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RADIATION PROBLEMS WITH HIGH-ENERGY PROTON ACCELERATORS*

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Abstract

We shall restrict the discussion to proton accelerators in the multi-GeV energy range and of the alternating-gradient synchrotron type, with special attention given to the existing 30-GeV and the proposed 200- to 300-GeV machines.

Radiation problems can be divided into two broad groups: those produced by the accelerator while it is running and those associated with the shut-down machine. The expense and difficulty of coping with these radiation problems influence the choice of design beam intensity.

The problems while the machine is running are penetration of radiation through the shielding, muon shielding, penetration of radiation through ducts and labyrinths, skyshine, diffusion of radioactive air, and radiation damage to components. Some results of an LRL-CERN-Rutherford shielding experiment on the CERN-PS are presented.

Problems of the shut-down accelerator include induced activity in the machine components and enclosure walls. These radiation fields affect maintenance procedures and require appropriate handling tools and shielded vehicles.

Introduction

Our primary concern has been with the radiation problems associated with the contemplated 200- to 300-GeV strong-focusing proton accelerators.[1-3] From the radiation-protection standpoint, these machines offer the advantage over the existing Brookhaven and CERN synchrotrons that, being nonexistent, there is no prior restriction on component design or operating principles imposed by existing structures. We have also studied the radiation problems at the CERN-PS and BNL-AGS, since these can be considered as models for the higher-energy machines, and the physical processes involved in cascade production are qualitatively the same for energies above about 12 GeV. Considerable lower-energy radiation investigation has taken place at several proton machines: Bevatron, Nimrod, Saturne, PPS, and ZGS. For all multi-GeV proton and electron accelerators, for example, the Stanford Linear Accelerator,[4] most of the radiation problems are quite similar, the differences being related to mechanisms of beam loss and cascade development and machine structure.

Both the existing CERN-PS and BNL-AGS have had continuously increasing circulating beams, so that at present they routinely accelerate 4 to 6 x 10^{11} protons/s in the 20- to 30-GeV energy range. This represents some 1 to 2 kW of beam power, and the problems associated with radiation are already troublesome. Both machines have improvement programs underway that will increase their circulating beam currents from 10 to 30 times.[5,6] Structural modifications such as increased thickness of earth shielding will be required as well as increased use of external beams. The 200- and 300-GeV designs are capable of greater than 10^{13} protons/s or some 500 kW of beam power. Under the worst circumstances, radiation problems could make the accelerator site uninhabitable, the accelerator inoperable, and maintenance unreasonable. By identifying these problems from the beginning of the design process, it seems feasible to build and maintain a high-current synchrotron ($>10^{13}$ protons/s) for a relatively small penalty in capital and operating costs as compared with a low-current synchrotron ($\approx 10^{11}$ protons/s).

Figure 1 is a symbolic drawing of an accelerator and its associated radiation problems (see Table I), both while running and when shut down

Table I. Radiation Problems

	Problem	Running	Shut Down
1.	Strongly interacting particles (S.I.P.) penetrating shield	XX	
2.	Leakage through ducts and labyrinths	XX	
3.	Muons penetrating shield	XX	
4.	Skyshine	XX	
5.	Radiation damage and heating	XX	
6.	Radioactive air, water and dust	XX	XX
7.	Induced activity in accelerator		XX
8.	Induced activity in tunnel walls		XX

Wherever primary protons are lost, all of the above-mentioned radiation problems appear and, in a sense, will be proportional to the number of protons interacting in a given region. The distribution of this beam loss is a strong function of targeting and has led to primary reliance on extracted external proton beams in the proposed 200- to 300-GeV and improved CERN-PS and BNL-AGS. In this way the most formidable problems can be moved to the target stations at the ends of the extracted beams and the radiation source inside the accelerator tunnel will be reduced to that fraction of the circulating beam that is not successfully extracted. Operation and maintenance of these external target stations will be difficult, but one can work on any one of them without having to turn off the accelerator, assuming that one has multiple external-beam capability.

The above radiation problems will be discussed in the framework of the 200-GeV design which has an initial circulating current of 1.5 times 10^{13} protons/s and an ultimate intensity capability of 5 times 10^{13} protons/s and an assumed extraction efficiency of 85%. More detailed treatment is found in the references cited above. The current picture is indicated in the following sections.

Problem 1.

Strongly Interacting Particle Shielding

Figure 2 shows earth shields and machine tunnels for the CERN-PS, BNL-AGS, SLAC, and 200-GeV machines, all shields adjusted to about the same earth density. For the CERN-PS and AGS accelerators, the solid lines are for the existing shields above the nontarget areas, and the dashed lines are for the shielding above these quiet regions after their present improvement programs. For the SLAC and the 200-GeV machines the shields are designed for the ultimate intensity, since it is unduly expensive to augment shielding later. For these latter machines the dashed lines represent the shielding above the target or extraction areas. The scale of the 200-GeV machine is such that a reduction of 6 ft in the shield thickness (from an original 23-ft thickness) represents a reduction in cost \$ 3M. Hence it behooves one to reduce uncertainty here as far as possible, and I'll report below on a recent experiment that was carried out at the CERN-PS by groups from LRL, CERN, and Rutherford.

Problem 2.

Leakage Through Ducts and Labyrinths

There are many types of penetrations through the shielding that offer a path from the inside of the tunnel to the outside. These range from small ducts for conduits to large openings for personnel and truck access. As the source of radiation increases and the main shielding gets thicker, the leakage paths must be decreased through these penetrations. New measurements on radiation transmission through ducts were made as part of the experiment mentioned above and will be available later.

Problem 3.

Muon (μ) Shielding

The muon is a weakly interacting particle, and so the shielding provided for the S.I.P. may or may not be sufficient to shield against them. Pions, which are readily produced in high-energy interactions, can decay into the weakly interacting muon ($\pi \rightarrow \mu + \nu$), or, in material, can strongly interact themselves. Similarly kaons can decay into muons ($K \rightarrow \mu + \nu$). Most energetic muons are from pions and kaons that have decayed in flight in the air path between a target and the shield face. Some muons result from pion decay in the relatively short range or interacting length of the pion in condensed matter. In either case muons are strongly peaked in the forward, or primary proton beam, direction and the muon energy spectrum extends up to the primary proton energy.

The physical basis for the difficulty in shielding from muons is that they are weakly interacting and cannot lose a large fraction of their energy in nuclear interactions. The ionization loss for a muon is roughly 2 MeV/g-cm^{-2}, although this dE/dX is somewhat altered at different energies because of pair production and relativistic rise effects, and through a Z dependence, different materials have slightly different values. The length of shield necessary to stop a muon is rougly proportional to its initial energy. For strongly interacting particles, on the other hand, we speak of an exponential removal mean free path, say 130 g-cm^{-2}. After the buildup process, this means that the energy left in the cascade after one mean free path is one/eth that at the beginning. As the primary proton or pion energy increases, the apparent dE/dX increases, because the observed removal mean free path is roughly constant with energy above a few hundred MeV.

Figure 3 displays the difference in the shielding of strongly interacting particles and muons. Here we are concerned with shielding in the straight-ahead direction, which is pertinent for the primary beam-disposal area and external-beam target stations. For S.I.P.'s, after the usual buildup, one sees an exponential decay vs depth curve with a mean free path of some 130 g-cm^{-2}. For an incident proton energy of 200-GeV, an equivalent mean free path for muons is some 6000 g-cm^{-2}. At the shield thickness needed for S.I.P.'s, 3000 g-cm^{-2} or approximately 6000 lb-ft^{-2}, the muon flux is more than two orders of magnitude greater than that for S.I.P.'s. At the present 30-GeV synchrotrons this problem is less severe, since the equivalent mean free path for muons is about one fourth that for 200-GeV protons. That is, the muon curve is steeper than the one shown in Fig. 3, while the removal mean free path for S.I.P.'s is the same as at 200-GeV. The absolute beam intensity also plays a role here, as inspection of the curves in Fig. 3 will show. As the intensity increases, one must go to lower transmission on the S.I.P. curve, which is relatively easy because of the steep slope. There is relatively less decrease in the muon transmission for the same thickness increase. The improved 30-GeV machines will have forward shielding in which the thickness is determined by muons and not by S.I.P.'s, as in the current situation.

Figure 4 shows a 200-GeV external-beam double target station. The muon shield is made of depleted uranium and some 5000 tons are required for each single station, the muon range being close to the 100-ft length shown. Uranium seems to be the best material because its high density and high Z results in a compact, and probably minimum cost, shield. The entire facility requires some 18000 tons of uranium at a total cost of some $ 10M. The design of muon shields requires elaborate computer calculations but, in light of the expense involved, these design calculations are preferred to cut-and-try methods.

Problem 4. Skyshine

One can accept higher radiation levels directly on top of the accelerator shield than over those portions of the site where almost all of the staff are located. This is because few people spend their entire work week on top of the shield. Radiation escaping from the shield can propagate to other parts of the site and even to the site boundary, beyond which the regulations for general uncontrolled population apply. This propagation of escaping radiation over distances of several hundred meters is called skyshine, since radiation that is initially directed upwards is air-scattered downwards at these distant points. If the radiation levels at the accelerator shield surface are equal to or less than the maximum permissible level for radiation workers -- generally taken to be 2.5 mrem/h -- then a separation distance of a few hundred meters to occupied buildings and site boundaries is sufficient to reduce this skyshine radiation to acceptable levels. This same line of reasoning demands that radiation through the ring shield not exceed this 2.5 mrem/h unless the high-radiation region is more than several hundred meters from buildings and boundaries.

Problem 5.

Radioactive Air, Water, and Dust

Air, water, and dust within the accelerator tunnel will be made radioactive while the machine is in operation. During operation the air and water are continuously recirculated through pumping systems that communicate with the outside environment. A certain amount of leakage and makeup are unavoidable. Attention must be paid to the concentration of the radioactive effluents escaping from the tunnel and from the site boundaries.

After machine turn-off these radioactive products can affect maintenance personnel entering the tunnel. We estimated in the 1965 200-GeV Design Study,[1] that if a worker enters the tunnel immediately after beam turn-off, the radioactive air present in the quiet, or nontarget, portions of the tunnel would give him an integrated exposure of 13 mrem; therefore, immediate entry into these areas is not precluded. However, in the target or extraction areas an integrated exposure of some 8000 mrem is possible; so immediate entry here is precluded. Therefore, before anyone enters target areas, the air will be purged, which will take approximately 1 h. The radioactive magnet-cooling water is not a serious problem, since the system is closed. If magnets are to be drained, normal radioactive-monitoring techniques are required. Some experimental data exist on the radioactive air problem.[7,8] The nature of our calculations and the available experimental data are such that one would not expect great accuracy in the above estimates, but they do seem to be correct to a factor of about five. New measurements and calculations are called for before a final ventilation system is specified. The problem seems amenable to solution.

Problem 6.

Radiation Damage and Heating

With several hundred kW of beam power available, we have enough power to burn holes in vacuum chambers, extraction septa, targets, and beam dumps. Control of beam loss and protective design at possible loss points are needed to solve the thermal problem. The primary proton energy is converted through the cascade process to ionizing radiation that fills the tunnel and can cause radiation damage to susceptible materials therin. At the radiation levels expected around accelerators the physical properties of organics, semiconductors, and most insulators are adversely affected, while those of metals are not. The BNL-AGS at its present intensity has already had the coil insulation on a magnet downstream from a target fail due to radiation damage and, more recently, a rubber water hose failed for the same reason. Rubber vacuum seals are readily damaged at the AGS and in target regions are replaced frequently. Considerable effort is going into solving these problems for the increased intensity planned for the improved AGS. The vacuum tank is the machine component closest to the beam, and so one will find the highest radiation field there. Organic vacuum seals are unacceptable, as are organic vacuum tanks, so all-metal or metal-ceramic vacuum systems are required. Magnet coil insulation is exposed to the next-highest field, and research at several laboratories is directed toward developing more-radiation-resistant materials. This is an active field, and I think the best summary is that one or more solutions to this problem exist. As much other equipment as possible is removed from the tunnel, especially solid-state electronics. For the irreducible minimum, one selects the most resistant components available and, in addition, arranges for easy replacement.

Problems 7 and 8. Induced Activity in the Accelerator and in the Tunnel Walls

These two topics are grouped since together they are the cause of the shut-down radiation field inside the tunnel that affects maintenance procedures. Rather than go into detail, I'll refer you to the 200-BeV design document,[1] my talk at the 1965 IEEE meeting, and two talks at this meeting:[9]

W. Salsig	G-17	Capability Vs Cost for Servicing and Handling System Choices in 200-GeV Accelerator Design Study
R. Krevitt	H-18	Remote Maintenance Techniques Proposed for the 200-GeV Accelerator.

We conclude that through design, specification of materials, extensive use of extracted beams, and operating procedures designed to minimize excessive beam loss, most of the machine can be maintained by unshielded workers in the usual contact manner. In the much higher radiation levels found in the target areas, special shielded manipulator vehicles will be required. Recent measurements on induced activity in accelerator components and concrete tunnel-wall constituents yield results in rough agreement with those assumed in the 200-GeV design study.

CERN/LRL/RHEL 1966 Shielding Experiment at the CERN-PS

In late 1965 and early 1966 it became apparent to many who were involved in shielding calculations that the status of the experimental data was not satisfactory. There were several reasons for this: different experiments at different laboratories yielded different results when comparisons were possible, and often different types of detectors were used so comparison was indirect; many present accelerators have shielding of some 10 ft of earth cover and extrapolation to 20 ft and more for the problems of interest has inherent limitations; and finally, a comprehensive shielding experiment requires more people, equipment, and machine time than were available for the previous measurements. These laboratories participated in the recently concluded shielded experiment at the CERN-PS:** LRL had six participants - two from the 200-GeV Accelerator Study and four from the Health Physics groups; Rutherford High Energy Laboratory (RHEL) had three members from their Health Physics groups; CERN had members from their Intersecting Storage Ring division and from Health Physics, the Proton Synchrotron itself and its operating staff. We had exclusive use of the PS for eight 12-h periods between September 28, 1966 and November 28, 1966. Analysis of the data is in progress.

From previous experiments we learned that it was essential to monitor the beam-loss distribution while measurement of the radiation field was in progress. In practice this meant that beam control, or exclusive machine use, together with a large number of simultaneous measurements were required. Activation detectors allowed us to determine the radiation field at hundreds of locations inside the machine tunnel and within the earth shield. Machine time is conserved in that most of the detectors can be simultaneously exposed and counted after the end of the run. The response of these detectors is well understood, and spectral information can be obtained. We were able to cover a dynamic range from < 1 to 10^8 neutron cm^{-2} sec^{-1}. Counters were also used for special purposes. An impressive amount of equipment, with the corresponding human effort, was required to count the many samples within the times dictated by the induced activities and relevant decay lives. The Berkeley group air-freighted some two tons of counting electronics for this experiment. The Rutherford group counted some of their samples at CERN but air-transported most of their samples to Rutherford for counting. The CERN Health Physics group had several of their counters occupied in counting samples from this experiment. Table II lists most of the types of detectors used.

Table II. Detectors used in CERN shielding experiment

A. Activation Detectors	B. Counters	C. Other
$Au^{197} + n \rightarrow Au^{198}$	Integrating ion	TLD
$In^{115} + n \rightarrow In^{116}$	Moderated BF_3	Fission-track plate
$S \rightarrow P^{32}$	Thorium fission	Nuclear Emulsion
$Al \rightarrow Na^{24}$	Bismuth fission	
$C \rightarrow C^{11}$		
$Au \rightarrow Tb^{149}$		
$Hg \rightarrow Tb^{149}$		

Figure 5 is a plan view of the CERN-PS showing the 6-in. drilled holes for our detectors above the beam orbit and to the outside of the ring. Figure 6 is a cross-section view of the accelerator tunnel and shows a line of these holes. Detectors to be placed above the beam orbit were placed in a 10-ft-long sample holder, and cans of dirt were placed between samples to reduce particle streaming up these holes. These sample holders were raised and lowered by the use of rope and pulley attached to the tripod shown. The samples in the radial holes were placed at beam height and were raised by ropes. These holes were lined with plastic tubes. Figure 7 is a photo of the region above the target. One can see the capped tubes and general features. We were particularly fortunate in that the earth cover here is flat and doesn't fall to a lower grade as one goes outward, as it does over most of the ring. The radial holes were for the purpose of measuring attenuation at great shielding depth, which would not have been as convenient if the surface were not reasonably flat.

Runs were made with a clean-up collimator, or dump, some distance from the target. In every run the loss distribution around the ring was monitored by aluminum activation foils placed on the vacuum tank. Two primary proton energies were used -- 25.6 and 13.8 GeV. Figure 8 shows the loss pattern around the machine as measured on the vacuum tank. Figure 9 shows the pattern as measured inside the machine tunnel but near the roof level. Figure 10 shows the pattern at the ground level on top of the shield. The similarity in the peaks just downstream from the target is apparent.

In Fig. 11 are plotted particle fluxes in radial holes corresponding to magnet 33, as measured by the aluminum activation detectors. Although there are three straight lines on semi-log paper, each giving a mean free path, there is only one set of experimental data. When one mentions a mean free path, he is implicitly using a model that includes an exponential factor. If he doesn't explicitly state his geometrical model, he automatically causes confusion. Ignoring build-up factors and assuming we are well into a shield, we can use the following flux-attenuation models:

Plane wave $\Phi(t) = \Phi_o e^{-t/\lambda_{plane}}$

Cylindrical wave: $\Phi(t,R) = \Phi_o (R_o/R) e^{-t/\lambda_{cyl.}}$

Spherical wave: $\Phi(t,R) = \Phi_o (R_o/R)^2 e^{-t/\lambda_{sph.}}$

The plane case is clear, the cylindrical corresponds to an infinite line source, and the spherical corresponds to a point source. From the curves it is not clear that the experimental data are better fitted by one model than another, yet the λ's range from 110 g-cm^{-2} to 133 g-cm^{-2}. It turns out that if one requires additional shielding to reduce the flux by a factor of several hundred, all three models with their appropriate λ's yield nearly the same shield thickness. The above models are overly simple, and an integral representation of the problem (integrated over an extended source) will hopefully yield a single λ. The attenuation of radiation through the earth shield of the CERN-PS, for the proton loss pattern observed, can be fairly well represented by simple models and, we expect, satisfactorily represented by more detailed models. There are two chief problems in using these results to calculate the shielding for a 200- to 300-GeV accelerator. One has to do with the difference in the nature of the cascade produced by the higher-energy protons as compared with the present energies available. The other has to do with the nature of the primary proton-loss pattern around the proposed accelerator. This latter problem is the more difficult, since it depends on the detailed design of the accelerating structure. There are scaling laws that enable one to make this factor of ten in energy extrapolation in a conservative way.

References and Footnotes

1. 200-BeV Accelerator Design Study, UCRL-16000, Vols. I and II, July 1965; 200-BeV Accelerator Preliminary Project Report, UCRL-16606, Jan. 1966.

2. The Design Study of a 300-GeV Proton Synchrotron, CERN, AR/Int. SG/64-15, Vols. I and II, Nov. 1964.

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6. P. Standley, CERN, private communication.

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8. A. Rindi, Health Physics Dept., CERN, private communication.

9. W. Gilbert and R. Thomas, Problems of Induced Radioactivity Around the 200-BeV Alternating-Gradient Synchrotron, UCRL-11796, Feb. 1965; IEEE Trans. Nucl. Sci. NS-12, No. 3 (1965).

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RHEL: K. Shaw, G. Stevenson, R. Thomas

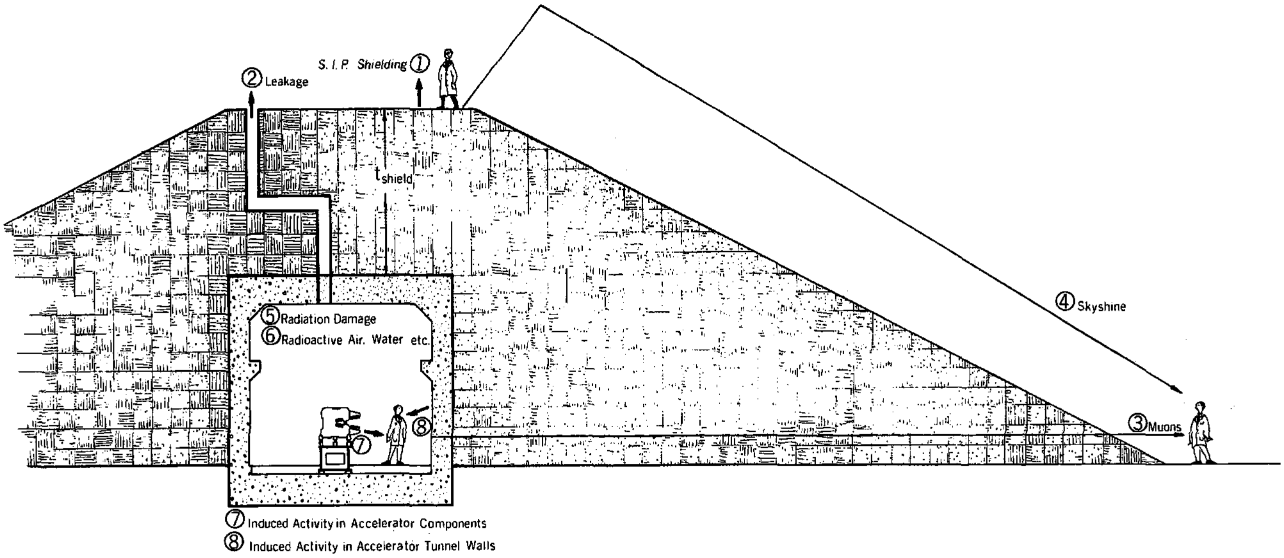

Fig. 1. Schematic representation of radiation problems.

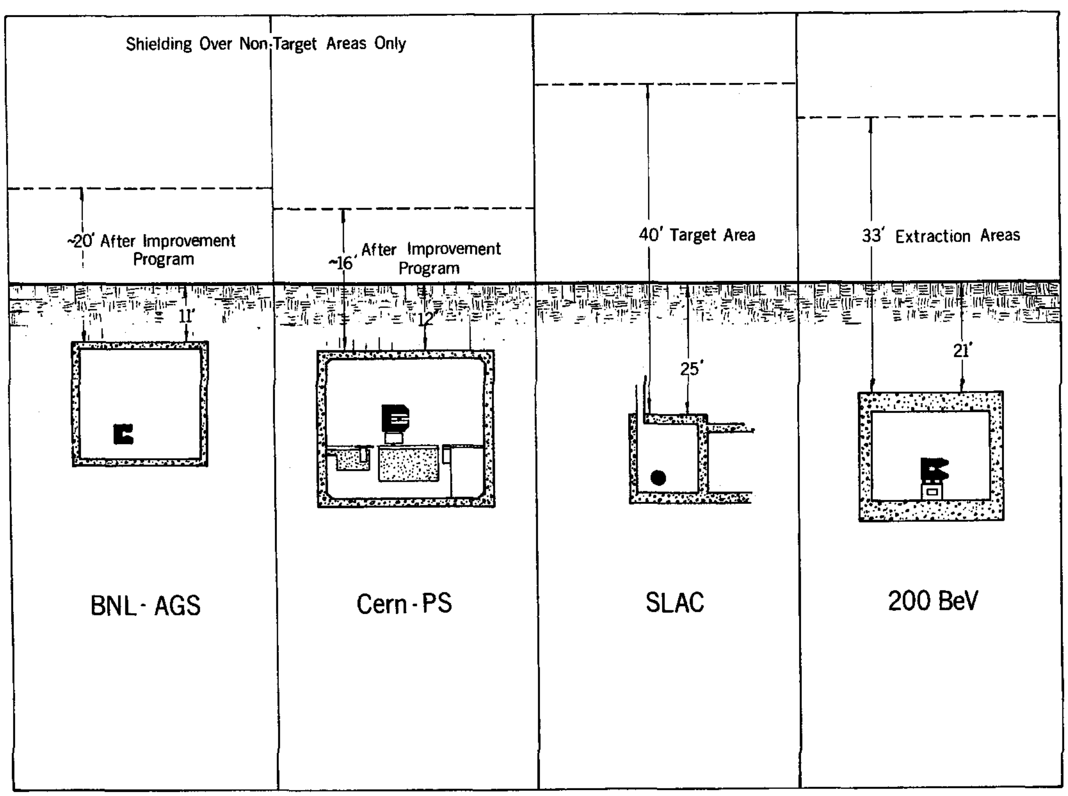

Fig. 2. Comparison cross sections of AGS, PS, SLAC, and 200-GeV accelerators.

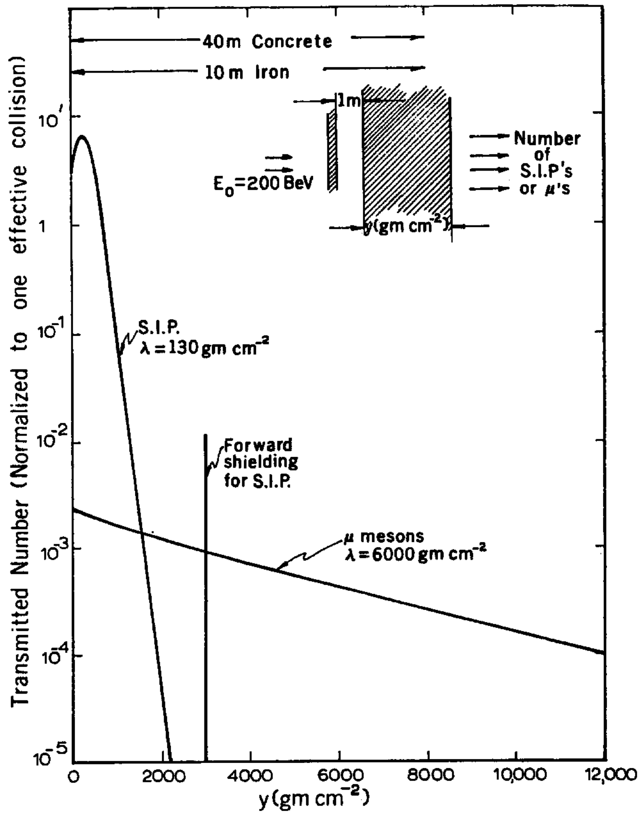

Fig. 3. Transmission vs shielding for strongly interacting particles (S.I.P.) and muons for incident 200-GeV protons.

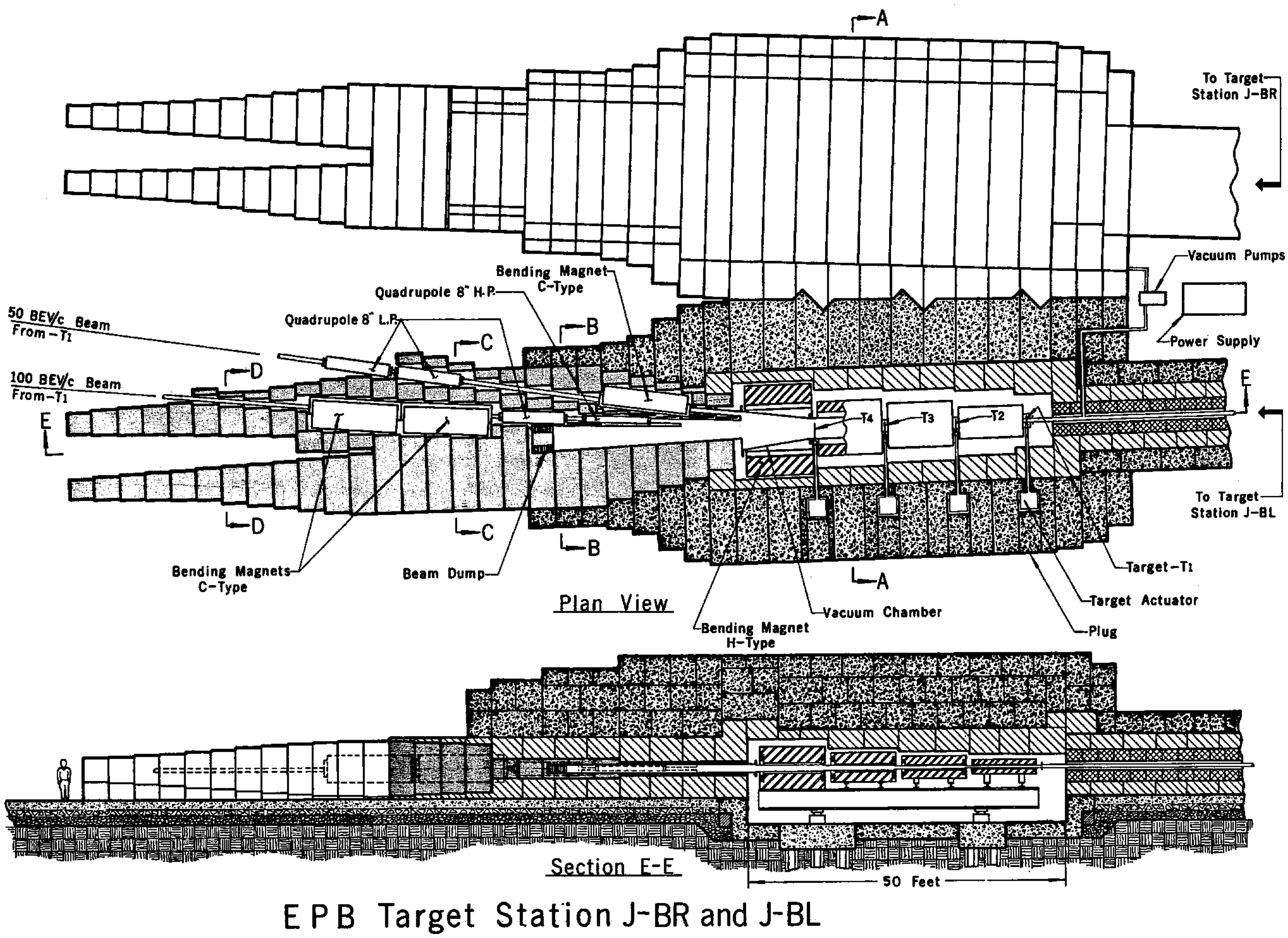

Fig. 4. EPB target stations for the 200-GeV proton accelerator.

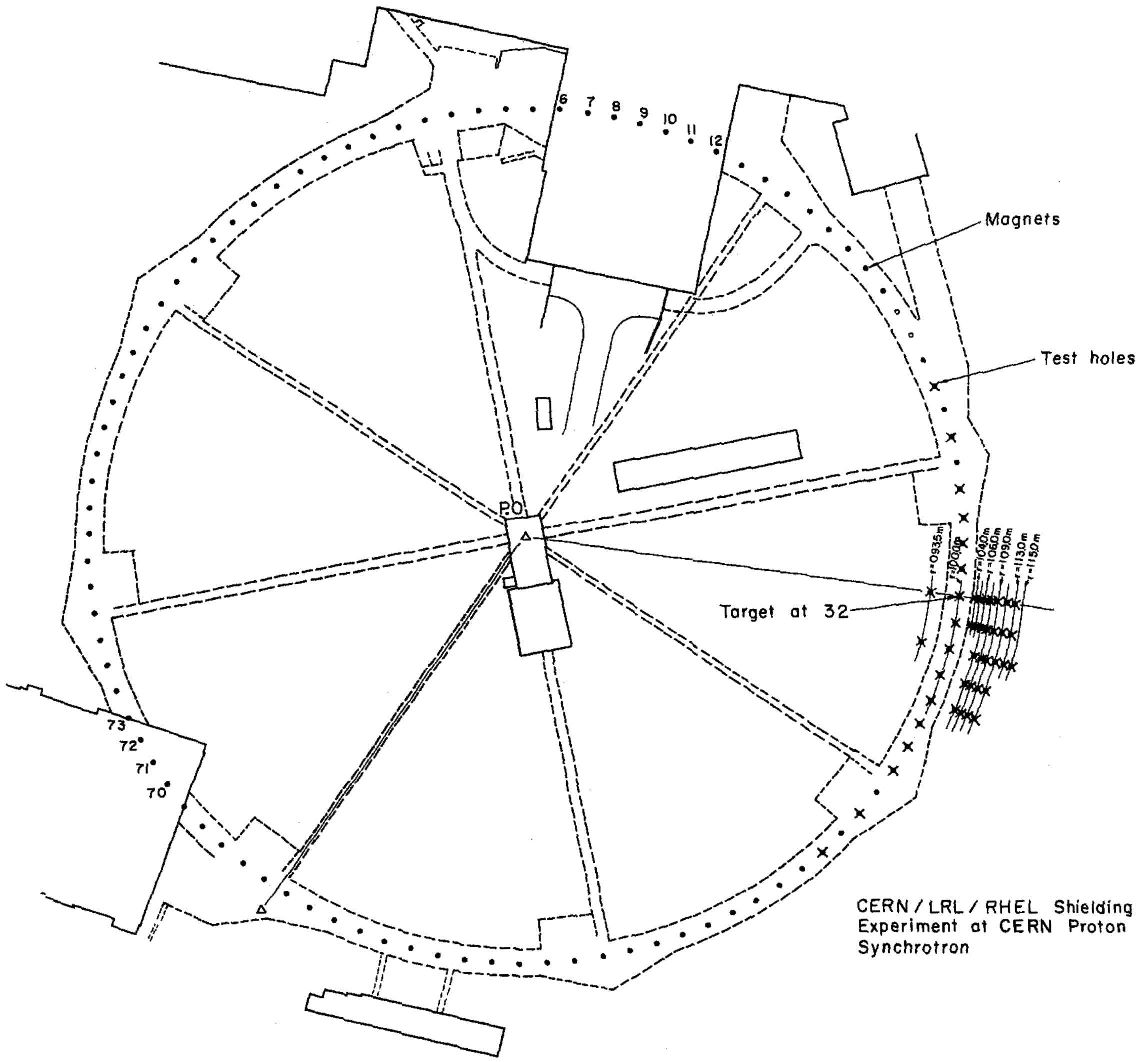

Fig. 5. Plan view of the LRL/CERN/RHEL shielding experiment.

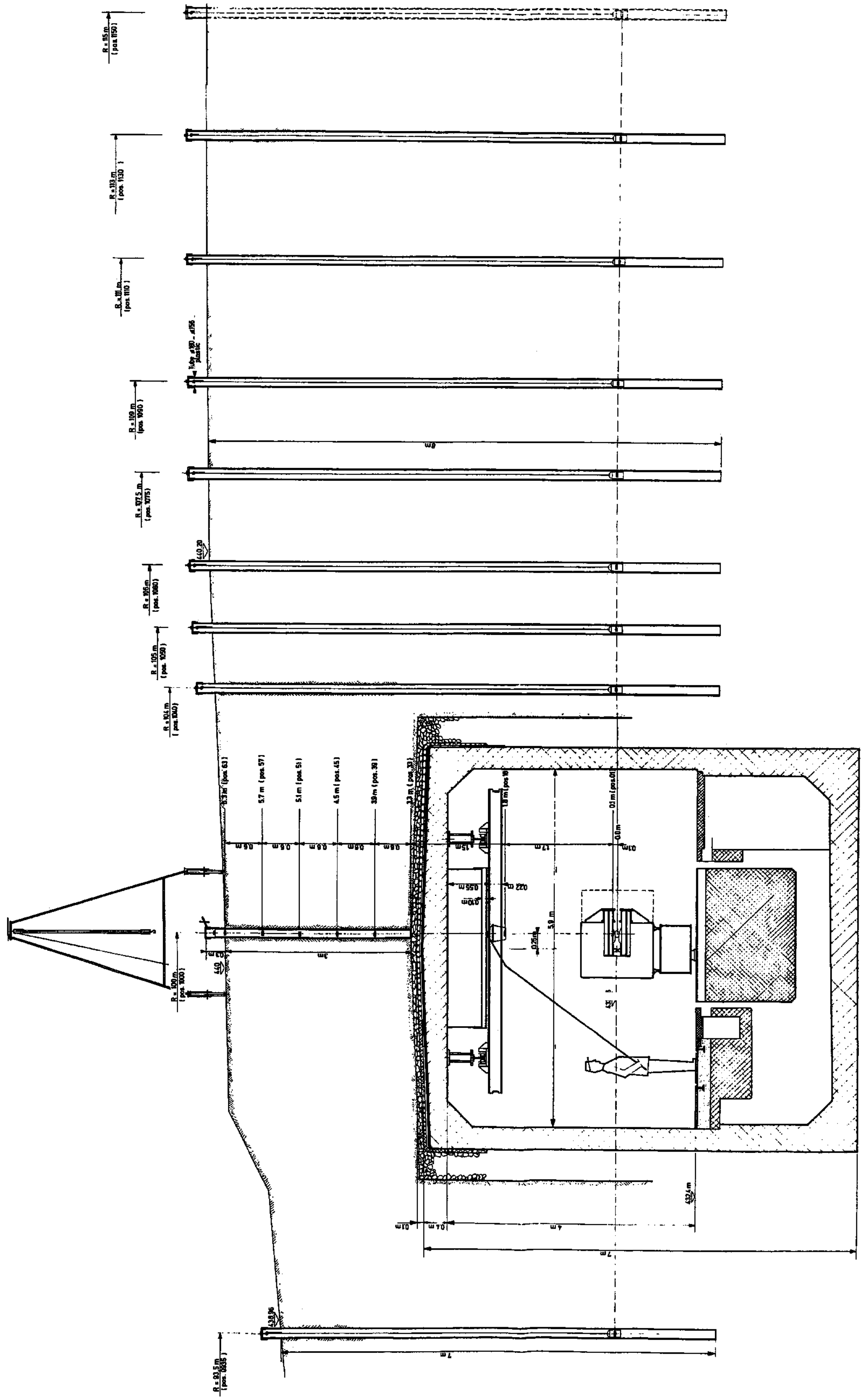

Fig. 6. Cross section view of the LRL/CERN/RHEL shielding experiment.

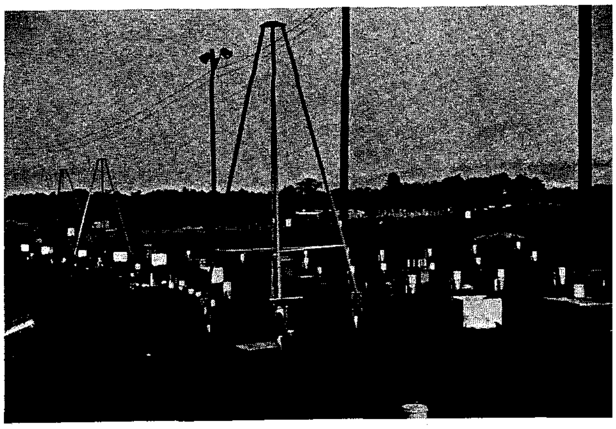

Fig. 7. Photo of the LRL/CERN/RHEL shielding experiment.

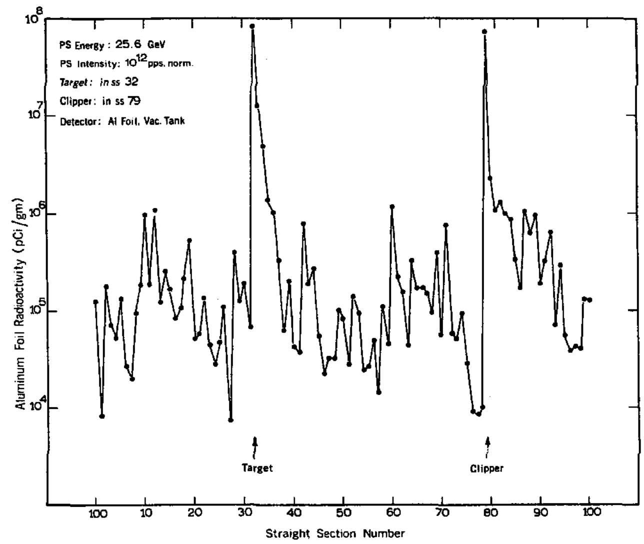

Fig. 8. Aluminum activation around the PS, on vacuum tank.

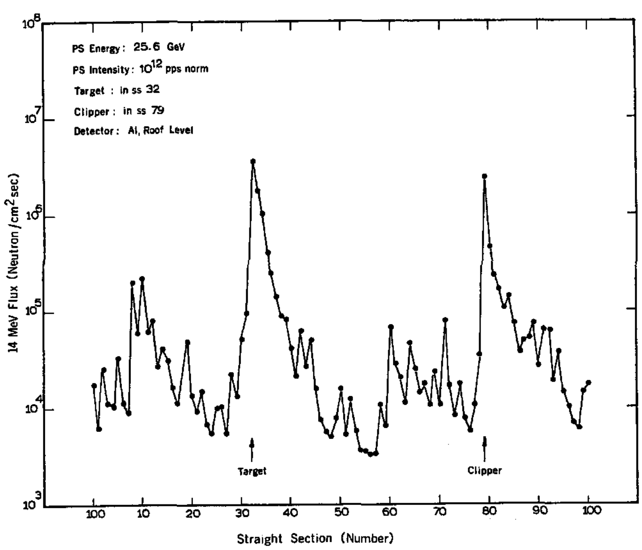

Fig. 9. Aluminum activation around the PS, inside tunnel at ceiling height.

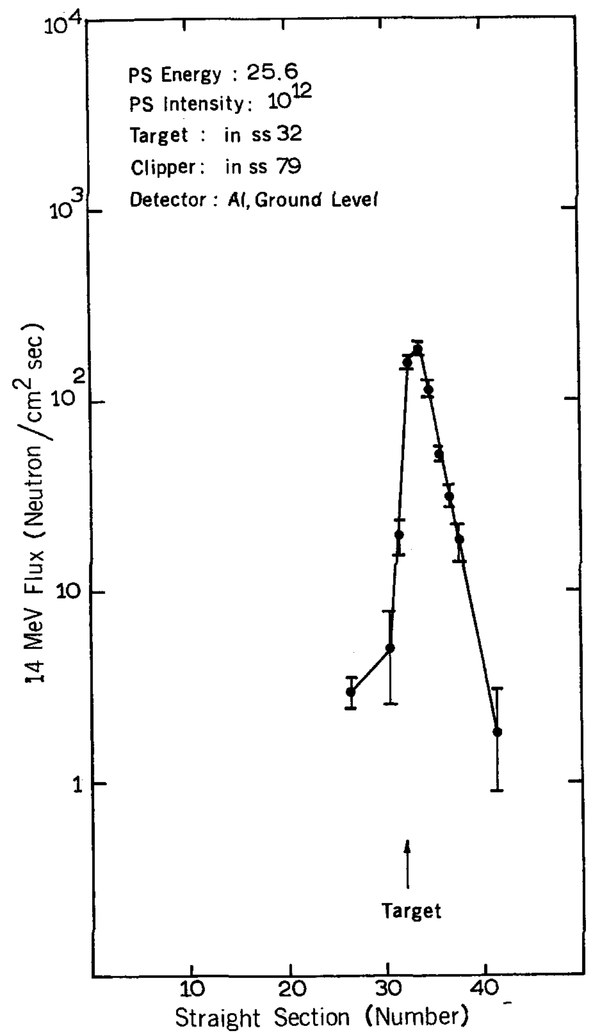

Fig. 10. Aluminum activation around the PS, on top of earth shielding at ground level.

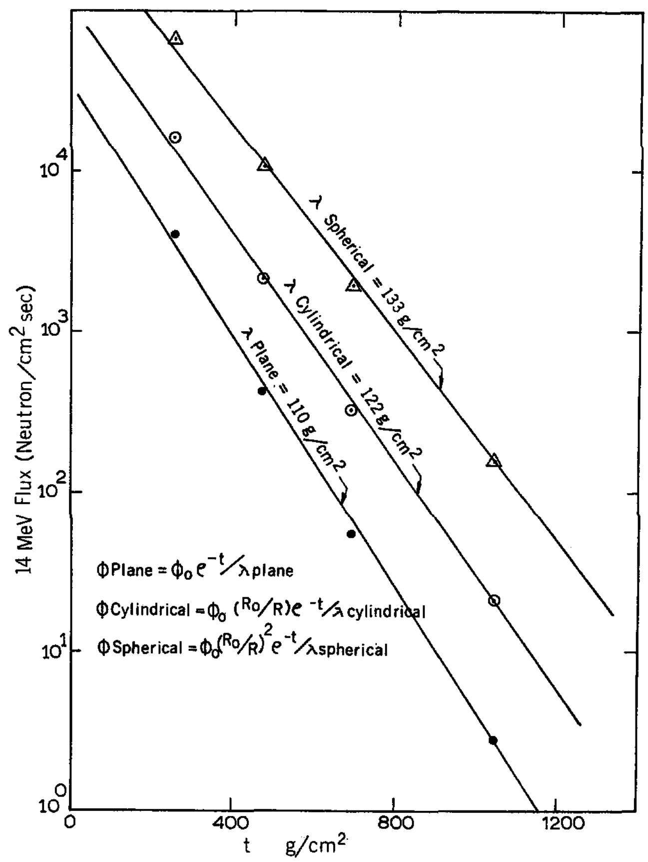

Fig. 11. Neutron flux attenuation through earth shield, measured radially outward from magnet No. 33.