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A SUMMARY OF SHIELDING CONSTANTS FOR CONCRETE

by

R. L. Walker and M. Grotenhuis

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A SUMMARY OF SHIELDING CONSTANTS FOR CONCRETE

by

R. L. Walker
Graduate Student
Michigan School of Mining and Technology
and
M. Grotenhuis
International Institute

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ABSTRACT

This report is intended to fulfill the need to consolidate, classify, and revise the present knowledge of the shielding constants of concretes. The densities, elemental compositions, and mixes, where available, are given for a wide range of concretes. From these data, various constants useful for shielding calculations have been computed. These constants include the removal cross sections, total cross sections, average thermal neutron absorption cross sections, thermal neutron diffusion coefficients, reciprocal thermal neutron diffusion lengths, total gamma ray linear attenuation coefficients, gamma-ray energy absorption linear attenuation coefficients, the effective atomic numbers for the determination of buildup factors, and the capture gamma-ray spectra. Experimental results are included where available.

INTRODUCTION

Extensive work has been done on the shielding of mobile reactors, especially in the submarine and aircraft propulsion programs. Not nearly as much attention was devoted to the shielding of power and research reactors, which have shields which are composed, at least in part, of concrete. As a result, the computation methods and constants for concrete shields are not quite as well developed as those used in the shielding of mobile reactors. The shields for stationary reactors are not so demanding as those of the mobile plants, but they do represent an economical factor. It is believed, therefore, that additional effort should be expended in improving the technology for the type of shields they require. This work has been undertaken with that objective in mind. This report represents an up-to-date expanded version of a similar effort which has been previously reported.[1,2]

The object of this report is to consolidate, classify, and revise certain shielding constants of various concretes. The revision was necessitated by the publication of new and revised data upon which these constants

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[1] Grotenhuis, M., Lecture Notes on Reactor Shielding, ANL-6000 (March 1959).

[2] Reactor Physics Constants, ANL-5800.

are based. These revised constants are suitable for shield design work or re-evaluation of present shields. The compilation presented is representative of all of the known types of concretes used for shielding purposes. A shield designer may use this collection to compare the concretes best suited for his particular specifications.

PRINCIPLES OF RADIATION SHIELDING

The primary value of this report is in the data. A brief review of the principles involved in shielding reactor radiations is given for those who may find it useful.

Types of Radiation

Radiation is a general term applied to nuclear particles or electromagnetic waves, which are a direct or indirect result of radioactive decay and fission. This radiation presents a dangerous environment for human activities and also affects materials and instruments. In order for a reactor to be used properly, it is necessary to predict and control the radiation fluxes.

There are several types of radiation emitted from a nuclear reactor: fission fragments, alpha particles, beta particles, neutrons, and gamma rays. Fission fragments, alpha particles, and beta particles all carry a charge. Fission fragments and alpha particles are quite massive when considered on a nuclear scale. The ranges of these particles are, therefore, quite short and are not usually considered in reactor shielding problems.

Neutrons. The neutron is an electrically neutral particle with a mass of 1.00897 amu (atomic mass units). Because it is uncharged, it does not experience a repulsive force as it approaches a nucleus. Consequently, a neutron loses energy or slows down only if it collides with other particles. The range of a neutron is dependent upon its initial energy and the number and type of collisions it undergoes.

Fission neutrons, those which are the product of the fission process, may have kinetic energy from 0.025 ev to the order of 15 Mev. When they escape the reactor core, they become a very important part of the radiation problem. Any neutron having energy of over one Mev is called a fast neutron. Fast neutrons will be slowed down by collisions with nuclei. As these collisions occur, a neutron will lose speed until its average kinetic energy is the same as that of the medium in which it is located. A neutron which is in thermal equilibrium with a medium is called a thermal neutron.

Gamma Rays. Gamma rays differ from X rays only in that gamma rays are nuclear in origin whereas X rays are atomic in origin. The term "photon" is applied to either X rays or gamma rays. In a nuclear reactor there are two types of gamma rays. Primary gamma rays originate from the fission process or are given off in the radioactive decay of the fission products. Secondary gamma rays originate from the interaction of neutrons with matter. One kind of secondary gamma ray, commonly called a capture gamma ray, is given off when a nucleus captures a neutron. The number and energies of these gamma rays that are emitted per neutron capture are very important factors in shielding considerations. Secondary gamma rays are also given off by inelastic scattering of fast neutrons with various nuclei. The data on the inelastic scattering gamma rays is not as complete as is that on the capture gamma rays.

Radiation Attenuation

The primary objective of the shielder is to be able to predict the radiation levels that exist in and around the reactor. This knowledge must be applied to the design of the reactor. A knowledge of the radiation levels in the materials surrounding the reactor will be required in order to provide the necessary cooling, to determine radiation effects, to design nuclear instruments with the proper ranges, as well as to satisfy the more obvious requirement of determining the biological shield thickness.

Neutron Attenuation. Fast neutrons interact with nuclei almost exclusively by scattering. There are two types of scattering. Elastic scattering is said to have occurred when only kinetic energy is transferred. This reaction is important with light nuclei which can absorb a large fraction of the neutron kinetic energy. An inelastic scatter takes place when the neutron and nucleus coalesce to form a compound nucleus, followed by emission of a neutron at a lower energy. Because of the state of excitation of the nucleus, it also emits a gamma ray. This is more prevalent for the heavy nuclei because of their numerous energy levels which permit this type of interaction.

An efficient neutron shield requires a balanced mixture of light and heavy nuclei. Both scattering processes may then take place simultaneously. The net result is that the slowing down of fast neutrons from high energy to intermediate energy is done mostly by inelastic scatters with heavy nuclei. The slowing down from intermediate energy to thermal is accomplished predominantly by elastic scatters with light nuclei. The process of attenuation is completed by the absorption of the neutron at thermal or near thermal energy. At this energy, absorption becomes an important process. A concrete shield, though not the most efficient, is an efficient way to include both light and heavy nuclei in a single material. It has the additional feature of economy required of nuclear power plant shields.

The attenuation of fission neutrons in materials may be computed by adaptation of the Boltzmann Transport Equation. The low-energy neutrons may be treated by diffusion theory if the source term is appropriate for long-distance attenuation. The high-energy neutrons may be treated by the Transport Equation, by means of either the Moments Method, Monte Carlo applications, or direct integration (NIOBE). In hydrogenous shields the phenomenological Removal Theory may be applied. This latter approach makes use of the nearly exponential character of fast neutron attenuation.

Gamma-ray Attenuation. The attenuation of gamma rays is accomplished by the interaction of gamma rays with matter. There are several ways in which this may occur. The three main processes are the photoelectric effect, Compton scattering, and pair production. The photoelectric effect, in which a photon may collide with an orbital electron, is most important at low energy. The kinetic energy of the photon is transferred to the electron which is ejected from its orbit. As the energy of the photon increases, the collision with an electron becomes more elastic and the photon is scattered rather than absorbed, although it does give up some kinetic energy. This is referred to as Compton scattering. If the energy of the photon is high enough while it is in the Coulomb field of a nucleus or charged particle, it can create a positron and electron (pair production). Only 1.02 Mev is required for the formation of the pair. Any excess energy would be transferred as kinetic energy to the two particles generated.

The total cross section for gamma rays, or the linear attenuation coefficient, is the sum of the individual cross sections for the photoelectric effect, Compton scattering, and pair production. The energy-absorption cross section is the total cross section less that for Compton scattering. The extents of the photoelectric effect and Compton scattering decrease with an increase in gamma-ray energy, whereas pair production increases. This means that the total cross section will have a minimum value at some energy, and gamma rays at that energy will stream through the material in greater numbers than those of other energies, either higher or lower.

In general, gamma rays are attenuated in proportion to the atomic mass of the material. It is thus advantageous to make a gamma-ray shield of the most dense material economically feasible.

The basic character of gamma-ray attenuation is exponential in nature. A simple exponential attenuation according to the total cross section would represent the uncollided flux. This would also be the total flux if absorption were the only interaction taking place. However, the flux at any point is a combination of uncollided and scattered flux. Therefore, a correction factor, called the buildup factor must be applied to the uncollided flux. Buildup factors have been computed and tabulated as a function of atomic number, gamma-ray energy, and the number of relaxation lengths traversed.

Shield Design

An important aspect of the shield design process is to select the material or materials to be used. In making this selection, the physical processes of attenuation must be kept in mind, as well as the engineering problems associated. For stationary plants this selection becomes strongly dependent on economical considerations.

Material Selection. The selection of a material for a reactor shield requires that there be heavy atoms and light atoms mixed in the proper ratio. This will insure that the neutrons may be scattered elastically and inelastically, and that there will also be proper attenuation of the secondary gamma rays. The most efficient combination of elements is not available in an intimate mixture in the proper ratio except at costs greater than those usually permitted in stationary reactor shields. Alternate slabs of the proper materials are quite efficient but still too expensive. Concrete is thus an economical compromise.

Concrete Shielding. Concrete is an excellent shielding material because it contains both hydrogen and heavy elements. The fact that its composition can be varied makes it a versatile shield material in that it can be altered to meet different situations. It has good mechanical strength, needs little maintenance, and is available at reasonable cost.

While concretes are relatively heat resistant, excessive temperatures may cause loss of water and, consequently, of some shielding ability. It may, therefore, have to be cooled in order to insure constant shielding value.

The efficiency of a concrete shield may be improved by introducing heavy elements. This can be done by utilizing special aggregates or by adding metal punchings or both. It may also be improved by the introduction of materials that have high neutron cross sections with little or no capture gamma production. This can be done by including boron in the aggregate or by arranging boron layers in effective places throughout the shield.

CALCULATION OF CONCRETE CONSTANTS

In performing shielding calculations it is necessary to know the composition of the shield as accurately as possible. Of course, there is no problem in determining the composition of lead and steel shields, but there is some difficulty concerning concrete shields. The retained water content of various concrete shields is an uncertainty; this is a very significant factor because the water is the almost exclusive source of hydrogen in the shield. The exact elemental composition of the concrete is also difficult to predict. It is, therefore, useful to have a compilation of several concretes of each type so that the effect of changes in elemental composition on the pertinent nuclear constants may be observed.

Types of Concrete

Many types of concretes have been used for shielding purposes. They vary from ordinary portland cement concretes to heavy concretes using iron ore and steel punchings as an aggregate.

Ordinary Concrete. There are many different types of ordinary concrete. The differences are due to a variation in the mix proportions and elemental composition of the cement, sand, gravel, and water. The density of ordinary concrete varies from about 2.2 to 2.4 g/cm^3. Some light-weight concretes using boron-containing aggregates have been developed recently which weigh only about 1.30 g/cm^3.

Heavy Concrete. The compositions of heavy concretes are more varied than those of ordinary concretes since many different ores are used as aggregates for the heavy concretes. Some of the iron-bearing aggregates used are the natural iron ores, magnetite and limonite along with ferrophosphorus, a by-product of a process used to obtain elemental phosphorus from phosphates. Barytes, a barium ore, and ilmenite, a titanium ore, have also been used as heavy aggregates. In addition, metal punchings may be included in the aggregate. The densities of these concretes vary radically from 2.5 to 4.5 g/cm^3 depending upon the aggregate used.

Special Concretes. Concretes are also made for special purposes, such as high-neutron absorption with low capture gamma-ray production.[3,4] This is done by including boron in the aggregate or as a special additive. Concretes may also be designed to hold water at elevated temperatures

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[3] Hungerford, H. E., et al., New Shielding Materials for High-temperature Application, Nuclear Science and Engineering, 6, 401-444 (Nov 1959).

[4] Gallaher, R. B., and A. S. Kitzes, Summary Report on Portland Cement Concretes for Shielding, ORNL-1414 (March 2, 1953).

Concrete Constituents

It is not easy, and more importantly, not economical, to specify the exact elemental constituents of the concrete desired. It is therefore useful to have an idea of the range of variation of the elements in a given type of concrete. It is even more important to know the effect of such variations on the shielding properties of the concrete. A summary of shielding constants for several mixes of a given type of concrete will then be a guide for setting specifications for a concrete shield.

Elemental Compositions. The compositions of concretes used for shielding are not always reported in the literature in a consistent manner. Some designers reported only the mix used, whereas others performed chemical analyses on the finished products. This leads to an uncertainty as to the amounts of the constituent elements. In some cases, such as the barytes concrete, the chemical analysis of the ore is incomplete. To resolve the uncertainty for the purpose of this report, the percentage not reported for the aggregate was assumed to be oxygen. It is reasonable to believe that this is not a bad assumption to make. First, it is likely that some oxygen was lost and not reported in the analysis, and second, this increase in oxygen content will be small percentagewise for this element, since it is one of the most predominant in these elemental compositions.

Water Content. There are some cases, particularly those for which the composition is based on reported mixes, for which the water content is very much in question. For instance, magnetite aggregate is reported to contain free mositure. It may be possible that the concrete was mixed with either a wet or dry ore, depending upon the atmospheric conditions wherever the ore was stockpiled. Furthermore, once the concrete has set and cured, one cannot be sure without a chemical analysis how much of the water added while mixing was retained.

As a result, three different cases are considered to demonstrate the effect of water loss. The first case considers the ore to be dry and the loss of mix water to be zero. The second case also considers the ore to be dry, but the mix water loss is arbitrarily chosen to be 50 percent. This choice is not based on any experimental data, but is merely the mean value of the extreme cases. The third case considers the ore to be wet and the total water loss to be zero. This case serves to illustrate the effect of maximum water content.

At Hanford,[5-8] considerable work has been done on the temperature effect on various concretes. This work has been reported here by the concrete symbols HW1, HW2, and HW3 for the as cured, heated to 100°C, and heated to 320°C states, respectively. Results indicate the relative loss of shielding value of the concrete due to the loss of water by heating.

Methods of Calculation of Constants

In the calculations of the macroscopic cross sections from microscopic cross sections, the concrete was considered to be homogeneous. The elemental cross sections were considered to be additive to obtain the total cross section for the concrete. Experimental data seem to support this procedure quite well.

Neutron Cross Sections. The absorption, scattering, and total microscopic neutron cross sections of the elements were taken from the compilation by Hughes and Schwartz.[9] The total cross sections were estimated from the data plotted between 1 Mev and 10 Mev. The removal cross sections were obtained from data published by Chapman and Storrs[10] with later revisions[11-13] (see Table I). Some of these cross sections have been determined experimentally, whereas the others were obtained from the empirical curve plotted in Figure 1.

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[5] Bunch, W. L., Attenuation Properties of High Density Portland Cement Concretes as a Function of Temperature, HW-54656 (Jan 22, 1958), p. 39.

[6] Peterson, E. G., Shielding Properties of Ferrophosphorus Concrete as a Function of Temperature, HW-64774 (July 5, 1960), pp. 43-44, 62.

[7] Peterson, E. G., Shielding Properties of Ordinary Concrete as a Function of Temperature, HW-65572 (Aug 2, 1960), p. 24.

[8] Wood, D. E., The Effect of Temperature on the Neutron Attenuation of Magnetite Concrete, HW-58497 (Dec 11, 1958), p. 16.

[9] Hughes, D. J., and R. B. Schwartz, Neutron Cross Sections, BNL-325 (July 1, 1958), 2nd Edition.

[10] Chapman, G. T., and C. L. Storrs, Effective Neutron Removal Cross Sections for Shielding, AECD-3978 (ORNL-1843) (Sept 19, 1955).

[11] Trubey, D. K., and G. T. Chapman, Effective Neutron Removal Cross Sections for Carbon and Oxygen in Continuous Mediums, ORNL-2197 (Sept 19, 1958).

[12] Miller, J. M., Effective Neutron Removal Cross Section of Zirconium, ORNL-2842 (Sept 1, 1959), p. 168.

[13] Miller, J. M., Effective Neutron Removal Cross Section of Tungsten, ORNL-2389 (Sept 1, 1957), p. 187.

Table I

REMOVAL CROSS SECTIONS FOR VARIOUS MATERIALS[a]

Material	σ_r (barns)	N_0 (at 20°C) (atoms/cm^3) (x 10^{24})	Σ_r (cm^{-1})
Hydrogen	1.00 ± 0.05		
Deuterium	0.92 ± 0.10	(computed from D_2O-O)	
Lithium	1.01 ± 0.04	0.0460	0.046
Beryllium	1.07 ± 0.06	0.120	0.128
Boron	0.97 ± 0.10	0.139	0.135
Carbon (Graphite)[b]	0.72 ± 0.05	0.0803	0.058
Oxygen[b]	0.92 ± 0.05		
Fluorine	1.29 ± 0.05		
Aluminum	1.31 ± 0.05	0.0603	0.079
Chlorine	1.2 ± 0.8		
Iron	1.98 ± 0.08	0.0848	0.168
Nickel	1.89 ± 0.10	0.0913	0.173
Copper	2.04 ± 0.11	0.0846	0.173
Zirconium[c]	2.36 ± 0.12	0.0423	0.10
Tungsten[d]	3.13 ± 0.25	0.0631	0.198
Lead	3.53 ± 0.30	0.0330	0.116
Bismuth	3.49 ± 0.35	0.0282	0.098
Uranium	3.6 ± 0.4	0.0473	0.17
Boric Oxide (B_2O_3)	4.30 ± 0.41		
Boron Carbide (B_4C)	5.1 ± 0.4		
Fluorothene (C_2F_3Cl)	6.66 ± 0.8		
Heavy Water (D_2O)	2.76 ± 0.11		
Lithium Fluoride (LiF)	2.43 ± 0.34		
Oil (CH_2)	2.84 ± 0.11		
Paraffin ($C_{30}H_{62}$)	80.5 ± 5.2		
Perfluoroheptane (C_7F_{16})	26.3 ± 0.8		

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[a] Chapman, G. T., and C. L. Storrs, Effective Neutron Removal Cross Sections for Shielding, AECD-3978 (ORNL-1843) (Sept 19, 1955).

[b] Trubey, D. K., and Chapman, G. T., Effective Neutron Removal Cross Sections for Carbon and Oxygen in Continuous Mediums, ORNL-2197 (Sept 19, 1958).

[c] Miller, J. M., Effective Neutron Removal Cross Section of Zirconium, ORNL-2842 (Sept 1, 1959), p. 168.

[d] Miller, J. M., Effective Neutron Removal Cross Section of Tungsten, ORNL-2389 (Sept 1, 1957), p. 187.

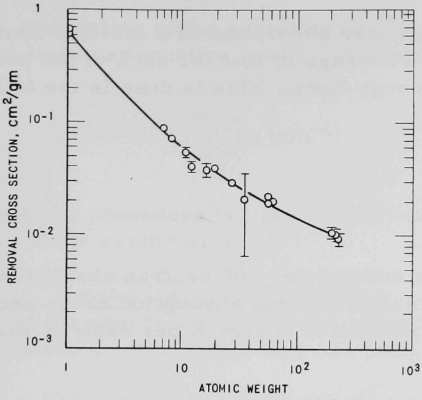

Figure 1

Experimental Removal Cross Section as a Function of Atomic Weight[a]

[a] Chapman, G. T., and C. L. Storrs, Effective Neutron Cross Sections for Shielding, AECD-3978 (ORNL-1843) (Sept 19, 1955).

The macroscopic cross sections of the concretes were determined by the addition of the individual cross sections weighted by the percentage of each element comprising the concrete, that is,

$$\sigma_a\ (\text{cm}^{-1}) = \sum_{i=1}^{n} \sigma_{ai}\ (\text{cm}^{-1}) \quad .$$

The average absorption cross section of thermal neutrons is the value used in the shielding calculations.[14] To obtain this value, the 2200-m/sec cross section is corrected for 1/v absorption in a Maxwellian distribution at 20°C by multiplying by 0.8862:

$$\overline{\sigma}_a\ (\text{cm}^{-1}) = 0.8862\ \sigma_a\ (\text{cm}^{-1}) \quad .$$

Gamma-ray Spectra. The gamma-ray spectra of the elements were obtained from the compilation by Troubetzkoy and Goldstein.[15] The spectra are reported as the number of photons of an energy emitted per 100 neutrons absorptions by an element.

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[14] Glasstone, S., Principles of Nuclear Reactor Engineering, D. Van Nostrand Company, Inc., Princeton, New Jersey (1955), p. 98.

[15] Troubetzkoy, E., and H. Goldstein, A Compilation of Information on Gamma Ray Spectra Resulting from Thermal Neutron Capture, ORNL-2904 (Jan 18, 1961); Gamma Rays from Thermal Neutron Capture, Nucleonics, 18 (11) p. 171, (Nov 1960).

The number of photons emitted per absorption of a thermal neutron in concrete is obtained by a weighted average of that for each of the possible 23 elements for each of the seven energy lines. This is done in the following manner:

$$N(E) = \frac{\sum_{i=1}^{23} \overline{\sigma_{ai}}\, N_i(E)}{100\ \overline{\sigma_a}} \quad .$$

Here $N_i(E)$ is the number of photons emitted per 100 neutron absorptions and $\overline{\sigma_{ai}}$ the average macroscopic thermal neutron absorption cross section for each element. $N(E)$ is given in photons of energy E per neutron absorbed in concrete.

It may be noted that the effect of titanium on the gamma-ray spectrum of the Ilmenite concretes is quite apparent in the 2-Mev group. It may also be noted that calcium is the source of the high numbers of photons from the type 01 ordinary concrete.

Diffusion Constants. From the diffusion theory approximation, the thermal neutron diffusion coefficient is given by

$$D\ (\text{cm}) = (1/3)\,\sigma_{tr} \quad ,$$

where σ_{tr} is the macroscopic transport cross section, which is calculated from the scattering cross section and the average cosine of the scattering angle:

$$\sigma_{tr}\ (\text{cm}^{-1}) = (1 - \mu_0)\,\sigma_s \quad .$$

The thermal neutron diffusion length is given by

$$L\ (\text{cm}) = 1/\kappa = \sqrt{D/\sigma_a} \quad .$$

The value of these constants for water was based on experimental data.[16]

Gamma-ray Linear Attenuation Coefficients. The total linear attenuation coefficients for the concrete are computed in a manner similar to the calculation of the neutron cross sections. The data used was from the report by Grodstein.[17] The individual elemental densities are multiplied by their respective mass attenuation coefficients.

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[16] Hogerton, J. F., and R. C. Grass, The Reactor Handbook, Vol. 1, Physics, AECD-3645 (March 1955), p. 487.

[17] Grodstein, G. W., X-ray Attenuation Coefficients from 10 kev to 100 Mev, NBS Circular 583 (April 30, 1957), p. 50.

The summation of the resulting linear attenuation coefficients will give the total linear attenuation coefficient for the concrete:

$$\mu(\text{cm}^{-1}) = \sum_{i=1}^{n} \mu_i\,(\text{cm}^{-1}) \quad .$$

The same procedure is used to determine the energy absorption linear attenuation coefficients.

Gamma-ray Buildup Factors. The determination of the buildup factor for concrete involves the selection of an effective atomic number for the mixture. This procedure has been outlined by Goldstein.[18]

The starting point for finding the equivalent atomic number is to compute the attenuation coefficients at various energies for the mixture. The shape of the curve of the total mass attenuation coefficient is then compared with the corresponding curves for individual elements by normalizing the curves over the region of interest. This is done by plotting μ/μ_0 vs. E over the energy range from 1 Mev to 10 Mev to find a reasonable match. The curves in Figures 2 and 3 for representative concretes have been normalized at 2 Mev and 8 Mev to provide a double check.

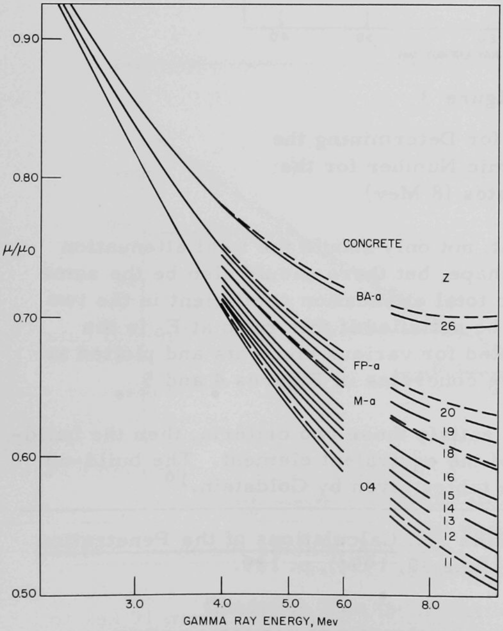

Figure 2

Condition One for Determining the Effective Atomic Number for the Concretes (2 Mev)

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[18] Goldstein, H., Fundamental Aspects of Reactor Shielding. Addison-Wesley Publication Co., New York (Feb 1959), p. 221.

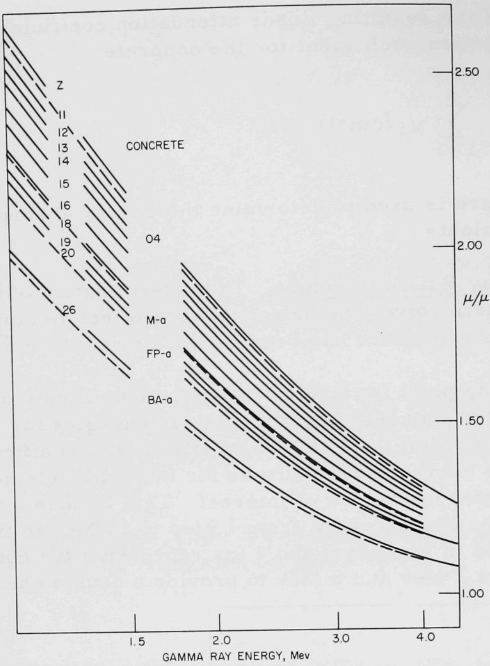

Figure 3

Condition One for Determining the Effective Atomic Number for the Concretes (8 Mev)

To be completely equivalent, not only should the total attenuation coefficient curves have the same shape, but there should also be the same ratio of scattering cross section to total attenuation coefficient in the two cases. This second condition will be satisfied if this ratio at E_0 is the same. This ratio has been calculated for various elements and plotted at 2 Mev and 8 Mev for representative concretes in Figures 4 and 5.

If the data for the concrete satisfy these two criteria, then the build-up factor for the concrete is that of the equivalent element. The build-up factors for the elements are in the tables given by Goldstein.[19]

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[19] Goldstein, H., and J. E. Wilkins Jr., Calculations of the Penetration of Gamma Rays, NYO-3075 (June 30, 1954), p. 189.

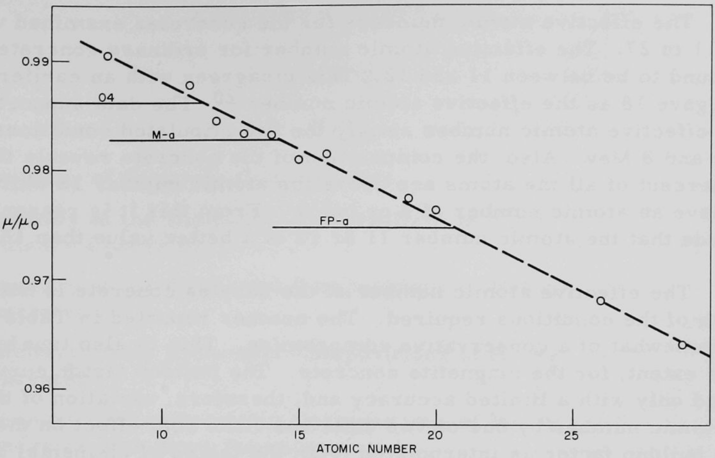

Figure 4

Condition Two for Determining the Effective Atomic Number for the Concretes (2 Mev)

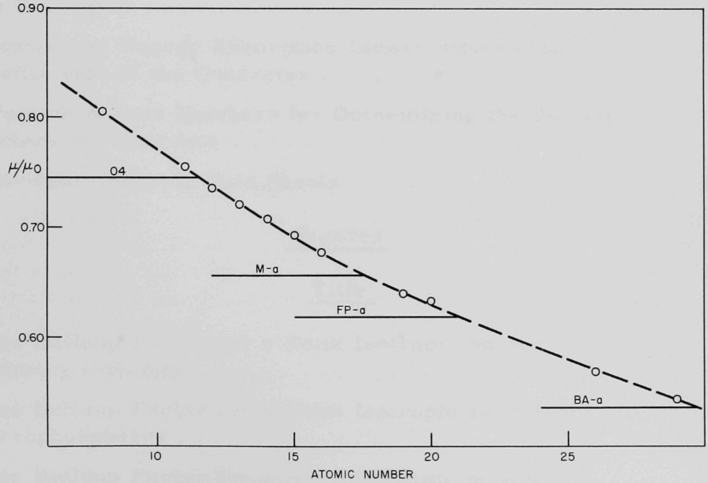

Figure 5

Condition Two for Determining the Effective Atomic Number for the Concretes (8 Mev)

The effective atomic numbers for the concretes examined varied from 11 to 27. The effective atomic number for ordinary concrete, type 04, was found to be between 11 and 12. This disagrees with an earlier result which gave 18 as the effective atomic number.[20] The data supporting the lower effective atomic number satisfy the two stipulated conditions at both 2 Mev and 8 Mev. Also, the composition of the concrete reveals that only 11.4 percent of all the atoms are above the atomic number 18 while 50 percent have an atomic number of 8 or below. From this it is reasonable to conclude that the atomic number 11 or 12 is a better value than 18.

The effective atomic number of the barytes concrete is not the same by both of the conditions required. The number reported in Table XII is thus somewhat of a conservative compromise. This is also true but to a lesser extent, for the magnetite concrete. The buildup factor curves can be read only with a limited accuracy and, therefore, variation of the effective atomic number by one or two units has little real effect on the value of the buildup factor as interpolated from the tables of elemental data.

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[20] Obenshain, F. E., The Theoretical Buildup Factor for Ordinary Concrete, WAPD-P-646 (March 1955).

CONCRETE CONSTANTS

Tables

Figures

Table II

SUMMARY OF THE CONCRETE COMPOSITIONS

CONCRETE	DENSITY ρ			COMPOSITION (lb/yd^3)					REFERENCE
	*SYMBOL	(gm/cm^3)	lb/ft^3	WATER	CEMENT	AGGREGATE	STEEL PUNCHINGS	TOTAL	
Ordinary									
1	01	2.33	145	260	318	3300 (Sand and Gravel)		3878	16
2a	02-a	2.30	144						16
2b	02-b	2.20	137						16
3 ORNL	03	2.39	149						4
4 NBS	04	2.35	147						8
5 Harwell	05	2.50	156						2
6 APDA	06	1.30	80	0.231 373	0.256 525	0.513 2032 950 (Serpentine) (Sand)	(Volume Fractions)	3887	11
7 APDA	07	2.09	130						11
0 HW1	0-HW1	2.33	145						14
0 HW2	0-HW2	2.26	141						14
Ferrophosphorus									
1a	FP-a	4.68	292	383	730	4070 2710 (Coarse) (Fine)		7893	10
1b	FP-b	4.57	285						10
HW1 Hanford	FP-HW1	4.82	301						13
HW3 Hanford	FP-HW3	4.67	292						13
Barytes									
1a	BA-a	3.50	219						16
1b	BA-b	3.39	212						16
H Harwell	BA-H	2.575	160						2
Haydite ORNL, X-10	BAHA	2.35	147	10.0	16.3	46.4 27.3 (Barytes) (Haydite)	(% by Wt)		5
Haydite ORNL, X-10	BAHA-d	2.28	142						5
OR ORNL	BA-OR	3.30	206	383	468	4711		5562	18
Magnetite									
1a EBWR	M-a	3.55	222	330	875	2623 2160 (Coarse) (Fine)		5988	7, 10
1b ANL, EBWR	M-b	3.45	215						7, 10
1c ANL, EBWR	M-c	3.62	226	330	875	2700 2200		6105	7, 10
HW1 Hanford	M-HW1	3.29	205						17
HW2 Hanford	M-HW2	3.27	204						17
Ilmenite									
1a New York Ore	I-1a	3.50	219	330	875	4695		5900	12
1b New York Ore	I-1b	3.40	212						12
2a Swedish Ore	I-2a	3.76	235	330	875	5140		6345	12
2b Swedish Ore	I-2b	3.66	228						12
NRU Chalk River	I-NRU	3.49	218						15
NRUe Chalk River	I-NRUe	3.44	215						15
Magnetite and Steel									
a ANL; EBWR	MS-a	4.70	293	340	940	1846	4800	7926	7, 10
b ANL; EBWR	MS-b	4.60	287						7, 10
c ANL; EBWR	MS-c	4.73	296	340	940	1900	4800	7980	7, 10
Limonite and Steel									
1a ANL, CP-5	LS-a	4.54	284	347	980	1661	4680	7668	9
1b ANL, CP-5	LS-b	4.44	277						9
1c ANL, CP-5	LS-c	4.65	290	347	980	1825	4680	7832	1
2a BNL	LS-BRa	4.16	260	296	940	1684	4100	7020	3
2b BNL	LS-BRb	4.08	255						3
2c BNL	LS-BRc	4.28	267	296	940	1880	4100	7216	3
HW1 Hanford	LS-HW1	4.23	264						6
HW2 Hanford	LS-HW2	4.14	258						6

*a Indicates 100% Water Retention
b Indicates 50% Water Retention
c Indicates 100% Water Retention Including Free Moisture in Mix
d Average Composition of Four Sample Cores
e Composition After Two Years

HW1 As cured concrete
HW2 Heated to 100°C
HW3 Heated to 320°C

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Table III

SUMMARY OF THE ELEMENTAL COMPOSITIONS OF ORDINARY CONCRETES

(gm element/cm^3 concrete)

CONCRETE ELEMENT	01	02-a		02-b	03	04	05	06	07	0-HW1		0-HW2
H	0.00484	0.023		0.0115	0.020	0.013	0.022	0.034	0.033	0.015		0.007
O in water	0.0384	0.183		0.0915	0.159	0.103	1.231	0.793	1.075	1.057		0.995
in mix	1.1106		1.037		0.980	1.062						
B								0.010	0.002			
C	0.130		0.0023		0.118		0.008		0.002			
Na			0.0368			0.040	0.029		0.008		0.041	
Mg	0.00486		0.005		0.057	0.006	0.002	0.003	0.281		0.085	
Al	0.0119		0.078		0.085	0.107	0.131	0.025	0.040		0.137	
Si	0.438		0.775		0.342	0.737	0.63	0.417	0.435		0.487	
P					0.007				trace		0.002	
S	0.00192				0.007	0.003	0.0037				0.002	
Cl									trace			
K			0.0299		0.004	0.045	0.025		0.008		0.015	
Ca	0.581		0.100		0.582	0.194	0.242	0.001	0.141		0.295	
Ti							0.017		trace		0.011	
V												
Cr												
Mn									trace			
Fe					0.003		0.045		trace		0.003	
Ni	0.00726		0.032		0.026	0.029	0.122	0.013	0.064		0.178	
Cu									0.002			
Zn												
Mo												
Ba												
density (g/cm^3)	2.33	2.30		2.20	2.39	2.35	2.50	1.30	2.09	2.33		2.26

Table IV

SUMMARY OF THE ELEMENTAL COMPOSITIONS OF HEAVY CONCRETES

(gm elements/cm^3 concrete)

CONCRETE ELEMENT	FP-a		FP-b	FP-HW1		FP-HW3	BA-a		BA-b	BA-H	BAHA	BAHA-d	BA-OR
H in water	0.0234		0.0117	0.021		0.004	0.0243		0.0122	0.007	0.026	0.0298	0.036
in ore											0.0045		
O in water	0.201		0.100	0.322		0.191	0.195		0.0975	0.710	0.209	1.084	0.291
in ore		0.041						0.872			0.494		0.971
in cement		0.154						0.118			0.138		
C		0.0023			0.004					0.0233			
Mg in ore					0.006							0.0441	0.0099
in cement		0.0047						0.00385			0.0046		
Al in ore					0.009					0.0123	0.0546	0.0565	0.0066
in cement		0.0187						0.0137			0.0161		
Si in ore		0.0796			0.090					0.180	0.308	0.232	0.139
in cement		0.0515						0.0352			0.0414		
P		0.967			1.049								
S					0.004			0.364		0.180	0.144	0.0094	0.287
Ca in ore					0.203			0.0203		0.148	0.109	0.209	0.135
in cement		0.197						0.147			0.172		
Ti					0.042								
V					0.084								
Cr		0.0023			0.084								
Mn		0.117			0.013								
Fe in ore		2.808			2.823			0.151		0.595		0.0338	0.277
in cement		0.014						0.0091			0.0107		
Ni					0.017								
Cu					0.008								
Zn													
Mo					0.042								
Ba								1.551		0.718	0.618	0.577	1.20
density (g/cm^3)	4.68		4.57	4.82		4.67	3.50		3.39	2.575	2.35	2.28	3.30

Table V

SUMMARY OF THE ELEMENTAL COMPOSITIONS OF HEAVY CONCRETES

(gm elements/cm^3 concrete)

CONCRETE / ELEMENT	M-a	M-b	M-c	M-HW1	M-HW2	I-1a	I-1b	I-2a	I-2b	I-NRU	I-NRUe
H in water	0.0219	0.0110	0.0219	0.015	0.0128	0.0219	0.0110	0.0219	0.0110	0.0115	0.0093
in ore			0.0076								
O in water	0.174	0.087	0.174	1.279	1.261	0.174	0.087	0.174	0.087	1.212	1.272
in ore	0.826	0.826	0.887			0.981		0.989			
in cement	0.187	0.187	0.187			0.187		0.187			
C										0.0185	0.0148
Mg in ore		0.0172		0.184		0.267		0.0148		0.0527	0.0571
in cement		0.0062				0.0062		0.0062			
Al in ore		0.0752								0.0743	0.0416
in cement		0.0218				0.0218		0.0218			
Si in ore		0.0670		0.129						0.121	0.0664
in cement		0.0561				0.0560		0.0560			
P		0.0006									
S		0.0037									
Ca in ore		0.0071		0.0220				0.0012		0.112	0.102
in cement		0.233				0.233		0.233			
Ti		0.0959				0.955		0.959		0.508	0.649
V		0.0062									
Cr		0.0030									
Mn		0.0024				0.0225		0.0302			
Fe in ore		1.730		1.460		0.560		1.049		1.38	1.309
in cement		0.0145				0.0145		0.0145			
density (g/cm^3)	3.55	3.45	3.62	3.29	3.27	3.50	3.40	3.76	3.66	3.49	3.44

Table VI

SUMMARY OF THE ELEMENTAL COMPOSITION OF HEAVY CONCRETES WITH STEEL PUNCHINGS

(gm elements/cm^3 concrete)

CONCRETE / ELEMENT	MS-a	MS-b	MS-c	LS-a	LS-b	LS-c	LS-BRa	LS-BRb	LS-BRc	LS-HW1	LS-HW2
H in water	0.0225	0.0112	0.0225	0.0232	0.0116	0.0232	0.0196	0.0098	0.0196	0.028	0.018
in ore			0.0036			0.0125			0.0130		
O in water	0.179	0.089	0.179	0.183	0.091	0.183	0.156	0.078	0.156	0.806	0.726
in ore	0.334	0.334	0.363	0.247	0.247	0.346	0.322	0.322	0.425		
in cement	0.200	0.200	0.200	0.210	0.210	0.210	0.201	0.201	0.201		
Mg in ore		0.0125						0.0036		0.039	
in cement		0.0071			0.0071			0.0065			
Al in ore		0.0237			0.0029			0.0095			
in cement		0.0231			0.0234			0.0231			
Si in ore		0.0107			0.126			0.0362		0.078	
in cement		0.0605			0.0629			0.0605			
P		0.0006			0.0005						
S		0.0018									
Ca in ore		0.0047									
in cement		0.251			0.262			0.251		0.250	
Ti		0.0676						0.0006			
V		0.0042									
Cr		0.0018									
Mn		0.0018			0.0053			0.0024		3.030	
Fe in ore		0.631			0.590			0.625			
in cement		0.0154			0.0160			0.0154			
in steel		2.846			2.779			2.432			
density (g/cm^3)	4.70	4.60	4.73	4.54	4.44	4.65	4.16	4.08	4.28	4.23	4.14

Table VII

TABULATION OF ELEMENTAL DATA

	CROSS SECTION DATA				CAPTURE GAMMA-RAY SPECTRA (photons/100 captures)[e]						
ELEMENT	σ_a^{+} (barns)	σ_s (barns)	σ_r (barns)[d]	σ_T (barns)[b]	1 Mev	2 Mev	3 Mev	4 Mev	6 Mev	8 Mev	10 Mev
H	0.33	99[c]	1.00	2.0	-	-	100	-	-	-	-
B	755	4	0.97	1.7	-	-	-	110	28	6	0.8
C	0.003	4.8	0.72	1.5	-	-	-	100	-	-	-
O	0.0002	4.2	0.92	2.0	-	-	-	-	-	-	-
Na	0.515	4.0	(1.14)	2.5	96	127	187	70	31	-	-
Mg	0.063	3.6	(1.18)	2.0	-	-	28	72	10	3.3	0.57
Al	0.230	1.4	1.31	2.5	236	195	69	62	19	19	-
Si	0.16	1.7	(1.30)	2.5	100	63	30	89	11	4.1	0.1
P	0.20	5	(1.39)	2.5	290	97	55	98	27	7.2	-
S	0.52	1.1	(1.41)	2.5	70	32	72	70	44	6.5	-
Ci	33.8	16	1.2	2.5	49	85	41	47	55	24	-
K	2.07	1.5	(1.51)	3.0	100	81	57	106	37	4.7	-
Ca	0.44	3.2	(1.52)	2.5	14	191	77	85	64	1.8	-
Ti	5.8	4	(1.61)	3.0	54	160	16	24	78	1.3	0.2
V	5.00	5	(1.64)	3.0	83	132	11.4	21	67	16	-
Cr	3.1	3.0	(1.64)	3.5	85	41	21	12	23	39	6.4
Mn	13.2	2.3	(1.67)	3.5	125	91	60	50	34	17	-
Fe	2.53	11	1.98	3.0	75	60	27	23	25	38	2.1
Ni	4.6	17.5	1.89	3.0	84	40	23	23	34	62	0.8
Cu	3.77	3.6	(1.88)	3.5	68	47	26	30	27	43	-
Zn	1.1	7.2	2.04	3.5	156	93	67	48	29	16	1
Mo	2.7	7	(2.21)	4.5	137	18	-	84	26	3	0.03
Ba	1.2	8	(2.69)	5.5	-	-	-	75	14	1.4	0.1

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[a] 2200 m/sec

[b] Estimated value for 1-10 Mev

[c] All hydrogen present is assumed to be in the form of water. The transport cross section for water is 2.083 cm^{-1}. Therefore, it was necessary to assign σ_s for hydrogen this value in order to obtain the required result.

[d] Parentheses around removal cross sections indicate that the value is empirical rather than experimental.

[e] Troubetzkoy, E., and H. Goldstein, A Compilation of Information on Gamma Ray Spectra Resulting from Thermal Neutron Capture, ORNL-2904 (Jan 18, 1961).

Table VIII

NEUTRON CONSTANTS FOR CONCRETES

CONCRETE	ρ (g/cm^3)	σ_r(cm^{-1}) CALC.	σ_r(cm^{-1}) EXPTL.	$1/\lambda$ (cm^{-1}) EXPTL.	σ_t(cm^{-1}) CALC.	σ_a(cm^{-1}) CALC.	D_{th}(cm)	κ_{th_1}(cm^{-1})
01	2.33	0.0740	0.083*	0.090	0.149	0.0059	0.968	0.0778
02-a	2.30	0.0849			0.174	0.0094	0.484	0.139
02-b	2.20	0.0748			0.154	0.0074	0.749	0.0993
03	2.39	0.0837	0.086		0.168	0.0097	0.512	0.137
04	2.35	0.0793			0.162	0.0086	0.688	0.112
05	2.50	0.0883			0.179	0.0187	0.485	0.196
06	1.30	0.0611			0.126	0.380	0.406	0.968
07	2.09	0.0836			0.168	0.0850	0.378	0.474
O-HW1	2.33	0.0781	0.078	0.083	0.156	0.0129	0.629	0.143
O-HW2	2.26	0.0712	0.0735	0.078	0.142	0.0115	0.926	0.112
FP-a	4.68	0.125	0.15*		0.216	0.0924	0.344	0.518
FP-b	4.57	0.115			0.195	0.0903	0.463	0.442
FP-HW1	4.82	0.125	0.131	0.139	0.216	0.0902	0.358	0.502
FP-HW3	4.67	0.111	0.128	0.136	0.187	0.0872	0.585	0.386
BA-a	3.50	0.0926		0.125	0.188	0.0197	0.440	0.212
BA-b	3.39	0.0817			0.165	0.0176	0.667	0.162
BA-H	2.575	0.0643			0.125	0.0220	0.912	0.155
BAHA	2.35	0.0770			0.155	0.0128	0.421	0.174
BAHA-d	2.28	0.0773		0.098	0.158	0.0111	0.412	0.164
BA-OR	3.30	0.0985	0.0993		0.199	0.0224	0.334	0.259
M-a	3.55	0.106			0.198	0.0553	0.393	0.375
M-b	3.45	0.0966			0.179	0.0534	0.540	0.314
M-c	3.62	0.113			0.212	0.0566	0.330	0.414
M-HW1	3.29	0.0984		0.114	0.186	0.0402	0.482	0.289
M-HW2	3.27	0.0965		0.105	0.182	0.0398	0.517	0.277
I-1a	3.50	0.107			0.209	0.0848	0.419	0.450
I-1b	3.40	0.098			0.190	0.0829	0.592	0.374
I-2a	3.76	0.111			0.213	0.0975	0.401	0.493
I-2b	3.66	0.107			0.193	0.0956	0.557	0.414
I-NRU	3.49	0.0990			0.188	0.0699	0.536	0.361
I-NRUe	3.44	0.0983		0.075	0.187	0.0766	0.579	0.364
MS-a	4.70	0.124			0.213	0.0953	0.337	0.532
MS-b	4.60	0.114			0.193	0.0933	0.445	0.458
MS-c	4.73	0.127			0.220	0.0959	0.313	0.554
LS-a	4.54	0.121	0.114*		0.207	0.0888	0.340	0.511
LS-b	4.44	0.111			0.187	0.0868	0.455	0.437
LS-c	4.65	0.132			0.230	0.0910	0.268	0.583
LS-BRa	4.16	0.110			0.191	0.0800	0.382	0.458
LS-BRb	4.08	0.102			0.173	0.0783	0.502	0.395
LS-BRc	4.28	0.122		0.159	0.214	0.0823	0.290	0.532
LS-HW1	4.23	0.118	0.128		0.208	0.0800	0.316	0.503
LS-HW2	4.14	0.110	0.119		0.190	0.0782	0.396	0.445

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*ANL Shield Facility (Collimated Beam)

Table IX

GAMMA-RAY SPECTRA FROM THERMAL NEUTRON CAPTURE IN THE CONCRETES

CONCRETE	σ_a(cm^{-1}) CALC.	PHOTONS PER NEUTRON CAPTURE						
		1 Mev	2 Mev	3 Mev	4 Mev	6 Mev	8 Mev	10 Mev
01	0.0059	0.355	1.29	0.676	0.715	0.408	0.0332	0.0003
02-a	0.0094	0.546	0.533	0.739	0.447	0.143	0.0542	0.0004
02-b	0.0074	0.694	0.678	0.668	0.569	0.182	0.0689	0.0005
03	0.0097	0.374	0.911	0.751	0.483	0.284	0.0514	0.0003
04	0.0086	0.675	0.765	0.694	0.595	0.218	0.0618	0.0004
05	0.0187	0.781	0.796	0.611	0.435	0.277	0.127	0.0006
06	0.380	0.0047	0.0032	0.0171	1.08	0.275	0.0593	0.0078
07	0.0850	0.0477	0.0475	0.0916	1.00	0.261	0.0017	0.0071
0-HW1	0.0129	0.636	0.813	0.584	0.420	0.270	0.151	0.0010
0-HW2	0.0115	0.713	0.912	0.533	0.471	0.302	0.169	0.0011
FP-a	0.0924	0.871	0.655	0.373	0.302	0.258	0.312	0.0016
FP-b	0.0903	0.890	0.670	0.359	0.308	0.264	0.319	0.0016
FP-HW1	0.0902	0.873	0.669	0.309	0.283	0.284	0.320	0.0036
FP-HW3	0.0872	0.903	0.692	0.286	0.293	0.294	0.331	0.0037
BA-a	0.0197	0.279	0.274	0.426	0.483	0.204	0.0920	0.0008
BA-b	0.0176	0.313	0.307	0.357	0.541	0.229	0.103	0.0009
BA-H	0.0220	0.576	0.511	0.323	0.372	0.244	0.257	0.0016
BAHA	0.0128	0.244	0.391	0.635	0.442	0.176	0.0278	0.0004
BAHAd	0.0111	0.195	0.344	0.618	0.374	0.139	0.0412	0.0005
BA-OR	0.0224	0.330	0.298	0.477	0.383	0.184	0.126	0.0009
M-a	0.0553	0.676	0.721	0.325	0.240	0.304	0.296	0.0020
M-b	0.0534	0.700	0.747	0.301	0.249	0.315	0.307	0.0020
M-c	0.0566	0.660	0.704	0.341	0.235	0.297	0.289	0.0019
M-HW1	0.0402	0.698	0.615	0.338	0.247	0.244	0.337	0.0019
M-HW2	0.0398	0.705	0.621	0.332	0.249	0.246	0.340	0.0019
I-1a	0.0848	0.568	1.34	0.242	0.250	0.636	0.0783	0.0018
I-1b	0.0829	0.581	1.37	0.225	0.256	0.650	0.0801	0.0019
I-2a	0.0975	0.599	1.25	0.248	0.248	0.588	0.116	0.0018
I-2b	0.0956	0.611	1.27	0.234	0.253	0.600	0.118	0.0019
I-NRU	0.0699	0.632	1.07	0.246	0.240	0.496	0.189	0.0020
I-NRUe	0.0766	0.618	1.15	0.229	0.239	0.540	0.165	0.0020
MS-a	0.0953	0.705	0.647	0.304	0.234	0.271	0.339	0.0020
MS-b	0.0933	0.720	0.661	0.290	0.239	0.277	0.346	0.0020
MS-c	0.0959	0.701	0.643	0.309	0.232	0.269	0.337	0.0020
LS-a	0.0888	0.713	0.600	0.315	0.237	0.245	0.352	0.0019
LS-b	0.0868	0.729	0.614	0.299	0.243	0.251	0.360	0.0020
LS-c	0.0910	0.696	0.585	0.332	0.231	0.239	0.344	0.0019
LS-BRa	0.0800	0.712	0.603	0.313	0.236	0.246	0.354	0.0020
LS-BRb	0.0783	0.728	0.616	0.298	0.241	0.252	0.362	0.0020
LS-BRc	0.0823	0.693	0.586	0.332	0.229	0.240	0.345	0.0019
LS-HW1	0.0800	0.695	0.589	0.324	0.230	0.241	0.339	0.0019
LS-HW2	0.0782	0.711	0.602	0.309	0.235	0.247	0.357	0.0020

Table X

TOTAL GAMMA-RAY LINEAR ATTENUATION COEFFICIENTS OF THE CONCRETES

CONCRETE	DENSITY (g/cm^3)	PHOTON ENERGY (cm^{-1})								
		0.5 Mev	1 Mev	2 Mev	3 Mev	4 Mev	5 Mev	6 Mev	8 Mev	10 Mev
01	2.33	0.2033	0.1482	0.1042	0.0851	0.0743	0.0675	0.0630	0.0570	0.0539
02-a	2.30	0.2017	0.1473	0.1034	0.0841	0.0732	0.0663	0.0615	0.0554	0.0520
02-b	2.20	0.1917	0.1400	0.0983	0.0801	0.0697	0.0632	0.0587	0.0529	0.0497
03	2.39	0.2095	0.1527	0.1074	0.0877	0.0766	0.0696	0.0649	0.0588	0.0556
04	2.35	0.2040	0.1489	0.1046	0.0852	0.0744	0.0674	0.0627	0.0566	0.0533
05	2.50	0.2188	0.1596	0.1122	0.0916	0.0801	0.0728	0.0679	0.0615	0.0581
06	1.30	0.1154	0.0843	0.0591	0.0479	0.0415	0.0374	0.0346	0.0309	0.0288
07	2.09	0.1841	0.1343	0.0943	0.0768	0.0668	0.0605	0.0561	0.0506	0.0474
0-HW1	2.33	0.2025	0.1476	0.1038	0.0849	0.0744	0.0677	0.0632	0.0575	0.0545
0-HW2	2.26	0.1957	0.1426	0.1004	0.0821	0.0720	0.0656	0.0613	0.0558	0.0529
FP-a	4.68	0.3946	0.2851	0.2024	0.1697	0.1529	0.1430	0.1371	0.1304	0.1280
FP-b	4.57	0.3839	0.2773	0.1969	0.1653	0.1491	0.1397	0.1341	0.1277	0.1256
FP-HW1	4.82	0.4058	0.2930	0.2080	0.1747	0.1576	0.1477	0.1418	0.1351	0.1329
FP-HW3	4.67	0.3915	0.2825	0.2007	0.1688	0.1526	0.1432	0.1377	0.1316	0.1297
BA-a	3.50	0.3168	0.2142	0.1517	0.1295	0.1187	0.1130	0.1097	0.1066	0.1064
BA-b	3.39	0.3054	0.2058	0.1459	0.1248	0.1147	0.1094	0.1065	0.1038	0.1038
BA-H	2.57	0.2265	0.1569	0.1112	0.0941	0.0856	0.0809	0.0781	0.0752	0.0745
BAHA	2.35	0.2108	0.1470	0.1038	0.0869	0.0782	0.0731	0.0698	0.0661	0.0647
BAHA-d	2.28	0.2038	0.1425	0.1005	0.0838	0.0751	0.0699	0.0666	0.0627	0.0610
BA-OR	3.30	0.2964	0.2030	0.1436	0.1217	0.1107	0.1047	0.1010	0.0972	0.0963
M-a	3.55	0.3027	0.2192	0.1550	0.1290	0.1150	0.1066	0.1014	0.0950	0.0922
M-b	3.45	0.2932	0.2132	0.1502	0.1251	0.1117	0.1036	0.0987	0.0927	0.0900
M-c	3.62	0.3093	0.2240	0.1684	0.1317	0.1174	0.1087	0.1033	0.0967	0.0937
M-HW1	3.29	0.2809	0.2037	0.1439	0.1192	0.1059	0.0977	0.0926	0.0863	0.0833
M-HW2	3.27	0.2789	0.2022	0.1429	0.1184	0.1052	0.0971	0.0921	0.0858	0.0828
I-1a	3.50	0.2997	0.2173	0.1535	0.1271	0.1129	0.1042	0.0987	0.0919	0.0886
I-1b	3.40	0.2902	0.2103	0.1486	0.1233	0.1096	0.1012	0.0960	0.0895	0.0864
I-2a	3.76	0.3193	0.2312	0.1635	0.1361	0.1214	0.1126	0.1071	0.1005	0.0975
I-2b	3.66	0.3090	0.2236	0.1582	0.1319	0.1178	0.1093	0.1042	0.0979	0.0951
I-NRU	3.49	0.2965	0.2147	0.1518	0.1263	0.1126	0.1043	0.0992	0.0930	0.0902
I-NRUe	3.44	0.2909	0.2106	0.1490	0.1241	0.1108	0.1028	0.0978	0.0919	0.0892
MS-a	4.70	0.3957	0.2855	0.2027	0.1706	0.1542	0.1446	0.1391	0.1328	0.1308
MS-b	4.60	0.3860	0.2783	0.1977	0.1666	0.1507	0.1416	0.1363	0.1304	0.1286
MS-c	4.73	0.3989	0.2878	0.2043	0.1719	0.1553	0.1456	0.1400	0.1336	0.1315
LS-a	4.54	0.3827	0.2761	0.1960	0.1650	0.1490	0.1398	0.1344	0.1283	0.1263
LS-b	4.44	0.3727	0.2688	0.1909	0.1609	0.1455	0.1367	0.1316	0.1258	0.1241
LS-c	4.65	0.3935	0.2840	0.2015	0.1694	0.1528	0.1432	0.1375	0.1310	0.1288
LS-BRa	4.16	0.3511	0.2533	0.1798	0.1513	0.1365	0.1280	0.1230	0.1173	0.1154
LS-BRb	4.08	0.3426	0.2471	0.1755	0.1478	0.1336	0.1253	0.1206	0.1152	0.1135
LS-BRc	4.28	0.3623	0.2615	0.1855	0.1558	0.1405	0.1315	0.1262	0.1201	0.1179
LS-HW1	4.23	0.3578	0.2583	0.1833	0.1539	0.1387	0.1298	0.1246	0.1185	0.1164
LS-HW2	4.14	0.3492	0.2519	0.1788	0.1503	0.1357	0.1271	0.1221	0.1164	0.1144

Table XI

GAMMA RAY ENERGY ABSORPTION LINEAR ATTENUATION COEFFICIENTS OF THE CONCRETES

CONCRETE	DENSITY (g/cm^3)	PHOTON ENERGY (cm^{-1}) 0.5 Mev	1 Mev	2 Mev	3 Mev	4 Mev	5 Mev	6 Mev	8 Mev	10 Mev
01	2.33	0.0694	0.0650	0.0558	0.0507	0.0477	0.0456	0.0444	0.0428	0.0423
02-a	2.30	0.0684	0.0644	0.0551	0.0499	0.0466	0.0443	0.0429	0.0410	0.0403
02-b	2.20	0.0650	0.0612	0.0524	0.0475	0.0444	0.0423	0.0410	0.0392	0.0386
03	2.39	0.0716	0.0670	0.0575	0.0523	0.0492	0.0470	0.0458	0.0441	0.0437
04	2.35	0.0693	0.0651	0.0558	0.0506	0.0475	0.0452	0.0439	0.0422	0.0415
05	2.50	0.0746	0.0699	0.0600	0.0546	0.0513	0.0491	0.0478	0.0461	0.0456
06	1.30	0.0391	0.0369	0.0315	0.0283	0.0263	0.0249	0.0239	0.0227	0.0222
07	2.09	0.0627	0.0589	0.0504	0.0456	0.0426	0.0406	0.0393	0.0376	0.0370
0-HW1	2.33	0.0691	0.0647	0.0556	0.0507	0.0478	0.0458	0.0447	0.0432	0.0429
0-HW2	2.26	0.0668	0.0625	0.0537	0.0490	0.0463	0.0444	0.0434	0.0420	0.0417
FP-a	4.68	0.1382	0.1251	0.1096	0.1040	0.1020	0.1015	0.1020	0.1035	0.1067
FP-b	4.57	0.1345	0.1217	0.1068	0.1014	0.0996	0.0993	0.0999	0.1015	0.1048
FP-HW1	4.82	0.1424	0.1286	0.1127	0.1072	0.1054	0.1051	0.1057	0.1075	0.1110
FP-HW3	4.67	0.1375	0.1240	0.1088	0.1038	0.1022	0.1022	0.1029	0.1049	0.1085
BA-a	3.50	0.1263	0.0978	0.0840	0.0813	0.0815	0.0825	0.0839	0.0869	0.0905
BA-b	3.39	0.1224	0.0941	0.0809	0.0786	0.0790	0.0802	0.0817	0.0848	0.0885
BA-H	2.57	0.0862	0.0705	0.0610	0.0585	0.0580	0.0583	0.0590	0.0605	0.0626
BAHA	2.35	0.0790	0.0659	0.0566	0.0534	0.0522	0.0517	0.0518	0.0522	0.0535
BAHA-d	2.28	0.0762	0.0639	0.0547	0.0514	0.0499	0.0493	0.0491	0.0492	0.0502
BA-OR	3.30	0.1153	0.0920	0.0791	0.0758	0.0752	0.0756	0.0764	0.0783	0.0811
M-a	3.55	0.1055	0.0962	0.0837	0.0784	0.0759	0.0746	0.0743	0.0742	0.0756
M-b	3.45	0.1022	0.0932	0.0811	0.0761	0.0738	0.0727	0.0724	0.0725	0.0740
M-c	3.62	0.1077	0.0984	0.0855	0.0800	0.0773	0.0760	0.0756	0.0754	0.0768
M-HW1	3.29	0.0976	0.0894	0.0776	0.0722	0.0695	0.0680	0.0674	0.0669	0.0678
M-HW2	3.27	0.0969	0.0888	0.0771	0.0717	0.0691	0.0676	0.0670	0.0665	0.0675
I-1a	3.50	0.1041	0.0955	0.0828	0.0770	0.0741	0.0725	0.0718	0.0712	0.0722
I-1b	3.40	0.1009	0.0924	0.0802	0.0747	0.0720	0.0705	0.0700	0.0695	0.0705
I-2a	3.76	0.1114	0.1016	0.0884	0.0828	0.0801	0.0789	0.0786	0.0785	0.0801
I-2b	3.66	0.1079	0.0982	0.0855	0.0803	0.0779	0.0768	0.0766	0.0767	0.0783
I-NRU	3.49	0.1033	0.0943	0.0820	0.0767	0.0743	0.0731	0.0727	0.0726	0.0740
I-NRUe	3.44	0.1015	0.0925	0.0805	0.0755	0.0732	0.0721	0.0718	0.0719	0.0733
MS-a	4.70	0.1392	0.1253	0.1100	0.1048	0.1032	0.1032	0.1039	0.1058	0.1095
MS-b	4.60	0.1359	0.1221	0.1073	0.1025	0.1011	0.1012	0.1020	0.1041	0.1078
MS-c	4.73	0.1403	0.1263	0.1108	0.1056	0.1039	0.1038	0.1045	0.1064	0.1100
LS-a	4.54	0.1345	0.1211	0.1063	0.1013	0.0997	0.0996	0.1004	0.1022	0.1057
LS-b	4.44	0.1311	0.1179	0.1036	0.0989	0.0975	0.0976	0.0984	0.1004	0.1039
LS-c	4.65	0.1382	0.1246	0.1092	0.1039	0.1021	0.1018	0.1024	0.1041	0.1075
LS-BRa	4.16	0.1234	0.1112	0.0975	0.0928	0.0913	0.0912	0.0918	0.0933	0.0964
LS-BRb	4.08	0.1205	0.1085	0.0952	0.0908	0.0895	0.0894	0.0901	0.0918	0.0950
LS-BRc	4.28	0.1272	0.1148	0.1006	0.0956	0.0938	0.0935	0.0940	0.0953	0.0984
LS-HW1	4.23	0.1257	0.1134	0.0993	0.0944	0.0926	0.0923	0.0927	0.0941	0.0971
LS-HW2	4.14	0.1227	0.1106	0.0970	0.0923	0.0907	0.0905	0.0910	0.0925	0.0956

Table XII

EFFECTIVE ATOMIC NUMBERS FOR DETERMINING THE BUILDUP FACTORS FOR CONCRETES

CONCRETE SYMBOL	DENSITY (g/cm^3)	TYPE	EFFECTIVE ATOMIC NUMBER	REFERENCES
01	2.33	Ordinary	12	Hogerton, J. R., and R. C. Grass, The Reactor Handbook, Vol I, Physics, AECD-3645 (March 1955) p. 674.
04	2.35	Ordinary	11	Grodstein, G. W., X-Ray Attenuation Coefficients from 10 kev to 100 Mev, NBS Circular 583 (Apr 30, 1957) p. 50.
0-HW1	2.33	Ordinary	12	Peterson, E. G., Shielding Properties of Ordinary Concrete as a Function of Temperature, HW-65572 (Aug 2, 1960) p. 24.
FP-a	4.68	Ferrophosphorus	21	Hamer, E. E., Personal Communication.
FP-HW1	4.82	Ferrophosphorus	21	Peterson, E. G., Shielding Properties of Ferrophosphorus Concrete as a Function of Temperature, HW-64774 (July 15, 1960) pp. 43-44.
BA-a	3.50	Barytes	27	The Reactor Handbook, AECD-3645 (March 1955) p. 674.
BA-OR	3.30	Barytes	25	Grantham, W. J. Jr., Barytes Concrete for Radiation Shielding: Mix Criteria and Attenuation Characteristics, ORNL-3130 (July 25, 1961) p. 44.
M-a	3.55	Magnetite	17	The Experimental Boiling Water Reactor, ANL-5607 (May 1957) p. 60.
M-HW1	3.29	Magnetite	17	Wood, D. E., The Effect of Temperature on the Neutron Attenuation of Magnetite Concrete, HW-58497 (Dec 11, 1958) p. 16.
I-NRUe	3.44	Ilmenite	18	Robson, J. M., The Attenuation of Neutrons by the Side Shield of the NRU Reactor, CRP-860 (Oct 1959) pp. 15-16.
MS-a	4.70	Magnetite and Steel	22	The Experimental Boiling Water Reactor, ANL-5607 (May 1957) p. 60.
LS-HW1	4.23	Limonite and Steel	21	Bunch, W. L., Attenuation Properties of High Density Portland Cement Concretes as a Function of Temperature, HW-54656 (Jan 22, 1958) p. 39.

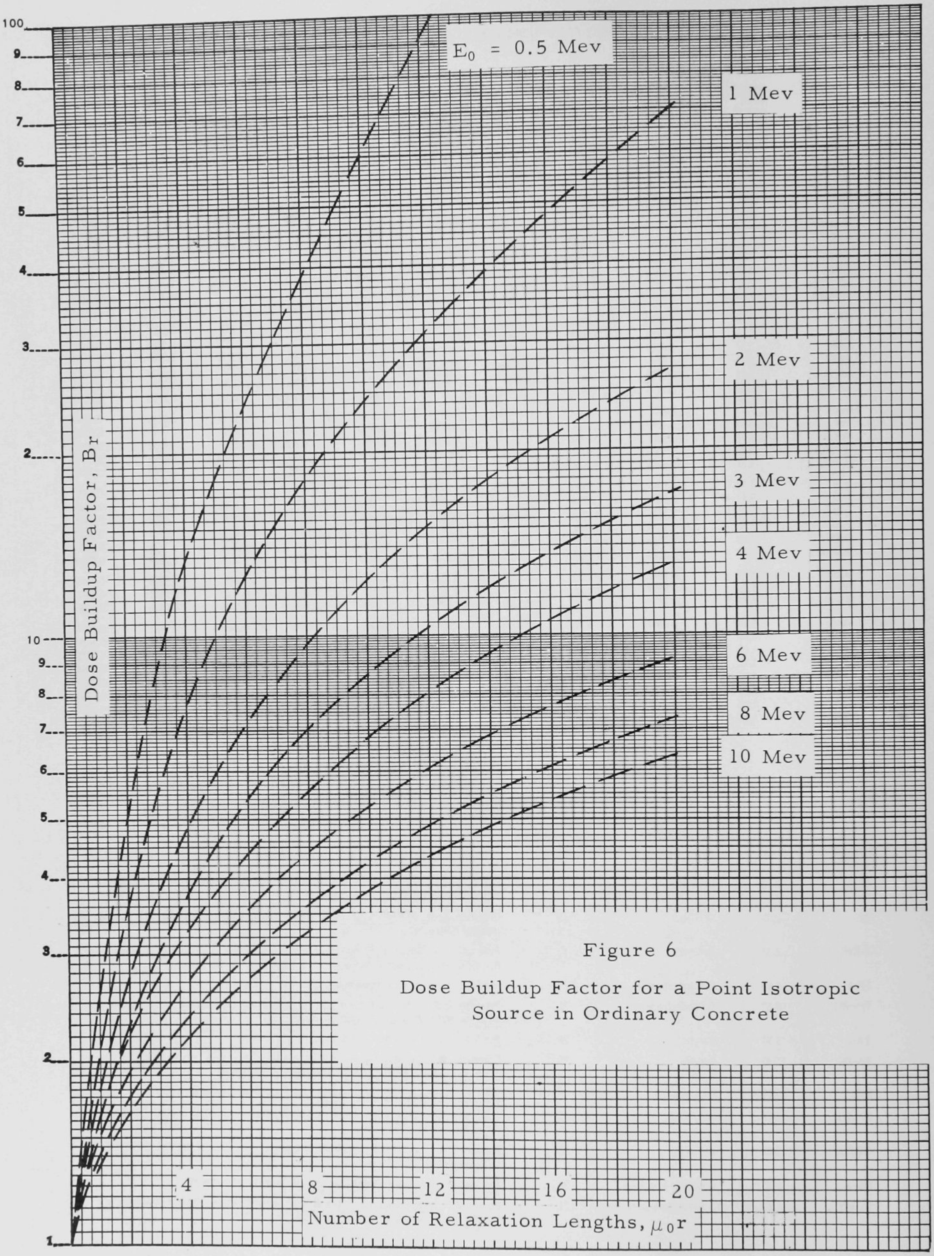

Figure 6

Dose Buildup Factor for a Point Isotropic Source in Ordinary Concrete

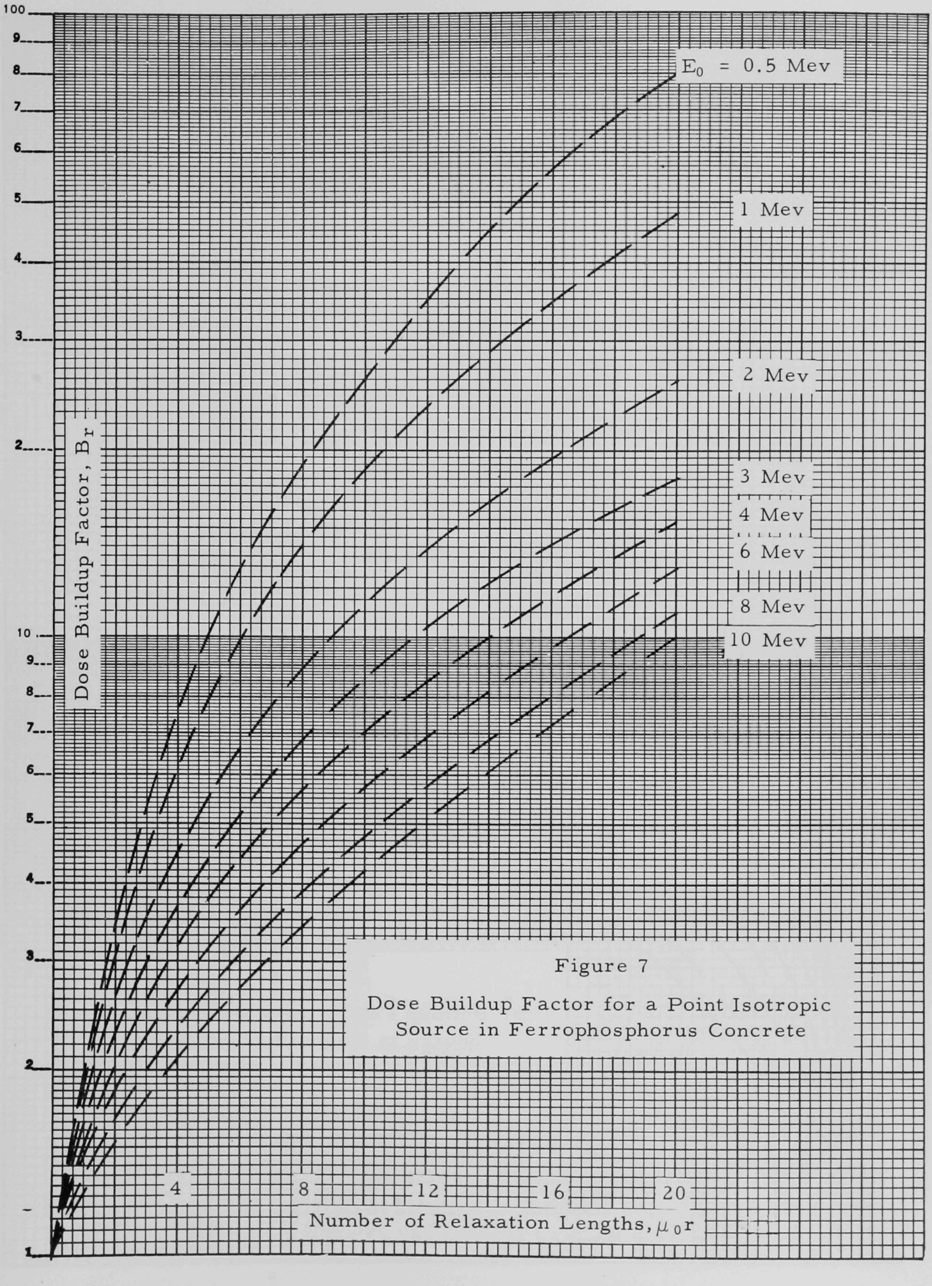

Figure 7

Dose Buildup Factor for a Point Isotropic Source in Ferrophosphorus Concrete

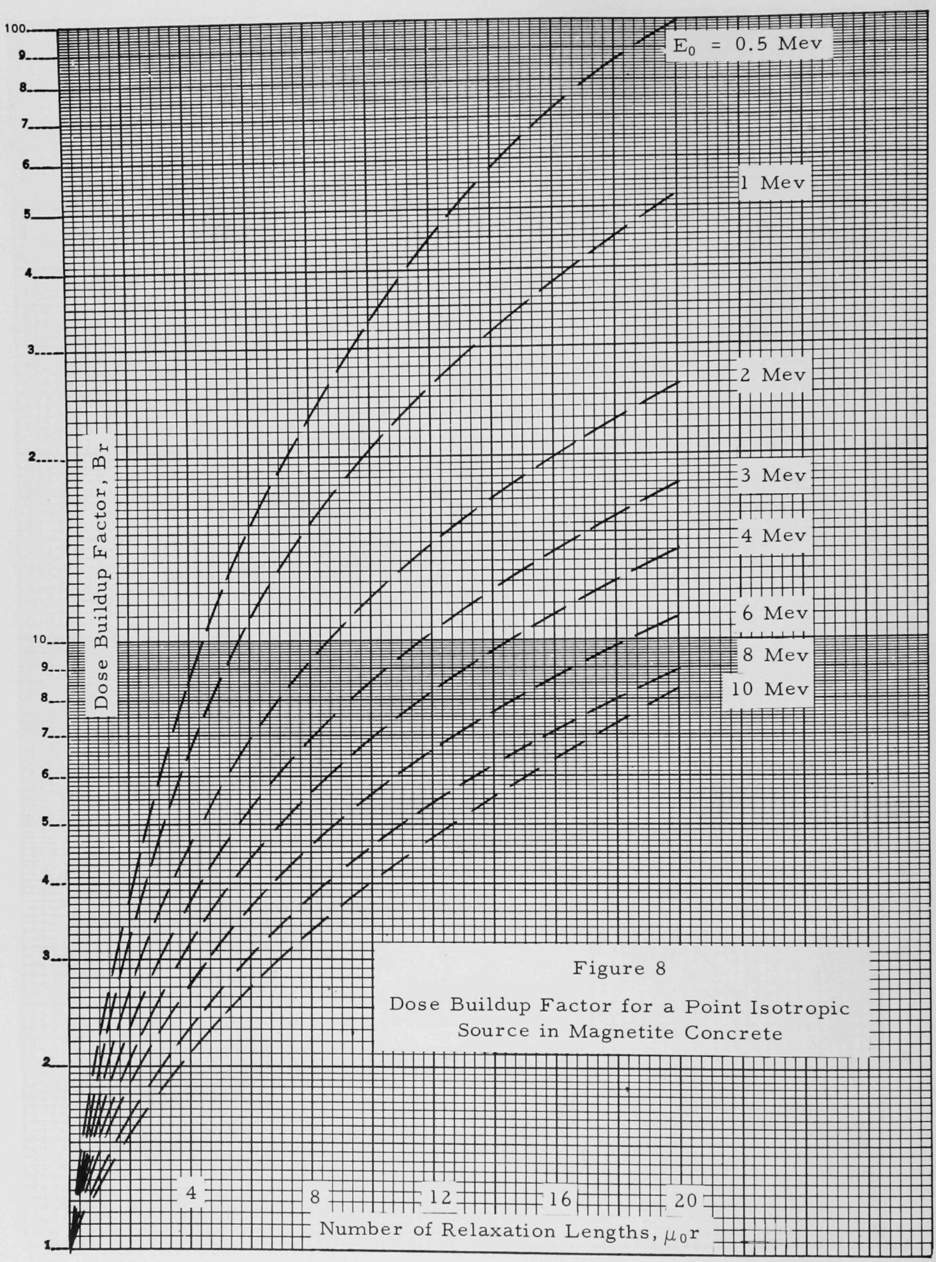

Figure 8

Dose Buildup Factor for a Point Isotropic Source in Magnetite Concrete

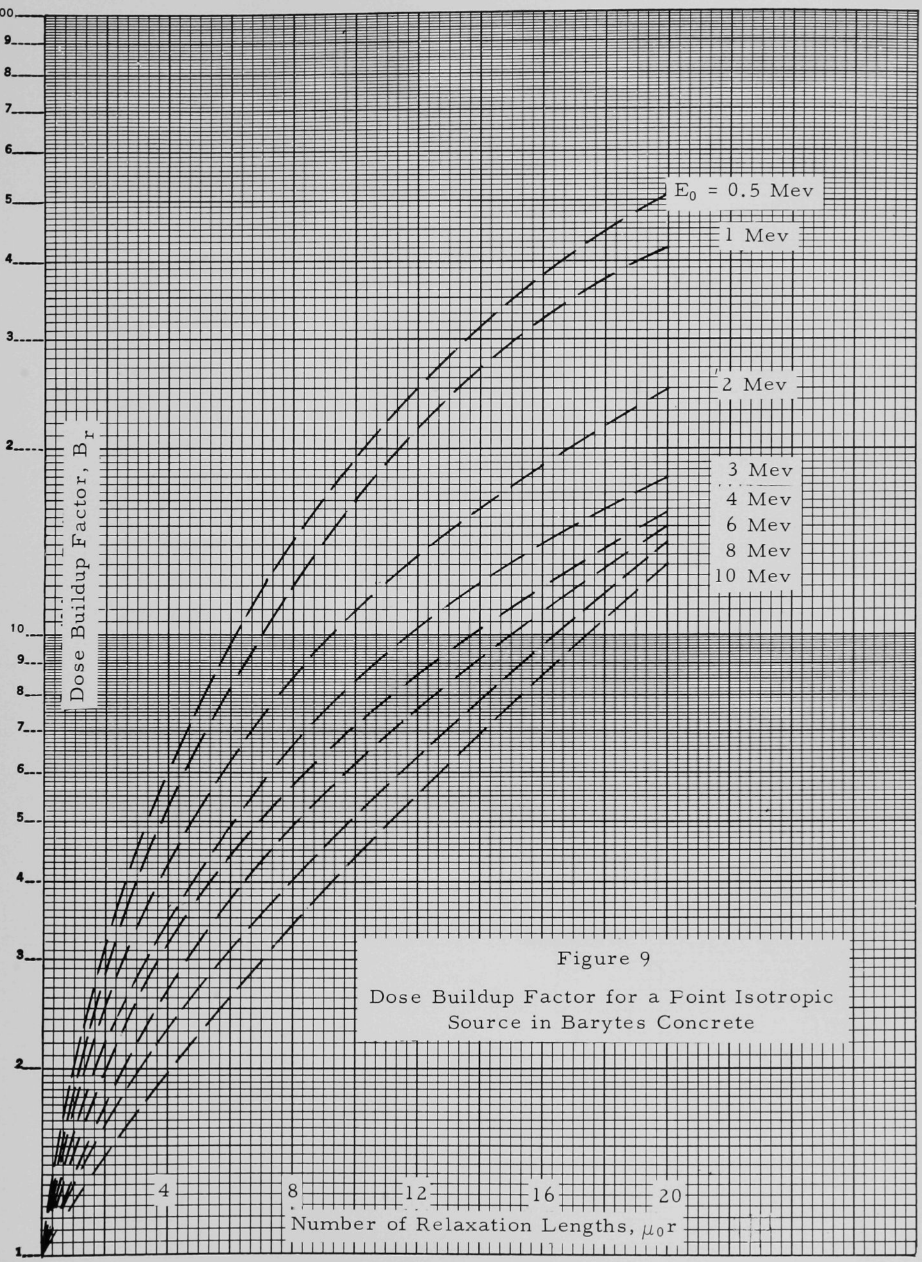

Figure 9

Dose Buildup Factor for a Point Isotropic Source in Barytes Concrete

INDIVIDUAL CONCRETE DATA SHEETS

Table XIII

C-1

		DENSITY	
CONCRETE TYPE	SYMBOL	g/cm^3	lb/ft^3
Ordinary	01	2.33	145

COMPOSITION (lb/yd)

Water	Cement	Aggregate	Steel	Total

REFERENCE: Hogerton, J. F. and R. C. Grass, The Reactor Handbook. Vol. 1, Physics, AECD-3645 (March 1955) p. 675, 725-727.

NOTE:

ELEMENTAL COMPOSITION (gm/cm^3)

H	in Water	0.00484	Cl		
	in Ore		K		
O	in Water	0.0384	Ca	in Ore	0.581
	in Ore	1.1106		in Cement	
	in Cement		Ti		
B			V		
C		0.130	Cr		
Na			Mn		
Mg	in Ore	0.00486	Fe	in Ore	0.00726
	in Cement			in Cement	
Al	in Ore	0.0119		in Steel	
	in Cement		Ni		
Si	in Ore	0.438	Cu		
	in Cement		Zn		
P			Mo		
S		0.00192	Ba		

Table XIII (Cont'd.)

C-2

CONCRETE TYPE	SYMBOL	DENSITY g/cm^3	DENSITY lb/ft^3
Ordinary	02-a	2.30	144

COMPOSITION (lb/yd)

Water	Cement	Aggregate	Steel	Total
260	318	3300 (sand and gravel)		3878

REFERENCE: Hogerton, J. F., and R. C. Grass, The Reactor Handbook. Vol. 1, Physics, AECD-3645 (March 1955) p.675, 725-727.

NOTE: Mix calculated from % wt given.

ELEMENTAL COMPOSITION (gm/cm^3)

H	in Water	0.023	Cl		
	in Ore		K		0.0299
O	in Water	0.183	Ca	in Ore	0.100
	in Ore	1.037		in Cement	
	in Cement		Ti		
B			V		
C		0.0023	Cr		
Na		0.0368	Mn		
Mg	in Ore	0.005	Fe	in Ore	0.032
	in Cement			in Cement	
Al	in Ore	0.078		in Steel	
	in Cement		Ni		
Si	in Ore	0.775	Cu		
	in Cement		Zn		
P			Mo		
S			Ba		

Table XIII (Cont'd.)

C-3

CONCRETE TYPE	SYMBOL	DENSITY g/cm^3	DENSITY lb/ft^3
Ordinary	02-b	2.20	137

COMPOSITION (lb/yd)

Water	Cement	Aggregate	Steel	Total

REFERENCE: See 02-a

NOTE:

ELEMENTAL COMPOSITION (gm/cm^3)

H	in Water	0.0115	Cl		
	in Ore		K		0.0299
O	in Water	0.0915	Ca	in Ore in Cement	0.100
	in Ore in Cement	1.037	Ti		
B			V		
C		0.0023	Cr		
Na		0.0368	Mn		
Mg	in Ore in Cement	0.005	Fe	in Ore in Cement in Steel	0.032
Al	in Ore in Cement	0.078	Ni		
Si	in Ore in Cement	0.775	Cu		
			Zn		
P			Mo		
S			Ba		

Table XIII (Cont'd.)

C-4

CONCRETE TYPE	SYMBOL	DENSITY g/cm^3	DENSITY lb/ft^3
Ordinary	03	2.39	149

COMPOSITION (lb/yd)

Water	Cement	Aggregate	Steel	Total

REFERENCE: Blizzard, E. P., and J. M. Miller, Radiation Attenuation Characteristics of Structural Concrete, ORNL 2193, (Aug 29, 1958) p. 2.

NOTE:

ELEMENTAL COMPOSITION (gm/cm^3)

H	in Water in Ore	0.020	Cl		
			K		0.004
O	in Water	0.159	Ca	in Ore in Cement	0.582
	in Ore in Cement	0.980	Ti		
B			V		
C		0.118	Cr		
Na			Mn		0.003
Mg	in Ore in Cement	0.057	Fe	in Ore in Cement in Steel	0.026
Al	in Ore in Cement	0.085	Ni		
Si	in Ore in Cement	0.342	Cu		
			Zn		
P		0.007	Mo		
S		0.007	Ba		

Table XIII (Cont'd.)

C-5

CONCRETE TYPE	SYMBOL	DENSITY	
		g/cm^3	lb/ft^3
Ordinary	04	2.35	147

COMPOSITION (lb/yd)

Water	Cement	Aggregate	Steel	Total

REFERENCE: Grodstein, G. W., <u>X-Ray Attenuation Coefficients from 10 kev to 100 Mev,</u> NBS Circular 583 (Apr 30, 1957) p. 50.

NOTE:

ELEMENTAL COMPOSITION (gm/cm^3)

H	in Water	0.013	Cl		
	in Ore		K		0.045
O	in Water	0.103	Ca	in Ore	0.194
	in Ore	1.062		in Cement	
	in Cement		Ti		
B			V		
C			Cr		
Na		0.040	Mn		
Mg	in Ore	0.006	Fe	in Ore	0.029
	in Cement			in Cement	
Al	in Ore	0.107		in Steel	
	in Cement		Ni		
Si	in Ore	0.737	Cu		
	in Cement		Zn		
P			Mo		
S		0.003	Ba		

Table XIII (Cont'd.)

C-6

CONCRETE TYPE	SYMBOL	DENSITY	
		g/cm^3	lb/ft^3
Ordinary	05	2.50	156

COMPOSITION (lb/yd)

Water	Cement	Aggregate	Steel	Total

REFERENCE: Avery, A. F. *et al.*, *Methods of Calculation for use in the Design of Shields for Power Reactors*, AERE-R-3216 (Feb 1960) p. c3-c4.

NOTE:

ELEMENTAL COMPOSITION (gm/cm^3)

H	in Water	0.022	Cl		
	in Ore		K		0.025
O	in Water	1.231	Ca	in Ore	0.242
	in Ore			in Cement	
	in Cement		Ti		0.017
B			V		
C		0.008	Cr		
Na		0.029	Mn		0.045
Mg	in Ore	0.002	Fe	in Ore	0.122
	in Cement			in Cement	
Al	in Ore	0.131		in Steel	
	in Cement		Ni		
Si	in Ore	0.63	Cu		
	in Cement		Zn		
P			Mo		
S		0.0037	Ba		

Table XIII (Cont'd.)

C-7

CONCRETE TYPE	SYMBOL	DENSITY g/cm^3	DENSITY lb/ft^3
Ordinary	06	1.30	80

COMPOSITION (lb/yd)

Water	Cement	Aggregate	Steel	Total
0.231 VF	0.256 VF	0.513 VF (Diatomaceous Earth)		1.00

REFERENCE: Hungerford, H. E., et al., New Shielding Materials for High-Temperature Application, Nuclear Science and Engineering 6, 401-404 (Nov 1959).

NOTE: Borated diatomaceous earth aggregate 0.8% borated. Fired for 24 hours at 1000°F $\sim$80 lb/ft^3.

ELEMENTAL COMPOSITION (gm/cm^3)

H	in Water	0.034	Cl		
	in Ore		K		
O	in Water	0.793	Ca	in Ore	0.001
	in Ore			in Cement	
	in Cement		Ti		
B		0.010	V		
C			Cr		
Na			Mn		
Mg	in Ore	0.003	Fe	in Ore	0.013
	in Cement			in Cement	
Al	in Ore	0.025		in Steel	
	in Cement		Ni		
Si	in Ore	0.417	Cu		
	in Cement		Zn		
P			Mo		
S			Ba		

Table XIII (Cont'd.)

C-8

CONCRETE TYPE	SYMBOL	DENSITY g/cm^3	DENSITY lb/ft^3
Ordinary	07	2.09	130.3

COMPOSITION (lb/yd)

Water	Cement	Aggregate		Steel	Total
		Serpentine	Sand	Plastiment	
373	525	2032	950	1.39	3887

REFERENCE: See 0-6 (APDA)

NOTE: Density given is after drying to constant weight at 130°F.

ELEMENTAL COMPOSITION (gm/cm^3)

H	in Water	0.033	Cl		trace
	in Ore		K		0.008
O	in Water	1.075	Ca	in Ore	0.141
	in Ore			in Cement	
	in Cement		Ti		trace
B		0.002	V		
C		0.002	Cr		trace
Na		0.008	Mn		trace
Mg	in Ore	0.281	Fe	in Ore	0.064
	in Cement			in Cement	
Al	in Ore	0.040		in Steel	
	in Cement		Ni		0.002
Si	in Ore	0.435	Cu		
	in Cement		Zn		
P		trace	Mo		
S			Ba		

Table XIII (Cont'd.)

C-9

CONCRETE TYPE	SYMBOL	DENSITY g/cm^3	DENSITY lb/ft^3
Ordinary	0-HW1	2.33	145

COMPOSITION (lb/yd)

Water	Cement	Aggregate	Steel	Total

REFERENCE: Peterson, E. G., Shielding Properties of Ordinary Concrete as a Function of Temperature, HW-65572 (Aug 2, 1960) p. 24.

NOTE: Hanford (As Cured)

ELEMENTAL COMPOSITION (gm/cm^3)

H	in Water	0.015	Cl		
	in Ore		K		0.015
O	in Water	1.057	Ca	in Ore	0.295
	in Ore			in Cement	
	in Cement		Ti		0.011
B			V		
C			Cr		
Na		0.041	Mn		0.003
Mg	in Ore	0.085	Fe	in Ore	0.178
	in Cement			in Cement	
Al	in Ore	0.137		in Steel	
	in Cement		Ni		
Si	in Ore	0.487	Cu		
	in Cement		Zn		
P		0.002	Mo		
S		0.002	Ba		

Table XIII (Cont'd.)

C-10

CONCRETE TYPE	SYMBOL	DENSITY g/cm^3	DENSITY lb/ft^3
Ordinary	0-HW2	2.26	141

COMPOSITION (lb/yd)

Water	Cement	Aggregate	Steel	Total

REFERENCE: See 0-HW1

NOTE: Hanford (heated to 100°C)

ELEMENTAL COMPOSITION (gm/cm^3)

H	in Water	0.007	Cl		
	in Ore		K		0.015
O	in Water	0.995	Ca	in Ore	0.295
	in Ore			in Cement	
	in Cement		Ti		0.011
B			V		
C			Cr		
Na		0.041	Mn		0.003
Mg	in Ore	0.085	Fe	in Ore	0.178
	in Cement			in Cement	
Al	in Ore	0.137		in Steel	
	in Cement		Ni		
Si	in Ore	0.487	Cu		
	in Cement		Zn		
P		0.002	Mo		
S		0.002	Ba		

Table XIII (Cont'd.)

C-11

CONCRETE TYPE	SYMBOL	DENSITY	
		g/cm^3	lb/ft^3
Ferrophosphorus	FP-a	4.68	292

COMPOSITION (lb/yd)

Water	Cement	Aggregate		Steel	Total
		Course	Fine		
383	730	4070	2710		7893

REFERENCE: Hamer, E. E., Draft of Revised Reactor Handbook, Tables 7.1 - 4.1, 7.1 - 4.2, Private Communication

NOTE: Assumed percentage not reported for aggregate to be oxygen.

ELEMENTAL COMPOSITION (gm/cm^3)

H	in Water	0.0234	Cl		
	in Ore		K		
O	in Water	0.201	Ca	in Ore	
	in Ore	0.041		in Cement	0.197
	in Cement	0.154	Ti		
B			V		
C		0.0023	Cr		0.0023
Na			Mn		0.117
Mg	in Ore		Fe	in Ore	2.808
	in Cement	0.0047		in Cement	0.014
Al	in Ore			in Steel	
	in Cement	0.0187	Ni		
Si	in Ore	0.0796	Cu		
	in Cement	0.0515	Zn		
P		0.967	Mo		
S			Ba		

Table XIII (Cont'd.)

C-12

CONCRETE TYPE	SYMBOL	DENSITY g/cm^3	DENSITY lb/ft^3
Ferrophosphorus	FP-b	4.57	285

COMPOSITION (lb/yd)

Water	Cement	Aggregate	Steel	Total

REFERENCE: See FP-a

NOTE:

ELEMENTAL COMPOSITION (gm/cm^3)

H	in Water	0.0117	Cl		
	in Ore		K		
O	in Water	0.100	Ca	in Ore	
	in Ore	0.041		in Cement	0.197
	in Cement	0.154	Ti		
B			V		
C		0.0023	Cr		0.0023
Na			Mn		0.117
Mg	in Ore		Fe	in Ore	2.808
	in Cement	0.0047		in Cement	0.014
Al	in Ore			in Steel	
	in Cement	0.0187	Ni		
Si	in Ore	0.0796	Cu		
	in Cement	0.0515	Zn		
P		0.967	Mo		
S			Ba		

Table XIII (Cont'd.)

C-13

CONCRETE TYPE	SYMBOL	DENSITY g/cm^3	DENSITY lb/ft^3
Ferrophosphorus	FP-HW1	4.82	301

COMPOSITION (lb/yd)

Water	Cement	Aggregate	Steel	Total

REFERENCE: Peterson, E. G., Shielding Properties of Ferrophosphorus Concrete as a Function of Temperature, HW-64774 (July 15, 1960) pp. 43-44, 62.

NOTE: Hanford (As Cured)

ELEMENTAL COMPOSITION (gm/cm^3)

H	in Water	0.021	Cl		
	in Ore		K		
O	in Water	0.322	Ca	in Ore	0.203
	in Ore			in Cement	
	in Cement		Ti		0.042
B			V		0.084
C		0.004	Cr		0.084
Na			Mn		0.013
Mg	in Ore	0.006	Fe	in Ore	2.823
	in Cement			in Cement	
Al	in Ore	0.009		in Steel	
	in Cement		Ni		0.017
Si	in Ore	0.090	Cu		0.008
	in Cement		Zn		
P		1.049	Mo		0.042
S		0.004	Ba		

Table XIII (Cont'd.)

C-14

CONCRETE TYPE	SYMBOL	DENSITY g/cm^3	DENSITY lb/ft^3
Ferrophosphorus	FP-HW3	4.67	292

COMPOSITION (lb/yd)

Water	Cement	Aggregate	Steel	Total

REFERENCE: See FP-HW1

NOTE: Hanford (heated to 320°C)

ELEMENTAL COMPOSITION (gm/cm^3)

H	in Water	0.004	Cl		
	in Ore		K		
O	in Water	0.191	Ca	in Ore	0.203
	in Ore			in Cement	
	in Cement		Ti		0.042
B			V		0.084
C		0.004	Cr		0.084
Na			Mn		0.013
Mg	in Ore	0.006	Fe	in Ore	2.823
	in Cement			in Cement	
Al	in Ore	0.009		in Steel	
	in Cement		Ni		0.017
Si	in Ore	0.090	Cu		0.008
	in Cement		Zn		
P		1.049	Mo		0.042
S		0.004	Ba		

Table XIII (Cont'd.)

C-15

CONCRETE TYPE	SYMBOL	DENSITY g/cm^3	DENSITY lb/ft^3
Barytes	BA-a	3.50	219

COMPOSITION (lb/yd)

Water	Cement	Aggregate	Steel	Total

REFERENCE: The Reactor Handbook, Vol. 1: Physics, AECD - 3645, (March 1955) pp. 675, 725-727.

NOTE: Assumed percentage not reported for aggregates to be oxygen.

ELEMENTAL COMPOSITION (gm/cm^3)

H	in Water	0.0243	Cl		
	in Ore		K		
O	in Water	0.195	Ca	in Ore	0.0203
	in Ore	0.872		in Cement	0.147
	in Cement	0.118	Ti		
B			V		
C			Cr		
Na			Mn		
Mg	in Ore		Fe	in Ore	0.151
	in Cement	0.00385		in Cement	0.0091
Al	in Ore			in Steel	
	in Cement	0.0137	Ni		
Si	in Ore		Cu		
	in Cement	0.0352	Zn		
P			Mo		
S		0.364	Ba		1.551

Table XIII (Cont'd.)

C-16

CONCRETE TYPE	SYMBOL	DENSITY g/cm^3	DENSITY lb/ft^3
Barytes	BA-b	3.39	212

COMPOSITION (lb/yd)

Water	Cement	Aggregate	Steel	Total

REFERENCE: See BA-a

NOTE:

ELEMENTAL COMPOSITION (gm/cm^3)

H	in Water	0.0122	Cl		
	in Ore		K		
O	in Water	0.0975	Ca	in Ore	0.0203
	in Ore	0.872		in Cement	0.147
	in Cement	0.118	Ti		
B			V		
C			Cr		
Na			Mn		
Mg	in Ore		Fe	in Ore	0.151
	in Cement	0.00385		in Cement	0.0091
Al	in Ore			in Steel	
	in Cement	0.0137	Ni		
Si	in Ore		Cu		
	in Cement	0.0352	Zn		
P			Mo		
S		0.364	Ba		1.551

Table XIII (Cont'd.)

C-17

CONCRETE TYPE	SYMBOL	DENSITY g/cm^3	DENSITY lb/ft^3
Barytes	BA-H	2.575	160

COMPOSITION (lb/yd)

Water	Cement	Aggregate	Steel	Total

REFERENCE: Avery, A. F. et al., Methods of Calculation for use in the Design of Shields for Power Reactors, AERE - R-3216, (Feb 1960) p. c3-c4.

NOTE:

ELEMENTAL COMPOSITION (gm/cm^3)

H	in Water	0.007	Cl		
	in Ore		K		
O	in Water	0.710	Ca	in Ore	0.148
	in Ore			in Cement	
	in Cement		Ti		
B			V		
C		0.0233	Cr		
Na			Mn		
Mg	in Ore		Fe	in Ore	0.595
	in Cement			in Cement	
Al	in Ore	0.0123		in Steel	
	in Cement		Ni		
Si	in Ore	0.180	Cu		
	in Cement		Zn		
P			Mo		
S		0.180	Ba		0.718

Table XIII (Cont'd.)

C-18

CONCRETE TYPE	SYMBOL	DENSITY g/cm^3	DENSITY lb/ft^3
Barytes Haydite	BAHA	2.35	147

COMPOSITION (lb/yd)

Water	Cement	Aggregate	Steel	Total
10.0%	16.3%	Barytes 46.4%	Haydite 27.3%	

REFERENCE: Blosser, T. V. et al., A Study of the Nuclear and Physical Properties of the ORNL Graphite Reactor Shield, ORNL-2195, (Sept 8, 1958) pp. 5-8.

NOTE: Elemental Composition computed from mix percentages given assuming 2.35 g/cm^3 density for wet mix.

ELEMENTAL COMPOSITION (gm/cm^3)

H	in Water	0.026	Cl		
	in Ore	0.0045	K		
O	in Water	0.209	Ca	in Ore	0.109
	in Ore	0.494		in Cement	0.172
	in Cement	0.138	Ti		
B			V		
C			Cr		
Na			Mn		
Mg	in Ore		Fe	in Ore	
	in Cement	0.0046		in Cement	0.0107
Al	in Ore	0.0546		in Steel	
	in Cement	0.0161	Ni		
Si	in Ore	0.308	Cu		
	in Cement	0.0414	Zn		
P			Mo		
S		0.144	Ba		0.618

Table XIII (Cont'd.)

C-19

CONCRETE TYPE	SYMBOL	DENSITY g/cm^3	 lb/ft^3
Barytes Haydite	BAHA-d	2.28	142

COMPOSITION (lb/yd)

Water	Cement	Aggregate	Steel	Total

REFERENCE: See BAHA

NOTE: Elemental Composition is average value for four core drillings.

ELEMENTAL COMPOSITION (gm/cm^3)

H	in Water	0.0298	Cl		
	in Ore		K		
O	in Water	1.084	Ca	in Ore	0.209
	in Ore			in Cement	
	in Cement		Ti		
B			V		
C			Cr		
Na			Mn		
Mg	in Ore	0.0441	Fe	in Ore	0.0338
	in Cement			in Cement	
Al	in Ore	0.0565		in Steel	
	in Cement		Ni		
Si	in Ore	0.232	Cu		
	in Cement		Zn		
P			Mo		
S		0.0094	Ba		0.577

Table XIII (Cont'd.)

C-20

CONCRETE TYPE	SYMBOL	DENSITY g/cm^3	DENSITY lb/ft^3
Barytes	BA-OR	3.30	206

COMPOSITION (lb/yd)

Water	Cement	Aggregate	Steel	Total
383	468	4711		5562

REFERENCE: Grantham, W. J., Jr., Barytes Concrete for Radiation Shielding: Mix Criteria and Attenuation Characteristics, ORNL-3130 (July 25 1961) p. 44.

NOTE:

ELEMENTAL COMPOSITION (gm/cm^3)

H	in Water	0.036	Cl		
	in Ore		K		
O	in Water	0.291	Ca	in Ore	0.135
	in Ore	0.917		in Cement	
	in Cement		Ti		
B			V		
C			Cr		
Na			Mn		
Mg	in Ore	0.0099	Fe	in Ore	0.277
	in Cement			in Cement	
Al	in Ore	0.0066		in Steel	
	in Cement		Ni		
Si	in Ore	0.139	Cu		
	in Cement		Zn		
P			Mo		
S		0.287	Ba		1.20

Table XIII (Cont'd.)

C-21

CONCRETE TYPE	SYMBOL	DENSITY	
		g/cm^3	lb/ft^3
Magnetite	M-a	3.55	222

COMPOSITION (lb/yd)

Water	Cement	Aggregate		Steel	Total
		Coarse	Fine		
330	875	2623	2160		

REFERENCE: The Experimental Boiling Water Reactor, ANL-5607 (May 1957) p. 60. Hamer, E. E. op. cit. (FP-a).

NOTE: This mixture assumes 100 per cent retention of mix water, but no free moisture in aggregate.

ELEMENTAL COMPOSITION (gm/cm^3)

H	in Water	0.0219	Cl		
	in Ore		K		
O	in Water	0.174	Ca	in Ore	0.0071
	in Ore	0.826		in Cement	0.233
	in Cement	0.187	Ti		0.0959
B			V		0.0062
C			Cr		0.0030
Na			Mn		0.0024
Mg	in Ore	0.0172	Fe	in Ore	1.730
	in Cement	0.0062		in Cement	0.0145
Al	in Ore	0.0752		in Steel	
	in Cement	0.0218	Ni		
Si	in Ore	0.0670	Cu		
	in Cement	0.0561	Zn		
P		0.0006	Mo		
S		0.0037	Ba		

Table XIII (Cont'd.)

C-22

CONCRETE TYPE	SYMBOL	DENSITY g/cm^3	DENSITY lb/ft^3
Magnetite	M-b	3.45	215

COMPOSITION (lb/yd)

Water	Cement	Aggregate	Steel	Total

REFERENCE: See M-a

NOTE: This mixture assumes 50 percent retention of mix water, but no free moisture in aggregate.

ELEMENTAL COMPOSITION (gm/cm^3)

H	in Water	0.0110	Cl		
	in Ore		K		
O	in Water	0.087	Ca	in Ore	0.0071
	in Ore	0.826		in Cement	0.233
	in Cement	0.187	Ti		0.0959
B			V		0.0062
C			Cr		0.0030
Na			Mn		0.0024
Mg	in Ore	0.0172	Fe	in Ore	1.730
	in Cement	0.0062		in Cement	0.0145
Al	in Ore	0.0752		in Steel	
	in Cement	0.0218	Ni		
Si	in Ore	0.0670	Cu		
	in Cement	0.0561	Zn		
P		0.0006	Mo		
S		0.0037	Ba		

Table XIII (Cont'd.)

C-23

CONCRETE TYPE	SYMBOL	DENSITY	
		g/cm^3	lb/ft^3
Magnetite	M-c	3.62	226

COMPOSITION (lb/yd)

Water	Cement	Aggregate		Steel	Total
		Coarse	Fine		
330	875	2700	2200		6105

REFERENCE: See M-a

NOTE: This mixture assumes all free moisture in aggregate to be retained.

ELEMENTAL COMPOSITION (gm/cm^3)

H	in Water	0.0219	Cl		
	in Ore	0.0076	K		
O	in Water	0.174	Ca	in Ore	0.0071
	in Ore	0.887		in Cement	0.233
	in Cement	0.187	Ti		0.0959
B			V		0.0062
C			Cr		0.0030
Na			Mn		0.0024
Mg	in Ore	0.0172	Fe	in Ore	1.730
	in Cement	0.0062		in Cement	0.0145
Al	in Ore	0.0752		in Steel	
	in Cement	0.0218	Ni		
Si	in Ore	0.0670	Cu		
	in Cement	0.0561	Zn		
P		0.0006	Mo		
S		0.0037	Ba		

Table XIII (Cont'd.)

C-24

CONCRETE TYPE	SYMBOL	DENSITY g/cm^3	DENSITY lb/ft^3
Magnetite	M-HW1	3.29	205

COMPOSITION (lb/yd)

Water	Cement	Aggregate	Steel	Total

REFERENCE: Wood, D. E., The Effect of Temperature on the Neutron Attenuation of Magnetite Concrete, HW-58497 (Dec 11, 1958) p. 16.

NOTE: Elemental composition reported in g/cm^3 with Mg-Al reported together. Hanford (As Cured)

ELEMENTAL COMPOSITION (gm/cm^3)

H	in Water	0.015	Cl		
	in Ore		K		
O	in Water	1.279	Ca	in Ore	0.220
	in Ore			in Cement	
	in Cement		Ti		
B			V		
C			Cr		
Na			Mn		
Mg	in Ore	0.184	Fe	in Ore	1.460
	in Cement			in Cement	
Al	in Ore			in Steel	
	in Cement		Ni		
Si	in Ore	0.129	Cu		
	in Cement		Zn		
P			Mo		
S			Ba		

Table XIII (Cont'd.)

C-25

CONCRETE TYPE	SYMBOL	DENSITY g/cm^3	DENSITY lb/ft^3
Magnetite	M-HW2	3.27	204

COMPOSITION (lb/yd)

Water	Cement	Aggregate	Steel	Total

REFERENCE: See M-HW1

NOTE: Elemental Composition reported in g/cm^3 with Mg-Al reported together. Hanford (heated to 100°C)

ELEMENTAL COMPOSITION (gm/cm^3)

H	in Water	0.0128	Cl		
	in Ore		K		
O	in Water	1.261	Ca	in Ore	0.220
	in Ore			in Cement	
	in Cement		Ti		
B			V		
C			Cr		
Na			Mn		
Mg	in Ore	0.184	Fe	in Ore	1.460
	in Cement			in Cement	
Al	in Ore			in Steel	
	in Cement		Ni		
Si	in Ore	0.129	Cu		
	in Cement		Zn		
P			Mo		
S			Ba		

Table XIII (Cont'd.)

C-26

CONCRETE TYPE	SYMBOL	DENSITY g/cm^3	DENSITY lb/ft^3
Ilmenite	I-1a	3.50	219

COMPOSITION (lb/yd)

Water	Cement	Aggregate	Steel	Total
330	875	4695		5900

REFERENCE: Palache, C. <u>et</u> <u>al</u>., <u>The System of Mineralogy (Dana's)</u> Vol. I, New York: John Wiley and Sons, Inc. (1951) p. 537.

NOTE: The same volumetric mix proportions as the magnetite concrete M-1. New York State Ilmenite.

ELEMENTAL COMPOSITION (gm/cm^3)

H	in Water	0.0219	Cl		
	in Ore		K		
O	in Water	0.174	Ca	in Ore	
	in Ore	0.981		in Cement	0.233
	in Cement	0.187	Ti		0.955
B			V		
C			Cr		
Na			Mn		0.0225
Mg	in Ore	0.267	Fe	in Ore	0.560
	in Cement	0.0062		in Cement	0.0145
Al	in Ore			in Steel	
	in Cement	0.0218	Ni		
Si	in Ore		Cu		
	in Cement	0.0560	Zn		
P			Mo		
S			Ba		

Table XIII (Cont'd.)

C-27

CONCRETE TYPE	SYMBOL	DENSITY g/cm^3	DENSITY lb/ft^3
Ilmenite	I-1b	3.40	212

COMPOSITION (lb/yd)

Water	Cement	Aggregate	Steel	Total

REFERENCE: See I-1a

NOTE:

ELEMENTAL COMPOSITION (gm/cm^3)

H	in Water	0.0110	Cl		
	in Ore		K		
O	in Water	0.087	Ca	in Ore	
	in Ore	0.981		in Cement	0.233
	in Cement	0.187	Ti		0.955
B			V		
C			Cr		
Na			Mn		0.0225
Mg	in Ore	0.267	Fe	in Ore	0.560
	in Cement	0.0062		in Cement	0.0145
Al	in Ore			in Steel	
	in Cement	0.0218	Ni		
Si	in Ore		Cu		
	in Cement	0.0560	Zn		
P			Mo		
S			Ba		

Table XIII (Cont'd.)

C-28

CONCRETE TYPE	SYMBOL	DENSITY	
		g/cm^3	lb/ft^3
Ilmenite	I-2a	3.76	235

COMPOSITION (lb/yd)

Water	Cement	Aggregate	Steel	Total
330	875	5140		6345

REFERENCE: Palache, C. *et al.*, *The System of Mineralogy (Dana)*, Vol I, New York: John Wiley and Sons, Inc. (1951) p. 537.

NOTE: The same volumetric mix proportions as the magnetite concrete M-1. Assumed percentage not reported for aggregate to be oxygen. Swedish Ilmenite

ELEMENTAL COMPOSITION (gm/cm^3)

H	in Water	0.0219	Cl		
	in Ore		K		
O	in Water	0.174	Ca	in Ore	0.0012
	in Ore	0.989		in Cement	0.223
	in Cement	0.187	Ti		0.959
B			V		
C			Cr		
Na			Mn		0.0302
Mg	in Ore	0.0148	Fe	in Ore	1.049
	in Cement	0.0062		in Cement	0.0145
Al	in Ore			in Steel	
	in Cement	0.0218	Ni		
Si	in Ore		Cu		
	in Cement	0.0560	Zn		
P			Mo		
S			Ba		

Table XIII (Cont'd.)

C-29

CONCRETE TYPE	SYMBOL	DENSITY g/cm^3	DENSITY lb/ft^3
Ilmenite	I-2b	3.66	228

COMPOSITION (lb/yd)

Water	Cement	Aggregate	Steel	Total

REFERENCE: See I-2a

NOTE:

ELEMENTAL COMPOSITION (gm/cm^3)

H	in Water	0.0110	Cl		
	in Ore		K		
O	in Water	0.087	Ca	in Ore	0.0012
	in Ore	0.989		in Cement	0.223
	in Cement	0.187	Ti		0.959
B			V		
C			Cr		
Na			Mn		0.0302
Mg	in Ore	0.0148	Fe	in Ore	1.049
	in Cement	0.0062		in Cement	0.0145
Al	in Ore			in Steel	
	in Cement	0.0218	Ni		
Si	in Ore		Cu		
	in Cement	0.0560	Zn		
P			Mo		
S			Ba		

Table XIII (Cont'd.)

C-30

CONCRETE TYPE	SYMBOL	DENSITY g/cm^3	DENSITY lb/ft^3
Ilmenite	I-NRU	3.49	218

COMPOSITION (lb/yd)

Water	Cement	Aggregate	Steel	Total

REFERENCE: Robson, J. M., The Attenuation of Neutrons by the Side Shield of the NRU Reactor, CRP-860 (Oct 1959) pp. 15, 16.

NOTE: Canadian Chalk River Research Reactor assumed percentage not reported for composition to be oxygen.

ELEMENTAL COMPOSITION (gm/cm^3)

H	in Water	0.0115
	in Ore	
O	in Water in Ore in Cement	1.212
B		
C		0.0185
Na		
Mg	in Ore in Cement	0.0527
Al	in Ore in Cement	0.0743
Si	in Ore in Cement	0.121
P		
S		
Cl		
K		
Ca	in Ore in Cement	0.112
Ti		0.508
V		
Cr		
Mn		
Fe	in Ore in Cement	1.38
	in Steel	
Ni		
Cu		
Zn		
Mo		
Ba		

Table XIII (Cont'd.)

C-31

CONCRETE TYPE	SYMBOL	DENSITY g/cm^3	DENSITY lb/ft^3
Ilmenite	I-NRUe	3.44	215

COMPOSITION (lb/yd)

Water	Cement	Aggregate	Steel	Total

REFERENCE: See I-NRU

NOTE: Elemental Composition two years after pour.

ELEMENTAL COMPOSITION (gm/cm^3)

H	in Water	0.0093	Cl		
	in Ore		K		
O	in Water in Ore in Cement	1.182	Ca	in Ore in Cement	0.102
			Ti		0.649
B			V		
C		0.0148	Cr		
Na			Mn		
Mg	in Ore in Cement	0.0571	Fe	in Ore in Cement in Steel	1.309
Al	in Ore in Cement	0.0416	Ni		
Si	in Ore in Cement	0.0664	Cu		
			Zn		
P			Mo		
S			Ba		

Table XIII (Cont'd.)

C-32

CONCRETE TYPE	SYMBOL	DENSITY	
		g/cm^3	lb/ft^3
Magnetite and Steel Punchings	MS-a	4.70	293

COMPOSITION (lb/yd)

Water	Cement	Aggregate	Steel	Total
340	940	1846	4800	7926

REFERENCE: *The Experimental Boiling Water Reactor*, ANL-5607 (May 1957) p. 60. Hamer, E. E., *op. cit.*, (FP-a).

NOTE:

ELEMENTAL COMPOSITION (gm/cm^3)

H	in Water	0.0225	Cl		
	in Ore		K		
O	in Water	0.179	Ca	in Ore	0.0047
	in Ore	0.334		in Cement	0.251
	in Cement	0.200	Ti		0.0676
B			V		0.0042
C			Cr		0.0018
Na			Mn		0.0018
Mg	in Ore	0.0125	Fe	in Ore	0.631
	in Cement	0.0071		in Cement	0.0154
Al	in Ore	0.0237		in Steel	2.846
	in Cement	0.0231	Ni		
Si	in Ore	0.0107	Cu		
	in Cement	0.0605	Zn		
P		0.0006	Mo		
S		0.0018	Ba		

Table XIII (Cont'd.)

C-33

CONCRETE TYPE	SYMBOL	DENSITY g/cm^3	DENSITY lb/ft^3
Magnetite and Steel Punchings	MS-b	4.60	287

COMPOSITION (lb/yd)

Water	Cement	Aggregate	Steel	Total

REFERENCE: See MS-a

NOTE:

ELEMENTAL COMPOSITION (gm/cm^3)

H	in Water	0.0112	Cl		
	in Ore		K		
O	in Water	0.089	Ca	in Ore	0.0047
	in Ore	0.334		in Cement	0.251
	in Cement	0.200	Ti		0.0676
B			V		0.0042
C			Cr		0.0018
Na			Mn		0.0018
Mg	in Ore	0.0215	Fe	in Ore	0.631
	in Cement	0.0071		in Cement	0.0154
Al	in Ore	0.0237		in Steel	2.846
	in Cement	0.0231	Ni		
Si	in Ore	0.0107	Cu		
	in Cement	0.0605	Zn		
P		0.0006	Mo		
S		0.0018	Ba		

Table XIII (Cont'd.)

C-34

CONCRETE TYPE	SYMBOL	DENSITY g/cm^3	DENSITY lb/ft^3
Magnetite and Steel Punchings	MS-c	4.73	296

COMPOSITION (lb/yd)

Water	Cement	Aggregate	Steel	Total
340	940	1900	4800	7980

REFERENCE: See MS-a

NOTE:

ELEMENTAL COMPOSITION (gm/cm^3)

H	in Water	0.0225	Cl		
	in Ore	0.0036	K		
O	in Water	0.179	Ca	in Ore	0.0047
	in Ore	0.363		in Cement	0.251
	in Cement	0.200	Ti		0.0676
B			V		0.0042
C			Cr		0.0018
Na			Mn		0.0018
Mg	in Ore	0.0125	Fe	in Ore	0.631
	in Cement	0.0071		in Cement	0.0154
Al	in Ore	0.0237		in Steel	2.846
	in Cement	0.0231	Ni		
Si	in Ore	0.0107	Cu		
	in Cement	0.0605	Zn		
P		0.0006	Mo		
S		0.0018	Ba		

Table XIII (Cont'd.)

C-35

CONCRETE TYPE	SYMBOL	DENSITY g/cm^3	DENSITY lb/ft^3
Limonite and Steel Punchings	LS-a	4.54	284

COMPOSITION (lb/yd)

Water	Cement	Aggregate	Steel	Total
347	980	Fine Limonite 1661	4680	7668

REFERENCE: Hamer, E. E., Private Communication

NOTE: Assumed percentage not reported for aggregate to be oxygen.

ELEMENTAL COMPOSITION (gm/cm^3)

H	in Water	0.0232	Cl		
	in Ore		K		
O	in Water	0.183	Ca	in Ore	
	in Ore	0.247		in Cement	0.262
	in Cement	0.210	Ti		
B			V		
C			Cr		
Na			Mn		0.0053
Mg	in Ore		Fe	in Ore	0.590
	in Cement	0.0071		in Cement	0.0160
Al	in Ore	0.0029		in Steel	2.779
	in Cement	0.0243	Ni		
Si	in Ore	0.126	Cu		
	in Cement	0.0629	Zn		
P		0.0005	Mo		
S			Ba		

Table XIII (Cont'd.)

C-36

CONCRETE TYPE	SYMBOL	DENSITY g/cm^3	DENSITY lb/ft^3
Limonite and Steel Punchings	LS-b	4.44	277

COMPOSITION (lb/yd)

Water	Cement	Aggregate	Steel	Total

REFERENCE: See LS-a

NOTE:

ELEMENTAL COMPOSITION (gm/cm^3)

H	in Water	0.0116	Cl		
	in Ore		K		
O	in Water	0.091	Ca	in Ore	
	in Ore	0.247		in Cement	0.262
	in Cement	0.210	Ti		
B			V		
C			Cr		
Na			Mn		0.0053
Mg	in Ore		Fe	in Ore	0.590
	in Cement	0.0071		in Cement	0.0160
Al	in Ore	0.0029		in Steel	2.779
	in Cement	0.0243	Ni		
Si	in Ore	0.126	Cu		
	in Cement	0.0629	Zn		
P		0.0005	Mo		
S			Ba		

Table XIII (Cont'd.)

C-37

CONCRETE TYPE	SYMBOL	DENSITY	
		g/cm^3	lb/ft^3
Limonite and Steel Punchings	LS-c	4.65	290

COMPOSITION (lb/yd)

Water	Cement	Aggregate	Steel	Total
347	980	1825	4680	7832

REFERENCE: Anderson, G. A., (Memo), Private Communications

NOTE:

ELEMENTAL COMPOSITION (gm/cm^3)

H	in Water	0.0232	Cl		
	in Ore	0.0125	K		
O	in Water	0.183	Ca	in Ore	
	in Ore	0.346		in Cement	0.262
	in Cement	0.210	Ti		
B			V		
C			Cr		
Na			Mn		0.0053
Mg	in Ore		Fe	in Ore	0.590
	in Cement	0.0071		in Cement	0.0160
Al	in Ore	0.0029		in Steel	2.779
	in Cement	0.0243	Ni		
Si	in Ore	0.126	Cu		
	in Cement	0.0629	Zn		
P		0.0005	Mo		
S			Ba		

Table XIII (Cont'd.)

C-38

CONCRETE TYPE	SYMBOL	DENSITY	
		g/cm^3	lb/ft^3
Limonite and Steel	LS-BRa	4.16	260

COMPOSITION (lb/yd)

Water	Cement	Aggregate	Steel	Total
296	940	1684	4100	7020

REFERENCE: Binner, C. R. et al., High Density Concrete Shielding, HKF-1, (Feb 5, 1949) pp. 12-13.

NOTE: 15 lb of plastiment was also included in mix chemical composition unknown. Believed to evolve gas or evaporate, therefore neglected.

ELEMENTAL COMPOSITION (gm/cm^3)

H	in Water	0.0196	Cl		
	in Ore		K		
O	in Water	0.156	Ca	in Ore	
	in Ore	0.322		in Cement	0.251
	in Cement	0.201	Ti		0.0006
B			V		
C			Cr		
Na			Mn		0.0024
Mg	in Ore	0.0036	Fe	in Ore	0.625
	in Cement	0.0065		in Cement	0.0154
Al	in Ore	0.0095		in Steel	2.432
	in Cement	0.0231	Ni		
Si	in Ore	0.0362	Cu		
	in Cement	0.0605	Zn		
P			Mo		
S			Ba		

Table XIII (Cont'd.)

C-39

CONCRETE TYPE	SYMBOL	DENSITY g/cm^3	DENSITY lb/ft^3
Limonite and (Brookhaven) Steel Punchings	LS-BRb	4.08	255

COMPOSITION (lb/yd)

Water	Cement	Aggregate	Steel	Total

REFERENCE: See LS-BRa

NOTE:

ELEMENTAL COMPOSITION (gm/cm^3)

H	in Water	0.0098	Cl		
	in Ore		K		
O	in Water	0.078	Ca	in Ore	
	in Ore	0.322		in Cement	0.251
	in Cement	0.201	Ti		0.0006
B			V		
C			Cr		
Na			Mn		0.0024
Mg	in Ore	0.0036	Fe	in Ore	0.625
	in Cement	0.0065		in Cement	0.0154
Al	in Ore	0.0095		in Steel	2.432
	in Cement	0.0231	Ni		
Si	in Ore	0.0362	Cu		
	in Cement	0.0605	Zn		
P			Mo		
S			Ba		

Table XIII (Cont'd.)

C-40

CONCRETE TYPE	SYMBOL	DENSITY	
		g/cm^3	lb/ft^3
Limonite and Steel Punchings	LS-BRc	4.28	267

COMPOSITION (lb/yd)

Water	Cement	Aggregate	Steel	Total
296	940	1880	4100	7216

REFERENCE: See LS-BRa

NOTE:

ELEMENTAL COMPOSITION (gm/cm^3)

H	in Water	0.0196	Cl		
	in Ore	0.0130	K		
O	in Water	0.156	Ca	in Ore	
	in Ore	0.425		in Cement	0.251
	in Cement	0.201	Ti		0.0006
B			V		
C			Cr		
Na			Mn		0.0024
Mg	in Ore	0.0036	Fe	in Ore	0.625
	in Cement	0.0065		in Cement	0.0154
Al	in Ore	0.0095		in Steel	2.432
	in Cement	0.0231	Ni		
Si	in Ore	0.0362	Cu		
	in Cement	0.0605	Zn		
P			Mo		
S			Ba		

Table XIII (Cont'd.)

C-41

CONCRETE TYPE	SYMBOL	DENSITY g/cm^3	DENSITY lb/ft^3
Limonite and Steel Punchings	LS-HW1	4.23	264

COMPOSITION (lb/yd)

Water	Cement	Aggregate	Steel	Total

REFERENCE: Bunch, W. L., Attenuation Properties of High Density Portland Cement Concretes as a Function of Temperature, HW-54656 (Jan 22, 1958) p. 39.

NOTE: Elemental composition given in g/cm^3 with Mg-Al reported together. Hanford (As cured)

ELEMENTAL COMPOSITION (gm/cm^3)

H	in Water	0.028	Cl		
	in Ore		K		
O	in Water	0.806	Ca	in Ore	0.250
	in Ore			in Cement	
	in Cement		Ti		
B			V		
C			Cr		
Na			Mn		
Mg	in Ore	0.039	Fe	in Ore	3.030
	in Cement			in Cement	
Al	in Ore			in Steel	
	in Cement		Ni		
Si	in Ore	0.078	Cu		
	in Cement		Zn		
P			Mo		
S			Ba		

Table XIII (Cont'd.)

C-42

CONCRETE TYPE	SYMBOL	DENSITY	
		g/cm^3	lb/ft^3
Limonite and Steel Punchings	LS-HW2	4.14	258

COMPOSITION (lb/yd)

Water	Cement	Aggregate	Steel	Total

REFERENCE: See LS-HW1

NOTE: Elemental Composition given in g/cm^3 with Mg-Al reported together. Hanford (heated to 100°C)

ELEMENTAL COMPOSITION (gm/cm^3)

H	in Water	0.018	Cl		
	in Ore		K		
O	in Water	0.726	Ca	in Ore	0.250
	in Ore			in Cement	
	in Cement		Ti		
B			V		
C			Cr		
Na			Mn		
Mg	in Ore	0.039	Fe	in Ore	3.030
	in Cement			in Cement	
Al	in Ore			in Steel	
	in Cement		Ni		
Si	in Ore	0.078	Cu		
	in Cement		Zn		
P			Mo		
S			Ba		

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