High Density Concrete for Shielding Radiations Below 1 MeV: Design, Construction, and Application

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A design for a high density, moderate strength concrete as an alternative to lead, for shielding radiations below 1 MeV is presented. When space is not of primary concern, high density concrete may prove an economical method of shielding the radioactive wastes discarded from the average nuclear medicine department. The concrete described is limited to small projects only because of its low structural strength. High strength concrete of a more complex formula, which has long been a favored material in high radiation shielding, is available but at additional costs. Using this information, the consultant in nuclear medicine may enhance the efficient traffic of radioactive wastes through preplanned waste areas constructed with high density concrete.

The primary aim in radiation shielding is to reduce radiation intensity to an acceptable level (*1*). Secondary factors are costs, strength, and design. Almost any material when placed in sufficient thickness will serve to reduce radiation. Use of materials requiring excessive thickness, such as basic concrete (146 lb/ft^3), may be prohibitive because of area limitations. The utilization of a high density metal, such as lead (704.8 lb/ft^3) (*2*), may be economically restrictive, as well as structurally undesirable. By drawing upon the best features of concrete, i.e., pliability, strength, and cost,, and those of high density metals, such as compactness and high-absorption coefficient, a concrete mixture may be obtained that provides sufficient shielding characteristics, moderate strength, and reasonable cost.

Concrete has long been the primary material in large shielding situations such as nuclear power plants, reactors, cyclotrons, linear accelerators. These projects require more complicated mixtures of concrete to inhibit passage of radiation emissions not generally found in nuclear medicine departments. Mixtures containing boron, magnetite, or limonite are employed to prevent passage of neutrons as well as gamma radiations (*3*). Reinforced concrete also requires additional design factors to account for secondary radiations produced by steel beams. The mixtures detailed herein are concerned only with the absorption of gamma and x-radiations below 1 MeV. Alpha and beta radiations will be neglected owing to their low penetrating capabilities.

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Materials and Methods

To evaluate the shielding properties of high density concrete, upper and lower limits of material thickness desirability must be established. After these limits are set, Portland cement and assorted aggregates may be combined to produce a concrete mixture with a high-unit weight, sufficient to reduce the radiation intensity to an acceptable level. This concrete should have favorable characteristics halfway between the limits determined herein.

To set these limits and standardize all variables, lead

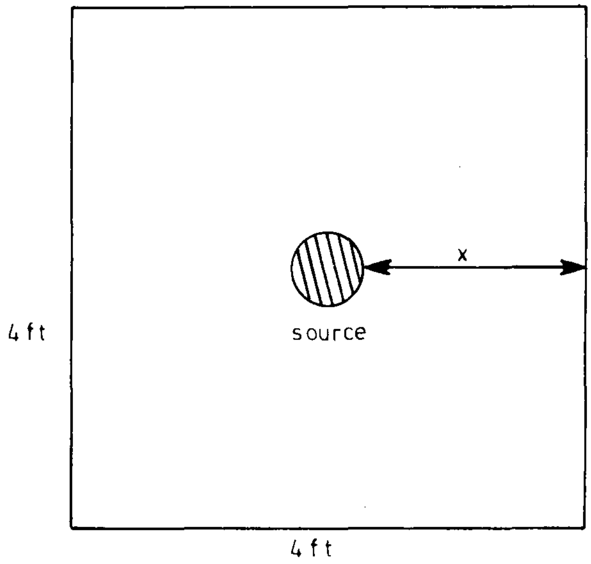

FIG. 1. Standard area to be shielded by lead and concrete from a 1 Ci source of Mo-99.

and basic concrete shielding are designed to adequately reduce the radiation intensity from a 1-Ci source of Mo-99, in a 4-ft × 4-ft square, 3-ft high area (Fig. 1). The first step in this process is to determine the intensity of radiation (I_o) from the Mo-99 source at the inside shield surface.

Use the formula

$$I_o = n\Gamma/S^2 \quad (1)$$

where n is the number of curies; Γ is the specific gamma ray constant in R/hr/mCi at 1 cm (for Mo-99 equal to 1.29) (*4*); and S the distance from the source to the interior shield wall. A result of 347 mR/hr is calculated for the radiation intensity 2 ft (60.96 cm) from the source.

After determining I_o, the attenuation reduction factor (R_I) must be calculated; however, an acceptable dose rate (D_a) must first be produced. If 0.00625 R/hr is accepted as a tolerable dose rate (*1*), then R_I may be evaluated from this formula

$$R_I = I_o/D_a, \quad (2)$$

producing a result of 55.52 for this design. The required number of half-thickness of material (N) may then be achieved from

$$N = 3.322 \log R_I, \quad (3)$$

yielding a value of 5.79 as the number of half-thickness of material needed for this shield.

To determine the thickness of the shield (X), the half-value layer ($X_{1/2}$) must be located (Fig. 2). The half-value layer (HVL) of lead (0.65 cm) and basic concrete (4.0 cm) is then multiplied by N. It has now been calculated that 3.76 cm (1.48 in.) of lead or 23.16 cm (9.12 in.) of basic concrete is needed to shield 1 Ci of Mo-99 at 2 ft.

The radiation intensity (I) on the outside wall of the shield may be confirmed by the following differential equation

$$dI/dx = -uI. \quad (4)$$

The differential dI/dx expresses the radiation intensity and material thickness rates of change. The equality is introduced by multiplying the intensity by the absorption coefficient (u). The negative sign denotes a decrease in the intensity. For work in this text, u will equal $\lambda/x_{1/2}$ (*5*), where λ is the decay constant 0.693, and $x_{1/2}$ equal to the half-value layer.

The HVL ($x_{1/2}$) is defined as the distance of travel through an absorber required to decrease the intensity of a beam of gamma rays to one-half its initial value. Thus after a ray has passed through a half-thickness of absorber, the intensity of the beam (I) is equal to one-half of I_o (*5*). Rearranging Eq. 5 and substituting one-half of I_o for its equal, I, the result obtained is

$$\ln (I_o/I) = ux;$$

$$2.303 \log [I_o/(1/2)I_o]) = 2.303 \log 2 = ux_{1/2};$$

and

$$u = 0.693/x_{1/2}. \quad (5)$$

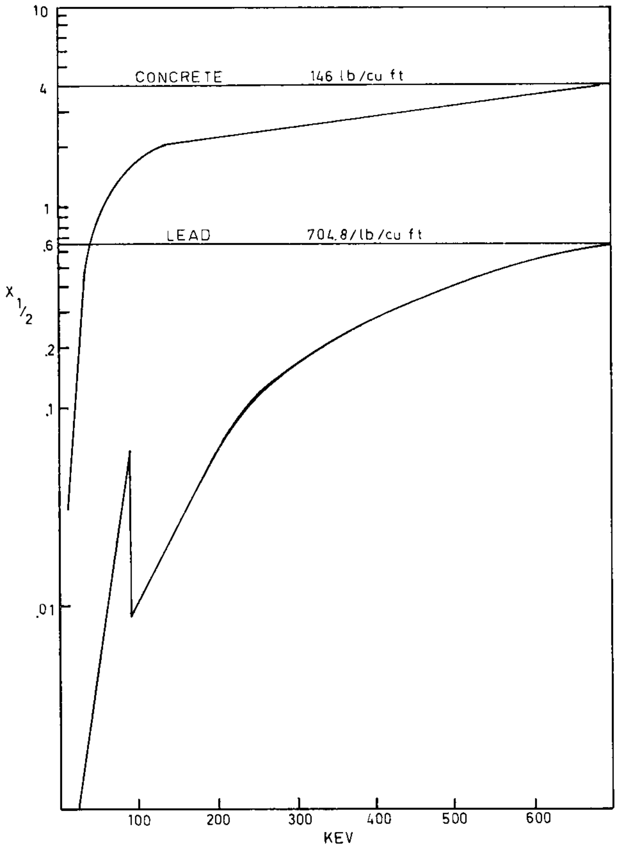

FIG. 2. Half-value layers of lead and concrete at specified energy levels.

The method for solving the differential equation describing mass absorption is

Equation:	$dI/dx = -uI$
Divide by I and multiply by dx	$dI/I = -udx$
Integrate both sides	$\int_{I_o}^{I} dI/I = -u \int_0^x dx$
	$\ln I = -ux + C$
(x = O)	$\ln I = -u(O) + C$
($I = I_0$; x = 0)	$\ln I = C$
	$\ln I_o = C$
Substitute	$\ln I = -ux + \ln I_o$
Manipulate	$\ln I - \ln I_o = \ln I/I_o = -ux$
And determine the antilog of both sides	$I/I_o = e^{-ux}$.

The solution to Eq. 4:

$$I = I_o e^{-ux}. \quad (6)$$

After the proper values are applied to this equation, a result of 0.0063 R/hr is calculated for the outside shield wall.

With these values in mind, the process of designing a concrete mixture with a high-absorption coefficient, but low HVL, may be undertaken. It is impossible to achieve as dense a material as lead; however, a satisfactory density falling between that of lead and basic concrete may be reached (*6*).

Concrete is a composite material, consisting essentially of Portland cement and water to form a cement paste, plus filler materials called aggregates. Aggregates may range from fine sands to stone fragments several inches in diameter (*7*). In determining concrete density, the unit weight of the aggregates plays an important role, for the aggregates may occupy roughly three-quarters of the given mass (*7*). Cement paste and air voids fill the remainder of the mixture.

The process of proportioning concrete mixtures may become complex; however, for purposes of shielding radioactive wastes from a nuclear medicine department, the basic methods recommended by the American Concrete Institute (ACI) are given (*8*). The procedure consists of the following steps to mix 1 cubic yard of concrete:

1. The consistency (slump) is determined (*7*). A maximum slump for radiation shielding of 3 in. is recommended (*9*).
2. Maximum size of aggregate is selected from Table 1 (*7*). A maximum aggregate size of 1-1/2 in. will be used for the 4 ft × 4 ft × 3 ft shield.
3. Total water in gallons per yd^3 of concrete is selected from Table 2 (*7*). Because air-entraining admixtures should be avoided (*9*), 36 gal of water per yd^3 of concrete is recommended for this batch.
4. A water:cement ratio (W:C) is selected. The lower the W:C, the higher the compressive strength. Since a minimum compressive strength of 3000 psi is suggested (*9*), a maximum W:C of 7 gal of water per sack of cement (94 lb) is permissible. However, to achieve a higher density, a W:C of 4 gal/sack will be used.
5. Cement content of the mixture is computed by dividing the total water content of the mixture by the W:C. In this example, a cement content of 9 sacks per yd^3 of concrete is achieved.
6. Overall volume of coarse aggregate per unit volume of concrete is found in Table 3 (*7*). If a fines moduli of 2.8 is used, then the solid volume of $0.72 \times 27\ \text{ft}^3 \times 100\ \text{lb per ft}^3$ equals 1,940 lb is calculated.
7. Solid volume of sand and metal is determined by subtracting the total volume of cement, coarse aggregates, water, and air (1%) from the total volume of concrete.

The measurements are then converted into cubic feet.

Solid volume of cement:

$$\frac{9\ \text{sacks} \times 94\ \text{lb/sacks}}{3.15 \times 62.4\ \text{lb/ft}^3} = 4.3\ \text{ft}^3;$$

Volume of water:

$$36\ \text{gal}/7.5\ \text{gal ft}^3 = 4.8\ \text{ft}^3;$$

Volume of coarse aggregate:

TABLE 1. Maximum sizes of Aggregates Recommended for Various Types of Construction.

Minimum dimension of section in inches	Maximum Size of Aggregate in In.			
	Reinforced walls, beams and columns	Unreinforced walls	Heavily reinforced slabs	Lightly reinforced or unreinforced slabs
2 1/2–5	1/2–3/4	3/4	3/4–1	3/4–1 1/2
6–11	3/4–1 1/2	1 1/2	1 1/2	1 1/2–3
12–29	1 1/2–3	3	1 1/2–3	3
30 or more	1 1/2–3	6	1 1/2–3	3–6

TABLE 2. Approximate Free Mixing-Water Requirements for Different Slumps and Maximum of Sizes of Aggregates

Slump non-air-entrained concrete	Water, gal/yd^3 of Concrete for Indicated Maximum Sizes of Aggregate in In.							
	3/8	1/2	3/4	1	1 1/2	2	3	6
1–2	42	40	37	36	33	31	29	25
3–4	46	44	41	39	36	34	32	28
6–7	49	46	43	41	38	36	34	30
	Approximate amount of entrapped air in non-air-entrained concrete (in percent).							
	3	2.5	2	1.5	1	0.5	0.3	0.2

$$\frac{1{,}940 \text{ lb}}{2.68 \times 62.4 \text{ lb/ft}^3} = 11.6 \text{ ft}^3;$$

Volume of entrapped air:

$$0.01 \times 27 \text{ ft}^3 = 0.27 \text{ ft}^3;$$

and total volume equals 20.97 ft^3.

The solid volume of sand and metal required to complete the cubic yard of concrete is 6.03 ft^3. By adjusting the volumes of sand and metal, the corresponding density of concrete is achieved (Fig. 3). The weights of materials for 1 yd^3 of high density concrete are as follows: cement (9 sacks)—846 lb; water (36 gal)—300 lb; coarse aggregates—1940 lb; sand—from Fig. 3; and lead fillings—from Fig. 3.

For the purpose of the 4 ft × 4 ft × 3 ft shield, a density of 251.2 lb/ft^3 is used. To prepare a proper mixture, use the following proportions by weight: cement—1 part; water—0.35 parts; sand—0.20 parts; lead—4.18 parts; and coarse aggregates—2.30 parts.

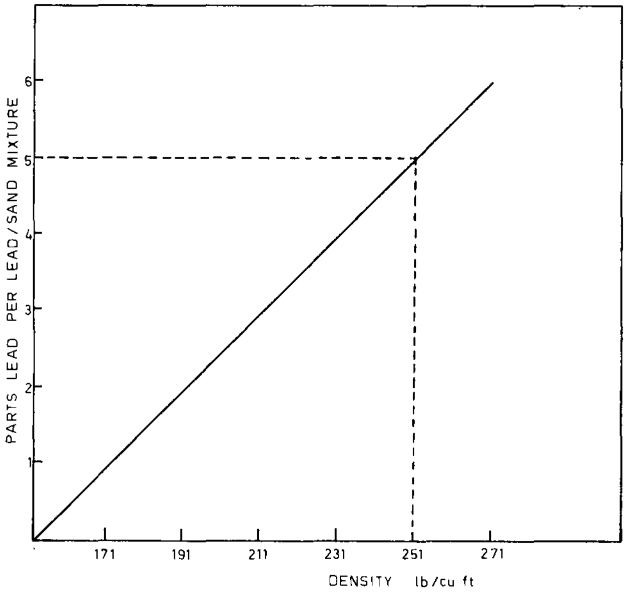

FIG. 3. Relationship of lead/sand mixture to density in lb/ft^3.

Before a bulk mixture for the wall is prepared, a test sample is mixed for slump and HVL testing. For the slump test (*10*), place a dampened, truncated cone-shaped mold, 12 in. high by 8 in. in diameter at the base and 4 in. in diameter at the top, on a smooth, moist, rigid base.

Place the newly mixed concrete in the mold in three layers, each approximately one-third the volume of the mold. When placing each scoopful of concrete, move the scoop around the top edge of the mold as the concrete slides from it, in order to ensure symmetrical distribution of the concrete within the mold. Rod each layer with 25 strokes of a 5/8 in. rod, 24 in. in length and rounded at the lower end. Distribute the strokes in a uniform manner over the cross section of the mold, each stroke just penetrating into the underlying layer.

After rodding the top layer, strike off the surface of the concrete with a trowel; leave the mold exactly filled.

Clean the surface of the base outside the cone of any excess concrete. Immediately remove the mold from the concrete by raising it slowly in a vertical direction. If the pile topples sideways, it indicates that the materials have not been uniformly distributed in the mold, and the test should be remade. The entire operation should be completed within an elapsed time of 1 1/2 min.

Measure the slump immediately by determining the difference between the height of the mold and the height of the vertical axis (not the maximum height) of the specimen. Immediately after using, clean the mold thoroughly.

To determine the HVL, a sample of concrete, 2 in. × 4 in. × 8 in. is prepared. A Mo-99 source, calibrated at 400 mCi, is placed 2 ft from the shield, while a G-M tube is placed on the opposite side of the brick. The intensity at the source side of the wall (I_o) is calculated to be 152 mR/hr from Eq. 1. The intensity measured by the G-M tube (I), is read as 40 mR/hr. By rearranging the equation, $\ln I - \ln I_o = -ux$, in the following manner:

$$\ln I - \ln I_o = -ux;$$

$$\ln I/I_o = -ux;$$

TABLE 3. Bulk Volume of Dry-Rodded Coarse Aggregate Per Unit of Volume of Concrete

Maximun size of aggregate in in.	Bulk (Overall) Volume of Dry-Rodded Coarse Aggregate Per Unit Volume of Concrete for Different Fines Moduli of Sand 2.4	2.6	2.8	3.0
3/8	0.46	0.44	0.42	0.40
1/2	0.55	0.53	0.51	0.49
3/4	0.65	0.63	0.61	0.59
1	0.70	0.68	0.66	0.64
1 1/2	0.76	0.74	0.72	0.70
2	0.79	0.77	0.75	0.73
3	0.84	0.82	0.80	0.78
6	0.90	0.88	0.86	0.84

TABLE 4. Composition and Specific Gravity of Aggregates Covered by Specification C 637-73

Predominant constituent	Class of Material	Chemical Composition of Principal Constitutents	Specific Gravity of Available Aggregate
Serpentine	Crushed Stone	$Mg_3Si_2O_5(OH)_4$	2.4–2.65
Lominite	Crushed Stone	$(HFeO_2)_X \times (H_2O)_Y$	3.4–3.8
Goethite	Hydrous Iron Ore	$(HFeO_2)$	
Barite	Gravel or Crushed Stone	$BaSO_4$	4.0–4.4
Ilmenite	Crushed Stone	$FeTiO_3$	4.2–4.8
Hematite	Iron Ore	Fe_2O_3	
Magnetite		$FeFe_2O_4$	
Ferrophosphorus	Synthetic	Fe_nP	5.8–6.3

$$\ln I_o/I = ux;$$

$$\frac{\ln I_o/I}{x} = u = \lambda/x_{1/2};$$

we produce

$$\frac{\ln I_o/I}{x} = u.$$

Having utilized x as 2 in., u is determined to be 0.667. From the equality $u = \lambda/x_{1/2}$ (*5*), the HVL for the 251.2 lb/ft^3 concrete is calculated to be 2.6 cm.

The required thickness (x), for the 4 ft × 4 ft × 3 ft. shielded area, may now be reached from Eq. 3. Multiplying n and $x_{1/2}$ yields a required thickness of 15 cm (5.9 in.) to shield 1 Ci of Mo-99 properly. To construct four walls 5.9 in. thick, 4 ft wide, and 3 ft high, 23.6 ft^3 of concrete mix is required. The required weights of material and approximate costs are:

cement	737.7 lb	8 sacks	$22.80
water	258.2 lb	31 gal	—
sand	147.5 lb	1.12 ft^3	2.00
c.a.	1696.7 lb	8.6 ft^3	1.00
lead	3083.5 lb	—	1110.00
		The total cost is	$1135.80

The density of 251.1 lb/ft^3 is not the highest that may be attained. By exchanging the gravel used as a coarse aggregate (specific gravity of 3.15), for a material of higher density, a concrete mixture with a density as high as 348 lb/ft^3 may be reached. Table 4 (*9*) demonstrates the specific gravity of some commercially available aggregates. If the gravel is replaced with Ilmenite ore (S.G.4.4.), then the density of the shield in Fig. 1 will be raised to 297 lb/ft^3. Before the mixture is designed, the availability and expense of the aggregate must be considered. Many aggregates that are common to one area of the country may be difficult to obtain and costly in another.

Discussion

In today's radiation protection and budget conscious nuclear medicine department, the application of a high density concrete as an addition to lead brick, is worthy of further consideration. While the standard lead brick will always be of value in table top shielding situations, the increased use of the Mo-99 generator demands increased specifications in waste disposal. In those departments where decay vaults are employed in remote areas of the hospital, the construction of a concrete container will provide the necessary shielding at a substantially reduced cost. Concrete in its pliable state may also provide shielding in difficult storage space by sculpturing around pipes, corners, and radiators, etc. Although the space necessary to apply concrete is about four times that of lead, the lower cost and construction values are of considerable advantage. The approximate price of the 4 ft × 4 ft × 3 ft shielded area is $1135.00 for concrete of 251.2 lb/ft^3 density. To achieve shielding characteristics of the same quality utilizing lead sheets at approximately 60¢ per lb would cost about $2503.00. By utilizing Ilmenite ore as the coarse aggregate, the expense is raised to approximately $1235.00 depending on shipping expense. If space is not of concern, high density concrete might be considered before the purchase of large quantities of lead.

The case for concrete may also be presented if new construction is being considered. Given enough foresight, the structural engineer might design and mix high density concrete for the walls of the preplanned closets, fume hoods, or specified restricted areas of the "hot lab." Concrete provides nuclear medicine personnel involved in planning with a variety of alternatives to radiation shielding.

References

1. Callan EJ: Concrete for radiation shielding. *J Am Concrete Institute* 50: 17–44, 1953

2. Wang Y: *Handbook of Radioactive Nuclides.* Cleveland, CRC Press, 1969, pp 69–70

3. Shirayama K: Properties of radiation shielding concrete. *J Am Concrete Institute* 60: 261–280, 1963

4. Sodee BD, Early PJ: *Technology and Interpretation of Nuclear Medicine Procedures.* St Louis, CV Mosby Co., 1972, pp 494–495

5. Chase GD, Rabinowitz JL: *Principles of Radioisotope Methodology.* Minneapolis, Burgess Publishing Co., 1967, pp 224–226

6. United States Atomic Energy Commission: *Radioisotope Shielding Design Manual.* New York, USAEC, No. 10721, 1963, p 1

7. Troxell GE, Davis HR, Kelly JW: *Composition and Properties of Concrete.* New York, McGraw-Hill, 1968, pp 3, 145, 148, 465

8. American Concrete Institute: *Recommended Practice for Selecting Proportions for Concrete: Proceedings of the American Concrete Institute.* vol 5, 1955, pp 49–64

9. *American National Standards Institute: Concrete Radiation Shields.* ANSI, No. 101.6, 1972, pp 10–12

10. American Society for Testing and Materials: *Aggregates for Radiation Shielding Concrete.* ASTM, No. C 673-73, pp 1–4