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ESTIMATING ISABELLE SHIELDING REQUIREMENTS

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ABSTRACT

Estimates have been made of the shielding thicknesses required at various points around the ISABELLE ring. Both hadron and muon requirements are considered. Radiation levels at the outside of the shield and at the BNL site boundary are kept at or below 1000 mrem per year and 5 mrem/year respectively.

Muon requirements are based on the Wang formula for pion spectra and the hadron requirements on the hadron cascade program CYLKAZ of Ranft. A muon shield thickness of 77 meters of sand is indicated outside the ring in one area, and hadron shields equivalent to from 2.7 to 5.6 meters in thickness of sand above the ring. Our suggested safety allowance would increase these values to 86 meters and 4.0 to 7.2 meters respectively. There are many uncertainties in such estimates, but we feel these last figures to be rather conservative.

1. Introduction

An analysis of shielding requirements for ISABELLE was given in the May 1974 proposal, BNL 18891 (Ref.1), but no modifications to the requirements set at that time were made in 1975. A minimum shielding thickness of 6 meters of sand was specified as a conservative figure, based on a worst-case analysis of 10^{15} protons lost at an arbitrary point in the ring. In the design of ISABELLE, however, great efforts are made to prevent such catastrophic beam loss, which would be likely to damage the machine severely, and the probability of such loss must be considered very small indeed. We have made estimates of shielding requirements based on somewhat different considerations, and give the procedure and present results here.

One objective has been to investigate whether a reduction in shielding thickness could be made which would reduce the cost of construction and still be satisfactory from a radiation safety point of view. In addition, reduced shielding thickness tends to make the machine more accessible and easier to use for high energy physics research. Unnecessary shielding reduces the effectiveness of the machine as a research tool. For these two reasons it is important to study shielding requirements carefully, to plan to provide adequate and effective shielding, and to avoid unnecessarily conservative overkill.

The present estimates are different from those made previously in a number of respects. In the first place, we have based our estimates of shielding requirements on estimates of radiation sources at different points in the ISABELLE rings. These sources depend on the number of protons injected, and the points at which they are lost by nuclear collisions, as discussed in Sec. 2. In the second place, we have used somewhat different values for acceptable radiation levels on the BNL site and at the site boundary, with main emphasis on the yearly dose. Because the ISABELLE ring is rather close to the site boundary, and acceptable levels are extremely low, control of levels at the boundary is an important consideration. (See Sec. 3 for discussion.)

From the sources and acceptable levels a required attenuation for the shielding is determined. The particles most likely to emerge are high-energy muons and lower energy neutrons. The shielding must then keep the number of muons and neutrons that emerge per interacting proton at a satisfactory level. In estimating muon shielding thickness, we have used new information on secondary particle spectra from 200 GeV proton interactions. In estimating neutron shielding, we have used the Monte Carlo hadron cascade program, CYLKAZ, prepared by Ranft. These are approximate calculations, but they should correspond to reality somewhat more closely than those used before. (See Secs. 4, 5, and 6 for discussion.)

There are many quantities entering such calculations that are not precisely known, and approximations whose accuracies are somewhat uncertain. The shielding requirements that we have obtained are the following:

	Calculated	With Safety factor
a. Radial thickness of muon shield	77 m	86 m
b. Height of muon shield above beam	4 m	4 m
c. Minimum transverse thickness of hadron shielding:		
1. Above external beam dump	5.3 m	6.8 m
2. Above scrapers and internal dumps	5.6 m	7.2 m
3. Above experimental halls		
Hadron	2.7 m	4.0 m
Lepton	2.8 m	4.1 m
Elastic	3.3 m	4.6 m
4. Above rest of tunnel	4.2 m	5.6 m

All thicknesses are given in meters of sand. The mass of concrete roofs should be taken into account as providing part of the required thickness.

We have not introduced any explicit safety factors in the calculated estimates, preferring to do so once to avoid an excessive cumulation of safety factors. We suggest adding (10% of the thickness + 1 meter) as a safety factor, which leads to the second set of numbers.

2. Sources of Radiation

a. Beam dumps

The energy stored in the ISA circulating beam is too large (up to 20 MJ) to allow it to strike the vacuum tank, so a fast extraction system is planned to dump the beam in an external absorber.^{2,3} This absorber is designed to absorb the energy without damage, and is described in Ref. 2 as "2.5 m of Be front absorber, cast in an enclosing iron sleeve . . . followed by an adequate length of iron as a backstop." Whenever the beam is dumped intentionally, it is ejected to hit this absorber, and whenever any machine malfunction occurs, appropriate monitors and interlocks cause the beam to be ejected automatically so that it ends up in the external beam dump absorber.

This automatic beam dump system is essential for the protection of the machine and must be highly reliable. To first order, the 200 GeV protons always hit the beam dump and nowhere else. Failures may occur, however, and a back-up system is envisaged for this contingency. It is expected to be an internal beam dump which provides a defining aperture for the rings such that any normal perturbation of the particle trajectories which causes them to blow up will cause them to hit at this point. It is not entirely clear to us whether this will be a passive system or whether it will have an independent beam kicker. We do not attempt to design this back-up system, but consider that ejector failure will cause protons to hit this internal dump.

2. A. van Steenbergen, "ISA Ejection System, Components and Parameters", July 1975.
3. A. van Steenbergen, "ISA Beam Dump Absorber", 1975 ISABELLE Summer Study, BNL 20550, p. 430.

The probability that the beam, as a whole, will hit somewhere else is very small, but not absolutely zero. It requires a combination of malfunctions whose probability we see no way to evaluate. On the other hand one or more of the 6×10^{14} circulating protons may have a very abnormal trajectory. It may, for example, hit a gas molecule and scatter at a large angle, hitting anything it chooses. We estimate some such happenings in the following discussion. The first approximation, however, is that all 200 GeV protons hit either external or internal beam dump absorbers. To be specific we assume that 90% hit the external beam dump and up to 10% hit the internal beam dump because the beam blows up and wipes off there. This fraction should be less than 10% if ISABELLE is working well. Extra shielding for the internal dump would be a good precaution in case it works poorly, giving unexpectedly large losses there.

General tolerance levels for radiation are based on a dose rate per year, so it is necessary to estimate the number of protons per year hitting the beam dump. We assume that ISABELLE is in operation 30 weeks per year out of 52, with the remaining time turned off for maintenance, experimental changes, and such purposes. During a week of operation we assume 5 days on and 2 days off. For each of the 5 days of operation we assume 3 fills of each ring at maximum intensity. A typical high energy physics run will last about a day, so this allows two additional fillings of the ring per day, or ten per week, for machine studies. The ratio of protons used for machine studies to protons used for physics research is

2 to 1. In many cases, of course, machine studies can be carried out at low intensity, so there may be more than 10 fillings per week for machine studies in such a case. Of course these numbers are not advanced as limits, but as estimates of what actual operation would be like. If the integrated proton intensity is higher than assumed, shielding requirements must be adjusted accordingly.

Overall, then, we assume $450 \times 6 \times 10^{14} = 27 \times 10^{16}$ protons per year in each of the two intersecting rings, with 24×10^{16} hitting the external dump and 3×10^{16} hitting the internal dump. A small fraction of the beam will hit kickers and septum magnets involved in the ejection process, which is considered to be included in the above. The final shielding design must cover these parts of the system also. The dumps are located in the south insertion.

b. Scrapers

Under this heading we include any fixed or variable aperture collimators that are used to define the circulating beam. The same absorbing material used for the internal dump will probably be part of the beam scraper system. When functioning as a dump, the beam strikes the absorber during a short time, under conditions that are not well defined. When functioning as a scraper the process will be gradual, with a (thin) scatterer intercepting the trajectories to be scraped and causing increased displacement from the stable

orbit so that protons hit the absorber. Using the beam loss estimates of van Steenbergen and Teng⁴ we find that the main radiation source from the scrapers is due to 30 GeV protons during stack formation and capture as follows:

Lost on low-p scraper during stacking	5%
Low-momentum clean-up after stacking	50%
Vertical scraping	10%
Adiabatic rebunching	~5%
TOTAL	70%

They estimate that beam losses during acceleration and colliding-beam operation will be negligible. In the discussion that follows we arrive at numbers that are small compared with 70%, but not by any means negligible from a shielding viewpoint.

It is worth pointing out that there will also be some beam loss in the transport system from AGS to ISABELLE. A description has been given by van Steenbergen.⁵ It is planned that "Adjustable collimators will be incorporated, upstream of the 10⁰ bend for momentum distribution clean-up." These points on the beam lines will need adequate shielding, but they are not part of the ISABELLE ring, the protons are at 30 GeV, and no special problems are involved. We will not consider them further.

4. A. van Steenbergen and L. Teng, "Sources and Characteristics of ISA Beam Loss", 1975 ISABELLE Summer Study, BNL 20550, p. 423.

5. A. van Steenbergen, "ISA Injection", ISA 75-6, July 2, 1975.

These estimates are based, of course, on a particular scheme for injection, stacking and capture, magnet aperture, and so forth. They would not apply if the design is changed. For example, use of a stacking ring as suggested by Month⁶ would presumably reduce the radiation sources in the ISABELLE ring, but the stacking ring would need appropriate shielding. We do not make an analysis of this option.

It is possible that an analysis of the microwave instability or other factors would cause one to modify the estimates of van Steenberg and Teng. We do not consider this question, which is beyond the scope of this report. For our purposes, the significant fact is the qualitative one that the scrapers are expected to be an important source of radiation.

The number of protons hitting the scraper absorber is then 70%/30% as great as that hitting the dump. This gives a figure of 63×10^{16} protons per year, with an energy of 30 GeV. In the final determination of shielding requirements this source is combined with the 3×10^{16} protons per year of 200 GeV hitting the internal dump absorber, since they may well be the same block of material.

c. Gas scattering

The protons in the beam will collide with nuclei of gas molecules in the vacuum tank. Since the gas pressure is very low

6. M. Month, "Scheme for Current Accumulation in ISABELLE using a Low Energy Stacking Ring", ISA 75-11, Oct. 3, 1975.

only a small fraction of the protons have such collisions, but this sets a lower limit for radiation sources around the ring. The 1974 proposal gives the number of beam-gas interactions as 1.5 per second per cm of vacuum pipe for maximum current of 10 amperes and vacuum of 10^{-11} Torr (see p. 229). A pressure of 3×10^{-11} is thought to be typical by Henry Halama. The circumference of the ring is 2960 meters. The protons in each ring then collide with gas nuclei and are lost at a rate of $3.0 \times 1.5 \times 2.96 \times 10^5 = 1.3 \times 10^6$ per second.

We assume that during one day's operation beam circulates for 20 hours = 7.2×10^4 seconds. Overall beam-gas loss rate: 9.5×10^{10} protons per day. For 150 operating days per year: 1.4×10^{13} protons per year. This is less than 1/10 000 of the total number of 200 GeV protons, and is spread around the ring pretty uniformly, so it is not a major source of radiation. If there were no other source, shielding might be unnecessary, but this is not the case.

d. Beam-beam collisions

ISABELLE is designed to operate with a luminosity of 10^{33} at a high-luminosity insertion. The p-p cross section will be about 45 millibarns, possibly more. This gives $45 \times 10^{-27} \times 10^{33} = 4.5 \times 10^7$ collisions per second in one intersection. This gives a proton loss rate: 3.3×10^{12} protons per day, 4.9×10^{14} protons per year. Thus about 1/500 of the 200 GeV protons would be lost by beam-beam collisions in a high-luminosity crossing. There might be as many as eight such crossings, but the number would normally be smaller.

This kind of source sets the minimum shielding that must be provided for experimental halls. It is a logical possibility to have an operating rule that some halls can have only lower-luminosity crossings, but that appears to be an undesirable limitation, and we assume that any hall may have a high-luminosity crossing in it.

e. Uncontrolled beam losses

The scraper and internal dump absorber are located at a certain distance from the equilibrium orbit, and this defines a stay-clear trajectory around the ring of varying dimensions.⁵ Other objects inside the vacuum tank must be located outside this stay-clear trajectory. Ideally the circulating particles will never hit any of the other objects because whenever resonances or perturbations cause them to depart from the central equilibrium orbit far enough to hit something, the scraper and dump will be the thing they hit. That is the first approximation.

There will be a number of other objects inside the vacuum tank such as clearing electrodes, beam position sensors, kicker magnets, and septum magnets. Certain experiments will require constrictions in the vacuum tank and detectors close to the beam. Experimental magnets will provide fields at certain intersections that perturb the equilibrium orbit. Any object very close to the stay-clear profile is a hazard. For it to become a source of radiation two other conditions must occur:

- 1) Beam oscillations must be large enough to have a significant number of protons at or near the stay-clear profile, and
- 2) the object may be placed closer than intended, or errors in closed-orbit control may shift the real limiting trajectory farther out than intended.

Shifts of a few millimeters will normally be highly significant.

As a theoretical question it may be difficult to evaluate the probability of such errors. As a practical matter, however, it is well-known that small errors in locating targets and other objects are common, and there would seem to be many human errors and bugs in the control system that can cause closed orbit deviations of an unexpected magnitude. The orbit control system is not yet designed in detail, so it is not possible to estimate the number of times an orbit displacement of a few centimeters might occur during a year's operation. It will be a complicated system with beam position sensors, many magnets whose position and current may be adjusted, in part manually, in part through a computerized system, with precision power supplies controlled by the digital system, but stabilized by electronic feedback. How many bad cables, faulty transistors, cold-soldered connections, wiring errors, wrong parameters, keypunch errors, etc., etc. will there be per year? If the beam is much out of place it will be very obvious and it presumably will be dumped, but if the departure is small, there will often be a little loss around the ring whenever some object is close for the beam to wipe off on.

Clearly that sort of loss is most likely during machine studies when new equipment is checked out, new procedures tried, and problems in beam control investigated. The shielding requirements must allow for this aspect of machine operation as well as stable runs for physics research.

We have assumed that approximately 1/10 of accelerated protons will wipe off on the internal dump and scraper assembly. For other points of the ring we assume that 1/100 of the accelerated protons may be lost at any arbitrary point, down another order of magnitude. This is, however, five times as many as at a high luminosity crossing. Such a loss would be very easy to detect with a radiation monitoring system, and we feel that if it persisted for several months, a major effort would be made to find out what was wrong and fix it. Integrated over a year, this corresponds to losing all the beam at some point 4.5 times, a series of accidents that it is certainly unreasonable to contemplate. Gradual loss from many fillings does seem possible, but to set the anticipated level at 1% of all protons we consider rather conservative. At any rate, that is the figure used in the subsequent estimates.

Loss at arbitrary point in the ring: 0.3×10^{16} protons per year mainly during machine studies periods.

3. Acceptable radiation levels

There is no sharp threshold below which radiation has no effect and above which the effects are unacceptable. Two levels are in normal use for planning control of radiation levels: a) 1000 mrem per year as a maximum for accessible areas at the laboratory, and

b) 5 mrem per year as a maximum for areas adjacent to the laboratory site.⁷ The latter is an increment to the naturally-occurring level which is approximately 100 mrem per year. Such a level is so low that it is not easy to measure experimentally.

The 1000 mrem per year is taken to apply at the outside of the shielding at the point where levels are highest, which will probably be at the top, somewhat downstream of the radiation source. Present plans do not call for people to actually work at such a position, but at the inside of the ring shielding where levels would actually be considerably lower. Our shielding estimates will limit the dose at the outside of the shield to 1000 mrem per year for a hypothetical individual who spends 40 hours a week in that location for the day shift, (which is expected to have the highest levels) throughout the year.

The 5 mrem per year is taken to apply at the site boundary and includes contributions from the different sources listed in Sec. 2, which must not add up to more than 5 mrem per year. The ISABELLE ring location is fairly close to the boundary of the laboratory site, and this limit will prove to be an important one. Since private houses are located nearby and additional ones may be built, we assume 168 hour-per-week occupancy of any point at or beyond the boundary of Brookhaven property.

7. ERDA Appendix 0524, Part V, April 8, 1975. The limit of 500 mrem/year is given in ERDA 0524 for nonradiation workers. Five mrem/year is thought to be a very conservative off-site limit.

The calculations that are described in the following section show that there are two significant contributions to radiation dose outside the shield, energy transported by secondary hadrons and by muons. The hadron cascade is a very complex process in which the original proton energy is given to secondary protons, neutrons, pions, kaons, electromagnetic showers, and other less important particles. Neutrons tend to be the most penetrating, and the hadrons emerging from shielding such as that planned for ISABELLE are mainly neutrons. Pions and kaons are unstable and decay to give muons. High energy muons are extremely penetrating. Such muons are emitted in an approximately tangential direction and enough shielding must be provided around the outside of the ISABELLE ring to reduce the muon flux to an acceptable level.

The hadron cascade calculation CYLKAZ, computes the number of stars (nuclear interactions) per cm^3 per interacting proton from an approximate Monte Carlo simulation of the hadron cascade process. We have used the conversion factor to rem given by van Ginneken and Awschalom,⁸ Figure VI 7. They give Max. Dose Equiv (Rem) per star/ cm^3 from 0.8 to 1.0×10^{-5} depending energy and depth in the shield. We use 1.0×10^{-5} throughout.

For muons we need a similar conversion from muon flux to dose rate. The "Particle Properties" handbook equates 3×10^7 minimum ionizing singly charged particles to 1 R.⁹ We use this factor for muons.

8. A. van Ginneken and M. Awschalom, "High Energy Particle Interactions in Large Targets", FNAL Report.

9. See e.g. "Particle Properties, April 1974" prepared by the Particle Data Group, p. 78. This value applies for carbon.

4. Shielding for dump and scraper areas

a. Procedure for estimating hadron shield

We have used the Ranft program, CYLKAZ, which generates hadron cascades by a Monte Carlo procedure¹⁰ for a cylindrical geometry with up to 5 different materials in both radial and longitudinal directions. We have not evaluated the validity of the program by comparing its results with experimental measurements. Ranft states that his procedure agrees with measurements to within a factor of 2-3. His programs have been used fairly extensively, and we consider them to be a useful basis for estimating shielding requirements.

We have made a comparison of results from CYLKAZ with those of the FNAL program CASIM for homogeneous absorbers of iron and concrete. Results for iron given in Figure 1 show that CYLKAZ indicates that a given intensity is reached with about 15% less radial thickness than is required by CASIM. Results are similar with concrete.

It is not possible to obtain meaningful statistics for star densities much below 10^{-8} stars/cm³ per proton with CYLKAZ with jobs of reasonable duration. We usually require 10^5 stars, taking about 250 sec of CDC 7600 time. In some cases the acceptable dose requires a considerably greater attenuation, and the shielding thickness must be estimated by extrapolation. Plots such as those of Fig. 1 are fairly close to being straight lines, though they are steeper at small radii than large. The $1/r^2$ factor is important

10. See, for example, J. Ranft and J. Routti, Computer Physics Comm., 7, 337 (1974).

at small radii, but after penetrating a meter or more of sand the calculated curves all look very similar, with about the same exponential attenuation with increasing radius. Some values are collected in Table I for the calculated distance to attenuate by a factor of 10, based on eyeball fits to the calculated curves. Using these values as a basis, we extrapolate by 100 cm for each additional factor of 10 that is needed beyond the level established by CYLKAZ.

Measurements made at the AGS of attenuation in sand gave an empirical value of 1.50 ft for the mean attenuation length.¹¹ This corresponds to $1.5 \times 2.3 \times 30 = 104$ cm for a factor of 10, which agrees well with the value used.

TABLE I. Distance radially in sand for factor 10 attenuation from CYLKAZ calculations

Tunnel configuration	Z = 600	80 cm
	Z = 800	87 cm
	Z = 1,000	92 cm
Dump configuration	Z = 250	88 cm
	Z = 400	102 cm
Scraper configuration	Z = 600	103 cm
	Z = 900	108 cm
	Z = 1,200	101 cm
	Z = 1,500	106 cm
Elastic hall	Z = 800	101 cm
	Z = 1,400	100 cm
	Z = 2,000	95 cm

Thus CYLKAZ provides a set of calculated curves for the star density per cm^3 per incident proton as a function of radius at various positions in the beam direction relative to the source. The radius required to provide an acceptable level goes through a

11. W. R. Casey, C. H. Distenfeld, G. S. Levine, W. H. Moore, and L. W. Smith, Nucl. Inst. and Methods, 55, 253 (1967).

Fig. 1. Comparison CYLKAZ - CASIM Iron Cylinder

broad maximum as a function of position along the beam and this is used to determine the shielding requirement for satisfactory levels outside the shield. It remains to check that the level at the site boundary is then satisfactory.

The distance to the site boundary is at least ten times the dimensions of the tunnel and shielding, so one can treat the latter as an effective point source. This is done with the idealized cylindrical geometry shown in Fig. 2a, with the assumption that neutrons emerging from the shield are isotropic. Then the level at the site boundary is computed from the $1/r^2$ geometrical factor and an attenuation in air which is not important for distances up to 1000 meters.¹² In the upper hemisphere (above ground) the effective source strength is found by integrating the neutron flux numerically at an appropriate radius. This gives an upper limit to the site boundary dose, since the real situation as indicated in Fig. 2b gives considerably better shielding for the site boundary.

b. Dump configuration hadron shielding estimates

The dump absorber is assumed to be a beryllium insert 15 cm in radius and 250 cm long embedded in an iron cylinder 60 cm in diameter and 750 cm long. (It could, of course, be put together in segments of convenient weight.) This is compatible with a radial bin size of 15 cm and lengthwise bin of 50 cm. The absorber is large enough that a large fraction of the energy loss and induced radio-

12. This procedure is consistent with the conclusion of Rindi and Thomas that "the dominant factor in reducing radiation intensity is the inverse square law" even in geometries with a large vertical flux and resulting "skyshine" effects. See A. Rindi and R. H. Thomas, Particle Accelerators 7, 23 (1975). Since ISABELLE is well-shielded the hadron radiation emerging from it will tend to be fairly isotropic.

a) Idealized case with cylindrical shield

b) Realistic shape with sloped berm and muon shielding

Fig. 2. Schematic geometry for site boundary calculations.

activity will be contained in the beryllium and iron. Probably less iron would be adequate, and a smaller radius for the Be insert possible, but we have not considered the various questions involved in the design of the dump absorber. As shown in Fig. 3, it is assumed to fit into a cylindrical tunnel with 90 cm radius, surrounded by sand shielding.

It is necessary to specify the atomic number, atomic weight, and density of the materials involved. For this purpose we treat sand as having an effective atomic number of 10 and atomic weight of 20, and consider air to be effectively nitrogen. (CYLKAZ effectively ignores the air, since its density is negligible.) The values are summarized in Table II.

TABLE II. Parameters of materials for dump configuration

	Atomic Number	Atomic Weight	Density g/cm ³
Beryllium	4	9.02	1.85
Iron	26	55.85	7.80
Air	7	14.0	.00125
Sand	10	20.0	1.81

The curves showing the attenuation of total stars per cm³ per proton as a function of radius are shown in Fig. 4 for the positions along the beam (Z-coordinate) where radiation extends farthest radially. Bins for Z = 200, 250, and 300 and Z = 350, 400, and 450 averaged to improve statistics.

Fig. 3. Dump Configuration

The required attenuation is given by the ratio:

$$\frac{10^5 \text{ stars per cm}^3 \text{ per year acceptable}}{16 \times 10^{16} \text{ protons per year hitting dump}}$$

The number of protons is that for a single ring because each ring has its own dump, and they are in separate positions.

$$\text{Required attenuation} = 6 \times 10^{-13} \text{ stars per cm}^3 \text{ per proton.}$$

It is necessary to extrapolate 3 meters from the point determined by the graph, which is 6×10^{-10} stars per cm^3 per proton at radius 320 cm. Since the sand shield starts at 90 cm, we have:

$$\begin{aligned} \text{required thickness} &= 320 + 300 - 90 \\ &= 530 \text{ cm of sand} \end{aligned}$$

If the tunnel wall is thick enough to provide appreciable shielding it can, of course, be subtracted. If the inside iron shield is different from 60 cm in radius, the sand requirement would be different.

c. Scraper configuration hadron shielding estimates

The scraper absorber system has not been described in detail, but it will probably consist of beryllium absorbers adjacent to the beam.⁴ We assume that there will be various iron shields at slightly larger radius. These elements will be fitted into the arrangement of quadrupole and bending magnets near the ends of the south insertion. From the viewpoint of an absorbed proton we assume that the system is equivalent to an inner cylinder of beryllium, and an outer cylinder of iron inside a sand enclosure. There are frequent empty spaces in both inner and outer areas, which we represent by giving the beryllium and iron reduced average density. From the description given by Ranft, Blumberg, Stevens

Fig. 4 - CYLKAZ Shielding Calculation
Dump Configuration

Fig. 5. Scraper-Absorber Configuration

and van Steenberg¹³ we estimate that beryllium of density 0.46 and iron of density 4.60 are appropriate. The radius of the beryllium is 12 cm and that of the iron 24 cm.

TABLE III. Parameters of materials for scraper-absorber configuration

	Atomic Number	Atomic Weight	Density
Beryllium	4	9.02	0.46
Iron	26	55.85	4.60
Air	7	14.0	.00125
Sand	10	20.0	1.81

The curves showing the attenuation of total stars per cm³ per proton as a function of radius are shown in Fig. 6 and Fig. 7. There are two cases to be considered, 200 GeV protons hitting the absorber due to scraping at full energy and other losses, and 30 GeV protons due to scraping during injection and stacking. As before, we have averaged over the bins for positions along the beam that give the maximum radial shielding requirement.

The required attenuations are given by the ratios:

200 GeV

$$\frac{10^5 \text{ stars per cm}^3 \text{ per year acceptable}}{2 \times 10^{16} \text{ protons per year hitting absorber}}$$

$$\text{Required attenuation} = 5 \times 10^{-12} \text{ stars per cm}^3 \text{ per proton}$$

30 GeV

$$\frac{10^5 \text{ stars per cm}^3 \text{ per year acceptable}}{63 \times 10^{16} \text{ protons per year hitting absorber}}$$

13. Ranft, Blumberg, Stevens, and van Steenberg, "Caloric Deposition Downstream of the ISA Beam Scrapers", 1975 ISABELLE Summer Study, BNL 20550, p. 452

Fig. 6. CYLKAZ Shielding Calculation Scraper Configuration 200 GeV Protons.

Fig. 7. CYLKAZ shielding calculation scraper configuration 30 GeV protons.

Required attenuation = 1.6×10^{-13} stars per cm^3 per proton.

The second is enough lower that this proves to be the controlling situation.

For 200 GeV protons Fig. 6 indicates a level of 5×10^{-10} stars per cm^3 per proton at 500 cm radius, so that the required attenuation is reached at 700 cm. The sand shield starts at 204 cm, so we have: required thickness = $500 + 200 - 204 = 496$ cm. The corresponding figures for 30 GeV protons are: required thickness = $465 + 300 - 204 = 561$ cm.

The external dump and internal scraper-absorber are both located in the same general area, the south insertion. The greatest shielding thickness is required for the 30 GeV protons on the scraper-absorber, so shielding designed for this consideration should be adequate for the others as well.

d. Requirement of site boundary levels

In Fig. 8 we plot the star density for the dump configuration at a radius of 210 cm, where the statistics are adequate, as a function of the Z-dimension along the beam. A similar curve is given for the 30 GeV protons for radius 300 cm. If we use $N(z)$ as the number of stars per cm^3 per proton and r_1 for the radius, we measure the source intensity by the integral, F,

$$F = \int_0^{\infty} \pi r_1 N(z) dz$$

This gives the number of stars per proton in a shell 1 cm thick at radius r_1 . This integrated flux is then attenuated by going to the radius of the required shielding, r_2 , as given in Table IV.

Using the total number of interacting protons per year and the radius

Fig. 8. Flux distributions in shielding along beam direction for dump and scraper-absorber.

TABLE IV. Numerical values used for site boundary
radiation level estimate

	Dump	Scraper
Radius for plotted curve r_1 , cm	210	300
Integrated flux, stars/cm/proton	2.1×10^{-3}	6.6×10^{-3}
Radius for shielding requirement, r_2 , cm	620	770
Difference in radii, $\Delta r = r_2 - r_1$, cm	410	470
Attenuation A_1 for Δr	1.1×10^4	4.5×10^4
Integrated flux at r_2 stars/cm/proton	1.9×10^{-7}	1.5×10^{-7}
Interacting protons per year	2.4×10^{16}	2.4×10^{16}
Radius to site boundary, r_3 cm	9.6×10^4	9.6×10^4
Area of hemisphere at r_3 , cm^2	5.8×10^{10}	5.8×10^{10}
Intensity at r_3 , stars/ cm^3 /year	0.81	1.7
Factor A_2 for attenuation in air	~ 0.5	~ 0.5
Final intensity estimate, stars/ cm^3 /yr	~ 0.4	~ 0.8
mrem/yr	~ 0.004	~ 0.008

to the site boundary, r_3 , the intensity at the site boundary is calculated as the product of several factors:

$$\text{Final intensity} = F \times A_1 \times A_2 \times B$$

where A_1 is the attenuation in going from r_1 to r_2

$$A_1 = 10^{-(r_2 - r_1)/100}$$

B includes the $1/r^2$ factor and protons interacting per year, N_p .

Converting from total flux to particles per unit area at r_3 gives

$$B = N_p / 2\pi r_3^2$$

and A_2 is a factor for attenuation in air to reach r_3 .

The final intensities given in Table IV of 0.004 and 0.008 mrem/year are low enough to show that no significant dose at the

site boundary is expected from the dump and scraper-absorber. In this case the two should be added and a factor of 2 applied to allow for two rings.

e. Muon shielding

Numerical predictions for muon range distributions will be given in Section 5, where muon shield thickness has to be calculated. Muon shielding is not a problem for the external dump and scraper absorber area because the energetic muons are emitted only at small angles to the beam and the beam is located at elevation 55 ft while natural grade level in the area around the south intersection varies from 70 to 80 ft. The general arrangement of the site is shown in Fig. 9, with approximate contours. Ground level slopes from a high area at the south and southwest to a low region at the north, where the ground level is only about 50 ft. The exact topography is irregular, but it is safe to say that in the region around the south intersection the muons emerging from decay of pions and kaons produced in proton interactions will be below ground level so that natural muon shielding is provided for the required distance (shown in Section 5 to be about 250 meters) from the points where protons interact. There may be some local depressions that will need to be filled in, but there is no problem in providing adequate muon shielding in this area.

At the north side of the ring, on the contrary, muon shielding will be a major problem, which is discussed in Sec. 5.

FIG.9- OVERALL SITE PLAN

5. Shielding for Tunnel

a. Hadron shielding estimates:

The beam circulates through the vacuum tank inside the series of dipole and quadrupole magnets that make up the ring lattice. Most protons that interact (since beam-gas interactions are rare) strike the vacuum tank wall or some electrode or other object inside it. Secondaries hit vacuum or magnet structure, and the hadron cascade develops with some hadrons making their way out to the sand and perhaps through it.

Most of the material inside the tunnel is iron, so we represent this process by protons incident on an iron cylinder with a radius of 24 cm. The actual magnets have a hole in them for the vacuum tank and there are air spaces between magnets. To simulate this we reduce the density of the iron cylinder by a factor of 0.78 for the central opening, and by a factor of 0.77 for the air spaces between magnets. The result is an effective density 4.62. This probably gives a simulated cascade with somewhat less spread along the beam than the actual geometry, which would tend to cause an overestimate of shielding requirements and be conservative.

The tunnel configuration used for calculations is shown in Fig. 10. Another simplification that should be noted is the absence of the second ring magnets in the cylindrical geometry of the CYLKAZ calculation. The additional iron would provide some shielding effect, but with a real shield the weakest shielding will be in the vertical direction, and the calculation should apply well there. Table V gives the parameters used.

Fig. 10 - Tunnel Configuration

Table V. Parameters of Materials for Tunnel Configuration

	Atomic Number	Atomic Weight	Density g/cm ³
Iron	26	55.85	4.62
Air	7	14.0	0.00125
Sand	10	20.0	1.81

The attenuation provided by the shielding is plotted in Fig. 11.

The required attenuation is given by the ratio:

$$\frac{10^5 \text{ stars per cm}^3 \text{ per year acceptable}}{3 \times 10^{15} \text{ protons per year lost}}$$

Required attenuation = 3.3×10^{-11} stars/cm³/proton. The estimates of shielding requirements extrapolated from the curves are:

	Radius	Thickness
Z = 200, 300, 400	610	406
500, 600, 700	620	416
800, 900, 1000	575	371

Thus, the maximum thickness is estimated to be 416 cm.

We use the same procedure as in Section 4.d. to estimate the resulting intensity at the site boundary from protons lost from the beam inside the tunnel. We consider the point at which the tunnel is closest to the site boundary, with a distance of approximately 275 meters. This will be the worst case and the site boundary radiation will be considerably less if the beam loss occurs at a point that is farther from the boundary.

In Fig. 12 we plot the star density for the tunnel configuration at a radius of 396 cm, as a function of the Z-dimension along

Fig. 11. CYLKAZ shielding calculation tunnel configuration.

Fig. 12 - Flux Distribution in Shielding Along
Beam Direction for Tunnel Configuration

the beam. The numerical values for the integrated flux and intensities at various radii are summarized in Table VI. The final estimate of 0.17 mrem per year is quite satisfactory, but it shows that if the tunnel were much closer to the site boundary than 275 m the site boundary criterion would become the controlling one for determining the hadron shielding requirement.

Table VI. Numerical Values Used for Site Boundary

Radiation Level Estimates for Tunnel Configuration

Radius for plotted curve, r_1 , cm	396
Integrated flux, stars/cm/proton	4.7×10^{-3}
Radius for shielding requirement, r_2 , cm	620
Difference in radii, Δr , cm	224
Attenuation, A_1 for Δr	150
Integrated flux at r_2 , stars/cm/proton	3.1×10^{-5}
Interacting protons per year	3×10^{15}
Radius to site boundary, r_3 , cm	2.75×10^4
Area of hemisphere at r_3 , cm^2	4.7×10^9
Intensity at r_3 , stars/ cm^3 /year	20
Factor A_2 for attenuation in air	0.88
Final intensity estimate, stars/ cm^3 /year	17
mrem/year	0.17

b. Muon shielding estimate

Muons of high energy arise mainly from the decay of pions and kaons where the muon is emitted forward in the rest system of the pion or kaon and that rest system has a high velocity. Because hadrons have small average transverse momenta the resulting energetic

muons are also concentrated at angles close to that of the parent proton. Pions of high momentum are considerably more numerous than kaons, so we have based estimates of muon flux on the pion spectra and ignored kaons. In fact, it is positive pions that dominate the high momentum end of the spectrum. We have used the empirical formula of Wang¹⁴ to calculate pion spectra. The expression is:

$$\frac{d^2N}{dP d\Omega} = A' P_m X(1 - X) \exp(-BX^C - DP_t)$$

and the units are pions/[sr(GeV/c) interacting proton]. Here X is the longitudinal momentum P_ℓ divided by P_m , the maximum kinematically allowed value of P_ℓ . P_t is the transverse momentum of the pion ($= P \sin \theta$) in GeV/c. The four parameters A', B, C, D are given in Table VII. The pion spectra calculated

Table VII. Numerical Parameters in Wang Expression
for Pion Spectrum

	π^+	π^-
A'	2.385	1.572
B	3.558	5.732
C	1.333	1.333
D	4.727	4.247

at an angle of 1 mrad are shown in Fig. 13 with the muon spectra derived from them.

14. C.L. Wang, Phys. Rev. 10D, 3876 (1974). This formula has been checked against recent Fermilab data by Wang, and found to be a satisfactory approximation to experimental observations.

The procedure used in calculating the muon spectrum follows that by Keefe and Noble,¹⁵ making the assumption, valid for momenta large compared with that of a μ from π decay at rest, that, "the decay of pions of momentum p' gives rise to a spectrum of muons with momentum p described by

$$\begin{aligned} \text{Muon spectrum} = \frac{dn}{dp} &= \frac{1}{(1 - K)p'} \quad \text{for } p' > p > Kp' \\ &= 0 \quad \text{for } Kp' > p > 0 \end{aligned}$$

where $K = 0.57$." The muon spectrum must be obtained by integrating over the range of pion momenta that can contribute. Both pion and muon spectra drop very rapidly with increasing momentum at the high momentum end.

Figure 14 shows muon spectra for pion production angles out to 100 milliradians. It is clear that the muon spectra also drop very rapidly with increasing angle at the high momentum end. It is the forward muon spectrum which emerges tangentially at the outside of the ring that is of main concern. We need, then, to determine the range spectrum to see how much shielding is needed to reduce the number of muons to a satisfactory level.

In considering this problem, Keefe and Noble used two pion spectra, the "Trilling" spectrum and "CKP". The Wang formula gives somewhat more high momentum pions than the others, but the results are qualitatively very similar.

To determine the shielding thickness, we need to know the number of muons with range greater than R , where R is expressed in meters

15. D. Keefe and C.M. Noble, "Radiation Shielding for High Energy Muons: The Case of a Cylindrically Symmetrical Shield and No Magnetic Fields", Nucl. Instrum. Methods 64, 173 (1968).

Fig. 14 - Wang Formula Spectra

Maximum Momentum 196 GeV/c
Decay Length 10 m
Various Angles

of sand. This requires an integration of the muon spectrum and the use of range rather than momentum. Tables of range energy relations have been prepared by Theriot for energetic muons.¹⁶ Values are given for Batavia soil whose density is about 10% higher than that of Upton sand. Table VIII gives the numerical details for an illustrative case. There are three main steps: i) integrating the muon spectrum to give the numbers with momentum higher than the value in question, ii) finding the range corresponding to that momentum, and iii) applying a solid angle factor to give the flux per cm^2 at the edge of the shield, and also at the boundary of the site.

As was the case for hadron shielding there are two cases to consider, the acceptable level at the outside of the shield, and at the site boundary. The southern part of the ISABELLE ring is below ground, and muon shielding is automatically provided. The northern part of the ring is above ground level, and a shield must be provided around the outside which is quite extensive. Protons that circulate counterclockwise striking an object in the vicinity of the north insertion will generate muons directed toward the site boundary adjacent to William Floyd Parkway, at a distance of about 600 meters. This distance has been used to compute the $\mu^+/\text{cm}^2/\text{proton}$ at boundary value in the final column. The resulting curves for flux penetrating shields of given (tangential) thickness are given in Fig. 15.

We must now introduce the acceptable muon flux. We convert from millirem to muon flux using $1 \text{ mrem} = 3 \times 10^4 \text{ muons/cm}^2$. The acceptable fluxes are then:

16. D. Theriot, "Muon dE/dx and Range Tables: Preliminary Results for Shielding Materials", FNAL TM-229 (March 30, 1970).

Table VIII. Calculation of integral μ^+ Range Spectrum

Momentum of μ^+	Lower bin Boundary	μ^+ /proton per sr per GeV/c	μ^+ in 10 GeV/c bin	Total no. with higher Momentum	Range in meters ^a	sr for 1 cm ²	μ^+ /cm ² per proton at shield	μ^+ /cm ² per proton at boundary
150	145	0.0010	0.010	0.010	285	1.2×10^{-9}	1.2×10^{-11}	2.8×10^{-12}
140	135	0.0019	0.019	0.029	267	1.3×10^{-9}	3.9×10^{-11}	8.1×10^{-12}
130	125	0.0032	0.032	0.061	250	1.5×10^{-9}	9.1×10^{-11}	1.7×10^{-11}
120	115	0.0055	0.055	0.116	232	1.7×10^{-9}	2.0×10^{-10}	3.3×10^{-11}
110	105	0.0094	0.094	0.210	213	2.0×10^{-9}	4.2×10^{-10}	5.9×10^{-11}
100	95	0.0150	0.150	0.360	195	2.4×10^{-9}	8.6×10^{-10}	1.01×10^{-10}
90	85	0.0230	0.230	0.590	176	2.9×10^{-9}	1.7×10^{-9}	1.65×10^{-10}
80	75	0.0360	0.360	0.950	157	3.6×10^{-9}	3.4×10^{-9}	2.7×10^{-10}
70	65	0.0560	0.560	1.510	138	4.6×10^{-9}	6.9×10^{-9}	4.2×10^{-10}

^aFor FNAL soil; for BNL sand add ~ 10%.

Fig. 15 - μ^+ Flux

For 10 Meter Decay Path

flux at edge of shield $\geq 1000 \times 3 \times 10^4 = 3 \times 10^7$ muons/cm²/year

flux at boundary $\geq 5 \times 3 \times 10^4 = 15 \times 10^4$ muons/cm²/year

We must allow for 3×10^{15} interacting protons per year, so we need to have sufficient shielding to achieve the following ratios:

$$\frac{3 \times 10^7 \text{ muons/cm}^2/\text{year}}{3 \times 10^{15} \text{ protons/year}}$$

required level 10^{-8} muons/cm²/proton

$$\frac{15 \times 10^4 \text{ muons/cm}^2/\text{year}}{3 \times 10^{15} \text{ protons/year}}$$

required level 5×10^{-11} muons/cm²/proton. From Fig. 15 we read a thickness of 128 meters for the on site criterion and 218 meters for the off site criterion. The latter is considerably more stringent. To convert to BNL sand we must add 10%, arriving at a thickness of 240 meters. Since this value is large there is great merit in having the beam elevation as low as practical to minimize the amount of sand that must be moved to provide it.

There is an assumption in these calculations concerning the flight path for decay of the pions, which is taken to be 10 meters. The real path before the pion hits some block of material and interacts depends in the exact geometry of the collision in which the pion was produced. If it occurs inside a lattice magnet, the pion is likely to hit the magnet within a few meters. If it occurs in the vicinity of the beam crossing, the pion is likely to go 20 meters or more before hitting anything. The figure of 10 meters seems like a reasonable overall estimate, but it is quite uncertain.

Another uncertainty is the question of muon straggling.¹⁷

Muon-electron collisions sometimes lead to substantial energy loss

17. See Dennis Theriot, "Muon dE/dx and Range Tables: Results for Shielding Materials Using Collision Losses Only", FNAL TM-260 (July 21, 1970).

and this means that the muons have a distribution of ranges. This might increase the shielding thickness needed by a few percent, but the amount does not seem likely to be significant. We have left the question to be studied later if more refined estimates become worthwhile.

The muons pass tangentially through shielding which is approximately circular, so that the radial thickness is not so great.

Figure 16 shows the approximate geometry, with the ring treated as a circle whose radius is $a_1 = 476$ m.¹⁸ The inner wall of the shielding is about 2 m greater radius, so that d_1 is given by with $a_2 = 478$ m.

$$a_2^2 = a_1^2 + d_1^2 .$$

Then $d_1 = 43.6$ m. (It is not appropriate to use 43.6 m for the decay flight path because the pions hit magnets and other objects before the tunnel wall.) Correspondingly,

$$\begin{aligned} a_3^2 &= a_1^2 + (d_1 + d_2)^2 \\ &= 476^2 + 283.6^2 \end{aligned}$$

$$a_3 = 555 \text{ meters.}$$

The shielding thickness is then $555 - 478 = 77$ m.

This very massive shield is clearly an element of major importance in the overall site plan. Two further questions need to be considered: i) Is such a thickness required at all points, that is, at all azimuths?, and ii) What vertical thickness is needed?

The answer to the first question is negative. At other azimuths the muon path to the site boundary becomes somewhat longer, which permits reduction in thickness. At any given point one must consider muons produced by both clockwise and counterclockwise rotating proton beams. In addition, to the north of the ISABELLE ring there is

18. M. Month, "ISABELLE Ring Structure and Performance", BNL Report ISA 75-10 (July 8, 1975).

Fig. 16 - Approximate Muon Shielding

Geometry, Showing Tangential and Radial Thicknesses

an area of higher ground which provides natural shielding for the site boundary to the north. This clearly makes some reduction in muon shielding in the northeast quadrant possible. A detailed study would be needed to lay out the exact shielding contour. This has not been done.

Two factors have to be considered in deciding on the vertical extent of the muon shield. In the first place, the pions have some distribution in angle as well as momentum, and, in the second place, the muons are deflected by multiple Coulomb scattering. We simply use the estimates of these effects made by Theriot and Awschalom.¹⁹ They plot contours of equal flux per interacting proton which indicate a lateral extent of about 4 meters corresponding to a forward range of 240 meters. This vertical extent is needed for about the first 35 meters in radius, with some reduction in vertical extent allowed at the greater radii.

6. Shielding for Experimental Halls

a. Hadron shielding estimates

At seven of the beam crossing regions experimental halls are planned that have various sizes and shapes. They all provide space considerably larger than the tunnel so that the shielding walls are at a greater distance from the beam. The shielding can be somewhat thinner because the $1/r^2$ factor is larger. Since the larger experimental halls have roof spans of 16 meters, the structure needed to support thick shielding is heavy and expensive, and it is important to provide shielding that is no thicker than it need be.

19. D. Theriot, "Muon Shielding: Multiple Coulomb Scattering of Muons with Energy Loss", FNAL TM-261 (July 29, 1970);
D. Theriot and M. Awschalom, "Muon Shielding: Design Studies of Homogeneous Soil Shields at 200 GeV", FNAL TM-245 (May 14, 1970).

The present designs of experimental halls are basically rectangular in shape. In some cases there is a central main hall with smaller beam arms extending along the beam line direction. Table IX gives a summary of dimensions for all seven halls. We have chosen the Lepton Hall, Hadron Hall, and Elastic Hall for CYLKAZ calculations.

Table IX. Present Dimensions of Experimental Halls

	Main Hall			Beam Arm		
	Length	Width	Height beam to roof	Length	Width	Height beam to roof
Lepton	39	16	9.7	--	--	--
Hadron	29	14	9.7	25.4 ^a	8	4.6
Little Lepton	31.5	14	8	--	--	--
Little Hadron	25	12	8	17.3 ^a	6	4
Wide Angle	16	33.6	7	--	--	--
Small Angle	80	8	5	--	--	--
Elastic	110	6	4	--	--	--

All dimensions are in meters.

^aAverage, two sides slightly different.

The greater size of the experimental halls is not the only difference between them and the tunnel. The material near the beam is also different. The tunnel contains dipole and quadrupole magnets in a lattice with little free space, while there is a magnet-free area for 20 meters along the beam on either side of the crossing region. For certain experiments, of course, magnets may be installed, but frequently the material near the crossing area will be only vacuum pipes, counters,

wire chambers, and relatively light material. In simulating this arrangement for CYLKAZ we cannot describe the geometry in detail, so we make calculations for a central cylinder of aluminum of reduced density. Near the insertion the density is taken as 0.5, then a value of 0.1 is assumed out to 20 meters. At this point the material becomes iron of density 4.6 to represent the quadrupole pair. Aluminum of density 0.1 again follows. These regions are indicated in Fig. 17, which shows the geometries used for calculations.

These parameters give a source near the crossing in which a large fraction of the protons interact, but not sufficiently massive for much cascade generation. The quadrupole region at 20 m is also a strong source, thick enough that the hadron flux emerging from its downstream end is fairly low. Figure 18 shows a distribution of star density along the Z-dimension in the central cylinder. This seems to be a reasonably realistic representation of a radiation source in the experimental hall.

The complete set of parameters used in the experimental hall simulations includes iron with density of 2.40 for the matching section, where magnets are more loosely-spaced than in the lattice. The values are listed in Table X.

Table X. Parameters of Materials for Hall Configurations

	Atomic Number	Atomic Weight	Density g/cm ³
Aluminum (crossing)	13	26.97	0.50
(free space)			0.10
Iron (quadrupole)	26	55.85	4.60
(matching)			2.40
Air	7	14.0	0.00125
Sand	10	20.0	1.81

Fig. 17. Experimental Hall Geometries

In using CYLKAZ it is necessary to pick certain bin sizes to use in radial and Z-directions. Changes in material have to occur at the boundary of a bin, so that dimensions are approximately those of the experimental hall plans, but not exactly. In any case, one is approximating rectangular halls with the cylindrical geometry of CYLKAZ. Figure 17 shows the geometry provided to CYLKAZ for each of the experimental hall calculations. Note that radial and Z-dimension scales are different by a factor of 4 for this figure.

In each case the required attenuation is given by the same ratio as for the tunnel configuration:

$$\frac{10^5 \text{ stars per cm}^3 \text{ per year acceptable}}{3 \times 10^{15} \text{ protons per year lost}}$$

$$\text{Required attenuation} = 3.3 \times 10^{-11} \text{ stars/cm}^3/\text{proton}.$$

The curves showing the attenuation of total stars per cm^3 per proton as a function of radius are shown in Figs. 19 and 20 for the Lepton Hall, and Fig. 21 for Hadron Hall and Fig. 22 for Elastic Hall. The shielding thicknesses indicated for the roofs of the three halls are summarized in Table XI. As expected, these thicknesses are considerably less than those estimated for the tunnel configuration.

Table XI. Indicated Roof Thicknesses for Halls

	Indicated radius	Start of sand	Indicated thickness
Lepton Hall	1120	840	280
Hadron Hall	1265	1000	265
Elastic Hall	830	504	326
Hadron Hall Beam Arm	830	500	330

Fig. 18. Source Distribution from CYLKAZ Calculation Lepton Hall Configuration

Fig. 19. Lepton Hall - Tunnel Configuration

Fig. 20. Lepton Hall and Tunnel Configuration

Fig. 21. Hadron Hall Central Part

Fig. 22. Elastic Hall

The greater distance is responsible in part, but the low density of the material in the center of the hall also contributes. The radiation source is more diffuse, and secondaries emerging from the quadrupole mass do not give appreciable radiation at the roof of the hall.

The forward collimation of the secondaries from proton collisions means that the downstream vertical walls of the experimental halls are a more sensitive area than the roof. Figure 20 shows the transition from hall part to tunnel part, and makes clear that the shielding thickness must be somewhat greater for the wall than roof. In Fig. 23 the contour for the acceptable radiation level is plotted to show this. As a practical matter, a slope, like 30° , which is suitable for the transition from the level above the roof to the level above the tunnel provides quite adequate hadron shielding at the end of the hall. Similar plots have been made for the Hadron Hall and Elastic Hall and lead to the same conclusion.

These estimates have been made without involving the particular equipment that is to be placed in the hall. For example, the design of the lepton detector involves a magnet and muon identifier weighing about 5000 tons.²⁰ This would give considerable sidewise shielding and a corresponding reduction in sand shielding would be possible if the lepton detector were known to always be in place. We have not

20. R. Burnstein, W.C. Carithers, M. Duong-van, R. Imlay, M. Kreisler, U. Nauenberg, C. Rubbia, L. Sulak, G. Snow, H.H. Williams, E. Paschos, M. Sakitt, C.L. Wang, L.L. Wang, "Design of a Lepton Detector for ISABELLE", Proc. 1975 ISABELLE Summer Study, Vol. I, p. 9, BNL Report 20550.

Fig. 23 - Section Through Lepton Hall and Tunnel

made such an assumption.

b. Requirement at site boundary

The Elastic Hall is on the east side of the ISABELLE ring at a sufficient distance from the site boundary to have no significant contribution. The Lepton Hall and Hadron Hall are close enough, that evaluation is necessary. The longitudinal distributions of flux are plotted in Fig. 24. For the hadron hall contributions from both main hall and beam arm must be considered. The numerical values involved in the level estimates are summarized in Table XII.

Table XII. Numerical Values for Site Boundary Contribution
from Lepton and Hadron Halls

	Lepton Hall	Hadron Main Hall	Hadron Beam Arm
Radius for plotted curve, r_1 , cm	912	1075	600
Integrated flux, stars/cm per proton	1.5×10^{-2}	6.5×10^{-3}	1.4×10^{-2}
Radius for shielding requirement, r_2 , cm	1120	1265	830
Difference in radii, Δr , cm	208	190	230
Attenuation, A_1 , for Δr	125	80	200
Integrated flux at r_2 , stars/cm/proton	1.2×10^{-4}	8.1×10^{-5}	7.0×10^{-5}
Interacting protons/year	3×10^{15}	3×10^{15}	3×10^{15}
Radius to site boundary, r_3 , cm	3.2×10^4	3.2×10^4	3.2×10^4
Area of hemisphere at r_3	6.4×10^9	6.4×10^9	6.4×10^9
Intensity at r_3 , stars/cm ³ /year	57		69
Factor A_2 for attenuation in air	~ 0.84	~ 0.84	
Final intensity estimate, stars/cm ³ /year	48		58
mrem/year	0.48		0.58

Fig. 24 - Flux Distributions in Shielding along Beam Direction for Lepton and Hadron Halls

The estimates of 0.48 mrem/year for Lepton Hall and 0.58 mrem per year for Hadron Hall are satisfactory, but do not provide a wide margin. We assume that a given beam loses 1% of its protons in one hall or the other, but not in both, for a total of 2%. There are, however, two circulating beams. One might have protons lost in the Lepton Hall and the other in the Hadron Hall. In that sense a combination of the two would be possible, consistent with our assumptions. This, of course, would still be below the acceptable limit of 5 mrem per year.

c. Muon shielding requirement

Muons that originate from pions from proton collisions in an experimental hall will enter the downstream tunnel if they are produced at small angles. The muon shielding estimates made in Sec. 5.b. can be used for this case, though some pions will have path lengths greater than 10 meters before interacting. This will tend to increase the muon flux. To explore this, calculations would have to be made with details of insertion geometries included. As stated on p. 41, the 10 meter decay path is a rough estimate from which we derive the radial shielding thickness of 77 m around the outside of the ring. In addition, however, provision must be made for muons emerging at larger angles, which strike the downstream wall of the experimental hall. For the Lepton Hall configuration shown in Fig. 23 the angles from 120 mrad to 420 mrad strike the downstream wall and larger angles strike the roof.

We have accordingly computed the muon spectrum at various angles and evaluated the amount of shielding needed to keep the muon flux at the acceptable level at the 600 meter distance. This would determine the muon shielding requirement for an experimental hall in the north intersection. The results are plotted in Fig. 25. The quali-

tative result is that for angles above 100 mrad the thickness required for muon shield is rather small, and will be automatically supplied by the hadron shielding.

The values from Fig. 25 are used to plot a muon range requirement on Fig. 23 although the Lepton Hall is not located in the north intersection, but in the northwest. The distance to the site boundary along the tangent line from the northwest intersection is considerably greater than 600 meters, so shielding could be thinner. For muons at such angles a further safety factor is introduced by their elevation above ground at the boundary. Taking 150 mrad and 600 meters we have an elevation of 90 meters or 297 feet above ground level. Perhaps 30-story buildings will be erected there during the lifetime of ISABELLE, but there are none at present.

Overall, then muon shielding adds no significant thickness to the requirements for the experimental halls.

7. Induced Radioactivity

A different kind of radiation problem arises from induced radioactivity at places where many protons hit. We have not made any study of this problem, and it might be a reason for introducing more shielding around dump or scraper or some other change of that sort.

Most of ISABELLE should have very low levels of induced radioactivity, and the number of protons hitting dump or scrapers is less than the number hitting the target of a conventional machine, when integrated over an operating period. Consequently no difficulties seem likely that have not been familiar from conventional machines.

There is, of course, the problem of radiation heating in superconducting magnets. Provisions for shielding them from radiation is a separate topic that requires study. CYLKAZ is also being used for calculations concerned with radiation heating of the magnets.

Fig. 25. Muon Shielding to Satisfy Site Boundary Requirements at 600 m.

8. Access Tunnels and Other Penetrations

The experimental halls and tunnel must be provided with ways to get people and equipment in and out. In addition, there are power and signal cables, cooling water pipes, plumbing for gases and vent pipes and ventilating systems that lead to a large number of passages of various sizes from the inside of halls and tunnel to the outside. We have not considered the design of these openings, nor made any estimate of the additional radiation flux that will be transmitted through them.

It is clearly important for a study of this topic to be made, based on the shielding thicknesses that are indicated by this study. It is planned to have the main access via the experimental halls, with an entrance about 5 meters square from a road at the inside of the ring, as shown on the site plan in Fig. 9, at each hall. Large trucks can be backed in and unloaded via these entrances. When the machine is in operation they will be closed off by shielding doors of adequate thickness.

An additional smaller entrance for people, cables, and pipes is planned for each hall which will be long enough and provided with enough zig-zags to keep emerging radiation at a satisfactory level. Some emergency exits will be needed at other points. We feel that it is probably more practical to base the design of these features on practical experience at AGS, ISR and Fermilab than to estimate their properties by Monte Carlo calculations. At any rate, CYLKAZ does not provide facilities for studying such problems.

9. Experience at the CERN ISR

We do not have detailed information on ISR experience, but it

appears that the shielding in place there has kept radiation levels outside it very low. After the first few years operation a summary²¹ concluded that, "The radiation protection problems arising from the operation of the CERN Intersecting Storage Rings as outlined above are shown to be much smaller than experienced around high energy proton synchrotrons like the PS at CERN." For example, the dose received by the ISR staff for 1972 was 26 mrem/man, about 1/5 the average for all CERN personnel, and not much above cosmic ray dose rates. A site station 60 m from the top of the shielding above the dump region registered a total dose of 14 mrem, of which about 10 mrem could be ascribed to the PS.

The shielding over the high loss area at the ISR is 9.8 ton/m^2 on the outside, which would correspond to 5.4 meters of BNL sand. This is similar to the requirements that we estimate for dump and scraper areas. Thus, CERN experience seems to give a general indication that such thicknesses should be quite adequate. More information suitable for such comparisons would, of course, be most interesting.

21. J.W.N. Tuyn, "Radiation Protection Problems Arising from the Operation of the CERN Intersecting Storage Rings", HP-73-131 (3 Oct. 1973).