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Technical Report

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GAMMA-RAY SHIELDING EFFECTS
OF METAL DOORS IN DUCTS

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U. S. NAVAL CIVIL ENGINEERING LABORATORY
Port Hueneme, California

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GAMMA-RAY SHIELDING EFFECTS OF METAL DOORS IN DUCTS

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by

P. R. Bryson and J. S. Grant

ABSTRACT

Results are presented of an experiment carried out on the shielding effects of a steel door in a two-legged 11 x 11-inch concrete duct using Co^{60} as a gamma-ray source. Two door positions and two door thicknesses were used. A relatively strong Inscatter effect was measured when the door was placed at the corner where direct radiation was received. When a 3/8-inch steel door was placed in the second leg 22 inches from the corner, the radiation was reduced 50 to 60 percent. It can be expected that the farther down the second leg the door is placed, the less radiation it will transmit; that the thicker the door, the greater its shielding effectiveness will be. A method of scaling the results to large ducts is presented based on the experimental measurements.

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The Laboratory invites comment on this report, particularly on the
results obtained by those who have applied the information.

INTRODUCTION

Experimental measurements of the effects of a steel door on the gamma-ray streaming in an 11-inch-square concrete duct were made as part of the radiation shielding studies being conducted at the U. S. Naval Civil Engineering Laboratory. The present work was done to secure information that might aid in determining the attenuation factor obtained by placing a steel door in the entranceway of a radiation shelter and to determine the effects of changing the thickness and location of the door. To make it possible to scale the results for the small experimental duct to large-sized entranceways, additional measurements were made to determine the contributions due to corner-lip penetration.

THEORETICAL CONSIDERATIONS

Considerable success has been achieved in explaining and calculating gamma-ray streaming in two-legged ducts using basic scattering principles.^{1, 2, 3, 4} In harmony with these basic principles, duct streaming may be divided into two parts: that which is scattered from the surfaces within the duct without penetration, and that which penetrates the corner lip in the scattering process. The part of the streaming which involves only surface scattering is called the "scaling part" in this study because it is readily scaled from one duct size to another. When the leg lengths of the two ducts are in proportion to their widths, the scaling can be done by using the formula

$$Af_{(\text{large duct})} = Af_{(\text{small duct})} \left(\frac{\ell_1}{L_1} \right)^2$$

where Af is the attenuation factor, and ℓ_1 and L_1 are the first leg lengths or source distances, for the small and large ducts respectively. The source distances used in this investigation were 39.4 and 20.8 inches, measured from the intersection of the centerlines of the first and second legs.

The corner-lip effect does not scale with the size of the duct. The scaling part of the radiation was obtained by subtracting the corner-lip contribution from the total streaming in the following manner. The total dose rate in the second leg was measured with the duct open; then lead shielding was placed at the corner of the duct, and the corner-lip contribution was measured; the latter measurements were subtracted from the former to give the scaling contribution.

DESCRIPTION OF APPARATUS

A 2.2-currie Co^{60} source was used for most of the measurements and was considered to be a point source. It was necessary to use a 0.26-currie Co^{60} source when taking Geiger counts with the 20.8-inch first leg lengths because of the high count rate. These readings were normalized to the large source readings by using a factor of 8.5.

Dose rates were measured with 100-mr and 10-mr Landsverk dosimeters. These dosimeters have been compared and found to give slightly different readings, in the ratio of 1.05 to 1.00 respectively. A second 10-mr Landsverk dosimeter, used for a few of the early measurements, was found to give consistently lower readings than the other, with the ratio of 0.95 to 1.00. All dosimeter readings were converted to agree with the most used 10-mr dosimeter by using the appropriate conversion factors. Measurements that were to be critically compared were made with the same dosimeter when possible to minimize error from this source.

The Geiger counts were made as a general check of the results of the dosimeter measurements. The counts were made with a halogen-quenched tube with a stainless-steel case (Navy Type 5980/RS-2). The ratio of counts per second to milliroentgens per hour is believed to give some indication of the degradation of energy of the photons, with a relatively higher ratio indicating a higher proportion of low-energy components.

The concrete duct was formed in two sections. The first section, used as the first leg of a two-legged duct, consisted of a 40x40x24-inch block of concrete with the 11x11-inch duct running through it. The second leg was built up from blocks of convenient sizes to permit opening the duct for placement of the steel doors and lead shielding as required for the several tests. Figures 1 and 2 show two views of the duct. The lead shielding was accomplished by laying a 1x11x11-inch lead plate flat in the duct and stacking 2x4x8-inch lead bricks on it to completely block the opening.

THE EXPERIMENT

Steel Door Inscatter Measurements

Since it was expected that a steel door set at the corner where it would receive direct radiation from the source would furnish inscatter to the detector, measurements were made to determine this effect. Figure 3 illustrates the experimental arrangement. Lead bricks were used to eliminate corner-lip transmission, and the first leg was removed so as to eliminate secondary radiation. Thus only primary radiation was received by the door. Two source distances were used where the first leg would ordinarily be as indicated by dashed lines in Figure 3.

Dosimeter readings were made with the steel door at position A in the direct radiation; then similar measurements were made with the door at position B in the shadow of the lead bricks. The difference between those readings is the inscatter. Table I gives the data and computed inscatter for two different doors, 3/8-inch and 3/4-inch thick, with two source distances. Figure 4 shows the inscatter effect, with dose rate plotted against the distance from the center of the corner. Figure 5 is a graph of the Geiger-count inscatter data plotted against distance from the door in position A. This graph shows a nearly exact inverse-square relationship. It can be seen that for a source distance of 20.8 inches the inscatter of the thick door is greater than that of the thin door, whereas for a source distance of 39.4 inches just the opposite is true. This is probably due to the change in angle of incidence. The dosimeter data similarly plotted (Figure 6) shows a departure from an inverse-square relationship, indicating that the energy of the average photon is less for large values of L_2 .

Two-Legged Duct Measurements

Door at the Corner. Measurements to determine the effect of the steel door when placed at the corner of the duct were made as illustrated in Figure 7 with (a) the steel door in place, (b) the duct open, and (c) the duct blocked with lead to measure the corner-lip effect. These measurements were made at several points in the second leg, using a 3/8-inch and a 3/4-inch door, with the source positioned for first leg lengths of 39.4 inches and 20.8 inches. The difference between the readings for the open duct and the lead-blocked duct is the scaling part of the radiation streaming. The difference between the readings with the steel door in place and the lead-blocked duct gives the transmission plus inscatter for the steel door. These results are shown in Figure 9 and Tables II and III. In each case the distance is measured from the point where the centerlines of the two legs cross. The importance of the door inscatter becomes apparent when it is noted that a large portion (from 40 to 90 percent) of the scaling radiation dose with the door at this corner is due to this inscatter effect.

Door 22 Inches in the Second Leg. Three sets of measurements were made with the thin door placed in the second leg 22 inches (twice the width of the duct) from the intersection of the centerlines of the legs: (a) with only the door in place, (b) with the passage blocked with lead next to the door, and (c) with the passage blocked with lead at the corner. (See Figure 8). The measurements were made with $L_1 = 39.4$ inches and with $L_1 = 20.8$ inches. The difference between the readings for just the steel door and the readings with the lead at the corner gives the transmission plus inscatter of the door. The data is given in Tables IV and V and plotted in Figure 9 together with the plots for the corner door effect. The measurements of part (b) were not considered important to the present problem, but the data was included since it shows there is some gamma-ray penetration of walls, ceiling, and floor even at this large distance down the second leg.

DISCUSSION

The Attenuation Factor of the Steel Door

The attenuation factor of a steel door can be defined as the ratio of the total dose rate with the door in place to the total dose rate without the door. When so defined, the door offers less shielding when the attenuation factor is higher.

The following results, obtained from Tables II, III, IV, and V, are found for the experimental duct. The attenuation factors expressed in percent are averages for the several dosimeter positions.

Door at Corner				Door 22 Inches From Corner	
$L_1 = 39.4$ in.		$L_1 = 20.8$ in.		$L_1 = 39.4$ in.	$L_1 = 20.8$ in.
Thick door	Thin door	Thick door	Thin door	Thin door	Thin door
79%	97%	87%	97%	45%	51%

Note that the door is most effective when placed in the second leg out of the corner region.

The graphs of Figures 10 through 13 summarize the attenuation factors for the doors as determined in the experiment.

Calculating the Attenuation Factor of a Steel Door in a Two-Legged Duct

The above results as they stand are of use only for a concrete duct with the dimensions of the experimental duct. If they are to be useful for other ducts, the effects in terms of scaling part and corner-lip contributions must be calculated separately. The results of the calculations are given in Tables VI and VII.

From the geometry it is apparent that the door, when placed at the corner, will have very little effect on the corner penetration part of the radiation.

To apply the percent attenuation factor values to a large duct, it is necessary first to know the fraction of the radiation which penetrates the corner, and second to assume that the percent attenuation of the corner part by the door remains the same for larger ducts. This latter appears to be likely from a consideration of the geometry, but measurements in larger ducts have not been made to confirm it.

For the relative amounts of corner effect and scaling part, use can be made of the computer code set up by Chapman² for calculating duct streaming in terms of primary and secondary scattering and corner effects. Table VIII gives some values for comparison.

To illustrate the method of scaling the experimental data to fit a large duct, the following example is given. The large duct in the example is 6 x 6 feet with $L_1 = 2W$ and $L_2 = 2.5W$. This scales with the 11 x 11-inch experimental duct with $L_1 = 20.8$ inches and $L_2 = 27$ inches.

Contribution	Attenuation Factor	
	Thin Door at Corner	Thin Door at 22 Inches
Scaling part	$0.76 \times 0.85 = 0.65$ (65%)	$0.76 \times 0.36 = 0.29$ (29%)
Corner part	$0.24 \times 1.00 = 0.24$ (24%)	$0.24 \times 0.52 = 0.12$ (12%)
Total effectiveness	89%	41%

In the first of the above calculations the factor 0.76 is the fraction of the streaming due to the scaling part and is taken from Chapman's calculations. The factor 0.85 is the fraction of transmission by the door at the corner taken from Table VI, which is data from the present experiment. The factor 1.00 in the corner part calculations is used because the door at the corner does not interfere with the corner penetration.

Effect of Location and Thickness of the Door

The door should be located down the second leg of the duct away from the corner where it will not receive direct radiation because of the strong inscatter effect. Also it is expected that the farther down the second leg from the corner the more degraded, on the average, will become the radiation. This is borne out by the comparison between Geiger-count and dose-rate data. Since the mass absorption coefficients are larger for lower energy photons, it can be expected that the farther down the leg the door is placed, the less radiation it will transmit. Some support of this is given by the fact that the door at 22 inches down the second leg of the duct passes only half as much radiation as when placed at the corner position.

The thicker the door, the greater will be its shielding effectiveness. One would expect that doubling the thickness would square the transmission fraction since the thickness appears in the exponent; i.e., $e^{-\mu x}$, where μ is the linear attenuation coefficient. This does not occur with the door at the corner, but this is due to the strong inscatter effect of the door. The relationship is expected to apply down the duct away from the corner where the door inscatter effect is missing.

Error in Dosimeter Readings

The manufacturer suggests that an error of 2 percent can be expected in the dosimeter readings. A study of the data indicates this to be a little too low, with 3 percent a better value. Allowing for 3 percent error in the readings, the resulting error in the attenuation factors of the door can be rather large. Using the relationships

$$\sigma(a-b) = \sqrt{[\sigma(a)]^2 + [\sigma(b)]^2}$$

and

$$\sigma\left(\frac{a}{b}\right) = \sqrt{\left(\frac{\sigma(a)}{b}\right)^2 + \left(\frac{a \sigma(b)}{b^2}\right)^2}$$

probable errors for these examples were worked out. The values are included in Tables VI and VII, and error bars are included in Figures 10, 11, and 13.

Making due allowance for dosimeter reading errors, it is apparent that the attenuation factor of the door when placed at the corner increases appreciably as L_2 (dosimeter positions) becomes longer. This means that the door at the corner removes a smaller fraction of the radiation at points successively farther from the corner.

When the door is two duct widths down the second leg, the attenuation factor increases a very small amount, if at all, with an increase in L_2 .

On the above evidence, it is speculated that the effect of an increase of attenuation factor with an increase in L_2 becomes progressively less pronounced as the door is moved farther down the second leg.

FINDINGS

The attenuation factor of a steel door is high when placed at the corner of a two-legged duct. When placed at a point down the second leg a distance two times the duct width from the center of the corner, the 3/8-inch door removed 50 to 60 percent of the radiation. Greater reduction in transmitted dose is expected for thicker doors and for doors farther from the corner in the second leg.

ACKNOWLEDGMENTS

Appreciation is expressed to J. M. Chapman for his aid in performing the experiments and his fruitful discussion of the results.

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1. U. S. Naval Civil Engineering Laboratory. Technical Report R-289: Gamma-ray streaming through ducts, by C. M. Huddleston and W. L. Wilcoxson. Port Hueneme, Calif., Feb. 1964.
2. _____. Technical Report R-264: Computer calculations of dose rates in two-legged ducts using the albedo concept, by J. M. Chapman. Port Hueneme, Calif., Oct. 1963.
3. _____. Technical Report R-195: Attenuation of gamma radiation in a two-legged 11-inch rectangular duct, by D. W. Green. Port Hueneme, Calif., May 1962.
4. _____. Technical Report R-349: An empirical formula for calculating gamma-ray dose attenuation in concrete ducts, by W. C. Ingold and C. M. Huddleston. Nov. 1964.

Table 1. Dosimeter and Geiger-Count Data for
Steel Door Inscatter Measurements

L ₂ Dosimeter Positions (in.)	Thick Door			Thin Door		
	Door Positions		Inscatter	Door Positions		Inscatter
	A	B		A	B	
L ₁ = 39.4 inches (mr/hr)						
18	27.5	14.2	13.3	33.3	16.6	16.7
27	8.02	4.15	3.87	9.58	4.27	5.31
36	3.40	1.31	2.09	3.95	1.73	2.22
(counts/min)						
18	4,600	2,600	2,000	5,400	3,048	2,352
27	1,463	802	634	1,660	871	789
36	623	300	323	710	326	384
L ₁ = 20.8 inches (mr/hr)						
18	150.3	42.1	108.2	159.7	49.5	110.2
27	52.3	16.0	36.3	53.1	17.7	35.4
36	21.92	5.05	16.87	21.8	6.0	15.8
(counts/min)						
18	21,500	7,360	14,140	21,600	8,600	13,000
27	7,700	2,970	4,730	7,590	3,280	4,310
36	3,270	990	2,280	3,180	1,120	2,060

Table II. Dosimeter and Geiger-Count Data for Steel Door Experiments
With $L_1 = 39.4$ Inches and Door at Corner

L2 Dosimeter Positions (in.)	Open Duct (a)	Thick Door (b)	Thin Door (c)	Lead and Thin Door (d)	Total Scaling Part of Transmission (a-d)	Transmission and Inscatter of Door	
						Thick (b-d)	Thin (c-d)
(mr/hr)							
13.5	230	190	215	156	74	34	59
18.0	99.4	82.8	93.2	61.5	37.9	21.3	31.7
22.5	51.6	39.8	47.7	28.1	23.5	11.7	19.6
27.0	29.1	21.8	27.2	14.9	14.2	6.9	12.3
31.5	18.0	14.2	17.2	8.7	9.3	5.5	8.5
36.0	12.6	9.6	11.8	5.8	6.8	3.8	6.0
(counts/min)							
18.0	16,500	12,240	14,100	8,540	7,960	3,700	5,560
27.0	5,490	396	4,580	2,410	3,080	1,550	2,170
36.0	2,510	1,780	2,090	957	1,550	822	1,130
(ratio of counts/min to mr/hr)							
18.0	2.76	2.46	2.52	2.31	3.50	3.89	2.92
27.0	3.14	3.02	2.81	2.70	3.60	3.73	2.95
36.0	3.32	3.08	2.96	2.75	3.79	3.61	3.12

Table III. Dosimeter and Geiger-Count Data for Steel Door Experiments
With $L_1 = 20.8$ Inches and Door at Corner^{1/}

L ₂ Dosimeter Positions (in.)	Open Duct (a)	Thick Door (b)	Thin Door (c)	Lead and Thin Door (d)	Total Scaling Part of Transmission (a-d)	Transmission and Inscatter of Door	
						Thick (b-d)	Thin (c-d)
(mr/hr)							
13.5	2,270	1,930	2,150	1,780	490	157	371
18.0	1,014	888	978	789	225	98.8	181
22.5	507	437	486	385	122	52.3	102
27.0	268	233	257	194	74	39	62.7
31.5	151	127	148	104	47.5	23.8	44.7
36.0	89.0	79.0	90.5	60.6	28.4	18.4	29.9
(counts/min)							
18.0	146,000	133,000	137,000	114,000	32,000	19,000	23,000
27.0	43,000	35,800	39,000	28,200	14,800	7,600	10,800
36.0	16,300	12,900	14,300	9,200	7,100	3,700	5,100
(ratio of counts/min to mr/hr)							
18.0	2.39	2.49	2.33	2.40	2.36	3.20	2.11
27.0	2.67	2.55	2.52	2.43	3.31	3.23	2.84
36.0	3.05	2.70	2.62	2.51	4.16	3.34	2.84

^{1/} The dosimeter readings were made with the 100-mr dosimeter, and the Geiger-count readings were made with the small source. Both sets of readings were converted to agree with the other data.

Table IV. Dosimeter and Geiger-Count Data for Steel Door Experiment
With $L_1 = 39.4$ Inches and Thin Door at $L_2 = 2W$ (22 inches)

L_2 Dosimeter Positions (in.)	Door at 22 Inches (a)	Door at 22 Inches, Lead at Corner (b)	Door and Lead at 22 Inches (c)	Transmission Plus Inscatter of Door (a-b)
(mr/hr)				
27.0	12.7	7.0	1.20	5.70
31.5	8.37	4.21	0.97	4.16
36.0	5.67	2.88	0.82	2.79
(counts/min)				
27.0	2,234	1,070	184	1,164
31.5	1,445	682	157	763
36.0	1,009	468	137	541
(ratio of counts/min to mr/hr)				
27.0	2.94	2.56	2.62	3.39
31.5	2.87	2.70	2.68	3.05
36.0	2.95	2.70	2.77	3.23

Table V. Dosimeter and Geiger-Count Data for Steel Door Experiment
With $L_1 = 20.8$ Inches and Thin Door at $L_2 = 2W$ (22 inches)^{1/}

L_2 Dosimeter Positions (in.)	Door at 22 Inches (a)	Door at 22 Inches, Lead at Corner (b)	Door and Lead at 22 Inches (c)	Transmission Plus Inscatter of Door (a-b)
(mr/hr)				
27.0	139	106	16.0	33.0
31.5	80.3	62.2	16.8	18.1
36.0	48.2	34.3	9.3	13.9
(counts/min)				
27.0	19,600	14,700	2,220	4,900
31.5	12,200	8,760	2,440	3,440
36.0	7,360	5,100	1,320	2,260
(ratio of counts/min to mr/hr)				
27.0	2.35	2.31	2.31	2.47
31.5	2.52	2.34	2.41	3.13
36.0	2.53	2.47	2.39	2.70

^{1/} The dosimeter readings were made with the 100-mr dosimeter, and the Geiger-count readings were made with the small source. Both sets of readings were converted to agree with the other data.

Table VI. Attenuation Factors by the Door at the Corner (Scaling part)

L ₂ Dosimeter Positions (in.)	L ₁ = 39.4 Inches		L ₁ = 20.8 Inches	
	Thick Door (%)	Thin Door (%)	Thick Door (%)	Thin Door (%)
13.5	46 ± 10.6	80	32	76
18.0	56 ± 9.6	83	41	81
22.5	50 ± 7.2	83	43	83
27.0	49 ± 6.5	87	53	85
31.5	59 ± 6.6	91	50	95
36.0	56 ± 6.1	88	65	106

Table VII. Attenuation Factors by the Thin Door at L₂ = 2W

L ₂ Dosimeter Positions (in.)	L ₁ = 39.4 Inches		L ₁ = 20.8 Inches	
	Corner Part (%)	Scaling Part (%)	Corner Part (%)	Scaling Part (%)
27.0	47	40 ± 4	55	45 ± 9
31.5	48	45 ± 4	60	38 ± 8
36.0	50	41 ± 1.5	57	49 ± 8

Table VII. The Fractions of Duct Streaming Due to Corner Effect
and to Scaling Part

Method	Square Duct	L ₁	L ₂	Corner Lip	Scaling Part
Experiment	11 x 11-inch	39.4"	27"	51%	49%
Experiment	11 x 11-inch	20.8"	27"	72%	28%
Chapman Calculations ²	11 x 11-inch	20.8"	27"	67%	33%
Chapman Calculations ²	6 x 6-foot	2W	2.5W	24%	76%
Ingold Calculations ⁴	6 x 6-foot	4W	4W	15%	85%
Ingold Calculations ⁴	6 x 6-foot	4W	6W	11%	89%

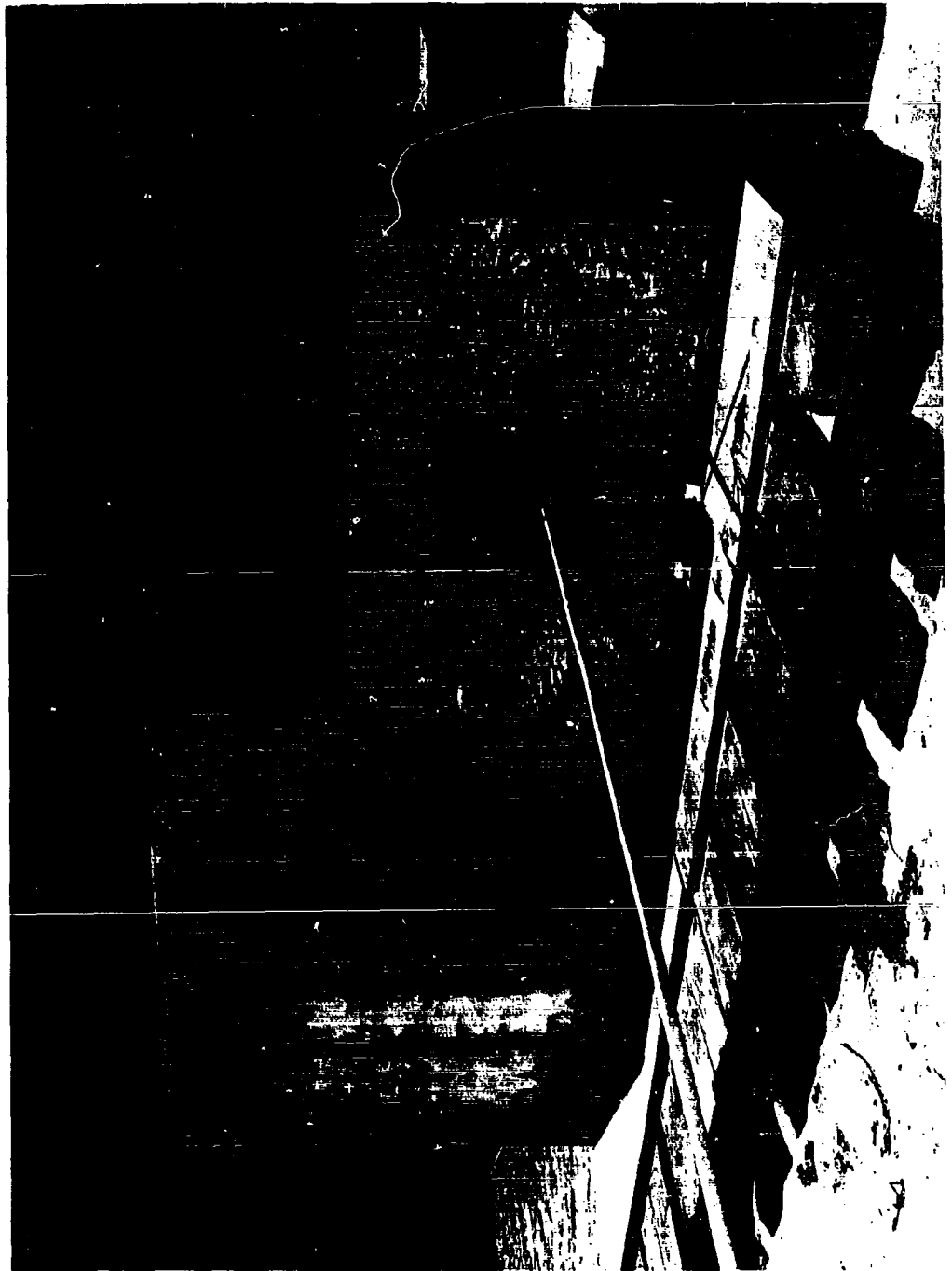


Figure 1. Photograph of first leg of duct.

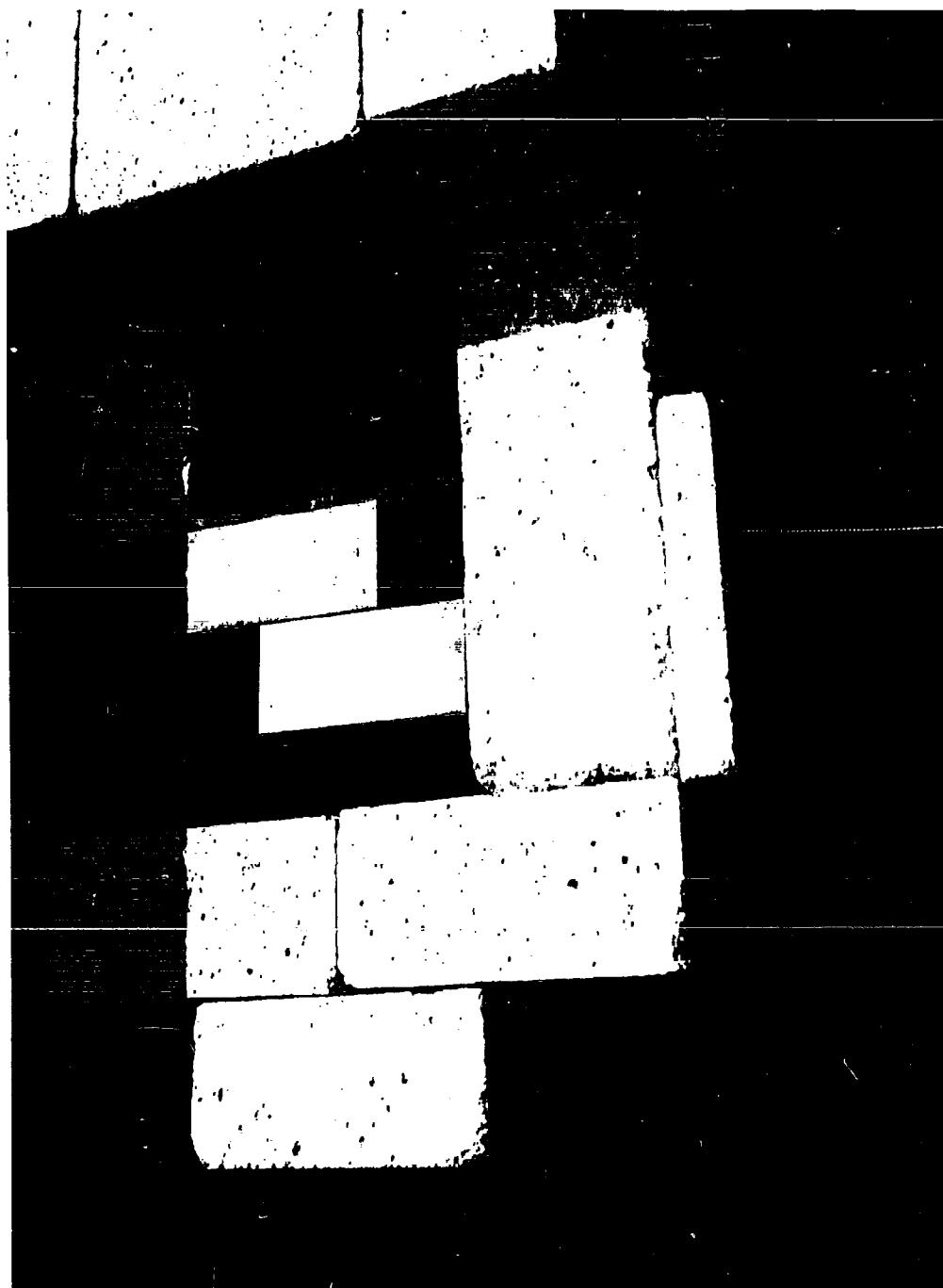


Figure 2. Photograph of second leg of duct showing steel door and lead in place.

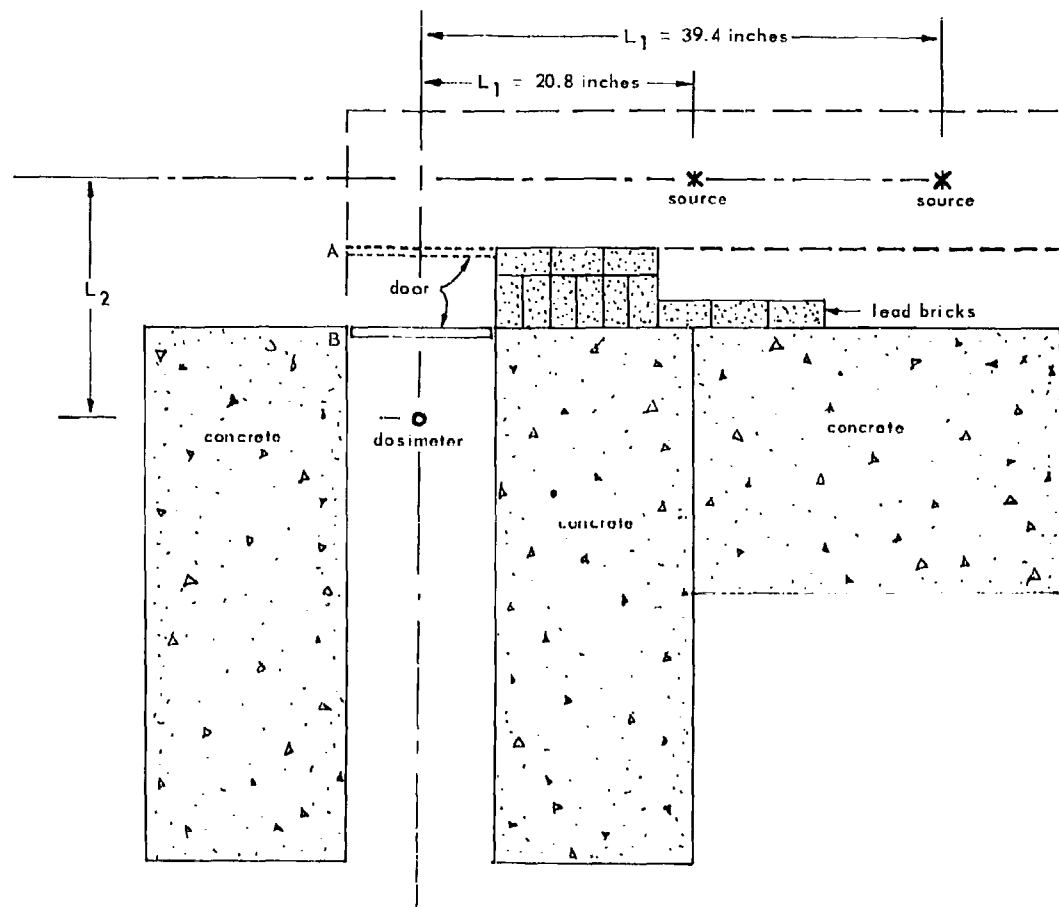


Figure 3. Plan view of inscatter experiment, with the first leg removed (indicated by dashed lines) to eliminate secondary radiation. The measurements were made with the door at position A and then position B.

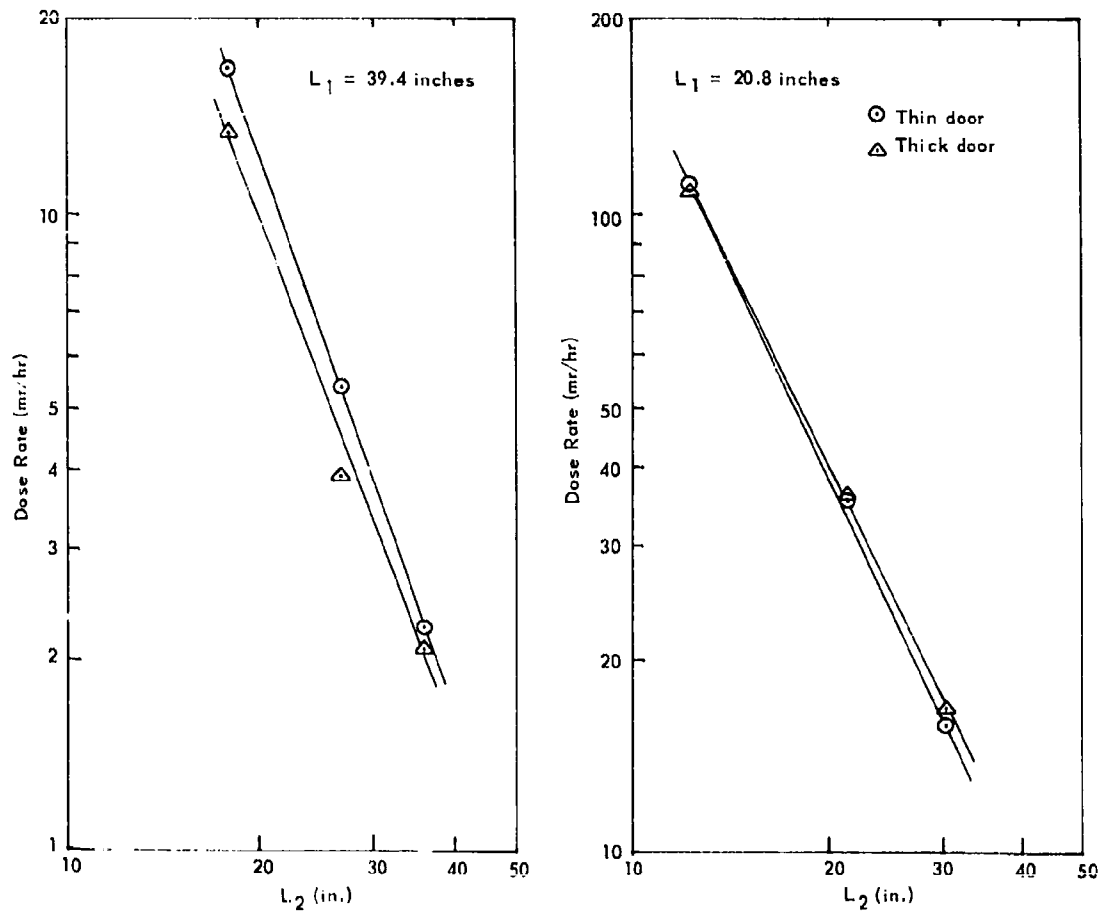


Figure 4. Dose rate due to inscatter from the steel door. The distance is measured from the center of the corner.

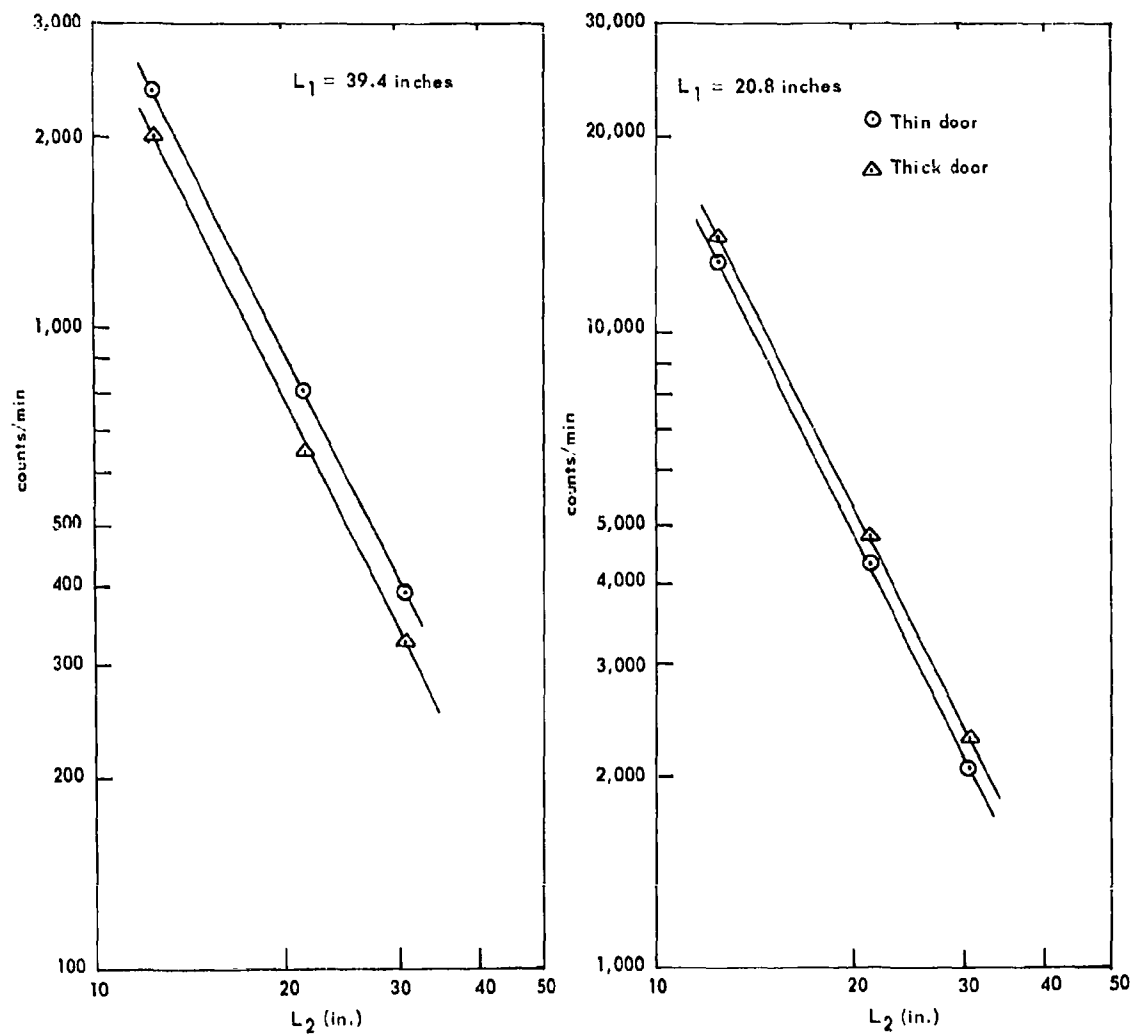


Figure 5. Geiger-count inscatter data. The distance is measured from the steel door in position A.

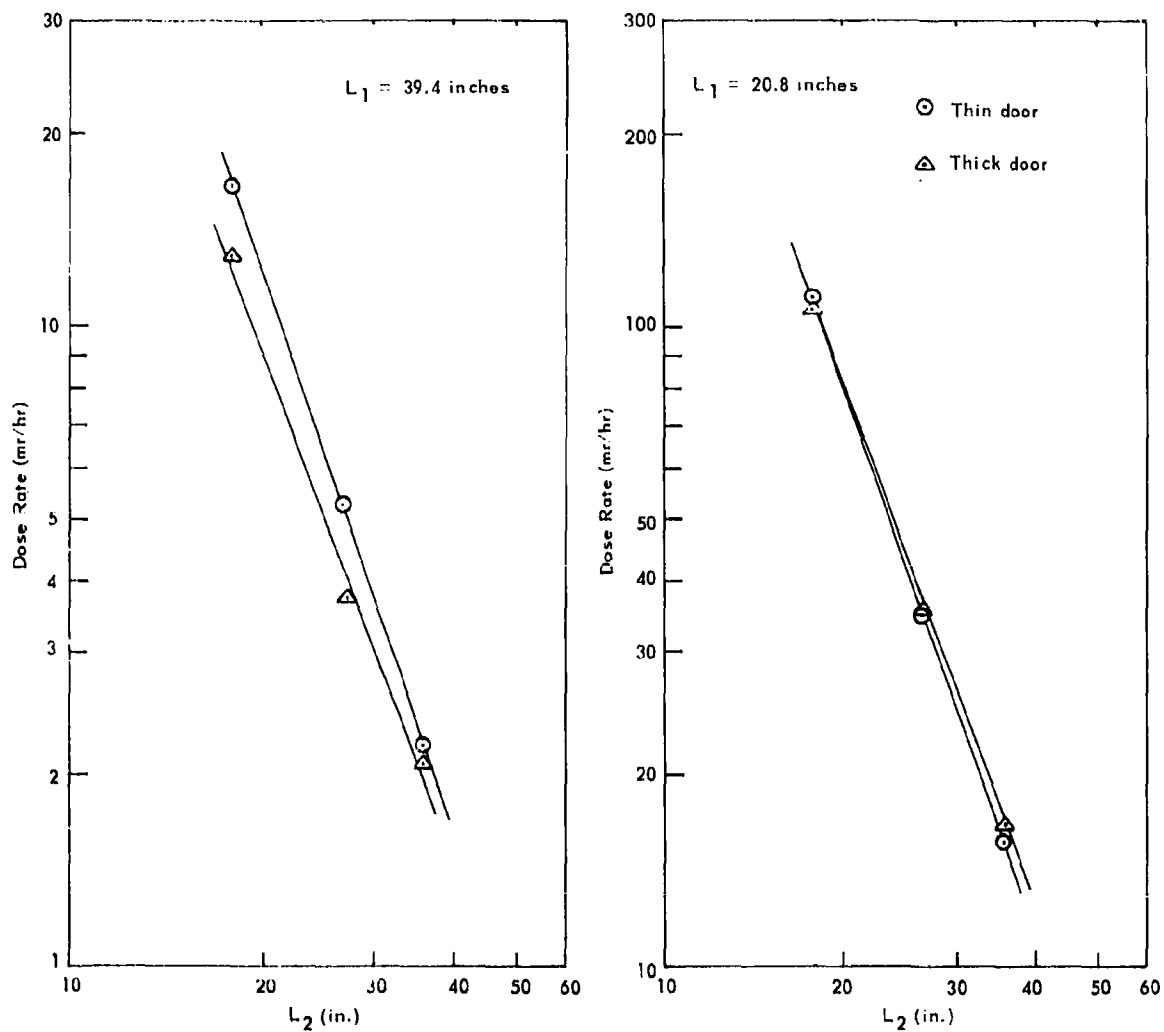


Figure 6. Dosimeter readings. The distance is measured from the steel door in position A.

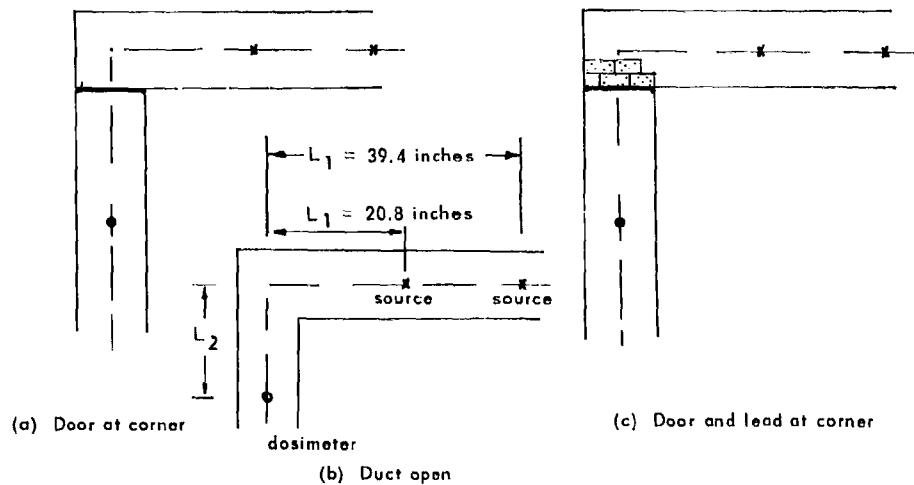


Figure 7. Diagrams of two-legged duct as used in determining the effect of the steel door in the corner, showing the method of blocking the duct with lead for measuring the corner-lip effect.

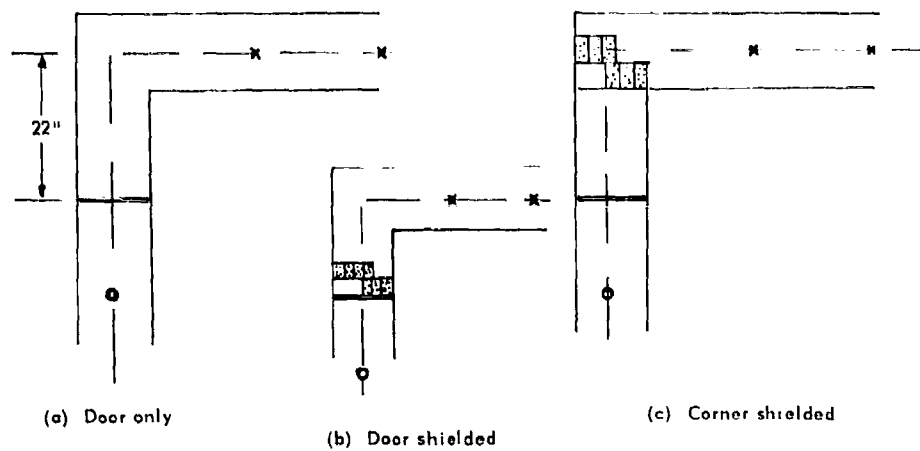


Figure 8. Diagrams of two-legged duct as used in determining the effect of the steel door 22 inches in the second leg.

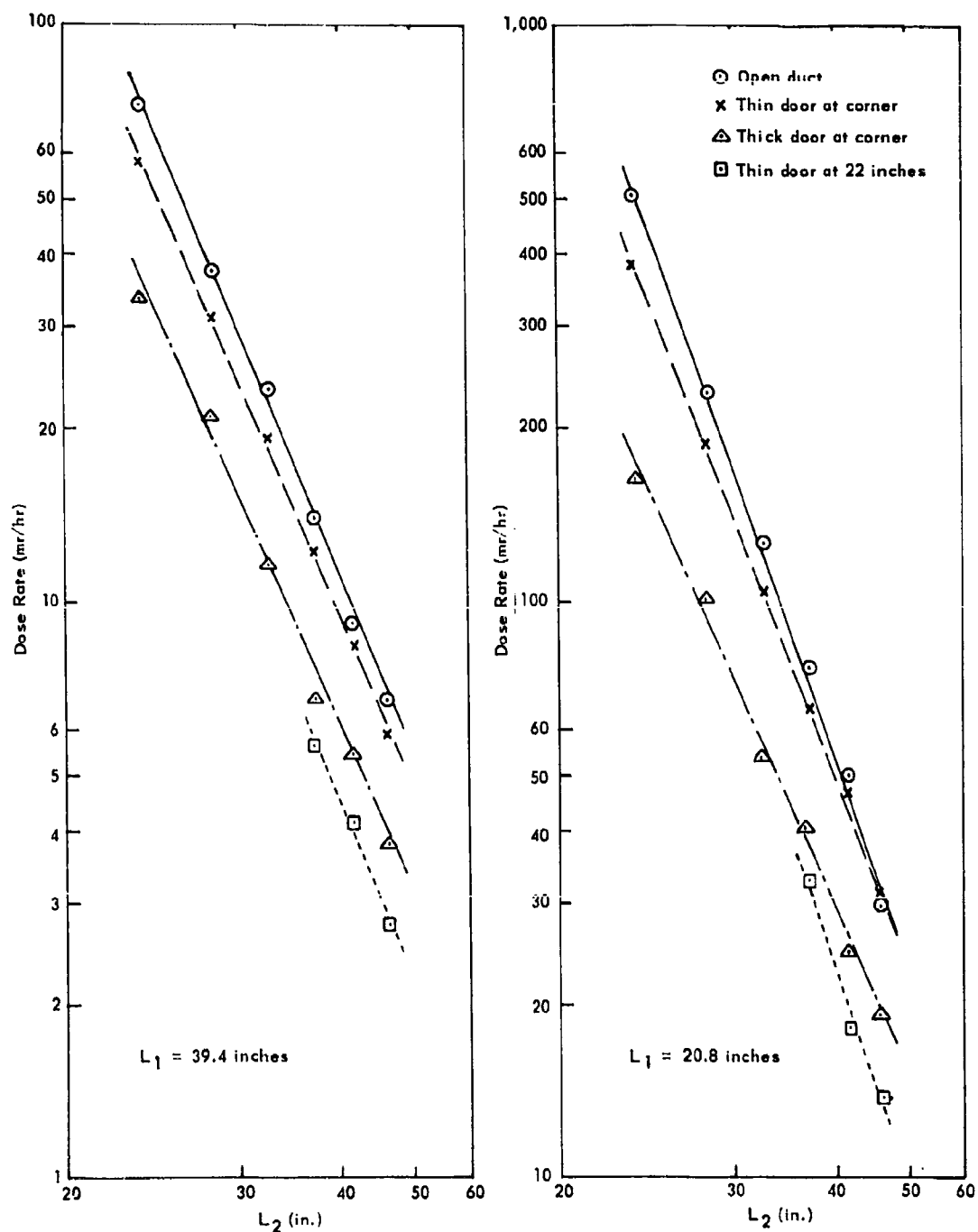


Figure 9. Dose rate due to transmission plus inscatter for the steel door at two positions in the duct.

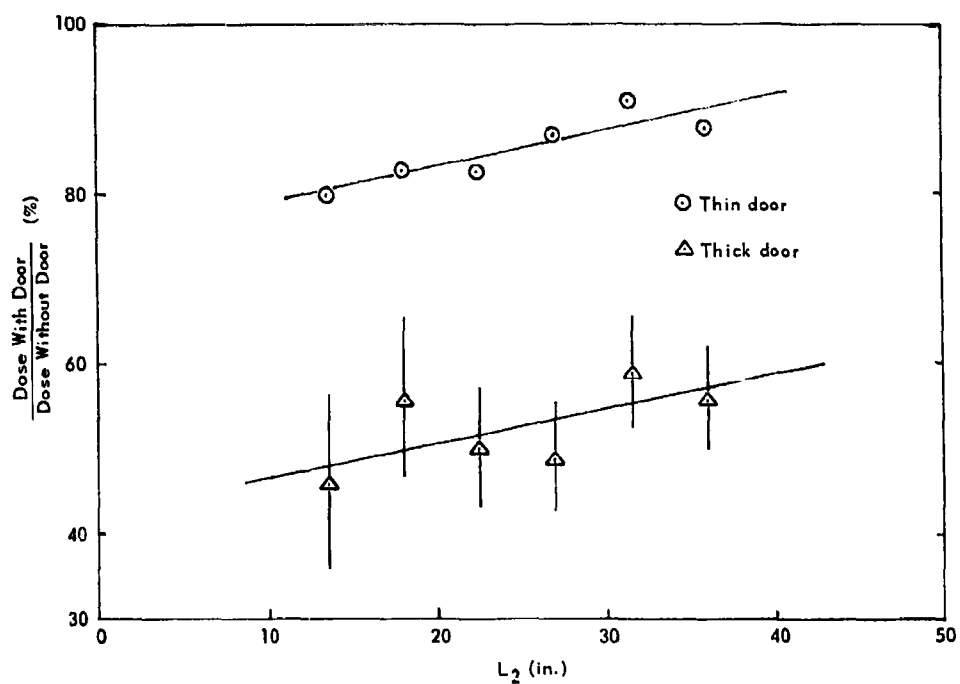


Figure 10. The effect of the attenuation factor of the door on the scaling part of the radiation when the door is at the corner and $L_1 = 39.4$ inches.

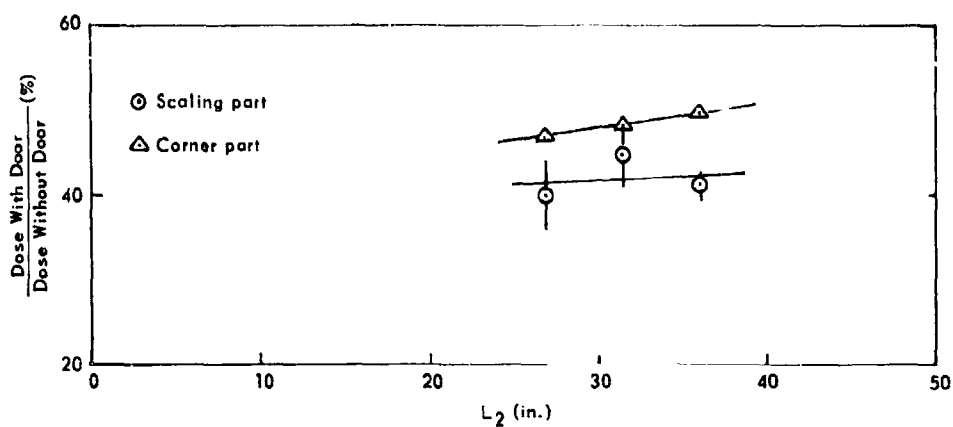


Figure 11. The attenuation factor of the thin door when the door is 22 inches from the corner and $L_1 = 39.4$ inches.

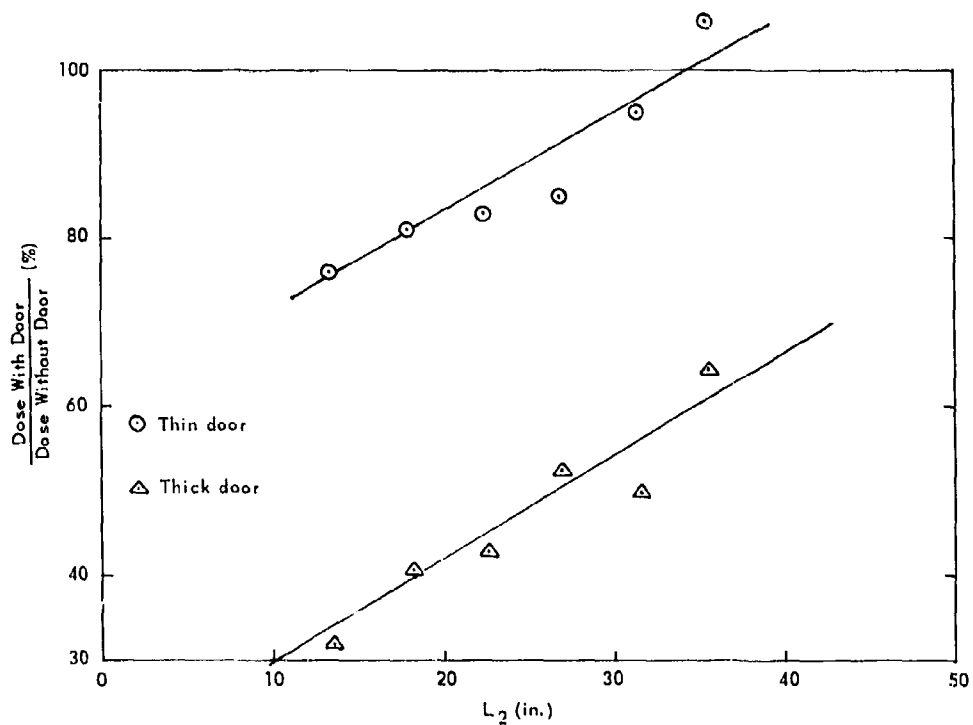


Figure 12. The effect of attenuation factor of the door on the scaling part of the radiation when the door is at the corner and $L_1 = 20.8$ inches.

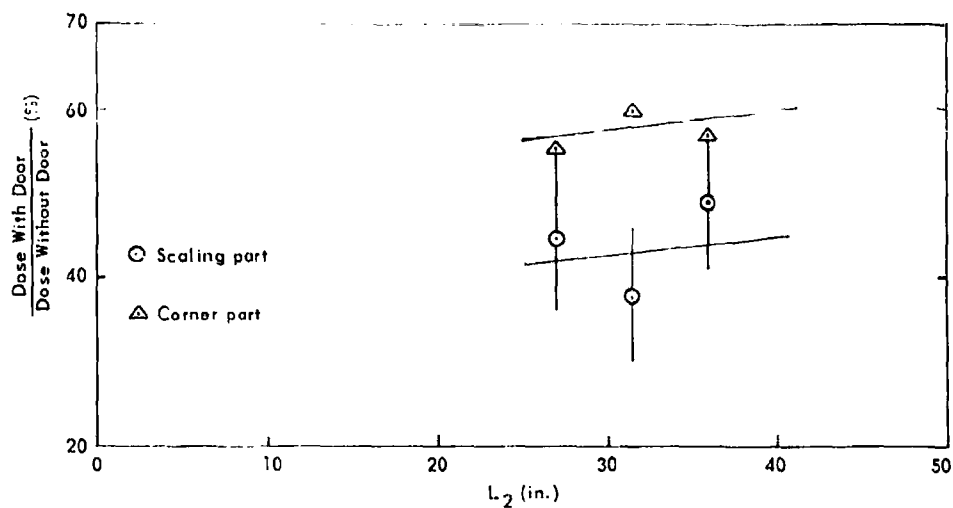


Figure 13. The attenuation factor of the door when the door is 22 inches from the corner and $L_1 = 20.8$ inches.

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13. ABSTRACT Results are presented of an experiment carried out on the shielding effects of a steel door in a two-legged 11x11-inch concrete duct using Co ⁶⁰ as a gamma-ray source. Two door positions and two door thicknesses were used. A relatively strong inscatter effect was measured when the door was placed at the corner where direct radiation was received. When a 3/8-inch steel door was placed in the second leg 22 inches from the corner, the radiation was reduced 50 to 60 percent. It can be expected that the farther down the second leg the door is placed, the less radiation it will transmit; that the thicker the door, the greater its effectiveness will be. A method of scaling the results to large ducts is presented based on the experimental measurements.		

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Doors	10					
Ducts	9					
Shelters	9					
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