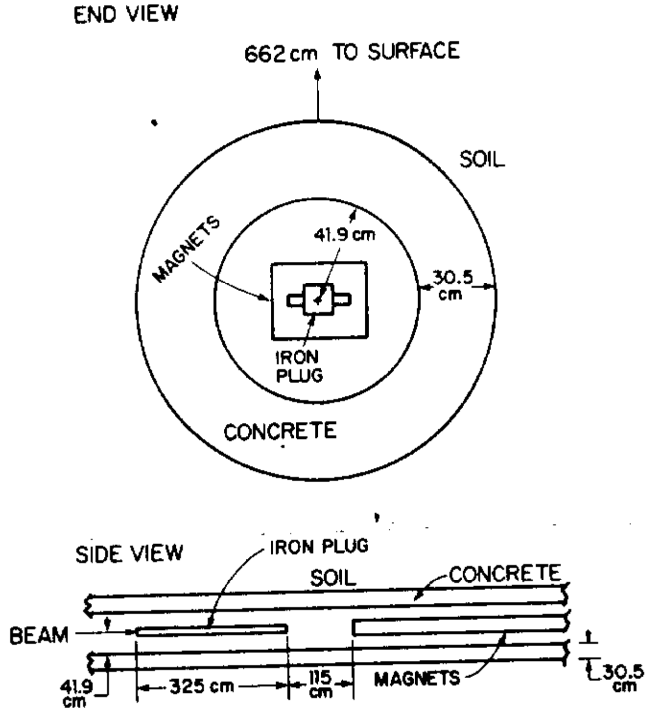


Figure 3. Two views of the approximation to the geometry of Fig. 2 made in the Monte-Carlo calculations.

This simplification in the programming also reduces statistical errors by integration over the azimuth. Figure 4 shows the absorbed dose calculations (histograms)

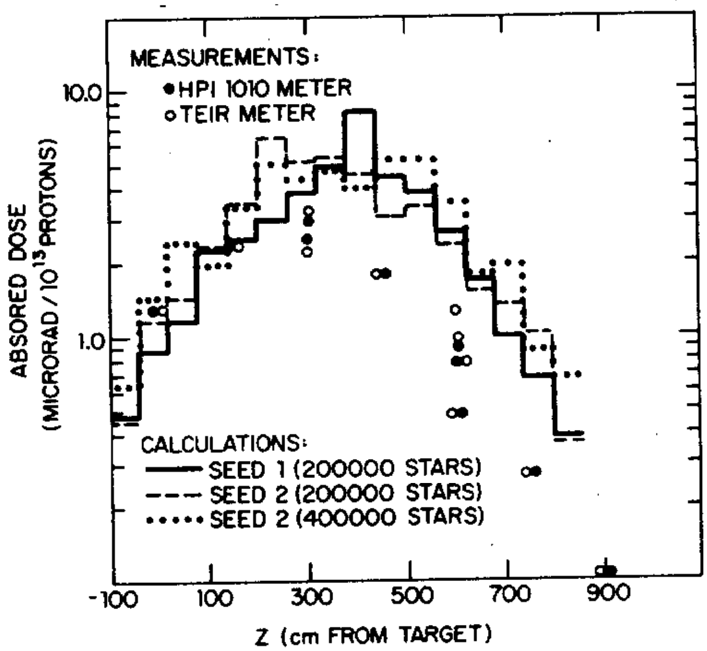


Figure 4. CASIM calculations (histograms; each the result of a different random number "seed") and absorbed dose measurements (dots) above the enclosure plotted as a function of longitudinal coordinate Z.

compared with measurements (circles) taken with two different instruments; an in-house developed tissue equivalent ion chamber (TEIR) and a commercial tissue equivalent proportional chamber (HPI 1010, Health Physics Instruments, Santa Barbara, CA 93101) as a function of the longitudinal coordinate Z at the surface. This coordinate is parallel with the beam, having its origin at the point of impact. The agreement within a factor of 2 to 3 is acceptable for such a thick shield. The statistical accuracy in the Monte-Carlo at this large shielding thickness is indicated by the observed the variations using different random number initial values or "seeds".

The second example is for an even more complicated geometry, shown in Fig. 5,

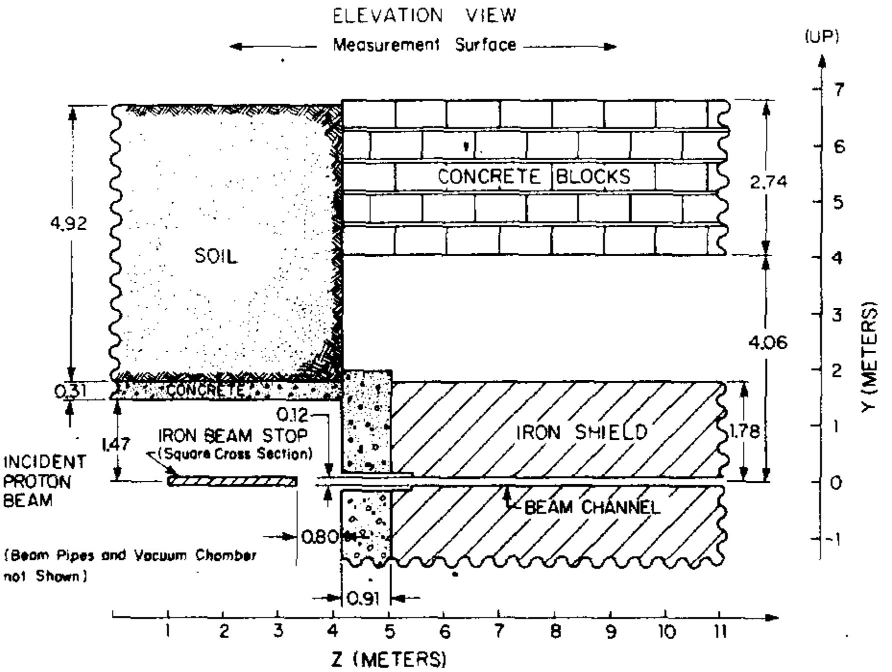


Figure 5. Elevation view of the geometry used in a test at 400 and 800 GeV. The absorbed dose measurements were made atop the shield. Note that the coordinate Z has its origin 1 m upstream of the impact point of the beam on the iron beam stop.

where a proton beam of 1 mm X 1 mm FWHM was incident on an iron beam stop followed by a beam channel. Again, absorbed dose measurements were made using the HPI 1010 tissue equivalent proportional chamber above the beam line at 400 GeV and, several years later, at 800 GeV. The geometry was modeled exactly for components within approximately 0.5 meter of the beam and as concentric cylinders corresponding to the material interfaces at larger radii. Figure 6 shows results of calculations done at several energies compared with the available measurements. Again, satisfactory agreement of within a factor of 2 is the result. Such accuracy is typical if the beam loss mechanisms and the geometry are well understood. For poorly understood loss mechanisms (e.g., scraping losses of small amounts of beam in pipes), "worst-case" assumptions are made. A number of "cookbook" cases are available in internal laboratory reports for convenience in making rapid shielding estimates.

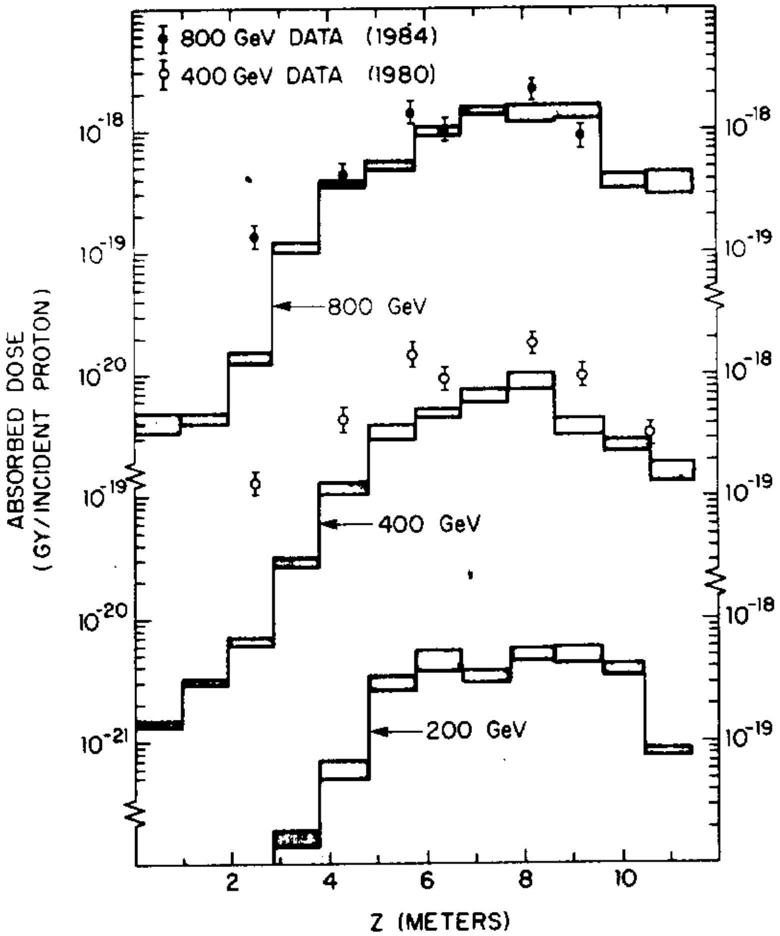


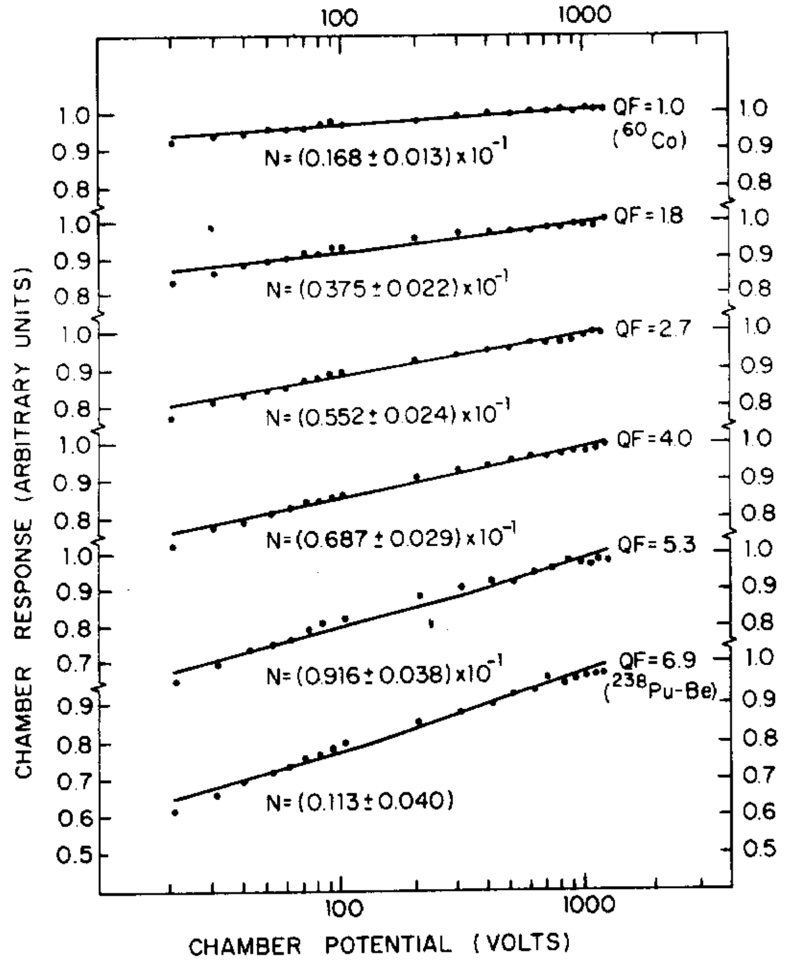
Figure 6. Measurements (data points; error bars indicate reproducibility) and calculations (histograms; widths are statistical errors) of absorbed dose atop the shield geometry of Fig. 5.

Quality Factor Measurements

The quality factor of the radiation field is needed in addition to the absorbed dose to determine the dose equivalent. To measure this somewhat arbitrarily defined quantity, we have used the recombination chamber technique with a high pressure tissue equivalent ion chamber (Model REM-2 Chamber, Radiation Dosimetry Instrument Division, ZZUJ, "Polan", Bydgoszcz, Poland). The method was developed by A. Sullivan of CERN (8) and described by Patterson and Thomas(1). Briefly, the response of such a chamber, I, depends on the applied voltage, V approximately as

$$I \propto V^N,$$

where N is an increasing function of the quality factor. Figure 7 (top) shows the measured response as a function of applied voltage for a variety of radiation fields with known quality factors due to suitable mixtures of calibrated photon and neutron sources (9). From this the correlation of N and QF is determined and shown in Fig. 7 (bottom). The chamber response can then be measured in an unknown radiation field to determine N and hence QF. In situations involving thick shielding, values of QF near 5 have been determined, in agreement with the results of Patterson (10). Figure 8, taken from (4), illustrates the chamber response in such a field.



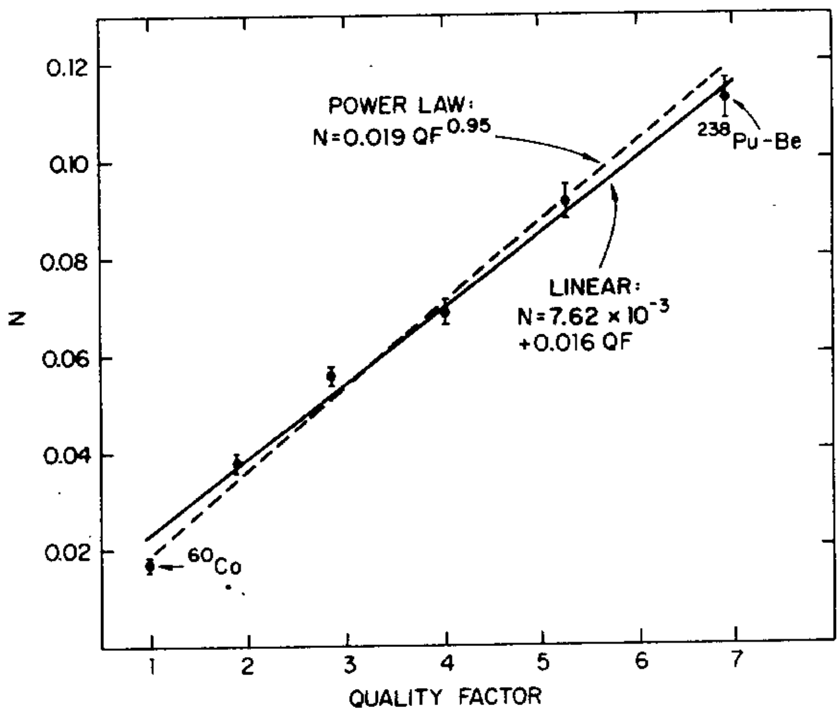


Figure 7. Response curves of the recombination chamber taken in fields of differing quality factors (top) along with a plot of the dependence of the parameter N with QF (bottom).

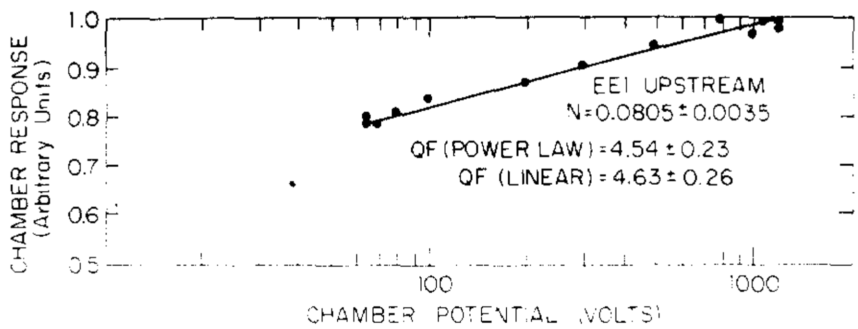


Figure 8. Recombination chamber response curve used to determine the quality factor outside of a thick shield using the dependence of Fig. 7.

Scaling Shields with Proton Energy

Since construction of higher energy accelerators is under study in the US (the SSC), in Europe (the LHC), and in the Soviet Union (UNK), one must be concerned about how to scale the size of the shield with proton energy, E. A useful framework for doing this is the Moyer model reviewed in Ref. 1 and updated more recently (11,12). In Ref. 12, Thomas and Thomas use some of the results of Ref. 6 to increase confidence that the energy dependence of the dose equivalent, H, outside of a given shield goes as,

$$H \alpha E^{0.8\pm0.1}.$$

This energy dependence agrees with results of calculations using CASIM (7) and is quite useful in practical situations.

Special Considerations in Hadron Shielding Design

It would be remiss to ignore two other considerations. First, iron shields must be surrounded by material of light elements to attenuate low energy neutrons (<1MeV) which leak through such shields (13). This constraint is not always appreciated by accelerator designers, as illustrated by the striking example described by Elwyn and Cossairt at this meeting (14). Second, it is the general experience of many that thin roof shields can cause problems in distant locations due to neutron skyshine (e.g., 15).

DESIGN OF LABYRINTHS

The design of a bulk shield must also include consideration of the penetrations through it. Early in the design of Fermilab, this problem was described by Gollon and Awschalom (16) who extensively studied such labyrinths with a Monte-Carlo program. A number of practical examples were presented in Ref.16 so that generally one can use these to determine the attenuation of the labyrinth (defined as the ratio of dose equivalent at the exit relative to that of the "mouth", the inner entrance near the beam). It is well known that the attenuation of a labyrinth depends very weakly on the beam energy, if the labyrinth views the target at large angles (greater than 20 degrees or so). That is, attenuation curves measured at lower energy accelerators are approximately valid at much higher energies. This is because the average energy of neutrons in such a labyrinth is expected to be quite low. An alternative method of calculating labyrinth attenuation has been developed by K. Tesch (17) of the DESY laboratory in Hamburg in which simple formulae are found to fit existing attenuation data for personnel-size penetrations. To determine the actual dose equivalent at the labyrinth exit based on any attenuation method, one, of course, has to supply some estimate of the intensity of the radiation field at the beam loss point. These "source terms" can be "rules-of-thumb" or elaborate calculations, and increase nearly linearly with proton energy.

Figure 9 shows plan and elevation views of a labyrinth which was available for study (18). Here, a beam of 400 GeV protons from the Tevatron struck an aluminum target (15cm X 15 cm X 30 cm long) in a vacuum box underneath the floor.

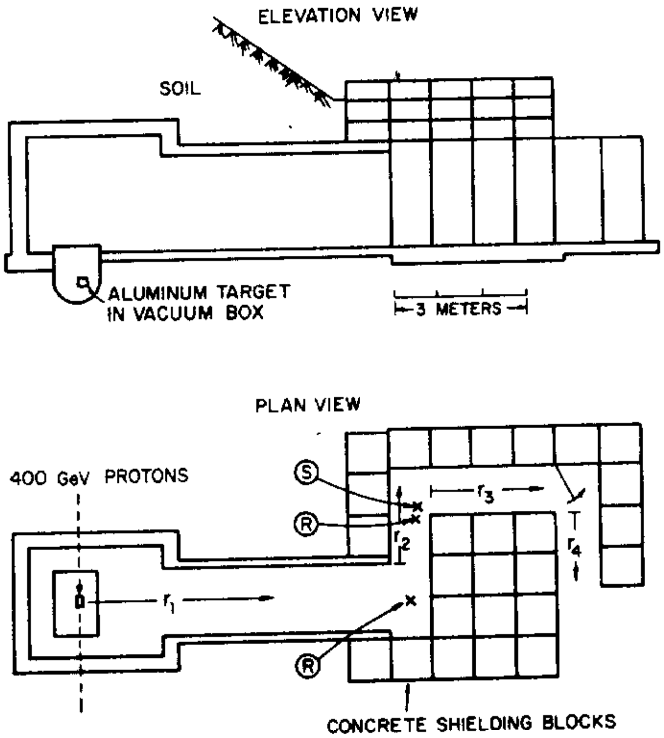


Figure 9. Plan and elevation views of the access labyrinth studied. Coordinates used in the text are defined in this figure. Locations of sphere (S) and recombination chamber (R) measurements are marked.

The secondary particles produced in the forward direction along with the remaining protons continued far downstream without further interaction. Absorbed dose measurements were made in this enclosure using in-house-built ion chambers read out remotely from various coordinates (defined in Fig. 9) in the enclosure. The absorbed dose above the aluminum target was estimated using CASIM. Both the results of Gollon and Awschalom and of Tesch were used to estimate the attenuation and are compared with the measurements in Fig. 10. The attenuation curves were arbitrarily normalized to the ion chamber data at the mouth of the labyrinth (r_1 = 1.98 m). (The value of unity in the normalized absorbed dose at this position is purely coincidental). Adequate agreement of the CASIM result with the ion chamber measurement directly above the target was obtained. It appears that the attenuation estimates of Refs. 16 and 17 are reasonable. The deviation seen in the attenuation curves occurred principally in the third section, caused perhaps by leakage through the cracks in the concrete shielding blocks (not considered in the calculations).

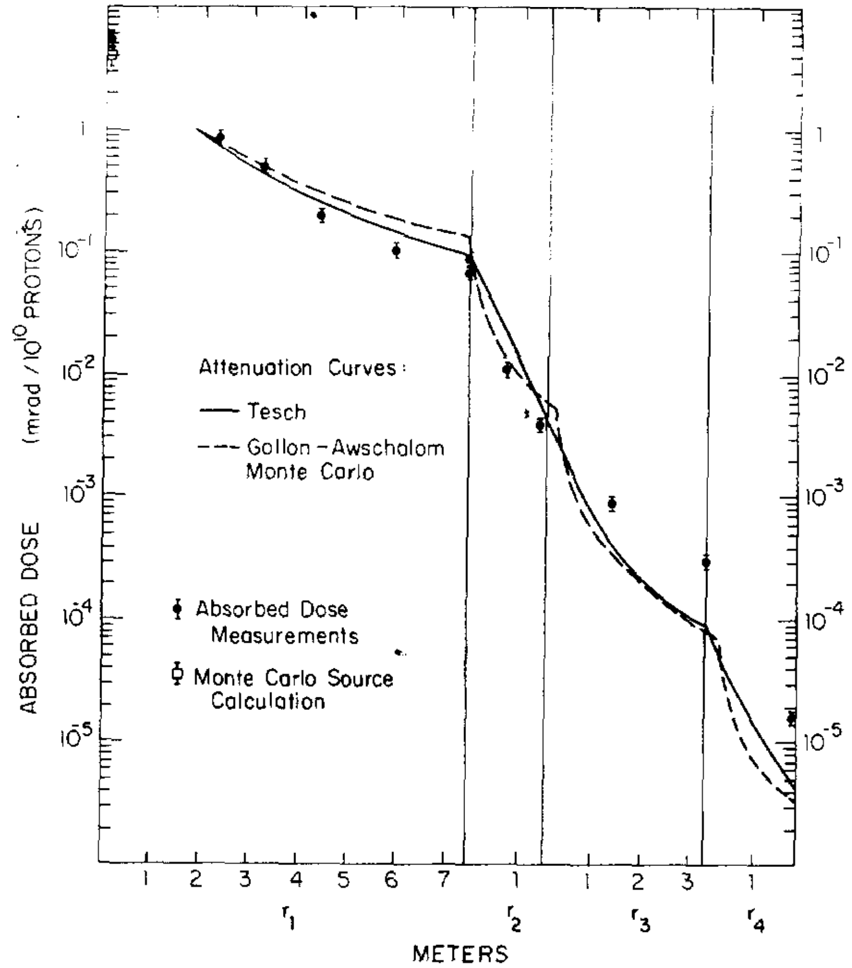


Figure 10. Absorbed dose measurements and predictions plotted as a function of labyrinth coordinates. A Monte-Carlo prediction for the absorbed dose directly above the target is also shown.

The quality factor in the labyrinth was measured at the two locations denoted "R" in Fig. 9 by use of the recombination chamber technique, resulting in the response curves in Fig. 11. At $r_1 = 7.4$, the QF $= 5.59 \pm 0.65$ while at $r_2 = 0.85$ m, QF $= 3.37 \pm 0.13$. The latter result also agreed with the value 3.1 ± 0.7 derived from a neutron spectrum measurement in the same location using the multisphere technique7. The multisphere work gave the unfolded neutron energy spectra shown as Fig. 12, which indicates the fluence at $r_2 = 0.85$ m to be largely thermal.

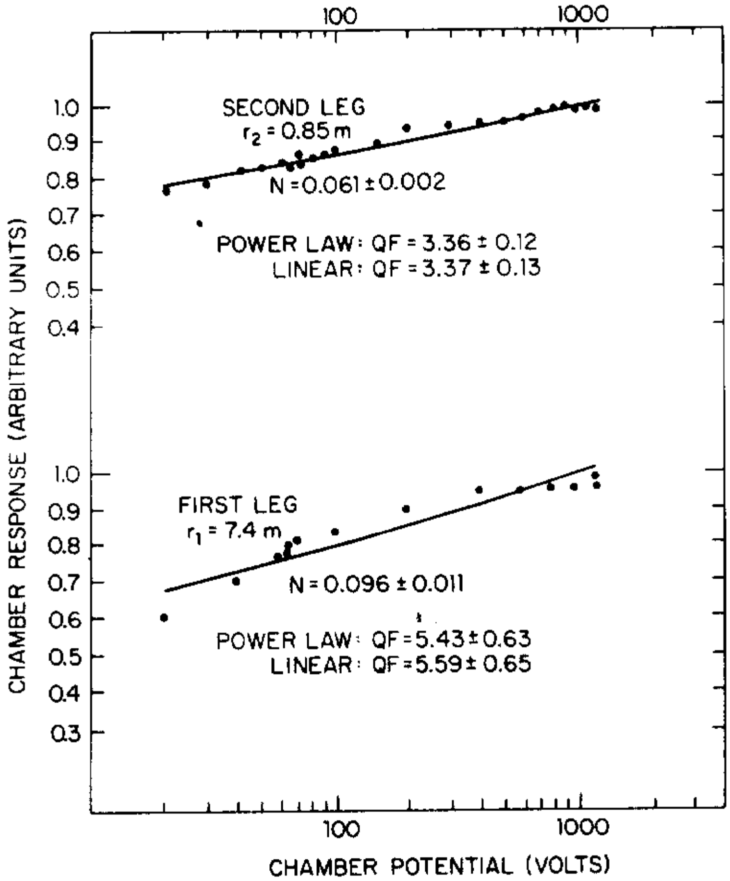


Figure 11. Recombination chamber response curves measured in the labyrinth.

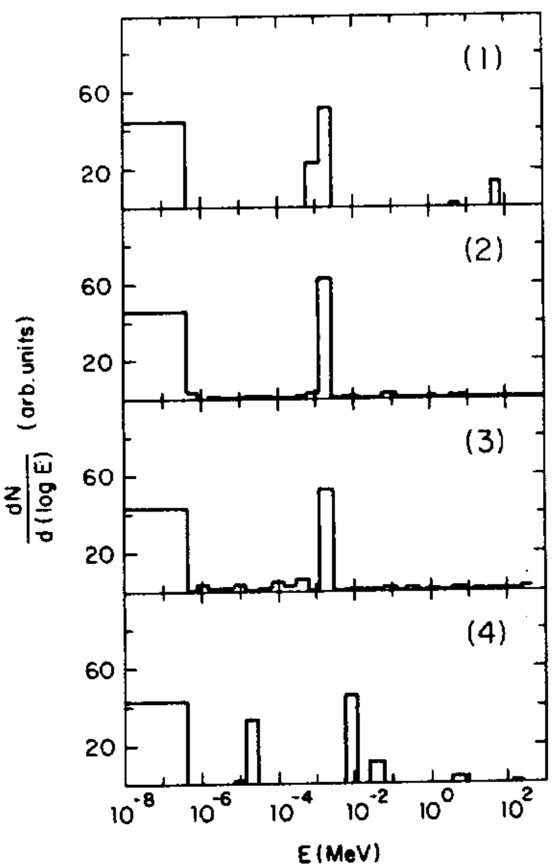


Figure 12. Four best-fit spectra from the multisphere data taken in the labyrinth.

DESIGN OF MUON SHIELDING

High energy physics experiments using secondary particle beams tend to be aligned at small angles relative to the proton beams extracted from the accelerator in order to minimize the numbers of bending magnets required. Accordingly, the background due to forward-peaked muons in the experiments are of great concern. Often the program HALO (19), developed at CERN, is used to predict these muon distributions. This program creates the muons at a point and propogates them through the shielding using a set of standard tunnel and bulk shield geometries specified by the user who must also supply collimator and magnet geometries. By the use of detailed magnetic field maps it is capable of handling complicated beam lines. It produces histograms of fluence which can be readily converted to dose equivalent with conversion factors given, for example, by Stevenson (20). Various particle production models are available for this Monte-Carlo program which correctly treats multiple Coulomb scattering and energy loss. It is most useful in situations where one is concerned with muons produced by the first interactions of particles (usually the accelerated protons) in a target. This situation exists where the protons transmitted by the target are absorbed in a well-shielded dump so that the hadronic shower is adequately shielded. If the shower is inadequately shielded, a recent version of CASIM optimized for following these shower muons will be applicable. Here, an example of each situation is given.

Elwyn and Freeman (21) have made a series of measurements of the muon fluence due to the Fermilab PW beam. The PW beam of 800 GeV protons interacts in a one interaction length beryllium target to produce a secondary pion beam for experimental use. The protons, after their passage through this production target, proceed to an underground beam dump where the shower is well contained below grade level. The secondary beam is transported by a quite complicated beam line of many elements which affect the muon paths. HALO is the appropriate code to use for this situation. Figure 13 compares the muon fluence measurements with the predictions of this program at two locations longitudinally distant from the target. The measurements were made with a pair of large scintillation counters mounted in a truck. In spite of the many complications, the agreement is surprisingly good and shows that this program may be used as a design tool for environmental predictions, often concerned with such "fringes" of the muon distributions. The program is generally trusted near the center of the so-called "muon cone".

For the second example, Figure 14 shows a situation where an 800 GeV proton beam is incident on a target followed by two magnets and a beam dump. The magnets serve to sweep the protons downward into a beam dump and away from a channel for secondary particles (principally neutrals) desired by a physics experiment (not shown) further downstream. The beam dump and its associated shielding is rather short compared to the ranges of many of the muons. In order to reduce the dose equivalent rates for personnel working in nearby places (not shown in the figure), the steel shielding was added downstream of the dump on one side of the beam. Measurements using the HPI 1010 tissue equivalent proportional chamber were made downstream of this beam dump and the geometry was modeled with CASIM rather

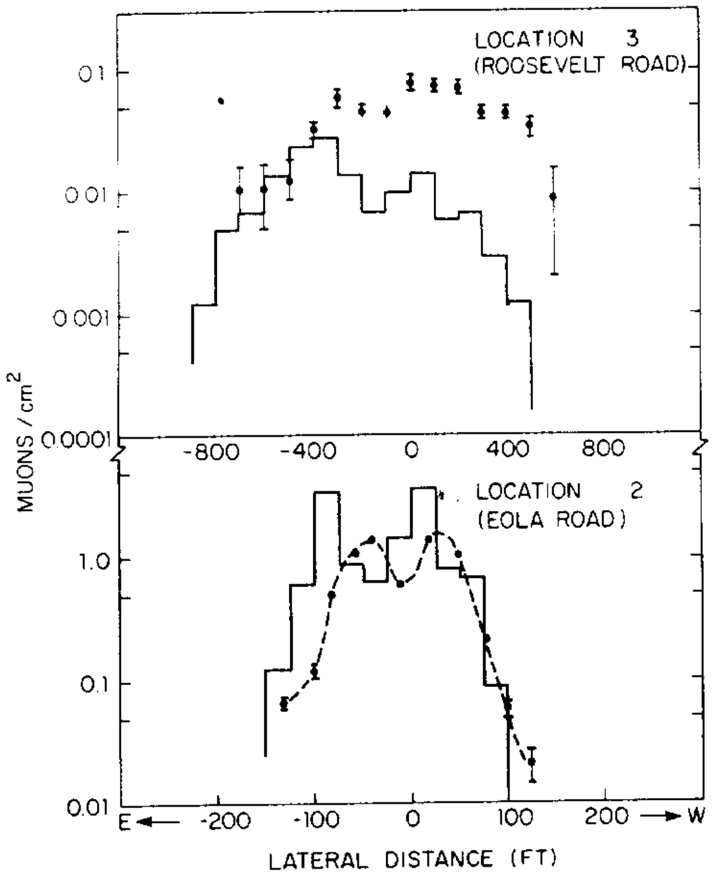


Figure 13. The lateral distribution of muon fluence per 10^{12} incident protons at two locations which are 800 m (lower) and 3240 m (upper) downstream of the target struck by the protons from the accelerator. The data points are measurements using plastic scintillators while the histograms are HALO calculations.

than HALO, since studies with the beryllium target removed indicated domination by shower muons from the beam dump. The calculations were averaged over the azimuthal bins exemplified in the elevation view, separately for $X \geq 0$ and $X < 0$ without "artificial" normalization. Figure 15 compares the measurements (dots) with the calculations (bands) at two values of longitudinal coordinate Z as a function of transverse coordinate X. As seen, the agreement is satisfactory at Z =100 m. Some of the points at Z = 50 m where the measurements exceed the calculations may include muons from other sources, since the programmatic impact was too severe to turn other beams off to do the measurements. An additional check was provided by a comparison in Fig. 16 of the shape of the muon momentum spectrum computed at Z = 50 m with that measured further downstream by a physics experiment using a large magnetic spectrometer. The comparison is valid only for momenta > 10 GeV/c, the approximate threshold of the magnetic spectrometer system (designed for measuring much higher momenta). Within statistical uncertainties evidenced by the differences between the results of different random number "seeds", the agreement is qualitatively quite good.

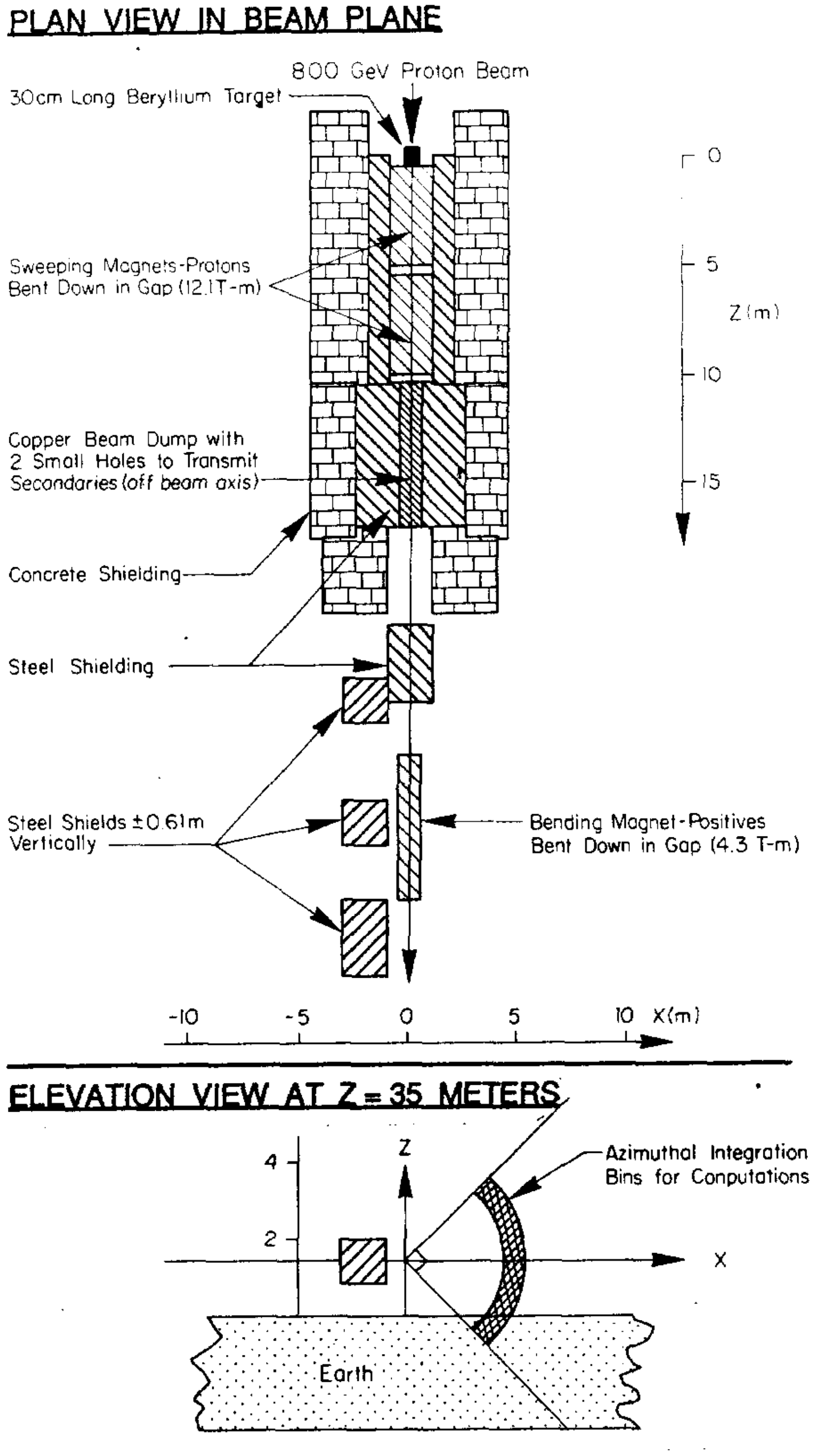


Figure 14. Two views of beam dump geometry which provided a source of muons. Absorbed dose measurements along transverse coordinate X at beam height were made at various downstream locations. An example of the azimuthal bins used to optimize statistics in the Monte-Carlo calculations is shown.

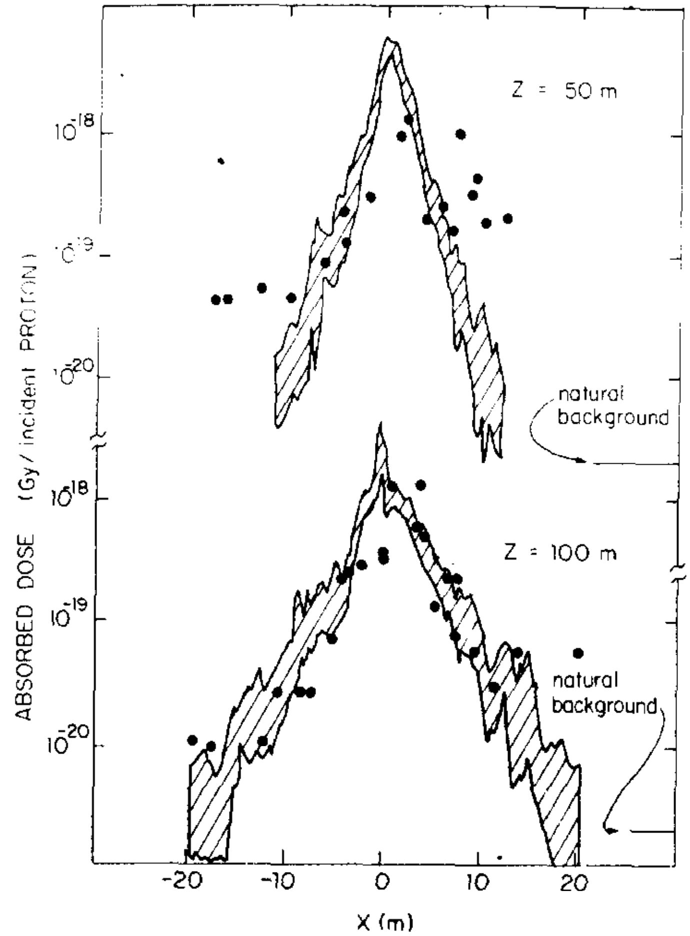


Figure 15. Comparison of absorbed dose measurements (dots) with CASIM calculations (bands; widths indicative of the statistical errors).

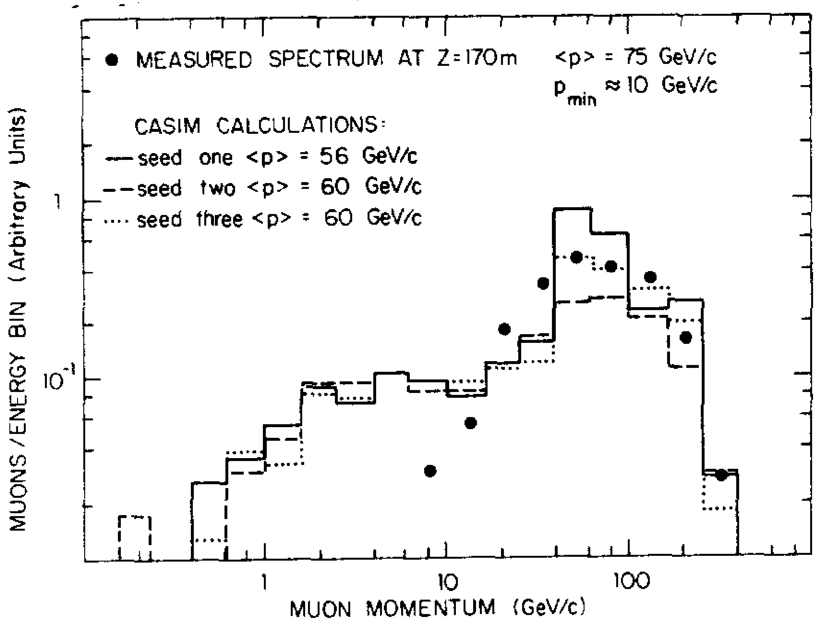


Figure 16. Comparison of calculated muon momentum spectra (histograms; each the result of a different random number initial value or "seed") with measurements (dots) made in a large magnetic spectrometer system having an effective threshold of about 10 GeV/c.

CONCLUSIONS

I have summarized the methods used by the Fermilab staff for shielding design and have presented comparisons with experimental measurements. These techniques have served us well and should also be, in general, applicable to the next generation of particle accelerators. Of course, the efforts will continue to develop these methods and broaden our understanding of the shielding of high energy proton accelerators both theoretically and experimentally.

ACKNOWLEDGEMENT

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