MARTIN MARIETTA ENERGY SYSTEMS LIBRARIES
3 4456 0361430 0

CENTRAL RESEARCH LIBRARY
DOCUMENT COLLECTION

ORNL-2891
UC-38 – Equipment, Methods, and Techniques
TID-4500 (15th ed.)

AN EVALUATION OF SOLID MODERATING MATERIALS

T. S. Lundy
E. E. Gross

CENTRAL RESEARCH LIBRARY
DOCUMENT COLLECTION
LIBRARY LOAN COPY
DO NOT TRANSFER TO ANOTHER PERSON
If you wish someone else to see this document, send in name with document and the library will arrange a loan.

OAK RIDGE NATIONAL LABORATORY
operated by
UNION CARBIDE CORPORATION
for the
U.S. ATOMIC ENERGY COMMISSION

Printed in USA. Price $0.50. Available from the

Office of Technical Services
Department of Commerce
Washington 25, D.C.

LEGAL NOTICE

This report was prepared as an account of Government sponsored work. Neither the United States, nor the Commission, nor any person acting on behalf of the Commission:

A. Makes any warranty or representation, expressed or implied, with respect to the accuracy, completeness, or usefulness of the information contained in this report, or that the use of any information, apparatus, method, or process disclosed in this report may not infringe privately owned rights; or

B. Assumes any liabilities with respect to the use of, or for damages resulting from the use of any information, apparatus, method, or process disclosed in this report.

As used in the above, "person acting on behalf of the Commission" includes any employee or contractor of the Commission, or employee of such contractor, to the extent that such employee or contractor of the Commission, or employee of such contractor prepares, disseminates, or provides access to, any information pursuant to his employment or contract with the Commission, or his employment with such contractor.

ORNL-2891
UC-38 – Equipment, Methods, and Techniques

Contract No. W-7405-eng-26

METALLURGY DIVISION
and
REACTOR PROJECTS DIVISION

AN EVALUATION OF SOLID MODERATING MATERIALS

T. S. Lundy
E. E. Gross

DATE ISSUED

APR 11 1960

OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee
operated by
UNION CARBIDE CORPORATION
for the
U. S. ATOMIC ENERGY COMMISSION

MARTIN MARIETTA ENERGY SYSTEMS LIBRARIES

3 4456 0361430 0

CONTENTS

Abstract 1

Introduction 1

Calculation of Moderating Ratio 1

Calculation of Neutron Age 2

Continuous Slowing Down 5

Hydrogen Slowing Down 8

Results 8

Acknowledgments 9

AN EVALUATION OF SOLID MODERATING MATERIALS

T. S. Lundy E. E. Gross

ABSTRACT

Calculations of moderating ratio and neutron age have been used to evaluate potential solid moderators for nuclear applications. A desirable moderator would have a large moderating ratio and a small neutron age. Only materials that were stable solids at 300°C were considered. The minimum moderating ratio was taken as 20, and the maximum fission-to-thermal neutron age was set at 500 cm^2. Moderating ratios and neutron ages were calculated for many materials. Twelve hydrides and five nonhydrides were found that met the criteria. In general, the hydrides have low moderating ratios and neutron age values, whereas the nonhydrides have high values for both these nuclear properties.

INTRODUCTION

This work is part of a general survey undertaken by the Metallurgy Division to collect chemical, physical, and mechanical data on potential solid moderators. To somewhat limit the number of materials in the survey, only those that are stable solids at 300°C were considered. Further screening was accomplished by the use of the two nuclear parameters – moderating ratio and neutron age. The former considers only relative values of neutron slowing down and neutron absorption.

CALCULATION OF MODERATING RATIO

A good moderator should readily thermalize fast neutrons and have a small probability for absorbing the neutrons which have been thermalized. The moderating ratio of a material, defined as the ratio of the slowing-down power to the macroscopic absorption cross section, takes both factors into consideration.[1] This nuclear property is therefore useful in evaluating potential moderating materials. The moderating ratios of accepted moderators were examined, and a minimum value of 20 was selected as a screening criterion.

The moderating ratio for a mixture of N elements is given by

$$MR = \frac{\sum_{i=1}^{N} (SDP)_i}{\sum_{i=1}^{N} \Sigma_{a_i}} = \frac{\sum_{i=1}^{N} \xi_i \Sigma_{s_i}}{\sum_{i=1}^{N} \Sigma_{a_i}} , \qquad (1)$$

where

$(SDP)_i$ = the slowing-down power of atomic species i,

Σ_{a_i} = the macroscopic absorption cross section for i,

Σ_{s_i} = the macroscopic scattering cross section for i,

ξ_i = the average logarithmic energy decrement of the neutron per collision with i.

Since

$$\Sigma_{s_i} = N_i \sigma_{s_i}$$

and

$$\Sigma_{a_i} = N_i \sigma_{a_i} ,$$

where

N_i = the atomic concentration of species i,

σ_{s_i} = the microscopic scattering cross section for i,

σ_{a_i} = the microscopic absorption cross section for i,

Eq. (1) can be rewritten as

$$MR = \frac{\xi_1 \sigma_{s_1} + \xi_2 \frac{N_2}{N_1} \sigma_{s_2} + \ldots + \xi_N \frac{N_N}{N_1} \sigma_{s_N}}{\sigma_{a_1} + \frac{N_2}{N_1} \sigma_{a_2} + \ldots + \frac{N_N}{N_1} \sigma_{a_N}} . \qquad (2)$$

Thus, the moderating ratio is a function of the atomic ratios of the different species, their average

[1] S. Glasstone, *Principles of Nuclear Reactor Engineering*, Van Nostrand, New York, 1955.

logarithmic energy decrements per collision, and their microscopic scattering and absorption cross sections. It is independent of the material density.

For all calculations the average microscopic absorption cross sections for neutrons with velocities of 2200 m/sec were obtained from BNL-325.[2] The values were corrected to give the Maxwellian averaged thermal cross section at 20°C. The microscopic scattering cross sections evaluated at epithermal energies were obtained from the same source. Most of the values for the average logarithmic energy decrement per collision, ξ, were obtained from *Introduction to Nuclear Engineering;*[3] the remaining values were calculated from the equation

$$\xi = \frac{2}{A + \frac{2}{3}}, \tag{3}$$

where A is the mass of the struck particle. This formula is a good approximation for ξ when A is greater than 10 (ref 1).

The materials that were considered are listed in Table 1, along with the known melting points and the calculated moderating ratios. The materials which met the additional requirement that their moderating ratio be greater than 20 are retabulated in Table 2, along with the known densities, macroscopic-absorption cross sections, and slowing-down powers.

The low-absorbing B^{11} and Li^7 isotopes were used for the boron- and lithium-base materials. Supplementary calculations were made to determine the amount of high-absorbing B^{10} and Li^6 which could be tolerated in each case, consistent with the requirement of a minimum moderating ratio of 20. Of the boron compounds considered, $B_2^{11}O_3$ has the highest moderating ratio, 32.8. Other boron compounds with moderating ratios greater than 20 are $Li^7B^{11}O_2$ and $K_2B_2^{11}H_6$. The moderating ratio of $B_2^{11}O_3$ is decreased to 20 by reducing the isotopic purity of B^{11} to 99.9995%. Boron compounds were not considered further because of the unavailability of the B^{11} in isotopic purities required.

Of the lithium compounds considered, Li^7H has the highest moderating ratio, 64.8. Other Li^7 compounds with moderating ratios greater than 20 are $Li_2^7CO_3$, $Li_2^7C_2$, $Li^7B^{11}O_2$, Li^7HS, Li_2^7O, and Li^7F. Plots of the moderating ratios for these lithium compounds vs Li^7 isotopic purity are presented in Fig. 1. It may be seen that both Li^7H and Li^7HS have moderating ratios greater than 20 for reasonable isotopic purity ranges. However, uncertainties in the physical properties of LiHS, in addition to a low moderating ratio (25 at 99.99% Li^7 in Li), make its further consideration unnecessary.

One characteristic of hydrides is that the hydrogen content per unit volume varies with the temperature and pressure. It is necessary, therefore, to examine the nuclear properties of these materials in terms of varying hydrogen content. Curves of moderating ratio vs hydrogen content for the various solid hydrides considered are given in Fig. 2. As expected, the moderating ratio is strongly dependent on hydrogen content.

Of the materials considered, graphite, beryllium, beryllium oxide, and beryllium carbide are in a group by themselves on the basis of their high moderating ratios. It is natural, therefore, that they have been used or considered for use in thermal reactors where emphasis is placed on neutron economy.

CALCULATION OF NEUTRON AGE

Along with the moderating ratio, another important quantity which is useful in reactor design is the neutron age. The age is related to the fast nonleakage probability, P_f, through the relation

$$P_f = e^{-B^2\tau}, \tag{4}$$

where τ is the neutron age and B^2 is the geometrical buckling, which is inversely proportional to the square of the core dimensions. Therefore, the age is seen to be related to the size of a reactor core, since to limit the leakage of fast neutrons from the core to a given small amount, the volume of the core will vary as $\tau^{3/2}$.

Since the age is not simply related to cross-section data and since there is a lack of experimental age measurements, values for this property are hard to obtain for many reactor designs. To supplement available age data, calculations were

[2] D. J. Hughes and J. A. Harvey, *Neutron Cross Sections*, BNL-325 (July 1, 1955).

[3] R. L. Murray, *Introduction to Nuclear Engineering*, Prentice-Hall, Englewood Cliffs, N. J., 1954.

Table 1. Materials Known To Melt Above 300°C That Were Considered as Potential Moderators

Material	Melting Point (°C)	Moderating Ratio	Material	Melting Point (°C)	Moderating Ratio
Al	660	0.5	$Ca(B_2^{11}O_2)_2$	1154	7.3
AlB_2^{11}		4.8	$CaB_4^{11}O_7$	986	10.8
AlB_{12}^{11}		10.5	CaC_2	2300	4.5
Al_3C	2500*	1.6	$Ca(CN)_2$	>350*	1.2
Al_4C_3	2200*	2.8	$CaCN_2$	1300	<1.2
AlH_3		57.3	$CaCO_3$	1339	6.3
Al_2O_3	2050	4.0	CaH_2	1000	42.9
$AgLi^7$	955	0.0	CB_6^{11}		16.3
$AuBe_5$		0.1	CeB_4^{11}		3.3
B^{11}	2300	14.1	CeB_6^{11}		4.3
$B_4^{11}C$	2450	19.7	CeC_2		2.3
$B^{11}N$	3000**	1.1	CeH_2		34.1
$B_2^{11}O_3$	450	32.8	CoB^{11}	2760	0.3
$B_2^{11}S_3$	310	0.6	CrB^{11}	2760	0.3
$B_2^{11}S_5$	390	0.6	$Cr_3B_2^{11}$		<0.3
BaB_6^{11}	2270	3.0	CrC	1900	0.3
BaC_2		1.4	Cr_3C_2	1890	<0.3
BaH_2	1000	25.3	Cr_4C	1550*	<0.3
Be	1278	164.1	Cr_5C_2	1665	<0.3
Be_2C	>2100*	169.1	Cr_7C_3	1665	<0.3
$BeCl_2$	440	0.1	CoH		1.3
BeF_2	800	86.3	$Co_3B_2^{11}$		0.2
BeI_2	510	0.1	CuH		9.8
Be_3N_2	2200	2.0	FeB^{11}		0.4
BeO	2530	217.0	FeB_2^{11}		<1.0
$BeSO_4$	570	7.1	Fe_2B^{11}	1400	<0.4
$BiLi_3^7$	1145	0.0	$Fe_2B_3^{11}$		<1.0
C	>3500	191.2	$Fe_2B_5^{11}$		<1.0
CaB_6^{11}	2235	6.4	Fe_3C	1837	0.3

Table 1 (continued)

Material	Melting Point (°C)	Moderating Ratio	Material	Melting Point (°C)	Moderating Ratio
HfC	3887	< 1.0	Li_2^7NH		11.7
HfH		< 1.0	Li_2^7O	> 1700	21.2
$K_2B_2^{11}H_6$	300*	23.3	Li_3^7Pb	658*	4.5
$KB^{11}F_4$	530	1.2	$Li_3^7PO_4$	837	14.8
$KB^{11}O_2$	950	0.9	Li_2^7S	950	1.5
KH	840	16.6	Li_3^7Sb	> 950	0.2
KHS	455	8.3	$Li_4^7SiO_4$	1256	15.6
KNH_2	335	11.0	Li_4^7Sn	752	2.1
LaB_6^{11}	2210	0.5	$Li_2^7SO_4$	860	5.1
LaC_2		0.2	$Mg(AlH_4)_2$		58.7
LaH_3		11.6	MgC_2	800*	30.1
Li^7	186	11.2	Mg_2C_3	800*	24.6
Li^7AlO_2	> 1625	5.6	MgH_2	300*	64.4
Li_3^7As		0.3	MgO		15.2
$Li_3^7AsO_3$		0.7	$Mn_3B_4^{11}O_9$		0.2
$Li^7B^{11}O_2$	840	28.2	MoB_2^{11}		0.6
Li^7Br	547	0.1	MoC	2690	0.4
$Li_2^7C_2$		34.1	$NaAlH_4$		14.4
Li^7Cl	613	0.4	$NaB^{11}H_4$	> 400	16.0
$Li_2^7CO_3$	618	48.4	$Na_2B_4^{11}H_4$	741	0.7
$Li_2^7CrO_4$		1.0	Na_2C_2	700	0.2
Li^7F	870	20.8	NaH	855	7.3
Li^7H	680	64.8	NbB_2^{11}	2900	1.3
Li^7HS		27.7	NbC	3900	0.8
Li^7I	446	0.1	NbH		16.3
$Li_2^7MoO_4$	705	1.1	NdH		0.8
Li_3^7W	840	1.3	NiB^{11}		0.3
Li^7NH_2	375	19.5	NiH_2		8.9

Table 1 (continued)

Material	Melting Point (°C)	Moderating Ratio	Material	Melting Point (°C)	Moderating Ratio
Pd_2H		2.3	TiC	3140	0.2
PrH_3		9.3	TiH		3.3
PuH_2		0.1	TiH_2		6.8
RbH	300*	22.8	$TIB_2^{11}O_5$	434	1.2
SiB_3^{11}		8.0	$TIB^{11}O_2$	472	0.8
SiB_6^{11}		11.4	VB_2^{11}		0.3
SiC	2600	6.6	VC	2810	0.2
Si_2C		3.8	WB_2^{11}	2900	0.1
SiO_2		8.7	YbC		0.0
SmC_2		0.0	YH_3		29.3
SrH_6^{11}	2235	3.0	YC_2		1.1
SrC_2		1.5	ZnH_2		27.0
SrH_2	~1000*	25.6	ZrB_2^{11}	3000	5.6
TaB_2^{11}	3000	0.1	ZrC	3540	5.1
TaH		1.8	ZrH_2		55.3
TiB_2^{11}	2600	0.3			

*Material decomposes without melting.

**Sublimation temperature.

made employing the continuous slowing-down theory for nonhydrogenous materials and a semi-empirical slowing-down theory for hydrogenous materials. These calculations neglected the contributions of inelastic scattering to the slowing-down process. The resulting ages were used to further screen moderating materials by considering the maximum allowable age to be 500 cm^2.

Continuous Slowing Down

According to the continuous slowing-down theory,[1] the slowing-down density, q, in an infinite medium from a monoenergetic point source at the origin is given by

$$q(r,\tau) = \frac{S_0\, e^{-r^2/4\tau}}{(4\pi\tau)^{3/2}}\,, \qquad (5)$$

where S_0 = source strength in neutrons/sec. The age is given by

$$\tau(u) = \int_0^u \frac{du}{3\Sigma_{tr}(u)\,\xi\Sigma_s(u)}\,, \qquad (6)$$

where

$$\Sigma_{tr}(u) = \sum_i N_i\,\sigma_{s_i}(u)\left(1 - \frac{2}{3A_i}\right). \qquad (7)$$

The second moment of the distribution given by Eq. (5) is

$$\overline{r^2}(\tau) = \frac{\int_0^\infty (r^2 e^{-r^2/4\tau})\, r^2\, dr}{\int_0^\infty e^{-r^2/4\tau}\, r^2\, dr} = 6\tau\,. \qquad (8)$$

Table 2. Materials from Table 1 with Moderating Ratio > 20

Material	Moderating Ratio	Density (g/cm^3)	$\bar{\Sigma}_{a_{th}}$ at 20°C (cm^{-1})	SDP (cm^{-1})
BeO	217.0	2.80	0.00061	0.1322
C	191.2	1.62	0.00032	0.0616
Be_2C	169.1	1.90	0.00083	0.1397
Be	164.1	1.85	0.00110	0.1797
BeF_2	86.3	1.986	0.00066	0.0573
Li^7H	64.8	0.82	0.01985	1.2864
MgH_2	64.4	1.42	0.02081	1.3401
$Mg(AlH_4)_2$	58.7	3.50*	0.06800	3.9916
AlH_3	57.3	2.50*	0.05381	3.0833
ZrH_2	55.3	5.47	0.02629	1.4536
$Li_2^7CO_3$	48.4	2.111	0.00099	0.0480
CaH_2	42.9	1.70*	0.02348	1.0075
CeH_2	34.1	5.50*	0.02809	0.9579
$Li_2^7C_2$	34.1	1.65	0.00017	0.0589
$B_2^{11}O_3$	32.8	1.844	0.00261	0.0855
MgC_2	30.1	1.33*	0.00102	0.0307
YH_3	29.3	4.04*	0.05526	1.6191
$Li^7B^{11}O_2$	28.2	3.00*	0.00267	0.0753
Li^7HS	27.7	1.50*	0.01704	0.4720
ZnH_2	27.0	5.00*	0.06816	1.8403
SrH_2	25.6	3.27	0.03543	0.9070
BaH_2	25.3	4.21	0.02955	0.7475
Mg_2C_3	24.6	2.92*	0.00250	0.0615
$K_2B_2^{11}H_6$	23.3	1.18	0.03575	0.8329
RbH	22.8	2.00*	0.01267	0.2888
Li_2^7O	21.2	2.013	0.00238	0.0504
Li^7F	20.8	2.601	0.00223	0.0464

*Density not known, but a reasonable value assumed; both Σ_a and SDP are directly proportional to the density.

Regarding Eq. (8) as the definition for τ, the age from a spectral source may be shown to be

$$\bar{\tau}(u) = \int_0^u du' S(u') \int_{u'}^u \frac{du''}{3\Sigma_{tr}(u'')\,\xi\Sigma_s(u'')} , \quad (9)$$

where $S(u')$ is the normalized source spectrum.

Equation (9) has been coded for the Oracle by Tobias.[4] The integration is approximated by a summation over Eyewash lethargy groups[5] ranging from zero lethargy at 10 Mev to a lethargy of 19.0 at an energy of 0.045 ev. First and last flight corrections were added to the Oracle results using the relations[6]

$$F_1 = \frac{1}{3\Sigma_t^2(E_1)} \quad (10)$$

and

$$F_2 = \frac{1}{3\Sigma_t^2(E_2)} , \quad (11)$$

where

F_1 and F_2 = the first and last flight corrections, respectively,

$\Sigma_t(E_1)$ = total macroscopic cross section at 2 Mev,

$\Sigma_t(E_2)$ = total macroscopic cross section at 0.045 ev.

Resulting ages to 0.045 ev for nonhydrogenous materials are presented in Table 3. Since neutron

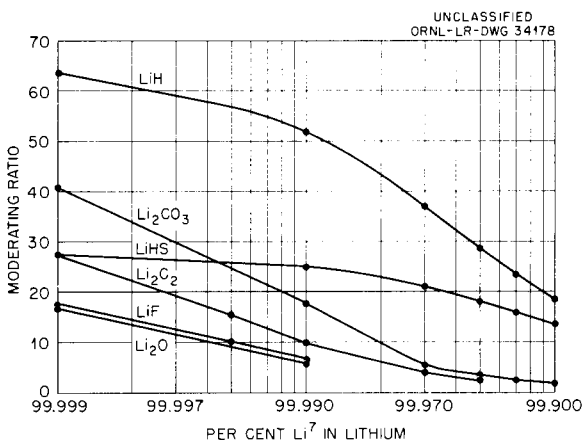

Fig. 1. Moderating Ratio vs Li^7 Content for Various Lithium Compounds.

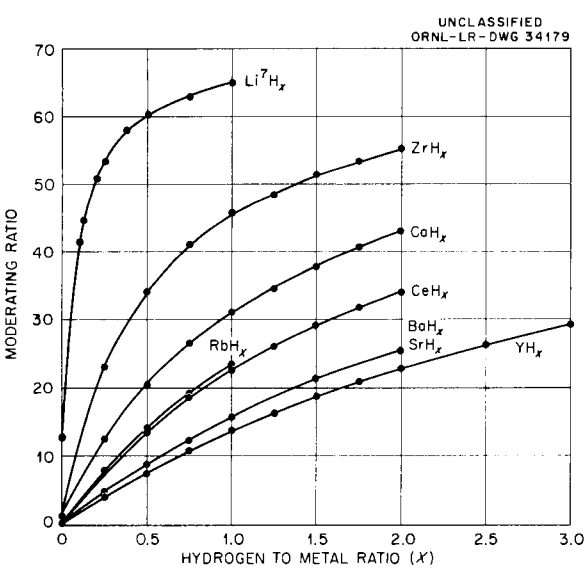

Fig. 2. Moderating Ratio vs Hydrogen Content for Selected Hydrides.

[4]M. Tobias, *An Oracle Code for Calculations of Fermi Ages by Numerical Integration*, ORNL CF-56-4-53 (1956).

[5]J. H. Alexander and N. D. Given, *A Machine Multigroup Calculation*, ORNL-1925 (1955).

[6]A. M. Weinberg and E. P. Wigner, *The Physical Theory of Neutron Chain Reactors*, p 327, University of Chicago Press, 1958.

Table 3. Fermi Age for Nonhydrogenous Materials

Material	Density (g/cm^3)	Calculated Age to 0.045 ev (cm^2)	Published* Age to 0.025 ev (cm^2)
Be	1.85	79.94	98
BeO	2.80	115.80	110
Graphite	1.62	342.31	350
Be_2C	2.20	82.52	
BeF_2	1.986	387.88	
Li_2CO_3	2.111	368.18	
Li_2C_2	1.65	318.43	
MgC_2	2.00	442.90	
Mg_2C_3	1.80	260.95	
Li_2O	2.013	394.62	
LiF	2.601	342.13	

*S. Glasstone, *Principles of Nuclear Reactor Engineering*, Van Nostrand, New York, 1955.

age is inversely proportional to the square of the moderator density [Eq. (2)], corrections for different density materials may easily be made. In comparison with available experimental data the agreement is quite good, except for the case of beryllium.

Hydrogen Slowing Down

The continuous slowing-down model is known to be a poor representation of hydrogen slowing down, especially for neutrons with energies greater than a few hundred kilovolts. Flügge[7] has suggested treating high-energy collisions in a stepwise fashion until the neutrons slow down to about 100 kev. Below 100 kev the slowing-down process is treated as continuous slowing down, that is,

$$\tau(10^5 \text{ ev} \rightarrow 0.045 \text{ ev}) = \int_{0.045}^{10^5} \frac{1}{3\Sigma_{tr}(E)\,\xi\Sigma_s(E)} \frac{dE}{E} . \quad (12)$$

Above 10^5 ev the second moment of the slowing-down distribution is taken to be

$$\overline{r^2}\left(E_0 \rightarrow \frac{E_0}{e^N}\right) = 2 \sum_{n=0}^{N} \lambda_{sn}\left(\frac{E_0}{e^n}\right) , \quad (13)$$

where $\lambda_{sn}(E_0/e^n)$ is an "effective" mean free path for scattering at the neutron energy E_0/e^n and N is such that $E_0/e^N \leq 0.1$ Mev, in the notation of Tittle.[8] The form of Eq. (13) arises when considering the mean square distance that a neutron travels between successive collisions. Tittle gives a semiempirical method for obtaining the "effective" mean free path, which may be summarized by the equation[9]

$$\frac{\lambda_{sn}(E_0/e^n)}{\lambda_{sT}(E_0/e^n)} = 2.16 - 0.016 \frac{\lambda_x(E_0/e^n)}{\lambda_H(E_0/e^n)} , \quad (14)$$

where $\lambda_{sT}(E_0/e^n)$ is the total mean free path for scattering, $\lambda_x(E_0/e^n)$ is the mean free path for scattering from nonhydrogenous nuclei, and $\lambda_H(E_0/e^n)$ is the mean free path for hydrogen scattering; all mean free paths are evaluated at the energy E_0/e^n. The total age from an initial energy, E_0, down to 0.045 ev is then given by

$$\tau(E_0 \rightarrow 0.045) = \frac{1}{3} \sum_{n=0}^{N} \lambda_{sn}^2\left(\frac{E_0}{e^n}\right) + \int_{0.045}^{E_0/e^N} \frac{1}{3\Sigma_{tr}(E)\,\xi\Sigma_s(E)} \frac{dE}{E} , \quad (15)$$

and the average age over a spectral source is given by

$$\overline{\tau}(0.045) = \frac{\int_0^\infty S(E_0)\,\tau(E_0 \rightarrow 0.045)\,dE_0}{\int_0^\infty S(E_0)\,dE_0} , \quad (16)$$

where $S(E_0)$ is the source distribution. Equation (16), together with the auxiliary Eqs. (14) and (15), has been coded for Oracle computation[10] by using the same lethargy grouping and fission spectrum as in the previously described continuous slowing-down age code.[11]

The code was used to compute neutron ages for the solid hydrogenous materials. Ages for water and aluminum-water mixtures were also calculated so that the values could be compared with published experimental data.[12] Results of the calculations are given in Table 4. Agreement of the calculations with published experimental values is good.

RESULTS

The process of using calculations of moderating ratio and neutron age appears to be a useful method for screening materials that might possibly be considered as solid moderators for nuclear reactors. The hydrides and nonhydrides investigated which met the established screening criteria are listed in Table 5 in order of decreasing moderating ratios and in Table 6 in order of increasing age values.

---

[7] F. S. Flügge, *Physik. Z.* 44, 445–55 (1943).

[8] C. W. Tittle, in *Nuclear Shielding Studies*, NP-1418, p 35–55 (1949).

[9] R. L. Murray, *Nuclear Reactor Physics*, p 279, Prentice-Hall, Englewood Cliffs, N. J., 1957.

[10] R. R. Bate *et al.*, *Description and Operating Manual for the Three Group Oracle*, ORNL CF-55-1-76 (January 1955).

[11] M. Tobias, *An Oracle Code for Calculations of Fermi Ages by Numerical Integration*, ORNL CF-56-4-53 (1956).

[12] J. E. Hill, L. D. Roberts, and T. E. Fitch, *J. Appl. Phys.* 26, 1018 (1955).

Table 4. Fermi Age for Hydrogenous Materials

Material	Density (g/cm^3)	Calculated Age to 0.045 ev (cm^2)	Material	Density (g/cm^3)	Calculated Age to 0.045 ev (cm^2)
H_2O	1.0	31.29 (31.8)*	ZrH	4.80	49.12
Al-H_2O (2:1 by vol)		108.85	Zr_2H	5.00	81.45
Al-H_2O (1:1 by vol)		78.17 (79.8)*	YH_3	4.00	17.71
Al-H_2O (1:2 by vol)		59.38 (51.6)*	YH_2	3.96	31.66
AlH_3	2.5	5.71	YH	3.91	72.24
AlH_2	2.42	11.79	CaH_2	1.70	49.49
AlH	2.33	33.77	CaH	1.66	147.60
$Mg(AlH_4)_2$	3.50	3.37	CeH_2	4.00	70.79
MgH_2	1.42	29.00	CeH	3.97	174.95
MgH	1.35	79.36	ZnH_2	5.00	12.86
$LiAlH_4$	2.50	4.88	ZnH	4.93	33.12
LiH	0.82	26.89	SrH_2	2.50	72.51
ZrH_2	4.50	25.85	SrH	2.49	164.02
Zr_2H_3	4.60	34.96	BaH_2	4.21	56.55
			BaH	4.18	129.32
			RbH	2.00	210.39

*Published age: R. L. Murray, *Nuclear Reactor Physics*, p 279, Prentice-Hall, Englewood Cliffs, N. J., 1957.

There are marked differences in the nuclear properties of the hydrides and the nonhydrides. The hydrides, as a group, have ages considerably less than 500 cm^2 but moderating ratios close to the minimum value of 20. The nonhydrides, on the other hand, have much higher ages but extremely good moderating ratios. Only the nonhydrides need be considered for thermal-reactor application where neutron economy is of primary importance and reactor size is secondary. For a reactor with emphasis on minimum size instead of neutron economy, a hydride would be favored as the moderator.

ACKNOWLEDGMENTS

The authors appreciate the assistance of M. Tobias, W. Nestor, and W. E. Kinney in implementing the neutron-age calculations. Thanks are also extended to D. T. Bourgette and J. H. Cherubini for their help in determining available isotopic purities of Li^7 and B^{11}, and to R. C. Waugh for his helpful comments in preparation of the manuscript.

Table 5. Hydrides and Nonhydrides in Order of Decreasing Moderating Ratio

Material	Moderating Ratio
Hydrides	
Li^7H	64.8
MgH_2	64.4
$Mg(AlH_4)_2$	58.7
AlH_3	57.3
ZrH_2	55.3
CaH_2	42.9
CeH_2	34.1
YH_3	29.3
ZnH_2	27.0
SrH_2	25.6
BaH_2	25.3
RbH	22.8
Nonhydrides	
BeO	217.0
Graphite	191.2
Be_2C	169.1
Be	164.1
BeF_2	86.3

Table 6. Hydrides and Nonhydrides in Order of Increasing Age

Material	Density (g/cm^3)	Calculated Age to 0.045 ev (cm^2)
Hydrides		
$Mg(AlH_4)_2$	3.5	3.37
AlH_3	2.5	5.71
ZnH_2	5.0	12.86
YH_3	4.0	17.71
ZrH_2	4.5	25.85
Li^7H	0.82	26.89
MgH_2	1.42	29.00
CaH_2	1.7	49.49
BaH_2	4.21	56.55
CeH_2	4.0	70.79
SrH_2	2.5	72.51
RbH	2.0	210.39
Nonhydrides		
Be	1.85	79.94
Be_2C	2.20	82.52
BeO	2.80	115.80
Graphite	1.62	342.31
BeF_2	1.986	387.88

INTERNAL DISTRIBUTION

1. G. M. Adamson
2. J. W. Allen
3. R. J. Beaver
4. D. S. Billington
5. E. P. Blizard
6. A. L. Boch
7. E. G. Bohlmann
8. E. S. Bomar, Jr.
9. B. S. Borie
10. C. J. Borkowski
11. D. T. Bourgette
12. G. E. Boyd
13. R. B. Briggs
14. C. E. Center (K-25)
15. R. A. Charpie
16. J. H. Cherubini
17. G. W. Clark
18. R. E. Clausing
19. R. S. Cockreham
20. J. H. Coobs
21. E. Creutz (Consultant)
22. F. L. Culler
23. J. E. Cunningham
24. J. H. DeVan
25. D. A. Douglas
26. J. C. Ebersole
27. L. B. Emlet (K-25)
28. J. I. Federer
29. J. H. Frye, Jr.
30. N. J. Grant (Consultant)
31. R. J. Gray
32. W. R. Grimes
33. E. E. Gross
34. E. Guth
35. J. P. Hammond
36. C. S. Harrill
37. V. O. Haynes
38. R. L. Heestand
39. T. Hikido
40. M. R. Hill
41. E. E. Hoffman
42. A. Hollaender
43. A. S. Householder
44. L. K. Jetter
45. W. H. Jordan
46. P. R. Kasten
47. C. P. Keim
48. M. T. Kelley
49. W. E. Kinney
50. W. J. Kucera
51. J. A. Lane
52. H. Leidheiser, Jr. (Consultant)
53. C. F. Leitten, Jr.
54. A. P. Lotts
55. S. C. Lind
56. R. S. Livingston
57. T. S. Lundy
58. H. G. MacPherson
59. W. D. Manly
60. H. C. McCurdy
61. C. J. McHargue
62. J. R. McNally
63. A. J. Miller
64. E. C. Miller
65. K. Z. Morgan
66. J. P. Murray (Y-12)
67. F. H. Neill
68. M. L. Nelson
69. P. Patriarca
70. A. M. Perry
71. D. Phillips
72. M. L. Picklesimer
73. P. M. Reyling
74. H. W. Savage
75. A. W. Savolainen
76. L. D. Schaffer
77. H. E. Seagren
78. T. S. Shevlin (Consultant)
79. E. D. Shipley
80. M. J. Skinner
81. C. S. Smith (Consultant)
82. G. P. Smith
83. A. H. Snell
84. E. E. Stansbury (Consultant)
85. J. A. Swartout
86. A. Taboada
87. E. H. Taylor
88. W. C. Thurber
89. M. Tobias
90. T. D. Watts
91. M. S. Wechsler
92. A. M. Weinberg

93. G. C. Williams
94. R. C. Williams
95. J. C. Wilson
96. C. E. Winters
97. M. L. Winton
98. H. L. Yakel, Jr.
99-118. Laboratory Records Department
119. Laboratory Records Department, ORNL R.C.
120. Biology Library
121-122. Central Research Library
123. Health Physics Library
124. Metallurgy Library
125-127. ORNL – Y-12 Technical Library
Document Reference Section
128. Reactor Experimental Engineering Library

EXTERNAL DISTRIBUTION

129. Capt. L. P. Crocker, APB-DRD, AEC, Washington
130. R. C. Dalzell, DRD-AEC, Washington
131. E. C. Edgar, Alco Products, Inc., Schenectady, New York
132. J. G. Gallagher, Alco Products, Inc., Schenectady, New York
133. K. Kasschau, Alco Products, Inc., Schenectady, New York
134. Lt. Comd. C. W. Mallory, APB-DRD, AEC, Washington
135. J. O'Brien, Martin Co., Nuclear Division, Baltimore, Maryland
136. S. Paprocki, Battelle Memorial Institute
137. Lt. D. A. Pistenma, APB-DRD, AEC, Washington
138. R. Ray, KAPL
139. Major W. E. Ray, NPFO, EROL, Ft. Belvoir, Virginia
140. R. D. Robertson, Alco Products, Inc., Schenectady, New York
141. Lt. Col. H. C. Schrader, APB-DRD, AEC, Washington
142. J. M. Simmons, DRD-AEC, Washington
143. R. C. Waugh, Metals and Controls Nuclear, Inc., Attleboro, Mass.
144. Col. D. G. Williams, APB-DRD, AEC, Washington
145. Division of Research and Development, AEC, ORO
146–601. Given distribution as shown in TID-4500 (15th ed.) under Equipment, Methods, and Techniques category (75 copies – OTS)