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CONCRETE AS A PROTECTIVE MATERIAL AGAINST HIGH-VOLTAGE X-RAYS [1]

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ABSTRACT

A description is given of relative X-ray-transmission measurements on a group of especially prepared concrete specimens and commercial building blocks selected to sample the concrete mixes and cover the range of concrete densities in common use. It was found that the lead equivalent of any concrete was an increasing function of its mass per unit area and independent of the nature of the mix. Relations between lead equivalence, density, mass, and thickness are given, from which the thickness of concrete necessary for adequate protection can be calculated for any voltage in the voltage interval 200 to 400 kv.

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I. INTRODUCTION

Within the past few years the highest excitation potentials commonly used in X-ray therapy have been raised considerably above the 200-kv limit of 15 years ago; 400-kv equipment is now commercially available, and there are numerous X-ray generators of various types operating at potentials between 400 and 1,000 kv. There has been a corresponding extension in the application of X-rays to the inspection of metals, and in the use of X-radiation as a scientific tool in the physical laboratory. With this trend, the need for adequate protection of personnel against very penetrating radiation has become more urgent than ever.

Lead has been the most commonly used protective material, both in metallic form as sheet lead and lead shot and in combination with other materials, as in lead-rubber and X-ray protective glass. For the most penetrating X-radiation available a few years ago, no other

[1] Preliminary report presented at Fifth International Congress of Radiology, Chicago, September 1937.

protective material compared at all favorably with lead except barium, and the usefulness of the latter was limited by practical difficulties in making a homogeneous barrier. For this reason, the Advisory Committee on X-ray and Radium Protection has made all recommendations for X-ray protection [2] in terms of lead and has recommended that the effectiveness of all other materials be measured by their lead equivalents. In table 1 are given the recommended lead barriers for direct X-radiation excited by potentials up to 600 kv—the present voltage limit of the recommendations. The recommendations of the committee are given in columns 1 and 2 of table 1. Column 3 has been added to show the approximate weight per square foot of lead barrier recommended in column 2. The weight of the required barrier is seen to increase so rapidly with increasing excitation potential that above 200 kv the cost of lead for such a barrier becomes very high and the problem of supporting the required lead mass becomes serious.

TABLE 1.—*Mass of lead barrier for adequate protection*

Potential	Recommended minimum equivalent lead thickness	Weight of barrier [1]
1	2	3
kv	*mm*	*lb/ft²*
75	1.0	2.4
100	1.5	3.5
150	2.5	5.9
175	3.0	7.1
200	4.0	9.5
225	5.0	14
300	9.0	21
400	15.0	35
500	22.0	52
600	34.0	80

[1] Approximate.

One possible solution is to make the protective barrier of a material which is self-supporting. Concrete suggests itself at once. In any case, however, for radiation of a given quality, the mass of an adequate concrete barrier will always be greater than that of a corresponding lead barrier; but since the concrete is self-supporting and relatively inexpensive, this increase in weight is not particularly objectionable except in the case of installations in existing buildings unable to withstand the additional loading.

Such data [3] as have been published on the lead equivalence of concrete are old and are confined to X-ray excitation potentials not exceeding 200 kv. It is the purpose of the present paper to give the results of measurements on a series of concrete samples and commercial building blocks for X-ray potentials ranging from 200 to 400 kv.

[2] Handb. BS (1936) H20.
[3] G. W. C. Kaye, Roentgenology (Paul B. Hoeber, Inc., 1928), p. 95; Brit. J. Radiol. **23**, 158 (1937). Kaye and Owen, Proc. Phys. Soc. **35**, 33D (June 1923). C. B. Braestrup, Am. Architect (September 1929).

II. METHOD

The lead equivalent of each concrete sample was obtained by direct comparison with sheet lead, 99.9 percent pure, meeting Federal specifications for grade *A* lead. The method used is essentially that previously described for determining the lead equivalence of X-ray glass.[4] The experimental arrangement is shown in figure 1; for complete constructional details of the X-ray tube, ionization chamber, and current-measuring system, the original paper describing this apparatus should be consulted.[5]

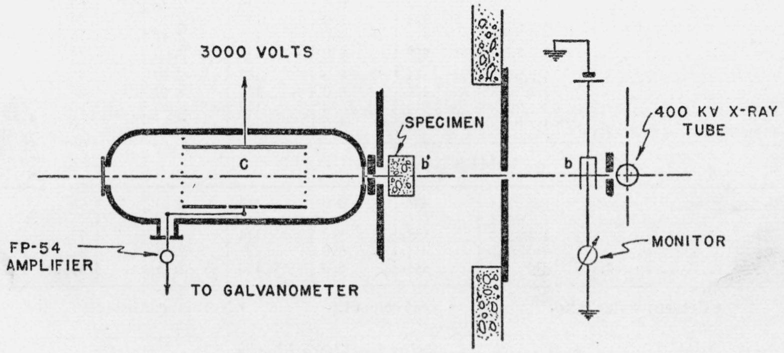

FIGURE 1.—*Diagram of apparatus used in determining the lead equivalent of concrete.*

The beam of radiation, *bb'*, emerges from the tube at an angle of 90 degrees to the tube axis, and after passing through the concrete test cylinder shown, enters the ionization chamber, *c*. The cross-section of the beam is limited by the four diaphragms shown. The resulting ionization current, after amplification, is measured by direct deflection of a high-sensitivity galvanometer in the output of the amplifier. When measuring radiation through heavy protective barriers the residual ionization current due to scattering, radioactive contamination, and cosmic radiation, is a considerable fraction of the total current measured. For such measurements requiring the highest sensitivity, a rate-of-drift method is used in order to get the benefit of a time average for this background radiation; this average remains fairly constant and affects alike the measurements of the standard filters and test specimens, so that, as a rule, no zero correction in the ionization readings is necessary.

III. DESCRIPTION OF CONCRETE

The concrete specimens on which tests were made were selected so as to cover adequately the types of mixes and range of densities most commonly used. These specimens fall into two classes, (*a*) the first consists of a group of especially prepared test specimens;[6] (*b*) the second consists of a group of solid building blocks which were obtained on the market. Tables 2 and 3 give data on all specimens.

[4] George Singer, J. Research NBS **16**, RP 870, 1936.
[5] L. S. Taylor, G. Singer, and A. L. Charlton, J. Research NBS **21**, 19 (1938) RP 1111.
[6] We are indebted to John Tucker, Jr., of the Cement Section of the National Bureau of Standards, who selected the test samples and under whose supervision they were prepared.

TABLE 2.—*Prepared concrete specimens*

Specimen	Proportions (cement to sand to gravel)	Approximate dimensions		Density of specimens at 24 hours		C/W[a] ratio	Consistency, expressed as approximate slump
		Height	Diameter				
GRAVEL CONCRETE							
		Inches	*Inches*	*lb/ft³*	*g/cm³*		*Inches*
G1	1:2.2:3.8	4¼	6.0	148	2.3_7	1.60	6
G2	1:2.2:3.8	6⅛	6.0	146	2.3_4	1.60	6
G3	1:2.2:3.8	8½	8.0	147	2.36	1.60	6
G4	1:2.2:3.8	4¼	6.0	152	2.47	1.75	3
G5	1:2.2:3.8	6⅛	6.0	147	2.36	1.75	3
G6	1:2.2:3.8	8¼	8.0	150	2.40	1.75	3
G7	1:2.2:3.8	4 5/16	6.0	150	2.40	1.90	1
G8	1:2.2:3.8	6½	6.0	150	2.40	1.90	1
G9	1:2.2:3.8	8 1/16	8.0	148	2.37	1.90	1
LIMESTONE CONCRETE							
L1	1:3.6:2.4	4⅛	6.0	144	2.31	1.75	3
L2	1:3.6:2.4	6⅜	6.0	147	2.36	1.75	3
L3	1:3.6:2.4	8 1/16	8.0	144	2.31	1.75	3
N	[b]	4 1/16	6.0	132	2.1_2	4.17	[c]
NN	[b]	4 1/16	6.0	132	2.1_2	4.17	[c]

[a] Cement-water ratio. [b] Neat cement. [c] Normal consistency.

TABLE 3.—*Solid building blocks*

Specimen	Dimensions	Density
	Inches	*g/cm³*
B4	3¾×7½×11¾	2.0_3
B6	5½×6×9	2.0_2
B8	7½×8×13	2.1_0

1. PREPARED SPECIMENS

Three types of specimens were prepared. Specimens *N* and *NN* were made of neat cement of normal consistency (24 percent of water). Specimens *G* were nominal 1:2:4 mixes, the exact cement-sand-gravel proportions being 1:2.2:3.8, respectively, by weight. Potomac River sand (quartz), fineness modulus 3.1, was used as fine aggregate. Potomac River gravel (quartz), size No. 4 to 1½ inches, was used as coarse aggregate in mix *G*, and Potomac River sand and West Virginia limestone in mix *L*. In mix *L* the sand–coarse-aggregate ratio was adjusted to give maximum density for the mix with the size limestone (No. 4 to ⅜ in.) that was available. The proportions of mix *L* were 1:3.6:2.4.

The specimens were cylinders 6 or 8 inches in diameter and approximately 4, 6, or 8 inches in thickness, the thickness in all cases was not more than the nominal diameter. They were kept in molds for 24 hours, then stored in a moist room for 3 weeks, after which they were permitted to dry slowly in laboratory air until tested. The gravel concrete was made in three wetnesses. The wettest specimen had as much water as should be used in ordinary construction; the driest was of a consistency that could be used for very special work, in which the extra cost of spading, rodding, and tamping the concrete into the form would be justified by the increase in desirable properties which could be obtained by this rather dry concrete.

2. BUILDING BLOCKS

In addition to the prepared samples, three different building blocks were tested. These are listed in table 4. These blocks were part of a purchase of several hundred made from a manufacturer and contractor in the vicinity of Washington for use in the construction of protective barriers for the 400-kv X-ray generator of the National Bureau of Standards. Block *B4* was a solid block of rectangular cross section; blocks *B6* and *B8* had the horizontal cross section of the usual three-web building block but were solid, that is, the two cylindrical cores ordinarily used in making three-web blocks were omitted. The nature of the mix was not known except that in accordance with the usual commercial practice the mix was made sufficiently dry to permit prompt removal of the blocks from the machine molds, the ideal mixture for blocks being that which will barely retain its shape when the forms are removed immediately after the concrete has been deposited and pressed into shape. This is a great deal drier than the mixtures ordinarily used in poured concrete.

TABLE 4.—*Lead equivalent of concrete*

Sample	Thickness	Diameter	Density	Lead equivalent at—					Mass per unit cross section
				200 kv	250 kv	300 kv	348 kv	400 kv	
	cm	*cm*	*g/cm³*	*mm*	*mm*	*mm*	*mm*	*mm*	*g/cm²*
G1A	10.5	15.3	2.37	1.60	2.26	3.01	3.82	4.88	24.9
G1B	10.9	15.3	2.37	1.66	2.33	3.13	3.91	4.64	25.8
G2A	15.4	15.3	2.34	2.60	3.86	5.09	6.18	7.42 7.32	36.0
G2B	15.4	15.3	2.34	2.58	3.96	5.12	6.23	7.45 7.42	36.0
G3	20.4	20.4	2.36	-------	5.97	8.03	9.86	11.00	48.1
G4A	10.9	15.3	2.47	1.70	2.40	3.17	3.97	4.73	26.9
G4B	10.7	15.3	2.47	1.70	2.37	3.12	3.98	4.66 4.68	26.4
G5A	15.4	15.3	2.36	2.63	4.01	5.13	6.30	7.40	36.3
G5B	16.0	15.3	2.36	2.77	4.20	5.44	6.66	7.97 7.92	37.8
G6A	20.6	20.3	2.40	-------	5.80	7.73	9.59	11.59	49.4
G6B	21.4	20.3	2.40	-------	6.06	8.11	9.97	12.16	51.4
G7A	10.8	15.3	2.40	1.70	2.34	3.12	3.98	4.68	25.9
G7B	10.1	15.3	2.40	1.58	2.21	2.90	3.64	4.31	24.2
G8A	16.3	15.3	2.40	2.90	4.42	5.64	6.93	8.22	39.1
G8B	16.4	15.3	2.40	2.93	4.40	5.77	6.92	8.32	39.4
G9A	20.4	20.3	2.37	-------	5.59	7.47	9.23	11.29	48.3
G9B	20.3	20.3	2.37	-------	5.76	7.70	9.48	11.58	48.1
G10A	10.1	-------	-------	1.49	2.00	2.70	3.47	4.02	-------
G10B	10.6	-------	-------	1.58	2.16	2.95	3.69	4.33	-------
G11A	15.1	-------	-------	2.36	3.74 3.73	4.89	5.97	7.02 7.06	-------
G11B	15.5	-------	-------	2.55	3.92	5.10	6.23	7.42 7.33	-------
L1A	10.7	-------	2.31	1.67	2.30	3.07	3.80 3.78	4.49	24.7
L1B	10.3	-------	2.31	1.57	2.13	2.85	3.50 3.55	4.19	23.8
L2A	15.9	-------	2.36	2.77	4.22	5.40	6.56	7.80	37.5
L2B	15.8	-------	2.36	2.78	4.19	5.39	6.57	7.76	37.3
L3A	20.4	-------	2.31	-------	5.61	7.45	9.19	11.10	47.1
L3B	20.2	-------	2.31	-------	5.57	7.33	9.02	10.92	46.7
NA	10.2	-------	2.12	1.52	2.03	2.69	3.34	3.92	21.6
NNA	10.3	-------	2.12	1.52	2.00	2.68	3.34	3.90	21.8
X	20.7	-------	-------	-------	5.72	7.67	9.44	11.52	-------
B4	-------	-------	-------	1.33	1.48	1.99	2.53	2.99 2.98	19.5
B6	-------	-------	-------	1.80	2.74 2.76 2.89	3.80	4.65 4.60 4.70	5.76 ------- 5.73	29.7
B8	-------	-------	-------	-------	4.58	6.03 6.07	7.52 7.50	9.04	41.6

IV. RESULTS

1. VARIATION OF LEAD EQUIVALENT WITH X-RAY VOLTAGE AND THICKNESS OF CONCRETE

The lead equivalent of each sample was determined at each of the following excitation potentials: 200, 250, 300, 348, and 400 kv. No beam filter was used, the only filter being 2 mm of copper and 10 mm of aluminum inherent in the X-ray tube.

The results of these tests are tabulated in table 4 and are plotted in figures 2, 3, and 4. It is apparent from these data that the lead

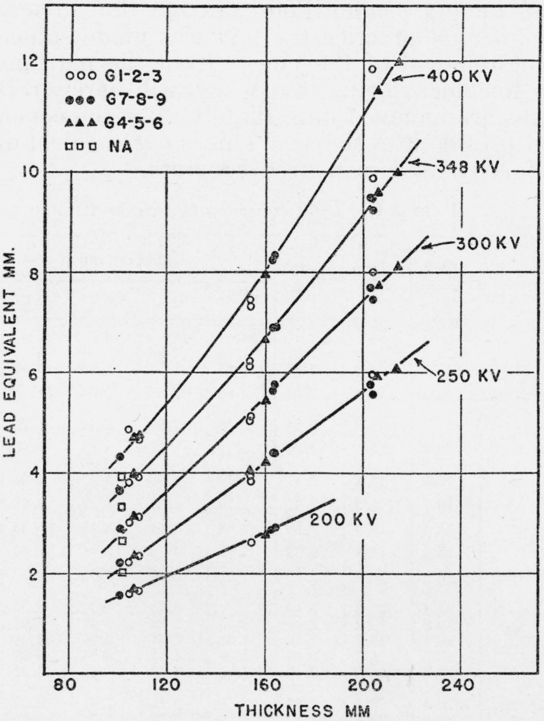

FIGURE 2.—*Variation of lead equivalent of a concrete barrier with thickness.*

See table 4 for description of specimens.

equivalent of a sample of given density depends not only on its thickness but also on the X-ray excitation potential as well, and above 200 kv.[7] increases with both.

2. VARIATION OF PROTECTION COEFFICIENT WITH DENSITY

Figure 5 is a typical plot of the protection coefficients [8] as a function of density for samples of approximately equal thickness. The samples of figure 5 were cylinders approximately 4 inches thick;

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[7] The complete curve showing the lead equivalent of concrete as a function of the excitation potential has a minimum at approximately 200 kv and a low maximum at about 100 kv. However, the portion of the curve below 200 kv is of little practical value.

[8] "Protection coefficient" has been defined as follows by the American Advisory Committee on X-ray and Radium Protection:

"The protection coefficient of a material is the ratio of the thickness of lead to the thickness of the material which absorbs a given X-ray beam to the same extent."

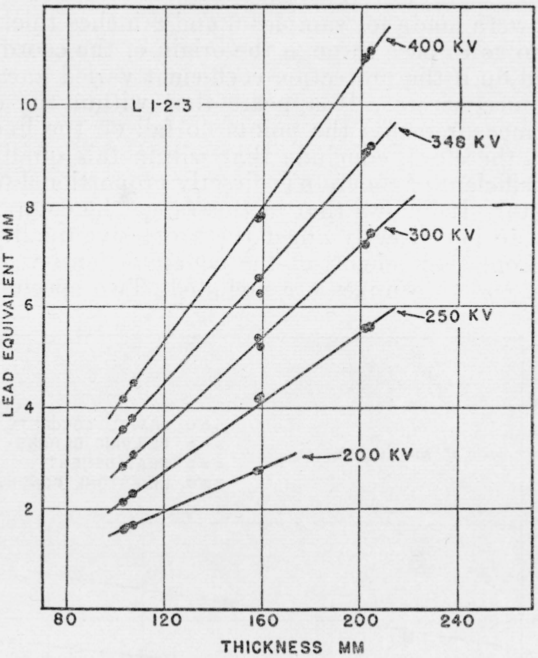

FIGURE 3.—*Variation of lead equivalent of a limestone concrete barrier with thickness.*

See table 4 for description of specimens.

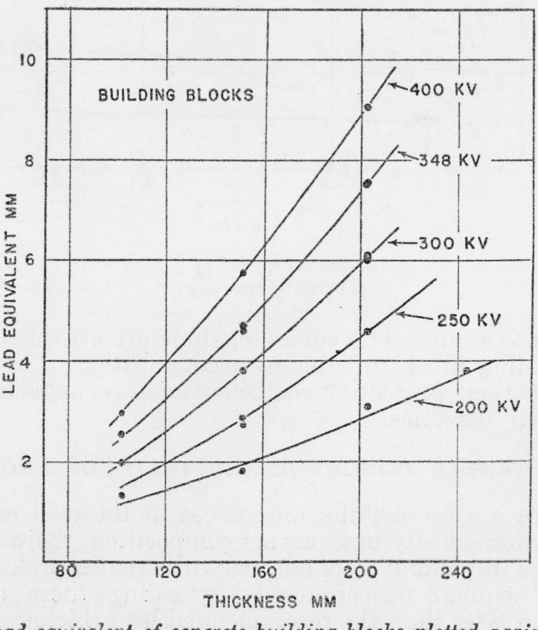

FIGURE 4.—*Lead equivalent of concrete building blocks plotted against thickness of blocks.*

See table 5 for description of specimens.

similar plots were made for samples 6 and 8 inches thick. The lines were drawn so as to pass through the origin of the coordinate system as they would do if the protection coefficient varied linearly with the density of the concrete. It appears that within the experimental error of the measurements the points do fall on the lines so drawn, and we may, therefore, conclude that within this quality range the protection coefficient of concrete is directly proportional to the density of the concrete. It follows that in this range the components of the concrete mix do not directly affect the protective quality of the material aside from their effect on the concrete density. In figure 5, four different concrete mixes are included: Two specimens are neat

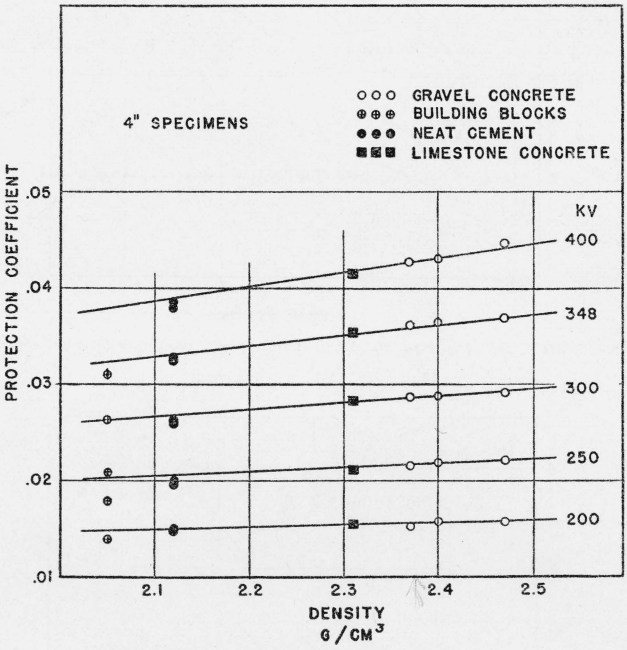

FIGURE 5.—*Variation of protection coefficient of 4-inch concrete test cylinders with density of specimens.*

cements, one is a limestone concrete, three are gravel concretes, and two are building blocks of unknown composition; yet the observed differences in their protective coefficients can be explained simply in terms of their densities.

3. THICKNESS OF CONCRETE REQUIRED FOR PROTECTION

Since there are no striking differences in the lead equivalents of samples of equal density but varying composition, there is no particular advantage in making tests on many different samples; and, therefore, all subsequent measurements extending these tests to lead equivalents greater than the recommended lead thicknesses were confined to two groups of samples designated as *G* (density 2.36) and *B* (building blocks, density 2.0 to 2.1_0). These data are summarized in table 5 and are plotted in figures 6 and 7. In these figures the intersection of the dotted curve with the full-line curves gives the thickness of this concrete required to give the degree of protection recommended by the Advisory Committee on X-ray and Radium Protection. For concrete of some slightly different density, the required thickness can be obtained if its density is known, since for

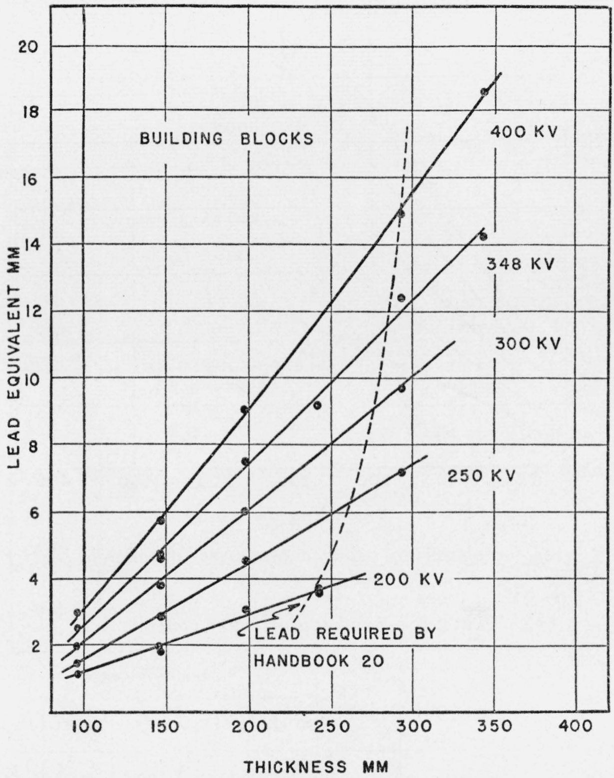

FIGURE 6.—*Curves for obtaining required thickness of barrier made of building blocks of average density 2.05 g/cm³.*

samples of approximately equal thickness the lead equivalent varies linearly with density. However, in using figures 6 and 7 to compare concretes of widely different densities, it should be remembered that the protection coefficient of a sample depends also on the sample thickness. Therefore, to determine the required thickness of any concrete it should be compared with a concrete of greater rather than with one of smaller density; by making this determination in this way a thickness somewhat greater than that required will be obtained and the error resulting will be on the safe side.

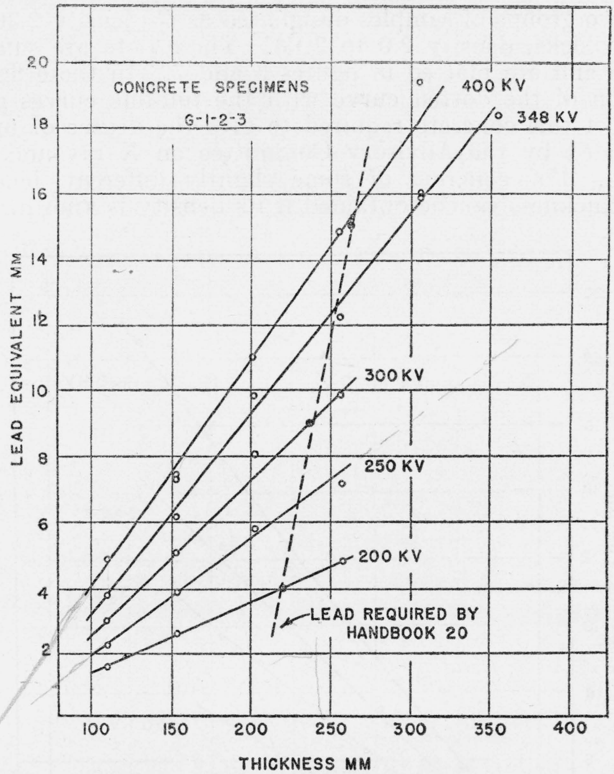

FIGURE 7.—*Curves for obtaining required thickness of concrete barrier of average density 2.35 g/cm³.*

TABLE 5.—*Lead equivalent of concrete*

Sample	Average density	Thickness	Lead equivalent					Mass per unit cross section
			200 kv	250 kv	300 kv	348 kv	400 kv	
	g/cm³	*cm*	*mm*	*mm*	*mm*	*mm*	*mm*	*g/cm³*
G1A	2.37	10.5	{1.59, 1.60}	2.26	3.01	3.82	4.88	24.9
G2A	2.34	15.4	2.60	3.86	5.09	6.18	{7.42, 7.32}	36.0
G3	2.36	20.4	------	5.97	8.03	9.86	12.00	48.1
G1A+G2A	2.35	25.9	4.79	7.14	9.81	{12.2, 12.2}	14.8	61.1
G1A+G3	2.36	30.9	------	------	------	{15.9, 15.8}	19.3	72.9
G2A+G3	2.35	35.8	------	------	------	18.3	------	84.1
B4	2.0_3	9.6	{1.15, 1.33}	1.48	1.99	2.53	{2.99, 2.98}	19.5
B6	2.0_2	14.7	{1.89, 1.80}	{2.74, 2.76, 2.89}	3.80	{4.65, 4.60, 4.70}	{5.76, 5.73}	29.7
B8	2.1_0	19.8	3.0_7	4.58	{6.03, 6.07}	{7.52, 7.50}	9.04	41.6
B4+B6	2.0_9	24.3	{3.58, 3.90, 3.67}	------	------	9.14	10.5	49.1
B4+B8	2.0_7	29.4	------	7.1_8	9.6_8	------	{14.2, 14.9}	61.2
B6+B8	2.0_6	34.5	------	------	------	14.2	18.5	71.7
Required for adequate protection	------	------	4.0	------	9.0	------	15.0	------

4. VARIATION OF LEAD EQUIVALENT OF CONCRETE WITH MASS PER UNIT AREA

All absorption data on concrete given above for various mixes, densities, and thicknesses are conveniently summarized in figure 8, in which the lead equivalent of a concrete barrier is plotted against the mass of the barrier per unit cross-sectional area. For a given voltage all samples in this graph fall on a single curve no matter what the composition, density, or thickness of the individual samples may be. For this reason the thickness of a concrete barrier required for adequate protection can be most conveniently obtained from figure 8 by use of the relation $L=M/D$, where L is the thickness of concrete barrier; M is the mass of barrier per unit area required to give the desired degree of protection—obtained from figure 8; and D is the density of the concrete used.

As has already been noted, the curves in figures 6 and 7 must be used with caution when the density of a given concrete is widely different from those used as standards in these two graphs. It is clear that no such precautions are necessary in making the same determination by means of figure 8 and for this reason its use is recommended.

5. CONCRETE-LEAD MASS RATIO

In figure 8 the dotted curve is for metallic lead; this is included for the purpose of comparing the mass of a concrete wall with that of a lead barrier providing equivalent protection. Table 6 contains a summary of such a comparison for 200-, 300-, and 400-kv radiation.

In column 5 of table 6 there are given the ratios of the mass of a concrete barrier to the mass of its lead equivalent. The ratio is high at the lower excitation potentials; at 200 kv an adequate concrete barrier has about 12 times the mass of its lead equivalent, while at 400 kv the concrete barrier has only 3.5 times the mass of an equivalent lead shield.

TABLE 6.—*Concrete-lead mass ratio*

Potential	Recommended lead equivalent	Mass per unit area		Mass of concrete / Mass of lead
		Lead	Concrete	
1	2	3	4	5
kv	*mm*	*g/cm²*	*g/cm²*	
200	4.0	4.5	53	11.8
300	9.0	10.2	57	5.6
400	15.0	17.0	60	3.5

V. CONCLUSION

Since the protection coefficient of concrete increases rapidly with increasing excitation potential, the thickness of the concrete barrier which will provide adequate protection at, say 400 kv, is not very much greater than that required to give the same degree of protection at a much lower voltage. So, from figure 6, we see that for the building blocks tested, a barrier about 30 cm (11.8 in.) is adequate at 400 kv, while at 200 kv the thickness required is about 22 cm (8.7 in.). Similarly, from figure 7, the thickness of concrete required at 400 kv is about 26.5 cm, while the required thickness at 200 is 22 cm.

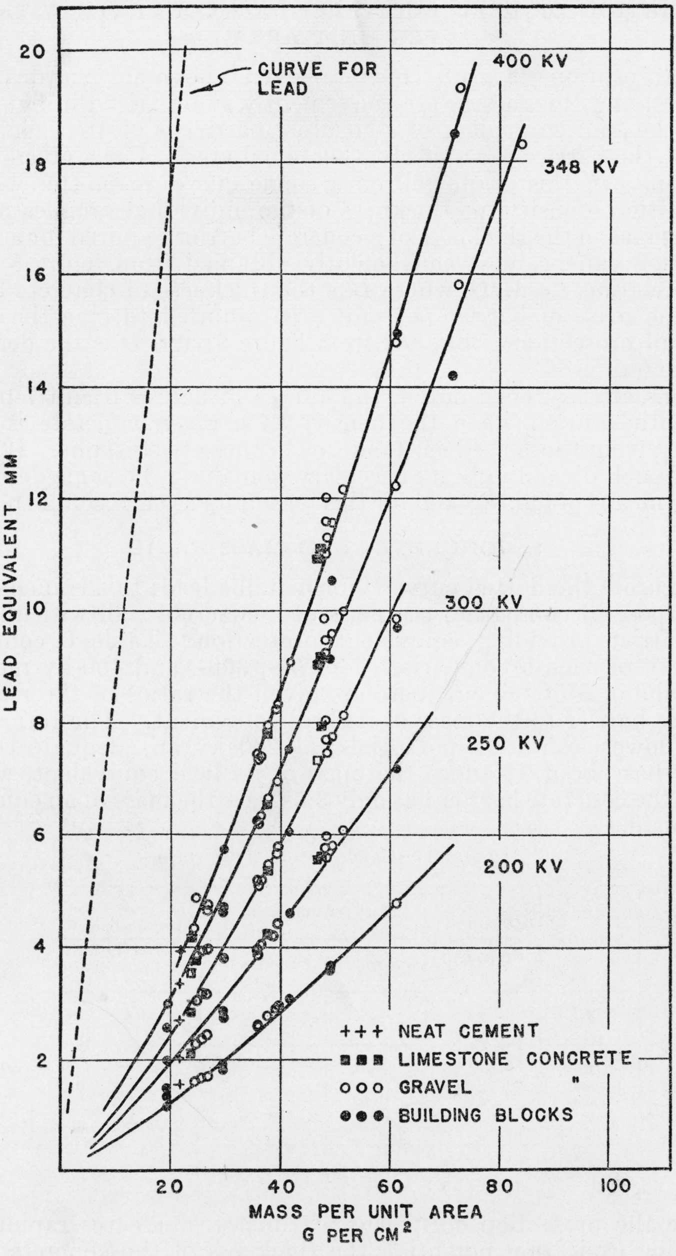

FIGURE 8.—*Lead equivalent of any concrete barrier as a function of the mass of the barrier per unit cross-sectional area.*

In both cases the additional thickness required in going from 200 to 400 kv is small and a barrier providing adequate protection at a given excitation potential will also be adequate at a lower voltage.

WASHINGTON, July 20, 1938.