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CONSTRUCTION OF CHEAP SHIELDS: A SURVEY

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Technical Division

Section IV, Engineering Materials

R. N. Lyon, Section Chief

CONSTRUCTION OF CHEAP SHIELDS: A SURVEY

Theodore Rockwell, III

JAN 16 1950

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ABSTRACT

A survey of shielding a radiation source at minimum cost is presented. Concrete and metal shields are discussed. Factors which influence the cost of high density concrete shields are evaluated. Mixing and handling techniques for concrete are recommended, and various aggregate materials are suggested.

Various metal shields are suggested. The advantages and disadvantages of these shields are enumerated. Non "thermal shields" have questionable value; "Boral" is expensive, and "Boroxal" is cheap but not as good as "Boral".

A number of tables are included in this report showing the properties of the various "cheap shields", "cheap" aggregate, and boron vehicles. Cost data are supplied where available.

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CONSTRUCTION OF CHEAP SHIELDS: A SURVEY

1.0 Introduction

The preceding article in this series[1] discussed the attempts that are being made to synthesize the best materials obtainable for the attenuation of reactor radiation in a minimum weight of shielding. Slight improvements in this direction justify very large financial outlays, since the saving in weight will pay for itself elsewhere in the vehicle on which it is installed.

This paper surveys the more mundane problem of shielding a source of radiation at minimum cost; concurrently--but secondarily--the desire to decrease shield volume is recognized. The work is aimed primarily at builders of hot laboratories and chemical plants, stationary reactors, accelerators, and miscellaneous sources (isotope handling equipment, hot pipes and storage, experimental apparatus, etc.) in approximately that order of interest.

Like the early days of automatic control application, when miscellaneous instruments were individually "tacked on" to a finished plant by outsiders, shielding until recently has been a minor consideration, almost never having even one person assigned full-time to it. As a result, shields were built costing millions of dollars[2] which we now know could have been made for a few percent of that sum. This is

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1) VP Calkins and WJ Koshuba, NEPA 1045-SCR-50 AEC Restricted Data
2) e.g. OS Petrescu, Summary of Hanford Shield Data, in ORNL Shielding Symposium Notes, Supplement No. 1, CF 48-10-44, p 220-222 or The Ferguson Report HKF-1, both AEC Restricted Data

not disgraceful or even surprising: the manpower which might have saved this money was busy elsewhere saving even greater sums, and mastering problems which might have otherwise doomed entire reactors. But the situation is now quite different. The meager manpower and time needed for these studies is available, and a start has been made. The way is now clear for reducing the cost of many shields by a factor of ten or perhaps a hundred, at the same time getting a better shield.

Cheap shielding generally means high-density concrete, a field of some background even before the war. Dr. H. H. Steinour of the Portland Cement Association has been very helpful in acquainting the project with this early work.

I. Lyse and J. M. Holme, Ibid. 5 121-8 (1930) and Vol. 30 of the Proceedings, in a discussion of aggregates, describe such a material and show that no corrosion results from freezing and thawing tests. R. B. Rothschild, Eng. News-Record 115 788 (Dec. 5, 1935) tells of scooping up naturally-concentrated magnetite along California beaches to make 400 cubic yards of high-strength concrete with a density of nearly 3.0. A Belgian patent, issued in 1942, describes lead-slag aggregate concrete for cyclotron shielding, and the writer has been told that a Swedish cyclotron shield containing iron ore was started before the

war. Heavy cements, containing lead or barium, for x-ray protection, were also under development in the late 30's and are discussed below under "cements".

Dr. Steinour states: "We understand that magnetite was used extensively during the war for making heavy concrete for ship ballast... we also know of iron ore tailings being used as aggregate in concrete for ballasting ships. Some crushed iron ore tailings were also used in road construction in northern New York with apparently satisfactory performance (as of April 1943). We also know of arsenopyrite having been proposed as heavy aggregate."

The cyclotron shield recently completed at Carnegie Tech used very fine magnetite and portland cement. No coarse aggregate was used, and the large surface of the fines held a great quantity of water for neutron moderation. This shield is described in an excellent article by Creutz and Downes to appear soon in the Journal of Applied Physics.

Because of the difficulty of exchanging information on this subject with persons and organizations outside the Project, most of the above work was not known to the Project, and the material outlined below was developed independently.

2.0 Shield Construction

The first variable to be set, and the one influencing cost most strongly, is the construction method used. Below are outlined the most common ones, with some of the characteristics of each.

2.1 Monolithic Concrete

This technique is the most conventional, finding application in isotope shipping containers of a few cubic inches, up to chemical plants, accelerators and reactors, each requiring over a thousand cubic yards of shielding. It is used on installations with simple, imperforate shields, and on those requiring thousands of complex, machined through-tubes. Cost have run from \$30 to \$1200/yd^3 and densities from 2.2 to 6.0 g/cc have been cast on actual construction jobs. The only requirement these jobs had in common was some degree of permanence. Let us see how they differ.

A major cost-determining factor is the dimensional tolerances allowed. The best actually obtained (to this writer's knowledge) by such a technique, is about plus or minus one-sixteenth inch. Steel can be flame-cut to one thirty-second, and this is probably closer than assembly can be made. Plywood forms, drilled oversize and shimmed in the field by a survey crew, have achieved one thirty-second tolerance on a large job, and this technique seems very satisfactory. As an added precaution, simple portable steel jigs could be used with plywood forms. To repeat a warning from Dr. Cohen's paper earlier in this series[1], the designer should consider carefully the tolerances he sets for shield apertures: non-removable prefabricated steel forms may cost hundreds of thousands of dollars on a large job, without actually enhancing the tolerances obtained.

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1) K Cohen, CF 49-5-278, AEC Restricted Data

2.1 Monolithic Concrete (Con't.)

By using ores or other aggregate of moderate density (see below), concretes of densities up to one and one-half or two times normal (normal being 2.3 g/cc, 144 lb/ft^3, 2 tons/yd^3) can be made, which handle easily in conventional mixing and conveying equipment. When steel aggregate is used, to obtain densities up to six plus (nearly three times normal), several difficulties occur:

1) Higher density decreases the volume capacity of the mixing machinery not only by the density ratio as might be expected, but also by an additional factor caused by the mix being concentrated at the outside of the drum where it acts through a greater lever arm. Brookhaven concrete, with a density of nearly twice normal, was handled with two cubic yards in a mixer designed for four; "MO" (a magnesium oxychloride, steel aggregate concrete)[1], with a density only two and one-half times normal is more safely handled one yard per mixer. Where the material is handled in wheel-barrels or by shovels, a corresponding decrease is found.

2) When small volumes of concrete are handled in a large mixer, the quantity which normally sticks to the walls of the mixer becomes an appreciable fraction and presents a serious problem. The cement and fine aggregate tend to stick preferentially, so that the concrete discharged from the mixer varies from the design mix charged. The sticky nature of MO[1], and its tendency occasionally to react autocatalytically, accentuate this problem. A conventional additive, such as Plastiment, may alleviate this situation as it did with the Brookhaven concrete.

3) There is an action of the iron aggregate on the cement which tends to accelerate the setting unpredictably; it is not known whether this action is predominantly chemical, or a physical effect due to abrasive exposure of fresh surface. It has been observed with both oxychloride and portland cements.

4) Handling steel aggregate is necessarily time-consuming and should be minimized.

5) The presence of large irregular pieces in the steel aggregate seems to be unavoidable in the absence of expensive screening. The presence of such pieces in a mixer is obviously undesirable.

1) See page 24 below

Except for the last-named, all of these difficulties may often be overcome by use of a concrete pump. It is recommended that such a technique be considered, particularly for workable cements such as MO, but only when initial set and maximum aggregate size are carefully controlled.

A less conventional, but more fool-proof, technique involves handling the mortar separately in normal construction equipment, and adding the iron--or other dense aggregate--to the form directly. This procedure was first observed by the writer at Argonne, where approximately 6 inches of mortar (2:1, sand: PC) was poured into the form, and then steel punchings, approximately 1 inch in diameter and 1/2 inch thick, similar to those used in the Battelle, and ORNL work, were poured into the form with continuous intensive vibration from an ordinary internal pneumatic concrete vibrator. This method allowed the punchings to shake down to 30% voids (the voids of course being filled with mortar), whereas normal rodding or vibration in air can achieve only 50% density. Later work at ORNL indicated that a 2:1 mortar of crushed iron powder and cement (no sand) would produce, with the punchings, a density of nearly 7 g/cc.

In the case of a combined neutron and gamma shield, it is generally not desirable to reduce the cement phase to this low volume-fraction. At ORNL, a mortar was made consisting of magnesium oxychloride cement and a small quantity of stainless steel snagging scrap (small curlicues about 0.01 to 0.1" long). The latter prevents the punchings from packing too tightly and also insures a distribution of fine aggregate through the

cement phase, which mechanically stabilizes it and tends to inhibit cracking and dimensional changes. By adjusting the ratio of punchings to snagging scrap, the same composition achieved with punchings and shot can be obtained. By not putting the coarse aggregate in the mixer, an increased lenience can be given the coarse aggregate specifications, and the possibility of obtaining voids is greatly decreased by the unusually long vibration period. This method seems to have considerable merit and it is suggested that the potential users of heavy aggregate concrete investigate it.

2.2 Brick or Block Shields

The most common forms of prefabricated shield are the familiar lead bricks, concrete blocks, and paraffin slabs which provide the lion's share of the shielding in most hot labs and experimental irradiation set-ups. The obvious advantage to such a shield is portability, resulting (when loose stacking or weak mortar is used) in easily changed geometries and nearly complete salvagability.

There, as in monolithic shielding, drastic cost reductions are possible: 2 x 4 x 8 inch lead bricks, cast oversize and machined (in accordance with present practice in many laboratories) cost $6.70 apiece, whereas 8 inch lengths of 2 x 4 steel barstock can be supplied in quantity for $1.50; sawed, deburred, galvanized, and delivered. Cast iron bricks would cost considerably more, would have as much as 10% lower density, and would probably vary dimensionally by nearly one-quarter inch. Cast aluminum, sometimes mentioned for this purpose, seems to have only the advantage of corrosion resistance, a quality easily imparted to steel by

2.2 Brick or Block Shields (Con't)

plating, plastic-coating, or surface-treating (e.g. galvanizing, sherardizing), while combining an undesirably low density with a cost greater than lead.

A word of caution is advisable here: it is frequently assumed that gamma shielding can be specified by surface density alone (gm/cm^2 or lb/ft^2), i.e. that the ratio of densities of two materials is also the ratio of their gamma-shielding power. By this criterion, 1.45 inches of steel is equivalent to 1.00 inch of lead. This is essentially true at 1 to 3 Mev, where the maximum penetration occurs, and for which most shielding should be designed. But at much lower or high energies, this assumption may be incorrect by a factor of three or more. Higher energies are seldom encountered outside of reactor or accelerator work, and radiation of lower energies is so much less penetrating that it seldom determines shield thickness. Note, therefore, that a density ratio is a satisfactory comparison criterion for the gamma radiation of highest penetrating power, but not at appreciably lower or higher energies; the graphs[1] in Figure 1 present this picture more completely.

Dimensional tolerances again play an important part. The eighth-inch variation common to concrete blocks is generally tolerable, since it represents, in the worst case for a 6 x 6 x 12 block, only two percent of the total brick face area, and gives a slot whose length-to-thickness ratio is at least 48. For a smaller block, such cracks become appreciable, and one sixteenth or one thirty-second of an inch is probably preferable.

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1) Adapted from information in "Isotopes Division Circular B-4" by GW Morgan.

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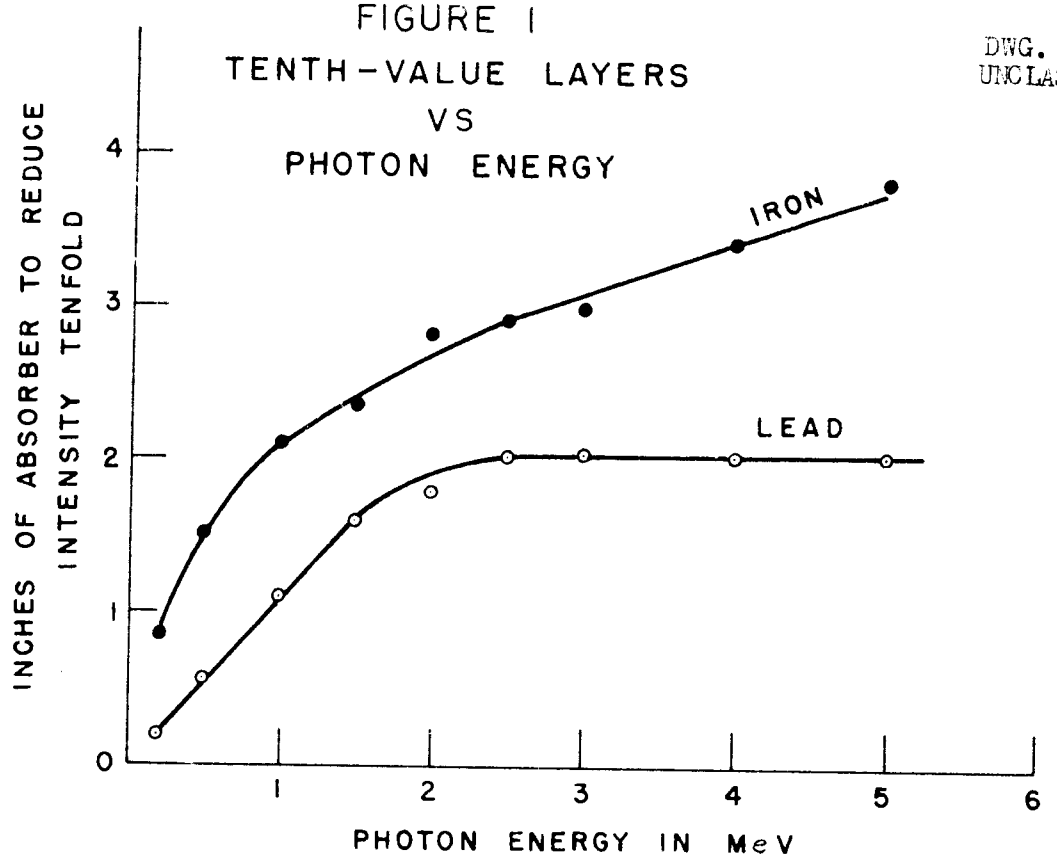
FIGURE 1
TENTH-VALUE LAYERS
VS
PHOTON ENERGY



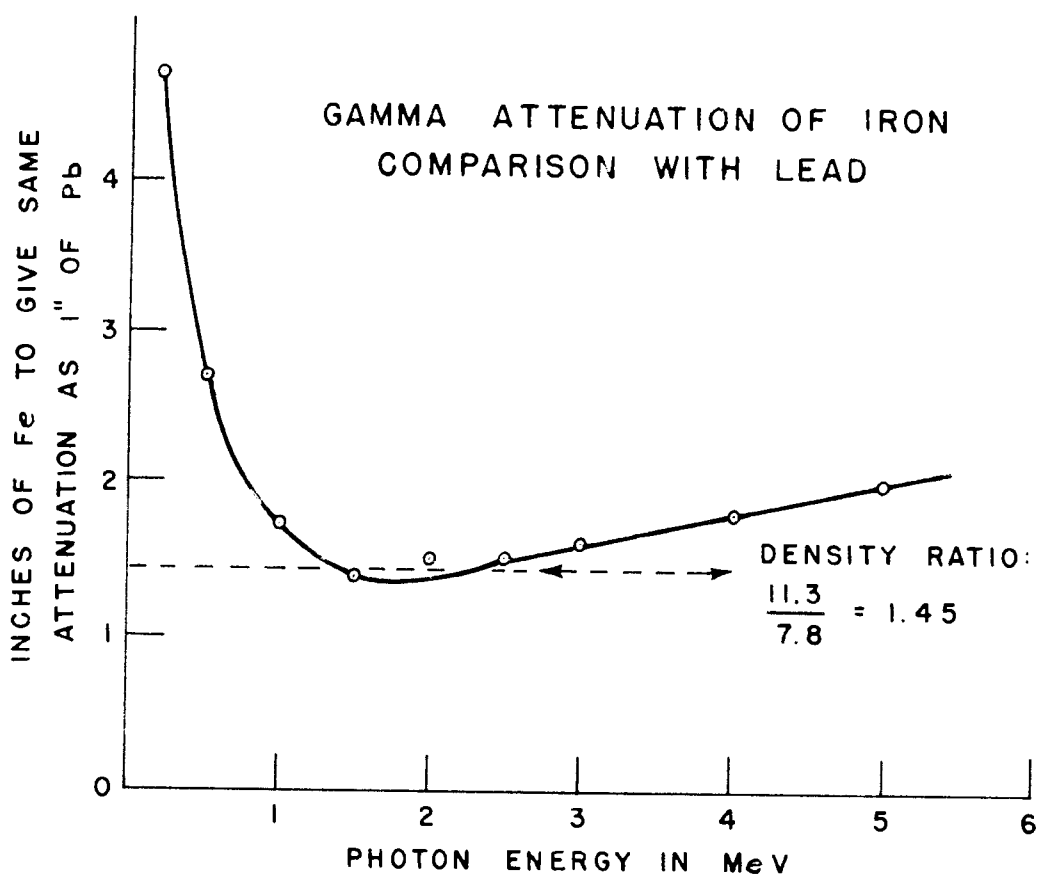


Table I - Properties of Various Shielding Blocks

Material	Material Cost, ¢/lb	Density, g/cc	Tolerance, ± fraction of inch (e.g. "16" = 1/16th in.)	Remarks
Normal concrete blocks, standard sizes	0.31	2.2	32, length and thickness; 16, height	Price for finished block, f.o.b. the block plant
Normal concrete blocks, special sizes	1.0	2.2	8 to 4, all sides	
Special concrete blocks, standard sizes	½ ¢/block, plus materials, delivered to block plant			
Cruetz, CIT Cyclotron (magnetite fines, PC)	~1.0	3.0	---	See Creuz & Downes, forthcoming J. App. Phys.
Chalk River concrete (Fe. sand, PC)	~2.5	4.7	---	See ED-16 (Secret)
Barytes ($BaSO_4$), PC)	1.0	3.5	---	See correspondance between Rockwell and Austin Co., Fall '49
(MO (magnesium oxychloride, Fe)	~3.0	5.8	---	See ORNL-17 (Secret) and ORNL-241 (Restricted)
Lead bricks, as cast (2 x 4 x 8")	20.	11.3	16 (before being dropped)	Latest casting technique may give 1/64"
Lead bricks, machined, three sides (inches)	25.	11.3	64 (before being dropped)	
Steel barstock, sawed into bricks	5.0	7.8	32	
Cast iron bricks	5.5	7.2	4	
Cast aluminum	20.	2.6	8	
Aluminum barstock	22.	2.7	32	
Paraffin slabs (crude)	7.	0.9	16	
Boroffin slabs (7% B by wt.)	15.	1.0	16	
Pitch, cheapest grade, 150°F MP	1.6	1.1		Would be canned
One gal. cans, square (6½ x 4 x 9½ in.)	13¢ ea.	--	32	Tolerance good, but will have cracks between cans
Five gal. cans, square (9 x 9 x 14 in.)	33¢ ea.	--	32	
Coating steel bricks (2 x 4 x 8 inch):	Cost, $/brick			
Painting (spray - three coats)	0.20			

Table I (Cont'd.) - Properties of Various Shielding Blocks

Material	Material Cost, ¢/lb	Density, g/cc	Tolerance, ± fraction of inch (e.g. "16" = 1/16th in.)	Remarks
Good plastic coat (spray - 3 coats)	0.25			
Galvanizing	0.20			
Cadmium plate, over copper	0.82			
Chrome plate, over nickel, over copper	1.20			

[redacted]

2.2 Brick or Block Shields (Con't.)

Thus, it is not generally advisable to go to dense concrete blocks without mortar: first, the cost of ordinary concrete blocks is approximately one-third cent per pound and this can seldom be matched in heavy aggregate; second, the blocks quickly become too heavy for easy handling, necessitating smaller bricks and thus closer tolerance. Steel barstock can be obtained within one thirty-second, particularly if an order for several thousand bricks is placed directly with a mill, noting that phosphorous, sulphur, and carbon content are not important, but that dimensional consistency and good density are. The price should be near 4¢/lb, and in quantity, should be hot-sawed at the mill.

Many materials, such as water, pitch, silica gel, or paraffin, make good shields but are not easily handled. Square five-gallon or one-gallon cans, filled with such materials, make convenient shielding blocks (even to having handles) at moderate expense, and were frequently used at early cyclotron installations. Compression test made at ORNL indicate that the one-gallon cans are strong enough to permit stacking several hundred high.

2.3 Laminated shielding, a favorite for calculation and experimental purpose, offers no construction advantages, in most cases, over monolithic or block shielding. An exception might be where an inner layer of greater thermal or radiation stability or with selective absorption characteristics is desired. This is considered in paragraph 2.5 below.

2.4 Prefabricating very large blocks (e.g. several tons each) offers several opportunities for improvement.

1) If there is any doubt of the quality or dimensional changes of a new material, prefabricated blocks can be made under laboratory conditions, tested rigorously.

2) If heat of setting (of a concrete) is a problem, separate blocks are more easily cooled than a monolithic structure. Curing, if required, can be precisely controlled. If desired, prestressed blocks can be made.

3) By making blocks large enough, techniques normally used for monolithic structures can be used. Inserts can be placed in the laboratory, where greater precision should be obtainable.

2.5 Thermal Shields

No discussion of shield construction could be complete without mentioning the subject of thermal shields. This ambiguous term refers to an inner wall, generally of steel, which lies between the pile and the bulk of the shield. Its function is to absorb most of the energy of the leakage radiation and thus protect the shield from damage due to heat and high intensity radiation. The Clinton Pile has no such protection, the bare concrete facing bare graphite. After five and a half years, with some 10^{18} total neutrons per square centimeter and nearly as many gamma quanta (approximately 3×10^{8} roentgens), compression tests and chemical analyses on core samples indicated little or no radiation damage. Experiments with high thermal gradients on many types of concretes have shown that the possibility of failure due to thermal stress might be considerably less than generally assumed. Add to this the fact that nearly all of the thermal neutrons captured in iron create penetrating gamma radiation, and it begins to look as if the entire subject of thermal shields is in need of intensive study.

2.5 Thermal Shields (Con't.)

A possible improvement of this situation is offered in the cerametal "Boral", a complex of aluminum and B_4C developed at ORNL[1]. A 1/4 inch sheet of this metal costs $15 per square foot* and weighs 3¼ pounds per square foot; it can attenuate thermal neutrons by 10^{10} without the production of hard secondary gammas and apparently without any radiation damage. This last point is still under investigation. If the flux incident on a shield were such that the thermal neutrons outnumbered the hard gammas by a factor of 100, this 1/4 inch of boral would effectively reduce the required gamma attenuation by a factor of 100. In other words, 1/4 inch of boral inside the shield might be equivalent to 26 inches of concrete outside the shield. E. Creutz estimates that the removal of approximately this much concrete from the outside of the CIT cyclotron shield by the use of dense concrete saved $20,000 in floor space and materials, over the increased cost of the special concrete. In a reactor, the savings might run to ten times this amount. Such a sheet might be hung from bolts set into the inner face of the concrete, thus allowing cooling on both sides and warpage from radiation damage if it should occur.

"Boroxal", a poor man's boral[2], composed of B_2O_3 and Al, has nearly one-third the boron content and most of the excellent mechanical properties of boral, at one-twentieth the cost. Radiation damage may be more severe, however, and this question is being studied. For small shields, "boroffin", a B_2O_3-paraffin mixture, appears to be useful and inexpensive.

---

1) VL McKinney and T Rockwell, ORNL-242, AEC Restricted Data
2) T Rockwell, CF 49-8-218, AEC Restricted Data
*) Possibly less than $10, if metallurgical grade B_4C is used

3.0 Aggregates

Most cheap shields consist of metallic or metalliferrous pebbles, encased in a continuous hydrogeneous medium; we shall refer generically to such material as "concrete", composed respectively of "aggregate" and "cement". The cements will be considered in paragraph 4.0 below; this section will consider aggregates, as defined above.

Most of the information on aggregates can best be presented in tabular form; Table II has been prepared for that purpose. Before referring to Table II, however, a glance at Figure 2 is in order. It shows how concrete density varies as a function of cement density, aggregate density and the volume fraction of the concrete which is occupied by cement. The relationship is simply:

$$D_{con} = D_{cem} \cdot f_{cem} + D_{agg} \cdot (1 - f_{cem})$$

The graph is presented in this form, rather than the simpler nomograph which is used at ORNL for actual computations, because it shows pictorially how the variables are interdependent: how, for example, the cement density is relatively unimportant from $f_{cem} < 15\%$; how there is limited need for cements over 3 g/cc; etc.

It is apparent that a similar relationship exists between the costs of concrete, cement, and aggregate (on a volume basis). If the abscissa is considered to be cost of cement, from one to five $/ft^3; the curve groups, cost of aggregate, 3, 4, 6, and 8, $/ft^3; then the ordinate will correctly read cost of concrete in dollars per cubic foot. Obviously, other conversions, to $/yd^3 or lb/ft^3, can be similarly made, or the scales can read 10 to 50 ¢/ft^3, etc.

FIGURE 2

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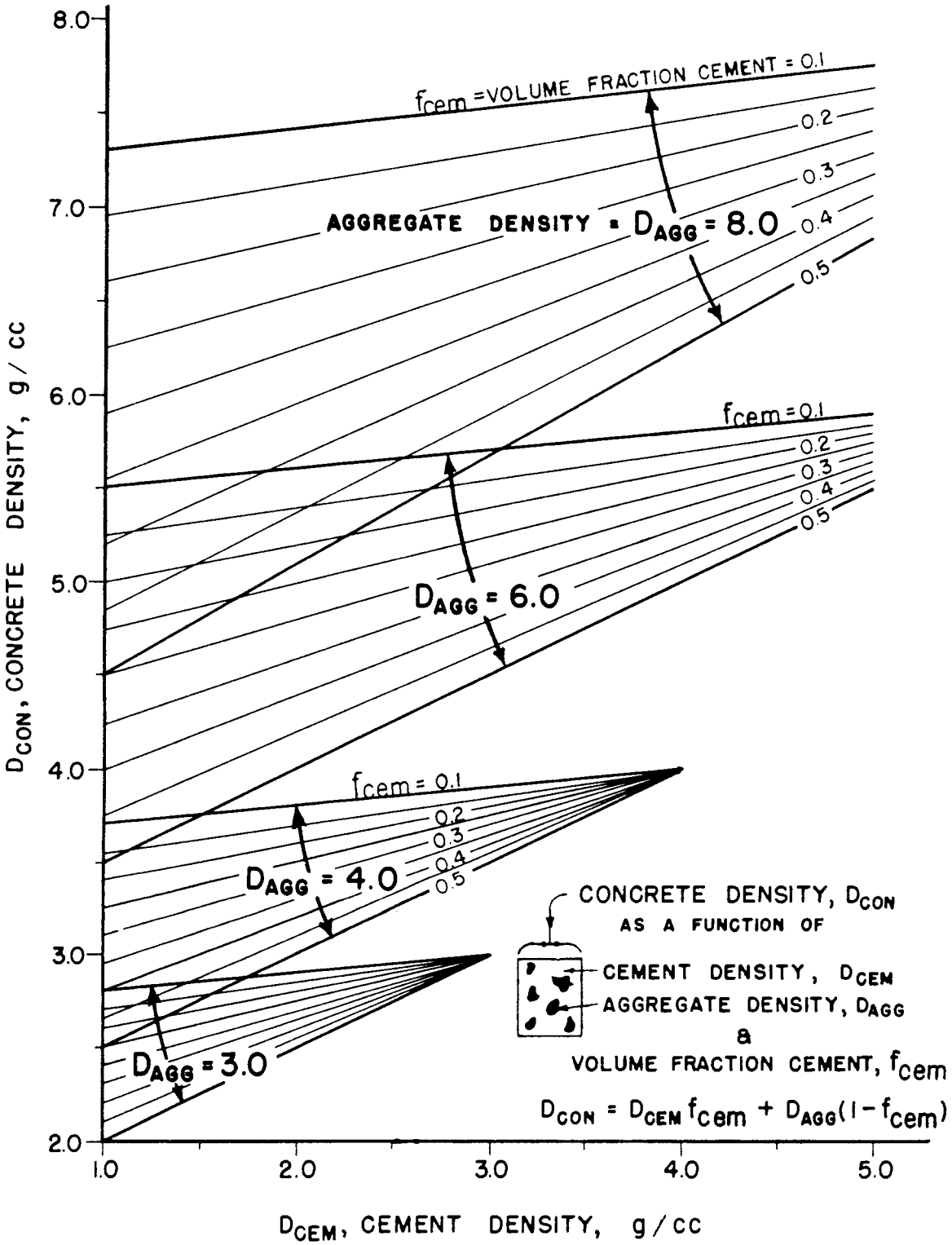

3.0 Aggregates (Con't.)

The selection of aggregate size and gradation for maximum density is discussed[1] by C. C. Furnas and F. O. Anderegg, Ind. Eng. Chem. 23 1052 (1931). They point out that maximum density requires a large ratio of coarse to fine aggregate diameters, while optimum workability requires a continuous gradation of size. Graphs are included, showing optimum number of components for different aggregates, and minimum voids obtainable under various conditions. As an example, for minimum voids, if the cement particle diameter is assumed to be 0.001 inch, the coarse aggregate should be 2.2 inch. If a compromise to one inch is made, the fine aggregate should be 28 mesh. The volume ratio, PC:fines:coarse should be $1:2\frac{1}{2}:6\frac{1}{2}$. Refinements are then made to include density of aggregates. This is admittedly a harsh mixture, and the second half of the article is devoted to reducing the mathematical results to working practice.

The authors conclude that maximum density requires that the ratio of the fraction of aggregate retained on any one sieve to that on the next smaller be 1.1 for sieves differing in mesh dimensions by $\sqrt{2}$, and 1.2 for sieves differing by 2. This screening should be applied continuously from the coarsest aggregate to (and including) the cement powder. In practice, most crushing processes tend to produce a product with such a gradation, so that crushed aggregates will generally produce a compact concrete. However, many contractors on conventional work have found that screening and grading aggregate can often pay for itself in cement saved, and where density is an objective, correct grading should not be overlooked.

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1) Later work along similar lines is covered in:
TC Powers, J. Am. Concrete Inst. 3, 419-48 (1932)
CAG Weymouth, Rock Products 26-30 (Feb 25, 1933)
CAG Weymouth, ASTM Proc. 38 (Pt. 2) 354-72 (1938)
CT Kennedy, J. Am. Concrete Inst. 11, 373-400 (1940)

[redacted]

Table II

Properties of Cheap Aggregates

Aggregate Name and Source	Chem. Analysis, %	¢/lb. f.o.b.	"True density" g/cc Handbook Avg.	"True density" g/cc Exper.	Sizes available	% voids Loose-packed
Hematite, deep ore, Birmingham, Ala.	34 Fe, 30 $CaCO_3$, 15 SiO_2	0.25	5.2	3.3	¼ 1" - 4" or SF*	37
Limonite, Birmingham, Ala.	50 Fe; Si and Al; 10% H_2O	0.30	3.8	3.3	ungraded	--
Magnetite concentrate fines, Adirondacks	60 Fe some Ti, Si, Al	0.28	5.1	---	very fine	--
Barytes, top grade, Sweetwater, Tenn.	95% $BaSO_4$	0.60	4.5	4.3	SC or SF	44
Galena, Joplin, Mo.	80% Pb	7.4	7.5	---	ungraded	--
Tennesse Limestone	>90% $CaCO_3$	0.10	2.5	2.6	all grades	--
Tennessee River sand	>90% SiO_2	0.10	2.3	2.6	all grades	38
Taconite, from Masabi range (magnetite in basalt)	Fe_xO	1.5	---	4.6	ungraded	--
Iron punchings, bolt clippings, foundry spillage	Fe	1.5	---	7.7	$1\frac{1}{2}$ to $\frac{1}{2}$	50
Cast iron borings	Fe	0.75	7.2	5.0	SF*	56
Cast iron grinding dust	Fe	1.5	7.2	---	assorted fines	--
Stainless snagging scrap	Fe + Cr + Ni	1.5	7.9	6.0	SF, after thru 1/4"	60
Chilled iron shot	Fe	4.5	---	7.6	SAE stds.	30
(Lead shot)	Pb	20.	11.3	11.4	SAE stds.	30
(Ferroboron)	15-20% B	130.	~5	---	lumps	--
(Ferrotungsten)	75-80% W	170.	~15	---	lumps	--

SC = ASTM standard coarse
SF = ASTM standard fine
*After screening through 1/4"

[redacted]

3.0 Aggregates (Con't.)

The classes of aggregates are few, and for the most part rather obvious. Ores or slags whose densities are appreciably greater than normal concrete aggregates (which seldom run above 2.7) are, of course, worth considering if their mechanical properties are acceptable and their delivered price within range. The actual material used will depend greatly on location. A second category, of more expensive materials, is the metals, generally limited to iron and steel, with small quantities of lead occasionally justified. If more exotic materials are wanted, it might pay to investigate the ferro-alloys which sell in tonnage lots and combine iron with various other elements. A typical price list and approximate analyses of such materials appears each week in Iron Age. Ferrotungsten, for example, or Ferroboron provide sources of tonnage lots of otherwise scarce materials.

Another possibility worth considering is that of coating cheap steel aggregate with a thin film of boron. This could probably be done in ton lots for a relatively low cost, and might make a great difference in the production of secondary gammas. Present shields consisting of iron and hydrogeneous material allow fast neutrons (which become degraded, but seldom captured in the iron) to become thermalized in the hydrogen, and then bounce back into the iron for capture and consequent gamma emission. A thin boron coating might greatly decrease the number of such events.

4.0 Cements

The main purpose of cements here considered is to provide hydrogen, bonding strength, and, if possible, a reasonably high density. A normal concrete, in which the aggregate size is specified with ordinary care, will contain at least 15% voids between the aggregate particles, which

4.0 Cements (Con't.)

must be filled with cement. Very careful grading of aggregate may reduce this to 10%, but probably not much less. In special concretes, where cost of the cement phase is not the price-determining factor and the cement is needed for its own shielding value, the cement volume may go up to as high as 50%. If a shield is assumed to be metal (aggregate) and hydrogen (cement), then the cement fraction should be kept low and its hydrogen content high; this has been the objective of the shielding concrete work today.

However, we have been given no clear picture of the effect of hydrogen content on shielding efficacy. Indeed, the experiments to date indicate surprisingly little effect of large variations in hydrogen content near the range of ordinary concretes (0.02 to 0.2 g/cc)[1]. Therefore, while the criterion of maximum hydrogen content is all we have to go on, it is important that we realize that its necessity has not yet been quantitatively proved.

The second criterion, strength, is adequately met by so many materials that it almost ceases to figure in our specifications. Materials such as silica gel, synthetic elastomers, and common pitch are receiving serious attention on the assumption that their low strength will be adequate when the shield is contained within permanent forms and the aggregate is essentially self supporting. The shield is seldom called upon

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to support more than its own weight and in the case of water or pitch shielding, the form walls will even do that.

The third criterion, density, can be seen to have little effect. The wide range of aggregate choice and the ability to cut the cement fraction to 0.15 of lower, allows the cement density to contribute little to the density of the concrete (See Figure 1).

Having nothing better to go on, however, we shall continue to use the criteria of hydrogen content, strength, and density to evaluate cements, with the implied addition of a fourth: permanence, under operating conditions of temperature, mechanical stress, radiation, etc.

A great deal of work has been done on the oxychloride cements[1], which are of interest because of their high water content, high strength, and excellent workability. "MO", previously mentioned, is magnesium oxychloride cement with steel punchings and shot for aggregate. The specifications for MO were declassified for use in the walls of the counting rooms of the Clinical Center Building, No. 10, Bethesda, Md., and are presumably obtainable from the National Institute of Health.

Other metallic oxyhalides were studied at some length, and a great many metals and cations are available as such cements, if desirable for special purposes. By-product rare-earth carbonates, with thermal cross-sections exceeding that of pure boron, have been calcined, mixed with $MgCl_2$ solutions, and made into similar cements.

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1) cf Pavlish, Snyder, Wynd, BMI-T-4 and 15
Rockwell, CF 48-1-118, ORNL-17, -240, and -520 all AEC Restricted Data

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Battelle has studied cements in the portland class, such as the refractory Lumnite and a specially-synthesized $3CaO.5Al_2O_3$. Barium cements were studied there and elsewhere[1]. Mortars loaded with PbO for x-ray rooms were investigated by National Lead Company even before the war.

The place of ordinary portland cement in this picture should be clarified. PC (as we shall refer to it) was assumed by many Project materials people to have the following disadvantages: low water content, poor thermal-gradient strength, low high-temperatures strength, poor shock and tensile strength. Moreover, it was difficult to get information within the Project of the type needed, and it was not known precisely who, on the outside, could help, if security clearance were obtained. Dupont had made the Clinton shield (now ORNL) of PC and haydite, a porous, calcined shale which could absorb large quantities of water, and coated the structure with bituminous paint to retard water loss. Barytes ($BaSO_4$) was used as coarse aggregate to bring the density back to normal[2]. This proved to be quite successful, and core drillings made five years later[3] showed that the water content was still nearly five times normal and no radiation damage was detectable, even at the unprotected inside face. This retention of several times the expected water content[4], complete freedom from radiation damage, high temperature

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1) Mining and Metallurgy 24 85 (1943)
2) The available information on this shield is summarized in the ORNL Shielding Symposium Notes, CF 48-10-44, Vol 1, p 233-237, (AEC Restricted Data)
3) See T Rockwell, ORNL-241, AEC Restricted Data
4) The very complex question of water content of PC is excellently discussed in the Portland Cement Association's Bulletin 22 by TC Powers and TL Brownyard, a series of reprints from the Jour. Am. Concrete Inst. Oct. 1946 to Apr. 1947, or the Proceedings, Vol 43 (1947)

4.0 Cements (Con't.)

gradient (90° F) without mechanical failure, and continued strength, reopened the question of PC shielding. Soaking the core samples doubled the water content, making a good concrete of normal density with ten times the water content of normal PC concrete and five times that of MO.

There is no reason why a concrete shield cannot be kept wet and this increased water content realized. Various experiments at ORNL to produce finely porous PC concrete with densities greater than 5.0 g/cc and water contents above 0.2 g/cc have proved quite successful. In the case of a sodium-cooled reactor, this additional "free water" might somewhat increase the explosion hazard. But half of the water in normal "dry" concrete is held similarly, and hot sodium falling in quantity on a "dry" concrete floor will generally cause a severe explosion from the suddenly-formed steam, even without a sodium-water reaction. Therefore, it is hard to evaluate the reality or magnitude of a hazard caused by the presence of additional water held in the microscopic and sub-microscopic pores of PC cement. This method of obtaining highly-hydrogenous cement (by keeping a specially-made porous cement wet) is obviously of interest for a water-cooled reactor, and is worthy of serious consideration for higher temperature shields as well. Exploratory experiments at ORNL on temperature gradients impressed on wet concrete samples indicate that high rates of heat dissipation may be expected. Even dry gradients of several hundred degrees[1], with and

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1) It should be noted (as first pointed out to the writer by AM Weinberg) that thermal stresses are functions of temperature difference, elastic modulus, expansivity and shape (but not size). Cf. any standard mechanics text.

4.0 Cements (Con't.)

without thermal cycling, have been imposed on test cylinders without decrease in strength other than that expected for the average temperature of the specimen. Chimneys and furnace stacks are further examples of such conditions.

To summarize:

1) Water content of PC, normally low, can be increased tenfold by judicious handling--this is higher than oxychlorides.

2) High temperature strength[1] and thermal gradient strength of PC concretes are much higher than previously assumed.

3) Shock and tensile strength are also improvable by several techniques, such as use of nails, curlicues, or wire in the aggregate (a few qualitative experiments tried at ORNL).

The pros and cons of a fluid water shield with or without aggregate, have been frequently presented[2]. The possibility of fixing the water with silica gel has been mentioned, as has the fixation of water in the fine pores of cement. For more expensive shielding, or for inner layer of a cheap shield, the use of porous metal with water has been informally suggested by Ralph Zirkind. Such a metal-and-water shield would be excellent nuclearly, could dissipate large quantities of heat, and yet, with pores of carefully-chosen size, would hold water capillarily should the system fail, and at the flow required, have a reasonable pressure drop. It is the ultimate extrapolation of the "swimming-pool-full-of-scrap-iron" shield.

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1) See as Battelle reports, BMI-P series, and HKF-1 Supplement No. 1
2) e.g. LA Ohlinger to AEC Shielding Group, Oct. 6, 1948, CF 48-10-136, and reply: CE Clifford, et al., Nov. 1, 1948, CF 48-11-57 both AEC Restricted Data

[redacted]

Table III

Properties of Cheap "Cements" for Shielding

Material	Density g/cc	gH/cc	¢/lb	$/ft^3	Compressive Strength, psi	Remarks
Portland cement, wet, in special concrete	2.0	0.100	0.62	0.62	4000	50% H_2O
Portland cement, "dry", but well-cured	1.8	0.060	0.62	0.62	4000	30% H_2O
Portland cement, poorly cured	1.6	0.018	0.62	0.62	2000	10% H_2O
Magnesium oxychloride	1.8	0.078	2.56	2.88	6000	39% H_2O
Lead-glycerine	3.8	0.079	20.7	38.76	4500	
Plaster of paris	2.3	0.041	0.53	0.76	4000	
Lumnite + $CaSO_4$ (Battelle)	1.9	0.06	---	---	5000	
$3CaO.5Al_2O_3$ (Battelle)	~1.8	0.07	---	---	3000	
Paraffin (~CH_2)	0.9	.128	7.0	3.93	--	
Pitch	1.1	.132	2.5	1.72	--	
Synthetic elastomers (~CH_2)	1.0	.143	2.0	12.50	--	
Water (or silica gel)	1.0	.111	0.13	0.082	--	Cost based on sodium silicate and boric acid
Wood (oak, maple)	0.7	.042	3.8	1.67	4500	
Masonite	1.3	.078	10.0	8.10	--	

[redacted]

5.0 Cost Data

A great many cost data are included in the following tables, which have been turned up in the work at ORNL; no guarantee is attached to any of them. Some were personally obtained by phone or letter. Some are from the ORNL purchasing or store departments. Some from Iron Age, Chem and Eng News, and Oil, Paint and Drug Reporter. Some are from UCRL-266 by E. H. Covey. All apply only to a certain region of the country and a certain date of inquiry.

A great deal of suspicion should greet every cost estimate, whatever its origin. A shielding block of special composition, costing 26¢, should not be discarded in favor of one costing 13¢, if the sole reason is that "it costs twice as much". It will cost $3 to place the brick; the material and fabrication cost of the brick itself will in most cases prove negligible.

Similarly with the case of the 2 x 4 x 8 inch steel brick, containing 62¢ worth of metal. The first estimate for 10,000 such bricks, chrome plated, was $9.00 each. Repeated and intensive follow-up brought estimates of $5.50, $3.90, and finally (for a galvanized brick) $1.45 and then $1.25. On 10,000 brick, a saving of $77,500 on a $12,500 final order could be achieved by a few phone calls.

UCRL-266 quotes 99.9% Mn at $30/lb in quantity; Electromanganese Corp. in Knoxville quotes the same purity at 30¢/lb. Similarly with tungsten, boron, and other raw materials, where variation of ten- to one hundred-fold are seen. These examples are quoted to drive home the point that a scientist or engineer cannot rely on casually-gathered cost data to guide him in utilizing or abandoning a given material for large quantity usage.

Table IV - Properties of Various Boron Vehicles

Material	g B/cc	%B	Total density	$/lb B	$/lb total (large lots)	Other elements g/cc	Remarks
Crystalline B, theoretical density and purity	2.33	100	2.33	150	150	--	Cost estimate for tonnage lots, 99% purity
Crystalline B, hot-pressed with B_2O_3	2.00	98 max.	2.04	--	--	--	
Amorphous B, hot-pressed with B_2O_3	1.8	80	2.3	20	15	Mg and C impurities	Quality could probably be improved
B_4C, Norton Abrasive Grade	2.0	80	2.5	~9	~7	<1% impurities	Cost decreases with quantity
B_4C, Norton Metallurgical Grade	1.8	78	2.3	~6	~4.5	Some Fe, C	
$B_{10}H_{14}$ (a paraffin-like material)	0.83	88.4	0.94	(high)	(high)	0.108H	Only gram lots presently available
Boral (1/4 inch sheet and Al wrapper)	1.012	40.	2.5	7.50	~3	1.3 Al, 0.25 C	Can be made in thousand ft^2 lots
Boroxal (1/4 inch sheet and Al wrapper)	0.305	15.	2.0	1.33	~0.20	1.0 Al, 0.7 O	Still experimental, though easily fabricated
B_2O_3	0.575	31	1.85	0.485	~0.15	1.3 O	Highly hygroscopic
Colemanite	0.0606	16.	2.3	0.234	0.038	0.056H	
Ammonium Pentaborate	(0.40)	20.	(2)	0.530	0.106	0.074H	$(NH_4)_2B_{10}H_{16}\cdot 5H_2O$
Borax	0.197	11.4	1.73	0.155	0.018	0.092H	$Na_2B_4O_7\cdot 10H_2O$
Boroffin (20% B_2O_3)	0.062	6.2	1.0	1.39	0.086	0.089H	
Sat'd H_3BO_3 soln. in H_2O (3%)	0.0093	0.93	1.0	0.272	0.0014	0.119H	
M1 cement (magnesium oxychloride plus colemanite)	0.0845	4.45	1.90	0.655	0.0281	0.072H	
Ferroboron	(1.0)	~20.	(5.0)	7.50	1.50	Fe, C,	Density assumptions made - see HKF-3 (Secret) for B-steel
Boron Steel	(0.152)	~2.0	(7.6)	(8.00)	(.16)	Fe, C, Mn	
Lead borate glass (assumed 60% PbB_2O_4 40% B_2O_3)	0.627	16.8	3.73	--	--	--	
Scrap pyrex glass	0.104	44.0	2.6	1.48	.06	--	1947 price quotation from Corning
Boron plastic, Monsanto	0.081	3.8	2.14	--	--	0.078H	Cellulose Acetate and zinc borate
Boron plastic, ORNL (to be reported)	1.07	67	1.6	--	--	0.027H	Tygon and B_4C

[redacted]

6.0 Conclusions

Better shields can be built for small fractions of the '42-'49 costs...heavy concrete used in the early 30's not new development

6.1 Construction

Monolithic most versatile...tolerances set cost...plywood forms, inserts shimmed by field survey crews, recommended for 1/32 inch...don't bore, flamecut...conventional handling equipment OK up to twice normal density...consider pumpcrete...vibration placement of steel aggregate directly into forms strongly recommended for very dense aggregate...can get over 400 lb/ft^3

Block shields cheap, convenient...steel bricks recommended for lead (save 80%)...normal concrete blocks good, heavy concrete blocks usually unsatisfactory...cast iron and aluminum bricks generally undesirable...square cans with water, pitch, etc. good for neutrons...laminated structures expensive...multi-ton prefab blocks offer unique advantages

Iron "thermal shields" have disputable value..."Boral" (B_4C-Al) is good but expensive..."Boroxal" (B_2O_3-Al) nearly as good, cheap as aluminum..."Boroffin" (B_2O_3-paraffin) useful for experimental work

6.2 Aggregates

Correct grading will increase density, as well as strength, workability and uniformity...ores, slags, metal, make good aggregate, if dense, cheap, strong, non-porous, and compact...ferroalloys provide tonnage source of scarce elements...boron-coating aggregate may be important.

6.3 Cements

Hydrogen, strength, and density desirable...but quantitative importance of these unknown...magnesium oxychloride and other metal oxyhalides thoroughly studied...portland and similar cements also well known...portland may be considerably better than formerly assumed...can be made to hold large quantity of water...metal-water shield possible in many cheap structures...porous metal, water cooled, cheap substitute for hydrides.

6.4 Cost Data

Must study entire situation, cannot reply on "pure data" from someone unfamilar with problem...ten- and hundred-fold errors may result.