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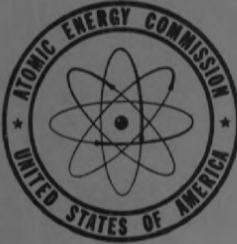
THE SHIELDING OF MOBILE REACTORS (PART I)

AEC RESEARCH AND DEVELOPMENT REPORT

By
E. P. Blizard
T. A. Welton

January 15, 1952
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THE SHIELDING OF MOBILE REACTORS (Part I)

By E. P. BLIZARD and T. A. WELTON

Oak Ridge National Laboratory

Report ORNL-1133

ABSTRACT

This article, the first of a series of three, describes, first, the several sources of neutrons and gammas which are of importance in the design of shielding systems for mobile reactors. Convenient approximations are indicated to the spectrum of fission neutrons. References are given for capture-gamma-ray data, and that information of greatest interest for shielding is tabulated.

Next, the cross sections for neutrons and gammas are treated. Very little is said about the latter because they are well covered elsewhere. The neutron data required for many shielding problems is shown to be just that which is most easily obtained from bulk shielding experiments. Inferences concerning relative shielding efficiencies of tested and untested materials are available, however, from comparison of total fast-neutron cross sections, as measured by a suitable accelerator.

INTRODUCTION

Until recently the prime virtues of a shield were adequacy and cheapness. With the advent of mobile power-producing reactors it has become important to make them light and thin as well.

Although many shielding problems arise in connection with stationary reactors, accelerators, radioactive isotopes, hot laboratories, etc., in none of these cases is the design of the shield as critical as in nuclear-powered aircraft, for here the shield could determine the very feasibility of the project. In the case of the nuclear-powered submarine the feasibility is certainly not in jeopardy, but the ability of the craft to compete successfully with other types depends to a large extent on the compactness of shield

design. Furthermore, a submarine cruise lasts many times longer than an aircraft mission; therefore the shield must reduce the radiation in occupied spaces to a correspondingly lower level. The result is that in many cases the submarine-shield-design problem is even more difficult than that of the aircraft.

The discussion in this article and the two that will follow in future issues of this journal will be slanted to the shielding of mobile reactors since this seems to be the crucial problem. The information, however, will be sufficiently general to apply to many parallel situations.

SOURCES OF RADIATION

There are a great many ways in which the fissions occurring in a reactor can cause harm-



ful radiation to reach personnel. To neglect one of these is to fail in the shielding project; therefore it is of paramount importance to point out at once the various problems which will arise. Figure 1 shows these schematically.

component, if unshielded, could easily yield a dose rate hundreds or thousands of times greater than tolerance. Thus a reactor in which the most important components are shielded still may be far from safe.

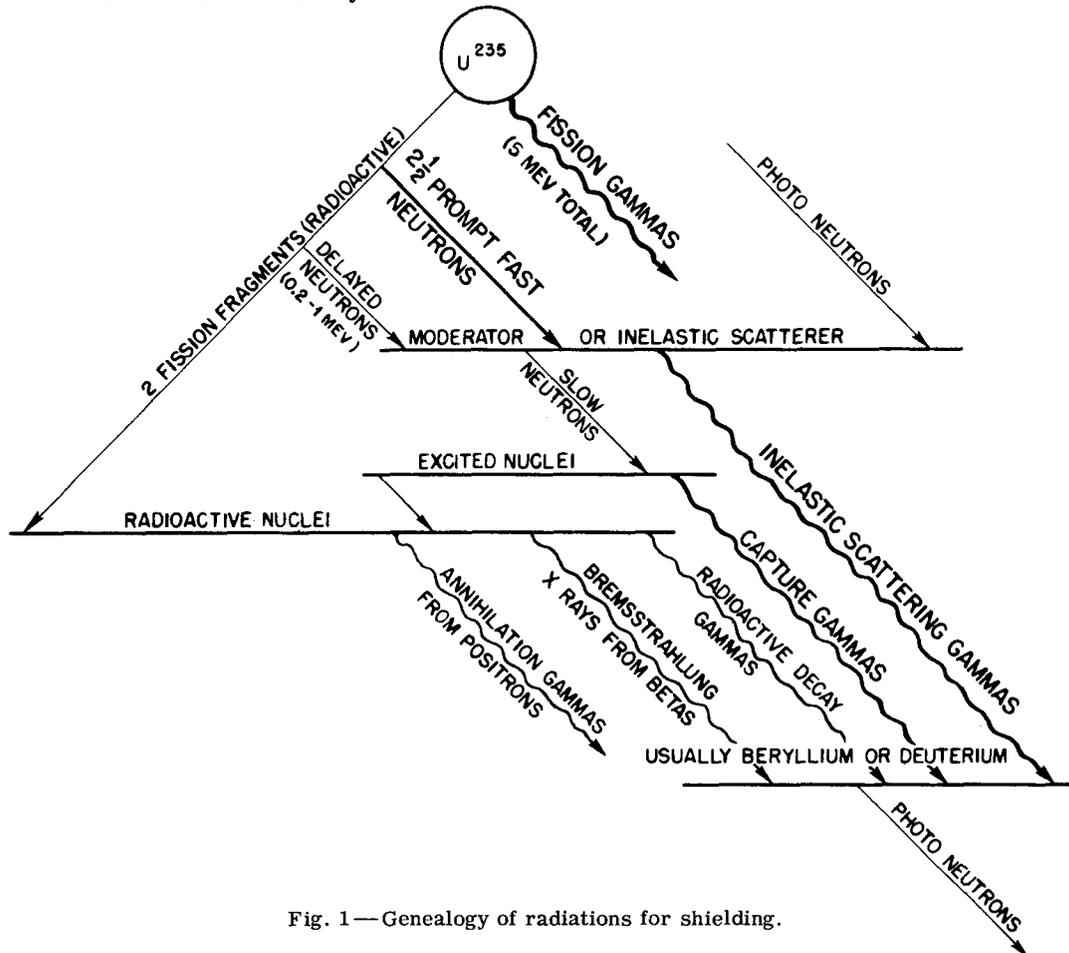


Fig. 1—Genealogy of radiations for shielding.

The relative importance of the several radiation components is difficult to specify for the general case since the situation can differ so radically from one design to another. The four which are accentuated in Fig. 1 are almost always important, but they are not always the most important. It will be noted that the figure shows only neutrons and gammas. These, of course, are by far the most penetrating radiations, since betas, alphas, and fission products can be easily stopped because of their electric charge.

It is necessary furthermore to point out that the attenuations which are required in shielding are so great that a single relatively unimportant

One more remark of a general nature seems appropriate. Even though some shielding materials are chosen for neutron attenuation and others are chosen for gamma attenuation, the problem is nevertheless not amenable to the dichotomic approach because this would ignore the very important processes by which the two are coupled. Shielding is a single problem in which many conditions must be satisfied simultaneously. This article is a description of the individual parts of the problem.

Fission Neutrons

The fission products emit neutrons which are classed as "prompt" if the time between fis-

sion and emission is not measurable and as "delayed" if it is measurable. In most cases the prompt neutrons are much more important because they are, in general, more energetic and more numerous.

1. Prompt Neutrons. The spectrum of prompt fission neutrons has been measured for U^{235} as well as Pu^{239} , the published work on the former being much more complete. Bonner, Ferrell, and Rinehart¹ measured the prompt spectrum from 0.075 to 0.6 mev, Hill² measured all neutrons (prompt as well as delayed) from 0.4 to 6 mev, and Watt³ covered the much less populous range from 3 to 17 mev. Watt combined all three sets of data and fitted them quite adequately with his own variation of a formula originally proposed by Feather.⁴

Watt's formula is

$$N(E) dE = \sqrt{\frac{2}{\pi e}} \sinh \sqrt{2E} e^{-E} dE \quad (1)$$

where $N(E) dE$ is the number of neutrons of energy E to $E + dE$ per neutron emitted and E is the neutron energy in million electron volts.

Nereson⁵ has measured the fission spectrum of Pu^{239} , using photographic plates, for the energy range from $\frac{1}{2}$ to 8 mev. His data fit Watt's formula fairly well, but there seems to be a somewhat greater abundance of the higher energy neutrons. The statistical accuracy is not, however, adequate to certify a genuine difference. Nereson only measured five tracks beyond 6.5 mev.

Since in most shields the attenuation is sufficient to keep all but the hardest neutrons from penetrating the full thickness, it is often permissible to use a simpler form of Eq. 1 which fits adequately in the high energies. Two of these are

$$N(E) dE \doteq \frac{1}{\sqrt{2\pi e}} e^{-(E-\sqrt{2E})} dE \quad (2)$$

$$N(E) dE \doteq 1.8e^{-0.75E} dE \quad (3)$$

The last of these is not derived from Eq. 1 but is, nevertheless, a fair approximation to the data from 4 to 12 mev. It is adjusted to agree in magnitude and slope with Eq. 2 at 8 mev. For a formula fitted to agree similarly at any other energy E_0 , the following is convenient:

$$N(E) dE \doteq \frac{1}{\sqrt{2\pi e}} \exp \left[\sqrt{\frac{E_0}{2}} - \left(1 - \frac{1}{\sqrt{2E_0}} \right) E \right] dE \quad (4)$$

This should not be used for E or E_0 less than about 3 mev.

2. Delayed Neutrons. Delayed neutrons are less energetic and less numerous; hence they are important only in special cases, for example, in a homogeneous circulating-fuel reactor. In this case the fuel is quite radioactive; therefore it would not be introduced to an occupied region, but the delayed neutrons introduce the further difficulty of a coolant, such as sodium, becoming radioactive in a fuel-to-coolant heat exchanger.

Hughes⁶ has summarized information on the delayed neutrons in a manuscript for the Plutonium Project Report, and his table of yields is reproduced as Table 1.

Table 1—Delayed Neutrons
[Absolute yields per 10^4 neutrons emitted
(prompt and delayed)]

Half life, sec	Energy, kev	Yield		
		U^{235}	U^{233}	Pu^{239}
55.6	250	2.5	1.8	1.4
22.0	570	16.6	5.8	10.5
4.51	412	21.3	8.6	12.6
1.52	670	24.1	6.2	
0.43	400	8.5	1.8	11.9
	Total	73.0	24.2	36.4

The term "yield" as used in Table 1 refers to the total fraction of all neutrons emitted which are associated with a given period.

The fact that the neutrons appear with definite half lives which are discernible in the fission fragments from several parent nuclei seems to indicate that the periods must be associated with certain radioactive nuclei. Indeed, the 55.6-sec period seems to be associated with the chemistry of Br^{87} and the 22-sec period with that of I^{137} .

Prompt Fission Gammas

Just as in the case of neutrons, fission-product gammas are also classed as "prompt" or "delayed," depending on whether or not the decay period is measurable. The term "fission gam-

mas'' is usually applied to the prompt emission, whereas the delayed radiation is always associated with the particular fission-product emitter.

There have been two measurements of the gammas emitted in coincidence with the fission of U^{235} . The data are given in Table 2. The agreement on energy per fission is adequate, that on the average energy per photon is not.

Table 2—Fission Gammas

Reference	Total energy per fission, mev	Average energy per photon, mev
Deutsch and Rotblat ⁷	5.1 ± 0.3	1
Kinsey, Hanna, and Van Patter ⁸	4.6 ± 0.1	2.5

Kinsey reports two independent photon-energy measurements, one by the absorption of Compton electrons by aluminum, the other by the absorption of the gammas by lead. In view of the fact that in both of these measurements a comparison is made with the 2.62-mev gamma from ThC'', it is difficult to see how his data could be incorrect. However, the data on electron absorption are sufficiently scattered to admit some difference in that the fission gammas might be softer than those of the ThC''. In the lead absorption setup the geometry was certainly such that the photons scattered (but not absorbed) in lead could register, and a correction for this would give 1.1 mev, in excellent agreement with Deutsch. On the other hand, this seems inadmissible since the same complaint should be lodged against the ThC'' data, the energy for which is unquestioned.

The time resolution was different for the two experiments, 2.8 μ sec for Deutsch and 0.7 μ sec for Kinsey, and, if the gammas which were sampled were sharply time dependent, then this might explain the discrepancy. However, the identical total energy would then be left unexplained. Furthermore, both teams investigated the effect of lengthening the resolution time to about 4 μ sec and found no observable difference.

Delayed Gammas from Fission Fragments

Delayed gamma rays from the fission fragments are of considerable importance in the

handling of reactors subsequent to shutdown. They have been examined by a number of investigators, probably the most complete survey being that of Way and Wigner.⁹ These investigators endeavored to find a rationale to describe in a general way the activities of the beta and gamma emitters. Since there are so many possible modes of fission, it is to be expected that there must be some general conclusions to be drawn from them.

Although Way and Wigner were able to obtain an approximate relation between decay constant and beta energy per disintegration, there appeared no simple form for gamma energy per photon. Nevertheless it is, in general, true that the emitters of hard gammas are the shortest lived. This fact, however, is not very useful because the average fission product suffers about three disintegrations before becoming stable and a daughter of a long-lived parent is often short lived and the emitter of a hard gamma.

The experimental data have been compiled by Way and Wigner, and a part of their table for gammas is given in Table 3.

More recently W. K. Ergen¹⁰ has demonstrated that the hard-gamma emitters are relatively few in number and are fairly well known. By means of simple, but careful, computation he has succeeded in attributing the results of several experimental measurements of photoneutrons produced in beryllium or deuterium to the hard-gamma emitters of relatively few well-known fission fragments. For many shielding problems the hard gammas are by far the more interesting, and for this reason a part of Ergen's data is given in Table 4.

In the use of Table 4 for shielding calculations it will always be necessary to multiply columns 3 and 4 to obtain gamma photons per 10^4 fissions. In the fifth column the symbol >D implies that the gamma energy is greater than the deuterium photoneutron threshold but otherwise is not measured.

Capture Gamma Rays

When a neutron is captured by a nucleus, a new nucleus is formed in an excited state. The excitation energy, called the "binding energy," of the new nucleus is dissipated almost at once ($\sim 10^{-13}$ sec) by the emission in most cases of one or more gamma-ray photons. Because the

Table 3—Delayed Gammas From U^{235} Fission Products

Rate, mev/sec/fission*	When valid	Reference
$0.90t^{-1.20}$	10 sec–1 day	S. Katcoff, B. Finkle, N. Elliot, J. Knight, and N. Sugarman, Report CC-1128, Dec. 11, 1943.
$4.2t^{-1.28}$	20 min–3 days	L. Borst, Report CL-697, November 1944, Sec. VIII, C4
$49.0t^{-1.41}$	50–100 days	L. Borst, Report CL-697, November 1944, Sec. VIII, C4

*t is in seconds.

Table 4—Fission-fragment Hard-gamma Emitters*

Half life†	Nuclides†	U^{235} fission yield, %	Yield per decay, %	Energy, mev
1 year, 30 sec	Ru^{106} , Rh^{106}	0.48	2	2.9(a)
275 days, 17.5 min	Ce^{144} , Pr^{144}	5.3	Weak	>D(a)
			2	2.185(a)
			2	2.6(b)
15.4 days	Eu^{156}	0.013	60	2(c)
12.8 days, 40 hr	Ba^{140} , La^{140}	6.1	3.2	2.5(d)
77.7 hr(e), 2.4 hr	Te^{132} , I^{132}	4.5(e)	2.7	2.0(f)
30 hr, 25 min	Te^{131*} , Te^{131}	0.45(e)	21.6	>D(g)
6.7 hr	I^{135}	5.6	1.95	2.4(h)
			4	1.8(i)
2.77 hr, 17.8 min	Kr^{88} , Rb^{88}	3.1‡	<15	2.8(j)
			19–34	1.85(j)

*References to other works are designated by letters as follows:

- (a) D. E. Alburger, E. der Mateosian, M. Goldhaber, and S. Katcoff, *Phys. Rev.*, 82: 332 (1951).
 (b) C. E. Mandeville and E. Shapiro, *Phys. Rev.*, 79: 243 (1950).
 (c) L. Winsberg in "Radiochemical Studies: The Fission Products," National Nuclear Energy Series, Division IV, Volume 9, Paper 198, McGraw-Hill Book Company, Inc., New York, 1951.
 (d) B. Russell, D. Sachs, A. Wattenberg, and R. Fields, *Phys. Rev.*, 73: 545 (1948).
 (e) A. C. Pappas and C. D. Coryell, *Phys. Rev.*, 81: 329 (1951).
 (f) F. C. Mainenschein, J. K. Bair, and W. B. Baker, private communication; G. W. Parker, private communication.
 (g) G. W. Parker, private communication.
 (h) H. A. Levy and M. H. Feldman, Report ORNL-286, Sept. 14, 1949, p. 80.
 (i) A. D. Bogard and A. R. Brosi, Report ORNL-65, June 16, 1948, p. 59.
 (j) M. E. Bunker, L. M. Langer, and R. J. D. Moffat, *Phys. Rev.*, 81: 30 (1951).

†If two entries occur, they refer to parent and daughter, and the latter is the hard-gamma emitter.

‡Interpolated value.

binding energies are, generally, large (~ 8 mev), this effect is of considerable importance in shielding. It is especially important since these radiations are produced throughout the shield and even outside it, so that they do not, as is the case with gammas originating in the core, traverse the shield before reaching sensitive areas.

It is important in shield design to choose and distribute materials so that the capture-gamma contribution to the biological dose outside is not more than, say, half the total. Conversely, it is unnecessary to suppress them to less than a few per cent. In order to accomplish this effectively, it is necessary to know at least approximately the spectra of capture gammas.

There have been a number of measurements of spectra, notably by Kinsey, Bartholomew, and Walker at Chalk River; by Hamermesh at Argonne National Laboratory; and by Millar, Cameron, and Glicksman at Chalk River (see references to Table 5).

Kinsey's group used a pair spectrometer, which enabled them to obtain detailed information about the energies involved. The determination of relative intensities has been more difficult but seems now to be well in hand. Kinsey's latest efforts have been directed in part toward determining the absolute number of photons per unit energy interval per neutron captured, and, of course, this is the essential number for shielding. Relative intensities which were at first reported by all investigators left some doubt since low-energy gammas and those internally converted were not measured.

Hamermesh, Millar, Cameron, and Glicksman used deuterium-loaded photographic plates in which the photoproton tracks were measured. This technique, being more crude than Kinsey's, does not reveal the spectral lines so clearly. Nevertheless, the sensitivity of the method is more easily calculated, and the detail is adequate for most shielding work.

Both the foregoing techniques become unsatisfactory for measuring energies of less than 3 to 4 mev, and this is unfortunate since the minimum in the lead-gamma cross section occurs at about $3\frac{1}{2}$ mev. There seems to be room for investigations using the scintillation-counter techniques which operate well to much lower energies. A start with this instrument is evident in the recent work of Pringle and Isford at the Uni-

versity of Manitoba, although they have not exploited the low-energy sensitivity of the method.

In addition to the spectral measurements mentioned above, there has been some interesting work done by C. O. Muehlhause, of Argonne National Laboratory, to determine approximately the average number of photons which are emitted per neutron capture. Since the total energy available (the binding energy) is fairly well known, Muehlhause's data give an indication of the general spectral shape.

From the shielding point of view capture-gamma-ray spectra fall into three classes in which (1) the ground-state transition giving the most energetic photon is dominant, (2) the gammas are smeared out, usually peaking at about half the maximum energy, and (3) the gammas are weak or nonexistent because of strongly competing particle emission.

In Table 5 are listed the spectra which have been studied, together with an indication of the type of spectrum, according to the categories of the foregoing paragraph, and the binding energy where measured. The isotopes indicated are the target nuclei before neutron capture. The data on spectral type and binding energy are in each case taken from the first-listed reference.

It is to be noted from Table 5 that most elements give multiple capture gammas. These photons, moreover, are often most numerous at the energy where the heavy element gamma cross sections are minimum. Probably the most interesting data are for boron and lithium, which fall into class 3 and hence are very desirable shield components. It is fortunate that these elements also have large absorption cross sections so that a small addition of boron or lithium effects a considerable suppression of the capture gamma rays.

As might be expected from energy-level density considerations, type 1 spectra are confined for the most part to light elements and those few heavy elements which behave like light elements in this respect (magic nuclei).

Inelastic-scattering Gammas

When a neutron is captured to form a compound nucleus, it is always possible that the excited nucleus so formed will pass to the ground state with the emission of a neutron. If the neu-

Table 5—Capture Gamma-ray Data

Target nucleus or element	Spectral type	Binding energy, mev	References*	Target nucleus or element	Spectral type	Binding energy, mev	References*
H ¹	1	2.23	p	Cu ^{63,65}	1	7.91 ± 0.01(63)	g,q
Li ⁶	3		r	Ge ⁷³	2		q
Be ⁹	1	6.797 ± 0.008	c,f,g	As ⁷⁵	2		e,q
B ¹⁰	3		o,r	Br ^{79,81}	2	8.5 - 9.0	i,q
C ¹²	1	4.948 ± 0.008	c,f,g	Cb ⁹³	2		q
N ¹⁴	2	10.823 ± 0.012	c,f	Ag ^{107,109}	2	~8.0	k,q
F ¹⁹	1	6.60 ± 0.03	a	Cd ¹¹³	2	~7.5	h,i,l,q,n
Na ²³	2	~6.35	h,a,q,g	In ¹¹⁵	2	7.0 - 7.5	m,q
Mg ²⁴	2	7.334 ± 0.012	a	Sb ^{121,123}	2		e
Mg ²⁵	2	10.93 ± 0.10	a	Ba	2		e
Mg ²⁶	2	6.44 ± 0.10	a	La ¹³⁹	2	7.5 - 8.0	i,k,q
Al ²⁷	1	7.724 ± 0.010	a,i,q,g	Sm ¹⁴⁹	2		q
Si ²⁸	2	8.476 ± 0.013	a	Eu ^{151,153}	2		q
Si ²⁹	2	10.53 ± 0.10	a	Gd ^{155,157}	2		q
Si ³⁰	2	6.597 ± 0.014	a	Dy ¹⁶⁴	2		q
S	2	8.66 ± 0.02	g	Hf	2		q
Cl ³⁵	2	8.56 ± 0.03	g,h,i,q,n	W	2	8.5 - 9.0	i,b
Ca	2	8.40	b	Re ^{185,187}	2		q
V ⁵¹	2		q	Ir ^{191,193}	2		q
Cr ⁵³	2		q	Au ¹⁹⁷	2	8.6 - 9.2	i,q
Mn ⁵⁵	1	7.25 ± 0.03	g,m,q,s	Hg	2	7.5 - 8.0	i,q
Fe ⁵⁶	1	7.63 ± 0.01	g,i,q	Tl ²⁰³	2	6.54 ± 0.02	e
Ni ⁵⁸	1	9.01 ± 0.03	g	Tl ²⁰⁵	2	6.23 ± 0.05	e
Ni ⁶⁰	1	8.55 ± 0.03	g	Pb ²⁰⁶	1	6.67 ± 0.02	g,d,t
Co ⁵⁹	1	7.73 ± 0.04	g,j	Pb ²⁰⁷	1	7.37 ± 0.02	g,d,t
				Bi ²⁰⁹	1	4.17 ± 0.015	d,t

*References to other works are designated by letters as follows:

- (a) B. B. Kinsey, G. A. Bartholomew, and W. H. Walker, Phys. Rev., 83: 519 (1951).
 (b) B. B. Kinsey and G. A. Bartholomew, private communication.
 (c) B. B. Kinsey, G. A. Bartholomew, and W. H. Walker, Can. J. Phys., 29: 1 (1951).
 (d) B. B. Kinsey, G. A. Bartholomew, and W. H. Walker, Phys. Rev., 78: 77L (1950).
 (e) B. B. Kinsey and G. A. Bartholomew, Report PR-P-7, August 1950 (preliminary survey).
 (f) B. B. Kinsey, G. A. Bartholomew, and W. H. Walker, Phys. Rev., 77: 723 (1950).
 (g) B. B. Kinsey, G. A. Bartholomew, and W. H. Walker, Phys. Rev., 78: 481 (1950).
 (h) C. H. Millar, A. G. W. Cameron, and M. Glicksman, Can. J. Research, A-28: 475 (1950).
 (i) B. Hamermesh, Report ANL-4447, May 1, 1950.
 (j) B. Hamermesh, Report ANL-4552, Dec. 8, 1950.
 (k) B. Hamermesh, Report ANL-4476, July 5, 1950.
 (l) B. Hamermesh, Report ANL-4277, Apr. 4, 1949.
 (m) B. Hamermesh, Report ANL-4515, Oct. 5, 1950.
 (n) C. D. Moak and J. W. T. Dabbs, Phys. Rev., 75: 1770 (1949).
 (o) J. K. Bøggild, Kgl. Danske Videnskab. Selskab, Mat. fys. Medd., 23: Nr4 (1945).
 (p) R. E. Bell and L. G. Elliott, Phys. Rev., 79: 202 (1950).
 (q) C. O. Muehlhause, Report ANL-4437, Apr. 5, 1950, p. 12; Phys. Rev., 79: 277 (1950).
 (r) W. F. Hornyak, T. Lauritsen, P. Morrison, and W. A. Fowler, Revs. Modern Phys., 22: 321 (1950).
 (s) R. W. Pringle and G. Isford, Phys. Rev., 83: 467 (1951).
 (t) B. B. Kinsey, G. A. Bartholomew, and W. H. Walker, Phys. Rev., 82: 380 (1951).

tron entered with adequate kinetic energy, it is possible, on the subsequent emission of a neutron, that the residual nucleus will be left in an excited state and will subsequently decay by the emission of one or more photons. This process, known as "inelastic scattering," becomes increasingly probable the higher the kinetic energy of the neutron since the density of allowed intermediate states (nuclear levels) is greater the higher the energy of the state.

Although the process has been observed for many years, not until recently have careful measurements been made of the gamma spectra, and as yet the data are very sparse.^{31,32} Fortunately the photon emission is probably similar to that in the capture process, although the available energies are often lower, and this enables some prediction of spectra to be expected. Thus light elements and magic nuclei probably give harder inelastic-scattering gammas than non-magic heavy nuclei.

CROSS SECTIONS

Introduction

The detailed calculation of attenuations has thus far not found a very clear use in shield work. This is largely because a really good attenuation calculation, even for a simple geometry, is a very complicated task. The point of such a calculation is, in addition, rendered very tenuous by the absence of pertinent cross-section data. The development of the lid-tank technique, on the other hand, permits the easy measurement of attenuations in a reasonable geometry and to good accuracy. It appears then that a valid set of functions to be performed by shield calculation might include the following:

1. The reliable conversion of lid-tank data to different geometries.
2. The approximate prediction of the behavior of shields of types similar to ones which have been measured but which contain different materials. (Many promising shield materials have not been investigated to date because of time or expense limitations. It might be hoped that calculation would serve to focus attention on the most promising configurations.)
3. Routine investigation of minimum shield weight and thickness obtainable for an aircraft reactor of arbitrary size and composition by

varying the shield materials and configuration.

This list is intended to be representative, not exhaustive.

It is important to note that in order to perform functions of the above type at all satisfactorily the shield theory should stress flexibility and ease of computation. Combined with these features must be a physical content sufficiently close to reality so that valid comparisons can be made of roughly similar shield configurations. It is felt that the placing of further restrictions on the theory may result in rendering it useless for practical work.

The theory to be described in this and future articles will then be intimately connected to bulk attenuation measurements, of which the lid-tank work is the prototype. Almost all this work has been confined to shields which are mixtures of water with iron or with lead, with some work on combinations of boron carbide and water. For this reason it is necessary to restrict discussion to the general type of shield in which neutrons are stopped by collisions with hydrogen and with heavy atoms and gamma rays are stopped principally by heavy atoms. It is fortunately true that shields of this type combine high performance with ease of computation, and the above restriction does not seem to be a serious limitation in practice.

Neutron Cross Sections

1. Qualitative. For purposes of exposition the neutron cross sections to be used will be treated first, and the detailed description of the associated calculation methods will be reserved for a following article. It should, however, be emphasized that the theory to be presented is a phenomenological theory, not a rigorous theory from first principles, and the cross sections to be used have a precise meaning only within the framework of the theory. It will be seen that this looseness of definition is in fact advantageous because the cross sections needed for a rigorous theory can come only from an extensive experimental program. In contrast, the cross sections required in the phenomenological theory are only cross sections already available or ones which follow immediately from the lid-tank work.

The theory to be developed is in reality only a picture of shield operation, and only this picture need be presented at this point. Consider a



neutron leaving the fission source. It will travel outward in a straight line until it collides with either a hydrogen nucleus or a heavier nucleus. If its first collision is with hydrogen, then its energy will usually be seriously reduced and its direction of travel will be altered. Either effect alone would be enough to render it less able to penetrate the shield than a similar neutron which has not made such a collision. It should, of course, be remembered that the neutron-proton cross section rises steeply as the neutron energy decreases. It is then clear that to good approximation a hydrogen collision is equivalent to absorption. (A slowly varying build-up function must, strictly speaking, be introduced to take into account the residual effectiveness of hydrogen-collided neutrons.)

Consider next a neutron that collides with oxygen (or carbon). The result will usually be an anisotropic collision with a small fractional energy loss by momentum transfer.* The effect of such a deflection is not easy to calculate in general. With hydrogen present in the proportion appropriate to water (or CH_2), the picture simplifies greatly. An isotropic collision is then equivalent to absorption because of the large extra path length usually introduced. A largely forward scattering will be less effective in absorbing the neutrons, but, in general, a reasonable part of the total cross section will be equivalent to absorption, and it is then convenient to define an "effective-removal cross section" as that part of the cross section which behaves like absorption. This quantity is a rather poorly defined concept inasmuch as its value depends on the position in the shield as well as on neutron energy. It is nevertheless true that suitable adjustment of this cross section can yield such good agreement with experimental attenuation data that further refinement of the concept seems to have only marginal usefulness.

Neutron collisions with heavy nuclei give a result which is simpler than, but similar to, that just described for oxygen and carbon collisions. Collisions with a medium or heavy nucleus are conveniently divided into two types. Collisions in which the incident neutron actually

enters the nucleus will be called "reaction collisions," and the cross section for a reaction collision is just that for the formation of the compound nucleus. Associated with this type of collision is another type, the so-called "shadow collision," which arises by the diffraction of the shadow cast behind the nucleus by the reaction collisions.

At low energies (below about 1 mev) these two types of collisions are difficult to distinguish since either leads to a roughly isotropic elastic scattering. At higher energies a reaction collision remains approximately isotropic, but the neutron is increasingly emitted with reduced energy. The shadow collisions, on the other hand, do not involve any nuclear penetration and so remain elastic. The angular distribution of scattered neutrons, in addition, becomes increasingly concentrated in the forward direction.

It is clear from preceding arguments that a reaction collision will behave as an absorption, whereas a shadow collision does not necessarily. The simplest procedure, which cannot be rigorously justified, is to argue that shadow collisions can be divided into two classes. The first class includes those deflections which are through too small an angle to affect the penetration, and the second class includes those deflections which markedly reduce the further penetration power. This argument is justified only by its success in explaining attenuation data, and further investigation of its validity is certainly in order.

2. Hydrogen Cross Section. It will be convenient to put the foregoing qualitative discussion into a more useful quantitative form. Consider first the neutron-proton cross section. Over the entire energy range of interest in shielding the differential cross section is isotropic in the center-of-gravity system. The total cross section is conveniently written in terms of singlet and triplet phase shifts, δ_S and δ_T . Write

$$\sigma = \frac{4\pi}{k^2} \left(\frac{3}{4} \sin^2 \delta_T + \frac{1}{4} \sin^2 \delta_S \right) \quad (5)$$

where k is the wave number of the relative motion and is given by

$$k^2 = \frac{ME}{2\hbar^2} \quad \text{absolute units} \quad (6)$$

$$= 1.21 \times 10^{24} E \text{ cm}^{-2}$$

*It will be shown in a later section that oxygen collisions play an important role only for neutrons with rather high energies, for example, above 5 mev.

where M is the nucleon mass and E is the neutron energy in million electron volts.

In the energy range of interest in shielding work the phase shifts can be well represented by^{11,12}

$$\begin{aligned} k \cot \delta_T &= -\frac{1}{a_T} + b_T k^2 \\ k \cot \delta_S &= -\frac{1}{a_S} + b_S k^2 \end{aligned} \quad (7)$$

The parameters a_T and a_S are the triplet and singlet scattering lengths, and b_T and b_S are one-half the corresponding effective ranges. If σ is measured in barns and $1/k^2$ is measured in barns (omit 10^{24} in the definition in terms of E), the above parameters are conveniently given in root barns (10^{-12} cm) as

$$\begin{aligned} a_T &= 0.54 & a_S &= -2.37 \\ b_T &= 0.089 & b_S &= 0.135 \end{aligned} \quad (8)$$

This choice yields

$$\begin{aligned} \sigma_0 &= 20.3 \text{ barns} \\ f &= 0.376 \text{ root barns} \\ \epsilon &= 2.237 \text{ mev} \end{aligned} \quad (9)$$

where σ_0 is the epithermal neutron-proton scattering cross section,¹³ f is the coherent scattering length for hydrogen,¹⁴ and ϵ is the binding energy of the deuteron.¹⁵ The singlet effective range has been chosen to be identical with the proton-proton effective range.^{12,16}

The choice of constants (Eq. 8) gives a remarkably good fit to the experimental neutron-proton cross section as a function of energy. Writing Eq. 5 in terms of $\cot \delta$,

$$\begin{aligned} \sigma &= \pi \left[\frac{3}{k^2 + (k \cot \delta_T)^2} + \frac{1}{k^2 + (k \cot \delta_S)^2} \right] \\ &= \pi \left[\frac{3}{k^2 + \left(\frac{1}{a_T} - b_T k^2\right)^2} + \frac{1}{k^2 + \left(\frac{1}{a_S} - b_S k^2\right)^2} \right] \end{aligned} \quad (10)$$

or, using Eq. 6 to rewrite Eq. 10 in terms of energy,

$$\sigma = \pi \left(\frac{3}{0.811E + 3.420 + 0.0116E^2} + \frac{1}{1.347E + 0.176 + 0.0267E^2} \right) \quad (11)$$

It is convenient to compare this formula with the graph which Adair¹⁷ bases on all the experimental information. We give in the first two columns of Table 6 a comparison of Eq. 11 with experiment, reading Adair's curve as accurately as possible. (This accuracy is probably greater than experimental uncertainties.) The agreement is seen to be excellent, and Eq. 11 may very well be more accurate than the experiments over much of the energy range used above. The disagreement at 12 mev is quite possibly an experimental uncertainty, although Eq. 11 must begin to fail at energies in this range.

Table 6—Comparison of Theoretical and Experimental Hydrogen Cross Section

E, mev	σ (theoretical)	σ (experimental)	10.97
			E + 1.66
0	20.3	20.3	6.6
2	2.91	2.9	3.00
4	1.94	1.9	1.94
6	1.43	1.4	1.43
8	1.14	1.15	1.14
10	0.94	0.95	0.94
12	0.79	0.82	0.80

For purposes of shielding calculation Eq. 11 is not very convenient. It will be seen that a useful form is

$$\sigma = \frac{A}{(E + \epsilon)^n} \quad (12)$$

where A , ϵ , and n are adjustable constants. It will appear further that the analytic fit which is used must agree well with Eq. 11 over the range of 4 to 10 mev but that small discrepancies outside this range will not be serious. A particularly simple, but not very good, approximation is obtained by setting $n = 1$ and $\epsilon = 0$ and adjusting A to fit as well as possible in the range of interest. A very much better fit is obtained by setting $n = 1$ and adjusting A and ϵ . The following expression seems adequate:

$$\sigma = \frac{10.97}{E + 1.66} \quad (13)$$

This is tabulated for comparison in the third column of Table 6. It is seen to more than fulfill our criterion for accuracy, and the improvement possible by adjusting n is probably not worth while.

A more directly useful form is obtained by multiplying Eq. 13 by the number of hydrogen atoms per unit volume to obtain a macroscopic cross section. It is convenient to use water as the standard hydrogenous material. Inserting the usual constants,

$$\begin{aligned} \Sigma_H &= \frac{2}{18} \times 0.603 \times \sigma \\ &= \frac{0.735}{E + 1.66} \text{ cm}^{-1} \end{aligned} \quad (14)$$

This is the basic macroscopic neutron cross section for shields of the general type under consideration.

3. Neutron Cross Sections for Heavier Elements. For an intelligent discussion of the neutron cross sections of heavier shield components, the eventual use of the cross-section information must be kept clearly in view. To this end it is instructive to use the result (Eq. 14) combined with the fission spectrum (Eq. 3) to obtain some idea of the neutron energies responsible for penetration to various distances in water from a fission source. Imagine a fission source sending neutrons normally into a slab of water, and neglect the oxygen cross section. At thickness t the spectrum of uncollided neutrons will be given by

$$\begin{aligned} S(E,t) &= e^{-\alpha E} e^{-\Sigma_H t} \\ &= e^{-\alpha E} e^{-\beta t/(E+\epsilon)} \end{aligned} \quad (15)$$

where a multiplicative constant has been ignored and

$$\begin{aligned} \alpha &= 0.75 \\ \beta &= 0.675 \\ \epsilon &= 1.66 \end{aligned} \quad (16)$$

At distance t the peak of the spectrum (the spectrum is bell-shaped) will be at an energy given by

$$\frac{d}{dE} \left(\alpha E + \frac{\beta t}{E + \epsilon} \right) = 0$$

$$\alpha = \frac{\beta t}{(E + \epsilon)^2}$$

or

$$E = \left(\frac{\beta t}{\alpha} \right)^{1/2} - \epsilon \quad (17)$$

In Table 7 we give this peak energy for several distances.

Several points are emphasized by Table 7. First, since mobile reactor shields have, in general, a water thickness of greater than 50 cm and less than 200 cm, both the approximate fission spectrum (Eq. 3) and the approximate hydrogen cross section (Eq. 14) will be adequate

Table 7—Peak Energy in Hydrogen Shield

t, cm	E, mev
50	5.0
100	7.8
150	9.9
200	11.7

for our purposes. The second point is that we shall require information about the neutron cross sections of the heavier shield constituents at energies in the range 5 to 12 mev.

The second point is the one that is pertinent here. Very little cross-section information exists in this energy region because of a combination of unfortunate and well-known limitations on present neutron sources. The situation is just now beginning to be rectified, but no useful experimental results can be expected for some time to come.

These difficulties can probably be surmounted without an extensive program of cross-section measurements. In the first place, it is just in the energy range of interest that rough theories of neutron interaction with nuclei become reasonably valid. By arguments given previously, only the total cross section, together with some information on the angular distribution of elastic scattering, will be of importance in calculating neutron attenuation. Methods for estimating these quantities are described in de-

tail in the final report of the Fast Neutron Data Project.¹⁸

This type of procedure, while promising for the future, still requires some experimental work to ensure the numerical values. It further requires a considerable amount of calculation in application to actual shield computations. A more direct approach, which seems to yield adequate precision, is fortunately available. This approach consists in the use of the concept of the effective-removal cross section previously mentioned. The lid tank can be regarded

Table 8—Measured Removal Cross Sections

Substance	σ_R , barns/atom
Pb	3.4
Fe	2.0
O	0.8
B ₄ C	0.9

as a device for measuring the cross sections of tested materials which are effective in removing neutrons from a beam. It will be shown in a subsequent article that neutron-attenuation tests on water plus other materials can, in general, be interpreted, to excellent accuracy, in terms of an energy-independent absorption coefficient for each element present (with the exception of hydrogen, whose absorption coefficient varies with energy as given by Eq. 14). This approach has been exploited by several workers,¹⁹⁻²¹ who have obtained more or less reliable removal cross sections for all materials which have been used in lid-tank tests to date. We designate the microscopic removal cross section by δ_R . The available results are given in Table 8.

The results in Table 8 are not of comparable accuracy, nor were they obtained in comparable geometries. The results for lead and iron are probably good to the number of figures given. They were obtained by analysis of lid-tank neutron data on lead-water²² and iron-water²³ mixtures. In each case a large quantity of data could be fitted with a single choice of δ_R . For these measurements the neutron detector was placed well out in water beyond the nearest metal, a particularly cleangeometry. The value quoted²⁴ for B₄C involves a similar geometry, but the data are very much less complete and δ_R is probably uncertain to within 0.1 barn.

The value for oxygen has been taken from a simple interpretation of the neutron attenuation in water, as measured in the lid tank. Unfortunately the oxygen removal must be deduced by adjusting a constant cross section so that in combination with the hydrogen-removal cross section (Eq. 14) the observed relaxation length in water (as a function of distance) is correctly reproduced. This is obviously less clean than the hypothetical procedure of introducing a slab of oxygen into a medium whose neutron attenuation has been measured. A value of δ_R for oxygen of 0.91 barn has been obtained by a straightforward use of the lid-tank thermal-flux measurements,²⁵ but present work indicates that a value of about 0.70 barn may follow from a careful analysis of the lid-tank dosimeter measurements.²⁶ The value quoted for oxygen must therefore be regarded as somewhat uncertain. It seems appropriate to reserve a discussion of the methods for obtaining these numbers to a later article, where attenuation calculations will be discussed in general.

It is perhaps well to emphasize that Table 8 could be made much more comprehensive and accurate by a very modest lid-tank program. Some of this work is now in progress, and results should be available shortly.

It is very worth while to attempt to condense Table 8 into a simple formula for removal cross section as a function of atomic weight. A definite trend of this sort is already apparent, and the simplest arguments indicate that such a formula should indeed make good sense. In the energy range of interest the scanty experimental evidence plus plausible theoretical arguments back up the contention that the total cross section is nearly constant with neutron energy and is closely given by

$$\sigma = 2\pi R^2 \quad (18)$$

where R is the nuclear radius. All evidence indicates that R is almost completely determined by the requirement that each nucleon in a nucleus be assigned a fixed volume (saturation property). We can then write R as

$$R = aA^{1/3} \quad (19)$$

where a is a length and A is the mass number of the nucleus. Although the constant a is known

to be about 1.5×10^{-13} cm, no very precise value is available.

Of the total cross section (Eq. 18), half will be reaction cross section and half will be shadow cross section. In accordance with arguments given earlier we therefore write

$$\delta_R = \pi R^2 [1 + f(E, R, x)] \quad (20)$$

In Eq. 20, the 1 inside the bracket takes into account the fact that all the reaction cross section acts as removal cross section. The quantity f is the fraction of shadow collisions which acts as removal cross section. This fraction is strictly a function of neutron energy and nuclear radius, as well as x , the position within the shield. The quantities E and R enter in the combination $R\sqrt{E}$, which is proportional to kR (k is the neutron wave number) and therefore determines the mean angle of shadow scattering (diffraction by an opaque sphere). Position in the shield should enter because a small-angle deflection far from the outer surface may be as effective in removing a neutron as a large-angle deflection near the outside.

Although the fraction f might be expected to vary rather little over the energy range of interest, the variation with $R(A^{1/3})$ and that with x may be more serious. A simple expression for f is the following, assuming, first, collision loss of the shadow-scattered neutron and a Gaussian (with correct behavior for small angles) for the differential shadow cross section,

$$f = \frac{\overline{\Sigma_R x}}{\overline{\Sigma_R x} + 0.10 A^{2/3} E} \quad (21)$$

The quantity $\overline{\Sigma_R x}$ is the normal distance to the outer surface of the shield (from the point of collision) multiplied by the average removal cross section for that section of shield. The second term in the denominator is essentially the reciprocal of the mean-square angle of deflection for shadow scattering. If $\overline{\Sigma_R x}$ is very large, then f is unity. This is also the case if the mean-square deflection angle is large so that Eq. 21 is quite plausible in form. The two terms in the denominator of Eq. 21 are quite commonly of the same order of magnitude, and f is then of the order of 0.5. There is certainly no a priori reason to assume a constant value for f , but no

large variation is to be expected for neutrons in the energy range of interest for medium and heavy nuclei which are followed by some hundred centimeters of shield. With these arguments in mind consider Table 9. The constancy of the values in the fourth column of Table 9 suggests that the variation of σ_R is principally just that of πR^2 , which in turn is fairly well correlated with that of the total cross section σ . The variation in the quantity f certainly shows up in the comparison of lead and iron, but perhaps more strongly than might be expected.

Table 9—Comparison of Experimental and Theoretical Removal Cross Sections

Substance	σ_R , barns/atom	A	$\sigma_R/\pi a^2 A^{2/3}$	σ
Pb	3.4	207	1.37	5.0
Fe	2.0	56	1.98	2.8
O	0.8	16	1.78	1.2
B ₄ C	0.9	11	2.56	

The concept of the removal cross section is then seen to be somewhat difficult to justify from first principles. In practice, however, it can give excellent results. In this connection it is important to remember that most of the neutron attenuation is performed by hydrogen; therefore the uncertainties we have described represent, for example, unimportant errors in shield-weight calculations. In the present state of knowledge it is a very reasonable procedure to predict a removal cross section for a new material by the use of Table 8 and judicious interpolation with the $A^{2/3}$ law. The very sketchy total-cross-section data can be used to supplement this procedure. Probably the most valuable further data to be obtained are the removal cross sections for a fair variety of materials, together with indications (as in the case of lead and iron) of the accuracy possible with such a simple procedure.

Gamma Cross Sections

The situation in regard to gamma cross sections for shielding work is very much different than that which we have described for neutrons. The gamma-ray cross sections are well known,

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but the gamma-ray sources (with the exceptions noted earlier in this article) are very poorly known. In actual attenuation calculations we shall therefore use a rough procedure which will be described and justified in a later article. For the present it is sufficient to remark that highly adequate tabulations of gamma-ray cross sections can be obtained from several sources.²⁷⁻³⁰

REFERENCES

1. T. W. Bonner, R. Ferrell, M. Rinehart, Report LA-715, Dec. 2, 1948; T. W. Bonner, Report AECD-3110, Dec. 2, 1948.
2. D. L. Hill, Report CP-3800, Apr. 14, 1947.
3. B. E. Watt, Report LA-718, Dec. 17, 1948.
4. N. Feather, Report BM-148.
5. N. Nereson, Report LA-1078, Mar. 8, 1950.
6. Donald J. Hughes, Report CF-3596, February 1946.
7. M. Deutsch and J. Rotblat, Report LA-170, Nov. 13, 1944.
8. B. B. Kinsey, R. C. Hanna, and D. Van Patter, Can. J. Research, 26A: 79 (1948).
9. K. Way and E. P. Wigner, Phys. Rev., 73: 1318 (1948).
10. W. K. Ergen, Report ANP-59, May 3, 1951.
11. J. M. Blatt and J. D. Jackson, Phys. Rev., 76: 18 (1949).
12. H. A. Bethe, Phys. Rev., 76: 38 (1949).
13. E. Melkonian, L. J. Rainwater, and W. W. Havens, Jr., Phys. Rev., 75: 1295 (1949).
14. D. J. Hughes, M. T. Burgy, and G. R. Ringo, Phys. Rev., 77: 291 (1950).
15. R. E. Bell and L. G. Elliot, Phys. Rev., 74: 1552 (1948).
16. J. D. Jackson and J. M. Blatt, Revs. Modern Phys., 22: 77 (1950).
17. R. K. Adair, Revs. Modern Phys., 22: 249 (1950).
18. B. T. Feld, H. Feshbach, M. L. Goldberger, H. Goldstein, and V. F. Weisskopf, Report NYO 636, Jan. 31, 1951.
19. R. D. Albert and T. A. Welton, Report WAPD-15, Nov. 30, 1950.
20. S. Podgor, Report ORNL-895, Jan. 23, 1951.
21. R. Zirkind, Report C.F. 51-8-102, Aug. 2, 1951.
22. C. E. Clifford et al., Report ORNL-768, Aug. 14, 1950, p. 36 ff.
23. C. E. Clifford et al., Report ORNL-768, Aug. 14, 1950, pp. 41-42.
24. E. P. Blizard and C. E. Clifford, Report ORNL-919, Feb. 27, 1951, p. 136.
25. E. P. Blizard and C. E. Clifford et al., Report ORNL-629, Apr. 19, 1950, p. 11.
26. E. P. Blizard and C. E. Clifford et al., Report ORNL-919, Feb. 27, 1951, pp. 125-126 and 131-132; E. P. Blizard and C. E. Clifford, C.F. 50-12-48, Dec. 15, 1950, p. 15 ff.
27. Richard Latter and Herman Kahn, Report R-170, Sept. 19, 1949.
28. W. S. Snyder and J. L. Powell, Report ORNL-421, Mar. 14, 1950.
29. G. R. White, Report NBS-1003 (to be printed).
30. G. Allen, N.A.C.A. Tech. Note 2026, February 1950.
31. L. E. Beghian, M. A. Grace, G. Preston, and H. Halban, Phys. Rev., 77: 286 (1950).
32. M. A. Grace, L. E. Beghian, G. Preston, and H. Halban, Phys. Rev., 82: 969 (1951).

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