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# "SKYSHINE -- A PAPER TIGER?"[*]

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> "The passion that left the ground to lose itself in the sky, "from Abt Vogler, by Robert Browning.

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# ABSTRACT

The study of the transport to large distances of radiation produced by high-energy accelerators is of fundamental interest and important in the calculation of the exposure of the population living in their environment. The most significant of the experimental data accumulated since the construction of the early particle accelerators and their theoretical interpretation are reviewed.

## 1. INTRODUCTION

An ancient Chinese proverb tells us that a man who takes a ride on a tiger is often too afraid to dismount. "Skyshine" has been, for many years, a tiger on whose back accelerator health physicists have been riding. We feel that it is time to dismount, look the tiger in the face, and see if he has any teeth.

Although the word "skyshine" is widely used in radiation physics, we have been unable to find a precise definition of the term. It was probably first used to describe air-scattered photons observed around "hot-cells" used for the manipulation of intense radioactive sources. Furthermore, the terminology in the literature is often confusing. For example, the word "skyshine" often describes all the radiation reaching points close to the accelerator, whether unscattered or scattered by the ground, air, or neighboring buildings, and often includes direct radiation, skyshine, and "groundshine." It is vital that these words be used more precisely if general understanding is to be improved.

The high radiation levels observed near particle accelerators built with little or no roof shielding in the 1950's were attributed to skyshine neutrons. For example, at the Brookhaven Cosmotron,[1] and at the 184-Inch Synchrocyclotron and Bevatron at Berkeley,[2] the radiation levels were sufficiently intense to interfere with accelerator operation. Initially no overhead shielding had been installed at these accelerators, both because the high-intensity operation common today was not foreseen and because the magnitude of skyshine observed was not anticipated. This interference with accelerator operation stimulated some theoretical and experimental studies of the production and propagation of radiation fields around high energy accelerators.

Lindenbaum[3,4] simulated a particle accelerator as an isotropic point source of neutrons of energy of about a few MeV. He modified an analytical solution of the neutron transport equation in a homogeneous medium[5] to take account of the presence of the earth, and derived a formula expressing the variation of scalar neutron flux density with distance from the source. His formula consists of two terms: One is called the "direct component" because it approximately expresses the flux density that would reach a point at distance from an isotropic source if neutrons were only absorbed or scattered out but not scattered in. This direct component only dominates the flux density at small distances from the accelerator. The second term, represents the "indirect" or scattered component, and it was given the name of "skyshine." It was shown to be the only part of the expression that was influenced by the presence or absence of a roof shielding over the source, and which dominates the flux density at large distances from the source.

Early measurements made within 300 m from particle accelerators were found to be in agreement with the Lindenbaum formulation within the experimental accuracy of the measurements (≈ factor of two). This experience in the early fifties[6,7] suggested that some overhead shielding is required for accelerators that produce neutron intensities greater than about $10^9$ n/sec[8] and so overhead shielding was adopted in the planning of new accelerators.

The skyshine problem was so serious at these first proton synchrotrons that great consideration was given to skyshine[9] during the preliminary design of shielding for the proposed strong-focusing synchrotron to be constructed at Geneva (1952). In the initial design it was proposed that a large earth mound be constructed to protect buildings adjacent to the synchrotron. This mound was, in fact, constructed and exists to this day, affectionately known as Mt. Citron—after its architect. Skyshine is thus one of the few, if not only, radiation phenomena to which a monument has been erected! With the provision of roof shielding or the construction of accelerators underground, radiation levels around high-energy accelerators became acceptably low.

The Lindenbaum equation proved sufficiently accurate for the estimation of radiation levels at distances up to a few hundred meters from accelerators and there was no compelling reason to investigate high-energy neutron transport phenomena with great accuracy. Nevertheless, several measurements were made and, as we shall see in the section on Experimental Data these tend to show that the neutron flux density decreases with distance faster than is predicted by the second term of equation (2)(Section 2). In comparing these early measurements with theoretical calculations, it is important to stress the difficulty of performing reliable measurements at large distances from accelerators where the intensity of the radiation field may be comparable to that of the natural background. Furthermore, the evaluation of the source strength appropriate to equation (2) is difficult.

Recently, however, because of increasing interest in the magnitude of population exposures due to nuclear facilities, interest has revived in estimating radiation levels at large distances from high-energy accelerators.

It has been shown by several authors[10,11] that the main component of the radiation measured outside the shielding of high-energy accelerators is neutrons of energy in the range between the thermal and the energy of the primary charged particle beam. Gamma rays and charged particles do not usually contribute more than 10 to 20% of the total dose, except at some electron accelerators. Muons may represent an important contribution at very-high-energy accelerators, but they are closely confined along the direction of the primary beam that they rarely present a problem. The dominant component to dose equivalent at large distances will be from neutrons in the 100 keV to 10 MeV energy range, but neutrons of higher energy are also important. Because of the great difficulty in making measurements beyond about 1000 m at existing high-energy accelerators, estimates of radiation levels at distances out to tens of kilometers (which may be necessary for population dose calculations) must depend upon theoretical extrapolations.

## 2. THEORETICAL STUDIES

No complete theoretical treatment of skyshine at high-energy accelerators presently exists. Any theoretical model, to be adequate, must treat the air transport of neutrons with energies of up to hundreds of MeV. In 1957, based on experience at the Cosmotron, Lindenbaum[3,4] reported one of the first theoretical studies of what he called skyshine phenomena at high-energy proton accelerators, and formulated an expression describing the propagation of low-energy neutrons (~ few MeV) through the atmosphere.

In essence, Lindenbaum used the expression for the neutron flux produced by a point source in an infinite isotropic scattering medium. This expression was derived by Case *et al.*,[5] using diffusion theory. Lindenbaum wrote the scalar neutron flux density, $\phi(r)$, in the form

$$\phi(r) = \frac{Qe^{-\Sigma_t r}}{4\pi r^2}\ \varepsilon(c,r) + \frac{Qk(c)\ e^{-k_0 r}}{4\pi\ D\ r}, \qquad (1)$$

with $Q$ = neutron source strength (neutrons $\sec^{-1}$),

$\Sigma_t$ = macroscopic total cross section,

$\Sigma_s$ = scattering cross section,

$D$ = diffusion coefficient,

$1/k_0$ = diffusion length,

$c$ = $\Sigma_s/\Sigma_t$, the ratio of the scattering to the total cross section,* and

$\varepsilon(c,r)$ and $k(c)$ are functions of c (ratio of scattering to total cross section).

The assumptions made in the Case formulation are:

a. It is a solution for the one-velocity case of neutron diffusion, i.e., the source emits monoenergetic neutrons, and the neutrons arriving at points distant from the source have the same energy as those emitted at the source (they do not lose any kinetic energy in elastic collisions).

b. The source is an isotropic point source.

c. Neutrons diffuse in an infinite uniform absorbing medium (taken to be air by Lindenbaum).

d. Scattering is isotropic in the center-of-the-mass system.

Given these assumptions, the general solution to the steady-state problem (i.e. a source intensity constant with time) has for the flux density the familiar form (1) given by Lindenbaum.

For neutrons of a few MeV transported in air, equation (1) reduces to:

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*This is the definition given by Lindenbaum.[3] However, in the original reference cited by Lindenbaum (Case *et al*.[5]), c is defined as the average number of secondaries emitted following an inelastic collision. Case *et al*. give values of c higher than 1. Of course, the ratio $\Sigma_s/\Sigma_t$ cannot be greater than 1.

$$\phi(r) = Q\left[\frac{7.9 \times 10^{-2}}{r^2} \exp(-r/1.4 \times 10^4) + \frac{1.4 \times 10^{-5}}{r} \exp(r/2.5 \times 10^4)\right], \qquad (2)$$

with $\phi$ in neutrons $cm^{-2}\ sec^{-1}$,

$r$ in cm,

$Q$ in neutrons $sec^{-1}$.

The presence of the ground requires some modification of equation (1). Lindenbaum suggested this could be adequately achieved by only changing the value of c. Such a change limits the use of the equation to the transport of neutrons of few MeV. Lindenbaum pointed out that if higher-energy neutrons were to be considered, changes in both mean free path and c would be necessary.

The first term of equation (1) is almost identical with the equation describing propagation of radiation from a point source with absorption but without scattering. With the values of the parameters proposed by Lindenbaum, the first term of equation (2) becomes negligible in comparison with the second for distances larger than about 3 mean free paths in air (some 300 m). The second term of equation (2) represents the component of the radiation field scattered to the point of measurement from <u>all</u> directions. In practice, the component arriving from the ground is much smaller than that arriving from the air, leading to its often being referred to in the literature as "skyshine."

Lindenbaum's equation was intended to describe those situations where the neutron-leakage spectrum into the air was composed of, or at least strongly dominated by, neutrons in a narrow band of energy in the MeV region. For those cases where the accelerator is well shielded with earth or concrete, the radiation field is controlled by high-energy neutrons

(E > 100 MeV), and Lindenbaum's equation cannot be expected to have great accuracy. However, even under such conditions it can often predict neutron dose-equivalent rates with accuracy sufficient for health physics purposes. When neutrons in the MeV region are dominant, as when, for example, there is either no roof shielding or the shield is constructed of materials containing little or no hydrogen (e.g. steel or lead), Lindenbaum's equation can predict neutron flux densities to within a factor of three at distances out to ~ 200 m. In particular, reasonable agreement (within a factor of 2) was found between measurements within a range of 30 and 150 m at the Cosmotron, and theoretical estimates using equation (2).[4] Other workers have developed treatments of skyshine similar to those of Lindenbaum.[12,13]

More recently, Lindenbaum's treatment of skyshine phenomena for low-energy neutrons has been verified by more sophisticated mathematical techniques. For example, Kinney [14] used a Monte Carlo analysis to determine the transport of neutrons of various source energies up to 20 MeV at an air-earth interface. Ladu et al.[15] have also carried out Monte Carlo calculations for an isotropic point source of 5-MeV neutrons at an air-earth interface. They also studied the influence of lateral shielding by performing the calculations for different values of the solid angle subtended upward by the source, $\omega = 2\pi(1 - \cos\theta)$. Values of $\theta$ chosen were $30^\circ$, $60^\circ$, and $90^\circ$. The first two cases correspond to accelerators without roof shielding but with thick lateral shielding, and the last case corresponds to no shielding. Ladu et al. summarize their results for these three cases by the empirical relations:

$$\phi(r) = Ar^{-\alpha} , \qquad 20\text{m} \leqslant r \leqslant 300 \text{ m}, \tag{3}$$

$$\phi(r) = B \exp\left({}^{-r}/\lambda\right), \qquad r > 300 \text{ m} . \tag{4}$$

Values of $\alpha$ and $\lambda$ were found to depend somewhat upon the value of $\theta$, but $\alpha$ was in the range of 1.5 to 1.6 and $\lambda$ in the range of 200 to 230 m. Figure 1 shows the variation with distance of total neutron flux density calculated by Ladu *et al*., compared with Lindenbaum's theory. Ladu *et al*. conclude that the transport of low-energy neutrons (~few MeV) produced at air-earth interfaces is quite well understood—a view supported by the good agreement both between various theoretical treatments of low-energy neutron and secondary $\gamma$-ray transport through air and between the calculations and experiment. An understanding of the transport of low-energy neutrons through the atmosphere has been necessary in the understanding of nuclear weapons' radiation effects and for the design of shielding in nuclear powered aircraft. These two programs have carried out rather comprehensive theoretical and experimental studies of air transport phenomena.[16]

As an example of the good agreement between theoretical calculations, Figure 2 shows the neutron dose as a function of distance from a fission neutron source calculated by discrete ordinates and Monte Carlo calculations.[17,18] There is a similar agreement for other energies up to 14 MeV. Figures 3 and 4 show good agreement between measured[19] and calculated[17] doses both for 14-MeV neutrons and secondary $\gamma$-rays.

Successful as the low-energy theoretical treatments have been, a complete theoretical treatment must include a discussion both of the diffusion of low-energy neutrons and the transport of the high-energy neutrons emerging from the accelerator. It was Lindenbaum who first pointed out that at distances of several hundred meters from accelerators with no roof shielding, and at all distances from accelerators with roof shielding, high-energy neutrons (E > 100 MeV) would control the external radiation field.

The presence of these high-energy neutrons was first demonstrated by Dakin[20] who measured neutron fluxes at distances between 105 and 500 m around the Bevatron by using a $BF_3$ counter shielded at the back and sides with concrete. Concrete was placed in front of the detector, and crude estimates were made of the fast-neutron energy spectrum. Dakin interpreted his results by assuming that the neutron spectrum consisted of two groups, the first having an average energy between 1.4 and 4 MeV and the second between 100 and 260 MeV. For both groups, the radial variation of neutron flux was similar, and, within the experimental accuracy, did not differ greatly from inverse square. By considering the transport of neutrons in the atmosphere, Moyer[21] was able to explain this rather surprising observation. At distances out to 500 m the radial dependence of low-energy diffusion neutrons and high-energy direct-flight neutrons is very similar (see Figure 5).

Somewhat later Tardy Joubert[22] showed that the neutron spectrum hardened with increasing distance from the 3-GeV proton synchrotron "Saturne," at Saclay. Figure 6 shows the mean neutron energy as a function of distance from the accelerator, which increases from 0.45 MeV to 1.2 MeV.

Stevenson[23] has reported fair success in describing the qualitative behavior of measurements made at CERN and Brookhaven with a computer code named ASPIC. In this program the inelastic interactions of high-energy neutrons with air nuclei were treated by a simple analytic and

Monte Carlo calculation. It was assumed that high-energy neutrons were emitted isotropically into the upper hemisphere where they interacted with a mean free path of 850 m producing a number of low-energy neutrons having a mean free path in air of 150 m. Further work is needed along these lines. The basic computational techniques for performing adequate numerical calculation of skyshine already exist.

There seems to be no fundamental reason why neutron transport codes of the type developed at Oak Ridge[24] should not be successfully applied to the problems of accelerator skyshine. Because accelerator skyshine radiation levels have not presented a serious problem in recent years, these calculations have not been made. However, the recent impetus given to environmental radiation studies makes such calculations most desirable.

## 3. EXPERIMENTAL DATA

The absence of any unifying theory has inhibited the development of experiments designed to provide an understanding of the mechanism of radiation attenuation at large distances from accelerators. Although measurements around several accelerators have been reported in the literature, many have been made as part of health physics radiation survey programs. Data accumulated in this way are often extremely difficult to interpret. Höfert _et al_. at CERN[25,26], and more recently, Jenkins at SLAC[10] have described these difficulties in some detail, which are clearly demonstrated in Figure 7 showing the data obtained from a radiation survey around the CERN 28-GeV Proton Synchrotron. The large experimental errors inherent in such measurements make, in our judgment, interpretation in terms of radiation-transport theories almost impossible.

In order to understand the radiation-transport phenomena involved, one needs carefully controlled experiments which, in the competitive atmosphere of front-line research accelerators, are difficult to mount. Skyshine alone has been sytematically studied[27] in possibly only one experiment at the 50-MeV proton linear accelerator of the Rutherford Laboratory. Neutrons were produced by stopping a 50-MeV proton beam in a thick aluminum target. Roof shielding was not provided but the target region was shielded with a 3-ft. (~1-m) thick, 12-ft(3.65-m) high concrete wall. Measurements were made of the neutron dose-equivalent rate as a function of distance from the shield wall. The wall was then increased to 5 feet (1.5-m) thick and 12 feet (3.65-m) high: and finally to 5 feet (1.5-m) thick and 19 feet (5.8-m) high. Figure 8 shows the neutron dose-equivalent rate as a function of distance from the shield. The upper curve shows that increasing the thickness of the shield from 3 ft. (0.9-m) to 5 ft. (1.5-m) had no significant effect on the radiation level, indicating that skyshine was the dominant source of neutrons. This was confirmed by measuring the dose-equivalent rate at a depth of 3 ft. (0.9-m) in the shield wall and outside the 5 ft. (1.5-m) shield wall. The dose rate at a depth of 3 ft. (0.9-m) was less than 1% of the rate outside the shield wall. Figure 8 demonstrates the shadowing effect of the concrete wall--the maximum radiation level moving outwards as the wall height increases. Under such conditions the observed neutron dose-equivalent is due to neutrons scattered from the atmosphere back to the ground and can be truly described as skyshine.

In some cases a direct view of the accelerator is possible. For example, at Berkeley where the Laboratory is situated in hilly terrain, many of the reported measurements were made looking down upon the Bevatron from the surrounding hillside.[28] The influence of site topography is not yet understood but it is probable that when hills intervene in the direct line of sight to the accelerator, the radiation levels measured would be substantially reduced. No systematic studies have been reported, but the shadowing effect of buildings and hills is often invoked to explain depressed radiation levels. McCaslin[29] has reported some data to support this view: In analyzing measurements obtained at three environmental monitoring stations of the Lawrence Berkeley Laboratory, all approximately at the same distance from the Bevatron, he observed that the dose equivalents recorded at two stations not in direct view of that accelerator were a factor of two lower than that recorded by the station in direct line-of-sight. Inside buildings with substantial walls, the neutron flux density will also be considerably reduced. For example, in cosmic-ray experiments Yamashita _et_ _al_.[30] noted a reduction by almost a factor of three in the counting rate of a paraffin-moderated $BF_3$ counter, when they moved the detector from the roof to inside the first floor of a four-story parking garage in Berkeley.

Table I summarizes a number of measurements of the variation of neutron flux density with distance, from a variety of types of particle accelerators, reported in the literature over the last twenty years. The techniques of measurement reported are varied, ranging from moderated $BF_3$ counters and Bonner spheres to Anderson rem meters. Comparison between neutron fluence and rem measurements can be obscure. The influence of site topography is not yet understood. Nevertheless, in almost all cases, attempts have been made to fit the experimental data to empirical or theoretical formulae. The functional form of the dose rate or flux density dependence with distance used in these fitting procedures ranged in sophistication from a simple exponential variation to evaluation of all the parameters of the Lindenbaum expression (1).

Cowan and Handloser[31] reported the first measurement of accelerator-produced radiation at large distances. Measurements were made with an ionization chamber of the radiation levels at distances between 75 and 300 m from the Cosmotron at Brookhaven. The absorbed dose rate in air at distance r from the accelerator, D(r) was expressed in the exponential form:

$$D(r) = D_O \, r^{-n} \tag{5}$$

with a value of $n = 2.3 \pm 0.2$.

Early measurements at the 184-Inch Suchrocyclotron, the 6-GeV Bevatron at Berkeley and the 50-MeV proton linac at the Rutherford Laboratory interpreted in this way gave values of n of 2.0 ± 0.2 and 1.97 ± 0.05 respectively.[32] Baarli[33] reported a value of $n = 2.46$ (no error quoted) to describe measurements taken around the CERN 28-GeV Proton Synchrotron (PS). Earlier measurements at the CERN 600-MeV synchrocyclotron (SC), made out to larger distances than those reported from the CERN PS, however, suggested a slower variation of dose-equivalent with distances.[34] The value of n measured at the CERN PS did not vary with accelerator operating conditions or with components of the radiation field measured (see Figure 9). This latter observation is consistent with the hypothesis than an equilibrium radiation spectrum emerges from the radiation shield. The CERN PS is well shielded underground and at the time these measurements were made, an internal target was used to produce secondary particle beams and was the dominant, highly localized (essentially a point) source of radiation. Under these conditions an emergent equilibrium spectrum is to be expected.

Ladu, Pelliccioni, and Rotondi[35] have reported measurements at the 1-GeV electron synchrotron at Frascati at distances between 50 and 300 m. The accelerator had no roof shielding when these measurements were made. Flux densities were measured in two mutually perpendicular directions and values of $n$ of 1.95 and 2.46 obtained, but no errors are quoted.

A simple exponential variation of dose-equivalent or fluence with distance was adequate to describe these early measurements because at distances up to several hundred meters from the neutron source the inverse square-law variation dominates the neutron transport (even in the Lindenbaum equation) and furthermore, these early measurements were of limited accuracy. The most recent measurement to be described in this manner is due to Katoh and Doke[36] who reported measurements at distances up to 200 m from a 50-MeV proton cyclotron with roof shielding removed. The dose equivalent rate was measured using a Bonner sphere system and an Anderson-type rem meter. Large values of $n$ of $2.7 \pm 0.1$ and $2.6 \pm 0.2$ for the variation of dose-equivalent rate with distance were determined, possibly indicating substantial absorption of low-energy neutrons in the atmosphere. All the measurements described in simple exponential form show a decrease of neutron flux density (dose equivalent) with distance that is at least as fast as the inverse square ($n \geqslant 2$).

An alternative interpretation, first suggested by Dakin[28] was to express the variation of neutron flux density with distance in the form:

$$\phi(r) = \frac{a}{4\pi r^2} e^{-r/\lambda} \qquad (6)$$

with the exponential term tentatively interpreted as representing neutron attenuation in the atmosphere. Measurements made at distances from 100 to 400 m from the Bevatron, using a moderated $BF_3$ counter, were more precise than earlier measurements made in the same location, and were well interpreted by equation (6).

Most of the earlier experiments have been also interpreted in terms of Lindenbaum's theoretical treatment of skyshine (2) which predicts the neutron fluxes observed around a large variety of particle accelerators, to within a factor of about three (which is usually sufficiently accurate for health physics purposes). For example, in the early work at the Rutherford Laboratory, the Lindenbaum theory was found to fit the shape of the neutron flux density distribution at distances between 30 m and 300 m from the effective neutron source.[37] Somewhat later Bathow et al.[38] reported measurements at the DESY 4-GeV electron synchrotron. A 4-GeV electron beam was directed onto an aluminum target whose thickness (130 cm) gave optimum neutron production. The shielding configuration around the target ensured that no direct radiation was measured. Measurements were made at distances from 55 to 545 m from the target. The average energy of neutrons produced in the target was 1 MeV, with 13% having energies greater than 25 MeV. Bathow et al. analyzed their experiments in terms of the skyshine of the Lindenbaum equation (i.e., the second term of equation (1)):

$$\phi\,(r) = Q\,\frac{Ke^{-k_0 r}}{4\pi\,Dr} \qquad (7)$$

In this experiment the neutron source strength, Q, was measured. The diffusion length ($1/k_0$) was determined from the experimental data as 140 m, where $k_0$ is given by:[5]

$$k_0 \approx \Sigma_t \left[(3 + 9c - 12c^2)/5\right]^{1/2} \quad , \qquad (8)$$

where $\Sigma_t$ is the macroscopic effective total section,

$c = \frac{\Sigma_s}{\Sigma_t}$ is the ratio of the macroscopic scattering cross section,

$\Sigma_s$, to the total cross section and $\Sigma_t$. Using an average neutron energy of 0.5 MeV, Bathow et al. calculated a value of $\Sigma_t$. of $1.3 \times 10^{-2}$ $m^{-1}$, and hence substituting for $k_0$ and $\Sigma_t$ into equation 7, they obtained $c \approx 0.88$.

The diffusion constant D is given by:[5]

$$D \approx (1/3\ \Sigma_t) \quad (9 - 4\ c/5) \quad . \qquad (9)$$

Substituting for c and $\Sigma_t$, a value of D = 28 m was obtained.

Bathow et al. concluded that it was possible to describe the skyshine due to neutrons with energy below 10 MeV quite simply, and to within a factor of two, by skyshine theory. They were encouraged by the apparent success with which the Lindenbaum theory could be used to analyze measurements made at several accelerators. Table II summarizes the parameters of equation (7) found to fit the experimental data measured at several different accelerators. The parameters found are quite similar, with the exception of those for the CERN SC. For this accelerator the mean neutron energy reported ( ≈ 10 MeV) was considerably higher than for the other accelerators ( ≈ 1 MeV), which may account for the value of 300 m obtained for the relaxation length (to be compared with 100 to 140 m for the other machines). The measurements made extended out to 1500 m from the radiation source, which itself was geometrically well defined. The 600-MeV protons were stopped in a water target, which had no overhead shielding, for this measurement. It must be emphasized, however, that similarity of the Lindenbaum parameters for most of the experimental data does not prove the validity of the Lindenbaum formalism. The accuracy of the prediction is only to within a factor of two, which can also be achieved by alternative formulae.

Relative measurements of dose-equivalent rate or flux-density are a poor test of any model, because the dominant factor in reducing radiation intensity is the inverse square law. Jenkins[10] has shown that relative measurements of the neutron dose rate around the Stanford 20-GeV electron linear accelerator cannot discriminate between alternative theoretical or empirical formalisms of skyshine (see Figure 10). This inability to discriminate is probably due to the presence of high-energy neutrons in the leakage spectrum. As Moyer[21] noted, the spatial dependence of low- and high-energy neutrons emerging from the accelerator (Figure 5) and its shield are similar for distances up to at least 500 m. Any test of the Lindenbaum formalism requires an absolute measurement of the source intensity in addition to the neutron flux density as a function of distance.

Only one of the reported experiments appeared to have all conditions satisfied for a realistic comparison with the Lindenbaum skyshine formalism in equation 7.[32,39,40] The 50-MeV proton linear accelerator at the Rutherford Laboratory was surrounded by a flat area completely free of buildings. A beam of 30-MeV protons was stopped in a thick aluminum target about 1.5 m above the ground, producing a point-source of low-energy neutrons. Direct radiation was eliminated by a thick shield wall. No neutrons greater than 30 MeV could be produced, and neutrons in the few MeV region dominated. Outside the shield wall measurements of mean neutron energy gave a value close to 0.75 MeV. Absolute measurements of the neutron flux at distances between 30 and 750 m were made with a calibrated long counter, whereas fluxes between 1 and 30 m were measured with sulfur capsules and moderated indium foils. It was also possible to make an accurate estimated of the neutron source strength, which permitted an absolute comparison with Lindenbaum's prediction. Measurements at distances up to 300 m indicated that Lindenbaum's expression predicts fluxes considerably higher than those observed (a factor of 3 at 300 m). The measurements by Simpson and Laws[40] at distances out to 750 m even further accentuate the divergence as may be seen in Figure 11 which compares various measured values of flux density with those calculated using Lindenbaum expression for values of $c = 0.5$ and $0.9$. The parameter $4\pi r^2 \phi(r)/Q$ is plotted as a function of distance. This method of presentation is useful in that it removes the dominant role of the inverse square law and draws attention to residual variations.

With this apparent failure of the Lindenbaum formalism and the absence of adequate alternative theoretical predictions, recourse has been made to empirical descriptions of experimental data. Thomas[41] has analyzed the experimental data obtained at Berkeley, Harwell, and Saclay and found an unexpected agreement that is probably fortuitous. The Berkeley[42] and Harwell[39,40] data have already been described. Tardy-Joubert and DeKerviler[43] have reported measurements made around "Saturne", the Saclay 3-GeV proton synchrotron. They do not give numerical data or errors, but show a smooth curve between 37 and 700 m from the machine. Figure 11 shows the experimental data obtained at these three laboratories. Only the Harwell data included a precise estimate of the source strength Q. For the Berkeley data, an arbitrary normalization was chosen so that $4\pi r^2 \phi(r)/Q = 1.0$ at $r = 280$ m. The source strength taken for the Saclay data was obtained by extrapolating the smooth experimental curve back to $r = 0$.

The main features of the curve are the buildup to a maximum of 1.6 at 110 m, return to 1.0 at 280 m, and exponential decrease thereafter with attenuation length of 267 m. The experimental results for all three laboratories are seen to be in fair agreement (discrepancies ≈ 6%). An empirical expression that fits the experimental data well (within 5%) at distances greater than 50 m is:

$$\phi(r) = \frac{a\,Q}{4\pi r^2}\left(1-e^{-r/\mu}\right) e^{-r/\lambda}, \quad r \geqslant 5 \times 10^3 \text{ cm}, \qquad (10)$$

with $a = 2.8$

$\mu = 5.6 \times 10^3$ cm, and

$\lambda = 2.67 \times 10^4$ cm.

Komochkov[44] has reported that measurements at the Dubna 10-GeV Synchrophasotron are better interpreted by equation 10 than by the Lindenbaum equation out to a distance of 440 m from the accelerator.

It is of interest to note that the value of attenuation mean free path in air for the neutrons obtained from measurements around these accelerators is in fair agreement with that found for fission neutrons. Stephens and Aceto,[45] using reactor facilities at the Nevada Test Site found $\lambda \approx 224$ m. Differences may be expected in the leakage neutron spectra from a reactor and from high-energy accelerators, but may be significant that, of the four accelerators whose radiation fields are described by equation 10, three were proton synchrotrons with no or very thin roof shielding, while the fourth was a 5-MeV linac.

The variation with distance from an accelerator of both the intensity of skyshine neutrons and the average neutron energy will initially depend upon the leakage spectrum of neutrons emerging from the accelerator into the atmosphere. This leakage spectrum is initially determined by the particles accelerated, their energy, and the quantity and type of roof shielding. DeStaebler[46,47], has shown that the radiation field outside well-shielded high-energy, high-intensity electron accelerators is very similar to that found around shielded high-energy proton accelerators. Under such conditions, the nuclear cascade has achieved an equilibrium to be controlled by neutrons with energy greater than 100 MeV.

It has been the experience at high-energy laboratories that neutrons contribute the greater part to radiation levels at large distances from both electron and proton accelerators. For example, Hack[27] reports the dose-equivalent composition of skyshine from a 50-MeV proton linac as:

| | |
|---|---|
| Fast neutrons (mean energy ~ 1/2 MeV) | ~ 90% |
| Gammas | ~ 10% |
| Slow neutrons | ~ 1%. |

At electron accelerators the experience is similar. Figure 12 shows the gamma and neutron dose levels recorded at one of the Stanford Linear Accelerator Center monitoring stations. The data shown include natural background, and periods of intense accelerator operation may be readily observed. Neutrons are seen to dominate the accelerator-produced radiation.

At well-shielded accelerators the leakage neutron spectrum will reach equilibrium in the accelerator shield. This equilibrium is controlled by neutrons of energy greater than about 100 MeV and the characteristics of their interaction in matter. At the interface between different media some change will occur in this equilibrium--most noticeably at energies below about 10 MeV. Equilibrium to a spectrum determined by the nuclear properties of the new medium will be reestablished in a depth corresponding to the high-energy inelastic mean free path (~95 g $cm^{-2}$ or 800 m in air). The nuclear properties of concrete and air are quite similar so consequently one would expect the radiation in air close to a concrete shield to be almost in equilibrium. The data reported by Baarli[33] Figure 9 from measurements at the CERN PS are consistent with this hypothesis. Photons, thermal neutrons, and fast neutrons all show the same radial dependence over the range 10 to 900 m from the accelerator. This suggests that the neutron-leakage spectrum from the CERN PS shield is in equilibrium and that this equilibrium does not greatly change in the air. However, in the case of an accelerator constructed with a large iron magnet, which has no overhead shield, the leakage spectrum of neutrons streaming upwards into the air from the iron magnet yokes will be relatively rich in neutrons in the few-hundred-keV energy region. Early measurements of skyshine made at the Cosmotron and Bevatron and later at "Saturne"[22] (Figure 6) show spectrum hardening. Distenfeld[48] has reported measurements of the leakage spectrum from a steel experimental back-stop used at the Brookhaven 30-GeV Alternating Gradient Synchrotron (AGS) using Bonner spheres. His measurements confirm the presence of low-energy neutrons which will be of great importance in determining the character of skyshine.

We might therefore expect to observe substantial differences in the form of the variation of skyshine with distance depending upon the particles accelerated, their energy, and the quantity of accelerator shielding. In particular, in the empirical expression of equation (10), the observed value of λ may vary widely. A reasonable lower limit would be that measured for fission neutrons of ≈ 225 m.[45] If the accelerator is capable of producing neutrons of energy greater than about 100 MeV, it is reasonable to assume that at large distances when an equilibrium spectrum has been established in air, λ will take on the value corresponding to high-energy neutrons. The high-energy attenuation length in air may be calculated as ~ 95 g $\text{cm}^{-2}$. In cosmic ray studies we have measured the attenuation of strongly interacting particles produced in extensive air showers and obtained values in the range of 100 to 120 g $\text{cm}^{-2}$. It is reasonable, therefore, to take an upper limit of λ as ≈ 100 g $\text{cm}^{-2}$ (850 m).

The transport of fission neutrons through the atmosphere was measured during Operation BREN (Bare Reactor Experiment Nevada).[49,50] In this experiment the ORNL Health Physics Research Reactor (HPRR) could be hoisted up to heights of several hundred meters above the ground. The HPRR is a small fast reactor that produces an essentially isotropic distribution of unmoderated fission neutrons. Figure 13 shows measured neutron doses as a function of distance from the reactor for three positions of the reactor above the ground,[50] with the neutron detector always at ground level. Figure 13 shows that at distances beyond 300 m from the reactor, the neutron dose has the form of equation (10), with λ ≈ 224 m (23 g $\text{cm}^{-2}$), in agreement with the measurement of Stephens and Aceto.[45]

As the radiation source is lowered toward the ground, the neutron dose decreases by about a factor of two.

Measurements of the transport of 14-MeV neutrons through air were made during Operation HENRE[19] (High-Energy Neutron Reaction Experiment). The 14-MeV neutrons were produced, using the D-T reaction, by an accelerator that could be raised above the ground to a maximum height of 366 m. Figure 4 shows measurements made with the accelerator 336 m and 8.2 m above the ground. In the first experiment the detector was at the same height above the ground, as the source, and the experimental conditions approximated an infinite air medium; in the second experiment the detector was on the ground. Measurements were made out to about 1000 m from the source. At distances beyond about 500 m, $\lambda$ has the approximate value of 25 g $cm^{-2}$ (close to that observed in the reactor experiment).

The HENRE measurements are particularly interesting in that some experimental investigations of the mechanisms of skyshine were made.[51] With a fixed source position above the ground the detector height was varied from 0.2m to 21 m from the ground. Measurements were made of the total neutron dose, and of the contributions to dose due to neutrons arriving from both the upper and lower hemispheres. Figure 14 summarizes the experimental data. It is readily seen that the absorbed dose produced by neutrons arriving from above is little influenced by the detector position. The number of neutrons reaching the detector from below are, however, strongly dependent upon detector height above the ground. French[52] was able to estimate the perturbation on an infinite air medium due to the presence of its interface with ground, using a model called the First-Last Collision Model. The model assumes that the interface effects are primarily due to the influence of the first collision on neutrons near the source and the influence of the last collision on neutrons near the detector. Figure 14 shows quite good agreement between this model and the experimental data.

It may be concluded that transport of neutrons of energy up to 14 MeV through the atmosphere and at an air/earth interface is theoretically well understood. The value of $\lambda \approx 267$ m suggested by Thomas[41] from measurements obtained at the PLA, Bevatron, and "Saturne" is consistent with the known leakage spectrum from these accelerators.

At well-shielded high-energy accelerators, higher values of $\lambda$ would be expected. Distenfeld and Colvett[53] have made measurements out to 900 m from the Brookhaven AGS and report a value of $\lambda \approx 600$ m (72 g cm$^{-2}$). Although the experimental inaccuracies in such measurements are high and the value of $\lambda$ not well constrained, the higher value is consistent with the hypothesis suggested. A recent analysis of the environmental monitoring data at the Lawrence Berkeley Laboratory tends to support a value of $\lambda \approx 850$ m for the attenuation in air of neutrons produced by the Bevatron and the 184-Inch Synchrocyclotron.[54]

There are conflicting data, however, not supporting this general hypothesis. Höfert <u>et</u> <u>al</u>.[25,26] have recently reported values of $\lambda$ in the range 244-290 m around the CERN PS, which do not agree with the value of $\lambda$ obtained at the CERN SC.[33,34] Since the CPS is a well-shielded accelerator--similar in construction to the Brookhaven AGS--one would have expected a value of $\lambda$ close to 850 m. These inconsistencies in the published data indicate the need for continuing study of the skyshine problem. Such studies are not merely of academic interest. For example, regulatory agencies often require estimates of population exposure resulting from the operation of nuclear facilities. Stephens et al.[55] have shown that estimates of population exposure resulting from the operation of a high-energy accelerator are proportional to $\lambda^{2/3}$. With values of $\lambda$ ranging from 244 to 850 m, the corresponding uncertainty in population dose is more than a factor of two.

To summarize the experimental data, we have selected some of the measurements from those previously discussed and plotted them in Figures 15a to 15f. The criteria for selection were:

a. The measurements were performed at distances up to at least 100 m.

b. Fast neutron flux density was measured, rather than dose equivalent.

These curves are all fitted by an expression of the type (10). Table III summarizes corresponding values of buildup factors, buildup distances, and attenuation parameters $\lambda$. While the buildup factors and buildup distances agree quite well with each other, the values of $\lambda$ vary between about 300 and 900 m. These differences in $\lambda$ might be explained by differences in the energy spectrum of the source. However, the lack of precise information of the source spectrum, wide differences in energy sensitivity of neutron detectors, and perturbation due to topography and buildings do not allow any firm conclusion to be drawn.

## 4. CONCLUSIONS

Despite the lack of precise experimental data and the absence of an adequate theoretical study, skyshine phenomena at high-energy accelerators are empirically understood. Provided that an estimate of the source strength can be obtained, radiation levels up to distances of several hundred meters may be estimated to within a factor of about three. This is usually adequate for radiation protection purposes.

Unfortunately, the early theoretical work of Lindenbaum[1] has not been followed up. Lindenbaum was aware that his treatment of the problem was limited to neutrons of a few MeV and suggested improvements suitable for higher energies. His work has not been extended, perhaps because skyshine has not been of great practical importance with the accelerators built after the Cosmotron and Bevatron.

The absence of any adequate theory of radiation transport around accelerators makes interpretation of experimental data difficult. This difficulty is enhanced by the inaccuracies inherent in the measurements. Although a great deal of experimental data has been reported, many data, however, were taken under conditions where topography or the presence of buildings perturbed the measurements. Despite such difficulties, the available experimental data are consistent with our present understanding of electromagnetic and hadron cascade phenomena as obtained from shielding experiments, and we conclude that:

1. The radiation intensity decreases at least as fast as does the inverse of the square of the distance from the source.

2. At large distances from accelerators, neutrons are the dominant component of the radiation field.

3. For well-shielded accelerators in the GeV region, the neutron spectrum emerging from the shield is in equilibrium. At lower energies or at accelerators with inadequate overhead shielding, hardening of the spectrum with distance is observed.

4. The empirical relation

$$\phi\ (r) \approx \frac{a\ Q\ e^{-r/\lambda}}{4\pi\ r^2}$$

is a simple but adequate expression for the skyshine intensity around most accelerators. Values of $\lambda$ reported in the literature vary between 267 m and 850 m. At large distances (several thousand meters--from our understanding of high-energy hadron cascades), we would expect $\lambda$ to approach the value of $\sim$ 100 g cm$^{-2}$.

There are two reasons for improving our understanding of skyshine phenomena. The first is academic in that it is of interest in itself. The second reason is, however, more pressing and is of practical importance. There is increasing interest at the present time in estimating the population exposure resulting from nuclear installations. If such estimates are to be made, and used by administrators, they should be as accurate as possible. In an atmosphere of increasing public concern at even extremely small radiation exposures it may prove to be unwise to grossly overestimate population dose. It may therefore be necessary to obtain more precise data on skyshine. Such an experimental program should take account of the following facts:

1. Precise measurement of skyshine must include a reliable estimate of the neutron source strength.

2. Measurements must extend well beyond the existing range of

distances—preferably out to 2500 m. Intense source strengths will be necessary to achieve this and the accelerator used for these measurements should preferably be in a remote location.

3. Crude measurements of the relative composition of the radiation field—particularly of neutron spectra—should be made.

4. Experimental conditions should be as simple as possible. The region around the accelerator should preferably be as flat as possible with no hills or large buildings to perturb measurements. The influence of detector height above the ground should be studied.

When unexpectedly high radiation levels were observed around the early synchrocyclotrons and proton synchrotrons, it seemed that a "tiger" had been loosed on the world. Early theoretical studies identified the tiger as skyshine, but the experimental data obtained in the fifties were not sufficiently accurate to confirm this suggestion. The addition of roof shielding to accelerators was sufficient to substantially reduce radiation levels and seemed to make the tiger disappear into the jungle. It was not clear whether the tiger had teeth or whether he was a paper tiger. However, the "beaters" of the USAEC and EPA have been at work, and the tiger has reemerged. Let us hope he may soon be safely placed in his cage!

## ACKNOWLEDGMENTS

We would like to thank Mr. T. M. Jenkins of the Stanford Linear Accelerator Center and Dr. Graham Stevenson of CERN Lab II for helpful advice in the preparation of this paper.

Table I Summary of skyshine measurements.

| Accelerator | Particle Accelerated | Energy | | Date* | Comments | References |
|---|---|---|---|---|---|---|
| Cosmotron | Protons | 3 | GeV | 1953 | Measurements with ionization chamber - 75m-300m | 31 |
| 184-Synchrocyclotron | Protons | | | | Movements with moderated $8F_3$ counter to 500m. Presence of energetic neutrons demonstrated. | 42 |
| Bevatron | Protons | 6.2 | GeV | 1962 | | 42 |
| PLA(RHEL) | Protons | 50 | MeV | 1962 | True skyshine measured - absolute source measurement | 32,37,39,40 |
| Saturne | Protons | 3 | GeV | 1963 | | 22 |
| CERN SC | Protons | 600 | MeV | 1963 | | 34 |
| CERN PS | Protons | 28 | GeV | 1964 | | 25, 26,33 |
| Frascati | Electrons | 1 | GeV | 1965 | | 15 |
| AGS(Brookhaven) | Protons | 33 | GeV | 1966 | | 53 |
| DESY | Electrons | 6 | GeV | 1967 | | 38 |
| JAPAN | Protons | 50 | MeV | 1969 | Distances up to 200 meters | 36 |
| SYNCHRO PHASATRON (DUBNA) | Protons | 10 | GeV | | | 44 |
| SLAC | Electrons | 20 | GeV | 1973 | | 10 |

* Date of first publication given if several exist

Table II

Summary of Lindenbaum's equation parameters obtained from skyshine measurements at several accelerators.*

| Laboratory | Primary beam energy | Range of measurements (meters) | $1/k_0$ (meters) | $\Sigma_t$ ($m^{-1} \times 10^{-2}$) | $\bar{C}$ | D (meters) | Mean neutron energy (MeV) | Reference |
|---|---|---|---|---|---|---|---|---|
| CERN SC | 600-MeV protons | 80-1500 | 300 | 0.68 | 0.91 | 53 | 10 | 34 |
| Frascati | 1.1-GeV electrons | 50-200 | 100 | 1.7 | 0.86 | 22 | 0.25-0.4 | 35 |
| DESY | 4-GeV electrons | 50-550 | 140 | 1.3 | 0.88 | 28 | 0.5 | 38 |
| Harwell | 30-MeV protons | 30-300 | 140 | 1.2 | 0.86 | 31 | 0.71 | 32 |
| Dubna | 10-GeV protons | 100-500 | 140 | 1.0 | 0.81 | 37 | 0.7-3.0 | 44 |
| Saclay | 3-GeV protons | 50-600 | 135 | 1.0 | 0.77 | 39 | 0.9-4.0 | 43 |

*from Bathow _et al_.[38]

## Table III

Summary of some experimental measurements.

| Laboratory | Primary Beam | Type of Measurement | Buildup factor | Buildup distance (in meters) | λ for expression (10) (in meters) | Reference |
|---|---|---|---|---|---|---|
| CERN-PS | 29-GeV proton | Neutron fluence with a long counter | ~ 3 | 150 | 395 | 56 |
| Dubna | 10-GeV proton | Neutron fluence with a long counter | | <100 | 230 | 44 |
| BNL | 30-GeV proton | Neutron fluence with Bonner sphere | 2.8 | 125 | 610 | 53 |
| CERN-SC | 600-MeV proton | Neutron fluence with a long counter | 2.7 | 140 | 990 | 34 |
| DESY | 4-GeV electron | Neutron fluence with a $BF_3$ counter and scintillators | 6 or 7 | 150 | 330 or 270 | 38 |
| RHEL | 30-MeV proton | Neutron fluence with a long counter | 2.5 | 110 | 303 | 39,40 |

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## FIGURE CAPTIONS

Figure 1 Calculated neutron fluence as a function of the distance from an isotropic source ($\theta = 90^\circ$). The histograms represent the Monte Carlo calculations performed by the authors for the total fluence and the fluence of neutrons of energy >2.5 eV. A smooth curve has been plotted over the histograms. Calculations using the Lindenbaum expression are also shown. (From Ladu *et al.*[15])

Figure 2 Comparison of the neutron dose in an infinite air medium as a function of the distance from a point isotropic fission neutron source as calculated by discrete ordinates method (from Straker[17]), and by Monte Carlo method. (From Webster[18]).

Figure 3 Comparison of the measured and calculated neutron dose in an infinite air medium and in an air-over-ground geometry as a function of distance from a 14-MeV neutron generator. The neutron generator and the detector were raised to approximately 366 m to simulate an infinite air medium. (Operation HENRE Refs. [17,19])

Figure 4 Comparison of the measured and calculated secondary gamma-ray dose in an infinite air medium and in an air-over-ground geometry resulting from a 14-MeV neutron generator as a function of distance from the source. (Operation HENRE from Refs.[17,19])

Figure 5 Comparison of radial dependence of the flux densities of low-energy diffused neutrons (dashed line, calculated using the expression $\frac{10}{r}$ exp $-\frac{r-10}{250}$ ), and direct high-energy neutrons (solid line, calculated using expression $\frac{1}{r^2}$ exp $-\frac{r}{740}$ ) (After Ref. [21]).

Figure 6 Average neutron energy as a function of distance from the accelerator as measured at the 3-GeV Proton Synchrotron Saturne at Saclay (From Ref.[22])

Figure 7 Measurements of dose rate as a function of distance from the CERN 28-GeV proton synchrotron. The ordinate gives dose rate in rem per hour (normalized to an extracted proton beam intensity of $10^{12}$ protons per second) multiplied by the square of the distance (measured in meters) from the accelerator. The dashed line drawn through the data points has a relaxation length of 285 m at distances beyond 300 m. (After Höfert _et_ _al_.[25])

Figure 8 The variation of neutron dose rates as a function of distance from the 50-MeV proton linear accelerator of the Rutherford Laboratory. The inset shows the experimental arrangement. The upper (solid) curve is drawn through data points obtained with the original concrete shielding wall 12 ft high (3.65 m) and 3 ft (0.9m) thick ( ⊙ ) and with an additional shielding added to give a total thickness of 5 ft (1.5m) (⊡) but with the same height. The dashed line is drawn through points measured with a concrete wall 19 ft (5.8 m) high and 5 ft (1.5m) thick (◬). (After Hack[27])

Figure 9 Variation of dose equivalent as a function of distance from the CERN 28 GeV proton synchrotron. (After Baarli[33])

Figure 10 Measurements of relative dose rate as a function of distance around the Stanford 20-GeV electron linear accelerator. The circles and triangles are experimental data. The solid line shows a plotting of the Lindenbaum skyshine expression, and the dashed line shows a plotting of the expression

$$D = K \exp(-r/\lambda)/r^2$$

where $\lambda = 3280$ ft (1 km) (After Jenkins[10])

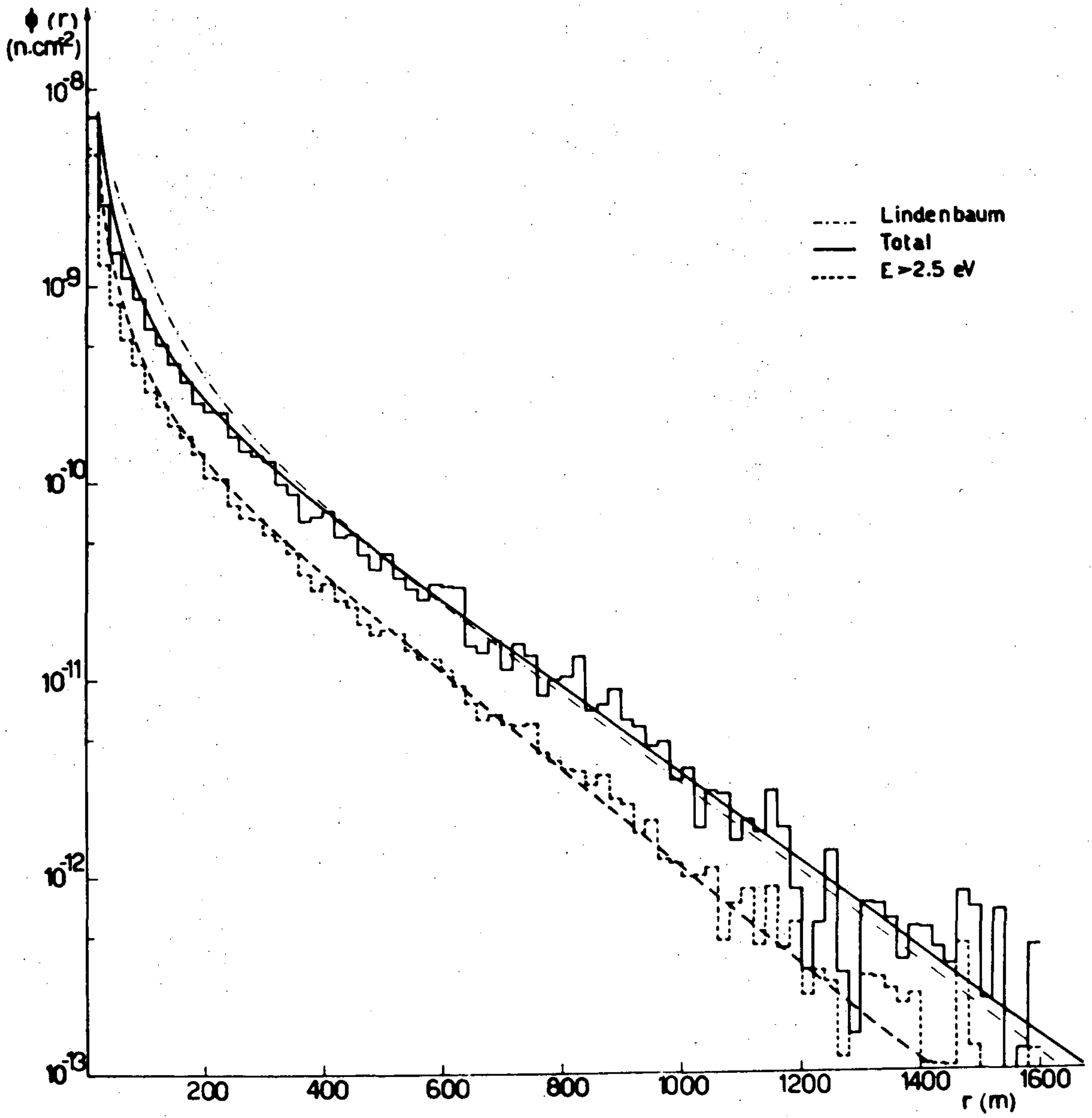
Figure 11 The neutron flux densities as a function of the distance from the source measured at three different accelerators[39,42,43] are plotted together with the Lindenbaum expression for values of $c = 0.9$ and $0.5$.

Figure 12 Quarterly dose plot recorded at a monitoring station located at the Stanford Linear Accelerator Center. (After Jenkins[10])

Figure 13 Neutron dose times slant range (distance) squared ($D \times R^2$) per unit power of the reactor as a function of slant range for a detector height ($H_D$) of 0 m and various reactor heights ($H_R$). (From[49])

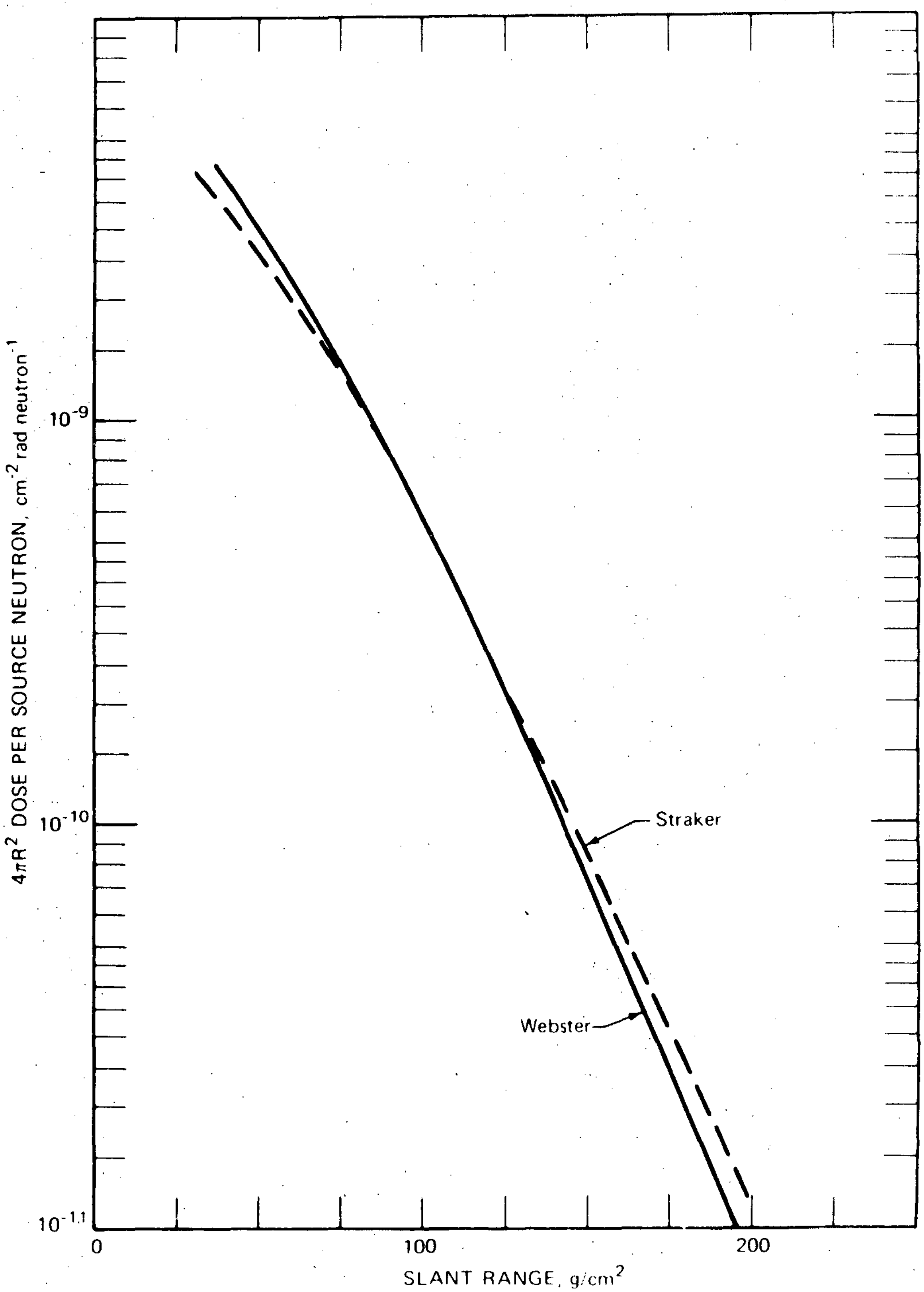
Figure 14 Comparison of measured and calculated scattered fast-neutron dose near air-ground interface 305 m from a 14-MeV neutron source. The insert at the bottom shows the relative position of the detectors and the source. (From [50])

Figure 15 Measurements performed around different accelerators. On the abscissa is the distance from the accelerator in meters, on the ordinate is the product of the measured neutron flux density by the square of the distance. In these coordinates a $1/r^2$ variation shows up as a horizontal line. a) Measurements of fast neutron flux density performed with a long counter from a "source point" (the PS bridge) at the CERN 28-GeV Proton Synchrotron[56]
b) Measurements of fast neutron flux density performed with a moderated $BF_3$ counter at the Dubna 10-GeV Proton Synchrophasotron.[44]
c) Measurements of dose-equivalent rate performed with a 12-in. (30 cm) Bonner sphere system at the Brookhaven 30-GeV Proton AGS.[53]
d) Measurements of fast neutron flux density performed with a long counter at the CERN 600-MeV Proton Synchrocyclotron.[34]
e) Fast neutron flux density measurements performed with a $BF_3$ moderated counter at the 7.5-GeV electron synchrotron, DESY.[38]
f) Fast neutron flux density measurements performed with a long counter at the Rutherford Laboratory 50-MeV proton linear accelerator. The solid dots indicate the measurements taken for a p beam of 30 MeV,[39] and the open dots for a p beam of 50 MeV.[40]



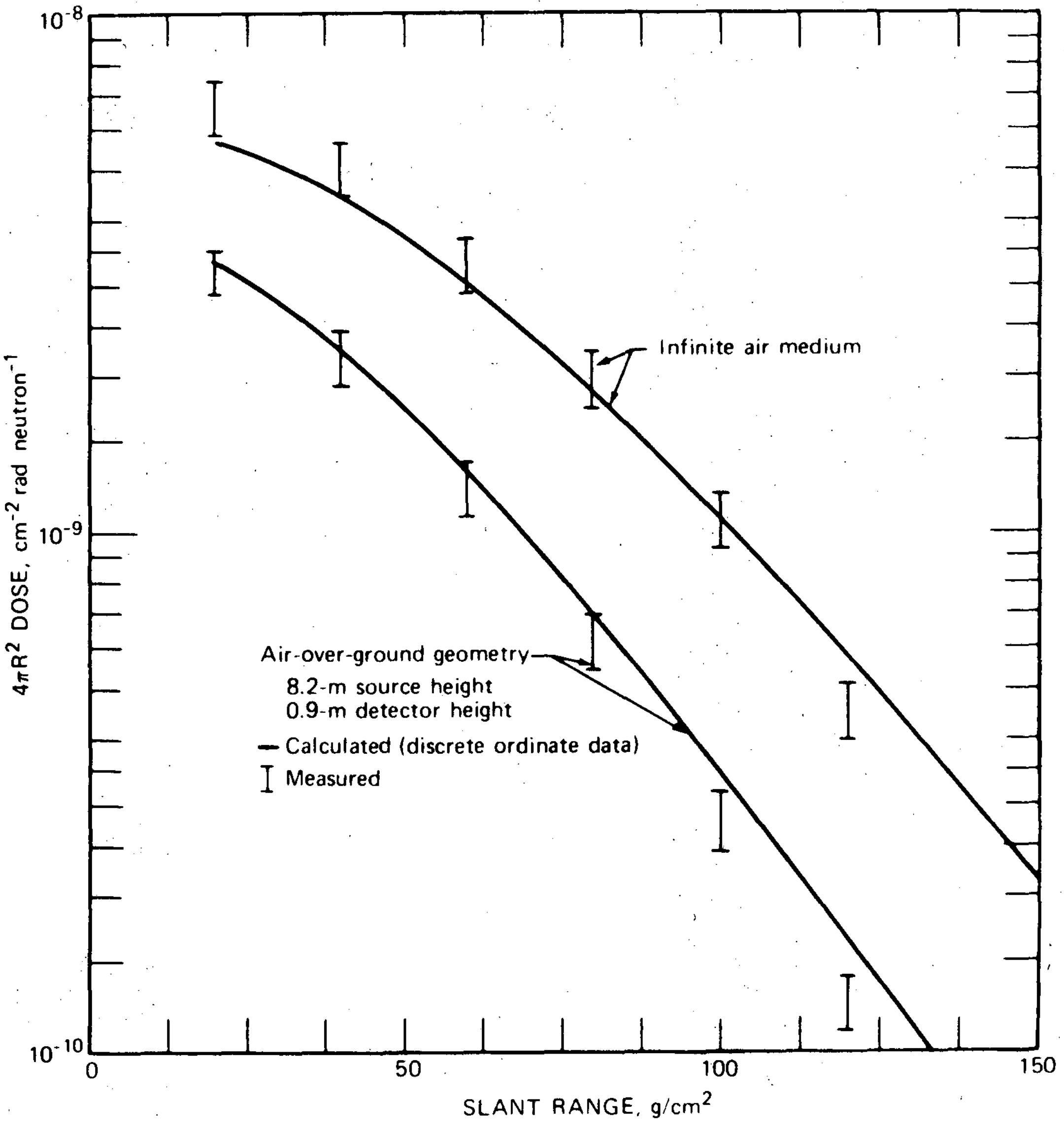
XBL 751-4

Fig. 1



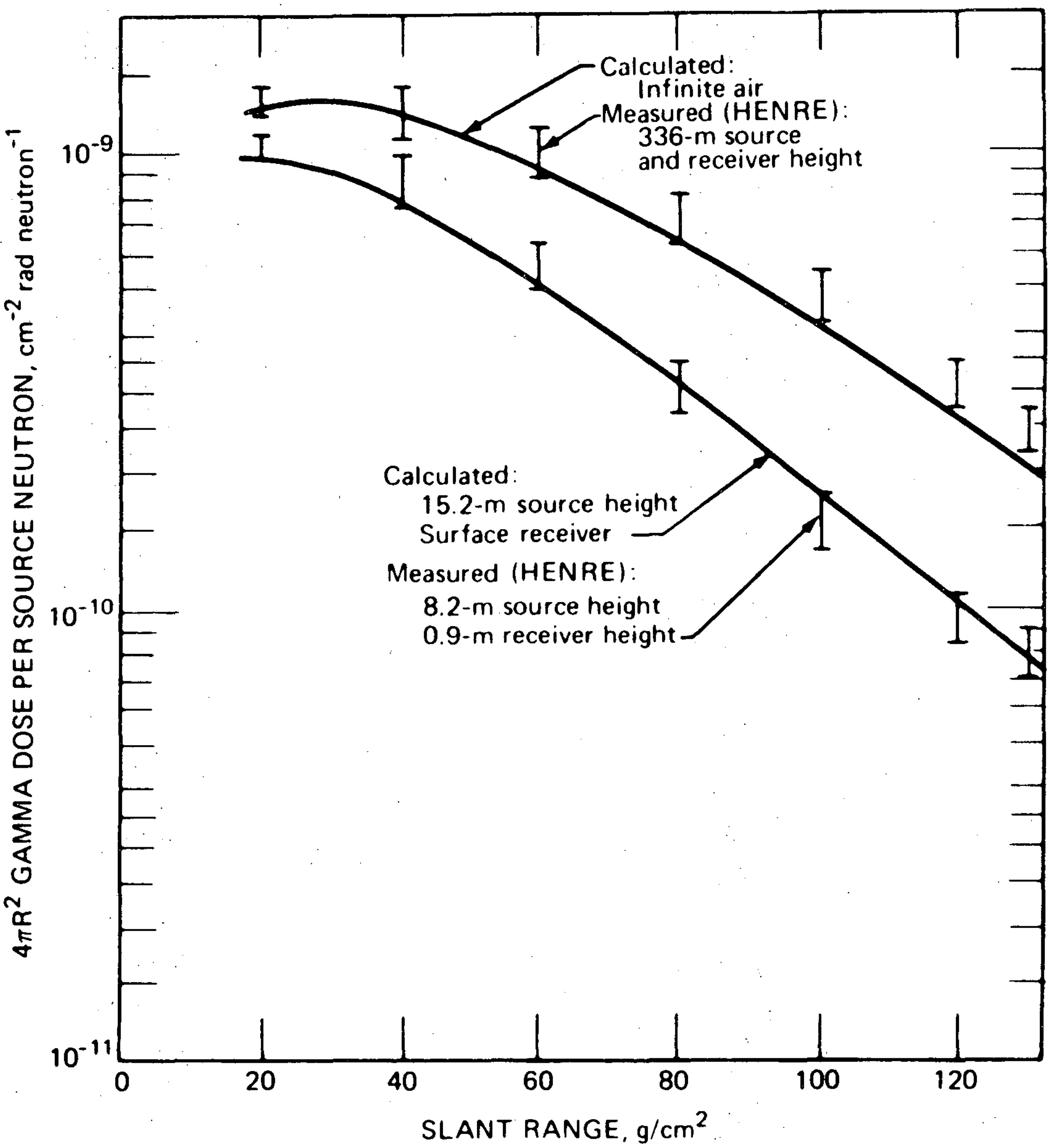
XBL 7412-7816

Fig. 2



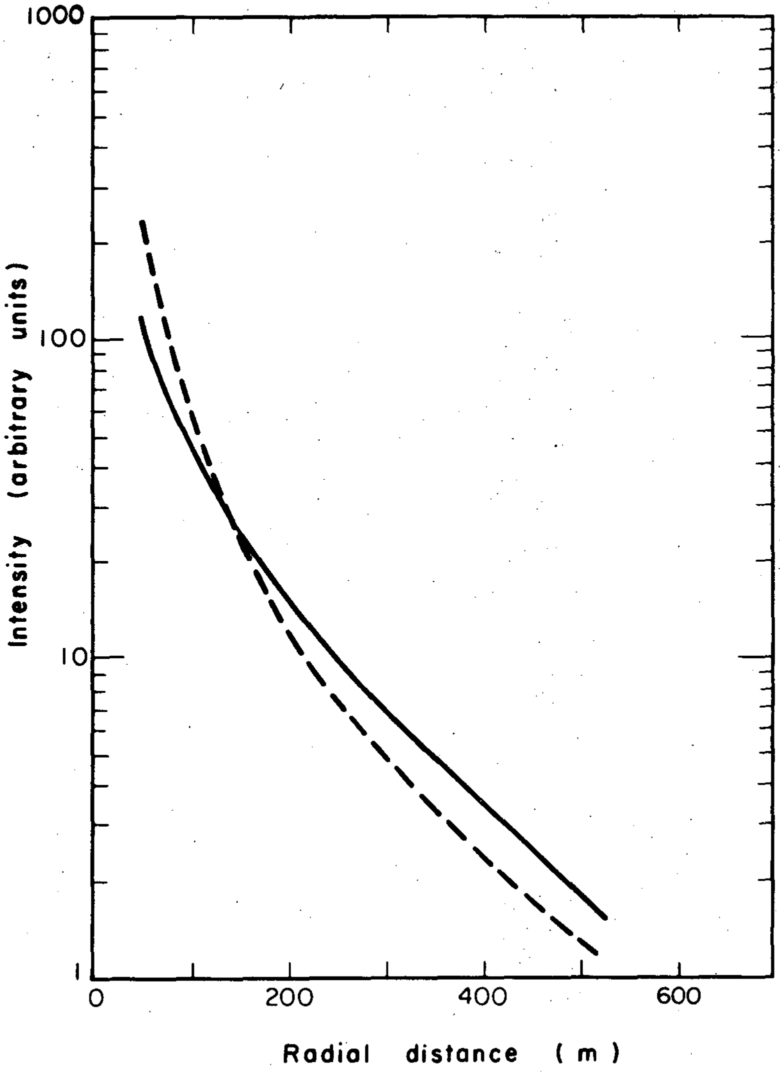
XBL 7412-7815

Fig. 3



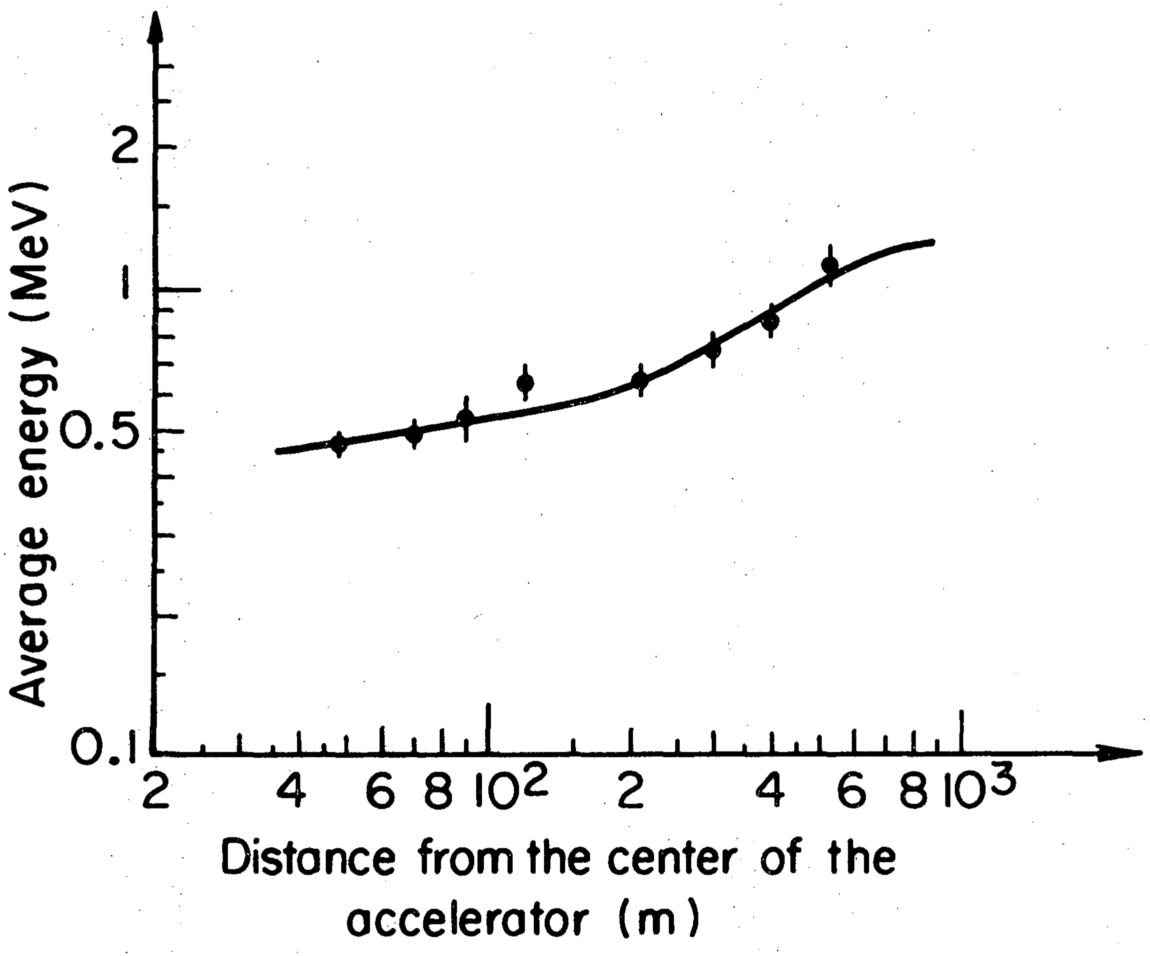
XBL 7412-7818

Fig. 4



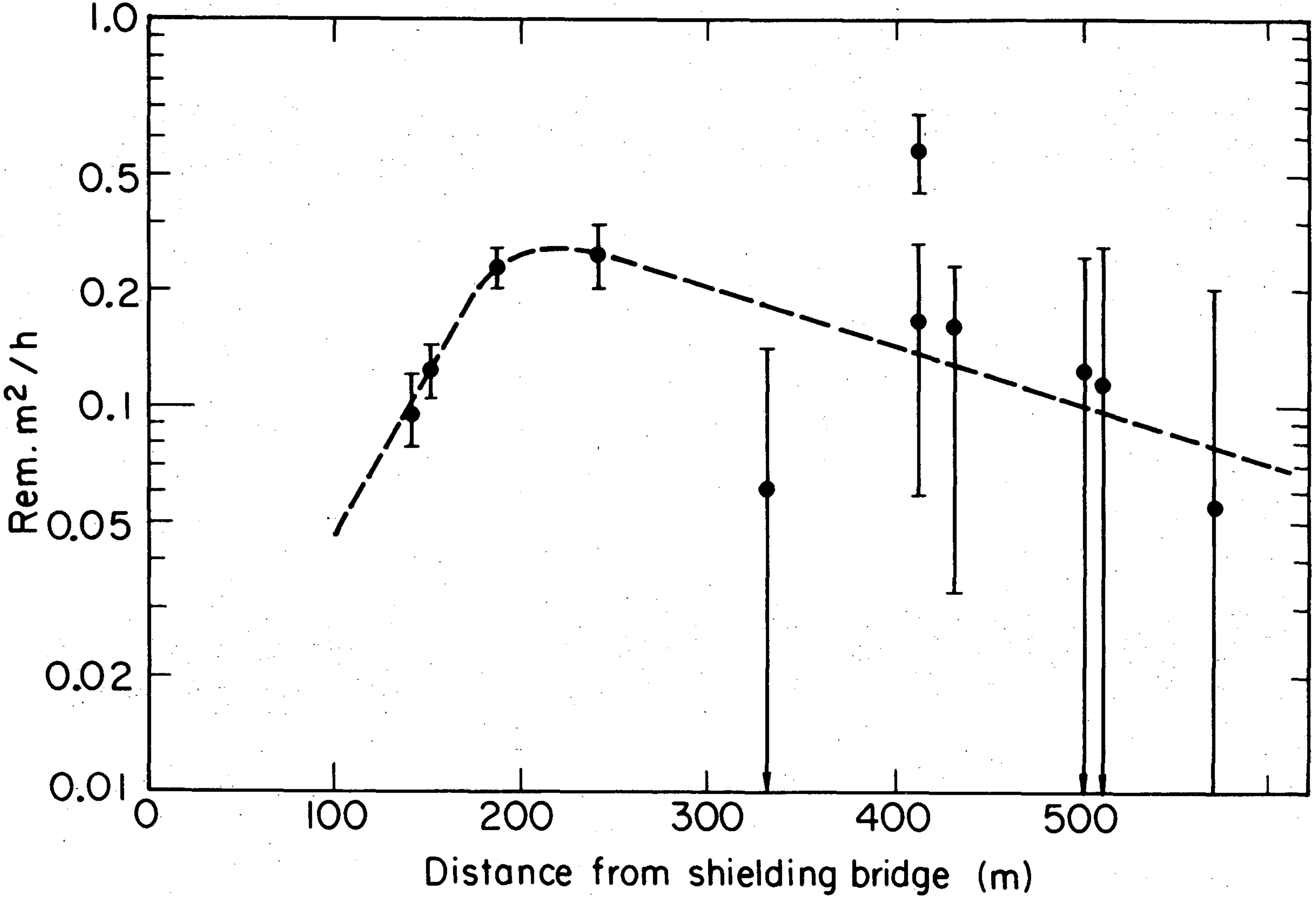
MU-25474

Fig. 5



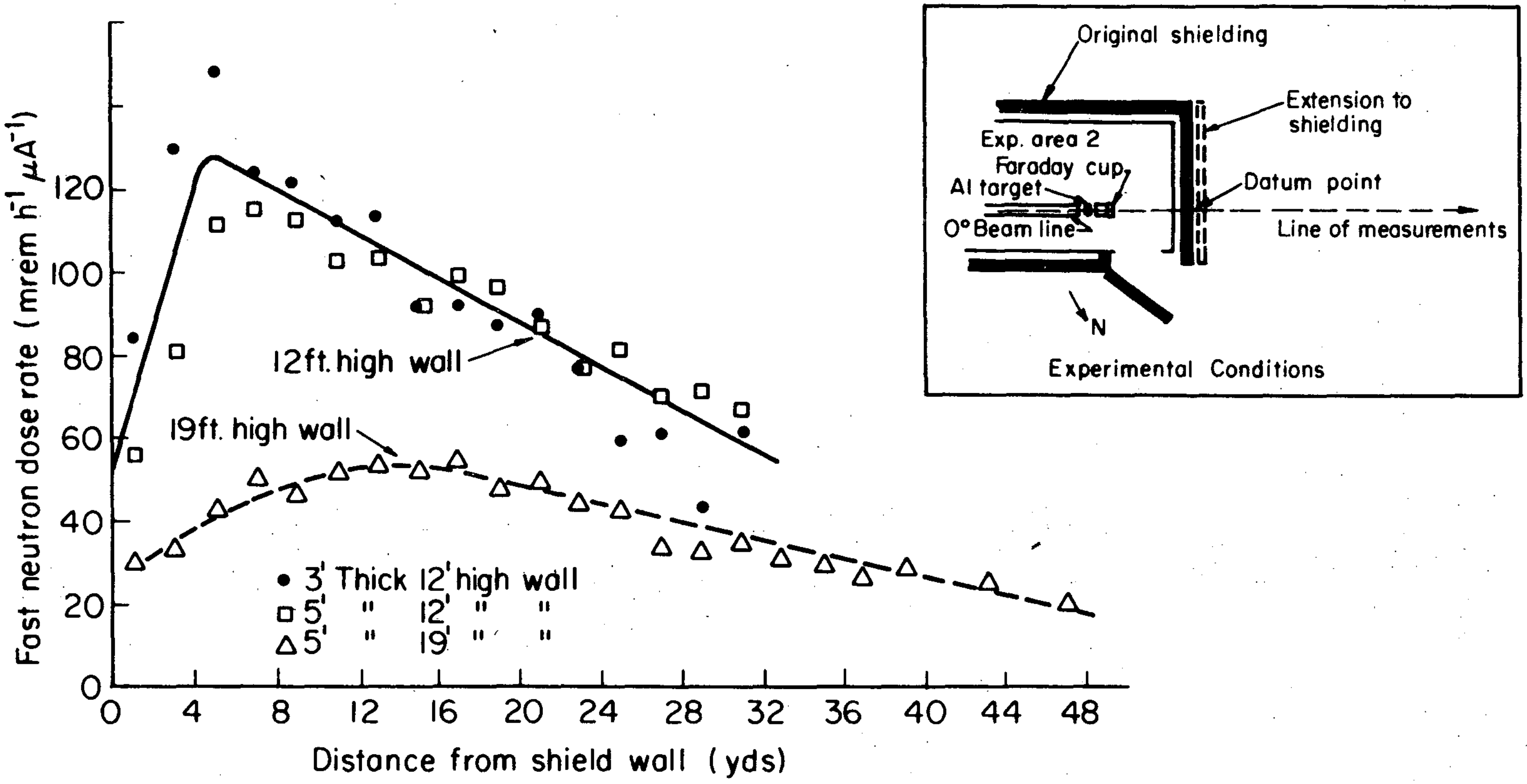
XBL752-2370

Fig. 6



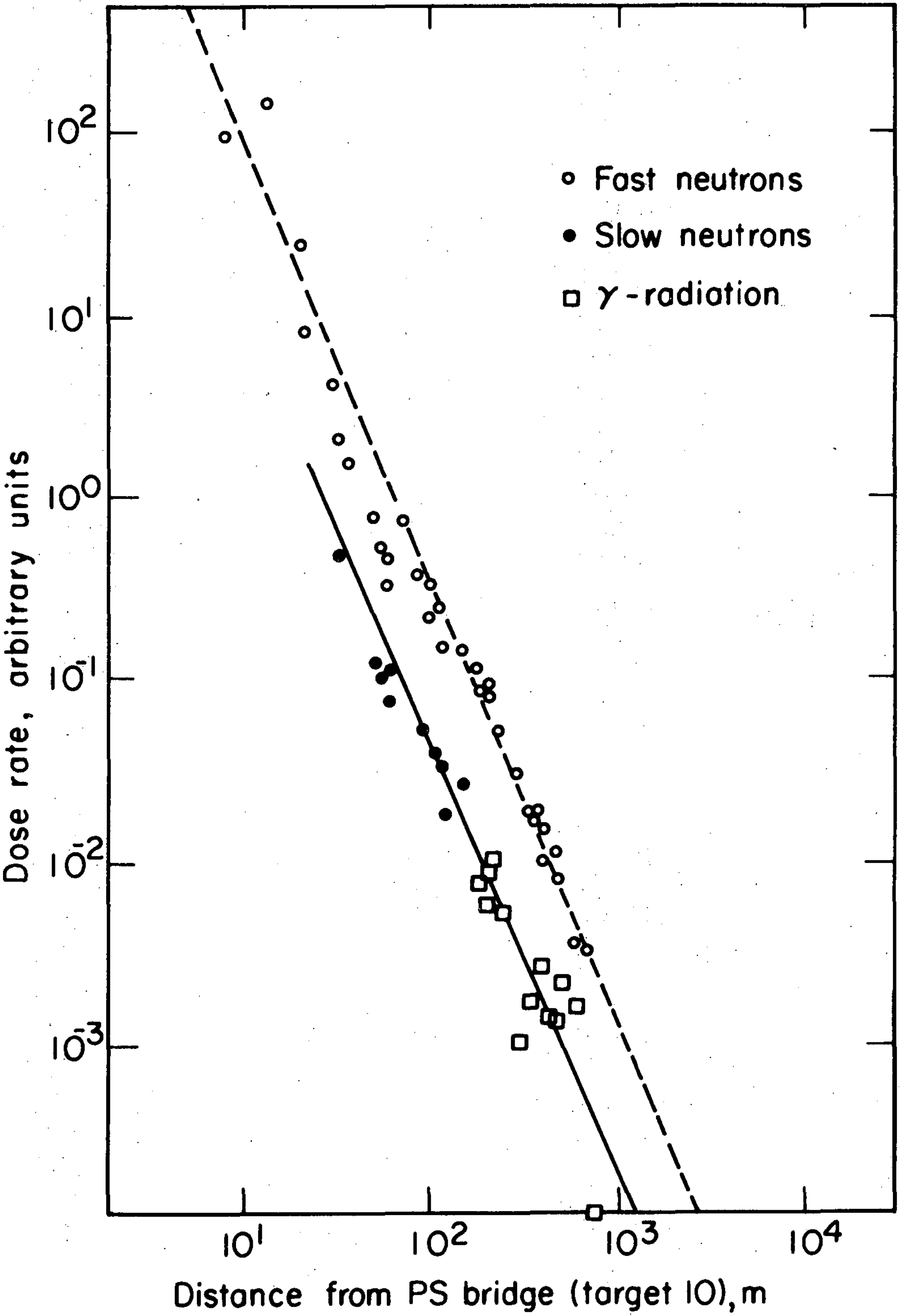
XBL752-2369

Fig. 7



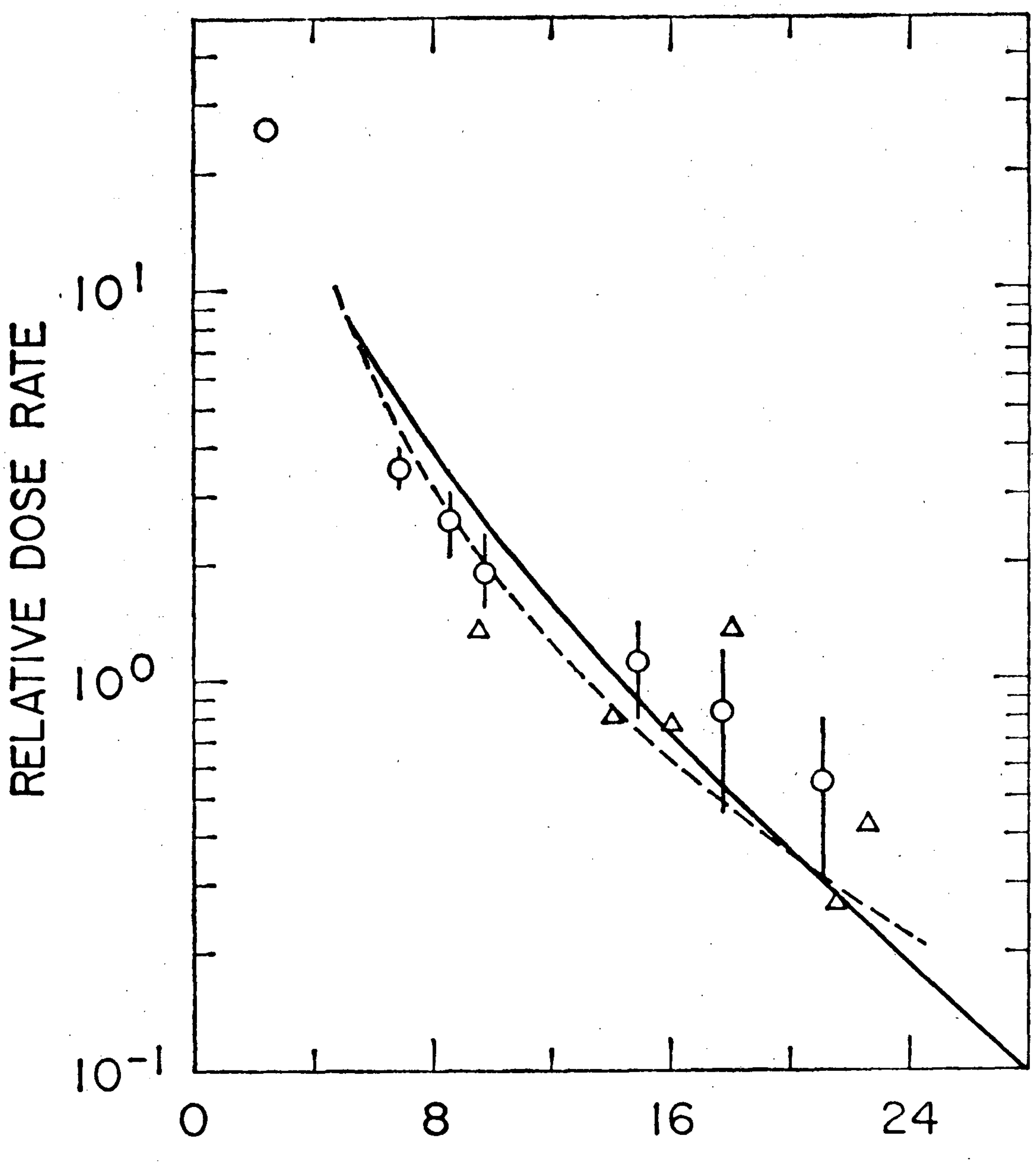
XBL752-2371

Fig. 8



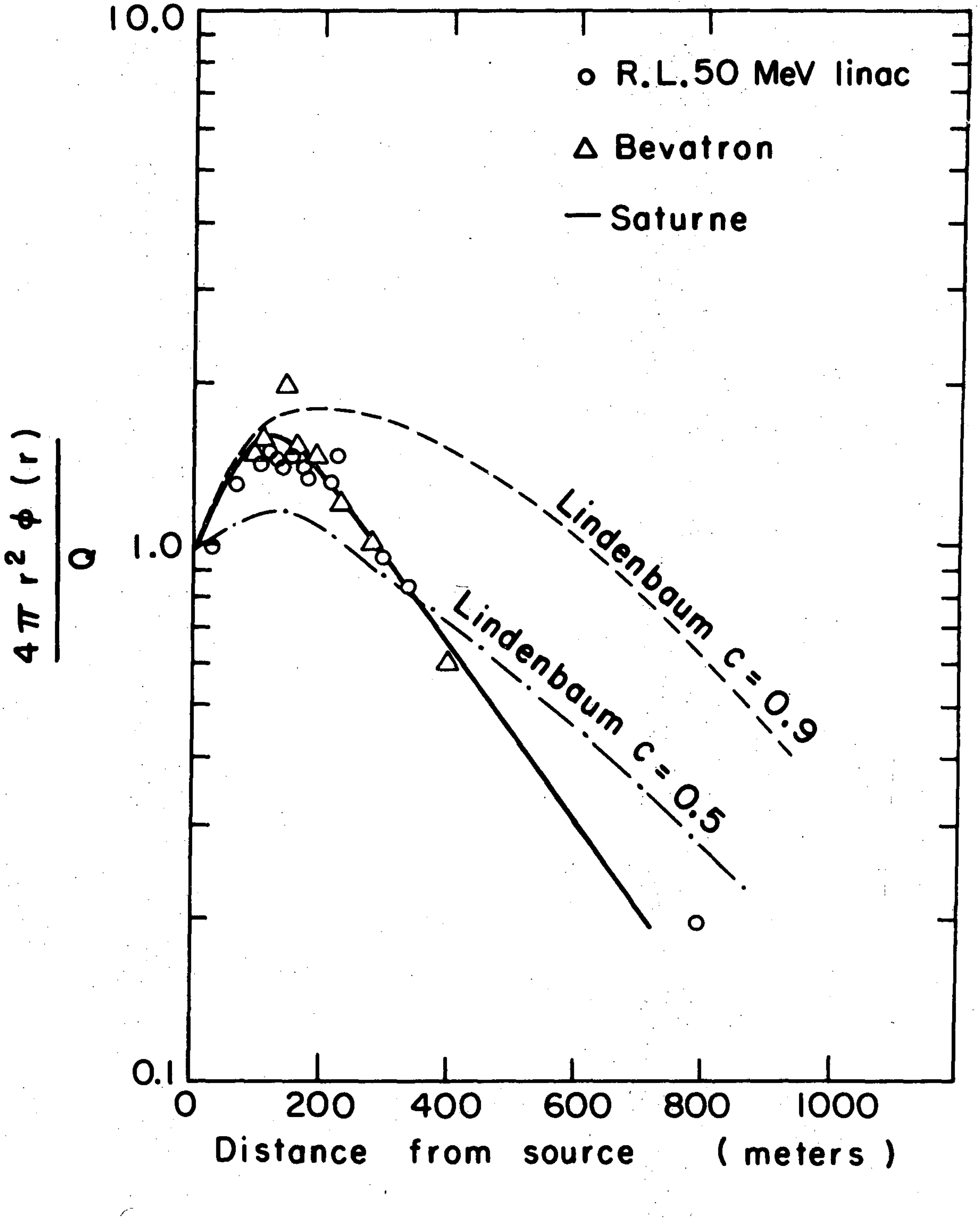
XBL752-2368

Fig. 9



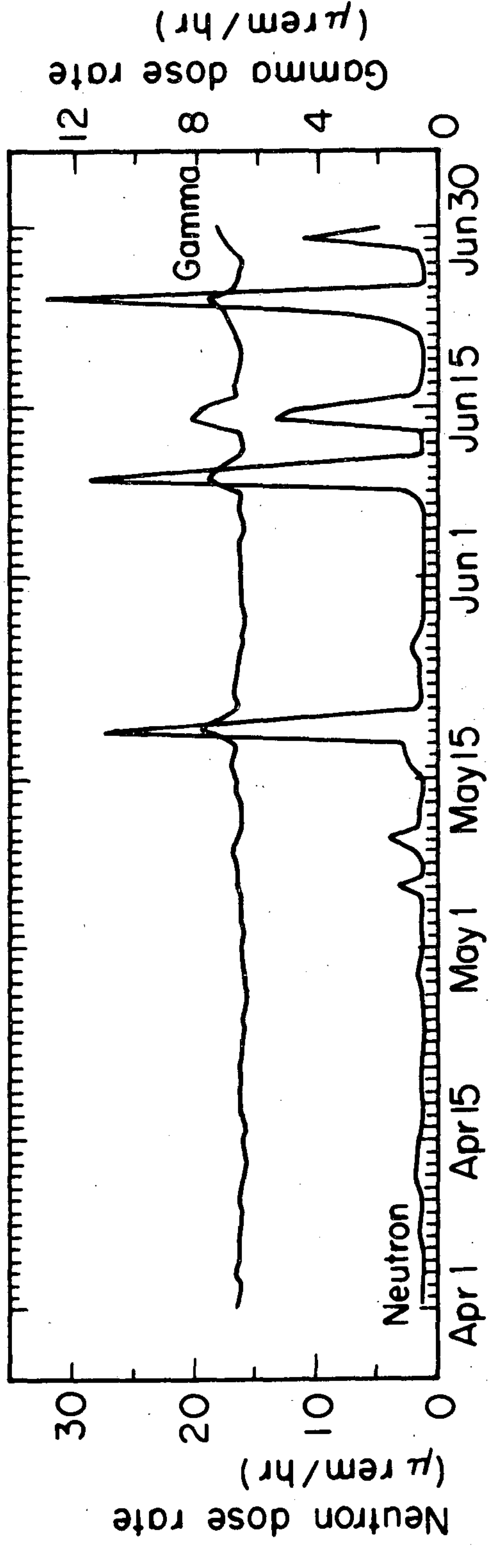
XBL 7412-7821

Fig. 10



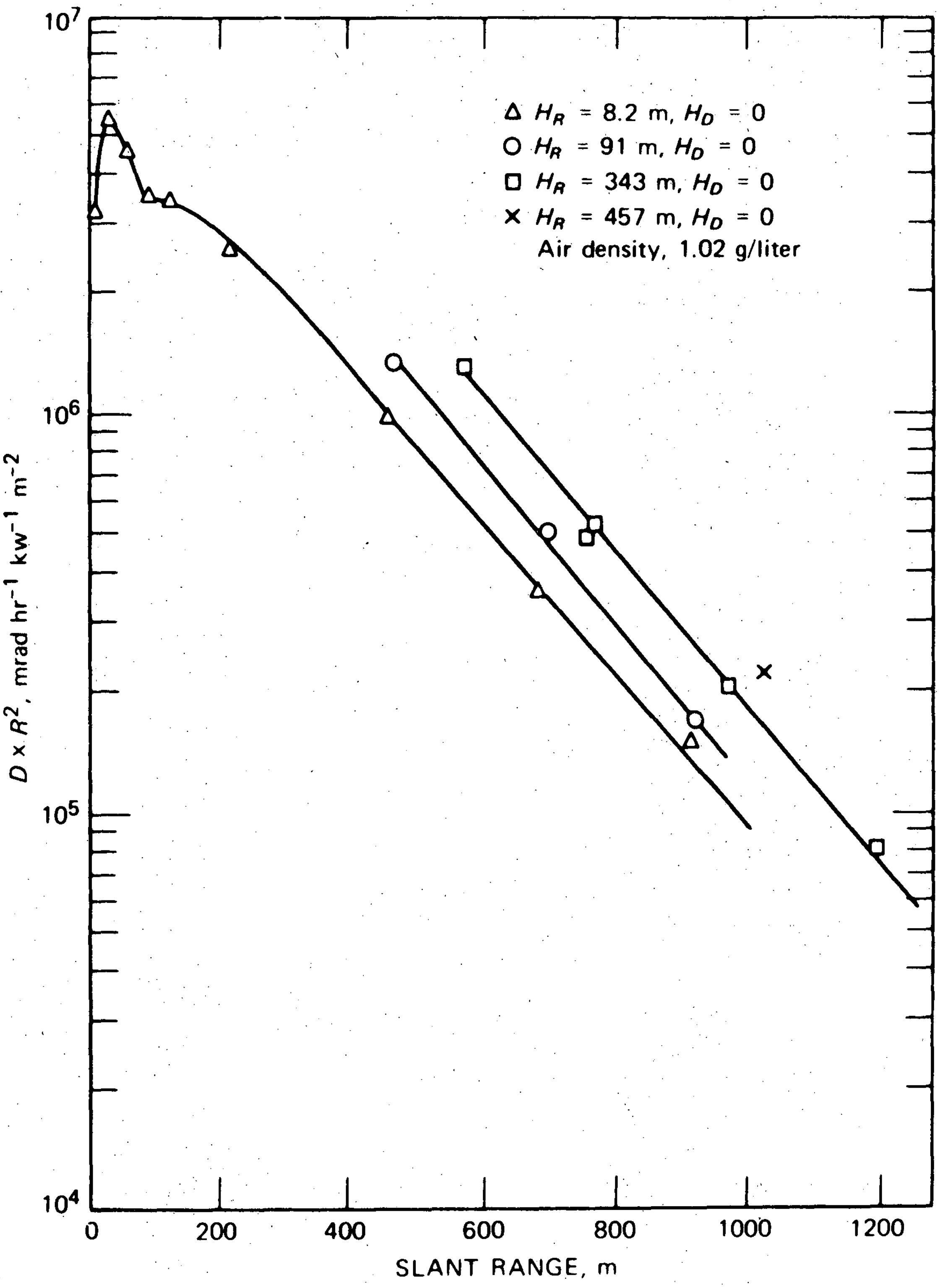
XBL754-2651

Fig. 11



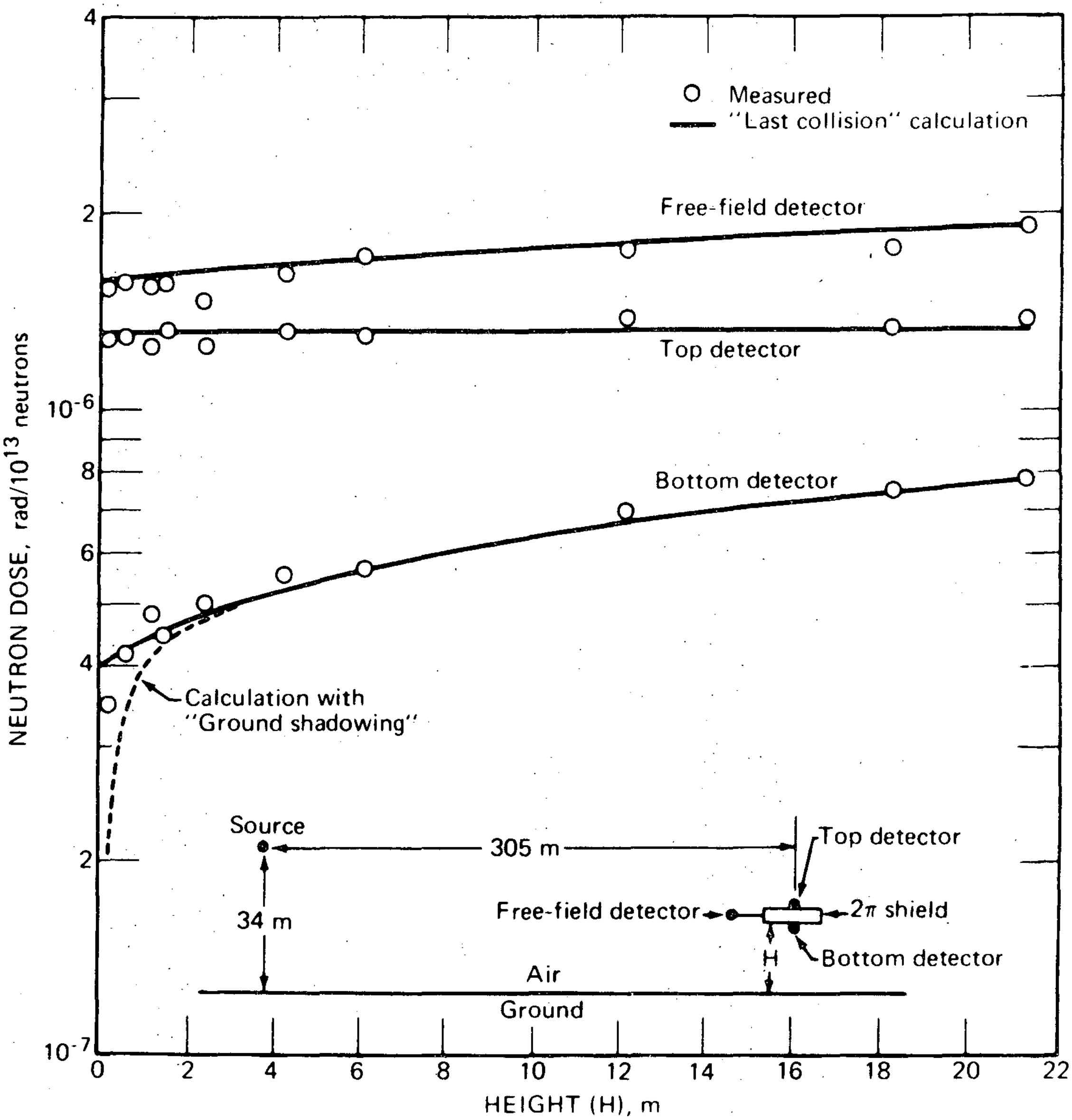
XBL752-2367

Fig. 12



XBL 7412-7819

Fig. 13



XBL 7412-7817

Fig. 14

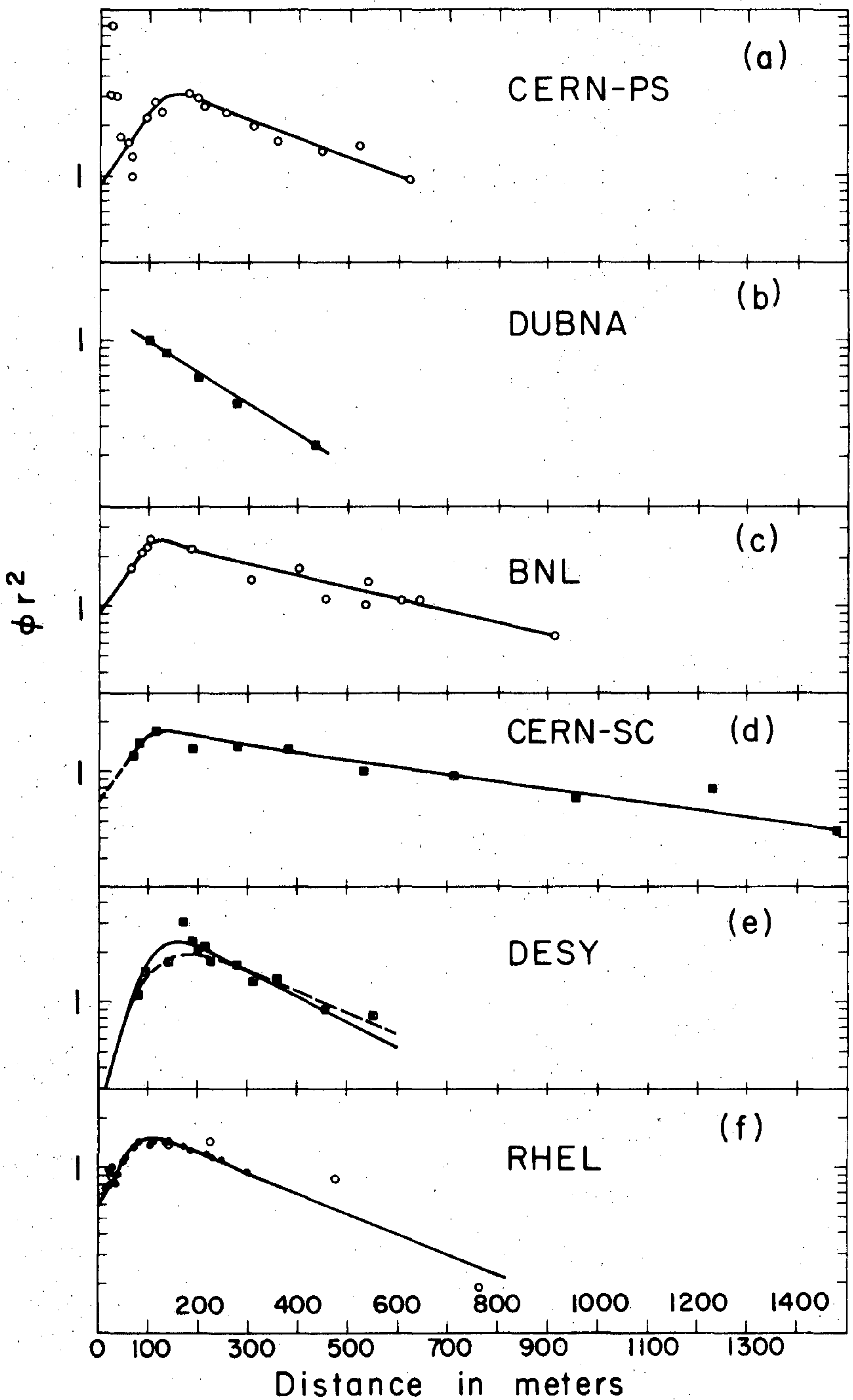

(a)
CERN-PS
(b)
DUBNA
(c)
BNL
(d)
CERN-SC
(e)
DESY
(f)
RHEL
1
1
1
1
1
1
$\phi r^2$
200
400
600
800
1000
1200
1400
0
100
300
500
700
900
1100
1300
Distance in meters
XBL7412-8445

Fig. 15

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