ANL-7273

ANL-7273

MASTER

Argonne National Laboratory

ON THE SHIELDING OF THE
EXTERNAL PROTON TUNNEL AREA OF
ARGONNE'S ZERO GRADIENT SYNCHROTRON

by

H. J. Howe, Jr., G. V. Oldfield,
D. J. Sreniawski, and R. V. Wheeler

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

The facilities of Argonne National Laboratory are owned by the United States Government. Under the terms of a contract (W-31-109-Eng-38) between the U. S. Atomic Energy Commission, Argonne Universities Association and The University of Chicago, the University employs the staff and operates the Laboratory in accordance with policies and programs formulated, approved and reviewed by the Association.

MEMBERS OF ARGONNE UNIVERSITIES ASSOCIATION

The University of Arizona
Carnegie Institute of Technology
Case Institute of Technology
The University of Chicago
University of Cincinnati
Illinois Institute of Technology
University of Illinois
Indiana University
Iowa State University

The University of Iowa
Kansas State University
The University of Kansas
Loyola University
Marquette University
Michigan State University
The University of Michigan
University of Minnesota
University of Missouri

Northwestern University
University of Notre Dame
The Ohio State University
Purdue University
Saint Louis University
Washington University
Wayne State University
The University of Wisconsin

LEGAL NOTICE

This report was prepared as an account of Government sponsored work. Neither the United States, nor the Commission, nor any person acting on behalf of the Commission:

A. Makes any warranty or representation, expressed or implied, with respect to the accuracy, completeness, or usefulness of the information contained in this report, or that the use of any information, apparatus, method, or process disclosed in this report may not infringe privately owned rights; or

B. Assumes any liabilities with respect to the use of, or for damages resulting from the use of any information, apparatus, method, or process disclosed in this report.

As used in the above, "person acting on behalf of the Commission" includes any employee or contractor of the Commission, or employee of such contractor, to the extent that such employee or contractor of the Commission, or employee of such contractor prepares, disseminates, or provides access to, any information pursuant to his employment or contract with the Commission, or his employment with such contractor.

Printed in the United States of America

Available from

Clearinghouse for Federal Scientific and Technical Information
National Bureau of Standards, U. S. Department of Commerce
Springfield, Virginia 22151

Price: Printed Copy \$3.00; Microfiche \$0.65

ANL-7273
Particle Accelerators and
High-Voltage Machines
(TID-4500)
AEC Research and
Development Report

ARGONNE NATIONAL LABORATORY
9700 South Cass Avenue
Argonne, Illinois 60439

CESTI PRICES

H.C. \$ 3.00; MN. .65

ON THE SHIELDING OF THE
EXTERNAL PROTON TUNNEL AREA OF
ARGONNE'S ZERO GRADIENT SYNCHROTRON

by

H. J. Howe, Jr., G. V. Oldfield,*
D. J. Sreniawski, and R. V. Wheeler

Industrial Hygiene and Safety Division

*U.S. Public Health Service Fellow, The University of Michigan

November 1966

LEGAL NOTICE

This report was prepared as an account of Government sponsored work. Neither the United States, nor the Commission, nor any person acting on behalf of the Commission:

A. Makes any warranty or representation, expressed or implied, with respect to the accuracy, completeness, or usefulness of the information contained in this report, or that the use of any information, apparatus, method, or process disclosed in this report may not infringe privately owned rights; or

B. Assumes any liabilities with respect to the use of, or for damages resulting from the use of any information, apparatus, method, or process disclosed in this report.

As used in the above, "person acting on behalf of the Commission" includes any employee or contractor of the Commission, or employee of such contractor, to the extent that such employee or contractor of the Commission, or employee of such contractor prepares, disseminates, or provides access to, any information pursuant to his employment or contract with the Commission, or his employment with such contractor.

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

TABLE OF CONTENTS

	<u>Page</u>
ABSTRACT	4
I. INTRODUCTION	5
II. DOSIMETRIC TECHNIQUE	5
A. Tissue-equivalent Ionization Chambers	8
B. Linear-energy-transfer Chamber	8
C. Film-badge Dosimeters	8
III. COLLECTION OF DATA	10
IV. RESULTS	11
A. General Radiation Levels	11
B. Film-badge Results	12
C. Dependence of Radiation Levels on Target Thickness	14
D. Dependence of Radiation Levels on Distance from the Shield	15
E. Calculation of λ_s and λ_c	15
F. Evaluation of Proposed Shielding	18
V. CONCLUSIONS	19
ACKNOWLEDGMENTS	19
REFERENCES	20

LIST OF FIGURES

<u>No.</u>	<u>Title</u>	<u>Page</u>
1.	Zero Gradient Synchrotron Site Plan.	6
2.	Experimental Proton Building	7
3.	Immediate Target Area	8
4a.	AC-operated Tissue-equivalent Ionization Chamber.	9
4b.	LET Chamber.	9
4c.	DC-operated Tissue-equivalent Chamber.	9
5.	Vertical Section of Tunnel.	10
6.	Absorbed Doses for Side Shielding	14
7.	Absorbed Doses for Top Shielding	14
8.	Angular Dependence of Absorbed Dose.	15
9.	Absorbed Dose Rate as a Function of Distance from Inside Shield Wall for a 5 in. Copper Target	15
10.	Geometrical Arrangement for Calculation of Attenuation Lengths	16
11.	Proposed Shielding Configuration for Thick-target Bombardments	18

LIST OF TABLES

<u>No.</u>	<u>Title</u>	<u>Page</u>
I.	Absorbed Dose Rates	12
II.	Dose Equivalents Received by Personnel.	13
III.	Absorbed Dose Rates	13
IV.	Mean Attenuation Lengths	17

ON THE SHIELDING OF THE EXTERNAL PROTON TUNNEL AREA OF ARGONNE'S ZERO GRADIENT SYNCHROTRON

by

H. J. Howe, Jr., G. V. Oldfield,
D. J. Sreniawski, and R. V. Wheeler

ABSTRACT

An experimental evaluation of the radiation levels in the area of the external proton tunnel (EPT) of the Argonne Zero Gradient Synchrotron (ZGS) under conditions of thick-target bombardment by approximately 2×10^{10} protons/sec has been completed. The radiation levels in the forward hemisphere from the target varied linearly with target thickness, and the maximum levels were observed between 60° and 70° from the incident beam direction. A reduction of radiation levels noted at smaller angles ($\theta < 40^\circ$) is attributed to the longer path length of shield materials traversed by secondaries emitted into the forward direction. A similar reduction of radiation levels observed at large angles ($\theta > 75^\circ$) is attributed to the smaller number of high-energy secondaries emitted from the target into these directions. The dependence of the radiation levels on distance from the shield wall was found to consist of an area of rapid decrease (approximately as $1/r^2$) followed by an area of less rapid decline (approximately as $1/r$).

Measurements of the stray radiation field with tissue-equivalent (TE) ionization chambers in normally occupied areas indicated absorbed dose levels of 0.2 to 0.8 mrad/hr with a 0.5-in. copper target and 0.3 to 3.0 mrad/hr with a 5.0-in. copper target. With an effective quality factor ($\overline{QF}$) of 5, determined from experimental linear energy transfer (LET) spectral measurements, these measurements yield dose equivalent rates ($\dot{DE}$) from 1.0 to 4.0 mrem/hr with the 0.5-in. target and from 1.5 to 15.0 mrem/hr with the 5.0-in. target. Hence, it was necessary to revise the shielding configuration to obtain more effective attenuation without a significant reduction of experimental space.

By means of a simple exponential attenuation model, the data were used to obtain estimates of the attenuation lengths λ_s and λ_c for steel and concrete, respectively. These estimates: $\lambda_s = 142 \pm 15 \text{ g/cm}^2$ ($\rho = 7.85 \text{ g/cm}^3$) and $\lambda_c = 173 \pm 18 \text{ g/cm}^2$ ($\rho = 3.8 \text{ g/cm}^3$), are in fair agreement with previously published results. Since accurate and reliable shielding calculations depend on the accuracy of these parameters, a more extensive evaluation of the shielding properties of ordinary concrete, high-density concrete, and steel is planned for the purpose of obtaining definitive values of λ_s and λ_c for the ZGS shielding materials.

I. INTRODUCTION

Measurements were made to determine the levels of the stray radiation field at various locations around the external proton tunnel (EPT) of the Argonne 12.5-GeV Zero Gradient Synchrotron (ZGS) under conditions of optimum beam extraction and thick-target bombardment. The purpose of this investigation was to evaluate the effectiveness of the existing shield configuration and to obtain estimates of certain shielding parameters with which the shielding of future experiments could be determined.

Approximately 20% of the circulating proton beam was extracted from the synchrotron into the proton building (see Fig. 1). Because of the possible existence of high radiation fields, access to the proton building during this experiment was limited to personnel involved with the experiment. Access to the EPT was prohibited by a door interlock system under the control of the operations group.

The sidewall shielding configuration during this experiment (see Fig. 2) consisted of 6.0 ft of high-density concrete ($\rho = 3.8 \text{ g/cm}^3$) with the exception of the immediate target area, where 1.5 ft of iron followed by 3.0 ft of high-density concrete was used (see Fig. 3). That portion of the beam remaining after traversal of the target was directed into an earth beam-stop located outside the proton building.

During the course of this experiment, approximately 3×10^{11} protons/pulse were accelerated at a pulse rate of 20 pulses/min. Of this amount, approximately 2×10^{10} protons/sec were extracted and focused onto copper targets 0.5 to 5.0 in. thick. Measurements of the absorbed dose rate ($\dot{D}$) were obtained at points shown in Fig. 2, and the results are tabulated in Table I (see Sect. IV).

II. DOSIMETRIC TECHNIQUE

The experimental data were collected using several tissue-equivalent (TE) ionization chambers, a linear-energy-transfer (LET) spectrum analyzer, film-badge dosimeters worn by personnel collecting the data, film-badge dosimeters attached to the biological shield, and polyethylene foils attached to the inside of the shield wall. Each of these systems will be discussed briefly below. Finally, beam monitoring was accomplished by means of ionization chambers of the type described by Swartz *et al.*¹ The response of the instruments was calibrated absolutely with the use of gold and polyethylene foils.²

Fig. 1. Zero Gradient Synchrotron Site Plan

Fig. 2
Experimental Proton Building

Fig. 3
Immediate Target Area

A. Tissue-equivalent Ionization Chambers (see Fig. 4a)

Ionization chambers of the Rossi type,³ consisting of 8-in.-outside-diameter spherical chambers of 1/4-in.-thick tissue-equivalent plastic⁴ filled with tissue-equivalent gas⁵ at a pressure of 0.8 atm, were utilized. The ionization produced by charged particles, gamma radiations, and proton recoils from fast-neutron interactions was amplified and measured with a vibrating-reed electrometer. The electrometer output was displayed by means of a chart-recorder system. Calibration of these chambers to permit the evaluation of the electrometer output (volts or volts/unit time) in terms of the absorbed dose D (mrad), or the absorbed dose rate $\dot{D}$ (mrad/hr) in tissue was provided by the Radiation Measurements and Instrumentation Group using a Pu-Be neutron source of known intensity.

B. Linear-energy-transfer Chamber (see Fig. 4b)

A spherical TE chamber of the type described above was operated as a proportional counter with the chamber pulse-height output collected by a 512-channel pulse-height analyzer. This pulse-height spectrum was used as input data for a computer analysis, described by Dvorak,⁶ the method being an extension of Rossi's⁷ technique of measuring the distribution of absorbed dose as a function of LET. An effective quality factor ($\overline{QF}$) was then derived from the analysis. The dose equivalent (DE) was obtained from these measurements by means of the expression

$$DE = D(\overline{QF}). \quad (1)$$

The usual units for the quantities in eq. (1) were used, i.e., DE is in rem units, D is in rad units, and $(\overline{QF})$ is in units of rem/rad.

C. Film-badge Dosimeters

The film monitors used were the standard Argonne National Laboratory personnel dosimeters, each containing a beta-gamma-sensitive packet

235-907

Fig. 4a. AC-operated Tissue-equivalent Ionization Chamber

235-1090

Fig. 4b. LET Chamber

143-846

Fig. 4c

DC-operated Tissue-equivalent Chamber

and a NTA neutron-sensitive packet. The film packets are enclosed in a plastic case incorporating aluminum, silver, and cadmium filters for use in estimating the particle and energy spectra as well as exposures due to thermal neutrons. The dose equivalent DE obtained from film-badge readings is given by

$$DE = 0.93 X_{\gamma} + DE_{n_t} + 1.9 n_f, \quad (2)$$

where X_{γ} is the exposure due to beta-gamma radiations in Röntgen units as obtained from calibrated densitometer readings behind the open-window section of the film badge, DE_{n_t} is the dose equivalent due to thermal neutrons obtained from the difference (if any is noted) between the open-window density and the density behind the cadmium shield with proper calibration against a thermal neutron source, and n_f is the number of recoil-proton tracks detected in scanning 29 microscopic fields (total area = $2.46 \times 10^{-2} \text{ cm}^2$). The conversion factor of 1.9 mrem/track/29 fields was determined from measurements of absorbed dose and quality factor.

III. COLLECTION OF DATA

The area in the vicinity of the second focus point of the EPT (see Fig. 3) was chosen for the majority of the measurements because of the simplicity of the shield configuration, the clear floor area, and the proposed thick-target experiments scheduled for that area. Experimental monitoring locations were chosen along radial lines (at approximately 15, 22.5, 30, 45, 60, 75, and 90° with the incident-beam direction) from the target position at beam height. These locations are shown as positions 7A to 1A, 6B to 1B, and 5C to 1C, respectively, in Fig. 3. Corresponding locations along the beam centerline above the roof shield were chosen and are shown by positions 1T to 7T in Fig. 5. At each location, three measurements were obtained of the ionization produced in the TE ionization chambers during

Fig. 5. Vertical Section of Tunnel

bombardment of three thicknesses of copper (0.5, 2.5, and 5.0 in.) by eight pulses of extracted protons. Measurements at corresponding locations at the side shield and the roof shield, i.e., 1A, 1T; 2A, 2T; etc., were obtained simultaneously to permit the accurate comparison of side to top radiation levels. In each of the series of eight pulses, a measurement

of the intensity (protons/pulse) of the incident proton beam was obtained with an ionization chamber located just upstream of the target. Averages of these measurements yield the absorbed dose per 10^{10} incident protons for each of 18 locations along the side shield and seven locations along the roof shield for each of the three target thicknesses.

Film-badge detectors were attached to the outside surfaces of the side and roof shields at locations corresponding to the intersection of the radial lines with the shield surface (locations 1FS to 7FS and 1FT to 7FT in Figs. 3 and 5, respectively). The interpretation of these exposures according to eq. (2) yields estimates of the integrated dose equivalent detected at each location.

LET pulse-height spectra were collected at various locations during the experiment and were analyzed to yield an effective quality factor ($\overline{QF}$) for use in eq. (1). The method of pulse-height collection and analysis and the subsequent data analysis to yield ($\overline{QF}$) is described by Dvorak.⁶

Measurements of absorbed dose rate at 22 positions (indicated on Fig. 2) around the EPT were obtained with portable d.c.-operated TE ionization chambers of the type shown in Fig. 4c. A measurement of the rate of ionization in the chamber, obtained by timing the deflection of the electrometer output, provided a value of the absorbed dose rate at each position.

Polyethylene discs were attached to the inside surface of the shield wall to obtain an estimate of the angular distribution of the high-energy particles ($E > 20$ MeV) emitted from the target. Counting the positron activity of the ^{11}C produced from ^{12}C by (n,2n), (p,np), and (x,nx) reactions provides such an estimate.

IV. RESULTS

In addition to providing information about the general levels of the stray radiation field in the experimental proton building during thick-target bombardment, the data obtained during this experiment were used to calculate the shielding parameters λ_s and λ_c , the attenuation lengths in steel and concrete, respectively. Also, an estimate of the response of the ANL film badge to the stray field was determined.

A. General Radiation Levels

The magnitude of the stray radiation field around the EPT, given in terms of absorbed dose rate $\dot{D}$ (mrad/hr), as measured by the TE d.c.-operated ionization chamber shown in Fig. 4c, is itemized as a function of target thickness in Table I.

TABLE I. Absorbed Dose Rates

Absorbed Dose Rate, mrad/hr				Absorbed Dose Rate, mrad/hr			
Location ^(a)	Target Thickness, in. =			Location ^(a)	Target Thickness, in. =		
	0.5	2.5	5.0		0.5	2.5	5.0
1	6.33	6.27	7.14	12	0.47	0.63	-(b)
2	0.29	0.52	0.63	13	4.87	6.96	-(b)
3	0.17	0.28	0.30	14	0.97	0.70	-(b)
4	0.18	0.32	0.32	15	0.12	0.24	-(b)
5	0.62	0.75	0.84	16	0.12	0.14	-(b)
6	0.19	0.29	0.30	17	0.13	0.14	-(b)
7	0.28	0.31	0.36	18	0.74	0.71	-(b)
8	0.37	0.30	0.33	19	0.78	0.85	-(b)
9	0.28	0.44	0.48	20	0.68	2.14	-(b)
10	0.47	0.56	0.81	21	1.88	3.03	-(b)
11	27.30	40.0	40.0	22	-(b)	1.34	-(b)

(a) Location refers to positions numbered on Fig. 2.

(b) Indicates that a measurement was not obtained because of time limitations.

With one exception, the levels indicated in Table I were generally as expected, the exception being position number 13, which was on the proton-tunnel crossover. Inspection of the shielding in this area indicated a crack through which scattered radiation was emerging. Surveys in this area were performed during thin-target experiments, during which time the stray radiation field levels were less than 0.1 mrad/hr. The higher level at the crack did not present a hazard. The higher levels at positions 1, 5, 11, and 18 through 22 were expected since these positions correspond to a beam port, an access door where more thermal neutrons were expected, a junction of the EPT and the Ring Building, and other beam openings. Generally, access to these areas is limited by physical barriers.

B. Film-badge Results

Since the operation of the TE ionization chambers required the presence of the personnel involved in this experiment, an accurate estimate of the absorbed dose received by each person was made from which information concerning the gross film-badge response was deduced.

The dose equivalents received by personnel making the experimental measurements, as estimated from measured absorbed dose and effective quality factor data, are itemized in Table II.

TABLE II. Dose Equivalents Received by Personnel

Individual	Dose Equivalent ^(a) as Reported by Routine Film-badge Evaluation, mrem	Absorbed Dose as Measured by TE Chamber, mrad				Effective QF as Measured with TE LET Chamber	Measured Dose Equivalent, mrem		
		0.5 in.	2.5 in.	5.0 in.	Total		γ	n_f	Total
A	835	18.6	33.9	39.8	92.3	5	40	422	462
B	235	4.4	9.4	11.9	25.7	5	0	128	128
C	220	9.5	7.3	5.2	22.0	5	0	110	110
D	245	-(b)	-(b)	-(b)	-(b)	5	0	130 ^(c)	130
E	165	-(b)	-(b)	-(b)	-(b)	5	0	88 ^(c)	88

(a) In the routine film-badge evaluation a factor of 3.6 mrem/track/29 fields was used in the evaluation of the dose equivalent due to fast neutrons.

(b) These individuals were not always in the same location as a TE chamber; hence, an accurate knowledge of their absorbed doses is not available.

(c) Obtained using 1.9 ± 0.1 mrem/track/29 fields.

By means of the dose equivalent obtained from the absorbed dose and effective quality factor measurements and the observed number of recoil-proton tracks in 29 microscopic fields ($2.46 \times 10^{-2} \text{ cm}^2$) as recorded by the film badges of personnel A, B, and C, a gross estimate of the response of the film badge to the stray radiation field in the EPT area was found to be 1.9 ± 0.1 mrem/track/29 fields. This confirms previous indications that the response factor of 3.6 mrem/track/29 fields used in the routine evaluation of film badges, as obtained from a Pu-Be calibration, overestimates the dose equivalent due to fast neutrons at the ZGS by approximately a factor of 2. We are presently undertaking an extensive study of the response of the ANL film badge to the stray radiation field of the ZGS.

Using the response factor of 1.9 mrem/track/29 fields, as indicated by the personal film badges, and assuming that the proportion of the total dose equivalent received by the experimental film badges during each targeting mode is the same as is indicated by the known absorbed dose to personnel A and B (C operated a TE chamber at a single stationary position; hence his absorbed dose is unrelated to experimental film badge indications), i.e., 20% at 0.5 in., 37% at 2.5 in., and 43% at 5.0 in., an estimate of the average absorbed dose rate as detected by experimental film badges attached to the surface of the side and roof shield walls was obtained and is given in Table III.

TABLE III. Absorbed Dose Rates

Position ^(a)	Average Absorbed Dose Rate, mrad/hr			Position ^(a)	Average Absorbed Dose Rate, mrad/hr		
	0.5 in.	2.5 in.	5.0 in.		0.5 in.	2.5 in.	5.0 in.
1FS	9.5	25.8	45.1	1FT	38.9	105.2	182.9
2FS	8.7	23.7	41.2	2FT	53.2	143.4	248.6
3FS	16.3	44.5	78.1	3FT	40.8	109.6	189.5
4FS	17.3	47.2	82.4	4FT	32.8	89.4	153.7
5FS	8.3	22.4	39.0	5FT	23.9	65.28	114.22
6FS	5.8	15.7	27.7	6FT	32.0	86.0	149.5
7FS	7.4	20.2	35.2	7FT ^(b)	10.9	29.4	51.6

(a) Corresponds to locations shown on Figs. 3 and 5.

(b) Position 7FT had 6.0 ft of concrete shielding; all others at top had 4.5 ft.

C. Dependence of Radiation Levels on Target Thickness

The absorbed dose as detected by the TE ionization chambers (normalized to a beam of 10^{10} incident protons) is plotted as a function of target thickness for each of the angular positions 1A to 7A at the side in Fig. 6 and for positions 1T to 7T at the top in Fig. 7. The dotted lines in these figures are the results at position 7, i.e., $\theta = 15^\circ$. There is a direct linear dependence of the absorbed dose with target thickness, both at the side and at the roof, which is to be expected because of the increased number of secondaries emitted from the target with increasing thickness. These levels reach a maximum at about $\theta = 60^\circ$ from the incident beam-line and then fall off at either side of this position. This is more apparent in Fig. 8, where the data of Figs. 6 and 7 have been plotted in a form which indicates the angular dependence. The rising tail seen in this distribution at small angles, especially evident for the 0.5-in. target, is due to the increased particle emission in the forward direction and also to interactions along the aluminum beam pipe by the incident beam particles not having interacted in the target.

Fig. 6. Absorbed Doses for Side Shielding

Fig. 7. Absorbed Doses for Top Shielding

Fig. 8. Angular Dependence of Absorbed Dose

E. Calculation of λ_s and λ_c

Previous experimental studies of the nuclear cascade in steel⁸ and concrete^{9,10} indicate that there is a region in which a buildup of high-energy secondaries occurs, followed by a region of approximately exponential attenuation with characteristic attenuation lengths λ_s and λ_c for the shield materials. Accordingly, the flux at some distance r at an angle θ with the incident-beam direction is described by the expression

$$\phi(r, \theta) = \frac{BQ(\theta) e^{-t/\lambda}}{2\pi r^2 \sin \theta},$$

where B is the constant "buildup factor," $Q(\theta)d\theta$ is the number of neutrons emitted per second into the angle $d\theta$ about θ , r is the line-of-sight distance from the target to the point of interest, and t is the effective thickness of shield

D. Dependence of Radiation Levels on Distance from the Shield

The distribution of the absorbed dose rate (mrad/hr) as a function of distance from the inside shield wall is shown in Fig. 9. The points from 7.5 to 28 ft were obtained with a TE ionization chamber. A smooth curve drawn through these points is seen to intersect the point obtained from the film-badge measurements (marked FB). An area in which the levels drop rapidly, approximately as $1/r^2$, is followed by an area of less steep decline which approximates a $1/r$ curve. The latter portion of the curve is attributed to scattered radiation from the higher levels penetrating the roof shield, i.e., sky shine, although it may be that the detector is "seeing" the wall as an area source. A more definitive statement about this dependence must await more extensive experimentation in which increased roof shielding can be used to depress the amount of scattered radiation reaching the detector.

Fig. 9. Absorbed Dose Rate as a Function of Distance from Inside Shield Wall for a 5-in. Copper Target

material with exponential attenuation length λ (see Fig. 10). It has been assumed that the thickness in which buildup occurs is independent of di-

d = layer in which exponential attenuation occurs.

d_b = layer in which buildup occurs, assumed to be constant with θ .

Fig. 10. Geometrical Arrangement for Calculation of Attenuation Lengths

rection θ . The buildup factor B is also a function of θ , but for the purpose of this analysis is considered to be constant. It is believed that these two considerations are reasonable for the purpose of this estimate. In terms of d , the perpendicular thickness of the shield after the buildup layer has been passed, one can write

$$e^{-t/\lambda} = e^{-d \csc \theta / \lambda} \quad (2)$$

One eliminates the unknown buildup factor B by taking ratios of flux values at two different angles θ , i.e.,

$$\frac{\phi_T(r_1, \theta_1)}{\phi_T(r_2, \theta_2)} = \frac{\phi_T(r_{1i}, \theta_1)}{\phi_T(r_{2i}, \theta_2)} \frac{(r_{1i}/r_1)^2}{(r_{2i}/r_2)^2} e^{-(d_{cT}/\lambda_c)(\csc \theta_1 - \csc \theta_2)}, \quad (3)$$

where one has determined $Q(\theta)$ from $Q(\theta)d\theta = \phi_T(r_{1i}, \theta_1) 2\pi r_{1i}^2 \sin \theta_1 d\theta$, with r_{1i} being the distance from the target to the inside of the shield wall along the radial vector $\vec{r}_1$ at angle θ_1 , and $\phi_T(r_{1i}, \theta_1)$ is the flux at that point. The subscript c refers to the material (concrete), and the subscript T refers to top, i.e., top shielding. From eq. (3) one obtains

$$\lambda_c = \frac{d_{cT}(\csc \theta_2 - \csc \theta_1)}{\ln \left\{ \left[\frac{(r_{2i}/r_1)^2}{(r_{2i}/r_1)^2} R_T \right] \right\}}, \quad (4)$$

where

$$R_T = \frac{\frac{\phi_T(r_1, \theta_1)}{\phi_T(r_2, \theta_2)}}{\frac{\phi_T(r_{1i}, \theta_1)}{\phi_T(r_{2i}, \theta_2)}} \quad (5)$$

One notes that since ratios of flux values are used, the unit of measurement is unimportant, i.e., any quantity proportional to flux can be used. In eq. (4) all quantities are measurable. Using the value 1.5 ft from Citron et al.⁹ as

the thickness of the buildup layer, one obtains $d_{cT} = 3.0$ ft. A similar analysis of eq. (1) for the side shield, where steel and concrete are the materials, yields the expression

$$\lambda_s = \frac{d_{ss}(\csc \theta_1 - \csc \theta_2)}{\ln \left\{ \left[\frac{(r_{2i}/r_{1i})^2}{(r_2/r_1)} \right] R_S \right\} + \frac{d_{cs}}{\lambda_c} (\csc \theta_1 - \csc \theta_2)} \quad (6)$$

where

$$R_S = \frac{\frac{\phi_S(r_1, \theta_1)}{\phi_S(r_2, \theta_2)}}{\frac{\phi_S(r_{1i}, \theta_1)}{\phi_S(r_{2i}, \theta_2)}} \quad (7)$$

Again, all quantities in eq. (6) are measurable, with d_{ss} , the effective thickness of steel at the side shield, 1.17 ft. It is assumed here that the buildup occurs within a 0.33-ft layer of steel, as indicated by the data of Ref. 8.

Inserting values for $\phi_S(r, \theta)$ and $\phi_T(r, \theta)$ at two different angles at the outside surface of the shield walls, obtained from film-badge results, and values of $\phi_S(r_i, \theta)$ and $\phi_T(r_i, \theta)$ at two different angles at the inside surface of the shield walls, obtained from polyethylene foils, eqs. (4) and (6) yield the values λ_s and λ_c shown in Table IV, where we also list values found elsewhere. One notes that the agreement for λ_s is excellent. On the other hand, the value of λ_c agrees within the experimental error with the values given in Refs. 9 and 11, but is in disagreement with the value quoted in Ref. 10. Resolution of these differences is of prime importance to shielding calculations and must await more extensive experiments which are planned for the near future.

TABLE IV. Mean Attenuation Lengths, g/cm²

	This Experiment	Ref. 8, p. 59	Ref. 9, p. 97	Ref. 10	R. Thomas at 6 BeV, Ref. 11
λ_s	142 ± 15	145	-	-	-
λ_c	173 ± 18	-	145 ± 10	108	160

F. Evaluation of Proposed Shielding

The shielding configuration proposed for future thick-target bombardment experiments is shown in Fig. 11, where the thickness of steel at the inside of the shield wall has been increased from 1.5 to 3.0 ft and is followed by 3.0 ft of concrete. That this shield configuration should be adequate can be found by inserting appropriate numbers into eq. (1) above. The source strength $Q(60)$ --where the maximum levels were found--is obtained from,

$$Q(\theta) = srfY, \quad (8)$$

where s is the beam strength in protons/pulse, r is the repetition rate in pulses/sec, f is the fraction of total neutrons emitted from the target which are emitted into θ , and Y is the total number of neutrons with energy $E > 150$ MeV emitted into all angles. The value used for f_{60} (i.e., $f_{60} \approx 0.03$) was obtained from Ref. 8 with the assumption that equal numbers of neutrons and protons are emitted. The yield $Y = 8$ was obtained from the report of Moyer.¹² Using an average beam strength of 6×10^{10} protons/pulse and a repetition rate of 1 pulse every 3 sec, one obtains $Q(60) = 4.8 \times 10^9$ n/sec. Inserting this value into eq. (1) and using $B_s = 3$ (from Ref. 8), one obtains the value $\phi(60^\circ) = 12.8$ n/cm²-sec. Applying the conversion 10^7 n/cm² = 1 rem, which Moyer describes as conservative, from which one obtains 7 n/cm² sec = 2.5 mrem/hr, one obtains $\dot{D}_E = 4.6$ mrem/hr at the exterior surface of the shield wall as the highest level to be expected. The rapid decrease with distance as shown in Fig. 9 will further reduce this level in accessible areas. These calculations indicate that the proposed shielding should be sufficient for purposes of personnel protection (i.e., less than 2.5 mrem/hr in areas of continuous 40-hr/wk occupancy) for beam strengths of the order of those reached for this experiment. The contribution due to gamma radiation is neglected since the data of Table II indicates that this component contributes less than 10% of the total.

Fig. 11
Proposed Shielding Configuration for Thick-target Bombardments

V. CONCLUSIONS

Data collected with personnel-monitoring film badges, experimental film badges, TE absorbed-dose detectors, and a LET spectrometer show that the effectiveness of the shield walls and roof of the external proton tunnel must be increased for experiments using thick targets (approximately one interaction length). It was found that the radiation levels increased linearly with increasing target thickness and that these levels were greatest at angles between 60 and 70°, where an appreciable number of secondaries are emitted from the target and where the effective path length through the shield is less than in the forward direction. In addition, an aluminum beam pipe downstream of the target acted as a source of beam losses by the remaining proton beam. Removal of this apparatus should reduce levels in the forward (i.e., $\theta < 30^\circ$) direction. The proposed shielding configuration takes advantage of the smaller attenuation length λ_s of steel by increasing the thickness of steel at the inside of the shield to 3.0 ft and following this with 3.0 ft of concrete ($\rho = 3.8 \text{ g/cm}^2$). The roof shielding will be increased to 6.0 ft of concrete. Extensive checks of the radiation levels will be performed during "tuneup" periods prior to routine thick-target bombardment.

Estimates of the attenuation lengths λ_s and λ_c for steel and high-density concrete, respectively, were found to be in fair agreement with previously obtained values; however, the uncertainty involved in the reliability of the model employed to obtain these values requires that more extensive determinations of the shielding properties of different materials are needed in order that shielding estimates have a firm experimental basis. Additional experimental data on the angular distribution of secondary neutrons emitted from a thick target is also needed for shielding calculations. Such experiments are being planned at Argonne's ZGS for the near future.

ACKNOWLEDGMENTS

The authors wish to acknowledge the assistance of Dr. Thomas Romanowski (HEP) and his associates for their aid in the planning and coordination of this experiment and their measurements of the incident beam intensities. Also, the LET spectral measurements by R. F. Dvorak and H. R. Sebastian (IHS), and the measurements of the absorbed dose rate of the stray radiation field by L. L. Denio (IHS) are gratefully acknowledged. Many fruitful discussions with H. J. Moe (IHS) are also appreciated.

REFERENCES

1. Swartz, C. E., Levine, G. S., and Carmen, R. L., *Rev. Sci. Instr.* **34**, 1398, (1963).
2. Romanowski, T. A., private communication.
3. Rossi, H. H., and Failla, G., *Nucleonics* **14**(2), 32 (1956).
4. Shonka, F. R., Rose, J. E., and Failla, G., *Proc. 2nd Int. Conf. Peaceful Uses Atom. Energy*, Geneva, Switzerland, 1958 **21**, 753 (1958).
5. Rossi, H. H., in *Radiation Dosimetry*, Hine & Brownell, 2nd Ed., p. 681, (1958).
6. Dvorak, R. F., Paper Presented at the 1966 Rome Meeting of the International Radiation Protection Association.
7. Rossi, H. H., *Radiology* **64**, 404-411 (1955).
8. Citron, A., *et al.*, *Nuclear Measurements and Instruments* **32**, 45-69 (1965).
9. Citron, A., *et al.*, *Nuclear Measurements and Instruments* **14**, 97-100 (1961).
10. Smith, A. R., *et al.*, *Radiation Field Inside a Thick Concrete Shield for 6.2-BeV Incident Protons*, UCRL-11331.
11. Thomas, R., *Shielding Experiment at 6 GeV*, UCID-10021.
12. Moyer, B., *Evaluation of Shielding Required for the Improved Bevatron*, UCRL-9769.