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SHIELDING EFFICIENCY OF METAL HYDRIDES AND BOROHYDRIDES IN FUSION REACTORS

by

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Mass attenuation coefficients, mean free paths and exposure buildup factors have been used to characterize the shielding efficiency of metal hydrides and borohydrides, with high density of hydrogen. Gamma ray exposure buildup factors were computed using five-parameter geometric progression fitting at energies 0.015 MeV to15 MeV, and for penetration depths up to 40 mean free paths. Fast-neutron shielding efficiency has been characterized by the effective neutron removal cross-section. It is shown that ZrH_2 and VH_2 are very good shielding materials for gamma rays and fast neutrons due to their suitable combination of low- and high-*Z* elements. The present work should be useful for the selection and design of blankets and shielding, and for dose evaluation for components in fusion reactors.

Key words: hydride, boron hydride, buildup, shielding, fusion reactor

INTRODUCTION

Radiation shielding is an important aspect when designing new and efficient materials for fusion reactors. New generation fusion reactors are compact in size and require low-thickness materials for shielding and heat removal. Materials for radiation shielding are selected from specifications of low radioactive waste (radwaste), low background radiation outside the shield and low nuclear heat. Radiation shielding depends on operating parameters and radiations in the reactor. High-energy and high-intensity neutrons, produced by fusion plasma, have a significant effect on the life span of components in fusion reactors. The deuterium-tritium fusion reaction in the plasma produces 14.1 MeV neutrons, whereas the average neutron energy in fission reactors is about 2 MeV. Thus, high-energy neutrons in a fusion reactor will induce reactions that do not occur in fission reactors. Emitted gamma rays have energies up to 10-20 MeV [1]. Gilbert *et al*. [2] have developed an integrated model for material irradiation, producing defects, transmutation of elemental atoms, swelling and embrittlement. Recently, metal hydrides and borohydrides have been suggested as advanced shielding materials for fusion reactors [3]. The shielding efficiency of gamma rays and neutrons in fission reactors has been investigated for concretes [4, 5] and alloys [6, 7]. However, a corresponding study of metal hydrides and borohydrides has until now been lacking.

Various researchers have used geometric-progression (G-P) fitting to determine gamma ray buildup factors for alloys [6], fly-ash materials [8], concrete shielding [5], brick materials [9], gaseous mixture [10], thermoluminescent dosimetric materials [11], heavy metal oxide glasses [12], and human organs and tissues [13]. These studies show that G-P fitting is useful for estimating buildup factors.

In the present work, we have investigated the shielding efficiency of metal hydrides and borohydrides in terms of the mass attenuation coefficient, the mean free path (mfp) and the exposure buildup factor (EBF). Exposure buildup factors were calculated using G-P fitting at photon energies 0.015-15 MeV, and for penetration depths up to 40 mfp. The results should be useful in various applications of radiation exposure and shielding, *e. g.* in the design of fusion reactors.

MATERIALS AND METHODS

Metal hydrides and borohydrides $Mg(BH_4)_2$, $NaBH_4$, VH_2, TiH_2, ZrH_2, and BaH_2 have been recommended by Hayashi *et al*. [3] for neutron shielding because of their high hydrogen concentration. The mass density is in the range 1.08 g/cm^3 to 5.6 g/cm^3. The hydrogen density ranges from 3.6 10^{22} cm^{-3} to 13.2 10^{22} cm^{-3}. The materials are available as powders and can easily be pre-

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pared in any shape desired. The compounds can also be mixed with other materials for tailoring the shielding properties.

Mass attenuation coefficients (μ/ρ) of the selected metal hydrides and borohydrides were calculated with the WinXcom software [14]. The mean free path, mfp, is the reciprocal of the linear attenuation coefficient (μ). Atomic weights of the elements have been taken from the recent technical report of the International Union of Pure and Applied Chemistry (IUPAC) [15].

The ANSI/ANS-6.4.3-1991 (ANS, 1991) [16] standard by the American Nuclear Society is a compilation of buildup factors at energies 0.015-15 MeV, and for penetration depths up to 40 mean free paths (mfp) and elements $Z = 4$ to $Z = 92$*. Harima *et al.* [17] have developed a five-parameter fitting formula, called G-P, which gives the buildup factors for compounds and mixtures, see also the historical review by Harima [21]. G-P fitting is known to be accurate within 5 %. The buildup factor $B(E, x)$ can be calculated from the following equations [17, 21]

$$B(E,x) = 1 + \frac{b-1}{K-1}(K^x - 1), \text{ for } K \neq 1 \qquad (1)$$

$$B(E,x) = 1 + (b-1)x, \text{ for } K = 1 \qquad (2)$$

$$K(e,x) = cx^a + d\frac{\tanh(x/X_K - 2) - \tanh(-2)}{1 - \tanh(-2)} \qquad (3)$$

where E is the source energy, x – the penetration depth in units of mfp, and a, b, c, d, and X_K are G-P fitting parameters.

The buildup of photons is mainly due to multiple Compton scattering, and for a compound or mixture it can be characterized by an equivalent atomic number Z_{eq}. The buildup factor of a given material can be calculated in a three-step procedure [5, 6, 8, 11, 12, 13]. First, Z_{eq} is calculated by logarithmic interpolation using the ratio, $(\mu/\rho)_{Compton}/(\mu/\rho)_{total}$. Knowing Z_{eq}, the G-P fitting parameters are then calculated using a similar interpolation formula [22, 23]. Finally, the buildup factors are calculated from the G-P fitting parameters using equations (1)-(3). Z_{eq} and the G-P fitting parameters of the present work are given in tabs. 1-6. The exposure buildup factors are given in tab. 7.

The effective removal cross-section is approximately constant for neutron energies 2-12 MeV [24]. The observed neutron removal cross-sections are roughly 2/3 of the total cross-section for neutrons having energies 6-8 MeV [25]. The effective neutron removal cross-section of a compound or homogenous mixture can with good approximation be calculated by the mixture rule using the removal cross-section Σ_R [cm^{-1}] or the mass removal cross-section Σ_R/ρ [cm^{2}g^{-1}] of the constituent elements [26]. Mass removal cross-sections of the elements have been taken from Kaplan, Chilten *et al.*, Profio, and El-Khayatt [24, 27-29].

* It should be mentioned that the ANSI/ANS.6.4.3 (ANS, 1991) standard has been administratively withdrawn. However, work is in progress for updating this much used standard, cf. Ryman *et al.* [18], Ruggieri & Sanders [19], and Luis [20]

Uncertainties

The uncertainty of Z_{eq} is determined by the uncertainties of the Compton and total attenuation cross-sections. Except for the fine structure immediately above absorption edges, the uncertainty is less than 1-2 % in the Compton region (10 keV-1 MeV). At medium energies (1-100 MeV), the uncertainty is slightly larger (2-3 %) due to the additional uncertainty of the pair-production cross-section, particularly in the photonuclear giant resonance region 10-30 MeV [30].

EBF values from ANSI/ANS-6.4.3, G-P fitting, and the general-purpose Monte Carlo N-Particle (MCNP-5) code [20] are compared in fig. 1 for water. The maximum deviation of EBF in G-P fitting is within 0.5-3 % [17]. The present calculations of the buildup factor agree with ANSI/ANS-6.4.3 for air and water within a few %. The MCNP-5 results differ at most by 14 % [20]. The values for the effective neutron removal cross- section are accurate within 10 % for aluminum, beryllium, graphite, hydrogen, iron, lead, oxygen, boron carbide, *etc.* [25].

RESULTS AND DISCUSSION

Gamma ray shielding efficiencies of selected metal hydrides and borohydrides have been investigated in terms of the mass attenuation coefficient, μ/ρ,

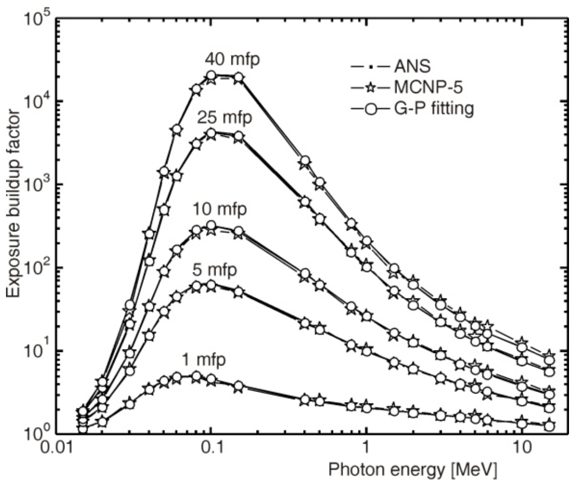

Figure 1. Exposure buildup factors of water obtained from the ANS, 1991 standard (line) and the MCNP-5 code (stars) compared with those of the present work using G-P fitting (circles) at photon energies 0.015-15 MeV, and for penetration depths 1-40 mfp

Table 1. Equivalent atomic numbers and G-P fitting parameters for Mg $(BH_4)_2$ for photon energy 0.015-15 MeV

Energy [MeV]	Z_{eq}	*a*	*b*	*c*	*d*	X_K
1.50E-02*	9.01	0.202	1.115	0.412	–0.103	13.448
2.00E-02	9.11	0.182	1.260	0.461	–1.282	14.199
3.00E-02	9.23	0.126	1.755	0.611	–0.066	15.575
4.00E-02	9.29	0.053	2.498	0.836	–0.030	14.843
5.00E-02	9.33	0.013	3.256	1.032	–0.017	13.912
6.00E-02	9.36	–0.032	3.736	1.241	0.004	13.514
8.00E-02	9.39	–0.086	4.035	1.532	0.031	13.649
1.00E-01	9.42	–0.112	3.927	1.697	0.041	14.106
1.50E-01	9.45	–0.127	3.518	1.811	0.044	14.600
2.00E-01	9.47	–0.134	3.134	1.845	0.047	14.348
3.00E-01	9.49	–0.128	2.756	1.779	0.043	14.157
4.00E-01	9.50	–0.119	2.549	1.698	0.041	14.675
5.00E-01	9.51	–0.112	2.407	1.628	0.039	14.557
6.00E-01	9.51	–0.102	2.303	1.561	0.034	14.917
8.00E-01	9.51	–0.090	2.148	1.472	0.033	14.751
1.00E+00	9.64	–0.076	2.054	1.382	0.028	15.139
1.50E+00	6.99	–0.058	1.969	1.271	0.025	14.796
2.00E+00	6.80	–0.041	1.865	1.179	0.018	13.957
3.00E+00	6.76	–0.014	1.726	1.060	0.005	13.500
4.00E+00	6.74	0.004	1.636	0.988	–0.005	18.057
5.00E+00	6.73	0.018	1.565	0.940	–0.012	13.810
6.00E+00	6.73	0.029	1.519	0.903	–0.018	12.947
8.00E+00	6.72	0.034	1.427	0.882	–0.021	13.094
1.00E+01	6.72	0.038	1.364	0.868	–0.022	13.711
1.50E+01	6.71	0.047	1.272	0.841	–0.033	15.104

* Read as 1.50 10^{-2}

Table 2. Equivalent atomic numbers and G-P fitting parameters for $NaBH_4$ for photon energy 0.015-15 MeV

Energy [MeV]	Z_{eq}	*a*	*b*	*c*	*d*	X_K
1.50E-02	9.13	0.203	1.111	0.410	–0.104	13.332
2.00E-02	9.19	0.184	1.253	0.458	–1.223	14.165
3.00E-02	9.28	0.128	1.745	0.607	–0.067	15.548
4.00E-02	9.31	0.054	2.488	0.833	–0.030	14.864
5.00E-02	9.34	0.013	3.253	1.031	–0.017	13.913
6.00E-02	9.35	–0.032	3.739	1.242	0.004	13.514
8.00E-02	9.37	–0.087	4.045	1.537	0.031	13.650
1.00E-01	9.39	–0.113	3.937	1.704	0.042	14.101
1.50E-01	9.41	–0.128	3.527	1.818	0.045	14.597
2.00E-01	9.42	–0.135	3.139	1.852	0.047	14.338
3.00E-01	9.43	–0.129	2.760	1.785	0.043	14.159
4.00E-01	9.44	–0.120	2.552	1.703	0.041	14.657
5.00E-01	9.44	–0.112	2.410	1.632	0.039	14.543
6.00E-01	9.44	–0.102	2.305	1.564	0.035	14.893
8.00E-01	9.45	–0.091	2.150	1.474	0.033	14.731
1.00E+00	9.45	–0.077	2.059	1.386	0.028	15.054
1.50E+00	7.69	–0.057	1.941	1.267	0.024	14.558
2.00E+00	7.55	–0.038	1.846	1.169	0.015	14.773
3.00E+00	7.52	–0.012	1.714	1.056	0.003	13.380
4.00E+00	7.51	0.004	1.627	0.990	–0.006	18.186
5.00E+00	7.50	0.017	1.557	0.944	–0.012	14.016
6.00E+00	7.50	0.027	1.511	0.909	–0.021	14.087
8.00E+00	7.49	0.033	1.420	0.889	–0.018	11.991
1.00E+01	7.49	0.038	1.359	0.872	–0.024	14.098
1.50E+01	7.48	0.049	1.268	0.841	–0.036	15.035

Table 3. Equivalent atomic numbers and G-P fitting parameters for VH_2 for photon energy 0.015-15 MeV

Energy [MeV]	Z_{eq}	*a*	*b*	*c*	*d*	X_K
1.50E-02	22.06	–0.194	1.006	0.956	0.212	6.496
2.00E-02	22.16	0.352	1.014	0.319	–0.293	11.086
3.00E-02	22.27	0.211	1.045	0.373	–0.200	18.834
4.00E-02	22.33	0.240	1.099	0.352	–0.129	13.054
5.00E-02	22.36	0.221	1.172	0.388	–0.125	14.085
6.00E-02	22.38	0.199	1.255	0.434	–0.112	14.216
8.00E-02	22.40	0.158	1.435	0.529	–0.088	14.406
1.00E-01	22.42	0.115	1.598	0.642	–0.067	14.217
1.50E-01	22.44	0.048	1.885	0.859	–0.037	13.879
2.00E-01	22.45	0.008	2.027	1.027	–0.025	12.866
3.00E-01	22.46	–0.026	2.102	1.185	–0.014	10.968
4.00E-01	22.47	–0.038	2.092	1.249	–0.011	10.186
5.00E-01	22.47	–0.044	2.056	1.276	–0.009	8.546
6.00E-01	22.47	–0.051	2.009	1.295	0.004	16.776
8.00E-01	22.48	–0.050	1.938	1.282	0.004	14.070
1.00E+00	22.48	–0.052	1.876	1.272	0.015	18.174
1.50E+00	21.98	–0.042	1.779	1.205	0.012	15.817
2.00E+00	21.53	–0.027	1.730	1.141	0.004	14.877
3.00E+00	21.33	–0.010	1.637	1.067	–0.008	12.933
4.00E+00	21.29	0.007	1.569	1.013	–0.017	12.259
5.00E+00	21.25	0.014	1.502	0.989	–0.024	13.189
6.00E+00	21.23	0.023	1.455	0.966	–0.031	13.231
8.00E+00	21.22	0.031	1.371	0.950	–0.038	13.549
1.00E+01	21.20	0.038	1.309	0.937	–0.045	13.682
1.50E+01	21.20	0.050	1.215	0.925	–0.056	14.012

Table 4. Equivalent atomic numbers and G-P fitting parameters for TIH_2 for photon energy 0.015-15 MeV

Energy [MeV]	Z_{eq}	*a*	*b*	*c*	*d*	X_K
1.50E-02	21.07	–0.093	1.006	0.788	0.173	6.745
2.00E-02	21.18	0.276	1.015	0.373	–0.201	10.999
3.00E-02	21.28	0.217	1.050	0.372	–0.165	15.748
4.00E-02	21.33	0.237	1.112	0.357	–0.132	13.475
5.00E-02	21.37	0.218	1.194	0.395	–0.122	14.107
6.00E-02	21.39	0.196	1.287	0.443	–0.112	14.230
8.00E-02	21.42	0.152	1.487	0.547	–0.085	14.384
1.00E-01	21.43	0.106	1.662	0.668	–0.064	14.250
1.50E-01	21.44	0.039	1.955	0.894	–0.033	13.804
2.00E-01	21.45	0.000	2.085	1.063	–0.023	12.754
3.00E-01	21.46	–0.031	2.142	1.213	–0.013	10.691
4.00E-01	21.47	–0.042	2.123	1.269	–0.010	10.020
5.00E-01	21.47	–0.046	2.084	1.287	–0.010	8.610
6.00E-01	21.48	–0.054	2.028	1.310	0.008	19.450
8.00E-01	21.48	–0.054	1.948	1.298	0.009	15.984
1.00E+00	21.48	–0.054	1.887	1.278	0.015	17.764
1.50E+00	20.95	–0.042	1.788	1.208	0.012	15.793
2.00E+00	20.52	–0.029	1.735	1.146	0.007	16.632
3.00E+00	20.33	–0.011	1.639	1.069	–0.007	13.161
4.00E+00	20.29	0.007	1.573	1.010	–0.017	12.098
5.00E+00	20.25	0.015	1.507	0.984	–0.023	13.206
6.00E+00	20.26	0.023	1.458	0.963	–0.031	13.199
8.00E+00	20.23	0.031	1.375	0.944	–0.037	13.526
1.00E+01	20.21	0.037	1.312	0.935	–0.043	13.615
1.50E+01	20.21	0.050	1.218	0.918	–0.055	13.929

Table 5. Equivalent atomic numbers and G-P fitting parameters for ZrH_2 for photon energy 0.015-15 MeV

Energy [MeV]	Z_{eq}	*a*	*b*	*c*	*d*	X_K
1.50E-02	20.22	–0.003	1.007	0.636	0.138	6.971
2.00E-02	39.36	0.153	2.285	1.690	–0.196	12.858
3.00E-02	39.38	0.126	3.187	0.965	–0.189	28.642
4.00E-02	39.47	0.113	3.455	0.323	–0.043	21.876
5.00E-02	39.51	–0.225	2.773	0.090	0.023	12.113
6.00E-02	39.53	0.961	2.196	0.063	–0.146	16.870
8.00E-02	39.54	0.673	1.584	0.100	–0.232	14.330
1.00E-01	39.51	0.269	1.179	0.334	–0.145	13.773
1.50E-01	39.36	0.161	1.289	0.522	–0.084	14.345
2.00E-01	39.21	0.151	1.515	0.574	–0.088	14.165
3.00E-01	39.01	0.065	1.644	0.791	–0.038	14.095
4.00E-01	38.92	0.027	1.751	0.941	–0.029	13.622
5.00E-01	38.87	0.007	1.801	1.022	–0.021	13.409
6.00E-01	38.84	–0.004	1.816	1.065	–0.016	12.798
8.00E-01	38.83	–0.014	1.813	1.105	–0.013	12.537
1.00E+00	38.82	–0.017	1.791	1.116	–0.011	12.163
1.50E+00	38.72	–0.032	1.648	1.166	0.003	9.594
2.00E+00	38.52	–0.021	1.623	1.126	–0.005	11.752
3.00E+00	38.35	–0.001	1.572	1.064	–0.025	12.685
4.00E+00	38.30	0.014	1.515	1.023	–0.039	13.250
5.00E+00	38.27	0.038	1.509	0.959	–0.060	13.507
6.00E+00	38.25	0.048	1.480	0.940	–0.069	13.671
8.00E+00	38.24	0.069	1.486	0.899	–0.087	13.986
1.00E+01	38.25	0.055	1.448	0.964	–0.073	14.134
1.50E+01	38.30	0.039	1.478	1.081	–0.061	14.240

Table 6. Equivalent atomic numbers and G-P fitting parameters for BaH_2 for photon energy 0.015-15 MeV

Energy [MeV]	Z_{eq}	*a*	*b*	*c*	*d*	X_K
1.50E-02	29.41	–0.290	1.001	1.981	0.238	11.205
2.00E-02	29.39	0.737	1.064	0.172	–1.024	10.870
3.00E-02	29.46	0.201	1.132	0.390	–0.058	12.864
4.00E-02	55.05	0.062	3.094	1.637	–0.060	15.055
5.00E-02	55.21	0.136	3.215	1.111	–0.116	19.402
6.00E-02	55.23	0.133	2.854	0.644	–0.129	13.626
8.00E-02	55.31	0.090	2.094	0.167	0.016	16.167
1.00E-01	55.35	0.667	1.453	0.043	–0.201	14.310
1.50E-01	55.38	0.343	1.200	0.256	–0.195	13.786
2.00E-01	55.38	0.190	1.209	0.461	–0.102	14.293
3.00E-01	55.35	0.125	1.330	0.595	–0.060	13.928
4.00E-01	55.32	0.082	1.442	0.730	–0.049	14.125
5.00E-01	55.30	0.056	1.516	0.819	–0.039	14.091
6.00E-01	55.28	0.037	1.560	0.881	–0.029	13.859
8.00E-01	55.27	0.019	1.610	0.949	–0.022	13.761
1.00E+00	55.25	0.011	1.622	0.987	–0.021	13.285
1.50E+00	55.19	–0.012	1.546	1.084	–0.009	13.803
2.00E+00	54.94	–0.003	1.554	1.062	–0.019	13.086
3.00E+00	54.55	0.014	1.536	1.025	–0.041	13.256
4.00E+00	54.35	0.029	1.504	0.994	–0.055	13.627
5.00E+00	54.23	0.061	1.565	0.914	–0.083	13.857
6.00E+00	54.17	0.069	1.583	0.903	–0.089	14.085
8.00E+00	54.07	0.074	1.718	0.923	–0.094	14.172
1.00E+01	54.01	0.040	1.748	1.071	–0.063	14.109
1.50E+01	53.98	0.015	1.936	1.271	–0.047	13.776

Table 7. Comparison of exposure buildup factors of metal hydride and borohydrides, steel magnetite (SM), SS316L alloy, and lead for photon energies of 0.05, 0.15, 1.5, and 15 MeV at 1, 5, 10, 20, and 40 mfp penetration depths

Energy [MeV]	(a) Exposure buildup factor for 1 mfp								
	$Mg(BH_4)_2$	$NaBH_4$	VH_2	TiH_2	ZrH_2	BaH_2	SM	SS316L	Lead
0.05	3.26	3.25	1.17	1.19	2.77	3.21	1.14	1.10	1.02
0.15	3.52	3.53	1.89	1.96	1.29	1.20	1.78	1.64	1.40
1.5	1.97	1.94	1.78	1.79	1.65	1.55	1.77	1.75	1.38
15	1.27	1.27	1.21	1.22	1.48	1.94	1.21	1.20	1.63
Energy [MeV]	(b) Exposure buildup factor for 5 mfp								
	$Mg(BH_4)_2$	$NaBH_4$	VH_2	TiH_2	ZrH_2	BaH_2	SM	SS316L	Lead
0.05	13.55	13.53	1.36	1.42	2.89	24.37	1.30	1.19	1.04
0.15	32.74	33.07	4.83	5.33	1.77	1.35	4.13	3.29	1.84
1.5	7.63	7.41	6.02	6.09	5.02	4.10	5.94	5.76	2.74
15	2.13	2.12	2.08	2.08	4.22	9.49	2.07	2.07	6.83
Energy [MeV]	(c) Exposure buildup factor for 10 mfp								
	$Mg(BH_4)_2$	$NaBH_4$	VH_2	TiH_2	ZrH_2	BaH_2	SM	SS316L	Lead
0.05	31.10	31.01	1.47	1.54	2.88	270.06	1.38	1.25	1.05
0.15	140.07	142.18	8.33	9.57	2.10	1.44	6.68	4.85	2.13
1.5	17.39	16.82	13.13	13.30	10.61	8.01	12.90	12.45	4.47
15	3.06	3.06	3.51	3.46	12.24	43.80	3.54	3.73	3.8E+1
Energy [MeV]	(d) Exposure buildup factor for 20 mfp								
	$Mg(BH_4)_2$	$NaBH_4$	VH_2	TiH_2	ZrH_2	BaH_2	SM	SS316L	Lead
0.05	92.76	92.43	1.62	1.72	2.87	80357.33	1.50	1.32	1.06
0.15	814.66	831.14	16.15	19.41	2.65	1.60	11.98	7.73	2.87
1.5	41.75	40.28	31.32	31.78	25.55	17.95	30.74	29.53	8.11
15	4.90	4.99	8.99	8.45	92.86	752.27	9.39	11.94	1.07E+3
Energy [MeV]	(e) Exposure buildup factor for 40 mfp								
	$Mg(BH_4)_2$	$NaBH_4$	VH_2	TiH_2	ZrH_2	BaH_2	SM	SS316L	Lead
0.05	434.06	432.14	1.76	1.88	2.89	2.46E+10	1.60	1.37	1.08
0.15	7293.39	7487.98	32.73	41.35	3.34	1.77	21.98	12.20	6.65
1.5	104.74	100.68	77.91	79.12	64.30	41.81	76.39	73.23	1.50E+1
15	8.09	8.39	37.97	31.91	3374.17	1.31E+5	42.97	85.61	5.59E+5

the mean free path, mfp, and the exposure buildup factor, EBF. Figures 2 and 3 show μ/ρ and mfp as functions of photon energy (0.015-15 MeV). Figure 4(a-f) and fig. 5(a-d) show the exposure buildup factor as a function of photon energy (0.015-15 MeV) and penetration depth (up to 40 mfp), respectively. The fast-neutron removal cross-section is shown in fig. 6 as a function of hydrogen density. The uncertainties in our calculations are negligible.

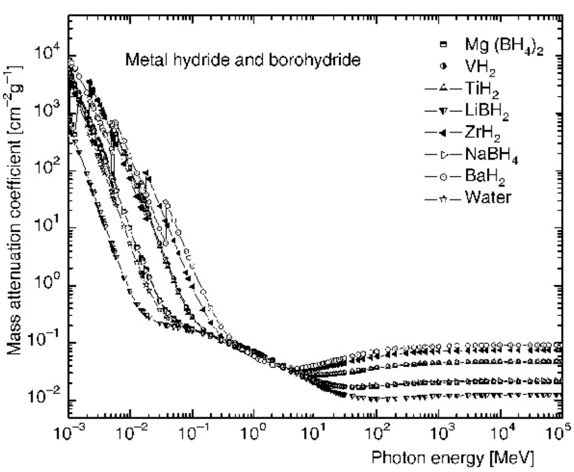

Figure 2. Mass attenuation coefficients of metal hydrides and borohydrides at photon energies 0.015-15 MeV

Attenuation coefficient and mean free path

Mass attenuation coefficients of selected metal hydrides and borohydrides are shown in fig. 2. It is seen that μ/ρ is very large in the photo-absorption region and reduces gradually to become almost constant in the Compton scattering region (100 keV to 3 MeV).

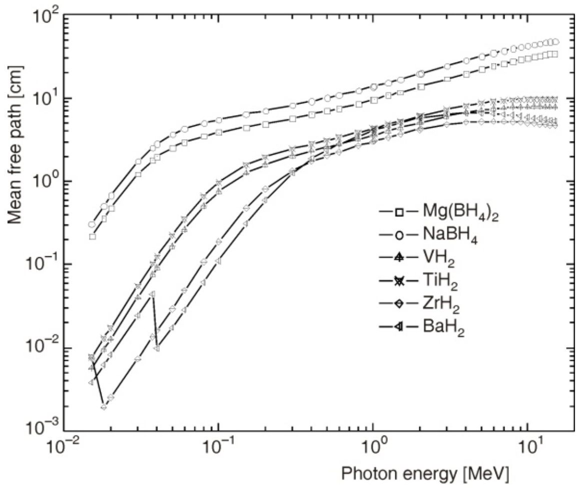

Figure 3. Mean free path in metal hydrides and borohydrides at photon energies 0.015-15 MeV

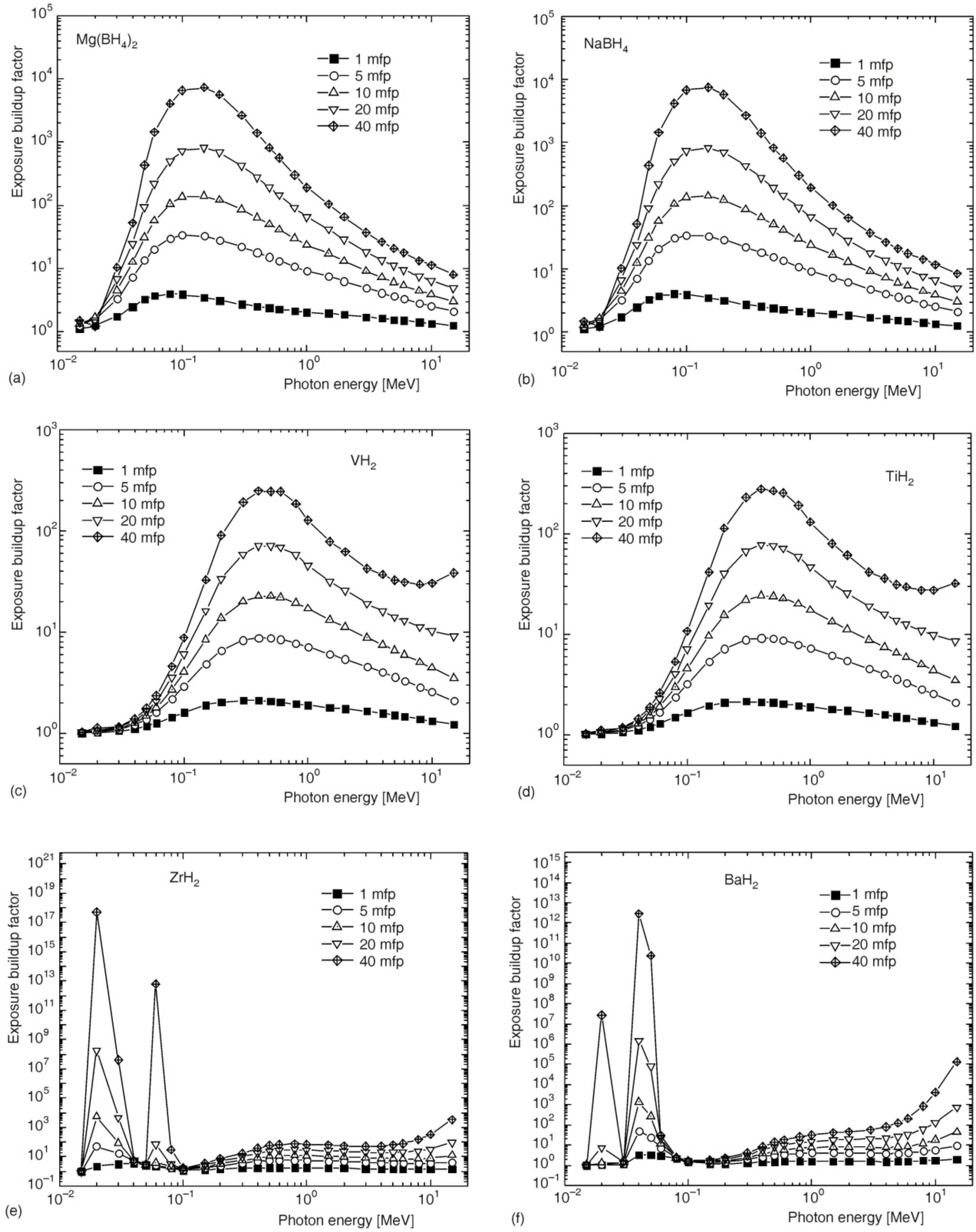

Figure 4(a-f). The exposure buildup factors of metal hydrides and borohydrides as a function of photon energy at penetration depths 1-40 mfp

For ZrH_2 and BaH_2 the *K*-absorption edges of Zr and Ba are observed as discontinuities at 18.00 and 37.44 keV, respectively.

The mean free path, mfp, varies as the reciprocal of the mass attenuation coefficient. It is noted in fig. 3 that $NaBH_4$ has the largest mfp in the entire energy region. In contrast, BaH_2 has the smallest mfp and therefore gives the best shielding among the selected compounds. This is because BaH_2 combines a high-*Z* element ($Z = 56$) and a high density of mass (4.2 g/cm^3). Also ZrH_2 is a very good gamma ray shielding material.

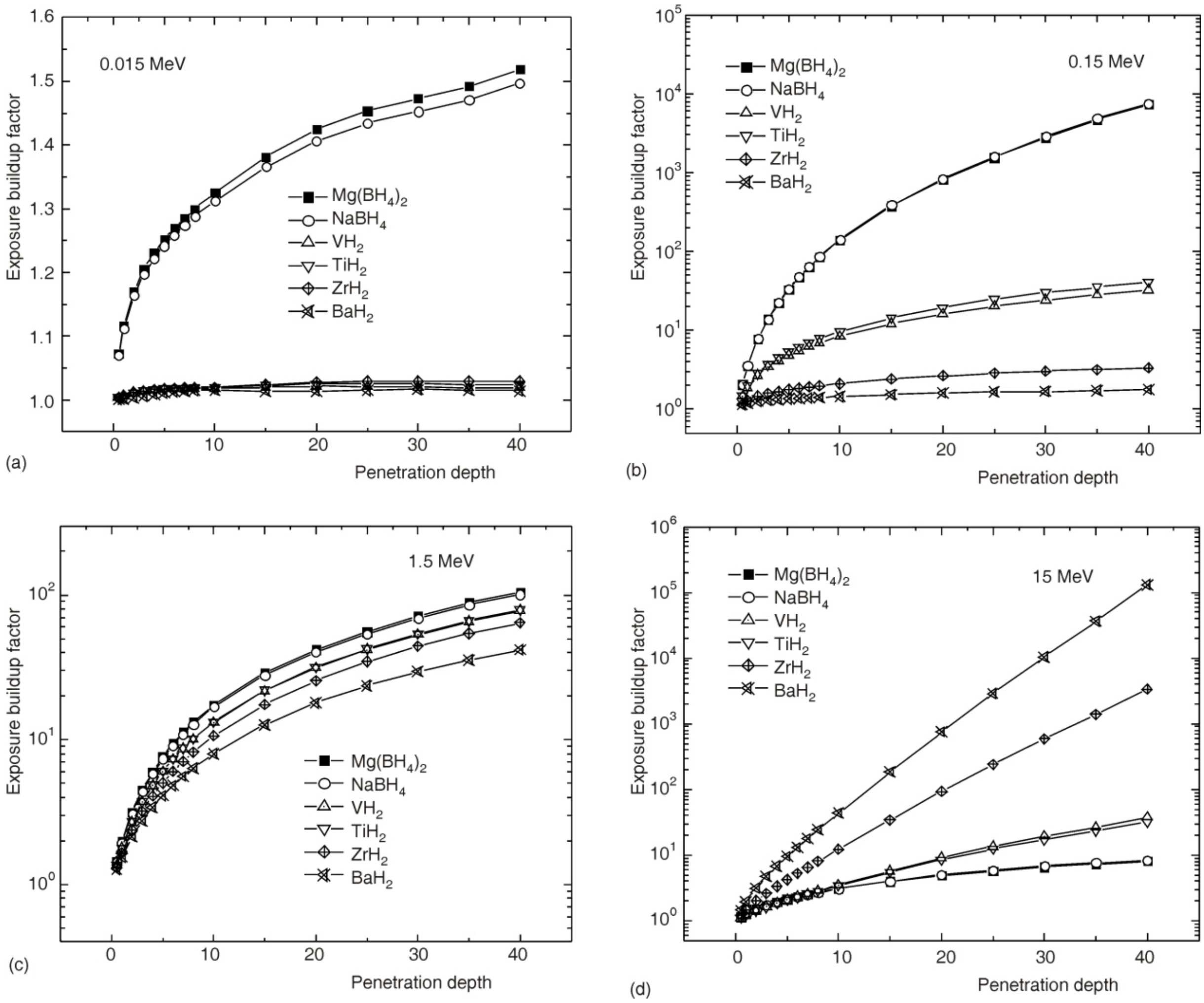

Figure 5(a-d). The exposure buildup factor of metal hydrides and borohydrides as a function of penetration depth (expressed in mfp) at photon energies 0.015-15 MeV

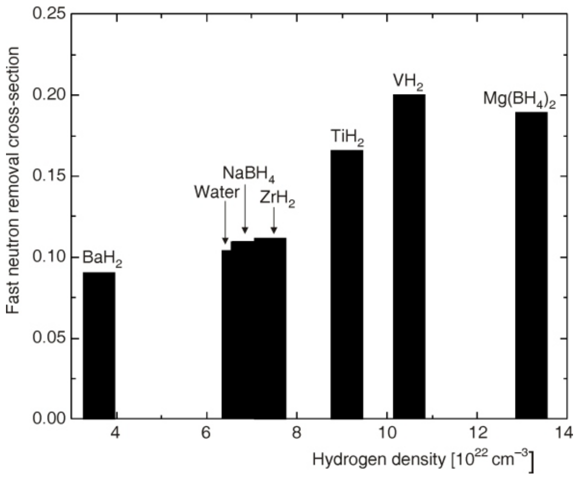

Figure 6. The fast-neutron removal cross-section [cm^{-1}] of metal hydrides and borohydrides as a function of hydrogen density [cm^{-3}]

Exposure buildup factors

The exposure buildup factor (EBF) of selected metal hydrides and borohydrides is shown in fig. 4(a-f) as a function of photon energy. The curves have the same general shape as observed for many other compounds. In particular, the dependence on the chemical composition is similar to what is observed for concretes [5]. Tables 1-6 shows that $NaBH_4$ and $Mg(BH_4)_2$ have lower values of Z_q than BaH_2. This is natural, since $NaBH_4$ and $Mg(BH_4)_2$ contains low-Z elements ($Z = 11$ and 12, respectively), whereas BaH_2 contains a high-Z element ($Z = 56$).

The exposure buildup factor (EBF) of metal hydrides and borohydrides is shown in fig. 5(a-d) as a function of penetration depth. Also here, the curves have the same general shape as observed for many other compounds. In tab. 7 we compare the EBF values of metal hydrides and borohydrides with steel magnetite [5], lead [16], and SS316L alloy [6].

Fast neutron removal cross-section

Figure 6 shows the effective fast-neutron removal cross-section Σ_R [cm^{-1}] of selected metal hydrides and borohydrides as a function of the hydrogen density. It is observed that the removal cross-section is largest (0.20 cm^{-1}) for VH_2 and smallest (0.090 cm^{-1}) for BaH_2. Generally, Σ_R increases with increasing hydrogen density. However, it is seen that Σ_R is larger for VH_2 (H density 10.5 10^{22} cm^{-3}) than for $Mg(BH_4)_2$ (H density 13.2 10^{22} cm^{-3}). Σ_R for steel-magnetite is 0.142 cm^{-1} theoretically and 0.168 cm^{-1} experimentally [4]. Σ_R equivalent to water can be achieved by using high-*Z* elements as shown in the fig. 6 for $NaBH_4$ and ZrH_2. The above observations signify that hydrogen density or low-*Z* is not the only deciding factors for fast-neutron attenuation. The fast-neutron shielding capability depends not only on low-*Z* but also on a suitable combination of low- and high-*Z* elements. Therefore, we conclude that a combination of low- and high-*Z* elements is vital for the fast-neutron shielding efficiency.

CONCLUSIONS

In the present study, we have examined the shielding properties of some advanced metal hydrides and borohydrides for possible use in fusion reactors. We have calculated the mass attenuation coefficient, the mean free path and the exposure buildup factor at photon energies 0.015-15 MeV, and penetration depths up to 40 mfp. Fast-neutron removal cross-sections of the metal compounds have been calculated by the mixture rule. VH_2 is found to be a very good fast-neutron shielding material at neutron energies 2-12 MeV. A combination of low- and high-*Z* elements is vital for fast-neutron shielding efficiency. ZrH_2 is found to be a very good gamma ray shielding material. The present study should be useful in selecting advanced shielding materials for the next generation of fusion reactors.

AUTHORS' CONTRIBUTIONS

The idea for investigation of the shielding efficiency for fusion reactor materials was put forward by V. P. Singh. The calculations were done by V. P. Singh, and analysis and discussion was carried out by V. P. Singh, N. M. Badiger, and L. Gerward. The manuscript and figures were prepared by V. P. Singh and N. M. Badiger.

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ЕФИКАСНОСТ ЗАШТИТНИХ СВОЈСТАВА МЕТАЛХИДРИДА И БОРХИДРИДА У ФУЗИОНИМ РЕАКТОРИМА

Извршена је карактеризација ефикасности заштитних особина металхидрида и борхидрида са високим густинама водоника коришћењем масених коефицијената слабљења, дужина слободног пута и фактора нагомилавања. Фактори нагомилавања гама зрачења израчунати су употребом геометријске прогресије са пет параметара фитовања, за енергије опсега од 0.015 MeV до 15 MeV и за дубине продирања до 40 дужина слободног пута. Ефикасност заштите од брзих неутрона описана је ефективним пресеком за уклањање неутрона. Показано је да су ZrH_2 и VH_2 веома добри материјали за заштиту од гама зрачења и брзих неутрона услед њихове погодне комбинације елемената са малим и великим атомским бројем *Z*. Овај рад је користан за избор и дизајн заштите од зрачења и за процену дозе компонената у фузионим реакторима.

Кључне речи: хидрид, борхидрид, нагомилавање, заштита од зрачења, фузиони реактор