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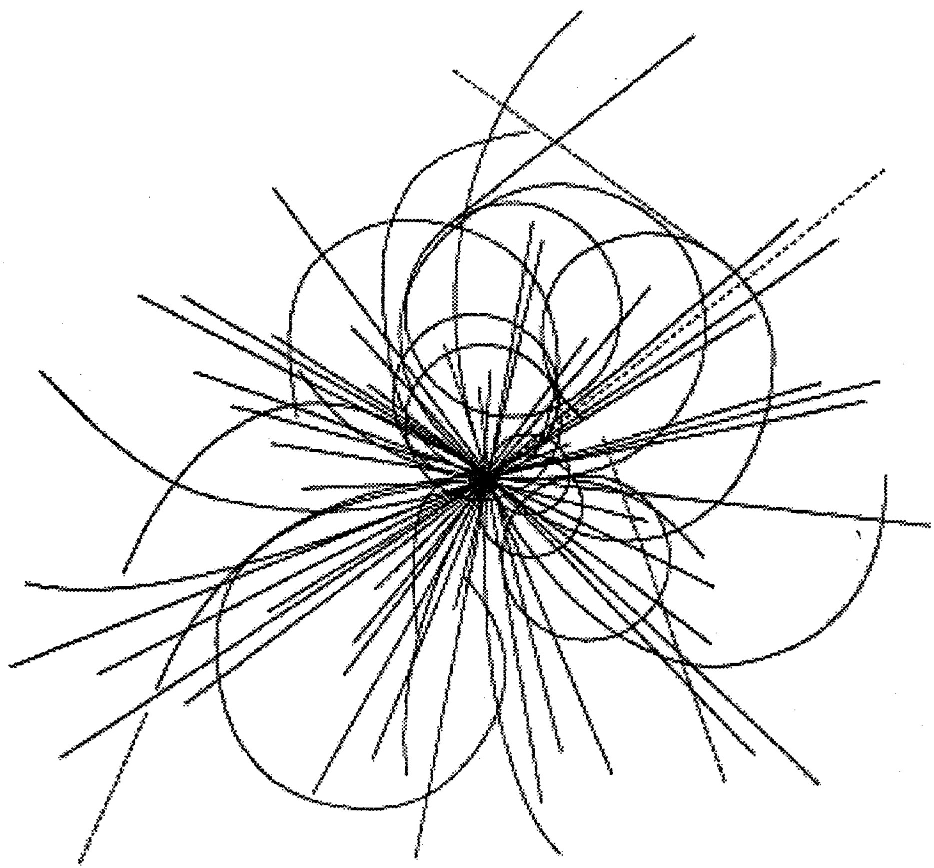

Superconducting Super Collider Laboratory

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Shielding Consideration for the SSCL Experimental Halls*

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SHIELDING CONSIDERATION
FOR THE SSCL EXPERIMENTAL HALLS

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ABSTRACT

The Superconducting Super Collider which is being designed and built in Waxahachie, Texas consists of a series of proton accelerators, culminating in a 20 TeV proton on proton collider. The collider will be in a tunnel which will be 87 km in circumference and, on average, about 30 meters underground. The present design calls for two large interaction halls on the east side of the ring. The shielding for these halls is being designed for an interaction rate of 10^9 Hz or 10^{16} interactions per year, based on 10^7 seconds per operational year. SSC guidelines require that the shielding be designed to meet the criterion of 1mSv per year for open areas off site .2mSv per year for open areas on site, and 2mSv per year for controlled areas. Only radiation workers will be routinely allowed to work in controlled areas. It should be pointed that there is a potential for an accidental full beam loss in either of the experimental halls, and this event would consist of the loss of the full circulating beam up to 4×10^{14} protons. With the present design, the calculated dose equivalent for this event is about 10% of the annual dose equivalent for the normal p-p interactions, so that the accident condition does not control the shielding. If, for instance, local shielding within the experimental hall is introduced into the calculations, this could change. The shielding requirements presented here are controlled by the normal p-p interactions.

Three important questions were addressed in the present calculations. They are 1) the thickness of the roof over the experimental halls, 2) the configuration of the shafts and adits which give access to the halls, and 3) the problem of ground water and air activation. The DTUJET code was used as an event generator for the Monte-Carlo calculations, because it seems to represent the generic 20 x 20 TeV collision rather well. A full-scale calculation with the MARS12 code shows that only a small fraction of the collision energy is lost in the detector. Twenty-two percent (22%) of the total energy is deposited in the collimator and the first two low beta quads (LBQ) in the experimental hall, so that this loss is the main source of radiation in the hall. About fourteen percent (14%) of the total interaction energy is deposited in the third and fourth LBQ's, which are in the tunnel. Twenty-four percent (24%) of the energy is carried by neutrals, and thirty-nine percent (39%) by high energy protons down the tunnel past the LBQ's.

In order to determine the roof thickness which would be required to achieve "open" status for the area directly above the experimental halls, several different calculations were carried out. A comparison of the results of all of these calculations gave a conservative estimate, that the thickness of the roof should not be less than 6 meters of concrete equivalent (density=2.4 g/cm3). This 6 meters of concrete gives an overall transmission of about 10^{-6} and it was decided to use this number as a guideline for estimating the neutron transmission required for the configuration of shafts and adits, which allow personnel access and various service to be brought into the hall.

In calculating the transmission through the various adits and shafts, the configuration, area and length have been obtained from the present design documents and universal curves for first and second sections of a labyrinth have been used. The possibility that the shafts and adits may be partially filled with cables and equipment has not used in the calculations and "neutrons traps", where they are included, are assumed to attenuate the transmission by a factor of two. In general it is assumed that no one will be allowed in the shafts or adits when the collider beam is on, so that the prompt radiation levels of interest are at the entrance of the shafts, at ground level. For the GEM experimental hall there is a special requirement that research workers be allowed to occupy the electronics rack room at the second floor level of the cable shaft. This requirement can be satisfied only if the electronics cable shaft is separated from the experimental hall by 6.5m concrete equivalent and the floor between the rack room and the lower level be 2m of concrete. In addition, it will be necessary that the workers in this room be protected from radiation that may leak through the cable holes in the concrete floor by using shielding walls and or stuffing any gaps between the cables running through the holes.

An interaction rate of 10^{16} per year could result in rather high levels of induced radioactivity in the components in the experimental hall and in addition will cause difficulty with air and ground water activation. To reduce the release of radioactivated air, the air in the hall will be recirculated and the controlled release of air will be minimized, while the beam in on. Uncontrolled release of air will be eliminated as far as possible. The current proposals for SSCL groundwater standards require that concentrations of waterborne radionuclides at saturation activity should not exceed the EPA community drinking water standard at distances greater than 1 m from an external surface of a concrete or other shield wall contiguous with earth or rock potentially associated with any groundwater. Reduction in this concentration by decay or dilution during water movement is assumed to provide concentrations adequately below the EPA limit for SSCL design purposes. Civil engineering design must reduce the possibility that this groundwater standard is exceeded. Any additional shielding required to protect the groundwater can be done by placing "local" shielding immediately around each radiation source, e.g., collimators and magnets. This local shielding is now under study for protection of detector components, ground water and air activation, and induced activity of equipment in the experiment halls

I. DESIGN CRITERIA

We have assumed that all areas on-site other than those specifically designated (radiation) controlled areas should be "open" areas and potentially accessible to members of the public. This means that no area on-site can result in a dose equivalent greater than 0.2mSv per year from accelerator operations, including the ground level "roof" areas above the experimental halls.

Areas close to shaft mouths we design to be "controlled" areas where the annual dose equivalent is 2 mSv or 1μSv per hour. We do this because access to controlled areas is restricted to radiation workers or to others under permit to enter: some management of personnel exposure can be done so that this design goal is less crucial than for open or off-site areas. Furthermore, the mouths of the shafts are rather small regions as compared with the extended areas of general shielding.

It should also be stated that there is a potential for an accidental full beam loss from the collider into the structure of the beam line, rather than in the abort dumps which are designed to accept dumped beam. The criteria for this event is that the instaneous dose received in "open" areas should not be more than 0.1 mSv per event and in "controlled" areas not more than 1mSv per event. This will be discussed further under source terms where it is shown that shielding designed for normal p-p interaction losses will be in excess of that required for the accident case.

II. SOURCE TERM

The layouts of the experimental halls and the low-beta collider lattice are the dominant source of radiation turns out to result from p-p interaction hadrons deposited in the low-beta quadrupoles (LBQ) and collimators and beam pipe.

It is noteworthy that there is an "accident" condition whereby the full circulating beam of 4×10^{14} protons is dumped in some beam line component. The calculated dose equivalent for such an event is about 10% of the annual dose equivalent from normal p-p interactions at the upgraded lumunosity of 10^{34}. This condition is discussed further in section 3. The accident condition could become dominant if the source term were to be reduced or perhaps credit were taken for local shielding in the roof shield specification, however, in our calculations this is not the case.

After some exploration we have chosen the DTUJET code[1] as an event generator to represent the generic 20 x 20 TeV collision. The calculated number of particles and the energy within a given angle are shown in Fig.1 (a) and (b). The energy spectra of neutrals which leaks out of the LBQ's are given in Fig.2. The full-scale Monte-Carlo calculations were done with MARS12 program[2] taking into account the SDC detector geometry, accelerator lattice and experimental hall geometry, presence of 3-D magnetic fields, production and transport of hadrons, muons and low energy neutrons. The calculated results on the roof shielding thickness are presented in the next section. Results on energy balance are given in Table 1.

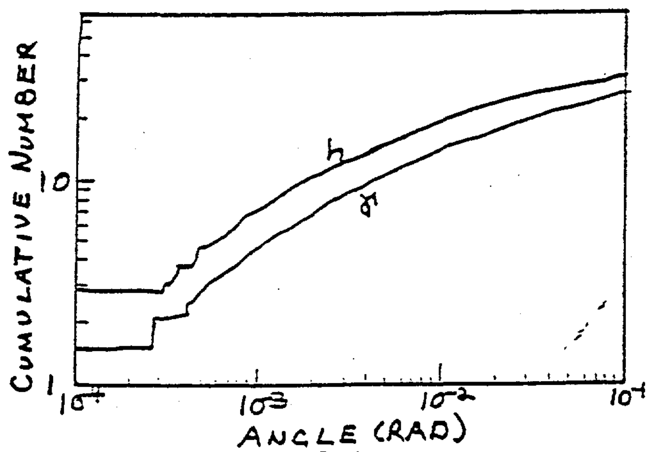

FIGURE 1
a) Number of hadrons and gammas within a given production angle in 20x20 TeV pp-collision. (1000 events)

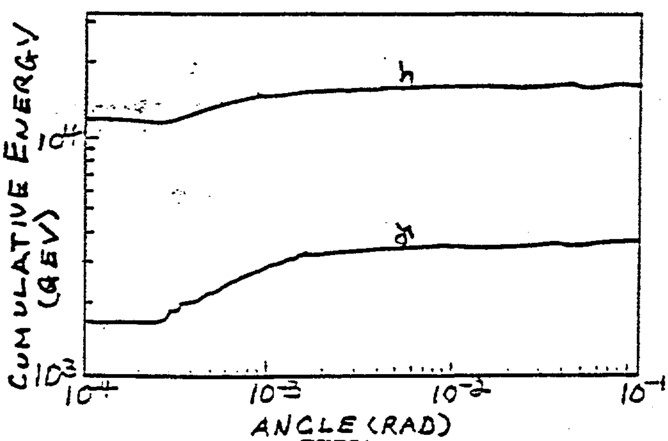

FIGURE 1
b) Energy carried by hadrons and gammas within a given production angle in 20x20 TeV pp-collision. (1000 events)

Table 1. Percentage of total interaction energy coming into the IR components. Last column shows fraction of energy carried by photons into the component stated in first column

Component	Length (m)	Energy (%)	γ / tot (E)
Detector	0 - 18	1.6	0.3
Collimator	18 - 20	4.2	
Q_1 - Q_2	20 - 45	18.0	0.5
Q_3 - Q_4	45 - 73	13.7	
Leak(Neutral)	> 73	23.5	0.6
Leak(Charge)	> 73	39.0	0

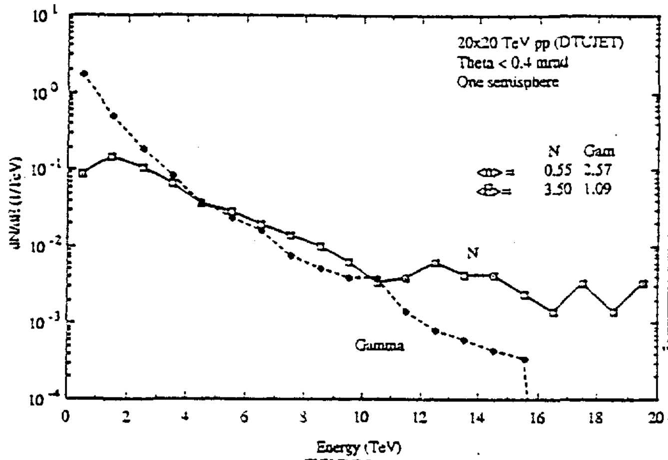

FIGURE 2
Energy spectra of gammas and neutral hadrons (mostly neutrons) in the very forward direction downstream of the interaction point.

Only negligible fraction of total interaction energy stays in the detectors. One can see that 22% of energy is deposited in the collimator and 2 first LBQ's contained in the hall, the rest goes down the tunnel. Therefore these three components are the major source of radiation in the hall. So, all the details of geometry and magnetic field there become the dominant factors. About 50% of energy deposited in the collimator and LBQ's are due to incident hadrons, another half is due to photons of primary π^0-decays.

III. ROOF SHIELDING CALCULATIONS

Using the criteria of Section 1, we have estimated the necessary roof shielding thickness for the experimental halls to achieve "open" area status. Our judgement was based on several different calculations for the amount of shielding needed over the IR Halls. These calculations have been summarized by plotting all of the predictions unto a single graph (Figure 3), expressed in terms of the number of p-p collisions versus shielding thickness (concrete) needed to reduce the dose equivalent to 0.2mSv/yr. The following is a brief description of each curve.

CASIM/Stevenson Approx.: This curve was produced by using CASIM[3] to calculate the radiation dose with the approximate source model proposed by Graham Stevenson.[4] This model approximates the source term by assuming that the result of a p-p interaction is a 20 TeV proton hitting each of the low-ß quads. For this calculation, the low-ß quad was a radiaus iron cylinder with a 3.6 cm diameter hole representing the beam pipe. The proton beam hits the magnet 1 cm from the outer edge of the inner cylinder. The ceiling of the IR Hall was 40 m from the beam pipe.

Two curves are taken from the draft ORNL report.[5] These calculations were based on detector geometries provided by the SSCL and used ISAJET to produce the source particles. Magnetic fields have been ,aglested

ORNL-Plug: The data for this curve was taken directly from the last column of Table 3 of the ORNL report which lists the dose rates for the construction shaft plug thickness. The Sv/hr values were converted to Sv per p-p interaction based on a 10^9 Hz interaction rate and then converted to the number of interactions resulting in a 20 mrem dose.

ORNL-Hall End: This curve represents the IR Hall roof thickness calculated at the end of the halls. The data for this curve was taken from Figure 11 of the ORNL report. Again, the rem/hr data was converted to rem per p-p collision and then to the number of interactions resulting in a 0.2mSv dose.

MARS/Mokhov: This line was calculated using the MARS 12 simulation code. This calculation approximated the real geometry, complete with detector and low-ß quad including magnetic fields. The source particles were calculated using DTUJET.

The last two lines are shielding estimates based on parameterizations of various shielding studies, whose results have been fitted to the empirical relation for maximum dose equivalent at a given radius,

$$H = \psi_0 \left(\frac{E_p}{E_0} \right)^{0.8} \frac{\exp(-x/\lambda)}{(x+d)^2}$$

where H is the dose equivalent in rem/proton, E_p is the proton energy in GeV with E_0 equal to 1 GeV, x is the shielding thickness, and d is the distance from the source to the shield wall. The source term, ψ_0,.and the apparent absorption mean free path, λ, have been calculated from both computer simulations and experimental data. A more detailed explanation of this model can be found in *Shielding Against High Energy Radiation* by A. Fasso, et. al.[6]

FLUKA Parameterization: The values of ψ_0 and λ used in this curve, 7 x 10^{-15} mSv·m^2 and 0.58 m respectfully, were obtained from calculations using the hadronic cascade program FLUKA.[7]

Moyer Parameterization: In this case, 1.8 x 10^{-14} mSv·m^2 for ψ_0 and 0.50 m for λ were used. These values are based on experimental shielding data from high energy accelerators.

All of these curves are shown on Figure 3. The 2000 hour year corresponds 7.2 x 10^{15} p-p interactions per year, which is indicated on Figure 3 by the dashed line. For this criteria, the shielding thickness estimates vary from 4.75 m to 7.25 m. The most conservative values are given by the Moyer model parameterizations. This is not surprising since they are intended to give worst-case estimates. These models are based on the highest expected dose at a particular distance from the beam axis, however far downstream from the loss point this occurs. In addition, no provisions are made for the actual geometry of the low-ß quads. Instead, an idealized target is used in the parameterizations which maximizes the estimated dose. The least amount of shielding is predicted by the ORNL-Plug curve. Again, this is expected since the plugs are approximately located directly above the low-ß quads. The maximum radiation dose from the quads will be peaked towards the ends of the halls.

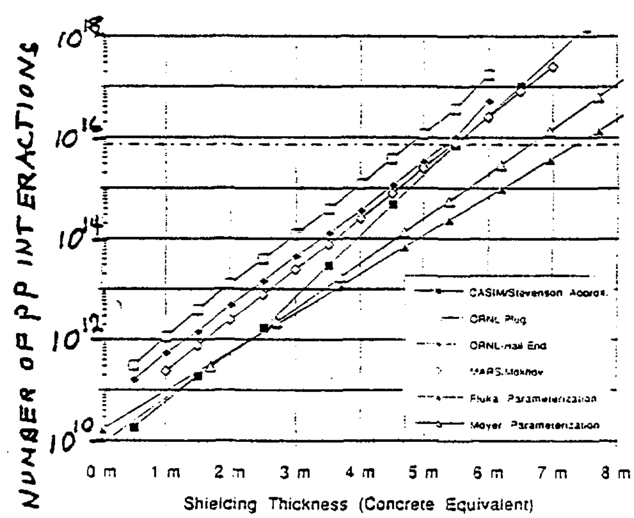

FIGURE 3
Number of pp interactions vs. IR Roof Shielding to achieve a .2 m Sv dose on top of the shield. The IR Hall ceiling is ~ 40 m from the beam line. (The dashed line indicates the 7.2x10^{15} p-p interactions per year.)

The remaining three curves differ by only a few tens of centimeters, with an average near 5.5 m. Given the uncertainties in the source term and geometries it is reasonable to choose 6 m of concrete equivalent for the minimum roof thickness. In fact, the Oak Ridge report recommends adding an additional 40 cm to their calculated value of 5.4 m presented for the hall end shielding as a margin of safety, therefore, adding an additional 40 cm to our estimate of 5.5 m results in a value rather close to our recommended thickness.

A second comparison can be made between CASIM and the ORNL report by looking at the shielding calculations for a point loss. Figure 4 is a graph of the shielding thickness versus dose for a point loss of 4 x 10^{14} protons at 20 TeV, corresponding to a catastrophic accident. At the .1 mSv per accident limit required for open areas, both codes are in fairly good agreement, indicating the need is 4.7 meters of concrete. At 6 m, the thickness recommended for the roof shields, the dose for a catastrophic accident is reduced to 2 μSv, a factor of 50 lower than the design limits, (but for the 5.5 m thickness estimate the factor is 10).

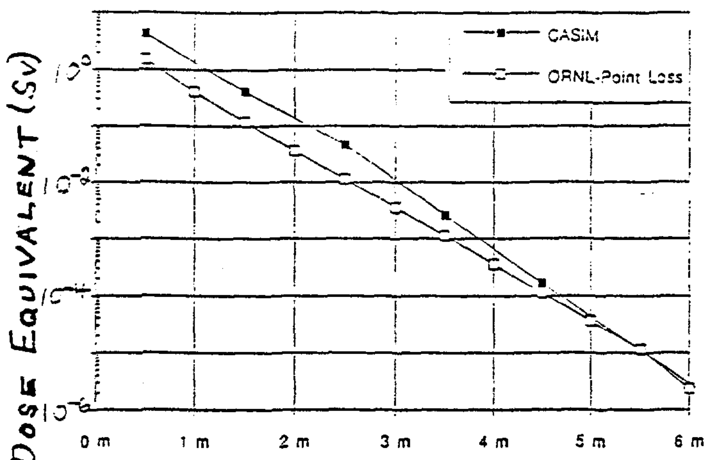

FIGURE 4
Dose Equivalent vs. IR Roof Shielding for a Point Loss of 4E14 20 TeV protons.
The IR Hall ceiling is ~40 m from the beam line.

We have concluded that the experimental halls should have a roof shield thickness not less than 6 m of concrete equivalent (ρ = 2.4 g/cm^3), this corresponds to earth cover of thickness 1440 g/cm^2. The roof shield transmission curves when extrapolated to zero roof thickness from 6 m of concrete give an overall transmission of 10^{-6} from inside the roof and while this cannot be used to define the exact radiation levels which might be measured inside the experimental halls, because of the complex nature of the radiation close to the source, it does permit the derivation of a simple guideline for estimating the neutron transmission required for the access and other shafts.

IV. ACCESS, SERVICE, CABLE SHAFTS AND ADITS

We require the radiation levels at the top of the shafts (at ground level) to conform to "controlled area" standards ie., 2 mSv per yr. As we stated in the previous section we estimate a transmission for the roof shielding of approximately 10^{-6} (for 0.2 mSv), however, an additional correction must be applied to the source term because the openings of the adits into the hall are much closer to the radiation source than the roof. We can increase the radiation source term for the labyrinths rather simply by just taking the ratio of the square of the distances (40 m/15 m)^2 between the roof and the entrance to the labyrinth entrance from the hall, this factor 7 increase in dose rate at the adit mouth (we assume it to be the same for all adit entrances although the distance from the source to each adit is somewhat different) provides us with a general shaft and adit transmission factor of 1.4 10^{-6} which we take as 10^{-6} as an approximate guideline for all adits and shafts. It should be stressed that the calculation of adit transmission assumes that the concrete adits are empty so that if a substantial fraction of the adit area is filled with cables and other material then the transmission will of course be less.

SDC Case Examination of the SDC shafts and adits indicate that the required transmission factors can be obtained. These calculations are summarized in Table 2. For each access shaft and adit, the cross sectional area and the length is listed. From this information, the length of the shaft divided by the square root of the adit cross-sectional area, is calculated. The transmission factor for each leg of the accessway can then be determined from the universal curves for dose attenuation in labryniths. Since the horizontal access adits open into much larger vertical shafts, an additional reduction in the dose occurs; this reduction is taken to be proportional to the ratio of the cross sectional area of the access shaft to the cross sectional area of adit. The total transmission factor is listed in Table 2, along with a comparison of the results from the Oak Ridge report.[4] It should be noted that several adits of similar size, configuration and length enter the same shaft so that the combined dose at the shaft mouth is the product of the single adit transmission and the number of adits. When the transmission for a given penetration works out to be very much smaller, usually because it is just a small duct, than is given for the transmission from the larger adits entering the vertical shaft then the small contribution from the small duct is ignored in the overall assessment of dose at the top of the shaft. All adits are assumed to have right angler and neutron types at the end of the first adit.

The neutron traps can provide a factor two reduction in the adit transmission factor and this improvement is included in Table 2. For the cable shaft, transmission factors are computed for both an 8 meter and a 9 m diameter vertical shaft.

An operational building to be located at the top of the cable shaft where all the cables are terminated will be regularly and routinely occupied by people and because this building must be better than "open" area category it is to be off-set from the shaft opening. From provisional drawings the off-set for the operational building is 8 m, which should provide adequate attenuation of the radiation both above ground and through the horizontal shaft located about 1 m underground to convey the cables from the vertical cable shaft to the operational building.

Table 2
Transmission Factors
SDC Access Shafts

Shaft	Description	ORNL Result*
Utility	Cable 1.2-8 Bottom 3.1-7	
	Total 6.5-7	9.6-7
Personnel	Upper 2.8-10	
Equipment	Middle 3.1-10 Lower 4.1-10	
	Total 2.0-9	5.3-9
Cable	8 m Diameter 2.4-7 9 m Diameter 3.7-7	

*ORNL results did not include neutron traps

Head-houses are needed to cover the top of the vertical shafts. In case of the personnel/equipment shaft the dose rate at the top is not likely to exceed "open" area conditions so that the head-house for this shaft need not include any further shielding requirements. The radiation levels at the other shaft mouths are "controlled" area (200 mrem/yr). We can make a very simple, but reasonable, calculation to get the size of the headhouse so that "open" area conditions apply immediately outside the head-house. We just assume that the headhouse is a hemisphere with an area ten times the area of the shaft.:

$$r_h = \sqrt{5}\ r_s$$

where r_s and r_h are the radii of the shaft and headhouse.

It is reasonable to take the diameter of the hemisphere to be the side of a rectangular headhouse. On the basis of this calculation the headhouses may be constructed of the cheapest material which might well be steel or aluminum sheet. If it is felt that it would be more cost-effective to utilize shielding material then a reasonable tenth value thickness for the neutron energy spectrum would be 85 g/cm^2 (35 cm of concrete). A combination of distance and shielding can also be used in which case the headhouse size could be obtained using a simple recipe such as:

$$r_h = \sqrt{5}\ r_s\ 10^{-t/70}$$

where t is the concrete thickness in cm.

GEM Case. Calculations similar to the ones for the SDC case have been performed for the GEM shafts and adits. Table 3 provides the results for the GEM shafts and adits.

Utility Shaft. The utility shaft for GEM must be separated from the GEM hall by 6.5 m concrete equivalent ($\rho = 2.4$ g cm^{-3}). There are three sets of two access adits from the hall to the shaft. The adits at the bottom of the shaft have sufficient attenuation to satisfy the radiation requirements but the adits at the middle and top will not meet radiation requirements unless they are partially filled either with equipment, utilities or shielding. The middle tunnels will require at least a half fill and Table 3 gives transmission results both for empty and half filled adits. The duct adits at the top will require a two thirds fill and results are given for empty, half-filled and two thirds filled. In the utility shaft, there are floors above the middle and top access tunnels and if one or more of these floors are made of concrete rather than steel diamond plate the attenuation in the shaft would be enhanced and such concrete floors might be another way to reduce the overall transmission to acceptable levels.

Cable Shaft. A special requirement of the GEM hall is that research workers require access to the electronics rack room at the second floor level of the cable shaft. This requirement can be met if the following conditions are satisfied:

1) the cable electronics shaft is separated from the hall by 6.5 m concrete equivalent,

2) there is a 2 m thick concrete floor below the rack room,

3) there is a 1 m concrete wall on the lower level (with a movable door) in front of the elevator and stairs,

4) while the beam is on, people are prevented from working immediately by the cable holes in the floor unless the gaps between the cables are blocked.

Table 3
Transmission Factors
GEM Access Shaft

Shaft		Empty	1/2 Full	2/3 Full
Utility	Top	2.6-6	7.1-7	3.6-7
	Middle	9.1-7	2.7-7	1.2-7
	Bottom	3.9-8	3.9-8	3.9-8
	TOTALS	7.2-6	2.0-6	1.0-6
Cable-Electronics Electronics Rack Room		1.6-7		

V. GROUND WATER ACTIVATION

A continuous loss of 10^{16} yr^{-1} will result in rather high levels of induced radioactivity in the LBQ's, collimators and other components intercepting the high energy yield. In addition to the operational problems resulting from such activation it is necessary, for civil engineering design, to consider activation in the earth surrounding the experimental hall. For this calculation we consider lateral geometry (source to side-wall and floor) and forward geometry (source to end-wall). For the lateral case we assume the distance from the source to the outside earth to the same for both side wall and floor (15 m). In the case of the floor we have been told that it is intended to place a substantial thickness of concrete at the base of the hall so that the ground underneath the hall would be well protected. For the end-on case the source to wall distance is assumed to the 35 m. In both cases the groundwater criterion is exceeded.

The current proposals for SSCL groundwater standards require that concentrations of waterborne radionuclides at saturation activity should not exceed the EPA community drinking water standard at distances greater than 1 m from any external surface of a concrete or other shield wall contiguous with earth or rock potentially associated with any groundwater. Reduction in this concentration by decay or dilution during water movement is assumed to provide concentrations adequately below the EPA limit for SSCL design purposes.

The additional shielding required to protect the groundwater can be done by placing "local" shielding immediately around each radiation source, e.g., collimators, magnets etc., and need not be included in the civil engineering of the halls. The thickness of local shielding would require for the lateral case an additional 75 cm of concrete (or 30 cm of iron) and for the end-on case extra thickness will be required. It must, however, be remembered that in the end-wall case for a given lateral thickness of material, the thickness presented in the forward direction will be very much greater and that precise dimensions of components in this region are not yet known. However, it is certain that local shielding for the LBQ's and collimators will be required both for ground activation and probably for operational control of access and for environmental releases of air.

Credit should not be taken for the local shielding in deciding the roof thickness or the labyrinth attenuations. Since groundwater activation builds up rather slowly over a period of years, it is possible to run without provisions for groundwater protection for a limited period of time. Such operation is not feasible when dealing with personnel exposure to prompt radiation.

We have been informed that groundwater surrounding the experimental halls will tend to migrate into the halls, thus eliminated its potential for release into the general groundwater. Hence the need for additional local shielding would not exist other than for local radiation protection from induced radioactivity. This subject will require further study, especially as local shielding will be required for detector performance.

6. CONCLUSIONS

This note is intended to provide a rapid assessment of the civil engineering design for radiation protection for the experimental halls. The assessment utilizes information contained in a specially commissioned ORNL report together with some independent calculations. Some attempt is made to simplify the design basis so as to make clearer how changes in design will affect dose rates in the occupied areas.

We believe that caution is required in the design of the experimental hall roofs so as to ensure that the design goals set for "open" areas on-site are achieved. This caution is motivated by the large area of the roofs and the extreme difficulty presented in making later improvements to the roof thickness.

Our recommendation for the roof thickness is 6 m of concrete equivalent (1440 g cm^{-2}).

The openings of access shafts at ground level are rather small in area and will be covered by head-houses. Therefore it is reasonable to treat the radiation levels at the shaft mouths as being "controlled" area status with the walls of the head-houses corresponding to the transition to "open" area status. Because occupancy of the head-houses will be subject to radiation control when the experimental halls are operating we believe we can adopt a simple radiation transmission criteria for all shafts and adits derived from the transmission of the roof shield. While this does not take into account the complex radiation fields inside the experimental halls it is not an unreasonable approximation in default of an extensive study. As our criterion for the shafts we take a simple transmission factor of 10^{-6} which for the internal dose rates given by the ORNL report might be too large (not small enough) by a factor 3 or so.[5] However, given the uncertainties in calculating shaft transmissions and in particular the effect of filling factors (for which no credit is taken in the SDC case) our approach seems reasonable. The GEM case is rather different in that without partial filling of the adits our standards cannot be met for the utility shaft and in the cable shaft case, rather heavy additional shielding is required to meet standards in the occupied electronics room.

Our results for the SDC shafts are given in Table 2 and show that the present design of the SDC shafts is likely to meet the design goal for controlled areas. The personnel equipment shaft is well in excess of the minimum design.

Our results for the GEM shafts are given in Table 3 and show that to meet standards for the utility shaft, considerable filling of the upper and middle adits will be required or some alternative means of improving the design.

The electronics room barely meets standards on this evaluation, but because the major source of radiation is through the relatively small cable ducts passing from the area below the shield floor, these could easily be filled after installation of the cables. This would result in radiation levels that would be acceptable. In the current design there is a wall placed between the occupied area and the top of the cable duct hole. It is possible that this wall could provide the desired additional shielding.

The suggestion that concrete floors could be used in the shaft, instead of just steel diamond plate (or whatever is intended) merits careful consideration. A concrete floor approximately 1 ft thick will give a tenth value thickness for radiation transmission and if the area of the holes through this floor are (say) 10% of the total shaft area then we can assume that the total transmission of this floor is approximately 0.2. For this to work in this way it will be necessary for the foor to be nearer the lower end of the shaft. However, even if it was not possible to put the floor low down in the shaft, it would still have the merit of reducing the total neutron yield entering the outside at the top of the shaft. Multiple concrete floors of lesser thickness could be made equally effective in this regard.

It will also be requirement to install instrumental radiation monitoring systems for accurately determining dose rates and integrated doses in any areas occupied by people. This is especially important where neutrons comprise the major part of the dose equivalent. The cost of such equipment must be included in the overall cost. This should apply at all access points and in the counting house and any other locations routinely occupied by people.

ACKNOWLEDGEMENTS

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