Title

THE EFFECT OF SHIELDING ON RADIATION PRODUCED BY THE 730-Mev SYNCHROCYCLOTRON AND THE 6.3-Gev PROTON SYNCHROTRON AT THE LAWRENCE RADIATION LABORATORY

Author
Patterson, H. Wade

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H. Wade Patterson

Lawrence Radiation Laboratory
University of California, Berkeley

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ABSTRACT

Calculation of shielding thickness should be compared with experimental data obtained with various detectors. Such data are presented for two accelerators. For the relatively well-shielded synchrocyclotron, emphasis is given to data which show how neutrons are attenuated in the primary shield and the composition of the remaining radiation field in areas close to the accelerator. For the Bevatron, which lacks a complete roof shield, data are given which show the distance dependence and the attenuation in concrete of neutrons that leave the machine in an upward direction.

*Work done under the auspices of the U.S. Atomic Energy Commission.

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I. Introduction

The duties of the Health Physics Department at the Lawrence Radiation Laboratory include estimating shielding thicknesses and measuring the effectiveness of different shielding materials. Also included in our duties are radiation surveys in the immediate vicinity of accelerators for the protection of employees, and along the boundaries of the Laboratory. These boundary surveys are necessary because we must comply with AEC regulations concerning nonoccupational exposures. This paper deals with three aspects of these responsibilities.

First, I will outline a simple but useful calculation of fast neutron attenuation in ordinary concrete. My purpose in this is to show that, at least in some situations, more sophisticated ways of calculating shielding effectiveness, such as the Monte Carlo method, are not necessary. Secondly, I will briefly describe experiments that measured the attenuation of high-energy neutrons from the cyclotron and Bevatron in concrete and show how these measurements agree with the above calculation. Finally, I wish to make some very general remarks about the composition of the radiation field outside the accelerator shields.

The data presented and the ideas expressed are the work of many individuals, collected over a period of years. Because Health Physics radiation surveys and attenuation measurements generally have a lower priority than the experimental physics program, we have done most of this work with little or no control over accelerator operation, and it has taken a long time to collect this information.

II. Calculation of Neutron Attenuation in Ordinary Concrete

The simplest way to use the available data in regard to cross section and concrete composition is with the equation

$$I = I_0 \exp(-N\sigma_a t),$$

where N = atoms/cm^3 of various kinds in the concrete available at Berkeley. N of course is affected strongly by changes in water content and the source of the aggregate used. Table I gives the relative abundance of the different constituents of Berkeley concrete.

Table I. N for Berkeley concrete ($\times 10^{22}$)

O	4.73
H	1.73
Si	1.57
Ca	0.26
Al	0.17
Fe	0.053
Na	0.028
K	0.028
Mg	0.013

The σ_a is the attenuation cross section or that fraction of the total cross section (σ_{tot}) which is effective in removing a neutron during its passage through a thick slab. At energies near 1 Mev we have arbitrarily made σ_a equal to σ_{tot}, and at energies greater than 150 Mev we have made σ_a equal to the inelastic cross section or one-half the total cross section, thus at

1 Mev $\sigma_a = \sigma_{tot}$,

5 Mev $\sigma_a = 0.65\ \sigma_{tot}$,

14 Mev $\sigma_a = 0.55\ \sigma_{tot}$,

$\geq$ 150 Mev $\sigma_a = 0.50\ \sigma_{tot}$.

An interesting consequence of this approach is that $N\sigma_a$ is a figure of merit for the efficacy of each element in the concrete. Table II gives $N\sigma_a$ for the important elements at three energies.

Table II. $N\sigma_a$ for various elements ($\times 10^{-2}$).

	1 Mev	14 Mev	270 Mev
O	16	4.4	0.89
H	7.8	0.64	0.026
Si	4.7	1.7	0.41
Ca	0.78	0.33	0.10
Al	0.51	0.16	0.05
Fe	0.16	0.045	0.028

The data in the table emphasize the importance of the heavier elements at high energies and of hydrogen at low energy.

Upon summing $N\sigma_a$ for all the elements at each energy and solving for the value of t to give a 50% reduction, we calculate the points shown in Fig. 1. Notice that the half-value thicknesses measured at the cyclotron at 90 and 270 Mev agree with those calculated. Another experiment at the Bevatron gave us the point plotted at 4.5 Gev. It must be emphasized that these data, both calculated and measured, apply only to thick shields and poor-geometry situations.

III. Measurements of Attenuation in Concrete of Cyclotron Neutrons

An extensive series of measurements was made in the forward direction from a cyclotron target at two neutron energies, 90 and 270 Mev. The measurements were made with ion chambers, film, BF_3 counters, bismuth fission chambers, and carbon discs. The attenuation measured with the ion chambers, film, and BF_3 counters agreed in every case with the measurements made with the high-energy neutron detectors, thus indicating that high-energy neutrons are the controlling component in the radiation field in question. Many other measurements were made in various holes and cracks which penetrate the concrete shield. Generally these agreed with the above measurements, but in some cases uncertainties in regard to average neutron energy and source location made interpretation difficult. However, when data were taken at locations nearly in the 0° direction from a well-defined target the average neutron energy was well known, and inverse-square and obliquity corrections could be made with confidence. An example of high-energy neutron attenuation through the shield is given in Fig. 2. These data were obtained with 350-Mev protons striking a Be target on the main probe, thus giving in the forward direction neutrons of 270 Mev average energy. The detectors were Ilford C-2 emulsions exposed simultaneously. Only stars formed by neutrons and having three or more prongs were counted. The exposure time was about 30 minutes. The data show first a transition region up to about 4 feet of concrete and then exponential absorption with a half-value thickness of about 18 in. Other detectors gave similar results.

Many radiation surveys have been made in the area near the cyclotron immediately outside the shield. However, the roof is thin (4 feet of concrete vs 15 feet for the walls) and there are wall areas where shielding is purposely thin or absent. Therefore the relation of the radiation field to neutron production in the cyclotron and subsequent attenuation of these neutrons in the shield is not simple. Under present operating conditions, when 1 μa of protons is accelerated to 730 Mev, we find that the fast neutron flux in the building varies between 10 and 250 neutrons/cm^2 sec. In special locations, such as immediately outside the wall of the physics cave, the flux of neutrons of energies greater than 50 Mev, as measured with a bismuth fission chamber, is approximately equal to the flux of secondary neutrons penetrating the shield. The average neutron energy, as measured with polyethylene-lined and moderated BF$_3$ proportional counters, usually lies between 0.5 and 10 Mev. Measurements made with tissue-equivalent ion chambers give 0.5 to 10 mr/hr. These levels mean that no permanent occupancy of the building can be allowed, and in fact the cyclotron control room and the operating crew are housed in another building some distance away. In addition, access to certain areas such as the overhead crane and the floor of the building immediately outside the physics cave is severely limited, or denied under certain operating conditions.

IV. Measurement of Attenuation in Concrete of Bevatron Neutrons

Because of the shape of the Bevatron magnet, and the pressure of the experimental physics program, it is difficult to make measurements of the sort made at the cyclotron. The magnet shape prevents placing counters directly ahead of a target without interference by the magnet steel; and the high priority of the experimental program has made time for the Health Physics work in effect nonavailable. However, one experiment was done at 12° from the forward direction by using bismuth fission chambers as both monitor and detector. To save time, 2-ft-thick concrete blocks were used, and consequently, fine details of the attenuation process were not observed. The result of the experiment is plotted as the top point on Fig. 1. However, owing to the 12° angle and some interference by the magnet support, the neutron energy is somewhat in question.

Since the Bevatron has an incomplete roof shield, and since the top of the Bevatron is in the line of vision from many Laboratory buildings and from the surrounding residential area, we have had to measure the distance dependence and the intensity of the radiation out to about 1500 ft. We have used moderated BF_3 counters, polyethylene-lined counters, bismuth fission chambers, and plastic-walled ion chambers. We find that under constant operating conditions the distance dependence of the radiation seen by these detectors follows the inverse-square law very closely between 300 and 1200 ft. Typical data taken with cadmium-paraffin-indium foil detectors are shown in Fig. 3. An inverse-square slope is drawn for reference.

We have also made a series of measurements of attenuation in concrete at different distances and directions in the following manner. Identical moderated BF_3 counters were used as the detector and monitor, with polyethylene-lined counters in conjunction to measure energy flux. The detectors were placed in a hollow concrete cube with walls 3 ft thick while the monitors were placed in a nearby trailer. The one open face of the cube was pointed toward the Bevatron and as incremental thicknesses of concrete blocks were added to the open face, detector/monitor ratios were taken. These data are shown in Fig. 4. We interpret the zero-thickness ratio of 0.5 as the effect of the five thick concrete walls on the detector. As might be expected, the slope of the attenuation curves shows that the average neutron energy is highest in the forward direction, and the measured half-thicknesses of 13 to 18 in. are consistent with our understanding of the attenuation process for neutrons of these energies. With the BF_3 and polyethylene-lined counters we also found that the average neutron energy increased with distance, being about 0.5 Mev at 300 ft and 1.5 to 2 Mev at 1500 ft.

When the Bevatron is operating at 6.3 Bev and 2×10^{11} protons/pulse, we estimate an integrated exposure at the inhabited project boundary of about 0.5 rem in a year. Fast neutrons between 50 kv and 20 Mev contribute 80% of this exposure. Neutrons of energy greater than 50 Mev, slow neutrons, and gamma rays contribute a few percent each. Since this exposure is the maximum permitted by the AEC, a complete roof shield is being installed simultaneously with the program presently under way to increase the Bevatron beam current by a factor of 50 to 100.

Acknowledgements

I wish to acknowledge the contributions made by other members of the Health Physics Department during the collection and interpretation of these data. Particularly helpful were Alan R. Smith, and B. J. Moyer, Department Head.

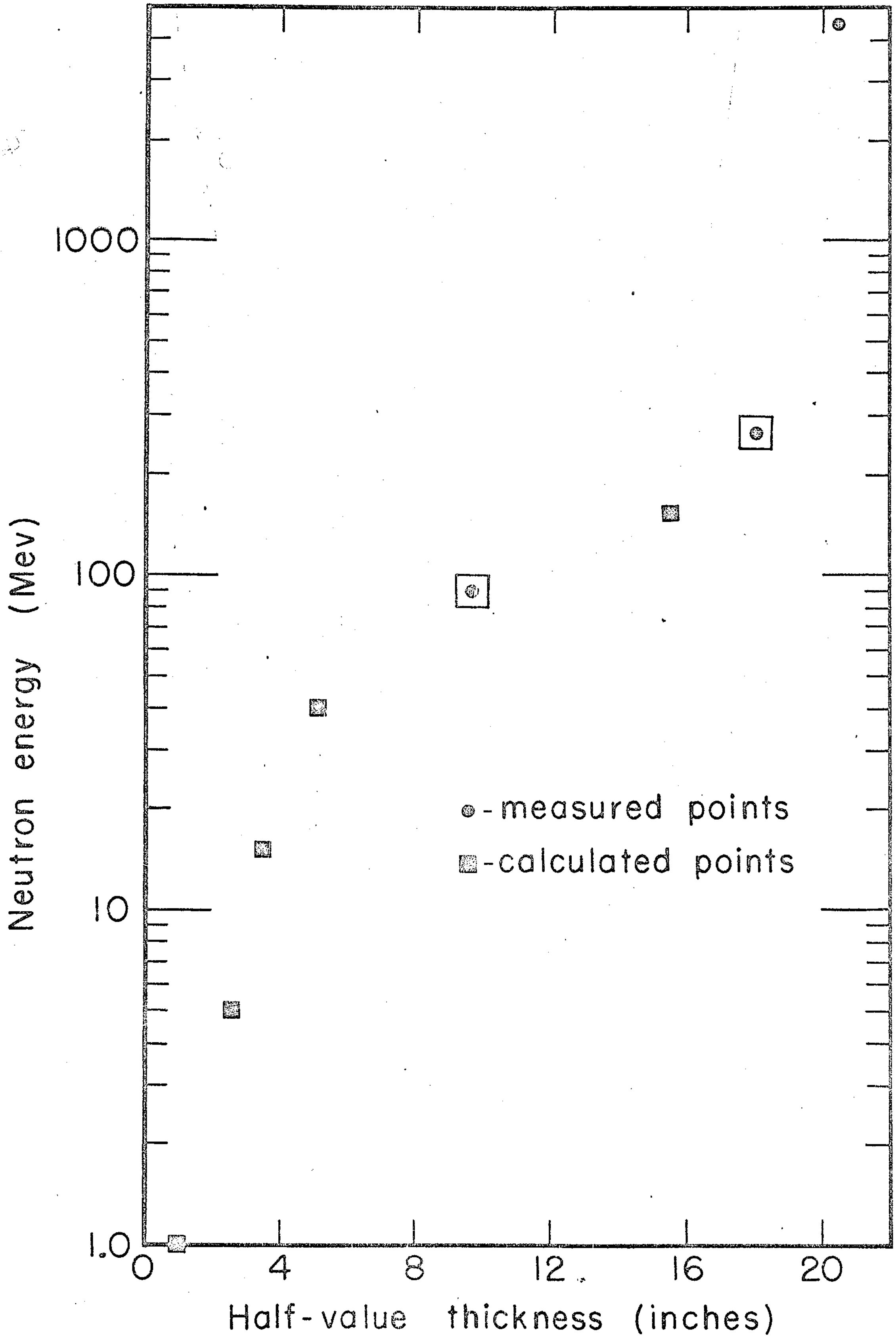

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Fig. 1. Attenuation of neutrons in ordinary concrete. At 90 and 270 Mev, measurements were made at the cyclotron. At 4.5 Gev the measurement was made at the Bevatron.

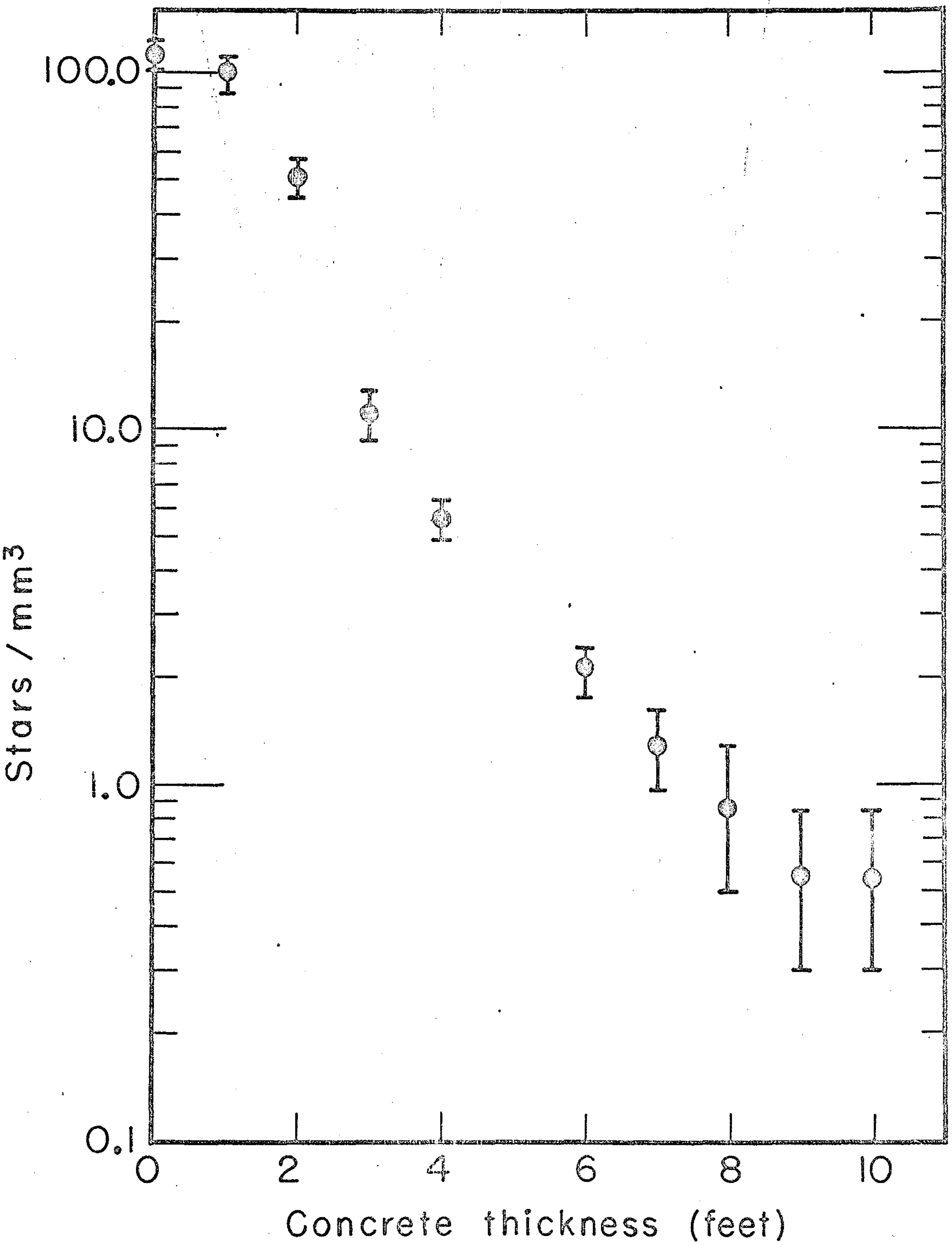

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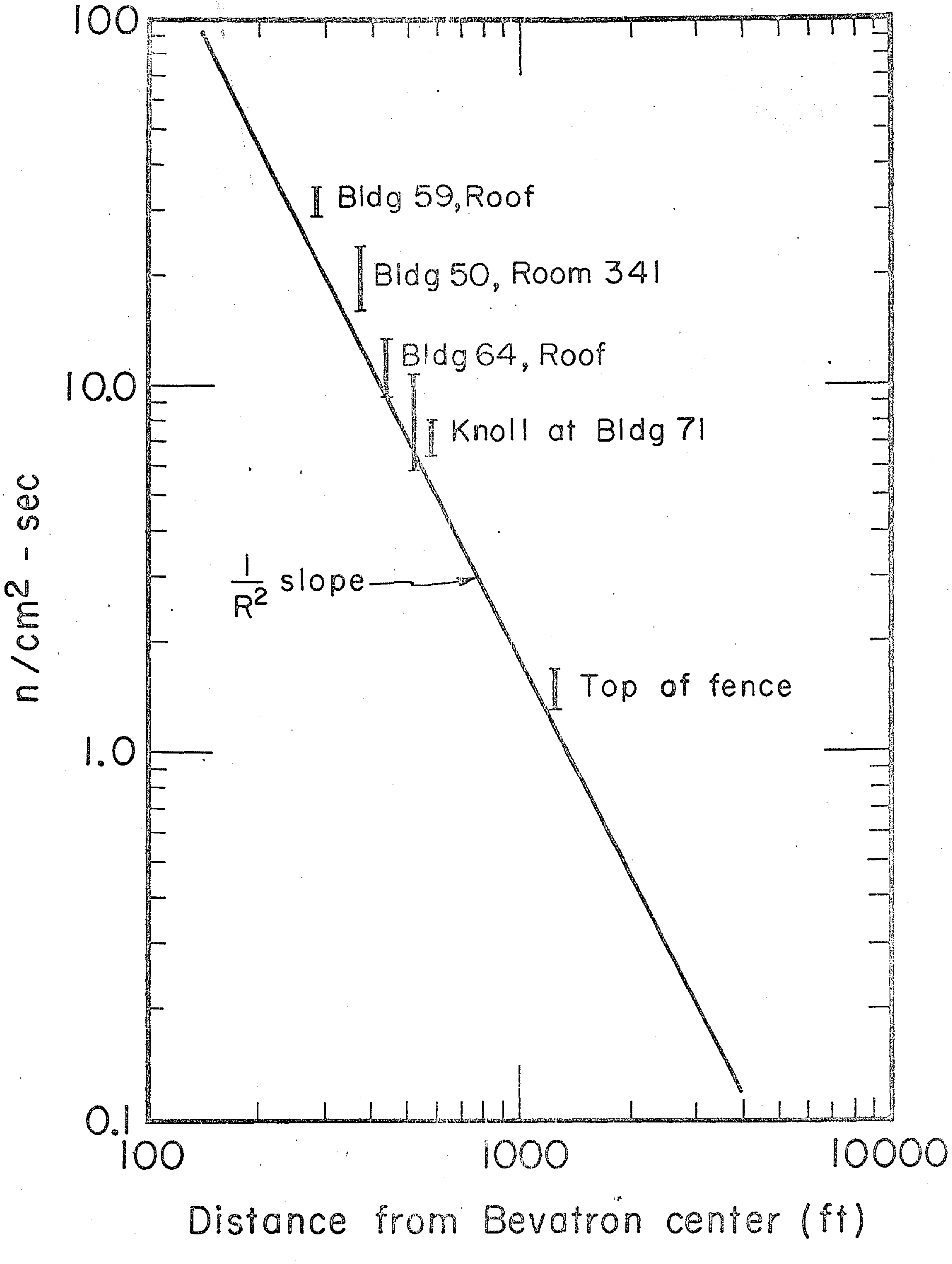
Fig. 2. Attenuation of star producing neutrons measured through the cyclotron shielding.



MU-25960

Fig. 3. Fast neutron flux measured with cadmium-paraffin-indium detectors at different distances from the Bevatron.

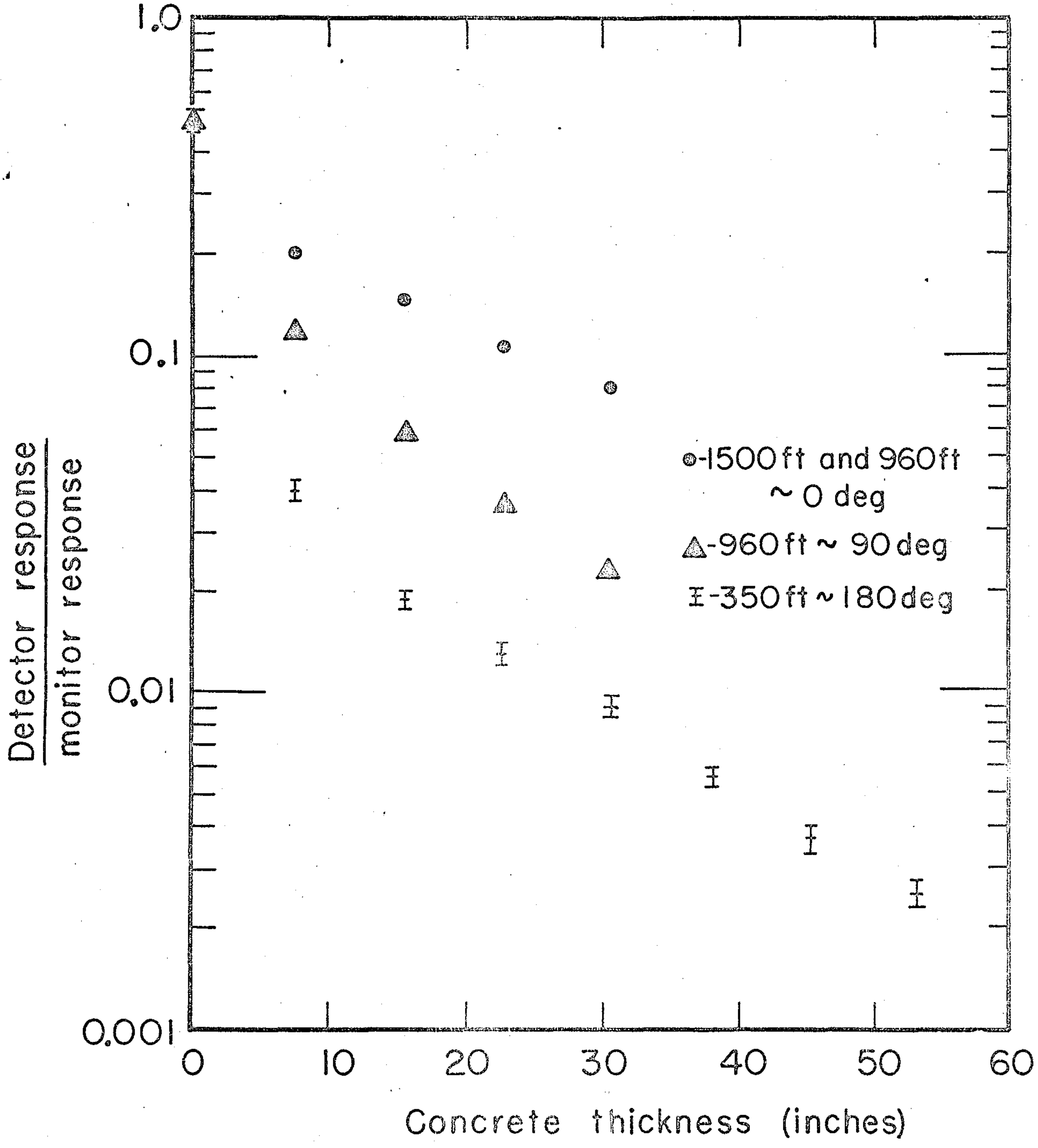


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Fig. 4. Attenuation in ordinary concrete of neutrons at different distances and directions from a Bevatron target.