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RANGE - ENERGY RELATIONS FOR PROTONS AND ALPHA PARTICLES IN VARIOUS EXPLOSIVES

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DOVER, NEW JERSEY

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ABSTRACT

Differential energy loss (Mev/mg/cm²) and range (mg/cm²) data have been calculated for low and medium energy protons and alpha particles in the following eight explosives: RDX (cyclotrimethylene trinitramine), HMX (cyclotetramethylene tetranitramine), TNT (2,4,6-trinitrotoluene), PETN (pentaerythritol tetranitrate), tetryl (2,4,6-trinitrophenyl methyl nitramine), lead styphnate, mercury fulminate, and lead azide. The well-known Bethe theory was followed in establishing the proton ranges. Experimental proton differential energy loss data and theoretical computations were used to establish atomic stopping number versus energy curves for the elements hydrogen, carbon, nitrogen, oxygen, and lead between 20 Kev and 25 Mev. From these curves, molecular stopping numbers were calculated. The alpha-particle ranges were obtained from the established proton ranges.

INTRODUCTION

In the course of investigations of heavy particle radiation damage to explosives, we have noted the absence of any accurate range-energy relations for these materials in the literature. The ranges in explosives for alpha particles and fission fragments were calculated in a Picatinny Arsenal technical report (Ref 1); however, the method used was not applicable to alpha particles.

Range-energy relations of protons in explosives can be calculated using the theory of Bethe (Ref 2). In this report, Bethe's method was used to calculate the ranges for protons of energies from 0.020 Mev (for the secondary explosives) or 0.050 Mev (for the primary explosives) to 25 Mev in eight different explosives (See Table 1, p 6). Alpha-particle range-energy curves were then derived from these proton ranges.

DISCUSSION

The differential energy loss ($Mev/mg/cm^2$) for protons is given by:

$$-\frac{dE}{dR} = 2\pi e^4 \left(\frac{M_p}{m_e}\right) \frac{N_o}{M}(B/E) \qquad (1)$$

Here, e is the electronic charge (for these calculations, it is convenient to take $e^2 = 14.397 \times 10^{-14}$ Mev-cm); M_p/m_e is the ratio of proton to electron masses (1836.6); N_o is Avogadro's number; M is the atomic weight of the element (or molecular weight of the compound) in mg/mole; B is a dimensionless quantity called the atomic (or molecular) stopping number; and E is the energy (Mev) of the proton.

By rearranging Equation 1, the atomic stppping number for each element can be expressed by

$$B = -dE/dR \; \frac{m_e}{M_p} \; \frac{M}{N_o} \; \frac{E}{2\pi e^4} \qquad (2)$$

The molecular stopping number of the explosives is obtained by summing the appropriate atomic stopping numbers (Refs 3 and 4) as follows:

$$B_{mol}\ (X_r Y_s \ldots\ldots) = rB_{atom}\ (X) + sB_{atom}\ (Y) + \ldots\ldots \qquad (3)$$

The proton ranges $R_p(E)$ (mg/cm^2) were calculated by graphical integration of

$$R_p(E) = \int_0^E \frac{dE}{(-dE/dR)} \qquad (4)$$

Stopping numbers were calculated down to 0.020 or 0.050 Mev (roughly the limit of the available data) to minimize the initial energy for which a range would have to be estimated. It should be noted that even rather large errors in the stopping number over this energy interval do not appreciably affect the value of the range for intermediate energy protons.

The ranges at 0.020 Mev or 0.050 Mev for these explosives were estimated by assuming (Ref 3) that the form of $-dE/dR$ over this interval is proportional to $E^{1/2}$.

Hence, integrating Equation 4 yields:

$$R_p(E) = 2KE^{1/2} \qquad (5)$$

The values of K were determined using the calculated $-dE/dR$ values at 0.020 or 0.050 Mev for the appropriate explosive.

Alpha-particle ranges were then obtained from the established proton ranges using (Ref 5)

$$1.007\ R_\alpha(3.972E) = R_p(E) + \delta_{mol} \qquad (6)$$

Each constant (δ_{mol}) represents the difference in range caused by variations in electron capture and loss. The value of δ_{mol} for each explosive was estimated from the known value for air (Ref 5) by assuming that this effect depended only upon the molecular electron density, i.e., that the product of δ_{mol} and the electron density is a constant for all materials.

RESULTS

Experimental proton differential energy loss data ($-dE/dR$) are available for hydrogen, carbon, nitrogen, oxygen, and lead primarily for energies of 1 Mev and below. These data, which are shown in Table 2 (p 7), were used to establish the atomic stopping number curves for hydrogen and carbon, nitrogen and oxygen, and lead as shown in Figures 1 through 3 (pp 12 through 14), respectively. The lower limits of the curves, 0.020 Mev for the light elements and 0.050 Mev for the lead, were chosen arbitrarily and some minor extrapolations were necessary to cover this range. Whenever the experimental data on the same element differed significantly, Whaling's evaluation (Ref 6) was followed. These curves were then extended to 25 Mev by means of the following theoretical computations:

1. The calculations of Aron and Hoffman (Ref 7) were used for carbon, nitrogen, and oxygen.

2. Hirschfelder and Magee's calculations (Ref 3) for hydrogen, which above 1 Mev agree well with Whaling's evaluation of the experimental data, were used here. The data were extrapolated from 15 to 25 Mev using the results given by Aron and Hoffman for hydrogen as a guide over the interval.

3. Sternheimer's (Ref 8) calculations were used for lead. In those cases (hydrogen and carbon) in which two or more theoretical curves were available over this energy region, the ones which agreed best with the data of Brolley and Ribe (Ref 9) for the 4.4^{+} Mev protons were used. Finally, where necessary (carbon, nitrogen, and oxygen), the theoretical data were adjusted by a constant multiplicative factor to agree with the 4.4^{+} Mev data.

The molecular stopping numbers of protons in the eight explosives were obtained using the proton atomic stopping number curves (Figs 1–3, pp 12-14) and Equation 3. These molecular stopping numbers are given in Table 3 (p 8). The differential energy loss ($-dE/dR$) for protons of energies up to 25 Mev in the explosives was then calculated by means of Equation 1. The values obtained are shown in Table 4 (p 9).

Ranges for protons of energies up to 25 Mev, calculated by graphical integration of Equation 4, are presented in Table 5 (p 10). Figures 4, 5, and 6 (pp 15, 16, and 17) present proton range-energy curves for: (1) RDX and HMX, which are also representative of the other secondary high explosives; (2) lead styphnate; and (3) lead azide, which is also representative of mercury fulminate. The data for mercury fulminate are less reliable than the rest since B_{Hg} was assumed equal to B_{Pb}. Experimental measurements (Refs 4 and 10) indicate that the additivity of atomic stopping numbers does not hold for protons of energy less than 0.150 Mev. Although ranges are given for energies below 0.150 Mev in Table 5, both the effects of chemical binding on the additivity and the greater experimental error in this region decrease their validity.

The alpha-particle ranges for energies up to approximately 100 Mev, obtained from the established proton ranges as discussed previously, are presented in Table 6 (p 11). Figures, 4, 5, and 6 (pp 15, 16, and 17) also present the appropriate alpha-particle range-energy curves.

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TABLE 1

Explosives Investigated

Explosive	Chemical Name	Formula	Molecular Weight (g)
RDX	Cyclo-trimethylene trinitramine	$C_3H_6N_6O_6$	222.13
HMX	Cyclo-tetramethylene tetranitramine	$C_4H_8N_8O_8$	296.17
TNT	2,4,6-trinitrotoluene	$C_7H_5N_3O_6$	227.13
PETN	Pentaerythritol tetranitrate	$C_5H_8N_4O_{12}$	316.15
Tetryl	2,4,6-trinitrophenyl methyl nitramine	$C_7H_5N_5O_8$	287.15
Lead styphnate	Lead styphnate	$C_6H_3N_3O_9Pb$	468.31
Mercury fulminate	Mercury fulminate	$C_2N_2O_2Hg$	284.64
Lead azide	Lead azide	PbN_6	291.25

TABLE 2

Selected Experimental Proton Differential Energy Loss Data Presented as Stopping Numbers

Proton Energy, Mev	Stopping Numbers for Hydrogen[a]	Carbon[b,c]	Nitrogen[d]	Oxygen[a]	Lead[e]
.020	.427	–	1.09	.937	–
.030	.700	–	1.82	1.63	–
.030	.732	1.82	2.02	–	–
.040	1.03	–	2.58	2.33	–
.040	1.05	2.52	2.86	2.55	–
.050	1.36	–	3.39	3.08	–
.050	1.34	3.09	3.72	3.43	–
.060	1.63	–	4.19	3.79	–
.060	1.62	4.12	4.57	4.24	–
.070	1.85	–	–	4.48	–
.070	1.86	4.90	5.49	5.02	–
.075	–	–	–	–	12.35
.080	1.87	–	–	5.09	–
.080	2.08	5.51	6.19	5.74	–
.090	2.27	6.15	6.87	6.50	–
.100	2.44	6.79	7.49	7.19	17.39
.125	–	–	–	–	22.47
.150	2.95	9.16	10.11	10.13	27.40
.175	–	–	–	–	32.12
.200	3.26	10.62	11.88	12.30	36.45
.250	3.48	11.79	13.08	13.87	43.58
.300	3.65	12.79	14.06	15.05	48.91
.350	3.80	13.61	14.84	16.13	53.41
.400	3.93	14.28	15.63	17.13	57.52
.400	–	–	–	–	57.53
.450	4.02	14.94	16.23	17.80	60.77
.450	–	–	–	–	61.52
.500	4.12	15.43	16.91	18.50	63.40
.500	–	–	–	–	64.80
.550	4.18	15.98	17.51	19.29	67.14
.550	–	–	–	–	68.06
.600	4.26	16.43	18.10	19.86	70.23
.600	–	–	–	–	70.74
.650	–	–	–	–	73.91
.700	–	–	18.65	–	75.50
.750	–	–	–	–	78.70
.800	–	–	–	–	80.60
.850	–	–	–	–	83.15
.900	–	–	–	–	86.54
.928	–	–	21.28	–	–
.950	–	–	–	–	88.96
1.00	–	–	21.81	–	91.97
4.40	–	–	–	36.42	–
4.42	–	–	32.52	–	–
4.43	–	29.26	–	–	–
4.44	6.22	–	–	–	–

[a]Hydrogen and oxygen data were obtained from References 4, 9, and 11.

[b]Carbon data were obtained from References 4 and 9

[c]The carbon values for the proton energies from 0.030 to 0.100 Mev were calculated from the data and method given in Reference 4.

[d]Nitrogen data were obtained from References 4, 9, 11, and 14.

[e]Lead data were obtained from References 12 and 13.

TABLE 3

Stopping Number B of Protons in Various Explosives

Proton Energy, Mev	Stopping Numbers for HMX	RDX	TNT	PETN	Tetryl	Lead Azide	Mercury Fulminate	Lead Styphnate
.020	23.92	17.94	18.04	24.14	22.18	–	–	–
.030	42.04	31.53	31.95	42.79	39.25	–	–	–
.040	61.56	46.17	46.84	62.99	57.60	–	–	–
.050	81.16	60.87	61.61	83.31	75.91	29.44	26.28	73.03
.060	99.92	74.94	76.09	102.7	93.71	36.46	34.86	90.45
.070	118.0	88.53	89.72	121.2	110.7	43.80	41.74	107.3
.080	134.1	100.6	101.9	137.8	125.8	50.34	48.06	122.7
.090	149.5	112.1	114.1	154.0	140.7	56.62	54.44	138.2
.100	164.4	123.3	125.8	170.0	155.1	62.34	60.46	153.0
.150	221.5	166.1	169.3	230.6	209.7	88.00	86.0	212.0
.200	261.2	195.9	199.7	273.8	247.9	107.3	105.9	256.0
.250	290.2	217.7	222.4	305.6	276.2	121.6	121.0	288.9
.300	312.0	234.0	239.2	328.7	297.2	132.9	132.3	313.1
.400	349.6	262.2	268.0	369.0	333.4	151.7	151.1	354.5
.500	378.0	283.5	290.7	399.9	361.5	165.4	165.8	386.5
.600	405.2	303.9	310.6	428.8	387.1	179.7	179.7	416.2
.700	427.4	320.6	327.8	452.7	408.6	190.7	190.9	440.8
.800	446.6	334.9	341.8	472.2	426.4	202.2	201.6	462.1
.900	464.8	348.6	356.0	492.7	444.2	211.9	212.1	484.2
1.0	482.5	361.9	368.9	511.0	470.7	221.8	221.4	503.4
1.5	548.6	411.5	419.6	581.0	524.4	259.4	258.8	579.8
2	600.2	450.1	459.0	637.7	574.1	288.6	288.9	641.6
3	661.0	495.8	505.9	701.5	632.9	332.0	332.0	720.1
5	736.1	555.5	566.3	783.7	707.2	387.6	390.2	825.0
7	792.4	594.3	607.9	842.4	760.4	432.4	433.6	900.6
10	842.4	631.8	646.1	895.6	808.5	476.2	477.2	973.9
13	891.0	668.2	683.3	947.0	855.3	510.0	511.0	1036
16	920.8	690.6	705.0	977.8	883.0	540.0	540.0	1082
19	952.4	714.3	729.3	1014	914.7	563.2	564.6	1127
22	980.4	735.3	751.1	1044	941.1	586.0	587.6	1167
25	1001.2	750.9	767.7	1063	961.3	604.2	604.6	1194

TABLE 4

Proton Differential Energy Loss (−dE/dR) Data for Various Explosives

	Proton Differential Energy Loss, Mev/mg/cm^2						
Proton Energy, Mev	RDX & HMX	TNT	PETN	Tetryl	Lead Azide	Mercury Fulminate	Lead Styphnate
.020	.582	.572	.550	.556	–	–	–
.030	.682	.675	.650	.656	–	–	–
.040	.749	.742	.717	.723	–	–	–
.050	.789	.781	.759	.762	.291	.284	.449
.060	.810	.805	.780	.784	.300	.294	.464
.070	.820	.813	.789	.793	.309	.302	.471
.080	.815	.808	.784	.789	.311	.304	.472
.090	.808	.804	.780	.784	.311	.306	.472
.100	.799	.797	.775	.778	.308	.306	.471
.150	.718	.716	.700	.701	.290	.290	.435
.200	.635	.633	.624	.622	.265	.268	.394
.250	.565	.564	.557	.554	.241	.245	.355
.300	.506	.506	.499	.497	.219	.223	.321
.400	.425	.425	.420	.418	.188	.191	.273
.500	.368	.369	.364	.363	.164	.168	.238
.600	.328	.328	.326	.324	.148	.152	.213
.700	.297	.297	.295	.293	.135	.138	.162
.800	.271	.271	.269	.267	.125	.128	.178
.900	.251	.251	.249	.248	.116	.119	.165
1.0	.235	.234	.233	.236	.110	.112	.155
1.5	.178	.177	.176	.175	.0855	.0873	.119
2	.146	.146	.145	.144	.0713	.0731	.0987
3	.107	.107	.107	.106	.0547	.0547	.0738
5	.0720	.0718	.0714	.0709	.0383	.0395	.0508
7	.0551	.0551	.0548	.0545	.0306	.0322	.0396
10	.0410	.0410	.0408	.0406	.0236	.0241	.0300
13	.0333	.0333	.0332	.0330	.0194	.0199	.0245
16	.0280	.0279	.0278	.0277	.0167	.0171	.0208
19	.0244	.0243	.0243	.0241	.0147	.0150	.0182
22	.0217	.0217	.0216	.0215	.0132	.0135	.0163
25	.0195	.0195	.0194	.0193	.0120	.0122	.0147

TABLE 5

Proton Range – Energy Results

Proton Energy, Mev	Proton Range, mg/cm² RDX & HMX	TNT	PETN	Tetryl	Lead Azide	Mercury Fulminate	Lead Styphnate
.020	.069	.070	.073	.072	–	–	–
.030	.085	.086	.089	.088	–	–	–
.040	.098	.10	.10	.10	–	–	–
.050	.11	.11	.12	.12	.34	.35	.22
.060	.12	.13	.13	.13	.38	.39	.24
.070	.14	.14	.14	.14	.41	.42	.27
.080	.15	.15	.16	.15	.44	.45	.29
.090	.16	.16	.17	.17	.47	.49	.31
.100	.17	.18	.18	.18	.51	.52	.33
.150	.24	.24	.25	.25	.67	.69	.44
.200	.31	.31	.32	.32	.85	.86	.56
.250	.40	.40	.41	.41	1.1	1.1	.69
.300	.49	.49	.50	.50	1.3	1.3	.85
.400	.71	.71	.72	.72	1.8	1.8	1.2
.500	.96	.96	.98	.98	2.3	2.3	1.6
.600	1.2	1.2	1.3	1.3	3.0	2.9	2.0
.700	1.6	1.6	1.6	1.6	3.7	3.6	2.5
.800	1.9	1.9	1.9	2.0	4.5	4.4	3.1
.900	2.3	2.3	2.3	2.3	5.3	5.2	3.6
1.0	2.7	2.7	2.7	2.8	6.2	6.1	4.3
1.5	5.1	5.2	5.2	5.2	11.4	11.2	7.9
2	8.2	8.3	8.4	8.4	17.8	17.5	12.5
3	16.3	16.4	16.6	16.6	34.1	33.3	24.1
5	39.5	39.7	40.1	40.2	78.9	76.7	57.1
7	71.5	72.0	72.6	72.8	138	134	119
10	135	136	137	137	252	244	190
13	217	217	219	220	393	382	300
16	315	316	318	319	560	545	433
19	430	431	433	435	753	733	587
22	561	562	564	567	969	944	761
25	707	708	711	715	1209	1177	957

TABLE 6

Alpha-Particle Range – Energy Results

Alpha-Particle Energy, Mev	Alpha-Particle Range, mg/cm^2 RDX & HMX	TNT	PETN	Tetryl	Lead Azide	Mercury Fulminate	Lead Styphnate
.0794	.32	.32	.32	.32	–	–	–
.1192	.33	.33	.34	.34	–	–	–
.1589	.35	.35	.35	.35	–	–	–
.1986	.36	.36	.37	.37	.64	.65	.50
.2383	.37	.38	.38	.38	.67	.68	.52
.2780	.38	.39	.39	.39	.71	.71	.54
.3178	.40	.40	.40	.40	.74	.75	.56
.3575	.41	.41	.42	.42	.77	.78	.58
.3972	.42	.42	.43	.43	.80	.81	.60
.5958	.49	.49	.50	.50	.97	.98	.71
.7944	.56	.56	.57	.57	1.1	1.2	.83
.9930	.64	.64	.65	.65	1.3	1.3	.97
1.192	.74	.74	.75	.75	1.6	1.6	1.1
1.589	.95	.95	.97	.97	2.1	2.0	1.4
1.986	1.2	1.2	1.2	1.2	2.6	2.6	1.8
2.383	1.5	1.5	1.5	1.5	3.3	3.2	2.3
2.780	1.8	1.8	1.8	1.8	4.0	3.9	2.8
3.178	2.2	2.2	2.2	2.2	4.7	4.7	3.3
3.575	2.5	2.5	2.6	2.6	5.5	5.5	3.9
3.972	2.9	2.9	3.0	3.0	6.4	6.3	4.5
5.958	5.4	5.4	5.4	5.4	11.6	11.3	8.2
7.944	8.4	8.5	8.6	8.6	18.0	17.6	12.7
11.92	16.4	16.5	16.7	16.7	34.1	33.3	24.2
19.86	39.5	39.7	40.0	40.1	78.6	76.4	57.0
27.80	71.3	71.8	72.3	72.5	137	133	102
39.72	135	135	136	137	250	243	189
51.64	215	216	217	219	390	379	298
63.55	313	314	316	317	557	542	430
75.47	428	428	430	433	748	728	583
87.38	557	558	560	564	963	937	756
99.30	703	703	706	711	1201	1169	950

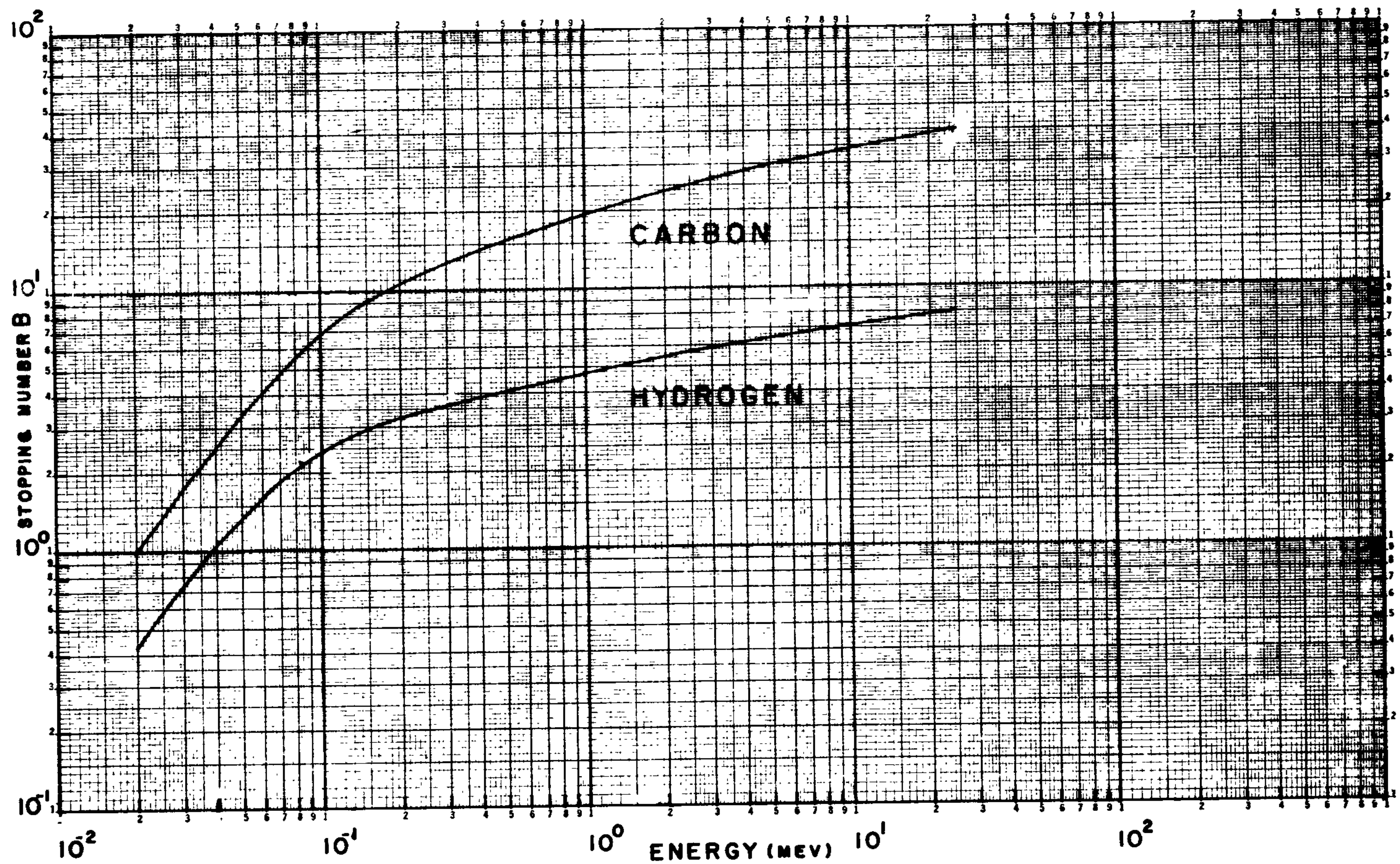

Fig 1   Stopping numbers of protons in hydrogen and carbon

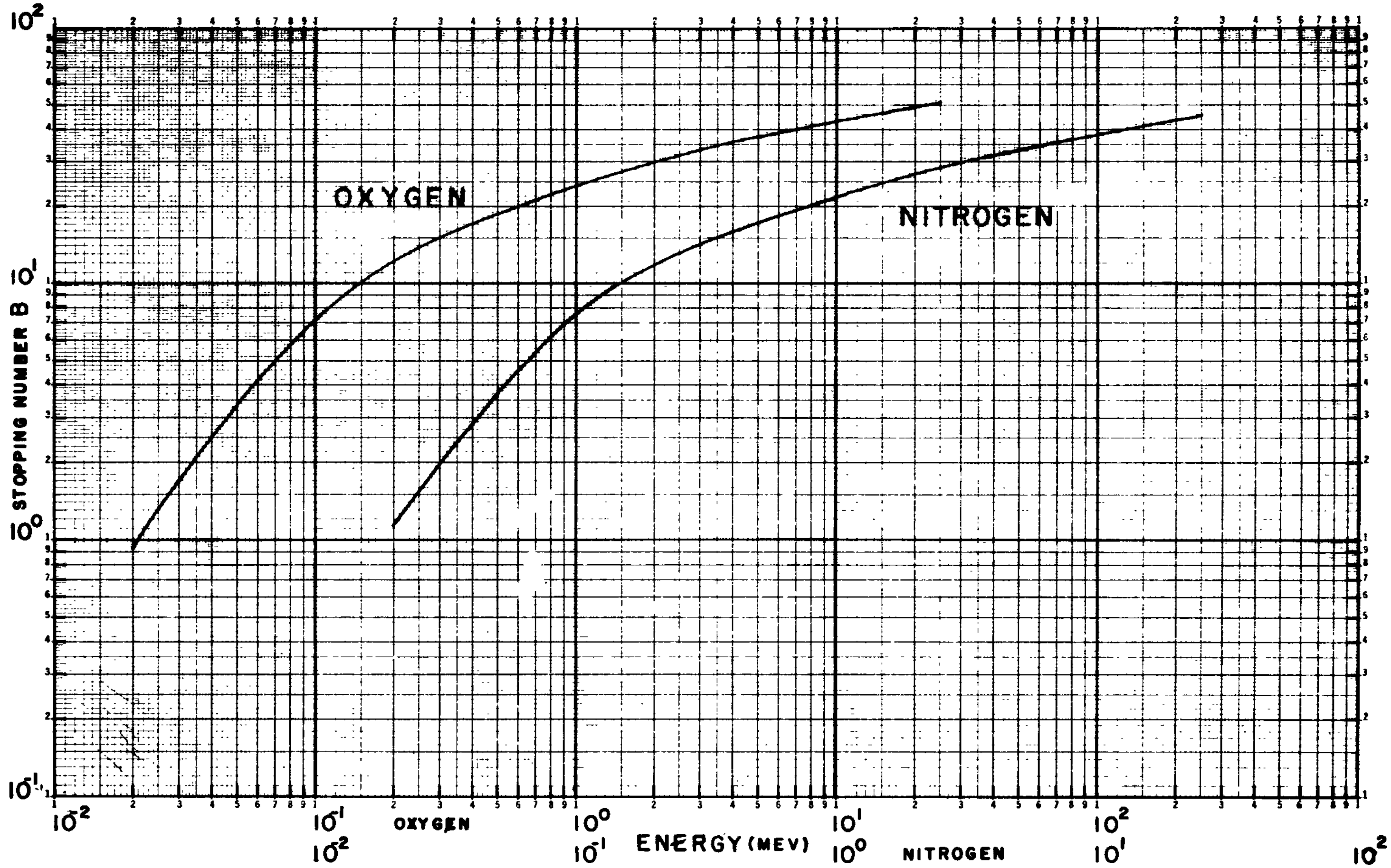

Fig 2 Stopping numbers of protons in nitrogen and oxygen

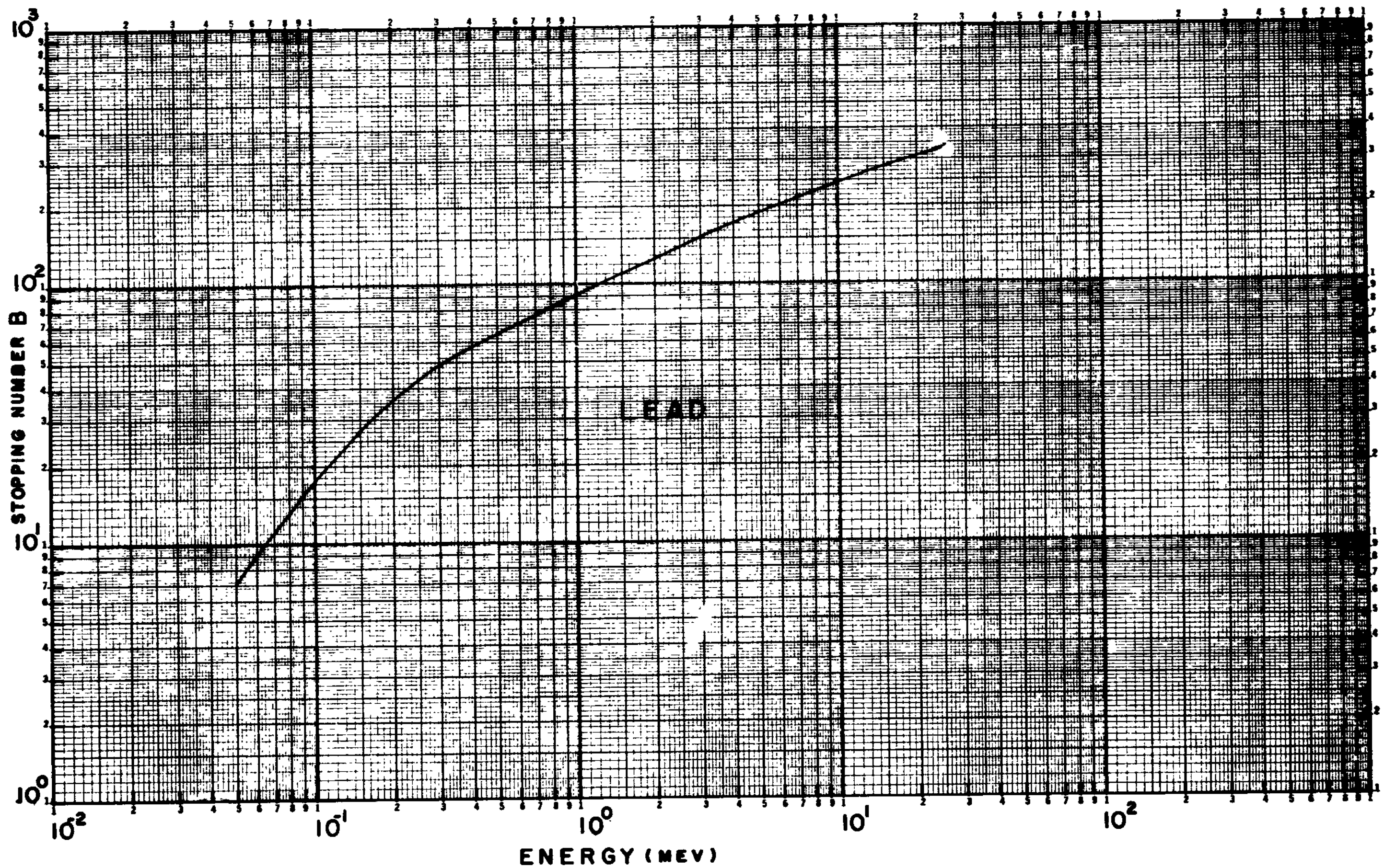

Fig 3 Stopping numbers of protons in lead

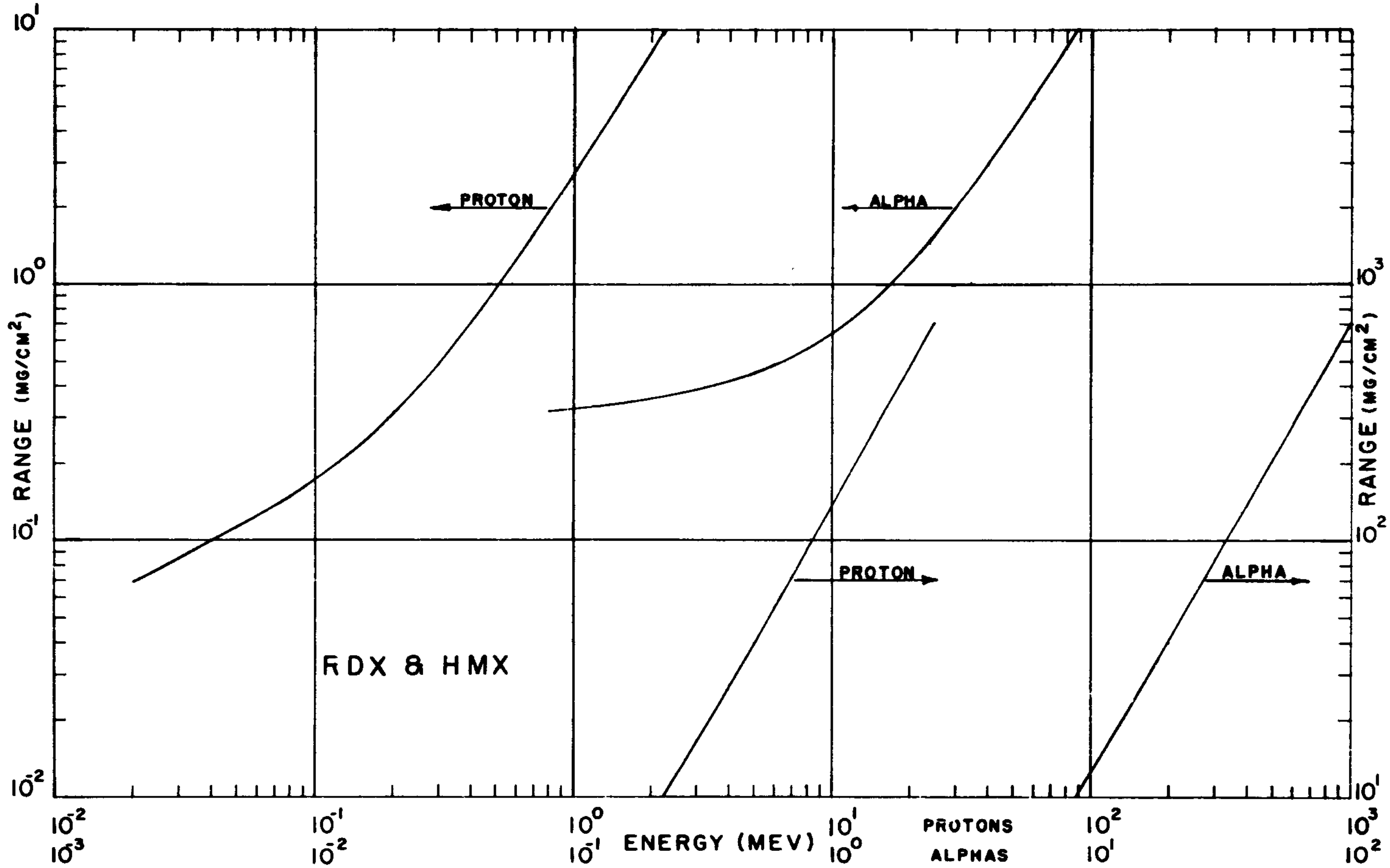

Fig 4 Proton and alpha-particle range-energy curves for RDX and HMX

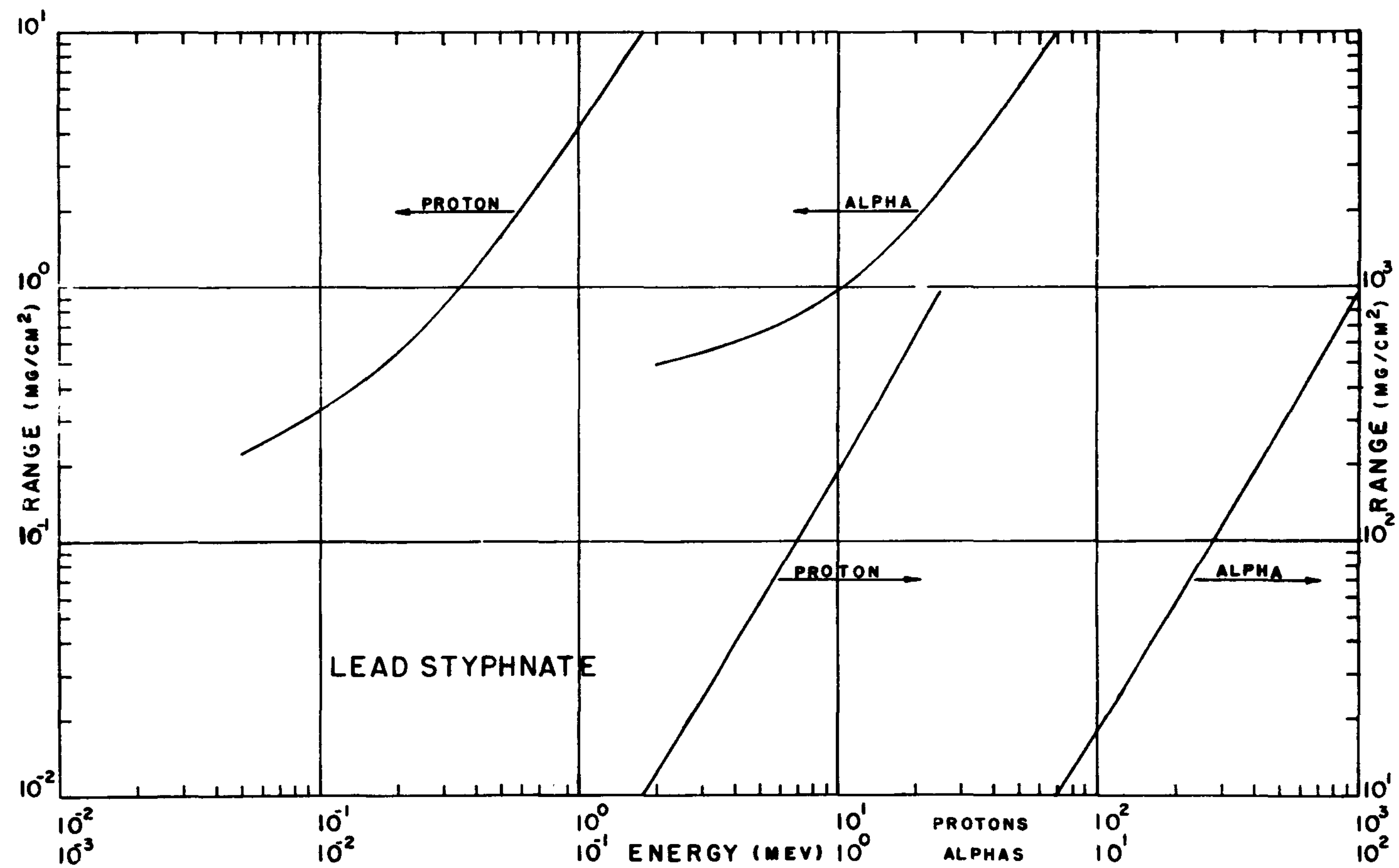

Fig 5 Proton and alpha-particle range-energy curves for lead styphnate

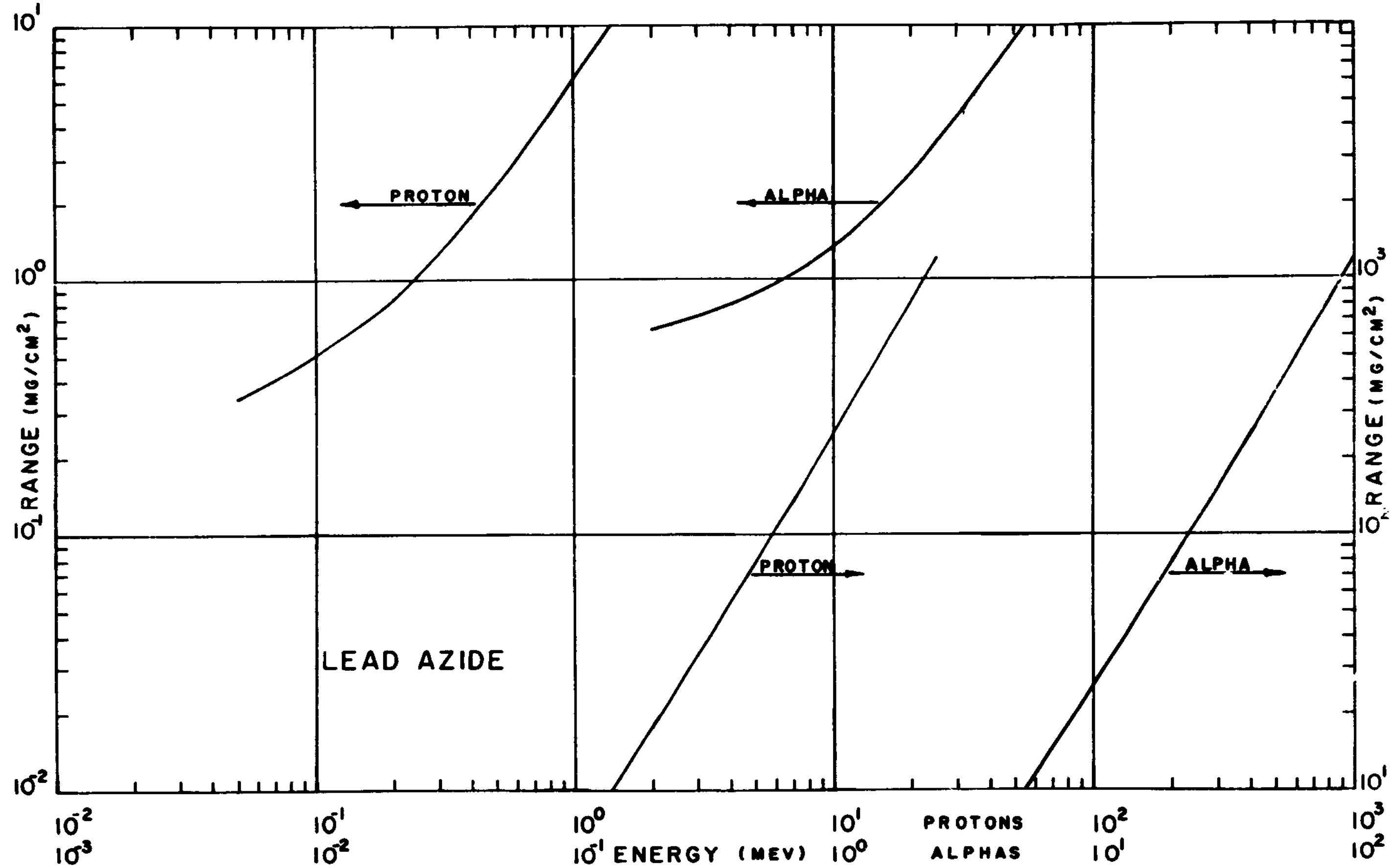

Fig 6 Proton and alpha-particle range-energy curves for lead azide

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RANGE-ENERGY RELATIONS FOR PROTONS AND ALPHA PARTICLES IN VARIOUS EXPLOSIVES

Joseph Cerny, and others

Technical Report 3070, May 1963, 20 pp, graphs, tables. AMCMS Code No. 5010.11.818, DA Proj 503-05-021. Unclassified report

Differential energy loss (Mev/mg/cm^2) and range (mg/cm^2) data have been calculated for low and medium energy protons and alpha particles in the following eight explosives: RDX (cyclotrimethylene trinitramine), HMX

(over)

1. Explosives – Effects of radiation
2. Protons – Range
3. Alpha particles – Range

I. Cerny, Joseph
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Range
Energy
Proton
Alpha particle
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