Radiological Control Group Note #93-15

Dose Rate Around "C" Stub Shielding Wall

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Synopsis

The Hall C tunnel configuration will consist partially of a shielding wall of SEG shielding blocks, essentially iron in construction. The dose rate on the side of the wall where workers may work is calculated for a loss of beam into one of the SLAC-type beam stops in the BSY. The dose rate is both a function of direct radiation (uncollided with buildup) and of scattered radiation, around one accessible end of the wall and above and below the wall. At the end, an opening of approximately 1.6 meters is left so that part of the wall may be slid open during non-operational mode. This opening is desired for laser-sighting alignments in the end station. A minimum of approximately 1 meter is required in order to comply with life-safety codes. The top and bottom will be considered to be 15 cm below the ceiling and above the floor.

The greatest contribution to potential dose rate on the personnel side of the wall is due to scattered radiation around the wall. Shadow shield placement greatly reduces the personnel dose equivalent rate, in the case of beam collision with a beam stopper.

Personnel safety systems are discussed.

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The Hall C beam transport line shielding (identified in TN 0172) specified a six-foot stacked concrete wall in the transport line labyrinth for personnel protection in the event of a catastrophic beam loss. Changing requirements for beam optics, diagnostics, and alignment resulted in reconsideration of the both shielding material and configuration. A more compact shield, constructed of SEG shielding blocks, will allow for installation of the additional optics. The SEG shielding blocks are essentially iron in construction. The dose rate on the side of the wall where personnel may work is calculated for a catastrophic loss of beam. The dose rate is both a function of direct radiation (uncollided with buildup) and of scattered radiation, around one accessible end of the wall and above and below the wall. At the end, an opening of approximately 1.6 meters is left so that part of the wall may be slid open during non-operational mode. This opening is desired for laser-sighting alignments in the end station. A minimum of approximately 1 meter is required in order to comply with life-safety codes. The top and bottom will be considered to be 15 cm below the ceiling and 15 cm above the floor.

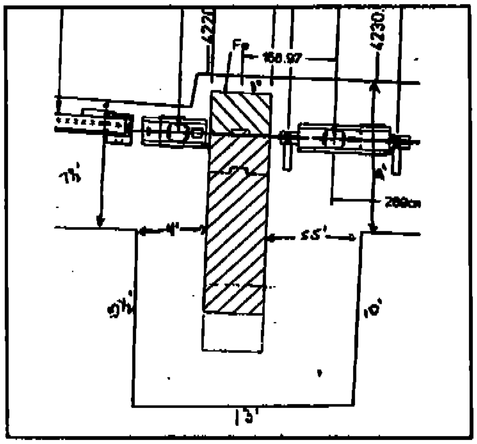

Figure 1

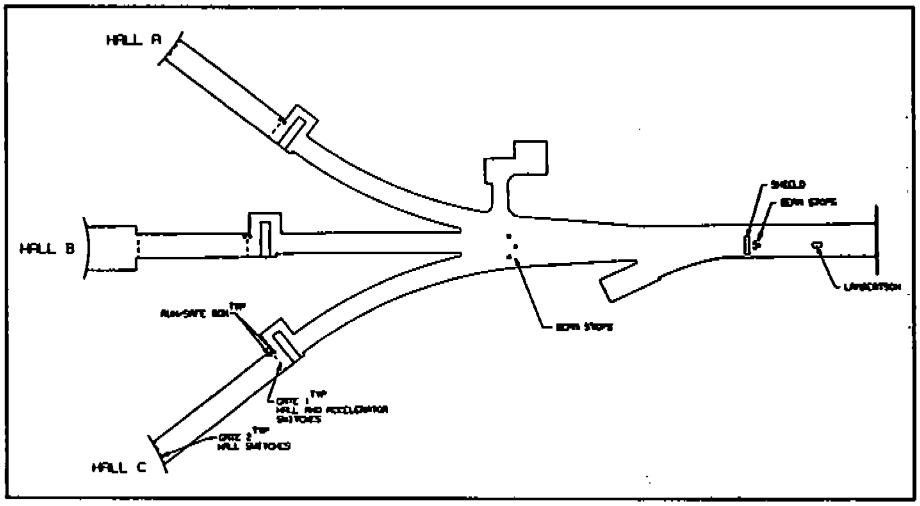

Figure 2

Calculation of Dose Rate Due to Giant Resonance, Mid-Energy, and High-Energy Neutrons

Direct Radiation

The direct neutron radiation through the shielding wall may be calculated by using SHIELD11, a program written by the Radiation Physics Group at SLAC and modified for use at CEBAF. The program identifies a source term for neutrons by production within a "target" of user-definable length, material, and radius. It then calculates transmission, taking into account angle to the point of interest (POI), angle of the shield, distance to the POI, and shielding thickness and material. Table 1 identifies the neutron dose equivalent rate for various distances and shielding thicknesses as calculated by SHIELD11. It assumes a power of 800 kW at 4 GeV, and that the full power of the beam is absorbed by one of the SLAC-type beam stoppers/ disaster monitors. It also assumes that the shielding is made of SEG shield blocks (essentially iron). A factor of 2 is included to account for in-scattering. The personnel barrier fence will be approximated at 2 meters behind the shield wall.

Also calculated is the dose rate with a 13" thickness (one depth of one SEG shielding block) for a shadow shield, placed nearly directly behind the SLAC disaster monitor. The 3 disaster monitors are all approximately 20 meters from the shield wall in the area of the beam switch yard where it separates into the three transfer tunnels.

Table 1

	19 m, 0 shielding	20 m, 0 shielding	20 m, 39" shielding	22 m, 39" shielding
neutron dose rate	2604 rem/hr	2352 rem/hr	7.9 rem/hr	6.8 rem/hr
w/ 13" shadow	174 rem/hr			1.1 rem/hr

The direct neutron dose equivalent rate at 22 m through the 39" of shielding is calculated to be **6.8 rem/hr.** In the event that the shadow shield is used, the dose rate is reduced to approximately **1.1 rem/hr.**

Scattered Radiation

Using universal transmission curves (and knowing the length and cross-sectional area of the labyrinth)(Sch,420-421), the scattering terms for the large opening around the wall assuming a 1.6 meter opening are:

scatter down first leg	**0.1**
scatter from first leg to second	**0.04**
scatter from second leg to third	**0.02**
scatter to gate (2 m)	**0.3**

The scattering term for the top and bottom openings of the wall assuming a 15 cm x 3 m area and 1 m pathlength is:

scatter through opening	**0.05**
scatter to gate (2 m)	**0.1**

The dose rate on the personnel side of the wall may be calculated using these scattering coefficients and geometric factors (*) to account for the solid angle into which the beam scatters:

$$H = H_0[(0.1)(0.04)(0.02)(0.3)(0.15^*)+2(0.05)(0.1)(1^*)] \\ =1.0E\text{-}2\,H_0 \tag{1}$$

The geometry factor of 1 is used for the top and bottom scatters, as these are essentially line-of-sight to the source. Table 2 shows the high energy neutron transmission coefficients for various shield distances from the wall. The 1.0 m, 1.2 m, 1.6m and 1.8m optional distances are those on the accessible end of the wall, and the 30 cm and 15 cm distances are those on the top and bottom.

Table 2

	Geometry *f*	1st scatter	2nd scatter	3rd scatter	4th scatter	Product
1.0 m	0.15	0.1	0.03	0.02	0.3	2.70E-6
1.2 m	0.15	0.1	0.035	0.02	0.3	3.15E-6
1.6 m	0.15	0.1	0.04	0.02	0.3	3.60E-6
1.8 m	0.15	0.1	0.05	0.02	0.3	4.50E-6
30 cm x 2	1	0.07	0.1	-	-	1.40E-2
15 cm x 2	1	0.05	0.1	-	-	1.00E-2

The direct neutron dose rate on the beam side of the wall, from Table 1, is calculated as 2604 rem/hr. For a 15 cm opening for the top and bottom and 1.6 m passage on the side, the dose rate due to the scattered neutrons is approximately **20.8 rem/hr.** The shadow shield reduces the initial dose rate to 174 rem/hr, and thus reduces the dose rate due to scattered neutrons to **1.7 rem/hr.**

Calculation of Dose Rate Due to Photons

Direct Radiation

The direct photon radiation through the shielding wall may be calculated by using SHIELD11, a program written by the Radiation Physics Group at SLAC and modified for use at CEBAF. The program identifies a source term for photons by production within a "target" of user-definable length, material, and radius. It then accounts for angle to the point of interest (POI), angle of the shield, distance to the POI, shielding thickness, and material. A second source term is also produced (herein called secondary photons) due to the hadron cascade within the shield. Table 3 identifies the photon dose equivalent rate for various distances and shielding thicknesses as calculated by SHIELD11. It assumes a power of 800 kW at 4 GeV, and that the full power of the beam is absorbed by one of the SLAC-type beam stoppers. It also assumes that the shielding is made of SEG shield blocks (essentially iron). A factor of 1.5 is included for primary photons to account for in-scattering. The personnel barrier fence will be 2 meters from the shield wall.

Table 3

	19 m, 0 shielding	20 m, 0 shielding	20 m, 39" shielding	22 m, 39" shielding
primary photons	19406 rem/hr	17532 rem/hr	1.41E-6 rem/hr	1.18E-6 rem/hr
primary w/ 13" shadow	5.8 rem/hr	4.7 rem/hr	6.4E-10 rem/hr	5.3E-10 rem/hr
secondary photons	0 rem/hr	0 rem/hr	0.25 rem/hr	0.209 rem/hr
secondary w/ 13" shadow	9.2 rem/hr (estimated)[1]	8.3 rem/hr (estimated)[1]	1.7E-2 rem/hr (estimated)[2]	1.4E-2 rem/hr (estimated)[2]

The direct photon dose equivalent rate at 22 m through the 39" of shielding is calculated to be **0.209 rem/hr.** The reduction in dose rate with the shadow shield in place results in a total dose estimate of **0.014 rem/hr.**

[1] Estimated by rule of inverse squares from a shadow shield dose rate calculation 1 meter from source.

[2] Estimated by taking the ratio of neutrons at the POI after placement of the shadow shield vs. before placement and multiplying the result by the secondary photon dose rate before shadow shield placement.

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Scattered Radiation

The scattering in the "labyrinth" around the shield may be estimated with the following formula (Sch,423):

$$H=H_0\times B(E_0,L,R)\ln[1+(\pi L^2)^{-1}] \tag{2}$$

H = dose rate after scattering
H_0 = initial dose rate due to primary photons
$B(E_0,L,R)$ = buildup factor due to the initial energy E_0, duct length L(m), and duct lateral dimension R. This value typically ranges from 1.0 to 1.5, so **1.5** was chosen as the more conservative value.

The dose rate on the personnel side of the wall may be calculated by using the initial dose rate, and applying equation (4) consecutively, along with geometric factors to account for the solid angle into which the beam scatters(*):

$$H = H_0(1.5)(0.03)(1.5)(0.03)(1.5)(0.01)(1.5)(0.378)(0.15^*) = 2.58E{-}6\,H_0$$ Side Scatter

$$H = H_0(2)(1.5)(0.077)(1.5)(0.077)(1^*) = 0.027\,H_0$$ Top and Bottom scatter

The total scattering coefficient is the sum, or **0.027.** Multiplying this factor by the primary photon dose rate on the beam side of the wall (19406 rem/hr) yields **518 rem/hr**. With the shadow shield, H_0 = 15 rem/hr (includes both primary and secondary from the shadow shield) and the scatter term becomes **0.405 rem/hr**. Clearly, the bulk of photon dose is due to the scattered radiation, not the direct radiation.

For other distances from the walls, the buildup factor may moderately change, but the exact effect is not clear. It may be generalized that there will be a moderate reduction in dose rate due to scattering when the shield is closer to the wall, and an increase in dose rate with larger openings.

Calculation of Dose Rate Due to Thermal Neutrons

Direct Radiation

The estimated transmission of thermal neutron flux from direct transmission through the SEG blocks may be considered to be inconsequential, as demonstrated by equation (5):

$$\begin{aligned}\phi &= \phi_0 e^{-\sigma_a N x} \\ &= \phi_0 e^{-(2.62)(0.0848)(99)} \\ &= 2.80E{-}10\,\phi_0\end{aligned} \tag{5}$$

Scattered Radiation

The thermal neutron production may be estimated using the formula (Patterson):

$$\begin{aligned}\phi_{th} &\approx \frac{1.25Q}{S} \\ &\approx 6.54E{+}6\ n/cm^2\text{-sec}\end{aligned}$$

ϕ_{th} = thermal neutron flux
Q = fast neutron flux (n/sec) ≈ 2.13E+12 (calculated @ 1cm from source)
S = Surface area of duct (cm^2) ≈ 4.07E+5 (calculated as $4\pi r^2$, r being the effective radius of the tunnel)

Thermal neutron transmission in a labyrinth may be approximated by two formulas (Price et al.). Transmission through the first straight cylindrical duct (19 m path to wall) may be approximated by equation (6):

$$\begin{aligned}\phi &= 2J'\left[1-\left(1+\left(\frac{a}{z}\right)^2\right)^{-\frac{1}{2}}\right] \\ &= 4.76E{-}3\ J' \\ &= 3.11E{+}4\ n/cm^2\text{-sec}\end{aligned} \tag{6}$$

J' = thermal neutron fluence rate (n/cm^2-sec)
a = effective radius of duct, cm
z = distance along duct, cm.

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Transmission through later bent cylindrical ducts of equal diameter may be approximated by equation (7):

$$\phi(z_i) = \frac{\phi_{jk} K a^2 \beta_{jk}}{2 z_i^2} \operatorname{cosec}\theta_i \qquad (7)$$

$\phi(z_i)$ = thermal neutron fluence rate, n/cm^2-sec, at a distance z along the duct i
$K\beta_{jk}$ = for thermal neutrons, approximates a constant of 1/3
β_{jk} = effective albedo from surface jk for thermal neutrons, $\approx$0.55
a,z = previously defined
θ_i = angle of the i duct (or tunnel)
ϕ_{jk} = thermal neutron fluence rate, n/cm^2-sec, from surface jk

Table 4 shows the thermal neutron transmission coefficients for various shield distances from the wall. The 1.0 m, 1.2 m, 1.6 m, and 1.8 m optional distances are those on the open end of the wall, and the 30 cm and 15 cm distances are those on the top and bottom.

Table 4

	1st scatter	2nd scatter	3rd scatter	4th scatter	Product
1.0 m	1.5E-2	1.0E-2	8.4E-3	8.2E-2	1.0E-7
1.2 m	1.5E-2	1.2E-2	8.4E-3	8.2E-2	1.2E-7
1.6 m	1.5E-2	1.7E-2	8.4E-3	8.2E-2	1.8E-7
1.8 m	1.5E-2	2.0E-2	8.4E-3	8.2E-2	2.1E-7
30 cm x 2	0.33	0.24	-	-	0.16
15 cm x 2	0.30	0.24	-	-	0.14

With an initial flux of 3.11E+4 n/cm^2-sec and a dose conversion factor of 3.68E-6 rem/hr per n/cm^2-sec, the dose rate at the personnel fence, with 1.6 m and 15 cm openings is calculated to be $\approx$**0.016 rem/hr.** The addition of a shadow shield would not significantly decrease this source term, due to the nature of the thermal neutron production.

It should be noted that the bulk of this scattering term is around the top and bottom gaps, and is the greatest source of transmission of thermal neutrons.

Conclusion

The greatest contribution to potential dose rate on the personnel side of the wall is due to scattered radiation, not direct radiation. The total dose rate, from both scattered and direct radiation for 15 cm openings above and below the wall and a 1.6 m opening in the open end is :

$$\dot{H}_t = \dot{H}_{n_d} + \dot{H}_{n_i} + \dot{H}_{\gamma_d} + \dot{H}_{\gamma_i} + \dot{H}_{th_d} + \dot{H}_{th_i}$$
$$= 6.8 + 20.8 + 0.209 + 518 + 0 + 0.016$$
$$= 546\ rem/hr$$

The addition of a shadow shield is calculated to cause the following dose rate:

$$\dot{H}_t = 1.1 + 1.7 + 0.014 + 0.405 + 0 + 0.016$$
$$= 3.24\ rem/hr$$

It is evident that the addition of a shadow shield of some kind is necessary to reduce the scattered component of the source term. Radiation monitoring and PSS features of the radiation safety requirements are discussed in the following paragraph.

ANSI 43.1 (NBS Handbook 107) suggests that maximum reliance should be placed on passive rather than active elements of a safety system. As a rule of thumb we are using a 10 rem/h limit on instantaneous dose equivalent rate beyond shielding during catastrophic beam loss conditions. Accordingly, passive controls (shielding) should be designed to prevent conditions which result in a dose equivalent rate greater than 10 rem/h. Active controls, those provided by the Personal Safety System (PSS), are required to detect and reduce the total dose equivalent by limiting the duration of a catastrophic beam loss.

PSS related systems are required to have redundant mechanisms for beam termination which are free from common mode failures. Devices used in work areas (those which measure radiation exposure to personnel, such as CARMs) require maintenance, quality assurance checks, and calibrations traceable to National Institute of Standards and Technology (NIST). Other devices will be used in conjunction with CARMs. These devices, such as slow beam loss ion chambers (SBLICs), do not measure personnel exposure in work areas but detect radiation produced by a beam loss conditions at locations near the point of beam loss. These devices detect radiation but are not used to directly calculate (or estimate) personnel exposure. The radiation field at the point of beam loss is too complex to be accurately characterized by a device like a SBLIC. However, detecting radiation near the point of loss is desirable since it is more efficient and more cost effective than placing large numbers of CARMs throughout work areas.

SBLICs, or their equivalent, would not require rigorous calibration or quality assurance checks. They would require characterization of a working model for response to, and function in, the anticipated radiation field. Periodic operational checks could be scheduled during accelerator startup and beam alignment by intentional loss of low current beam, or the function of the devices could be checked using the RCG's high range calibrator (if the configuration of the device allows it to fit in the calibrator).

Rather than have paired CARMs in personnel work areas where the potential impact of a "catastrophic" beam loss is high , a combination of SBLIC and CARMs is proposed. A pair of SBLICs (redundant in their function) located near potential points of beam loss with associated CARMs in key personnel locations is one acceptable configuration mentioned in TN 0172. Another configuration, not mentioned in TN 0172, which uses the "disaster monitor" function of the SLAC insertion type beam stopper and a pair of SBLICs (or equivalent) would be also be acceptable if the associated administrative controls (verification of magnet string power supply shut-off) and passive controls (shielding to $<$ 10 rem/hr) is used.

An appropriate coefficient to convert the apparent neutron fluence to dose equivalent is 20 fSv m² (or 1 neutron per cm² and s is equivalent to 0.7 μSv/h).

Figure A.11 also summarizes first-leg transmission for source conditions other than the point source on the tunnel axis. These curves are again composites from SAM-CE, ZEUS and AMC calculations. The value of the dose equivalent at the tunnel mouth should either be known from the measurements or estimated using the inverse-square law approximation and the source strengths discussed in the previous paragraphs.

For the transmission through the second leg in a labyrinth Goebel et al. [Goe 75], summarizing SAM-CE, AMC and ZEUS calculations, and taking into account the available experimental data, suggested that in most cases the transmission would lie close to the solid line in Fig. A.13. Generalized AMC calculations and the data from the NIMROD experiment lie close to this solid line; some SAM-CE calculations showed a higher transmission and their upper limit is shown by the upper dotted line in Fig. A.13. The ZEUS-albedo calculation (the Gollon and Awschalom "universal" curve) gives the lower bound shown by the other dotted line in Fig. A.13. It was proposed [Goe 75] that the solid line should give a satisfactory way of obtaining the transmission in the second leg of a multi-legged, concrete-lined tunnel, with the dotted lines indicating appropriate confidence limits. The same curve can be used to predict transmission in subsequent legs of multi-legged ducts.

An alternative approach to the prediction of tunnel transmission was proposed by Tesch [Tes 82]. A comparison of three procedures, that of Gollon and Awschalom, [Gol 71], Tesch [Tes 82] and Goebel et al. [Goe 75], for predicting tunnel attenuation is given in Fig. A 14 based on an experiment by Cossairt et al. [Cos 85]. There is fairly good agreement between the three procedures and the experimental data but that of Goebel et al. is closest to the data.

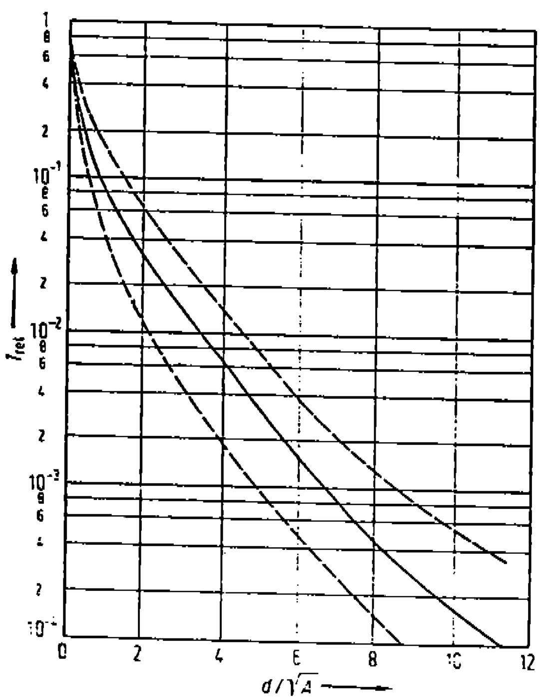

Fig. A.13. Universal transmission curves for the second and subsequent legs of labyrinths [Goe 75]. Abscissa: distance d from tunnel mouth expressed as $d/\sqrt{A}$ with A the cross-section area of the tunnel; ordinate: relative transmission T_{rel}.

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A.2.4 Prediction of transmission in ducts and labyrinths

One can conclude from the previous section that one needs only to consider the transmission of neutrons from a source having an energy distributed between 1 and 20 MeV. As far as a straight duct is concerned, the calculations of Vogt with SAM-CE [Vog 75] and Gollon and Awschalom with ZEUS [Gol 71] both show a faster than inverse square dependence of the transmission with depth in the tunnel due to reflections at or near the tunnel mouth. Thus, if one wishes to design the first leg of a labyrinth the transmission curve marked "point" in Fig. A.11 may be used to define the expected transmission. This is a composite curve derived by Goebel et al. [Goe 75] from the SAM-CE and ZEUS calculations.

An inverse square law should be used to determine the fluence of these neutrons at the mouth of the tunnel, or at the end of the first leg if the source is on the axis of the tunnel. The experiments of Stevenson and Squier [Ste 73] lead to a figure of one neutron produced per 1.6 GeV of proton energy lost from the beam at 7 GeV (isotropic). The yield for neutron production scales as $E^{0.8}$ above an energy of 7 GeV. Below this energy the thin-target curve of Fig. A.12 can be used to scale the neutron yield [Ste 86].

For a thicker target there is evidently an optimum size of block in which the cascade develops to produce the maximum number of neutrons. It was suggested by Routti [Rou 72] that one neutron would be produced per 0.25 GeV of energy from a proton beam at 25 GeV. This scales as $E^{0.2}$ above a proton energy of 3 GeV [Ste 86]. Below this energy, scaling according to the "thick target" curve of Fig. A.12 should be used.

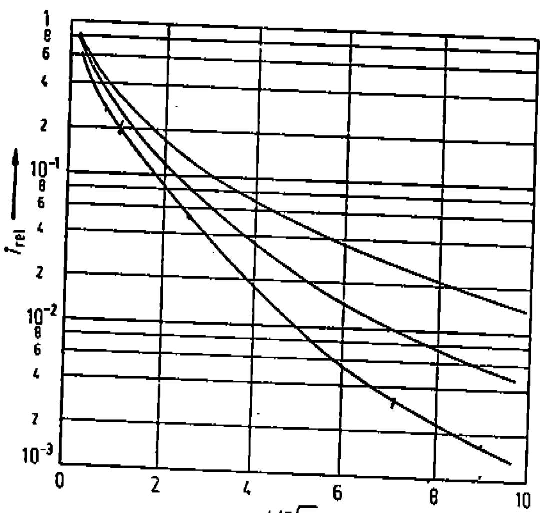

Fig. A.11. Universal transmission curves for the first leg of a labyrinth [Goe 75]. Abscissa: centre line distance d from tunnel mouth expressed as $d/\sqrt{A}$ with A the cross-sectional area, ordinate: relative transmission T_{rel}. Upper curve: point source, middle curve: line source, bottom curve: disk source (isotropic emission).

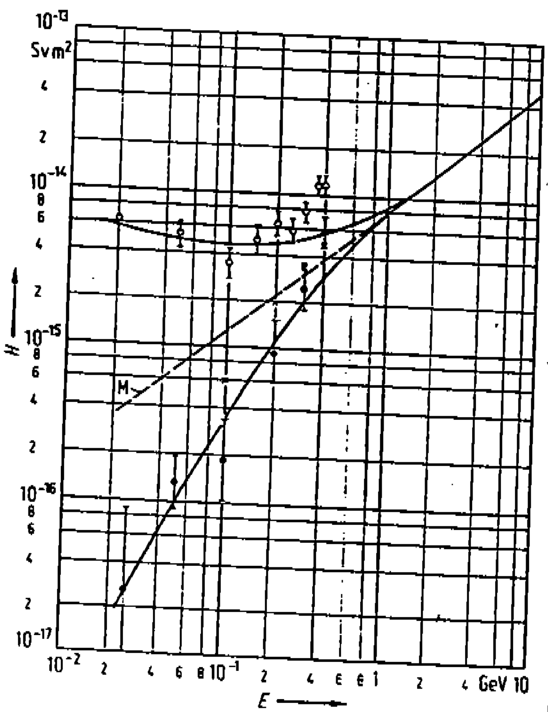

Fig. A.12. The source strength parameter for sideways shielding calculations at proton energies of less than 3 GeV. Ordinate: dose equivalent H at 1 metre and zero depth, abscissa: proton energy E. The dotted line "M" (Moyer) gives the increase of the dose equivalent with energy according to the formula $H = 7.6 \cdot 10^{-15} E^{-0.8}$ Sv m². Open circles are the thin target data, closed circles are the thick target data [Ste 86], crosses are data from [Bra 71].

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