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LEAD INDUSTRIES ASSOCIATION

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To Members of the Lead Industries Association:

SUBJECT: "MATERIALS AND METHODS OF X-RAY PROTECTION"

We are enclosing a copy of a reprint of the article "Materials and Methods of X-Ray Protection," which appeared in "Industrial Radiography," Fall, 1945, issue, and which was mentioned in our Lead Information Bulletin No. 17, dated December 26, 1945.

We have a supply of these reprints and can let you have additional copies at our cost of 5¢ per copy.

Very truly yours,

F. E. Wormser

Secretary.

Materials and Methods of X-Ray Protection

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The object in planning X-ray protection for any installation is to reduce the X-ray intensity at all positions where personnel will be stationed to a value such that no person will receive more than 0.1 r during any 24-hour period. No hard and fast rules need be laid down for accomplishing this; the methods to be used are best left to the ingenuity of those making the plans. Almost any space can be made safe against X-rays by the use of lead or concrete walls of sufficient thickness—in practice such an installation would probably be considered prohibitively expensive, especially when protection against very penetrating radiation is required. The alternative is to consider other methods of protection to be used in addition to radiation barriers. In the interest of economy, full consideration should therefore be given to all three of the following factors: 1. Distance from barrier to X-ray source; 2. Direction of X-ray beam; 3. Radiation barriers.

DISTANCE FROM BARRIER TO X-RAY SOURCE

The intensity of any beam of X-rays falls off inversely as the square of the distance from the X-ray tube target—this holds true for all X-radiation regardless of its penetrating power. For example, a twofold increase in distance from the tube target results in a fourfold decrease in the X-ray intensity, a tenfold increase in distance reduces the intensity to one percent of its initial value. By making the distance from the X-ray source to all operating stations as large as possible, a saving can be effected in the cost of lead sheet, concrete, or lead glass. Such savings increase rapidly as the penetrating power of the radiation goes up, for then progressively thicker barriers are required to reduce a given beam to, let us say, one percent of its initial value. Regardless of what the radiation quality may be, however, the same percentage reduction can be brought about by increasing the distance tenfold.

For reasons of economy, first consideration should, therefore, be given to the matter of distance between the X-ray source and all occupied spaces in the immediate vicinity. The X-ray room should be as far removed as conditions will permit from all offices, laboratories, and shops where workers remain throughout the working day. Where occupied rooms must be near the X-ray space, it is good practice to place them on opposite sides of a corridor. Inside the X-ray room the tube should be placed as far away as possible from all operators, consideration being given to the use for which the radiation is intended and to the space available for the purpose. In neither medical nor industrial X-ray rooms can full advantage be taken of the saving possible through increasing the distance from the X-ray source; it may be necessary to watch a patient during treatment or to palpate a patient during a fluoroscopic examination; in industrial radiography and fluoroscopy within protected cabinets, the presence of nearby operators may be essential. In any case, all persons concerned with the operation of an X-ray installation should understand clearly that the first defense against any radiation hazard is distance. The safe thing to do is to "stay away."

DIRECTION OF X-RAY BEAM

The second consideration in planning X-ray protection should be the direction of the X-ray beam. Wherever possible, the main beam should be directed away from occupied areas, preferably toward the ground or an outside wall remote from adjacent buildings or yards where men may be at work. So-called "ray-proof" tube housings, now in common use, are designed to reduce the radiation intensity transmitted by any part of the housing—other than the exit port—to about one percent of that of the useful beam. It must not be assumed that this is always so, many tube casings have insufficient protection, especially at the cathode end. Nevertheless, by directing the exit port away from all occupied spaces nearby, full use is made of such protection as has been built into the tube housing by the manufacturer. The problem is thereby simplified; protection remains to be provided only against the direct radiation not absorbed by the tube casing and the radiation scattered out of the main beam by the air and by irradiated objects. The thickness of lead provided by the tube housing may be subtracted from the total required to afford adequate protection, but only in those directions in which the shielding action of the case is known to be

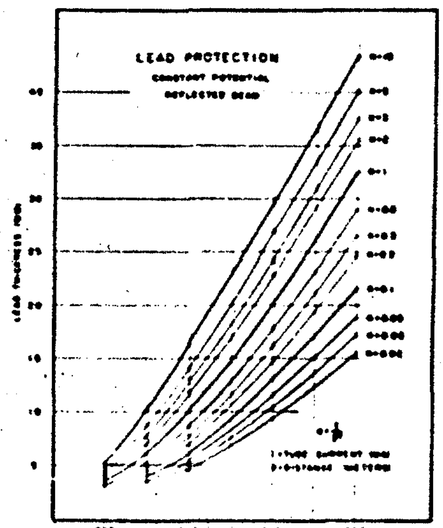

Fig. 1. Lead thickness required for protection against narrow X-ray beams generated by voltages between 200 and 500 KV for various distances between the tube target and operator.

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effective and for which sufficient protection against scattered radiation has been provided.

For many applications, it is essential that the X-ray tube head be left free to rotate into any desired position; then one has no choice but to provide protection against the full intensity of the useful beam by increasing the distance to all nearby occupied spaces, by interposing protective barriers of adequate thickness, or by a combination of both methods.

RADIATION BARRIERS

When full advantage has been taken of both distance and tube orientation, it will usually be found that the radiation intensity is still excessive at the control station and in adjacent rooms. Thought must then be given to protective walls or screens. For X-rays generated by voltage under 250 kilovolts, lead sheet is generally used for this purpose; for more penetrating radiation, concrete is most often chosen. The use of lead sheet in combination with concrete is becoming more common and has much to recommend it. The type of barrier selected is determined by relative cost and convenience.

Two classes of protective barriers should be distinguished:

1. Barriers against direct radiation—from the tube port, from leaks in the tube housing, and from radiation not absorbed by the tube housing.
2. Barriers against scattered radiation—scattered by the patient, walls of the room, or other irradiated objects.

The scattered radiation is generally less penetrating and less intense than the direct radiation; less protection is, therefore, needed against it.

From curves given in Figures I and II, it is possible to compute the thickness of the lead barriers necessary for shielding against direct X-radiation generated by constant potentials between 200 and 1400 kilovolts. The data needed for making this computation are: (1) the tube current, (2) tube voltage, and (3) the distance.

This computation is made as follows:

A. Find "K" by dividing the tube current in milliamperes by the square of the distance to the tube target in meters, thus:

$$K = \frac{I}{D^2}$$

where I = tube current in milliamperes.
D = distance in meters from target to nearest person.

For example, if the nearest person is 3 meters from a tube passing a current of 3 milliamperes at 1,000 kilovolts,

$$K = \frac{3}{(3)^2} = \frac{3}{9} = 0.33$$

B. Select the curve in Figure I or II having the value of "K" computed as shown above. If this value of "K" is not given, it may be necessary to interpolate between curves. Beginning at the extreme right, follow this curve down to the point where it cuts the vertical line corresponding to the tube voltage used. Read at the extreme left the lead thickness to which this point corresponds.

Thus, in the example given above having found K = 0.33, we select the curve in Figure II marked K 0.3, because it is nearest to our computed value. Following this curve down to the point where it intersects the vertical line for 1000 Kv we read off the required thickness—at the left margin of the chart—as 78 mm. or 3.1 inches.

By an identical procedure the concrete required for protection against direct X-radiation can be computed from Figures III and IV.

The procedure outlined above for computing "K" should be followed in all cases where no information

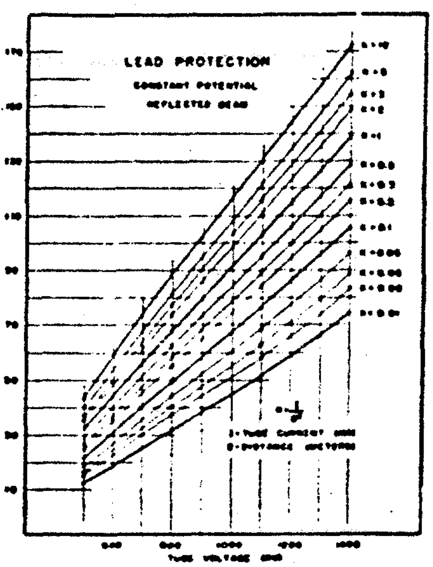

Fig. II. Lead thickness required for protection against narrow X-ray beams generated by voltages between 500 and 1400 KV for various distances between the tube target and operator.

is available as to the intensity of the useful beam. When this datum is given, a more exact estimate of protection is possible by taking this information into consideration. The curves in Figures I to IV, inclusive, were computed on the assumption that the X-ray tube output at various voltages is approximately that given in Table I.

TABLE I

X-ray Tube Output Assumed in Graphs I to IV inclusive:

Tube Voltage (K.V.)	Tube Output (r/minute m.a. at 1 meter)
200	1
400	5
600	10
800	20
1000	30
1200	50
1400	70

When the radiation intensity at one meter is known for any of the voltages listed in Table I, the value of "K", as computed above, should be multiplied by the ratio of the known output of the tube in question at this voltage to that given in Table I for the same voltage. A new value of "K" is then obtained—it will generally be smaller than the original—from which the lead barrier required is found by following the instructions given above under "B".

By way of example, suppose that in the case already cited, the tube output is known to be 15 r. per minute milliampere at a distance of one meter. For 1000 Kv. the output assumed in Table I is given in column (2) as 30 r. per minute milliampere at one meter. The value of "K" already computed (0.33) should, therefore, be multiplied by the ratio (15) giving
(30)

$$K = .033 \times \frac{15}{30} = 0.17$$

With the new value of "K", a more exact estimate of the required lead or concrete can be obtained by following the procedure outlined under "B". These values turn out to be 71 mm. or 2.8 inches of lead and 50 cm. or 19.7 inches of concrete.

Figures III and IV are for concrete weighing 157 pounds per cubic foot—specific gravity equals 2.2. For other concrete mixes the thickness required varies inversely as the specific gravity or weight of the material per cubic foot. For example, let the thickness of concrete weighing 160 pounds per cubic foot be required. If from Figure III a concrete thickness of 50 cm. is found, then the thickness for the 160 pound concrete is computed as follows:

$$50 \text{ cm.} \times \frac{157}{160} = 43 \text{ cm.} = 17 \text{ inches}$$

Like concrete, such materials as brick, plaster, earth, water, etc., afford some degree of protection against X-rays and may be used either in place of lead barriers or in combination with them. At voltages above 200 kv. concrete, brick and earth are frequently used without sheet lead. The combination of such materials with lead is, however, to be recommended wherever practicable for several reasons. In the first place, there is always the possibility that cracks may develop in thick non-metallic walls; the addition of sheet lead to such walls reduces the radiation hazards should such cracks develop. Furthermore, relatively light barrier materials attenuate an X-ray beam by scattering, a process which involves (a) the deflection of the radiation from its original path and (b) a reduction in its penetrating power. Some scattering takes place in all materials and for all qualities of radiation, but this effect is more pronounced in relatively light materials and for very penetrating radiation. So, for example, scattering is greater for concrete than for lead and is greater for penetrating radiation than for relatively soft X-rays. From the point of view of X-ray protection scattering is undesirable. When scattering occurs, a part of the X-radiation incident upon a barrier is scattered back upon persons within the protected space. The effect of back scattering from concrete or brick walls can be reduced by adding a relatively thin layer of lead to the side of the protective barrier upon which the radiation is incident. Another advantage—but a secondary one—resulting from the use of such a lead "veneer" is that the radiation on passing through the lead "veneer" is thereby hardened and since concrete is relatively more effective for hard radiation than for soft, the concrete portion of the barrier becomes relatively more effective.

Scattering also results in undesirable effects on the emergent side of concrete protective barriers. The radiation that penetrates barriers made of relatively light materials is less penetrating than the incident radiation. The addition of sheet lead on the far side of concrete barriers, therefore, effectively serves the purpose of absorbing the radiation which has penetrated the barrier and has been degraded in the process.

THE EFFECT OF BEAM WIDTH ON RELATIVE THICKNESS OF CONCRETE AND LEAD REQUIRED FOR ADEQUATE PROTECTION

In the foregoing paragraphs it has been assumed that the diameter of the X-ray beam against which protection is required is relatively small, being of the order of 2 to 5 centimeters. In practice X-ray beams as narrow as this are seldom used; this is true both in the medical and industrial applications of X-rays and is especially so in the latter field where very broad beams are often used. Increasing the width of an X-ray beam makes it necessary to increase the thickness of the protective barriers beyond that required for adequate protection when narrow beams are used. This necessary increase in barrier thickness is not the same for all materials, being relatively greater for light materials such as concrete and brick, than for lead. In Table II, there is shown the ratio of the thickness of concrete to the thickness of lead required to reduce the incident radiation to the same extent—to a level of approximately 10^{-5} r/sec—on the emergent side of the barrier. This

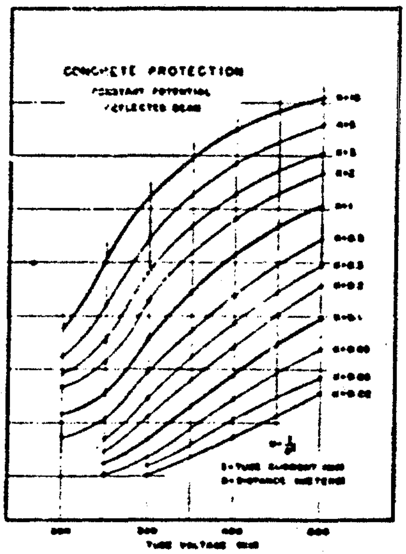

Fig. III. Concrete thickness required for protection against narrow X-ray beams generated by voltages between 200 and 500 KV for various distances between the tube target and operator.

table holds only for very narrow beams of X-radiation—of the order of a few centimeters in diameter.

The effect of increasing the diameter of an X-ray beam is to increase the ratio given in the second column of Table II. To say the same thing in another way, as the beam diameter is increased the percentage increase in the thickness of a concrete barrier must be greater than the corresponding increase in a lead barrier if the X-ray protection of both is to remain the same. This fact should be kept in mind when the data given herein are used since narrow beams have been assumed throughout this discussion. In making use of these data the barrier thickness used should be greater than that recommended if the use of broad beams is contemplated. Exact information on the increase required when broad beams are used is not now available because of the technical difficulties involved in obtaining such information. The following is offered as a suggestion: That, when broad beams are used, the thickness of the barrier in question be increased by one half-value layer of the barrier material used at voltages up to 500 kv., that for voltages between 500 and 1000 kv. the barrier thickness be increased by 2 half-value layers, and that for voltages between 1000 and 1500 kv. the barrier thickness be increased by three half-value layers.

Protection from scattered radiation should not be overlooked. A barrier between the X-ray tube and employees to protect them from the direct rays may not shield them from rays scattered by walls, ceilings, furniture or other objects. This might happen, for example, in a one-story foundry building where a concrete barrier seven feet high has been erected to stop the direct beam from the X-ray tube. If the unobstructed beam is directed towards the roof structure above the barrier, a part of the radiation will be scattered by the roof to reach the employees outside the barrier. This can be prevented by extending the barrier to the roof. The upper part which need only absorb the scattered rays can be much lighter than the lower part that must absorb the primary rays.

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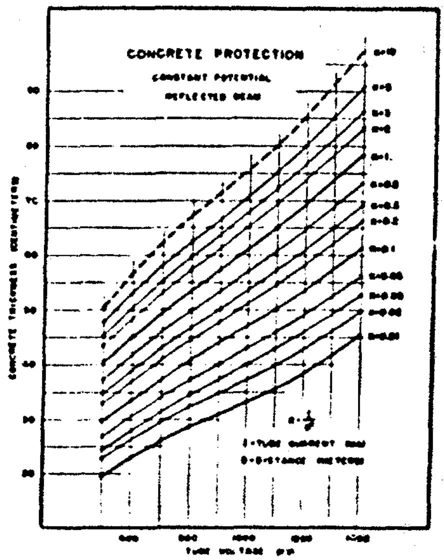

Fig. 11. Concrete thickness required for protection against narrow X-ray beams generated by voltage between 500 and 1400 KV for various distances between the tube target and operator.

TABLE II

Ratio of Thickness of Concrete to Thickness of Lead Required for Equivalent Protection

Kilovolts	Ratio (Thickness concrete / Thickness lead)
75	71
85	67
90	65
100	60
110	63
115	65
120	67
125	64
150	72
160	71
200	55
250	34
300	25
400	16
500	12
600	9.3
700	8.1
800	7.1
900	6.5
1000	6.1
1200	5.6
1400	5.2

TABLE III

Protection Against Scattered Radiation

Thickness of lead in inches required for protection against scattered radiation. (Tube operated at 10 ma.)

K. V.	Scattered Rays 3'	10'	20'	Rescattered Rays 3'	10'	20'	Safe distance no shield
50	.01	.01	—	—	—	—	3'
75	.02	.01	—	.01	—	—	4'
100	.03	.01	—	.01	—	—	5'
140	.05	.01	.01	.03	—	—	7'
200	.08	.03	.01	.04	—	—	10'
250	.12	.05	.02	.05	.01	—	13'
300	.16	.07	.04	.06	.01	—	20'
400	.22	.15	.08	.07	.01	.01	25'
500	.28	.22	.15	.09	.02	.01	29'
600	.35	.30	.20	.11	.03	.01	33'
800	.5	.4	.3	.13	.04	.01	35'
1000	.6	.5	.4	.15	.05	.02	—
1400	.6	.6	.5	.17	.06	.02	—
2000	.7	.7	.6	.20	.07	.03	—

The intensity of scattered radiation reaching personnel will depend on many factors including the nature of the surface and the distances and directions that the rays must travel as well as the kilovoltage and milliamperage of the source. It will always be weaker than the primary or direct radiation. It will also be less penetrating, particularly when using high kilovoltage apparatus. Lead is usually more economical and convenient than masonry or concrete for protection against scattered radiation only, and the thicknesses required are relatively small. Recommended thicknesses are tabulated in Table III for various kilovoltages of the apparatus and distances of the exposed scattering surface from the employees. In compiling this table, extremely unfavorable conditions were assumed, e.g., that the scattering surface was close to the X-ray tube and of a material that scatters efficiently.

The distinction between singly-scattered radiation and multiply-scattered radiation is important. In the example above of the tube behind a barrier seven feet high, the rotation of the tube might be so restricted that the direct beam could not be pointed at the roof and hence it might not be possible for rays to get over the barrier without being scattered at least twice, for example, by both floor and roof. Doubly-scattered radiation would be both weaker and less penetrating than singly-scattered radiation, and, therefore, would require less lead to absorb it. The recommended thicknesses for multiple scattering are given in Table III under the heading "Rescattered Rays." The final column gives the closest distance of safe approach to a wall emitting rescattered radiation when no protection intervenes.

The intensity of scattered radiation depends considerably on the material of the scattering surface. Ordinary structural materials like masonry, concrete, plaster and wood scatter much more radiation than heavy metals like lead. For this reason it is desirable to cover all such surfaces likely to be exposed to direct radiation with lead. A thickness of 1/8" is suitable and sufficient for this purpose. Even 1/16" lead over a masonry wall gives considerable improvement.