CHAPTER 10

Shielding Considerations

When a nuclear ship reactor generates useful heat for propulsion power, it generates also harmful radiation. The principal forms of this radiation are neutrons and gammas. Different shielding materials are required against each. On shipboard, the shielding structure has to conform to a variable configuration of plating and framing, and to numerous penetrations necessary for operation and maintenance of the reactor. To meet these practicalities, water, lead, and iron are the "common three" shielding materials used. Where it is impractical to use these common materials, various combinations of other materials are used. But even under the best circumstances, the fabrication and installation of shipboard shielding is complex, and the guarantee against radiation leakage is difficult. Possible simplifications might accrue from the use of heavy liquids which provide simultaneous attenuation of both neutrons and gammas. To appraise the possibilities involved, we should first investigate the mechanisms of nuclear attenuation.

10-1 Fission Source Radiations

For every fuel atom fissioned in a reactor core, there emanate approximately 2.5 neutrons and 10 gammas. The neutrons originate predominantly from fission. The gammas, however, originate from three sources, namely: (1) fission, (2) fission product decay, and (3) neutron activated materials. When we realize that it takes 3×10^{16} fissions per sec to produce 1 MW of heat power, identifying the number and source of these neutrons and gammas becomes rather impractical. They all intermix and each has equal probability of flight in any three-dimensional direction. Thus, the shielding system outside of the core sees one big ball of nuclear radiation.

The intensity of this radiation is indexed by its energy. A broad spectrum of energy is involved, since neither the neutrons nor the gammas radiate from any pre-selected energy level. The neutrons, for example, spread from 0 to 15 Mev; the gammas from 0 to 10 Mev (see Table 10-1). The weighted total energy of neutrons (per fission) is approximately 5 Mev as compared with about 15 Mev of gammas. Thus, there is a greater radiation energy from gammas than from neutrons, by a ratio of approximately 3 to 1. This energy ratio is increased when we take into account neutron absorption in the reactor core.

The neutrons, we recall (Sec. 1-7 and 1-8), are the productive mechanisms of fission. Consequently, considerable design effort is applied toward using the neutrons for the production of fission heat and toward preventing their escape from the core. In practice, however, about one-half neutron per fission gets out and this comes primarily from the high-energy end of the neutron spectrum (i.e., above 2 Mev). On the other hand, since gammas do not produce fission, they are of little concern in reactor core design. We can assume, therefore, that all but the softest gammas (i.e., below 1 Mev) will escape. As a net result, a 5 to 1 energy ratio of gammas-to-neutrons must be shielded against.

Table 10-1. Fission Energy Spectrum of Neutrons and Gammas

Energy, Mev	No. per Fission
Neutrons	
0 - 2	1.5050
2 - 4	.4725
4 - 6	.2075
6 - 8	.0505
8 - 10	.0114
10 - 12	.0024
12 - 15	.0006
Gammas	
0 - 2	9.3100
2 - 4	.7500
4 - 6	.0990
6 - 8	.0154
8 - 10	.0029

Ref: Introduction to Nuclear Engineering, R. Stephenson, McGraw-Hill, 1954, p. 209.

To a first approximation, we can assume that all radiation stems from a point-source in the geometrical center of the reactor core. At any distance "r" from the center, the radiation will pass through a spherical surface of area $4\pi r^2$. Accordingly, the incident radiation flux I_o becomes

$$I_o = \frac{3 \times 10^{16} \times P \times E}{4\pi r^2} \text{Mev/cm}^2\text{-sec} \qquad \text{[Eq. 10-1]}$$

$$= 2.6 \times 10^{15} \times P \times E \times \frac{1}{r^2}$$

where P is core power in MW, E is energy of radiation in Mev, and r is distance in cm.* In effect, the radiation "spreads out" at distances farther

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* Because nuclear core and shielding design are fundamentally physics phenomena, physics units of measure (grams-centimeters-seconds) are more generally used than engineering units (pounds-feet-hours).

and farther from the fission source. The corresponding flux intensity I_0 becomes less and less . . . by the factor $1/r^2$. This assumes no shielding of any kind.

10-2 External Source Gammas

The foregoing discussion pertains to radiation originating from the reactor core only. One of the complicating characteristics of nuclear shielding is that gammas *originate* also from sources *external* to the reactor core.

There are two types of external source gammas, so-called: "inelastic gammas" and "capture gammas." Both types of gammas are the result of neutron interactions with materials outside of the fission region of the core. Consider the *SAVANNAH*, for example: the external (to the core) gamma-emitting materials would be the steel thermal shields placed between the core and the reactor vessel inner wall, the reactor vessel wall itself, and the steel shielding structure (see Fig. 10-1).

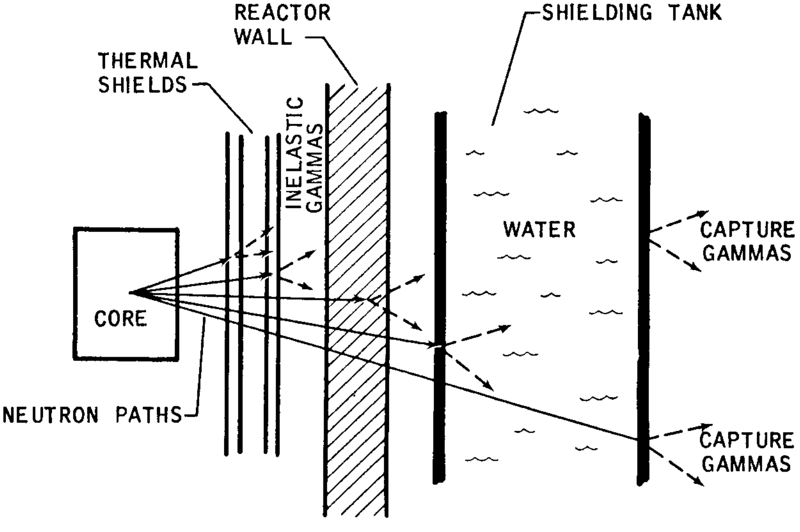

Fig. 10-1 Typical Neutron Induced External-to-Core Gamma Sources

Inelastic gammas result when a fast neutron strikes a heavy atom and the neutron is deflected. The term "inelastic" means that the energy of the neutron after deflection is not conserved (some is lost), and that the energy lost is re-radiated in the form of gamma rays. Capture gammas, on the other hand, result when a neutron is captured outright by an atom of material. In the capture process, there is a rearrangement of nuclear particles which results in there being considerable excess nuclear binding energy. This excess energy is released to the environment in the form of gamma rays. The emission of these capture gamma rays is a half-life phenomenon which may last minutes, hours, days . . . or years.

The important difference between inelastic and capture gammas is their energy content. The energy of inelastic gammas rarely exceeds 1 Mev, whereas the energy of capture gammas frequently goes as high as 10 Mev. Furthermore, capture gammas occur in just about every material known, whereas inelastic gammas occur in only certain materials. Consequently, we need concern ourselves principally with capture gammas. We are particularly concerned when these capture gammas originate in the outermost materials of the shielding system (see Fig. 10-1 again).

To appreciate the complexity of capture gammas—and the difficulties which they cause to shipboard shielding design—Table 10-2 is presented.

Table 10-2. Capture Gammas from Type 347 Stainless Steel

Composition	Wt. %	Neutron Absorption per Atom	Max. E-gamma	Half-Life
Chromium	18	2.9	9.7	—
Nickel	11	4.8	8.9	Many Years
Manganese	2	12.6	7.3	2.6 Hrs
Silicon	1	0.16	10.5	—
Niobium	0.8	1.1	7.0	Many Years
Copper	0.2	3.6	7.9	12.8 Hrs
Tantalum	0.1	21.3	6.1	117 Days
Phosphorus	0.04	0.19	8.8	14.3 Days
Cobalt	0.04	34.9	7.5	5.3 Years
Sulphur	0.01	0.49	8.6	—
Iron	Remainder (65 to 70)	2.43	10.2	—
Lead	(for comparison)	0.17	7.4	3.2 Hrs

This table represents the maximum energy of capture gammas from a typical structural material used aboard ship (namely: type 347 stainless steel). Take particular note of nickel and niobium. These constituents are added to structural materials to improve their corrosive resistance and high temperature properties. Yet, these constituents become a major source of capture gammas which last for a significant number of years. Note also the high energy of the capture gammas.

10-3 Attenuation of Neutrons

For our purpose, the "shielding system" consists of all materials *external to the fission core* itself. This means that the reactor vessel walls, for example, are part of the shielding system. Nuclear radiation will impinge on this system, and will be attenuated (i.e., degraded in energy) in accordance with certain characteristic behavior. The behavior is entirely different for neutrons than it is for gammas. Since the attenuation of neutrons is the more complex mechanism, we shall trace neutron attenuation first.

A neutron is degraded in energy only by interactions with the atomic nucleus of matter. The degree of attenuation varies for each class of nuclei encountered (see Fig. 10-2). Recall that upon fission, a neutron speeds out fast and has to be slowed down (moderated) before it can be re-used again. Though we desire that this happen in the core, the moderation process also takes place in the shield system.

A fast neutron escaping from the reactor core will "see" preponderantly the heavy nuclei of the shielding materials. Upon striking a heavy nucleus, the fast neutron will be deflected—and simultaneously attenuated—by inelastic scattering. This form of scattering is like a small, hard sphere bouncing off of a large, soft one. The two stick together momentarily, then part with some redistribution of the incident neutron energy.

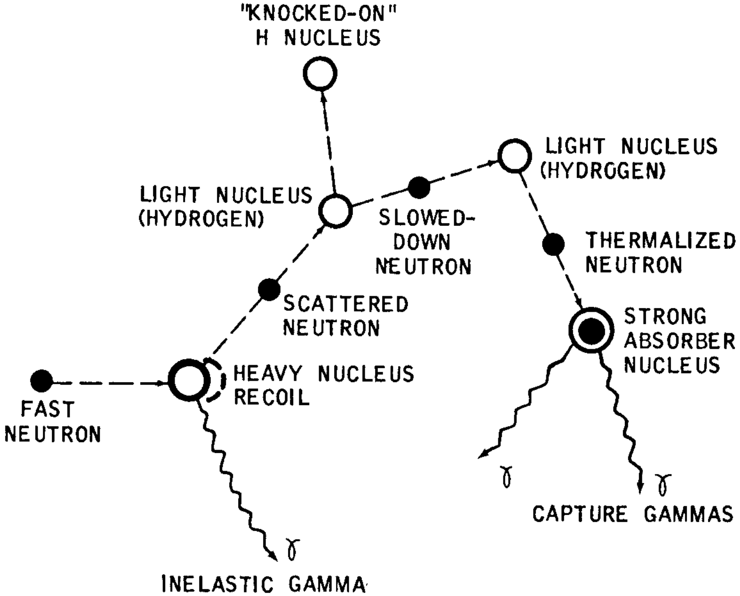

Fig. 10-2 Typifying the Mechanisms of Neutron Attenuation

When the inelastically scattered neutron is reduced to below 2 Mev, it subsequently experiences attenuation by elastic scattering from light nuclei . . . notably hydrogen. Elastic ("billiard ball") scattering is characterized by the fact that the mass of the struck nucleus (hydrogen) nearly equals that of the incident neutron. Thus, there is the greatest possible energy transfer from the moving neutron. Neutrons continue to be elastically scattered until thermalized in the shielding system.

Upon thermalization, the neutron wanders through the shielding system until it is captured by a vicinity nucleus. All shielding nuclei will capture thermal neutrons but in some materials (e.g., boron, cadmium, gadolinium), the capture probability is pronounced. When a thermal neutron is finally captured, it no longer can impart its kinetic energy of motion. What happens, however, is that the nuclear particles in the capturing nucleus become "excited" due to the presence of the intruder (the thermal neutron). This raises the nuclear binding energy of the capturing nucleus to the level where capture gammas are emitted.

It is significant to note that the energy content of the capture gammas is far in excess of that of the incident thermal neutron. Iron, for example, will capture a 0.03 ev neutron, and in turn will re-emit 6 to 7 Mev of capture gammas. This is a gamma energy increase of 200 million times!

10-4 Attenuation of Gammas

We should now note that the total gamma radiation impinging on a shielding system consists of three types; namely: (1) core gammas, (2) inelastic gammas, and (3) capture gammas. The result is a complex array of polyenergetic gamma radiation. Because gammas are negligible in mass, and are electromagnetic in character, they interact preponderantly with the *electrons* of matter. Electrons also are of negligible mass and electromagnetic in character. So the exchange of energy from gammas to electrons is a natural preference.

The number of electrons orbiting around the atomic nuclei of matter is proportional to the density of each shielding material. The greater the density, the more electrons there are available to attenuate the gammas.

Gammas are attenuated by four mechanisms, each of which is a function of the incident gamma energy and of the electron density of the attenuant material. These mechanisms are as follows:[*]

(1) Fluorescence (photoelectric effect)	~ 1 Mev
(2) Scattering (Compton effect)	~ 1-5 Mev
(3) Annihilation (pair production)	~ 5-10 Mev
(4) Bremsstrahlung (re-radiation)	~10 Mev

Processes (1), (3) and (4) exchange all of the incident gamma energy to the interaction electrons. These electrons in turn travel through the attenuating medium until they are stopped by friction. Process (2)—Compton scattering—results in an exchange of only part of the energy of the incident gammas. Consequently, the 1-5 Mev gammas are scattered back and forth many times. These Compton-scattered gammas may experience as many as 10 successive scatterings before they are completely attenuated.

The Compton scattering of gammas produces annoying uncertainties in gamma shielding calculations, particularly in the 1-3 Mev range. This results from two factors. One, the bulk of gamma radiation is in the 1-3 Mev range, with the consequence of a multiplicity of Compton gammas being scattered back and forth, called "buildup." Secondly, it so happens that all dense materials are gamma-transparent in the 1-3 Mev range. This means that, if possible, we should try to avoid the buildup of gammas at these energies.

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[*] Ref: "Gamma-Ray Attenuation, Part I—Basic Processes," U. Fano, *Nucleonics*, Aug., 1953, pp. 8 ff.

To get some feeling for the gamma-stopping ability of materials, Fig. 10-3 is presented. This figure is a generalized composite of the four gamma attenuation processes listed above. In general, the attenuation effectiveness of shielding materials decreases with increasing energy of incident gammas—to some minimum value—then rises gradually thereafter. At all energies, however, high-density materials—with their many electron clouds—are the most effective gamma attenuants.

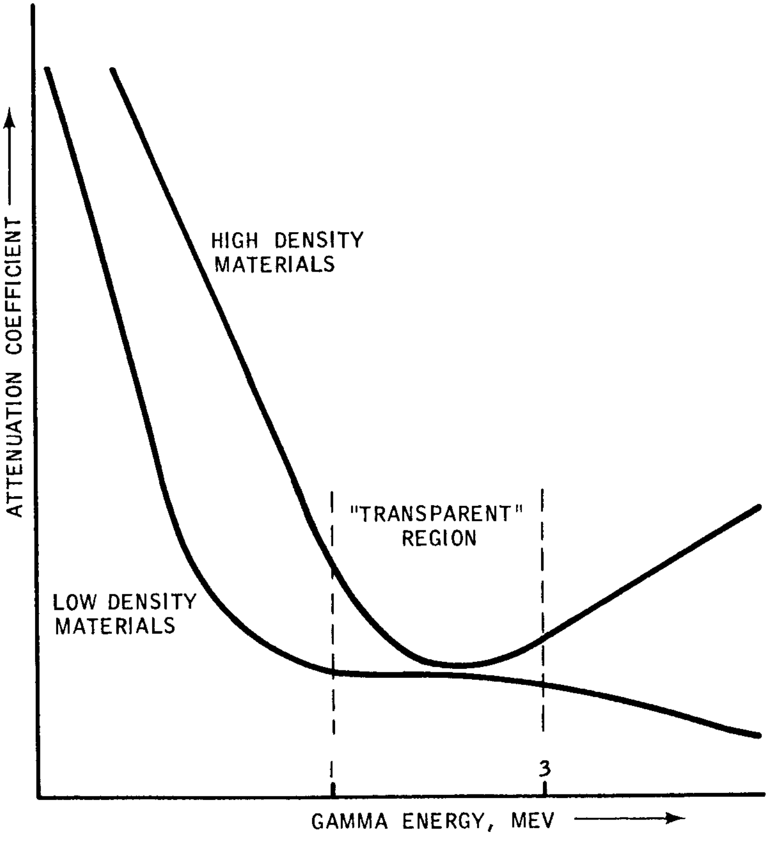

Fig. 10-3 Composite Attenuation Capability of Gamma Shielding Materials

10-5 Attenuation Coefficients

The probability of attenuation events is indexed by the nuclear cross section of absorption by each component of the shielding system. The term "cross section" here is an effective interaction between incident radiation and atomic matter, based on wave phenomena. This nuclear absorption cross section is a function of two factors, namely: (1) the energy content of the incident radiation and (2) the shielding material itself.

Thus, for each material in a shield, there is a separate energy spectrum of attenuation probability.

In the literature on shielding technology we shall run across two types of nuclear absorption cross sections. One is called the microscopic cross section (on a *per atom* basis) and the other, macroscopic cross section (on a *per cm*^{3} basis). The two are related as follows:

[Eq. 10-2]

$$\Sigma = N\sigma$$

where

Σ = (cap sigma) macroscopic cross section, cm^{-1}
σ = (small sigma) microscopic cross section, cm^2
N = number of atoms of material per cm^3

We can find N, in turn, in terms of

[Eq. 10-3]

$$N = \rho N_a/A$$

where

ρ = density of material in g/cm^3
N_a = Avogadro's Number (6×10^{23})
A = atomic weight, or mass number

Because all shielding calculations deal with unit volume attenuation, Σ is the principal index of interest. Because of its importance, it is referred to synonymously as "attenuation coefficient," "absorption coefficient," "removal coefficient" . . . and, possibly, other terms. There is a Σ-value for fast neutrons (Σ_R), for thermal neutrons (Σ_n), and for gamma rays ($\Sigma\gamma$). This last symbol $\Sigma\gamma$ is frequently found in the shielding literature as μ (mu). And to make things more symbolically complicated, the gamma term "mass absorption coefficient" is frequently used: μ/ρ. We shall try to stick to the use of Σ_R's, Σ_n's, and $\Sigma\gamma$'s in the hope of simplifying comparative shielding attenuations. We may also use Σ without a subscript to signify general attenuation concepts.

10-6 Common Shielding Materials

From the discussions in Sec. 10-3 and 10-4, the mechanisms of nuclear attenuation are such that **different materials** are required to **shield against each type of radiation.** To shield against fast neutrons, we need a heavy material; to slow neutrons down, we need a light material; and to finally capture the thermal neutrons, we need a high-capture material, preferably one which releases a minimum of capture gammas. To shield against gammas, we need a heavy material, preferably one which minimizes the buildup of Compton scattering in the 1-3 Mev range. Obviously, no one material could possibly satisfy all of these requirements, so we must resort to a *combination* of materials.[*]

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[*] Ref: "Shield Engineering," T. Rockwell, *Reactor Shielding Design Manual,* USAEC TID-7004, 1956, pp. 169 ff.

The most common combination of shielding materials that we could use is: water, lead, and iron. If we had no other shielding materials than these, we could do a pretty fair shielding job.

Water is an effective shield against moderate-energy neutrons. It is not particularly ideal against fast neutrons, and when it captures thermal neutrons, it releases capture gammas at 2.2 Mev. We contain the water in steel tanks. This is fortunate because the iron in the steel is quite effective against fast neutrons . . . and will shield against gammas, too. Iron is not ideal for gammas, but it will do. So, water-in-tanks, if thick enough, will do about any neutron shielding job we would want. The tank wall nearest the reactor core would cut down the fast neutrons; the water inside the tank would thermalize the neutrons . . . and would capture them also. The tank wall farthest from the reactor core would then annihilate the capture gammas from the water.

Lead is about the best natural gamma-shielding material there is. Oh, we could do better with uranium, but this is more useful as a nuclear fuel than as a nuclear shield. We could also do better with tungsten, but this is a very high cost material. So, lead is about it. But lead won't stand on its own, structurally, at temperatures above 150°F. Therefore, the lead must be bonded to steel, or it must be "canned." In either case, considerable fabrication care is required, and this detracts from the virtues of lead. Furthermore, lead captures thermal neutrons and re-emits capture gammas up to 7 Mev. This is better than its support structure (steel), which captures thermal neutrons about 20 times more readily and re-emits capture gammas up to 10 Mev.

In brief, then, water is a good neutron shield, primarily because its hydrogen content (6.7×10^{22} atoms/cm^3) ranks high. Hydrogen is the greatest neutron moderator-attenuant of all materials. This is because hydrogen has approximately the same mass as a neutron, whereupon each neutron-hydrogen interaction results in an optimum degradation of neutron energy. But water is not a good gamma shield. However, lead is a good gamma shield, but a poor neutron shield. Iron is between water and lead. It is a better fast neutron shield than lead; a better gamma shield than water.

On the basis of fast neutron attenuation, the "common three" shielding materials rank as follows:

	Σ_R	
Water	0.098	cm^{-1}
Lead	0.116	cm^{-1}
Iron	0.169	cm^{-1}

Thus, for an equal thickness, iron is 1.5 times more effective against fast neutrons than lead; for an equal weight, iron is 2.2 times more effective.

Of particular note is the fact that Σ_R is essentially constant for all neutron energies beyond 0.5 Mev.* Below this energy (which gets into

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* Ref: "Shield Materials," S. Glasstone, *Principles of Nuclear Reactor Engineering*, Van Nostrand, 1955, pp. 586 ff.

the thermal neutron range: Σ_n), iron and lead are "transparent" to neutrons. Water, then, has no competition as a thermal neutron shield.

On the basis of gamma attenuation, the "common three" rank as shown in Fig. 10-4. Note that the attenuation coefficient, $\Sigma\gamma$, varies with incident gamma energy. Note, also, that water is out of the competition as a gamma attenuant. The Fig. 10-4 curves include the effect of Compton-scattering buildup.

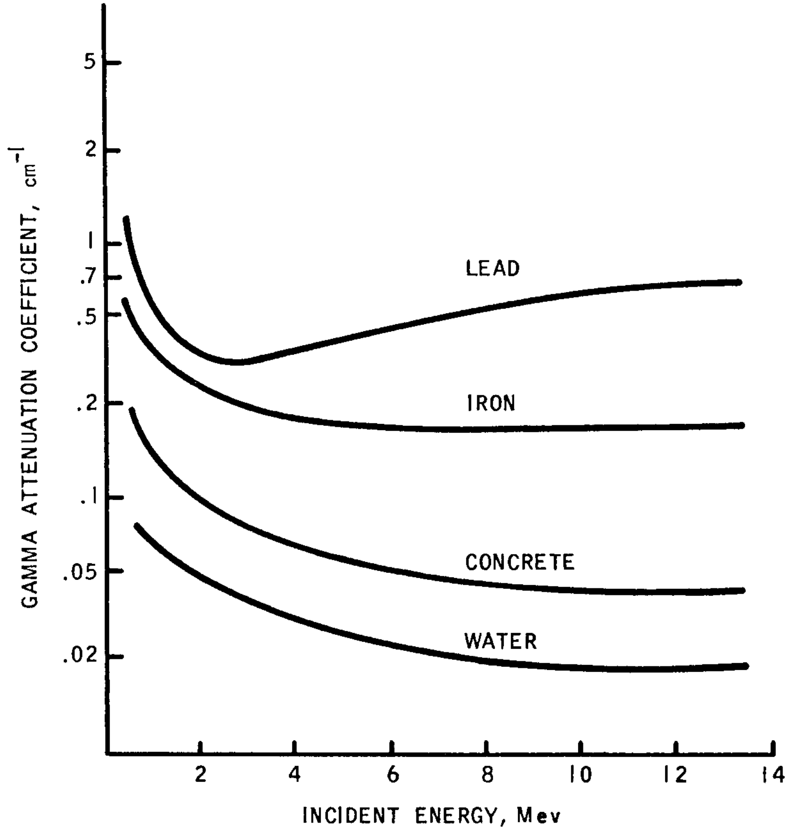

Fig. 10-4 Gamma Attenuation versus Incident Energy for Common Shielding Materials

10-7 Other Shielding Materials

Because the "common three" are not all-perfect, we attempt to use additives or alternate materials to improve a shielding design. For example, the hydrogen in water, upon capturing a thermal neutron, emits 2.2 Mev capture gammas. To lessen the effect of these capture gammas, boron can be added. This may be in the form of boric acid, borax, or other borate compounds. A boron additive is advantageous because, when a thermal neutron is captured, an alpha particle is given off, together with a weak (0.5 Mev) gamma. The capture alphas-plus-gammas from boron are much more easily stopped than the 2.2 Mev gammas from hydrogen. So, "borated water" is an improvement over ordinary water.

In those cases where it is desired to capture all stray thermal neutrons (e.g., the neutron shield around the UF_6 bottles in Fig. 9-3), the boron compound "boral" has become quite common. This is a sandwich plate mixture of boron carbide (B_4C) powder and aluminum, fabricated into thin sheets. It is very effective in capturing thermal neutrons. It will not thermalize (moderate) neutrons, so, consequently, it is placed outside of a water shield.

Where it is not practical to use water as a neutron shield (e.g., shielding around and above control rods), there are a number of solid hydrogen-containing materials that can be used. These are in the form of plastics and light metal hydrides. Their relative neutron thermalization is indexed by their hydrogen content compared with water (see Table10-3). Provided the shielding environment temperature is not much above 150°F, plastics, particularly polyethylene, are good substitutes for water. Where the temperatures are higher, the light metal hydrides, such as lithium hydride, have to be used, even though their hydrogen content is less than that of water.

Table 10-3. Hydrogen Content of Solid Neutron Shields Compared with Water

Material	Comparative H-content
Water	1.00
Paraffin	1.39
Polyethylene	1.18
Rubber (synthetic)	1.15
Rubber (natural)	0.97
Lucite	0.85
Lithium Hydride	0.85
Polystyrene	0.75
Zirconium Hydride	0.75
Calcium Hydride	0.73
Yttrium Hydride	0.63

Where the temperature gets high enough that the lead on the gamma shield begins to sag, one of three courses is open. Either we must: (1) use a greater thickness of steel structure; (2) use a commercially prepared heavy metal solid (e.g., with tungsten or nickel as a base); or (3) use a heavy molten metal such as lead-bismuth. Mercury also could be used. These molten metals would have to be contained in tanks, of course, with protection against their toxicity. Any of these heavy metal alternatives would provide good gamma and good fast neutron shielding. They would not do as neutron thermalizers: no hydrogen.

Where shielding fabrication difficulties arise, such as at ships' double bottom tanks, at cofferdam tanks, at curved surfaces interrupted by framing, and at piping and ducting, concrete has much in its favor.* Because it contains hydrogen and heavy additives, it is pretty much an all-purpose shielding material. It is relatively cheap; it is structurally useful, particularly as an anti-collision shield; it is quite versatile; it can be poured into almost any form desired and the additives can be a wide variety of barytes, iron punchings, or boron frits; all of these increase its density. As a gamma attenuant, heavy concrete compares favorably with lead and iron (see Fig. 10-4 again).

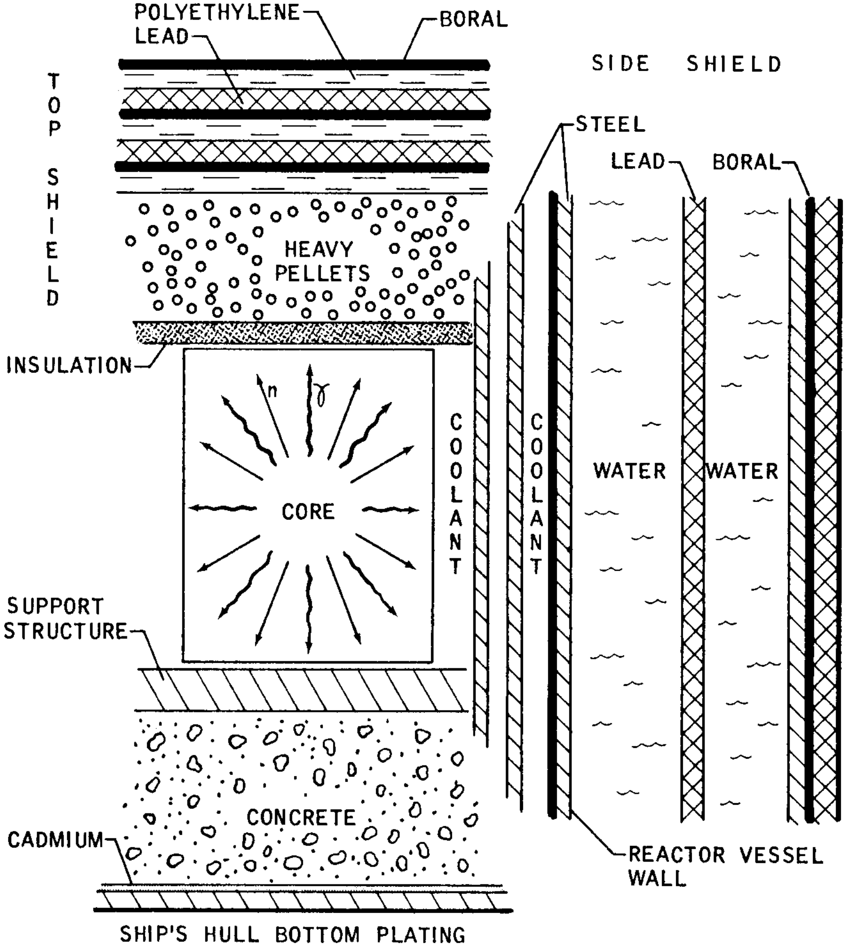

Fig. 10-5 Representative Combination of Various Shielding Materials

Though highly advantageous, heavy concrete is not a shielding cure-

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* Ref: "Concretes" in *Reactor Shielding Design Manual,* T. Rockwell, USAEC TID-7004, 1956, pp. 177 ff.

all. And the long-term operational effects of its installation aboard ship have not been determined. In intricate shielding configuration areas, mixing and pouring become difficult problems. The uniformity of aggregate distribution upon settling and the uniformity of aggregate size are uncertain. It dries with close to 15% void space. It is thermal-stress sensitive. For example, gamma heating as little as 100 Btu/ft^2 hr will raise its temperature 50°F. As its temperature increases, its hydrogen is driven out. To avoid this, special cooling is required. For these and other reasons, concrete shielding on shipboard is relegated to secondary shielding, such as external to the reactor containment shell where it also serves as a damage shield (recall Sec. 6-10).

Another form of all-purpose shielding is that of pelletized materials. These materials consist of compacted powders of a high density material, a hydrogenous material, and a high thermal-neutron capture material; for example, a blending of lead, titanium hydride, and boron. The powder mix is pressed (at about 160,000 psi) into ½-inch diameter pellets. The shielding pellets can be dumped into any size-shape shielding container and the void space filled with an organic material or hydrogenous liquid. Not too much development work has been done on pelletized shielding for nuclear ships.

To optimize the primary shielding aboard ship, it is necessary to combine many types of materials. This is typified in Fig. 10-5. Each material is used in that location where, for practical installation reasons, the maximum radiation attenuation is achieved.

10-8 Calculational Approximations

The basic principle by which neutrons or gammas attenuate through shielding materials is the exponential relationship

[Eq. 10-4]*

$$I_x = I_0 e^{-\Sigma x}$$

where

I_x = attenuated radiation at point x
I_0 = initial radiation impinging on shield, point o (recall Eq. 10-1)
Σ = attenuation coefficient, cm^{-1} (may be Σ_R, Σ_n, or Σ_γ as discussed in Sec. 10-5)
x = thickness or distance through shield, cm

This relationship holds for thin, homogeneous shields (i.e., all materials uniformly mixed together) against point source radiations. Furthermore, these radiations must be well collimated into a narrow beam without scattering or buildup of any kind. Though based on these idealized concepts, Eq. 10-4 is one of the most useful relationships for shielding design.

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* Ref: *Introduction to Nuclear Engineering*, R. Stephenson, McGraw-Hill, 1954, p. 177.

When Eq. 10-4 is rearranged to the more convenient form

[Eq. 10-5]

$$\Sigma x = \ln \frac{I_0}{I_x}$$ *

much qualitative information becomes apparent. For example, if we want to minimize x—the shielding thickness—Σ should be as large as possible for a specified attenuation ratio I_0/I_x. The fact that Σ varies with the energy of incident radiation (for a given material) means that x also will vary with energy. The fact that Σ for fast neutrons (Σ_R) is different from Σ for thermal neutrons (Σ_n), which is different also from Σ for gamma rays ($\Sigma\gamma$)—for the same material—means that x will vary with the type of incident radiation. These observations suggest that in order to simplify x-calculations, a shielding system should be sought which gives as large an all-purpose Σ as possible.

In practical shipboard shields (recall Fig. 10-5), the idealizations of Eq. 10-4 begin to fade. The shields are not thin; they are not homogeneous; the radiation does not originate from a "point source"; and there are no "well-collimated" radiation beams. Obviously, the fission core is a volume source (not a point source) from which radiation emanates non-uniformly . . . in spreading-beam fashion. During attenuation events in the shielding system, the radiation tends to degrade in energy on one hand, and tends to build up on the other. This non-uniformity of attenuation is brought about by structural features of the shield, by penetrations through it, and by cracks, voids, and irregularities in shield fabrication. The net effect of these practical considerations is that certain corrections must be applied to Eq. 10-4 before it is useful in predicting approximate shield material thicknesses.

10-9 Corrections to Shield Equations

We have already mentioned the buildup of gammas due to Compton scattering (Sec. 10-4) and to this we must add the buildup due to capture gammas. These capture gammas originate from a multitude of unpredictable point sources within the shield. Also, neutron energies tend to build up. This neutron buildup results from a tendency for the energy-spectrum of neutrons to "harden" as the neutrons progress through the shielding system. The initial and final attenuation events (of both neutrons and gammas) occur everywhere in the shielding materials. As a result, no satisfactorily analytical method yet has been developed for appraising a correction factor to be applied to Eq. 10-4, to account for radiation buildup (B). Recourse, therefore, must be taken to experiment and to the tedious recording of buildup data . . . for each type of shielding material.

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* Ln = natural logarithm.

A similar practicality is true for appraising a geometry correction factor (G) to be applied to Eq. 10-4. A compendium of geometry corrrection equations for every conceivable shape of radiation source can be found in the footnote reference.* When using the reference equations, one has to take into account such experimentally observed phenomena as neutron "streaming" and gamma "backscattering." An uncanny feature about neutrons is that they are able to find cracks, leaks, and structural framing paths by which they can literally stream through the shield unattenuated. Gammas sometimes get out of the shield and will scatter back toward it. This backscattering arises from material external to the shield, such as machinery, piping, hull plating, etc. Because there are so many practical consequences, much of the G-data must be obtained from experimental mock-ups of the shielding system.

Now, by applying both G and B correction factors, Eq. 10-4 evolves into the form

$$I_x = I_0 G B e^{-\Sigma x} \qquad \text{[Eq. 10-6]}$$

But G and B factors are not all. Each time a neutron or gamma experiences a non-absorption attenuation event (i.e., when it is scattered), it is degraded in energy. The exact amount of scattering energy loss is dependent upon the initial energy, the angle of incidence, the angle of deflection, and the type of attenuant material. This happens every $1/\Sigma$ in path length (called "mean free path" between attenuation events). Since Σ is energy-dependent (recall Sec. 10-5), each attenuation event results in a new value of Σ. Consequently, Σ is not constant throughout the shield.

For computing the total shield thickness, we have to take into account the changing values of Σ: for each type of radiation; for each type of material. We may show this in the form

$$I_x = I_0 G_0 B_0 e^{-\Sigma_0 X_0} + I_1 G_1 B_1 e^{-\Sigma_1 X_1} + I_2 G_2 B_2 e^{-\Sigma_2 X} \text{ etc.} \qquad \text{[Eq. 10-7]}$$

where 0, 1, 2 . . . are incident, first, second and all subsequent attenuation events.

Because of the laborious and repetitious nature of the Eq. 10-7 computations, it is necessary to resort to the use of electronic computers. Because of the chance nature of attenuation events, computer calculation techniques are fondly called "Monte Carlo" and "Russian Roulette."

10-10 Heat Generation and Radioactivation

Eventually, all of the energy-equivalence of the radiation attenuated by a shield is converted into heat. This is new heat generated in the shielding materials themselves; it is not thermal heat radiated from the fission core. This shield-generated heat arises, in part, from the friction of recoil by

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* Ref: "Effect of Geometry of Radiation Source," T. Rockwell, *Reactor Shielding Design Manual,* USAEC TID-7004, 1956, pp. 347 ff.

attenuant nuclei and electrons (recall Fig. 10-2) and, in part, from the friction of ionization of the attenuant molecules. Ionization is a form of secondary radiation whereby the neutrons and gammas split up the shielding material molecules into positive and negative—called "ionized"—particles. Then, these ionized particles move through the shielding material until they are stopped by friction.

The heat generated in the *shielding system* (recall definition Sec. 10-3) can represent up to as much as 9% of the total heat generated by the fission core (see Table 10-4). This can result in overheating of the shielding materials and structural parts nearest to the core. To prevent overheating of the shielding structure, the practice in *SAVANNAH*-type reactors is to position "thermal shields" between the core proper and the reactor vessel walls. In this position, the thermal shields absorb the largest percentage of the nuclear heating and, upon doing so, they can be conveniently cooled by the same primary coolant that flows through the reactor core.

Table 10-4. Distribution of the Total Heat Energy of Fission

PER FISSION EVENT

Particle Type	Mev*	Core	Shield (Operation)	Shield (Shutdown)
Fission fragments	168	168	--	--
Fission neutrons	5	3	2	--
Fission gammas	5	1	4	--
Capture gammas	7	1	6	--
Decay gammas	7	3	4	4
Decay betas	6	6	--	--
Capture decay	2	--	2	2
	200 Mev	182	18	6
% of total		91%	9%	(3%)

*Ref: Principles of Nuclear Engineering, S. Glasstone, Van Nostrand, 1955, p. 24.

Outside of the reactor vessel—using the *SAVANNAH* as an example again—the primary shielding water, in addition to being heated, becomes radioactivated. This radioactivation is caused by neutrons in the same manner as radioactivation of the primary coolant water (recall Sec. 5-12). To minimize the accumulation of this radioactivation, it is necessary to circulate a portion of the shielding water through the same purification system as the primary coolant water (recall Sec. 6-3).

In all reactor types, heat generation and radioactivation of the shielding materials take place. If solid materials are used, provision must be made for cooling the shield and for purifying the cooling medium used.

When the reactor is shut down, or, more likely, reduced to negligible neutron level, about 3% of shielding heat continues to be generated (Table 10-4 again). This heat is generated by the attenuation of decay betas and gammas from the core fuel elements, and by the attenuation of long-lived capture gammas from the shield materials. As an over-all result, even when a reactor is shut down, its shielding system has to be cooled.

10-11 Irregularities in Shields

For proper operation and control of the reactor, it is necessary that ducting, piping, wiring, rodding, access openings, etc., penetrate the shielding system. For effective installation and structural support of the shield, it is necessary that framing, stanchions, plating, bolting, etc., also penetrate the shielding system. All of these penetrations set up irregularities in the shield materials through which radiation may escape. Considerable effort, of course, is made to minimize these radiation leakage irregularities, but on shipboard, they cannot be completely avoided.

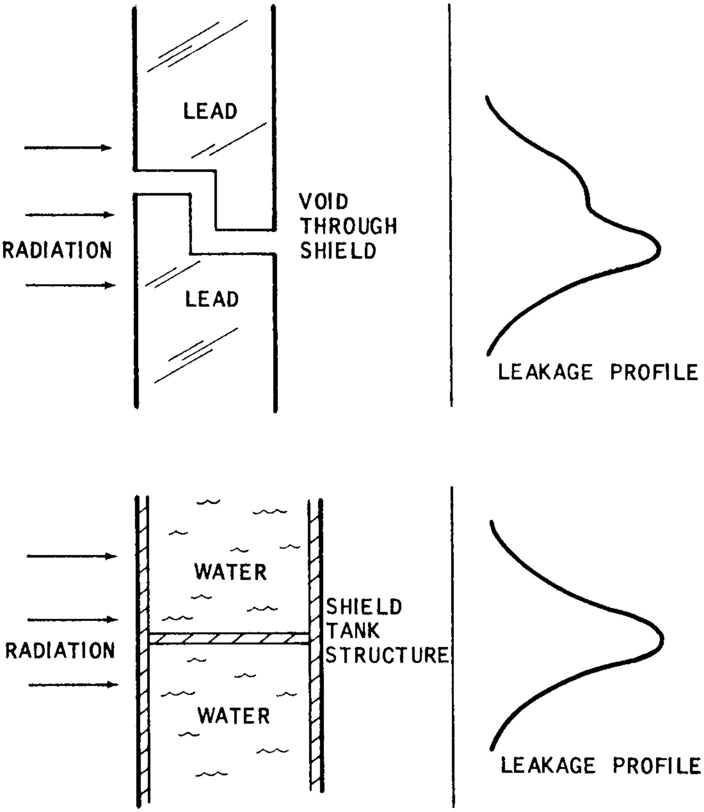

Fig. 10-6 Typical Radiation Profiles Through Shielding Voids and Structures

Fig. 10-6 typifies what happens when there are ducting voids and structural members in the shielding system. The radiation level just outside of irregularities remarkably reproduces the profile of the voids and structures. The explanation is that the radiation seeks the "valleys" in the Σ-coefficients of the irregularity materials. Correspondingly, the radiation traverses a given shield thickness with relatively less attenuation.

The Fig. 10-6 situation can be overcome by attaching shield "blisters" to the irregularity areas. These blisters are extra thicknesses of shielding material wherever radiation streaming occurs. On shipboard, this is not too practical, as there are many voids and structures hidden in the shielding system. The difficulty of locating every possible streaming path through a shield—these paths may open and close during heavy seas—has led to the practice of partial or shadow shields. These shadow shields are placed around radiation-sensitive equipment (e.g., electronic equipment, lubricants, etc.) external to the shielding system. Shadow shielding also takes advantage of attenuation by distance.

In addition to shield penetration problems, it is necessary to minimize the thermal and mechanical stresses in the shielding materials. To do this, special fabrication and inspection techniques are required. These procedures seek to assure the integrity of the shield materials . . . against cracks, ruptures, bulges, voids, and other imperfections. For maximum shielding protection, extremes in fabrication perfection are required. But seeking perfection in a practical shipboard environment is a rather elusive undertaking. We, therefore, inquire into the possibility of other shielding schemes that may avert the necessity for fabrication perfection.

10-12 Possibilities with Heavy Liquids

It has long been recognized that the ideal shield would consist of a hydrogenous matrix with a high-density material and strong neutron absorber in homogeneous mixture of such proportions to attenuate fast neutrons, thermal neutrons, gamma rays, and scattered fluxes—all at a random yet uniform rate.[*] This idealization has been the impetus behind such shielding concepts as heavy concretes, heavy pellets, and lead-water-lead combinations. These concepts have not proved practical for shipboard. So, possibly, could heavy *liquids* be used?

In the sense posed here, a heavy liquid is an aqueous (water) solution consisting of two solute materials. The primary solute would be a high-density material to attenuate fast neutrons and all gammas. The secondary solute would be a strong thermal neutron absorber, compatible in solution with the primary solute. The liquid nature of this shielding material would assure shipboard installation simplicity. It could be pumped into and out of shielding tanks. The tanks could be of any configuration desired: varied in thickness, height, and location. A typical heavy liquid shield section is shown in Fig. 10-7.

It happens that there are about 100 compounds of lead which are soluble in water. Let us pick the most soluble one and call it "lead-A."

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[*] Ref: *Principles of Nuclear Reactor Engineering,* S. Glasstone, Van Nostrand, 1955, pp. 576-589.

It also happens that there are about 50 compounds of another material—less well known but highly comparable to lead—which are soluble in water. This material is thallium; let us call its most soluble compound "thallium-A." There are other compounds which are soluble in water but none possesses the shielding consequences of these two. Both lead-A and thallium-A are heavy solutes; thus they are effective against fast neutrons and all gammas. The solvent (water), then, provides the hydrogenous content to thermalize those fast neutrons initially degraded by the heavy solute nuclei. Both lead-A and thallium-A will capture the thermal neutrons, but other solute materials will do this better.

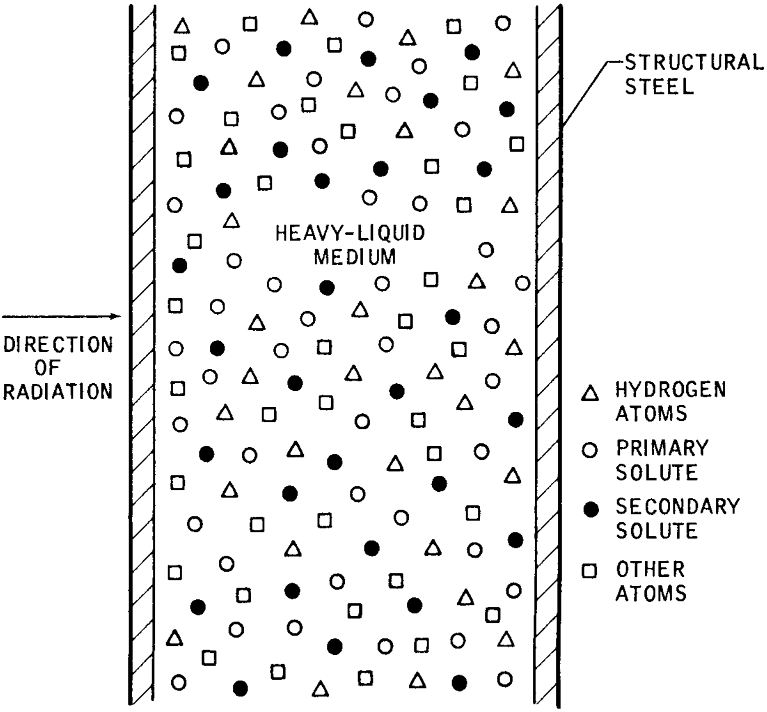

Fig. 10-7 Typical Heavy Liquid Shielding Section

Actually, either one or a combination of both heavy liquids above would serve satisfactorily as a shipboard shielding medium. But unless a further constituent is added, some thermal neutrons would penetrate into the steel tank structure and—upon capture by many alloys thereof—would be re-radiated as high energy capture gammas (see Fig. 10-1 again). These capture gammas would emerge from the external steel surfaces of the shielding tanks, and would be just as undesirable as though the gammas originated directly from the fission core itself. Fortunately, this possibility can be averted by adding to the heavy liquid a strong thermal neutron absorber. By properly selecting the number of atoms of this absorbing material, the probability of capturing all thermal neutrons within the heavy liquid medium can be assured.

Though compounds of boron are the most common additives to water, none of them would be compatible in solution with lead-A and/or thallium-A. The negative borate ions would combine with the positive lead or thallium ions to form precipitates. There are, however, a number of materials soluble in water—and compatible with lead-A and/or thallium-A—which are more potent than boron as thermal neutron absorbers. All of these high-capture materials give off capture gammas. So, let us pick the one which gives the least number of capture gammas in the unwanted 1-3 Mev energy range. This would be "cadmium-A."* Natural cadmium has a thermal neutron capture probability better than three times that of boron. And cadmium compounds are far more soluble in water than borate compounds.

For an equal number of cadmium atoms in the heavy liquid as there are number of high-capture atoms in the total steel structure, there would be a better than 150-to-1 probability that the thermal neutrons would be capured entirely within the heavy liquid rather than in the outer tank wall. Thus, since steel and the surrounding heavy solute nuclei are good gamma absorbers, the cadmium-emitted capture gammas are not likely to get outside of the shielding tanks.

10-13 Tenth-Value Thickness Comparisons

For comparative design purposes, it is convenient to compute the tenth-value thickness of shielding materials. The "tenth-value" is that thickness (in centimeters) which attenuates the incident radiation—whatever its magnitude—by a factor of ten. It is based on simple exponential attenuation, numerically equal to

[Eq. 10-8]

$$x_{1/10} \approx \frac{2.303}{\Sigma}\ \text{cm}$$

where Σ is the attenuation coefficient, as before. Σ, we recall, is radiation dependent, energy dependent, and material dependent. So, for each material and radiation situation there will be a corresponding tenth-value. The use of tenth-values is an engineering tool which permits shielding comparisons without the necessity for calculating total shield designs.

It was pointed out earlier that water is the most common neutron shielding material, and lead (in solid form) the most common gamma shield. Now, having indicated new shielding possibilities with heavy liquid materials, it is of interest to compare their tenth-value thicknesses with those of water and lead. But, first, we should select a particular heavy liquid and indicate the proportions of constituents involved.

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* Ref: "Gamma Rays from Thermal Neutron Capture," Mittelman and Liedtke, *Nucleonics,* May, 1955, pp. 50-51.

The choice between lead and thallium is a function of temperature (which affects solubility) and Σ-values. At temperatures below 150°F, lead-A is the more soluble constituent; but above 150°F, thallium-A is significantly more soluble (see Fig. 10-8). At any temperature, however, for an equal volume of each solution, thallium-A gives the higher Σ-values, and thus, the lower tenth-values. Since in any practical shipboard shielding system, temperatures approaching the boiling point of ordinary water can be expected, we can pick thallium-A as the principal constituent of our heavy liquid. We can add to this a small percentage of cadmium-A and adjust the combined volume of both solutes so as not to exceed 50% of the total heavy liquid medium. In other words, we would always have at least 50%, or more, water (by volume). Henceforth, we shall refer to this combination as the "heavy liquid."

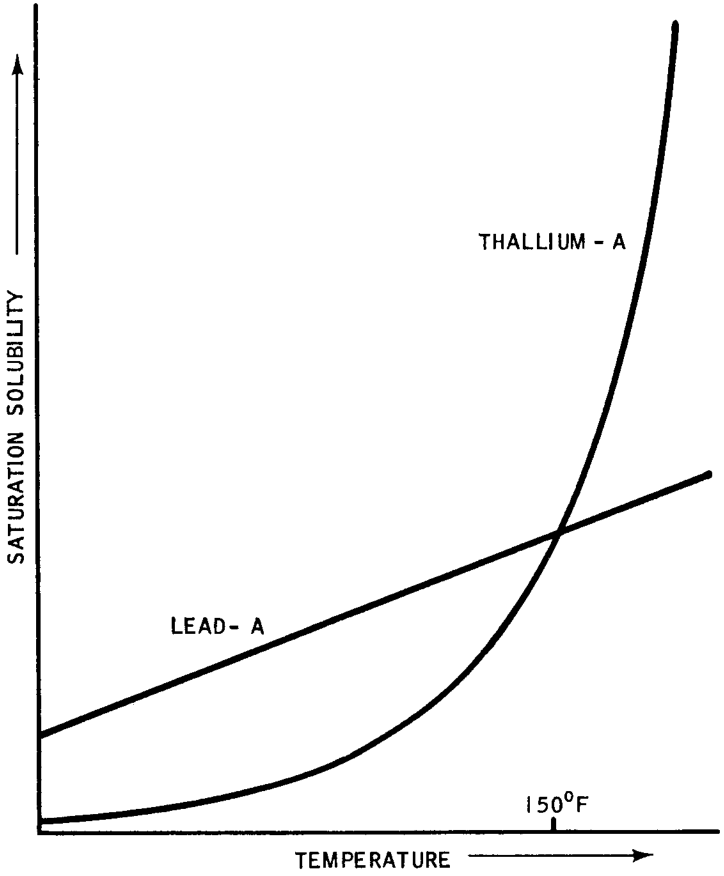

Fig. 10-8 Comparative Solubilities of Thallium and Lead Compounds

By means of the following general equation, we can compute the Σ-value for *each constituent* in our heavy liquid combination:

[Eq. 10-9]

$$\Sigma = \frac{\rho N_a}{A}(\nu_1\sigma_1 + \nu_2\sigma_2 + \nu_3\sigma_3 + \cdot\cdot\cdot)\ \text{cm}^{-1}$$

where all symbols except ν (nu) are the same as in Eq. 10-2 and 10-3; ν = molecular per cent of constituents 1, 2, 3, etc.

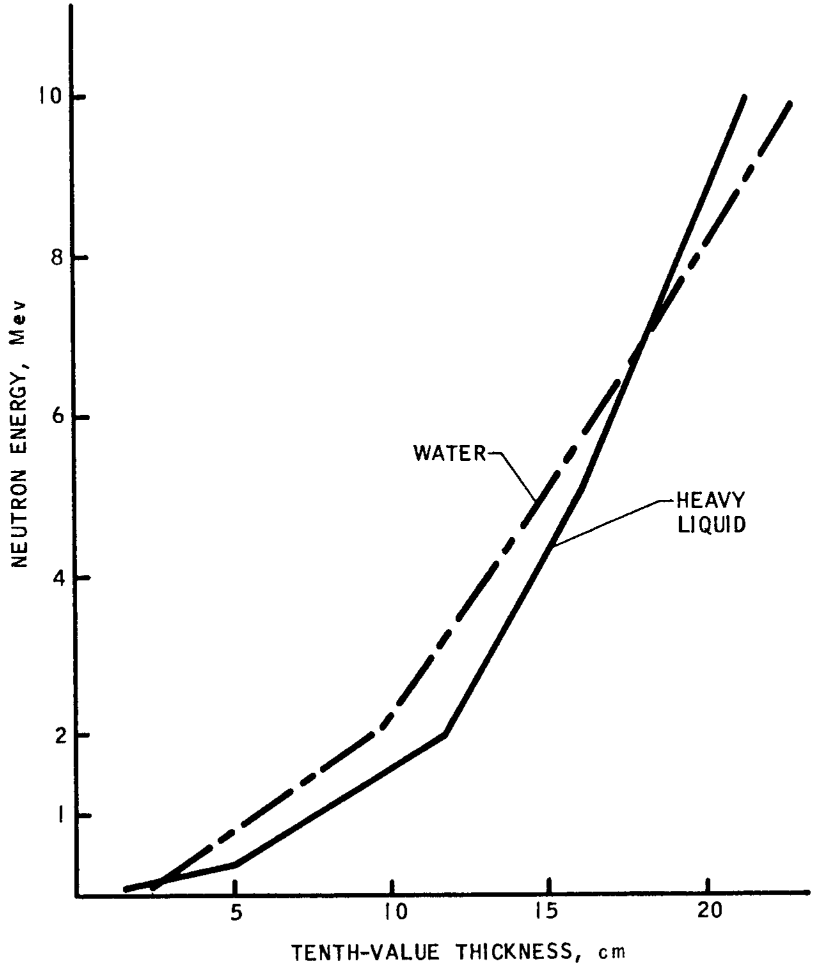

Fig. 10-9 Comparative Neutron Attenuation: Heavy Liquid versus Water

Without going into all the calculations involved, Fig. 10-9 shows the comparative tenth-value thicknesses of water and heavy liquid against neutrons. As we would expect from the smaller volume of water in the heavy liquid, all water is superior to heavy liquid . . . but only slightly so. It is significant to note that the tenth-value curve of heavy liquid closely resembles that of ordinary water, all along the neutron energy spectrum from zero to 10 Mev. This is because 50% (by volume) of the heavy liquid is water and because the heavy solutes themselves are effective attenuants against fast neutrons. Note that the maximum heavy liquid tenth-value thickness involved is approximately 20 cm.

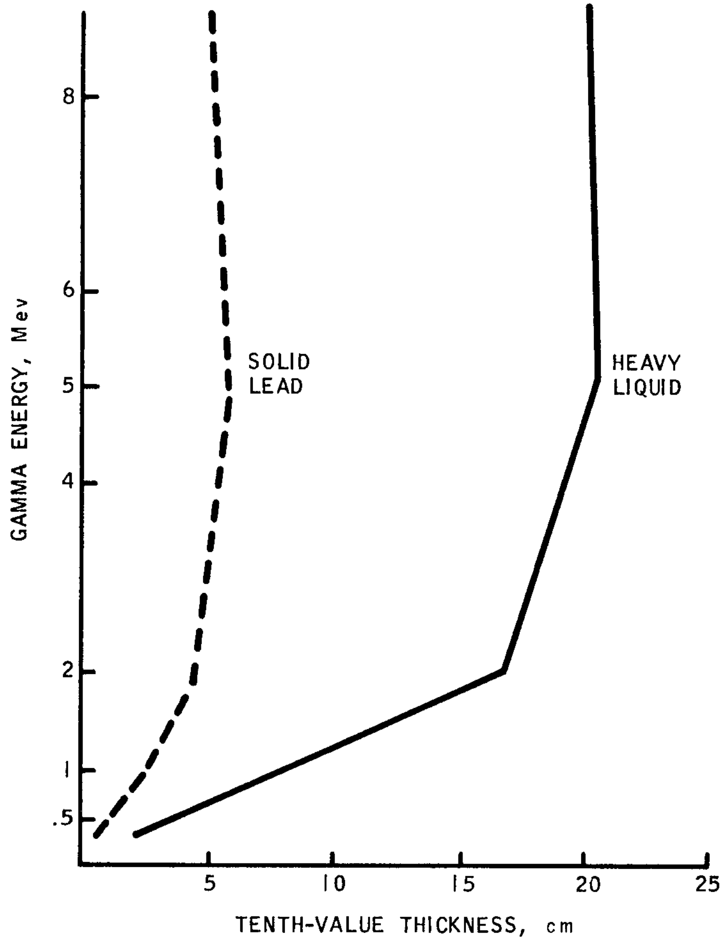

Fig. 10-10 Comparative Gamma Attenuation: Heavy Liquid versus Lead

Similarly, Fig. 10-10 shows the comparative tenth-value thicknesses of lead and heavy liquid against gammas. In this case, solid lead is considerably better than the heavy liquid, but note the parallelism in the curves.

This is because of the great quantity of thallium that can be loaded into solution. Actually, about 80% of the weight of heavy liquid is the thallium-A compound. Note here too, that the maximum tenth-value thickness involved is approximately 20 cm.

The basic feature of interest in Figs. 10-9 and 10-10 is this: Within the same thickness of water required for neutron attenuation, heavy liquid provides the same gamma attenuation as solid lead. To get the equivalent gamma attenuation with water alone, the thickness required would be from three to five times as great.[*] In other words, *the heavy liquid gives shielding protection* **simultaneously against both gammas and neutrons** *within the same maximum thickness required by ordinary water for neutron attenuation alone!* Specifically, this means that we could do away with solid lead shielding and solid neutron shielding, and thus avoid their problems of fabrication and installation. This is particularly advantageous for primary shielding of high temperature reactors where the shielding environment may reach 200°F and beyond.

10-14 Advantages for Shipboard

Aside from the fact that heavy liquid shielding would stop both neutrons and gammas simultaneously, it offers certain practical advantages for shipboard use. Because of the nature of this shielding medium it lends itself readily to remote fabrication. The mixing of solutes could be done at chemical process plants ashore where established practices of automation and mass production would maximize quality standards. After fabrication, the heavy liquid could be delivered to shipside in tank trucks or railroad tank cars, whereupon it could be pumped into the reactor shielding tanks. The result would be a minimum of direct handling by humans. This should significantly reduce both the shielding costs and the hazards involved.

Devoid (temporarily) of the shielding material, the shielding tanks could be designed and tested as a separate entity. The shielding tank thickness and its geometry could be arranged for any configuration desired. Spacing could be adjusted to compensate for penetrations, framing, ducting, conduits, piping, etc. If necessary, tank "bulges" could be added to give extra shielding protection in special areas (see Fig. 10-11). Maintenance access openings could be provided. All in all, the shield tanks could be optimized in every way, with the knowledge that the heavy liquid medium would conform to every irregularity therein.

Being all liquid in nature, a degree of self-homogeneity could be achieved, heretofore unattained in shipboard shielding art. This self-homogeneity would be brought about by temperature differences within the shielding medium. These temperature differences, due to direct

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[*] For example, for 2 Mev gammas $x_{1/10}$ H.L. $\approx$ 16.5 cm; $x_{1/10}$ water $\approx$ 47 cm. For 10 Mev gammas $x_{1/10}$ H.L. $\approx$ 20.5 cm; $x_{1/10}$ water $\approx$ 110 cm.

reactor heating and to the internally generated heat of recoiling nuclei and electrons, would set up natural convection currents in which the heavy solute ions would be free to move about to attain thermal, chemical, and nuclear equilibrium. The consequence is that any selected volume of the shielding medium would be nearly identical with that of any other selected volume. Thus, the normally adverse effects of inhomogeneities in shielding materials, structural irregularities, solute precipitation, and radioactivation would be self-compensating. A significant improvement in the uniformity of nuclear attenuation should result.

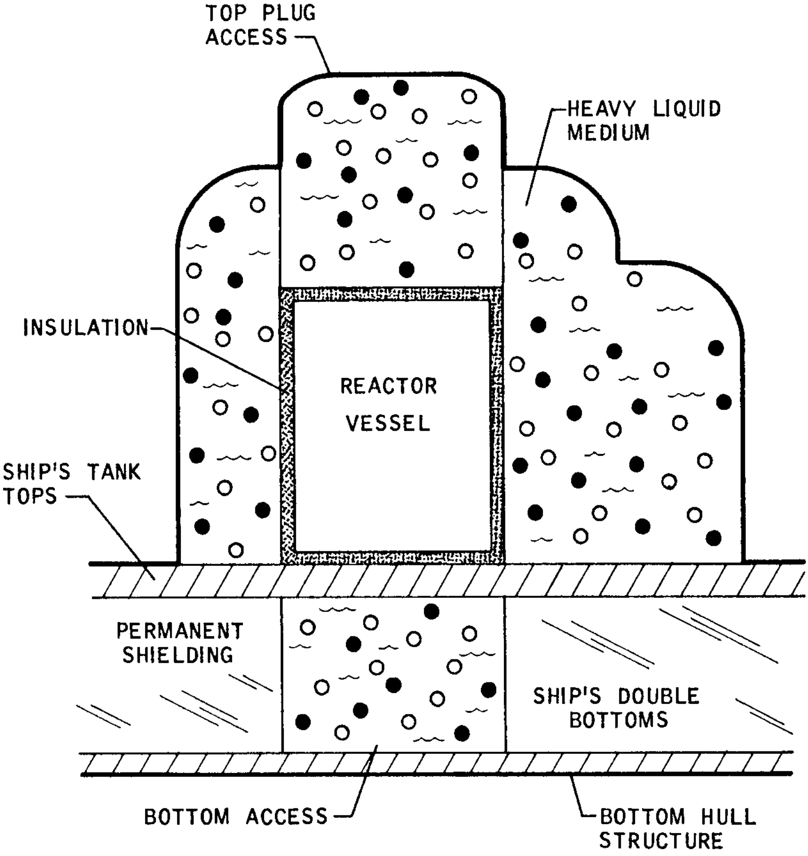

Fig. 10-11 Variable Shielding Geometry Possible with Heavy Liquid

10-15 The Disadvantages Involved

No shielding system is perfect. Though heavy liquids may solve one set of problems, they introduce others of their own. Foremost is the matter of temperature control. Prior to reactor startup, the shielding system would be at some ambient temperature—insufficient to maintain the desired heavy solute content. On the other hand, soon after the reactor is operating, the temperature would rise to the point where boiling could occur. Hence, to avoid precipitation of the heavy solutes at temperatures below some design value, and to avoid boiling, heating-cooling coils would be required within the shielding tanks. It would be necessary that these coils be heated during reactor shutdown, and that they be cooled during normal reactor operation . . . by external auxiliary means. To best do this, automatic temperature regulation would be required. This complicates the shielding system somewhat, but the penalty would not be too severe.

A further problem introduced by heavy liquids would be the matter of toxicity, in the event of shielding tank leaks. Thallium is a toxic material. But so is lead; so is mercury; so are a lot of other materials used aboard ship—carbon tetrachloride, for example. So, obviously, all shielding tank leaks would have to be minimized. We have to take precautions now against leaks in water shielding systems. Why not extend this precaution to heavy liquids?

Following the operation of a reactor and its shutdown, there would be the matter of neutron-induced radioactivity, similar to that of water and iron. The heavy liquid constituents of concern are thallium and cadmium. From thallium, five radioisotopes could be formed; from cadmium, eight radioisotopes. However, only two radioisotopes are of consequence, namely: Tl-204 and Cd-113. Both have long half-lives (3.5 yrs and 5.1 yrs, respectively), and in the course of time there could be considerable buildup of these radioisotopes. Fortunately, only soft beta radiations would be emitted (0.75 and 0.60 Mev, respectively), and these are easily shielded against. Consequently, no special protection against the buildup of these radioisotopes would be required other than ordinary radiological precautions which would become routine for all marine reactor plants.

Possibly the greatest disadvantage of heavy liquids for shipboard shielding is the cost of the raw materials involved. Thallium is a rare metal and cadmium is not too plentiful either. The cost of each is high. The primary reason for high cost is the rather limited commercial use of these materials today. The commercial production of thallium compounds is confined chiefly to rat poisons, whereas cadmium compounds are being used in electroplating. Future reductions in cost—particularly of thallium-A—would depend on developing new large-scale commercial applications, such as conceivably could evolve through heavy liquid shielding for a large fleet of nuclear ships. Whether such a course of events will occur is a matter of conjecture.

We have the precedent of another high cost nuclear material on which to postulate future thallium costs. Zirconium is the example. In 1948 the price of unfabricated zirconium was about $110 per pound. Because of its desirable nuclear and high temperature properties for cladding fuel elements, commercial production has risen sharply. In ten years, the zirconium price has come down below $5 per pound: a twenty-fold cost reduction.* Possibly, similar reductions could be anticipated for thallium.

10-16 Next Evolutional Step?

In the early days of reactor shielding design (mid-1940's) efforts to homogenize shielding materials to achieve the advantages of simultaneous attenuation of neutrons and gammas centered on "heavy concretes." It was found that by incorporating heavy materials such as iron, lead, barytes, and other aggregates, the density of concrete could be increased, with consequent greater attenuation . . . for the same shielding thickness. Attempts were made to borate the concrete to improve its thermal neutron absorption properties. But, as the concrete was fabricated in massive blocks (e.g., 3 × 4 × 6 ft weighing on the order of 10 tons), the cost of installation rose, as did the difficulties of preventing radiation leakage through keyways, abutment irregularities, and shield penetrations.

With the advent of nuclear ship reactors, the need arose for more systematic shielding designs with predictable attenuation efficiency. The resulting analytical concepts focused on laminations of solid materials, then subsequently on the combination of liquids and solids. It appears now on shipboard that hydrogenous materials are used to thermalize fast neutrons; borated materials to capture thermal neutrons; and heavy materials against very fast neutrons and all gammas. The total shield is built up of the best possible combination of water, solid lead, and steel. The cost of fabrication is high. Analytically, it is virtually impossible to predict radiation leakages at welding, bolting, flanging, sheathing, bulkheading, and void spaces, which constitute the shielding system.

Considering the sequence of events above, it would appear that the next evolutional step in shipboard *primary* shielding might consist of a single, all-purpose, heavy liquid medium . . . possibly along the lines discussed in Sec. 10-12. Such a medium, however, would produce no revolutionary reductions in shielding size and weight. Instead, it would lend itself to more precise shielding calculations, more precise geometry, greater simplicity—in general, to numerous refinements in shielding design. The most likely ultimate virtue of heavy liquids would be the standardization of nuclear ship shielding and the evolution of its fabrication into a mass production enterprise.

SUMMARY

We see now that shielding against nuclear radiation becomes quite involved. The involvements result largely from two facts, namely: (1) that neutrons and gammas are attenuated (degraded in energy) by different mechanisms, thus requiring different shielding materials against each; and (2) that the attenuation events occur in a chance manner and direction not amenable to simplified calculations.

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* Ref: "Zirconium and Hafnium," Mallory-Sharon Metals Corporation, Niles, Ohio.

The principal shielding effort is against gamma radiation (by an energy-stopping ratio of about 5 to 1). Gamma-shielding is the principal concern because the major reactor design effort is toward confining the neutrons to the fission core, where they are power productive. Complicatedly, those neutrons that do escape from the core promote additional gamma-shielding problems in the form of inelastic and capture gammas. The neutron-induced capture gammas require particular attention because they may occur in the outer structural walls of the shielding tank and, thus, could emerge unattenuated.

The probability of neutron and gamma attenuation is indexed by the coefficient Σ (cap sigma). There is a different Σ for neutrons and for gammas. Furthermore, each Σ-value is energy dependent and materials dependent, so that there is a spectrum of Σ-values for each material. Based on 2.3 times the reciprocal of this coefficient (i.e. $2.3/\Sigma$), a "tenth-value thickness" arises which is a useful engineering tool in comparing different shielding materials. A tenth-value thickness reduces the incident radiation—whatever its magnitude—to one-tenth of its original value.

The most common shielding materials for shipboard use are water, lead, and iron. Water is the best practical neutron moderator there is, but it is not effective against gammas. Lead is excellent against gammas but not against neutrons. Iron is better than water and lead against fast neutrons, and better than water against gammas. Iron, in structural shapes, is used to contain and support both water and lead. To improve these shielding materials, additives and alternatives can be considered. All shielding materials however, heat up due to the atomic and ionic friction of attenuation; and all become radioactivated to some extent.

The fabrication and installation of shielding materials aboard ship becomes a complex undertaking. The situation is aggravated by irregularities in the shield structure, by penetrations for operational devices, and by the necessity for maintenance and refueling. These aggravations can be offset by various methods. One method of potential interest is the use of an aqueous heavy liquid shielding medium. Such a medium could serve as a simultaneous neutron-gamma attenuant, and could be pumped in and out of any geometry of shielding tanks.

A heavy liquid would consist of at least 50% (by volume) of water in which there are primary and secondary solutes of thallium and cadmium compounds. The thallium solute would serve as the fast neutron and gamma attenuator; the cadmium as the thermal neutron absorber. The combined effect would be a shielding thickness (based on tenth-value comparisons) equivalent to that of ordinary water against neutrons alone . . . but attenuating also gammas. This means that we could do away with solid shielding materials—except the shielding tank structures—and thus greatly simplify fabrication and installation problems. This would be especially advantageous for the primary shielding of high temperature reactors.

There are two principal disadvantages to heavy liquid shielding. One, the necessity for preheating the shielding medium prior to reactor startup (to assure complete solubility of constituents). Two, the high cost of the thallium compound raw material. Thallium is a rare material largely because of its undeveloped commercial nature. However, its application to a large fleet of nuclear ships would reduce its cost many-fold. Sooner or later, we can anticipate future refinements in shipboard shielding art toward the direction of greater simplification and standardization.