Int. J. Appl. Radiat. Isot. Vol. 33, pp. 1189 to 1218, 1982
Printed in Great Britain.

0020-708X/82/111189-30$03.00/0

Evaluation of the Collision Stopping Power of Elements and Compounds for Electrons and Positrons

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(*Received* 15 *May* 1981)

This paper gives tables of material properties needed for the evaluation of the collision stopping power for electrons and positrons according to the Bethe theory. The key quantity is the mean excitation energy of the medium, which has been derived for many materials by a critical analysis of experimental data. Also given are the density-effect parameters of the theory of Sternheimer and Peierls. The material properties are given for the elements and for 180 compounds and mixtures, and the rules are described by which they could be obtained for other materials. Tables are also given of auxiliary quantities which depend only on the kinetic energy of the incident electron. These, together with the main tables, make possible the quick-and-easy evaluation of the collision stopping power.

1. Introduction

IN RADIATION DOSIMETRY it is important to have accurate information about the energy loss of charged particles in many different materials. The chief quantity of interest is the collision stopping power,* i.e. the average energy loss per unit pathlength, due to inelastic Coulomb collisions resulting in the ionization and excitation of atoms or molecules. Critical reviews of stopping power are required from time to time in order to take into account both the steady accumulation of new experimental stopping-power data and the continuing refinement of the methods for analyzing such data. Such reviews have led to the preparation of improved stopping-power and range tables for protons,[1] α-particles[2] and heavy ions.[3]

At sufficiently high energies (above $\sim$1 MeV for protons, above $\sim$10 keV for electrons) the preferred method of evaluating the collision stopping power is to use Bethe's stopping-power theory.[4] This theory contains a key parameter, the mean excitation energy of the stopping medium, which—in the present state of the art—cannot be calculated accurately on the basis of theory alone (except for simple atomic gases). It remains necessary to rely on a combination of experimental input data and theoretical considerations. The required input data consist either of measured stopping powers or ranges, or of experimental dipole-oscillator-strength distributions or dielectric-response functions which characterize the medium. The determination of the mean excitation energy is the principal non-trivial task in the evaluation of the Bethe stopping-power formula.

As part of a general review of stopping power, we have recently used the Bethe theory, and the Sternheimer density-effect correction,[5,6] to prepare new tables of electron collision stopping powers for elements and for selected compounds of biomedical interest.[7]† In the present paper this work is extended to a large set of other materials of interest in various areas of radiation science. Because of limitations of space it is not feasible to give in this paper extensive stopping-power tables for all of the materials treated. Instead we present tables of mean excitation energies, and tables of auxiliary quantities (some of which depend on the material only, others on the electron energy only) from which the collision stopping power for electrons (and positrons) can be determined with only a minimal amount of computation.

2. Stopping-power Formulas

The mass collision stopping power of a charged particle, in units of MeV/(g cm^{-2}), is given by

$$-\frac{1}{\rho}\left(\frac{dE}{dx}\right)_{coll} = \frac{0.153536}{\beta^2}\frac{Z}{A}B(T), \qquad (1)$$

where $B(T)$ is the stopping number, T is the kinetic energy of the particle, β its velocity in units of the velocity of light, Z/A‡ is the ratio of atomic number to atomic weight for the stopping medium, and ρ is the density of the medium. The expression for the stopping number depends on the type of charged par-

* For light particles, such as electrons or positrons, it is also of interest to know the radiation stopping power, i.e. the mean energy loss per unit pathlength due to the emission of bremsstrahlung quanta. A simple procedure for evaluating the radiation stopping power is given in an accompanying paper.

† The present paper uses the convenient universal fit of STERNHEIMER and PEIERLS[6] for the density-effect correction. In Ref. 7 we use directly computed numerical values of slightly greater accuracy (see footnote at end of Section 5).

‡ For molecular compounds, Z/A is replaced by $\langle Z/A \rangle$, which is the ratio of the number of electrons in the molecule to the molecular weight.

TABLE 1. Percentage decrease in the collision stopping power due to a 10% increase of the mean excitation energy. Results are given for electrons with kinetic energy T

Material	Mean excitation energy I (eV)	Density* (g cm^{-3})	Percentage decrease				
			$T = 0.01$	0.1	1	10	100 MeV
Air	85.7	1.205×10^{-3}	2.0	1.4	1.0	0.8	0.3
Xe	482	5.485×10^{-3}	3.1	1.8	1.3	0.9	0.5
Polystyrene	68.7	1.06	2.0	1.4	0.7	0.1	0.0
Water	75.0	1.00	2.0	1.4	0.7	0.1	0.0
Graphite	78.0	2.27	2.0	1.4	0.7	0.1	0.0
Al	166	2.70	2.4	1.6	0.9	0.2	0.0
Cu	322	8.96	2.8	1.7	0.9	0.2	0.0
Au	790	19.32	3.7	2.0	1.2	0.3	0.0

* Densities for gases at a temperature of 20°C and pressure of 1 atm.

ticle.§ For electrons and positrons it is given by

$$B(T) = B_0(T) - 2\ln(I/mc^2) - \delta, \tag{2}$$

where I is the mean excitation energy of the medium, δ is the density-effect correction and mc^2 is the electron rest mass (0.5110034 MeV). For electrons, $B_0(T)$ has the form[4]

$$B_0(T) = \ln[\tau^2(\tau + 2)/2] + [1 + \tau^2/8 - (2\tau + 1)\ln 2]/(\tau + 1)^2. \tag{3}$$

For positrons, it has the form[8]

$$B_0(T) = \ln[(\tau^2(\tau + 2)/2] + 2\ln 2 - (\beta^2/12)[23 + 14/(\tau + 2) + 10/(\tau + 2)^2 + 4/(\tau + 2)^3], \tag{4}$$

where $\tau = T/mc^2$ is the kinetic energy in units of the rest mass.

The density-effect correction, δ, represents the reduction of the collision stopping power due to the polarization of the medium caused by the passage of the incident charged particle. A comprehensive theory of this effect, applicable to all kinds of media, has been worked out by STERNHEIMER.[5,6] In the high-energy limit ($\beta \to 1$), the density-effect correction has the asymptotic form

$$\delta \to 2\ln(\hbar\omega_p/I) + 2\ln(\tau + 1) - 1, \tag{5}$$

where

$$\hbar\omega_p = 28.816(\rho Z/A)^{\frac{1}{2}} \tag{6}$$

is the plasma energy (in eV) with the density, ρ, in g cm^{-3}. The stopping number, in the high-energy limit, then has the form

$$B(T) = B_0(T) - 2\ln(\hbar\omega_p/mc^2) - 2\ln(\tau + 1) + 1, \tag{7}$$

and thus no longer depends on the mean excitation energy but only on the density of atomic electrons through the plasma energy.

§ For heavy charged particles whose velocity is not large compared to the velocities of the atomic electrons, the stopping number must include also a shell correction (to take into account the binding of the atomic electrons) and the so-called z^3 and z^4 corrections (where ze is the charge of the incident particle).

The mean excitation energy can be calculated, for gases, from the expression

$$\ln I = \int_0^\infty \frac{df}{dE} \ln E \, dE \Big/ \int_0^\infty \frac{df}{dE} dE, \tag{8}$$

where df/dE is the density of optical dipole oscillator strength (f) per unit energy of excitation (E) above the ground state. For condensed media, the mean excitation energy can be evaluated from the expression

$$\ln I = 2/(\pi\omega_p^2) \int_0^\infty \omega \, d\omega \, \mathrm{Im}[-1/\epsilon(\omega)] \ln \hbar\omega, \tag{9}$$

where $\hbar\omega_p$ is the plasma energy defined by equation (6), and where $\epsilon(\omega)$ is the complex dielectric-response function at frequency $\omega = E/\hbar$ ($\hbar$ is Plank's constant divided by 2π).

The relative uncertainty of the stopping power due to the uncertainty dI of the mean excitation energy is approximately equal to $(dI/I)/B(T)$, and is usually several times smaller than dI/I. This is illustrated by Table 1 which gives, for representative materials and energies, the change of the electron collision stopping power corresponding to a 10% change of the mean excitation energy. The higher the electron energy, the less is the dependence of the stopping power on I. One reason for this is the increasing magnitude of the contribution $B_0(T)$ to $B(T)$. The other reason is the tendency at high energies for the density effect to offset the I-dependence of the stopping power (see equations (5 and 7)).

3. Mean Excitation Energies for Elements

The value of the mean excitation energy, I, depends on the details of the electronic structure of the medium, and is especially sensitive to the arrangement of the valence electrons. Therefore it is influenced by molecular binding and by the physical state of aggregation of the medium. The accurate theoretical prediction of I-values is difficult, and reliance on experimental data is unavoidable.

Data in the form of experimental stopping-power and range data in the energy region where the Bethe

theory is applicable are rather abundant, especially for protons.[9] Of particular importance are measurements at high energies ($\gtrsim$300 MeV) where the extraction of I-values is simple and straightforward. The bulk of the data have been obtained at lower energies, between 1 and 20 MeV, where the application of shell corrections, and of z^3 and z^4 corrections, is necessary. These corrections are not always known with desirable accuracy, especially for materials of high atomic number, so additional uncertainties are introduced into the analysis. Such difficulties are absent when mean excitation energies are determined from moments of experimental dipole-oscillator-strength distributions or dielectric-response functions. Moreover, there are theoretical sum rules which provide valuable checks and constraints on such data, so that I-values derived in this manner tend to be rather accurate. However, such data are still relatively scarce and have become available in significant amounts only in recent years (see for example, DEHMER *et al.*[10] and INOKUTI and TURNER[11]).

Our choices of I-values are explained in some detail in Ref. 7. For 36 elemental substances, the selections were mainly based on stopping-power and range data, and were strongly influenced by (a) the data analysis of ANDERSEN and ZIEGLER,[1] involving the use of empirical shell corrections; and (b) a new analysis by BICHSEL which involves the use of Walske's K- and L-shell corrections (extended to higher shells by scaling),[12] the z^3 correction of ASHLEY *et al.*[13] and the z^4 correction from the theory of BLOCH.[14] For six gases, the chosen I-values were derived from experimental dipole-oscillator-strength distributions. The I-value for aluminum was taken from a particularly thorough analysis of the dielectric-response function,[15] and is also quite close to the value derived from many stopping-power experiments.

The elements for which I-values could be deduced from experimental data include the cases of greatest practical interest. Nevertheless, it was considered useful to estimate the I-values for other elements, especially with a view toward later application to com-

TABLE 2. Values of the mean excitation energy, I, for the elements (unless noted otherwise, the values are for the substance in the condensed phase)

Z	Element	Symbol	A[a] (g mol^{-1})	I[b] (eV)
1	Hydrogen	H	1.0079	19.2 ± 0.4 molecular gas 21.8 ± 1.6 liquid
2	Helium	He	4.00260	41.8 ± 0.8 gas
3	Lithium	Li	6.941	40 ± 5
4	Beryllium	Be	9.01218	63.7 ± 3.0
5	Boron	B	10.81	76.0 ± 8.0
6	Carbon	C	12.011	78.0 ± 7.0 graphite
7	Nitrogen	N	14.0067	82.0 ± 2.0 molecular gas
8	Oxygen	O	15.9994	95.0 ± 2.0 molecular gas
9	Fluorine	F	18.998403	(115 ± 10) gas
10	Neon	Ne	20.179	137 ± 4 gas
11	Sodium	Na	22.98977	(149 ± 10)
12	Magnesium	Mg	24.305	(156 ± 10)
13	Aluminum	Al	26.98154	166 ± 2
14	Silicon	Si	28.0855	173 ± 3
15	Phosphorus	P	30.97376	(173 ± 15)
16	Sulfur	S	32.06	(180 ± 15)
17	Chlorine	Cl	35.453	(174 ± 15) gas
18	Argon	Ar	39.948	188 ± 10 gas
19	Potassium	K	39.0983	(190 ± 15)
20	Calcium	Ca	40.08	191 ± 8
21	Scandium	Sc	44.9559	216 ± 8
22	Titanium	Ti	47.88	233 ± 5
23	Vanadium	V	50.9415	245 ± 7
24	Chromium	Cr	51.996	257 ± 10
25	Manganese	Mn	54.9380	272 ± 10
26	Iron	Fe	55.847	286 ± 9
27	Cobalt	Co	58.9332	297 ± 9
28	Nickel	Ni	58.69	311 ± 10
29	Copper	Cu	63.546	322 ± 10
30	Zinc	Zn	65.38	330 ± 10
31	Gallium	Ga	69.72	(334 ± 20)
32	Germanium	Ge	72.59	350 ± 11
33	Arsenic	As	74.9216	(347 ± 25)
34	Selenium	Se	78.96	(348 ± 30)
35	Bromine	Br	79.904	(343 ± 30) gas (357 ± 30) condensed
36	Krypton	Kr	83.80	352 ± 25 gas
37	Rubidium	Rb	85.4678	(363 ± 30)
38	Strontium	Sr	87.62	(366 ± 30)

TABLE—*continued*

Z	Element	Symbol	A[a] (g mol^{-1})	I[b] (eV)
39	Yttrium	Y	88.9059	(379 ± 30)
40	Zirconium	Zr	91.22	393 ± 15
41	Niobium	Nb	92.9064	417 ± 15
42	Molybdenum	Mo	95.94	424 ± 15
43	Technetium	^{98}Tc	97.907	(428 ± 35)
44	Ruthenium	Ru	101.07	(441 ± 35)
45	Rhodium	Rh	102.9055	449 ± 20
46	Palladium	Pd	106.42	470 ± 20
47	Silver	Ag	107.868	470 ± 10
48	Cadmium	Cd	112.41	469 ± 20
49	Indium	In	114.82	488 ± 20
50	Tin	Sn	118.69	488 ± 15
51	Antimony	Sb	121.75	(487 ± 40)
52	Tellurium	Te	127.60	(485 ± 40)
53	Iodine	I	126.9045	(474 ± 40) gas (491 ± 40) condensed
54	Xenon	Xe	131.29	482 ± 30 gas
55	Cesium	Cs	132.9054	(488 ± 40)
56	Barium	Ba	137.33	(491 ± 40)
57	Lanthanum	La	138.9055	(501 ± 40)
58	Cerium	Ce	140.12	(523 ± 40)
59	Praseodymium	Pr	140.9077	(535 ± 45)
60	Neodymium	Nd	144.24	(546 ± 45)
61	Promethium	^{145}Pm	144.913	(560 ± 45)
62	Samarium	Sm	150.36	(574 ± 45)
63	Europium	Eu	151.96	(580 ± 50)
64	Gadolinium	Gd	157.25	591 ± 20
65	Terbium	Tb	158.9254	(614 ± 55)
66	Dysprosium	Dy	162.50	(628 ± 55)
67	Holmium	Ho	164.9304	(650 ± 60)
68	Erbium	Er	167.26	(658 ± 60)
69	Thulium	Tm	168.9342	(674 ± 60)
70	Ytterbium	Yb	173.04	(684 ± 65)
71	Lutetium	Lu	174.967	(694 ± 65)
72	Hafnium	Hf	178.49	(705 ± 65)
73	Tantalum	Ta	180.9479	718 ± 30
74	Tungsten	W	183.85	727 ± 30
75	Rhenium	Re	186.207	(736 ± 70)
76	Osmium	Os	190.2	(746 ± 70)
77	Iridium	Ir	192.22	757 ± 30
78	Platinum	Pt	195.08	790 ± 30
79	Gold	Au	196.9665	790 ± 30
80	Mercury	Hg	200.59	(800 ± 75)
81	Thallium	Tl	204.383	(810 ± 75)
82	Lead	Pb	207.2	823 ± 30
83	Bismuth	Bi	208.9804	(823 ± 80)
84	Polonium	^{209}Po	208.982	(830 ± 80)
85	Astatine	^{210}At	209.987	(825 ± 80)
86	Radon	^{222}Rn	222.018	(794 ± 80) gas
87	Francium	^{223}Fr	223.020	(827 ± 80)
88	Radium	Ra	226.0254	(826 ± 80)
89	Actinium	Ac	227.0278	(841 ± 80)
90	Thorium	Th	232.0381	(847 ± 80)
91	Protactinium	Pa	231.0359	(878 ± 80)
92	Uranium	U	238.0289	890 ± 30
93	Neptunium	Np	237.0482	(902 ± 80)
94	Plutonium	^{239}Pu	239.052	(921 ± 85)
95	Americium	^{243}Am	243.061	(934 ± 85)
96	Curium	^{247}Cm	247.070	(939 ± 85)
97	Berkelium	^{247}Bk	247.070	(952 ± 85)
98	Californium	^{251}Cf	251.080	(966 ± 90)
99	Einsteinium	^{252}Es	252.083	(980 ± 90)
100	Fermium	^{257}Fm	257.095	(994 ± 90)

[a] The atomic weights (A) are those recommended by the Commission on Atomic Weights of the International Union of Pure and Applied Chemistry.[19] The values are for naturally occurring isotopic mixtures, unless a particular isotope is indicated.

[b] Values in parentheses are estimated by interpolation of I/Z vs Z, or by extrapolation for $Z > 92$.

TABLE 3. Comparison of mean excitation energies for elements recommended in various publications

	H_2 (gas)	C (graphite)	N_2 (gas)	O_2 (gas)	Al	Cu	Ag	Pb
NCRP (1961)[20]	—	78.4	—	—	164	306	462	812
FANO (1963)[21]	18.3	81	—	—	163	315	478	820
NAS-NRC (1964)[22]	18.7	78	85	89	163	312	480	795
JANNI (1966)[23]	18.3	77.3	87.5	88.9	163	318	459	779
BICHSEL (1968)[24]	18	78	78	100	164	322	475	820
TURNER *et al.* (1970)[25]	18.2	81.2	89.6	101	163	316	466	767
BICHSEL (1972)[26]	19.2	78	78	93	166	319	475	813
ANDERSEN and ZIEGLER (1977)[1]	18.8	77.3	86.7	97.7	162	322	466	759
AHLEN (1980)[27]	18.5	79.0	82	98.5	164	317	469	793
ZIEGLER (1980)[3]	19	79	86	99	162	330	470	761
JANNI (1980)[28]	20.4	73.8	97.8	116	160	321	462	788
Values adopted here	19.2	78.0	82.0	95.0	166	322	470	823

All values are given in units of eV.

pounds. For 57 elements, I-value estimates were obtained by interpolation with respect to atomic number Z. For $Z \gtrsim 20$, the ratio I/Z varies rather slowly with Z, and oscillates around the value $I/Z = 10$ eV. However, the interpolation is complicated by the fact that the Z-dependence is not smooth, due to the effects of atomic shell structure. Such a non-smooth dependence is predicted by the calculations of various authors[3,16] carried out on the basis of the local-plasma approximation of LINDHARD and SCHARFF,[17] and also by evaluations of I from theoretical oscillator-strength distributions.[10,18] We have followed ANDERSEN and ZIEGLER[1] in letting the interpolation of I/Z vs Z be guided by these theoretical results. We have also attempted to take the phase of the medium into account by basing the interpolation either on the neighboring gases or on the neighboring condensed materials for which experimental I-values were available. The complete list of adopted I-values (including estimated uncertainties) is given in Table 2. Values obtained by interpolation are enclosed in parentheses. Analyses leading to sets of recommended I-values have been made many times in the past. In Table 3, comparisons are made with recommendations from eleven previous papers.[1,3,20–28]

4. Mean Excitation Energies for Compounds

Although experimental data are available to determine mean excitation energies directly for a considerable number of compounds, there are many other compounds of interest for which one must rely on indirect determinations, usually through application of an additivity rule. It has been known since the early work of BRAGG and KLEEMAN[29] that the stopping power of a compound can be closely approximated by a weighted sum of the stopping powers for the atomic constituents. Within the framework of the Bethe theory, this additivity assumption is equivalent to assigning to a compound a mean excitation energy

$$\langle I \rangle = \exp\left\{\left[\sum_j w_j (Z_j/A_j) \ln I_j\right] \Big/ \langle Z/A \rangle\right\}, \quad (10)$$

where

$$\langle Z/A \rangle = \sum_j w_j Z_j/A_j, \quad (11)$$

and where w_j, Z_j, A_j and I_j are the fraction by weight, atomic number, atomic weight and mean excitation energy, respectively, of the jth constituent.*

In order to put the additivity rule into effect one must choose appropriate values of the mean excitation energies I_j for the atomic constituents. The simplest choice, which has been widely used in the past, is to use I-values for elemental substances, thereby disregarding molecular binding effects, and also disregarding the fact that input data, such as those for nitrogen and oxygen, may be for gases but must be applied to condensed materials.

A significant body of data pertaining to molecular binding effects was provided by the relative stopping-power measurements of THOMPSON[30] for 33 materials, including 26 organic liquids and water. Thompson measured partial ranges, relative to those in copper, for protons slowing down from 340 to 200 MeV. These data can be interpreted as stopping-power ratios at an intermediate energy (267.5 MeV). From his results, Thompson obtained relative stopping powers (and I-values) for the atomic constituents H, C, N, O and Cl which depend on the type of molecular bond involved. Thompson's results were interpreted by WESTERMARK[31] in terms of molecular polarizabilities, and this approach was further developed by BRANDT[32] into a theory for predicting I-values for compounds from molar refractivity data and the low-energy density effect. We have re-analyzed† the stopping-power ratios of Thompson,

* The density-effect correction, δ, should always be evaluated directly for the compound, i.e. as a function of the appropriate density and mean excitation energy.

† The analysis was done both relative to copper ($I_{Cu} = 322$ eV) and relative to water ($I_{H_2O} = 75$ eV). The two sets of I-values thus obtained differed by only 0.6%; therefore, the average was taken.

TABLE 4. Mean excitation energies from our analysis of THOMPSON'S[30] experiment

Element	I (eV)
Elemental Substances	
H_2 (liquid)	22.3 ± 1.6
C (graphite)	83.4 ± 3.6
N_2 (liquid)	90.5 ± 2.6
O_2 (liquid)	104.3 ± 3.4
Elemental Constituents of Condensed Organic Compounds	
Element in compound / Type of bonding/position in compound	I (eV)
H — Saturated	19.0 ± 0.8
H — Unsaturated	16.0 ± 0.8
C — Saturated	81.1 ± 2.5
C — Unsaturated	79.8 ± 2.3
C — Highly chlorinated	69.0 ± 3.7
N — Amines, nitrates etc.	105.7 ± 10.6
N — in ring	81.9 ± 7.0
O — —O—	104.6 ± 9.2
O — O=	94.4 ± 4.9
Cl — All	179.7 ± 11.9

The uncertainties given in this table attempt to combine both the measurement uncertainties quoted by Thompson, and the uncertainties inherent in our analysis.

applying small multiple-scattering and shell corrections in a procedure outlined by BICHSEL.[33] The resultant I-values for atomic constituents are given in Table 4.

In recent years, experimental I-values have become available for various other compounds through the analysis of stopping-power measurements, dipole-oscillator-strength distributions and dielectric-response functions. Table 5 lists experimental mean excitation energies for 54 compounds, including results derived by us from Thompson's earlier experiments and from the more recent work. We have found that the experimental I-values can be satisfactorily approximated by the additivity rule, equation (10), with the I-values for elemental constituents listed in Table 6. Different I-values are used depending on whether the compound is a gas or a condensed material. Thus no account is taken of possible differences between single and double bonds, between cyclic and non-cyclic structures, between covalent and ionic compounds, between monomers and polymers, between liquids and solids etc. In spite of these omissions, the assignment scheme provides good approximations to the experimental results, and is easier to apply to other materials than the more sophisticated assignments suggested by Thompson or Brandt. As shown in Table 5, for 52 compounds the direct experimental values of the mean excitation energies are in agreement (within the limits of experimental error) with the predictions of equation (10); only in 2 cases are there significant discrepancies.*

We have assumed that the additivity rule, equation (10), with I-values for atomic constituents from Table 6, can be used for predicting the mean excitation energies of other compounds. For low-Z gases and, particularly, for condensed organic compounds consisting of the constituents H, C, N, O, F or Cl, such predictions have a sound empirical basis. One would expect that the errors incurred thereby will have the same order of magnitude as the differences shown in Table 5 between direct experimental mean excitation energies and corresponding values from the additivity rule. The situation is less clear in regard to condensed compounds that contain also constituents other than H, C, N, O, F or Cl. The recommendation in Table 6 is to use I-values for these other constituents which are 13% larger than the corresponding I-values for condensed elemental substances in Table 2. This rule has been found to give a good fit to the direct experimental I-values for Al_2O_3, SiO_2, photographic emulsion, LiF and CaF_2. In the absence of better information, we have assumed that the 13% increase can be applied for other compounds as well.

There are some composite materials, e.g. tissue, glass and tissue-equivalent gas, which have constituent molecules whose I-values are known experimentally. In order to take advantage of this information, we have treated such composite materials via the additivity rule applied to the constituent molecules.

Table 7 lists mean excitation energies, as well as densities and elemental compositions, for 180 compounds and mixtures. In this Table, the symbol + indicates either I-values derived directly from experimental data or I-values for mixtures (such as air) all of whose constituents have experimentally determined I-values. The symbol + + indicates I-values derived by applying the additivity rule to molecular constituents, one or more of which have experimentally determined I-values. In all other cases, the I-values were obtained from the additivity rule, equation (10), with constituent I-values from Table 6.

A letter grade (A, B or C) is given next to each I-value in Table 7, to indicate the relative quality of these data. The assignment of these grades was based on the information contained in Table 5, but also involved some subjective judgements. For the most part the following guidelines were followed. Direct experimental I-values were given the grade A unless the experimental uncertainty was greater than 5%, in which case they were given the grade B. I-values for low-Z gas compounds were given the grade A. I-values for condensed compounds were given the grade B if the constituents consisted predominantly of the elements H, C, N, O, F or Cl. The grade C was given to I-values for condensed compounds which contain mainly other constituents whose I-values

* A particularly large discrepancy occurs for paraffin wax. Because the experimental I-value for paraffin wax is inconsistent with those for other straight-chain hydrocarbons (*n*-pentane, *n*-hexane, *n*-heptane and polyethylene), the value from the additivity rule has been used in the stopping-power calculation.

TABLES 5A–C. Approximation of experimental mean excitation energies for compounds by the additivity rule

A. Gas Compounds

Compound	Footnote	Experimental results* I_{expt} (eV)	Uncertainty (%)	Bragg additivity $\langle I \rangle$ (eV)	$\langle I \rangle / I_{expt}$†
Ammonia, NH_3	a	53.7	2	53.0	0.987
Butane, C_4H_{10}	b	48.3	2	47.8	0.990
Carbon dioxide, CO_2	c	85	2	88.7	1.044
Ethane, C_2H_6	b	45.4	2	45.5	1.002
Heptane, C_7H_{16}	b	49.2	2	49.0	0.996
Hexane, C_6H_{14}	b	49.1	2	48.7	0.992
Methane, CH_4	d	41.7	2	41.7	1.000
Nitric oxide, NO	a	87.8	2	89.7	1.022
Nitrous oxide, N_2O	a	84.9	2	87.2	1.027
Octane, C_8H_{18}	b	49.5	2	49.2	0.994
Pentane, C_5H_{12}	b	48.2	2	48.4	1.004
Propane, C_3H_8	b	47.1	2	47.0	0.998
Water, H_2O	a	71.6	2	70.2	0.980

* Derived from semi-empirical dipole-oscillator-strength distributions, except for CO_2.

† I_{expt} is the experimental value, and $\langle I \rangle$ the value calculated from equation (10), using I-values from Table 6 for the elemental constituents.

[a] From ZEISS *et al.*[34]

[b] From JHANWAR *et al.*[63]

[c] From α-particle stopping-power measurements of BICHSEL and HILKO.[64] Note that the 300–400 keV stopping-power data of BADER *et al.*[35] lead to a value of 88.7 ± 7.1 kV.

[d] From THOMAS and MEATH.[36]

B. Liquid Compounds

Compound	Experimental results* I_{expt} (eV)	Bragg additivity $\langle I \rangle$ (eV)	$\langle I \rangle / I_{expt}$
Acetone, C_3H_6O	64.2	66.1	0.971
Aniline, $C_6H_5NH_2$	66.2	66.3	1.002
Benzene, C_6H_6	63.4	65.9	1.039
n-Butyl alcohol, C_4H_9OH	59.9	60.5	1.010
Carbon tetrachloride, CCl_4	166.3	168.7	1.014
Chlorobenzene, C_6H_5Cl	89.1	90.4	1.015
Chloroform, $CHCl_3$	156.0	159.5	1.022
Cyclohexane, C_6H_{12}	56.4	56.5	1.002
1,2-Dichlorobenzene, $C_6H_4Cl_2$	106.5	108.1	1.015
Dichlorodiethyl ether, $C_4Cl_2H_8O$	103.3	103.0	0.997
1,2-Dichloroethane, $C_2Cl_2H_4$	111.9	124.2	1.110
Diethyl ether, $(C_2H_5)_2O$	60.0	60.5	1.008
Ethyl alcohol, C_2H_5OH	62.9	63.1	1.003
Glycerol, $C_3H_5(OH)_3$	72.6	73.2	1.008
n-Heptane, C_7H_{16}	54.4	54.5	1.002
n-Hexane, C_6H_{14}	54.0	54.1	1.002
Methanol, CH_3OH	67.6	66.3	0.981
Nitrobenzene, $C_6H_5NO_2$	75.8	77.5	1.022
n-Pentane, C_5H_{12}	53.6	53.7	1.002
n-Propyl alcohol, C_3H_7OH	61.1	61.5	1.007
Pyridine, C_5H_5N	66.2	68.4	1.033
Styrene, C_8H_8	64.0	65.9	1.030
Tetrachloroethylene, C_2Cl_4	159.2	159.7	1.003
Toluene, C_7H_8	62.5	64.3	1.029
Trichloroethylene, C_2Cl_3H	148.1	149.6	1.010
Water, H_2O	75.0[a]	75.3	1.004
Xylene, C_8H_{10}	61.8	63.2	1.023

* Derived from our analysis of THOMPSON's[30] experimental partial ranges of protons. The uncertainties of these I-values are estimated to be 3–4%.

[a] A compromise among the following experimental results: 75.4 ± 1.9 eV from our analysis of THOMPSON's[30] measurements relative to Cu, assuming I_{Cu} = 322 eV; 74.6 ± 2.7 eV from an analysis of the 61-MeV pion stopping-power measurements of NORDIN and HENKELMAN;[37] 75 eV from RITCHIE *et al.*[38] and 75.4 eV from ASHLEY,[65] both values derived from empirically-based models of the dielectric-response function for liquid water.

C. Solid Compounds

Compound	Footnote	Experimental results I_{expt} (eV)	Uncertainty (%)	Bragg additivity $\langle I \rangle$ (eV)	$\langle I \rangle / I_{expt}$
A-150 tissue-equivalent plastic	a	65.1	16	64.0	0.983
Adenine, $C_5H_5N_5$	b	71.4	5	73.5	1.029
Aluminum oxide, Al_2O_3	c	145.2	3	142.6	0.982
Calcium fluoride, CaF_2	d	166	8	158.2	0.953
Guanine, $C_5H_5N_5O$	b	75.0	5	76.3	1.017
Lithium fluoride, LiF	d	94	8	89.3	0.950
Nylon, type 6, $(C_6H_{11}NO)_n$	a	63.9	6	65.0	1.017
Paraffin wax, $C_{25}H_{52}$	a	48.3	7	55.9	1.157
Photographic emulsion	e	331	3	321.2	0.970
Polyethylene, $(C_2H_4)_n$	f	57.4	8	56.5	0.984
Polymethyl methacrylate, $(C_5H_8O_2)_n$	g	74.0	4	70.9	0.965
Polystyrene, $(C_8H_8)_n$	h	68.7	4	65.9	0.959
Polytetrafluoroethylene, "Teflon," $(C_2F_4)_n$	a	99.1	6	103.3	1.042
Silicon dioxide, SiO_2	c	139.2	3	141.0	1.013

[a] From 61 MeV pion stopping-power measurements relative to H_2O of NORDIN and HENKELMAN,[37] assuming $I_{H_2O} = 75.0$ eV.

[b] From dielectric-response function, J. ASHLEY (private communication).

[c] From range measurements of TSCHALÄR and BICHSEL[39] with 3–30 MeV protons.

[d] From stopping-power results of BADER *et al.*[35] for protons with energies between 300–400 keV.

[e] From range measurements of BARKAS *et al.*[40] using various charged particles with equivalent proton energies up to 700 MeV.

[f] PAINTER *et al.*[41] give a value 62.2 eV from their dielectric-response function measurements. THOMPSON's[30] 267.5 MeV proton stopping-power measurements lead to a value of 52.5 ± 1.5 eV. The adopted value 57.4 eV is an average.

[g] Bichsel (private communication) has revised the Tschalär–Bichsel value for PMMA (see footnote c) from 74.2 to 73.5 eV by applying z^3 and z^4 corrections. Our analysis of the Nordin–Henkelman data (see footnote a) gives a value 74.4 ± 4.7 eV. The adopted value, 74.0 eV, is an average.

[h] The value 68.7 eV is from ASHLEY's[42] measurement of the dielectric-response function. This value is close to the average of 71 ± 2 eV derived by PORTER *et al.*[43] from proton stopping-power measurements at 2.2–5.9 MeV, and of 65.2 ± 1.9 eV derived from THOMPSON's[30] measurements at 267.5 MeV.

were adjusted upward by the 13% rule. It is difficult to associate precise numerical values with these grades. A rather conservative estimate is to assign uncertainties of $\lesssim 5\%$ to grade A, 5–10% to grade B and 10–15% to grade C. Inspection of Table 5 suggests that the uncertainties may well be smaller.

In Table 8, I-values for selected materials from Table 7 are compared with values recommended or used in earlier publications. In some cases there are significant differences: for example, the value of 75 eV for water compared to the value of 65 eV used in Refs 22 and 59, or the value of 85.7 eV for air compared to the value of 93 eV given in Ref. 25. In many cases the present and earlier recommended values agree within the limits of the estimated uncertainties. However, the present recommendations have a broader empirical basis because they include experimental data that have become available in the last ten years. On the whole, Brandt's theoretical I-values for low-Z compounds are in reasonably good agreement with those adopted here; however, his I-values for compounds containing high-Z constituents tend to be too low, a fact already noted by BRANDT[32] with reference to photographic emulsion.

TABLE 6. Adopted values of mean excitation energies for elemental constituents in gas and condensed compounds

Constituent	Gas compounds	Solid and liquid compounds
H	19.2	19.2
C	70	81
N	82	82
O	97	106
F		112
Cl		180
Others		1.13 I[a]

[a] I-value for elemental substance in condensed phase, from Table 2.

5. Sternheimer's Density-effect Correction

Following FERMI's original paper,[60] and the work of WICK[61] and HALPERN and HALL,[62] STERNHEIMER[5] developed a rather accurate theory for predicting the density-effect correction in any material. The information which enters into Sternheimer's model of the dispersion properties of the medium in-

TABLE 7. Mean excitation energies I and other properties of compounds and mixtures

Material	<Z/A>	Density* (g/cm³)	I‡ (eV)	Gr§	Composition (constituent Z : fraction by weight)			
A-150 TISSUE-EQUIVALENT PLASTIC[a]	0.549031	1.127E+00	65.1+	B	1: 0.101327	6: 0.775501	7: 0.035057	8: 0.052316
					9: 0.017422	20: 0.018378		
ACETONE, C_3H_6O	0.550966	7.899E-01	64.2+	A	1: 0.104122	6: 0.620405	8: 0.275473	
ACETYLENE, C_2H_2	0.537680	1.097E-03	58.2	A	1: 0.077418	6: 0.922582		
ADENINE, $C_5H_5N_5$	0.518027	1.350E+00	71.4+	A	1: 0.037294	6: 0.444430	7: 0.518275	
ADIPOSE TISSUE (ICRP)[b]	0.558468	9.200E-01	63.2++	B	1: 0.119477	6: 0.637240	7: 0.007970	8: 0.232333
					11: 0.000500	12: 0.000020	15: 0.000160	16: 0.000730
					17: 0.001190	19: 0.000320	20: 0.000020	26: 0.000020
					30: 0.000020			
AIR, DRY (NEAR SEA LEVEL)[c]	0.499190	1.205E-03	85.7+	A	6: 0.000124	7: 0.755267	8: 0.231781	18: 0.012827
ALANINE, $C_3H_7NO_2$	0.538758	1.420E+00	71.9	B	1: 0.079190	6: 0.404439	7: 0.157213	8: 0.359159
ALUMINUM OXIDE, Al_2O_3	0.490382	3.970E+00	145.2+	A	8: 0.470749	13: 0.529251		
AMBER, $C_{10}H_{16}O$	0.551776	1.100E+00	63.2	B	1: 0.105930	6: 0.788973	8: 0.105096	
AMMONIA, NH_3	0.587185	8.260E-04	53.7+	A	1: 0.177547	7: 0.822453		
ANILINE, $C_6H_5NH_2$	0.536895	1.024E+00	66.2+	A	1: 0.075759	6: 0.773838	7: 0.150403	
ANTHRACENE, $C_{14}H_{10}$	0.527400	1.283E+00	69.5	B	1: 0.056550	6: 0.943450		
B-100 BONE-EQUIVALENT PLASTIC[d]	0.527397	1.450E+00	85.9++	B	1: 0.065471	6: 0.536945	7: 0.021500	8: 0.032085
					9: 0.167411	20: 0.176589		
BAKELITE, $(C_{43}H_{38}O_7)_n$	0.527919	1.250E+00	72.4	B	1: 0.057441	6: 0.774591	8: 0.167968	
BARIUM FLUORIDE, BaF_2	0.422069	4.890E+00	375.9	C	9: 0.216720	56: 0.783280		
BARIUM SULFATE, $BaSO_4$	0.445611	4.500E+00	285.7	C	8: 0.274212	16: 0.137368	56: 0.588420	
BENZENE, C_6H_6	0.537680	8.787E-01	63.4+	A	1: 0.077418	6: 0.922582		
BERYLLIUM OXIDE, BeO	0.479778	3.010E+00	93.2	C	4: 0.360320	8: 0.639680		
BISMUTH GERMANIUM OXIDE, $Bi_4Ge_3O_{12}$	0.420652	7.130E+00	534.1	C	8: 0.154126	32: 0.174820	83: 0.671054	
BLOOD (ICRP)[b]	0.549952	1.060E+00	75.2++	A	1: 0.101866	6: 0.100020	7: 0.029640	8: 0.759414
					11: 0.001850	12: 0.000040	14: 0.000030	15: 0.000350
					16: 0.001850	17: 0.002780	19: 0.001630	20: 0.000060
					26: 0.000460	30: 0.000010		
BONE, COMPACT (ICRU)[e]	0.530103	1.850E+00	91.9++	B	1: 0.063984	6: 0.278000	7: 0.027000	8: 0.410016
					12: 0.002000	15: 0.070000	16: 0.002000	20: 0.147000

TABLE 7—*continued*

Material	<Z/A>	Density* (g/cm³)	I‡ (eV)	Gr§	Composition (constituent Z : fraction by weight)			
BONE, CORTICAL (ICRP)[b]	0.521299	1.850E+00	106.4**	B	1: 0.047234 12: 0.002200 30: 0.000100	6: 0.144330 15: 0.104970	7: 0.041990 16: 0.003150	8: 0.446096 20: 0.209930
BORON CARBIDE, B_4C	0.470580	2.520E+00	84.7	C	5: 0.782610	6: 0.217390		
BORON OXIDE, B_2O_3	0.488378	1.812E+00	99.6	C	5: 0.310551	8: 0.689449		
BRAIN (ICRP)[b]	0.554227	1.030E+00	73.3**	A	1: 0.110667 11: 0.001840 17: 0.002360 30: 0.000010	6: 0.125420 12: 0.000150 19: 0.003100	7: 0.013280 15: 0.003540 20: 0.000090	8: 0.737723 16: 0.001770 26: 0.000050
BUTANE, C_4H_{10}	0.584966	2.493E-03	48.3*	A	1: 0.173408	6: 0.826592		
N-BUTYL ALCOHOL, C_4H_9OH	0.566630	8.098E-01	59.9*	A	1: 0.135978	6: 0.648171	8: 0.215851	
C-552 AIR-EQUIVALENT PLASTIC[f]	0.499687	1.760E+00	86.8**	B	1: 0.024680 14: 0.003973	6: 0.501610	8: 0.004527	9: 0.465209
CADMIUM TELLURIDE, CdTe	0.416649	6.200E+00	539.5	C	48: 0.468355	52: 0.531645		
CADMIUM TUNGSTATE, $CdWO_4$	0.427472	7.900E+00	468.3	C	8: 0.177644	48: 0.312027	74: 0.510329	
CALCIUM CARBONATE, $CaCO_3$	0.499554	2.800E+00	136.4	C	6: 0.120003	8: 0.479554	20: 0.400443	
CALCIUM FLUORIDE, CaF_2	0.486700	3.180E+00	166.0*	B	9: 0.486659	20: 0.513341		
CALCIUM OXIDE, CaO	0.499292	3.300E+00	176.1	C	8: 0.285299	20: 0.714701		
CALCIUM SULFATE, $CaSO_4$	0.499495	2.960E+00	152.3	C	8: 0.470095	16: 0.235497	20: 0.294408	
CALCIUM TUNGSTATE, $CaWO_4$	0.437610	6.062E+00	395.0	C	8: 0.222270	20: 0.139202	74: 0.638529	
CARBON DIOXIDE, CO_2	0.499889	1.842E-03	85.0*	A	6: 0.272916	8: 0.727084		
CARBON TETRACHLORIDE, CCl_4	0.481072	1.594E+00	166.3*	A	6: 0.078083	17: 0.921917		
CELLULOSE ACETATE, CELLOPHANE, $(C_6H_{10}O_5)_n$	0.530399	1.420E+00	77.6	B	1: 0.062162	6: 0.444462	8: 0.493376	
CELLULOSE ACETATE BUTYRATE, $(C_{15}H_{22}O_8)_n$	0.532794	1.200E+00	74.6	B	1: 0.067125	6: 0.545403	8: 0.387472	
CELLULOSE NITRATE, $C_6H_{7.7}O_{9.6}N_{2.3}$	0.514237	1.490E+00	87.0	B	1: 0.029216	6: 0.271296	7: 0.121276	8: 0.578212
CERIC SULFATE DOSIMETER SOLUTION[g]	0.552785	1.030E+00	76.7**	A	1: 0.107596 58: 0.002001	7: 0.000800	8: 0.874976	16: 0.014627
CESIUM FLUORIDE, CsF	0.421319	4.115E+00	440.7	C	9: 0.125069	55: 0.874931		
CESIUM IODIDE, CsI	0.415689	4.510E+00	553.1	C	53: 0.488451	55: 0.511549		

TABLE 7—*continued*

CHLOROBENZENE, C_6H_5Cl	0.515288	1.106E+00	89.1*	A	1: 0.044772	6: 0.640254	17: 0.314974					
CHLOROFORM, $CHCl_3$	0.485852	1.483E+00	156.0*	A	1: 0.008443	6: 0.100613	17: 0.890944					
CONCRETE, PORTLAND[h]	0.502736	2.300E+00	135.2**	A	1: 0.010000 12: 0.002000 20: 0.044000	6: 0.001000 13: 0.033872 26: 0.014000	8: 0.529107 14: 0.337021	11: 0.016000 19: 0.013000				
CYCLOHEXANE, C_6H_{12}	0.570337	7.790E-01	56.4*	A	1: 0.143711	6: 0.856289						
1,2-DICHLOROBENZENE, $C_6H_4Cl_2$	0.503389	1.305E+00	106.5*	A	1: 0.027425	6: 0.490233	17: 0.482342					
DICHLORODIETHYL ETHER, $C_4Cl_2H_8O$	0.517437	1.220E+00	103.3*	A	1: 0.056381	6: 0.335942	8: 0.111874	17: 0.495802				
1,2-DICHLOROETHANE, $C_2H_4Cl_2$	0.505257	1.235E+00	111.9*	A	1: 0.040740	6: 0.242746	17: 0.716515					
DIETHYL ETHER, $(C_2H_5)_2O$	0.566630	7.138E-01	60.0*	A	1: 0.135978	6: 0.648171	8: 0.215851					
N,N-DIMETHYL FORMAMIDE, C_3H_6ONH	0.547238	9.487E-01	66.6	B	1: 0.096523	6: 0.492965	7: 0.191625	8: 0.218887				
DIMETHYL SULFOXIDE, $(CH_3)_2SO$	0.537574	1.101E+00	98.6	C	1: 0.077403	6: 0.307467	8: 0.204782	16: 0.410348				
ETHANE, C_2H_6	0.598615	1.253E-03	45.4*	A	1: 0.201115	6: 0.798885						
ETHYL ALCOHOL, C_2H_5OH	0.564373	7.893E-01	62.9*	A	1: 0.131269	6: 0.521438	8: 0.347294					
ETHYL CELLULOSE, $(C_{12}H_{22}O_5)_n$	0.544046	1.130E+00	69.3	B	1: 0.090027	6: 0.585182	8: 0.324791					
ETHYLENE, C_2H_4	0.570337	1.175E-03	50.7	A	1: 0.143711	6: 0.856289						
EYE LENS (ICRP)[b]	0.548767	1.100E+00	73.3**	A	1: 0.099269	6: 0.193710	7: 0.053270	8: 0.653751				
FERRIC OXIDE, Fe_2O_3	0.475916	5.200E+00	227.3	C	8: 0.300567	26: 0.699433						
FERROBORIDE, FeB	0.465067	7.150E+00	261.0	C	5: 0.162174	26: 0.837826						
FERROUS OXIDE, FeO	0.473232	5.700E+00	248.6	C	8: 0.222689	26: 0.777311						
FERROUS SULFATE DOSIMETER SOLUTION[i]	0.553282	1.024E+00	76.4**	A	1: 0.108259 16: 0.012968	7: 0.000027 17: 0.000034	8: 0.878636 26: 0.000054	11: 0.000022				
"FREON-12", CF_2Cl_2	0.479681	1.120E+00	143.0	B	6: 0.099335	9: 0.314247	17: 0.586418					
"FREON-12B2", CF_2Br_2	0.448012	1.800E+00	284.9	C	6: 0.057245	9: 0.181096	35: 0.761659					
"FREON-13", CF_3Cl	0.478656	9.500E-01	126.6	B	6: 0.114983	9: 0.545622	17: 0.339396					
"FREON-13B1", CF_3Br	0.456651	1.500E+00	210.5	C	6: 0.080659	9: 0.382749	35: 0.536592					
"FREON-13I1", CF_3I	0.438975	1.800E+00	293.5	C	6: 0.061309	9: 0.290924	53: 0.647767					
GADOLINIUM OXYSULFIDE, Gd_2O_2S	0.422656	7.440E+00	493.3	C	8: 0.084528	16: 0.084690	64: 0.830782					

TABLE 7—*continued*

Material	<Z/A>	Density* (g/cm^3)	I‡ (eV)	Gr§	Composition (constituent Z : fraction by weight)			
GALLIUM ARSENIDE, GaAs	0.442473	5.310E+00	384.9	C	31: 0.482019	33: 0.517981		
GEL IN PHOTOGRAPHIC EMULSION[j]	0.539734	1.291E+00	74.8	B	1: 0.081180 16: 0.010880	6: 0.416060	7: 0.111240	8: 0.380640
GLASS, BOROSILICATE ("PYREX", CORNING 7740)[k]	0.497070	2.230E+00	134.0++	A	5: 0.040061 14: 0.377220	8: 0.539564 19: 0.003321	11: 0.028191	13: 0.011644
GLASS, LEAD[l]	0.421007	6.220E+00	526.4++	C	8: 0.156453 82: 0.751938	14: 0.080866	22: 0.008092	33: 0.002651
GLASS, PLATE[m]	0.497313	2.400E+00	145.4++	A	8: 0.459800	11: 0.096441	14: 0.336553	20: 0.107205
GLUCOSE, DEXTROSE, $C_6H_{12}O_6 \cdot H_2O$	0.534888	1.540E+00	77.2++	B	1: 0.071204	6: 0.363652	8: 0.565144	
GLUTAMINE, $C_5H_{10}N_2O_3$	0.533714	1.460E+00	73.3	B	1: 0.068965	6: 0.410926	7: 0.191681	8: 0.328427
GLYCEROL, $C_3H_5(OH)_3$	0.542921	1.261E+00	72.6+	A	1: 0.087554	6: 0.391262	8: 0.521185	
GUANINE, $C_5H_5N_5O$	0.516121	1.580E+00	75.0+	A	1: 0.033346	6: 0.397380	7: 0.463407	8: 0.105867
GYPSUM, PLASTER OF PARIS, $CaSO_4 \cdot 2H_2O$	0.511128	2.320E+00	129.7++	B	1: 0.023416	8: 0.557572	16: 0.186215	20: 0.232797
N-HEPTANE, C_7H_{16}	0.578823	6.838E-01	54.4+	A	1: 0.160937	6: 0.839063		
N-HEXANE, C_6H_{14}	0.580204	6.603E-01	54.0+	A	1: 0.163741	6: 0.836259		
"KAPTON" POLYIMIDE FILM, $(C_{22}H_{10}N_2O_5)_n$	0.512644	1.420E+00	79.6	B	1: 0.026362	6: 0.691133	7: 0.073270	8: 0.209235
LANTHANUM OXYBROMIDE, LaOBr	0.425878	6.280E+00	439.7	C	8: 0.068138	35: 0.340294	57: 0.591568	
LANTHANUM OXYSULFIDE, La_2OS	0.423481	5.860E+00	456.2	C	8: 0.049097	16: 0.098383	57: 0.852520	
LEAD OXIDE, PbO	0.403227	9.530E+00	766.7	C	8: 0.071682	82: 0.928318		
LITHIUM AMIDE, $LiNH_2$	0.522568	1.178E+00	55.5	B	1: 0.087783	3: 0.302262	7: 0.609955	
LITHIUM CARBONATE, Li_2CO_3	0.487203	2.110E+00	87.9	B	3: 0.187871	6: 0.162550	8: 0.649579	
LITHIUM FLUORIDE, LiF	0.462617	2.635E+00	94.0+	B	3: 0.267585	9: 0.732415		
LITHIUM HYDRIDE, LiH	0.503214	8.200E-01	36.5	C	1: 0.126797	3: 0.873203		
LITHIUM IODIDE, LiI	0.418393	3.494E+00	485.1	C	3: 0.051858	53: 0.948142		
LITHIUM OXIDE, Li_2O	0.468519	2.013E+00	73.6	C	3: 0.464570	8: 0.535430		
LITHIUM TETRABORATE, $Li_2B_4O_7$	0.484869	2.440E+00	94.6	C	3: 0.082085	5: 0.255680	8: 0.662235	
LUNG (ICRP)[b]	0.549652	1.050E+00	75.3++	A	1: 0.101278 11: 0.001840 17: 0.002660 30: 0.000010	6: 0.102310 12: 0.000730 19: 0.001940	7: 0.028650 15: 0.000800 20: 0.000090	8: 0.757072 16: 0.002250 26: 0.000370

TABLE 7—*continued*

M3 WAX[n]	0.555116	1.050E+00	67.9	B	1: 0.114318 20: 0.002883	6: 0.655823	8: 0.092183	12: 0.134792				
MAGNESIUM CARBONATE, $MgCO_3$	0.498137	2.958E+00	118.0	C	6: 0.142455	8: 0.569278	12: 0.288267					
MAGNESIUM FLUORIDE, MgF_2	0.481527	3.000E+00	134.3	C	9: 0.609883	12: 0.390117						
MAGNESIUM OXIDE, MgO	0.496224	3.580E+00	143.8	C	8: 0.396964	12: 0.603036						
MAGNESIUM TETRABORATE, MgB_4O_7	0.490139	2.530E+00	108.3	C	5: 0.240837	8: 0.623790	12: 0.135373					
MERCURIC IODIDE, HgI_2	0.409332	6.360E+00	684.5	C	53: 0.558560	80: 0.441440						
METHANE, CH_4	0.623340	6.672E-04	41.7*	A	1: 0.251306	6: 0.748694						
METHANOL, CH_3OH	0.561763	7.914E-01	67.6*	A	1: 0.125822	6: 0.374852	8: 0.499326					
MIX D WAX[o]	0.564789	9.900E-01	60.9**	B	1: 0.134040 22: 0.014386	6: 0.777960	8: 0.035020	12: 0.038594				
MS20 TISSUE SUBSTITUTE[p]	0.538856	1.000E+00	75.1	B	1: 0.081192 12: 0.130287	6: 0.583442 17: 0.000900	7: 0.017798	8: 0.186381				
MUSCLE, SKELETAL (ICRP)[b]	0.549378	1.040E+00	75.3**	A	1: 0.100637 11: 0.000750 17: 0.000790 30: 0.000050	6: 0.107830 12: 0.000190 19: 0.003020	7: 0.027680 15: 0.001800 20: 0.000030	8: 0.754773 16: 0.002410 26: 0.000040				
MUSCLE, STRIATED (ICRU)[e]	0.550051	1.040E+00	74.7**	A	1: 0.101997 11: 0.000800 19: 0.003000	6: 0.123000 12: 0.000200	7: 0.035000 15: 0.002000	8: 0.729003 16: 0.005000				
MUSCLE-EQUIVALENT LIQUID, WITH SUCROSE[q]	0.548281	1.110E+00	74.3**	A	1: 0.098234	6: 0.156214	7: 0.035451	8: 0.710100				
MUSCLE-EQUIVALENT LIQUID, WITHOUT SUCROSE[r]	0.550136	1.070E+00	74.2**	A	1: 0.101969	6: 0.120058	7: 0.035451	8: 0.742522				
NAPTHALENE, $C_{10}H_8$	0.530532	1.145E+00	68.4	B	1: 0.062909	6: 0.937091						
NITROBENZENE, $C_6H_5NO_2$	0.519856	1.199E+00	75.8*	A	1: 0.040935	6: 0.585374	7: 0.113773	8: 0.259918				
NITROUS OXIDE, N_2O	0.499855	1.831E-03	84.9*	A	7: 0.636483	8: 0.363517						
NYLON, DU PONT "ELVAMIDE 8062M"[s]	0.550625	1.080E+00	64.3	B	1: 0.103509	6: 0.648415	7: 0.099536	8: 0.148539				
NYLON, TYPE 6 AND TYPE 6/6, $(C_6H_{11}ON)_n$	0.547902	1.140E+00	63.9*	A	1: 0.097976	6: 0.636856	7: 0.123779	8: 0.141389				
NYLON, TYPE 6/10, $(C_8H_{15}ON)_n$	0.552359	1.140E+00	63.2	B	1: 0.107062	6: 0.680449	7: 0.099189	8: 0.113300				
NYLON, TYPE 11 ("RILSAN"), $(C_{11}H_{21}ON)_n$	0.556486	1.425E+00	61.6	B	1: 0.115476	6: 0.720819	7: 0.076417	8: 0.087289				

TABLE 7—*continued*

Material	<Z/A>	Density* (g/cm³)	I‡ (eV)	Gr§	Composition (constituent Z : fraction by weight)			
OCTANE, LIQUID, C_8H_{18}	0.577781	7.026E-01	54.7	B	1: 0.158821	6: 0.841179		
PARAFFIN WAX, $C_{25}H_{52}$	0.572748	9.300E-01	55.9	B	1: 0.148605	6: 0.851395		
N-PENTANE, C_5H_{12}	0.582122	6.262E-01	53.6+	A	1: 0.167635	6: 0.832365		
PHOTOGRAPHIC EMULSION[j]	0.454532	3.815E+00	331.0+	A	1: 0.014100 16: 0.001890	6: 0.072261 35: 0.349103	7: 0.019320 47: 0.474105	8: 0.066101 53: 0.003120
PLASTIC SCINTILLATOR (VINYLTOLUENE BASED)[t]	0.541415	1.032E+00	64.7	B	1: 0.085000	6: 0.915000		
PLUTONIUM DIOXIDE, PuO_2	0.405828	1.146E+01	746.5	C	8: 0.118055	94: 0.881945		
POLYACRYLONITRILE, $(C_3H_3N)_n$	0.527671	1.170E+00	69.6	B	1: 0.056983	6: 0.679056	7: 0.263962	
POLYCARBONATE,[u] "MAKROLON", $(C_{16}H_{14}O_3)_n$	0.526968	1.200E+00	73.1	B	1: 0.055491	6: 0.755751	8: 0.188758	
POLYCHLOROSTYRENE, $(C_{17}H_{18}Cl_2)_n$	0.525176	1.300E+00	81.7	B	1: 0.061869	6: 0.696325	17: 0.241806	
POLYETHYLENE, $(C_2H_4)_n$	0.570337	9.400E-01	57.4+	B	1: 0.143711	6: 0.856289		
POLYETHYLENE TEREPTHALATE,[v] "MYLAR" $(C_{10}H_8O_4)_n$	0.520370	1.400E+00	78.7	B	1: 0.041959	6: 0.625017	8: 0.333025	
POLYMETHYL METHACRYLATE,[w] $(C_5H_8O_2)_n$	0.539369	1.190E+00	74.0+	A	1: 0.080538	6: 0.599848	8: 0.319614	
POLYOXYMETHYLENE, $(CH_2O)_n$	0.532868	1.425E+00	77.4	A	1: 0.067135	6: 0.400017	8: 0.532848	
POLYPROPYLENE, $(C_3H_5)_n$	0.559985	9.000E-01	59.2	B	1: 0.122698	6: 0.877302		
POLYSTYRENE,[x] $(C_8H_8)_n$	0.537680	1.060E+00	68.7+	A	1: 0.077418	6: 0.922582		
POLYTETRAFLUOROETHYLENE,[y] "TEFLON", $(C_2F_4)_n$	0.479925	2.200E+00	99.1+	A	6: 0.240183	9: 0.759817		
POLYTRIFLUOROCHLOROETHYLENE,[z] $(C_2F_3Cl)_n$	0.480810	2.100E+00	120.7	B	6: 0.206250	9: 0.489354	17: 0.304395	
POLYVINYL ACETATE, $(C_4H_6O_2)_n$	0.534323	1.190E+00	73.7	B	1: 0.070245	6: 0.558066	8: 0.371689	
POLYVINYL ALCOHOL, $(C_2H_3OH)_n$	0.544798	1.300E+00	69.7	B	1: 0.091517	6: 0.545298	8: 0.363185	
POLYVINYL BUTYRAL, $(C_8H_{13}O_2)_n$	0.545366	1.120E+00	67.2	B	1: 0.092802	6: 0.680561	8: 0.226637	
POLYVINYL CHLORIDE, $(C_2H_3Cl)_n$	0.512011	1.300E+00	108.2	B	1: 0.048380	6: 0.384360	17: 0.567260	
POLYVINYLIDENE CHLORIDE, SARAN, $(C_2H_2Cl_2)_n$	0.495132	1.700E+00	134.3	B	1: 0.020793	6: 0.247793	17: 0.731413	
POLYVINYLIDENE FLUORIDE, $(C_2H_2F_2)_n$	0.499730	1.760E+00	88.8	B	1: 0.031480	6: 0.375141	9: 0.593379	
POLYVINYL PYRROLIDONE, $(C_6H_9NO)_n$	0.539844	1.250E+00	67.7	B	1: 0.081616	6: 0.648407	7: 0.126024	8: 0.143953

TABLE 7—*continued*

POTASSIUM IODIDE, KI	0.433728	3.130E+00	431.9	C	19: 0.235528	53: 0.764472						
POTASSIUM OXIDE, K_2O	0.488343	2.320E+00	189.9	C	8: 0.169852	19: 0.830148						
PROPANE, C_3H_8	0.589620	1.879E-03	47.1*	A	1: 0.182855	6: 0.817145						
PROPANE, LIQUID, C_3H_8	0.589620	4.300E-01	52.0	B	1: 0.182855	6: 0.817145						
N-PROPYL ALCOHOL, C_3H_7OH	0.565765	8.035E-01	61.1*	A	1: 0.134173	6: 0.599595	8: 0.266232					
PYRIDINE, C_5H_5N	0.530965	9.819E-01	66.2*	A	1: 0.063710	6: 0.759217	7: 0.177073					
RUBBER, BUTYL, $(C_4H_8)_n$	0.570337	9.200E-01	56.5	B	1: 0.143711	6: 0.856289						
RUBBER, NATURAL, $(C_5H_8)_n$	0.557854	9.200E-01	59.8	B	1: 0.118371	6: 0.881629						
RUBBER, NEOPRENE, $(C_4H_5Cl)_n$	0.519560	1.230E+00	93.0	B	1: 0.056920	6: 0.542646	17: 0.400434					
SILICON DIOXIDE, SiO_2	0.499298	2.320E+00	139.2*	A	8: 0.532565	14: 0.467435						
SILVER BROMIDE, AgBr	0.436700	6.473E+00	486.6	B	35: 0.425537	47: 0.574463						
SILVER CHLORIDE, AgCl	0.446550	5.560E+00	398.4	C	17: 0.247368	47: 0.752632						
SILVER HALIDES IN PHOTOGRAPHIC EMULSION[j]	0.436633	6.470E+00	487.1	B	35: 0.422895	47: 0.573748	53: 0.003357					
SILVER IODIDE, AgI	0.425944	6.010E+00	543.5	C	47: 0.459458	53: 0.540542						
SKIN (ICRP)[b]	0.549325	1.100E+00	72.7**	B	1: 0.100588 11: 0.000070 17: 0.002670 30: 0.000010	6: 0.228250 12: 0.000060 19: 0.000850	7: 0.046420 15: 0.000330 20: 0.000150	8: 0.619002 16: 0.001590 26: 0.000010				
SODIUM CARBONATE, Na_2CO_3	0.490618	2.532E+00	125.0	C	6: 0.113323	8: 0.452861	11: 0.433815					
SODIUM IODIDE, NaI	0.426968	3.667E+00	452.0	C	11: 0.153373	53: 0.846627						
SODIUM MONOXIDE, Na_2O	0.484035	2.270E+00	148.8	C	8: 0.258143	11: 0.741857						
SODIUM NITRATE, $NaNO_3$	0.494149	2.261E+00	114.6	B	7: 0.164795	8: 0.564720	11: 0.270485					
STILBENE, $C_{14}H_{12}$	0.532597	9.707E-01	67.7	B	1: 0.067101	6: 0.932899						
SUCROSE, $C_{12}H_{22}O_{11}$	0.531699	1.580E+00	77.5	B	1: 0.064779	6: 0.421070	8: 0.514151					
TERPHENYL, $C_{18}H_{10}$	0.521485	1.234E+00	71.7	B	1: 0.044543	6: 0.955457						
TESTES (ICRP)[b]	0.551083	1.040E+00	75.0**	A	1: 0.104166 11: 0.002260 17: 0.002440 30: 0.000020	6: 0.092270 12: 0.000110 19: 0.002080	7: 0.019940 15: 0.001250 20: 0.000100	8: 0.773884 16: 0.001460 26: 0.000020				

TABLE 7—*continued*

Material	<Z/A>	Density* (g/cm³)	I‡ (eV)	Gr§	Composition (constituent Z : fraction by weight)			
TETRACHLOROETHYLENE, C_2Cl_4	0.482410	1.625E+00	159.2+	A	6: 0.144856	17: 0.855144		
THALLIUM CHLORIDE, TlCl	0.408613	7.004E+00	690.3	C	17: 0.147822	81: 0.852178		
TISSUE, SOFT (ICRP)[b]	0.551210	1.000E+00	72.3++	B	1: 0.104472 11: 0.001130 17: 0.001340 30: 0.000030	6: 0.232190 12: 0.000130 19: 0.001990	7: 0.024880 15: 0.001330 20: 0.000230	8: 0.630238 16: 0.001990 26: 0.000050
TISSUE, SOFT (ICRU FOUR-COMPONENT)[aa]	0.549750	1.000E+00	74.9++	B	1: 0.101172	6: 0.111000	7: 0.026000	8: 0.761828
TISSUE-EQUIVALENT GAS (METHANE BASED)[bb]	0.549927	1.064E-03	61.2+	A	1: 0.101869	6: 0.456179	7: 0.035172	8: 0.406780
TISSUE-EQUIVALENT GAS (PROPANE BASED)[cc]	0.550268	1.826E-03	59.5++	A	1: 0.102672	6: 0.568940	7: 0.035022	8: 0.293366
TITANIUM DIOXIDE, TiO_2	0.475721	4.260E+00	179.5	C	8: 0.400592	22: 0.599408		
TOLUENE, C_7H_8	0.542651	8.669E-01	62.5+	A	1: 0.087510	6: 0.912490		
TRICHLOROETHYLENE, C_2HCl_3	0.487104	1.460E+00	148.1+	A	1: 0.007671	6: 0.182831	17: 0.809498	
TRIETHYL PHOSPHATE, $C_6H_{15}PO_4$	0.538001	1.070E+00	81.2	B	1: 0.082998	6: 0.395628	8: 0.351334	15: 0.170040
TUNGSTEN HEXAFLUORIDE, WF_6	0.429760	2.400E+00	354.4	C	9: 0.382723	74: 0.617277		
URANIUM DICARBIDE, UC_2	0.396869	1.128E+01	752.0	C	6: 0.091669	92: 0.908331		
URANIUM MONOCARBIDE, UC	0.391937	1.363E+01	862.0	C	6: 0.048036	92: 0.951964		
URANIUM OXIDE, UO_2	0.399959	1.096E+01	720.6	C	8: 0.118502	92: 0.881498		
UREA, $CO(NH_2)_2$	0.532841	1.323E+00	72.8	B	1: 0.067131	6: 0.199999	7: 0.466459	8: 0.266411
VALINE, $C_5H_{11}NO_2$	0.546320	1.230E+00	67.7	B	1: 0.094641	6: 0.512645	7: 0.119565	8: 0.273150
"VITON" FLUOROELASTOMER, $(C_5H_2F_8)_n$	0.485850	1.800E+00	98.6	B	1: 0.009417	6: 0.280555	9: 0.710028	
WATER, LIQUID, H_2O	0.555087	1.000E+00	75.0+	A	1: 0.111894	8: 0.888106		
WATER VAPOR, H_2O	0.555087	7.562E-04	71.6+	A	1: 0.111894	8: 0.888106		
XYLENE, C_8H_{10}	0.546309	8.700E-01	61.8+	A	1: 0.094935	6: 0.905065		

* Gas densities are for a pressure of 1 atm and a temperature of 20°C. Values for densities are taken from *Handbook of Chemistry and Physics*,[44] *The Condensed Chemical Dictionary*,[45] *The Reactor Handbook*,[46] manufacturers and suppliers literature, or from reports of other authors. Due to computer preparation of the tables, the densities are given to four figures, even though in some cases the values are significant to only two or three (usually indicated by the presence of terminal zeros); the number following the "E" indicates the power of 10. In some cases, the value given is nominal, representing the mid-point of a range of densities. Density enters into the calculation of the mass collision stopping power only in the evaluation of the density-effect correction.

‡ Unless indicated otherwise, the adopted mean excitation energies were obtained by the application of the Bragg additivity rule, equation (10), using I-values for elemental constituents given in Table 6. A plus (+) indicates a direct experimental mean excitation energy for the compound, taken from Table 5. The mean excitation energies for air and methane-based TE gas are indicated as experimental, because these mixtures consist of constituents all of which have experimentally determined I-values. A double plus (++) indicates that the material was treated as a mixture of compounds, of which some—but not all—have experimentally determined I-values.

§ The letter grade A, B or C following the I-value is a qualitative indication of the estimated uncertainty as discussed in the text.

[a] SMATHERS *et al.*[47] and GOODMAN:[48] 45.14% polyethylene ($(C_2H_4)_n$), 35.32% nylon (duPont Elvamide 8062M), 16.06% carbon and 3.85% calcium fluoride (CaF_2), by weight.

[b] From Tables 105 and 108 of ICRP.[49]

[c] *Handbook of Chemistry and Physics*:[44] 78.09% N_2, 20.95% O_2, 0.93% Ar and 0.03% CO_2, by volume.

[d] ICRU Report 26:[50] 30.0% polyethylene ($(C_2H_4)_n$), 21.6% nylon (duPont Elvamide 8062M), 14.0% carbon and 34.4% calcium fluoride (CaF_2), by weight.

[e] ICRU Report 10b.[51] Water content (15.0% in bone and 78.6% in muscle, by weight) and density taken from Table 105 of ICRP.[49]

[f] ICRU Report 26:[50] 78.4% polyvinylidine fluoride ($(C_2H_2F_2)_n$), 20.75% carbon, and 0.85% silicon dioxide (SiO_2), by weight.

[g] 0.015 molar ceric ammonium sulfate in 0.8 N sulfuric acid aqueous solution: 95.183% H_2O, 3.914% H_2SO_4, and 0.903% $Ce(SO_4)_2 \cdot 2(NH_4)_2SO_4 \cdot 2H_2O$, by weight.

[h] Composition from *The Reactor Handbook*.[46] It is assumed that Si and Al are present in the form of 72.1% SiO_2 and 6.4% Al_2O_3, by weight.

[i] 0.001 M ferrous ammonium sulfate in 0.8 N sulfuric acid aqueous solution. According to GREENE *et al.*:[52] 96.0% H_2O, 3.9% H_2SO_4, 0.039% $Fe(NH_4)_2(SO_4)_2 \cdot 6H_2O$ and 0.006% NaCl, by weight.

[j] Standard nuclear research emulsion, as given in Table 3.5.1 of BARKAS.[40]

[k] HUBBELL:[53] 80.9% SiO_2, 12.9% B_2O_3, 3.8% Na_2O, 2.2% Al_2O_3 and 0.4% K_2O, by weight.

[l] *The Reactor Handbook*:[46] 81.0% PbO, 17.3% SiO_2, 1.35% TiO_2 and 0.35% As_2O_3, by weight.

[m] *The Reactor Handbook*:[46] 72.0% SiO_2, 15.0% CaO and 13.0% Na_2O, by weight.

[n] WHITE:[54] 76.93% paraffin wax ($C_{25}H_{52}$), 22.35% MgO and 0.72% $CaCO_3$, by weight.

[o] WHITE:[54] 60.8% paraffin wax ($C_{25}H_{52}$), 30.4% polyethylene ($(C_2H_4)_n$), 6.4% MgO and 2.4% TiO_2, by weight.

[p] Composition from WHITE.[54]

[q] ROSSI and FAILLA:[55] 56.9% H_2O, 28.4% glycerol ($C_3H_8O_3$), 7.6% urea ($CO(NH_2)_2$) and 7.1% sucrose ($C_{12}H_{22}O_{11}$), by weight.

[r] GOODMAN:[56] 65.6% H_2O, 26.8% glycerol ($C_3H_8O_3$) and 7.6% urea ($CO(NH_2)_2$), by weight.

[s] Equivalent formula is $C_{47.1}H_{89.6}O_{8.1}N_{6.2}$.

[t] Composition (based on vinyltoluene, C_9H_{10}) and density characteristic of "NE 102", "NE 110", "NE 111", "NE 113", "NE 114", "Pilot B", "Pilot F", "Pilot U" and "Pilot Y" plastic scintillators produced by Nuclear Enterprises Inc.

[u] Also known as: "Lexan".

[v] Also known as "Melinex".

[w] Also known as: "Lucite", "Plexiglas", "Perspex", PMMA resist.

[x] Also known as: "Styrofoam", "Styron".

[y] Also known as: "Halon".

[z] Also known as: "Kel-F".

[aa] ICRU Report 33, p. 20.[57] Water content (64.5% by weight) taken from Table 105 of ICRP.[49]

[bb] ROSSI and FAILLA:[55] 64.4% methane (CH_4), 32.4% CO_2 and 3.2% N_2, by volume.

[cc] SRDOČ:[58] 55.0% propane (C_3H_8), 39.6% CO_2 and 5.4% N_2, by volume.

TABLE 8. Comparison of mean excitation energies for compounds recommended in various publications

Material	Formula	From Table 7	PAGES *et al.* (1972)[59]	DALTON and TURNER (1968)[25]	NAS-NRC (1964)[22]	BRANDT (1968)[32]
Propane, liquid	C_3H_8	52.0 ± 3.9	50.4	51.2	50.3	51.5
Polyethylene	$(C_2H_4)_n$	57.4* ± 4.6	54.7	55.8	54.6	59.6
Nylon, type 6/6	$(C_6H_{11}ON)_n$	63.9* ± 2.6	62.3	—	—	62.0
Polystyrene	$(C_8H_8)_n$	68.7* ± 2.7	63.7	65.5	63.6	65.1
PMMA	$(C_5H_8O_2)_n$	74.0* ± 1.5	65.7	69.2	65.6	69.0
Water, liquid	H_2O	75.0* ± 3.0	65.3	71.3	65.1	72.5
Polyoxymethylene	$(CH_2O)_n$	77.4 ± 5.8	69.8	—	—	76.6
Air		85.7* ± 1.7	86.8	92.9	86.8	—
Polyvinyl chloride	$(C_2H_3Cl)_n$	108 ± 8	112.5	—	—	112.7
Saran	$(C_2H_2Cl_2)_n$	134 ± 10	—	—	—	145.6
"Freon-13B1"	CF_3Br	210 ± 25	—	—	204.7	171.6
Photographic emulsion		331* ± 10	—	—	320	263.1
Sodium iodide	NaI	452 ± 50	433	411	433	—
Cesium iodide	CsI	553 ± 65	523	—	—	—

All values are given in units of eV.
* An experimental value.

cludes the plasma energy $\hbar\omega_p$ (see equation (6)), the mean excitation energy I and data on ionization potentials for electrons in various atomic shells. The immediate results of Sternheimer's calculations consist of numerical values of the density-effect correction for a particular material, as a function of the charged particle momentum. Sternheimer then represented his results in terms of the formula

$$\delta = \begin{cases} 0 \quad \text{for} \quad X \leqslant X_0 & \text{(12a)} \\ (2\ln 10)X - \bar{C} + a(X_1 - X)^k & \\ \quad \text{for} \quad X_0 < X < X_1 & \text{(12b)} \\ (2\ln 10)X - \bar{C} \quad \text{for} \quad \bar{X} \geqslant X_1, & \text{(12c)} \end{cases}$$

where δ is the density-effect correction in equation (2), and where

$$X = \log_{10}(p/mc) = \tfrac{1}{2}\log_{10}[\tau(\tau + 2)], \tag{13}$$

$$\bar{C} = 1 + 2\ln(I/\hbar\omega_p), \tag{14}$$

$$a = [\bar{C} - (2\ln 10)X_0]/(X_1 - X_0)^k. \tag{15}$$

In equation (13), p is the particle momentum and mc^2 its rest mass.

In his earlier papers, STERNHEIMER[5] gave numerical values of the parameters in equation (12) for some 50 materials. From the information contained in the results of these calculations, STERNHEIMER and PEIERLS[6] developed a prescription for specifying the parameters for any substance, using as input only the mean excitation energy I and the density ρ. First, the quantity $\bar{C}$ is calculated from equation (14).* The quantities X_0 and X_1 are then evaluated as functions of I and $\bar{C}$ according to the rules for gases, or for solids and liquids, summarized in Table 9. The expo-

* It should be noted that equation (12c) approaches the asymptotic result given by equation (5).

TABLE 9. STERNHEIMER–PEIERLS[6] prescription for evaluating parameters in equation (12) for the density-effect correction

Phase	Conditions		X_0	X_1
Solids and Liquids	$I < 100$ eV	$\bar{C} < 3.681$	0.2	2.0
		$\bar{C} \geqslant 3.681$	$0.326\bar{C} - 1.0$	2.0
	$I \geqslant 100$ eV	$\bar{C} < 5.215$	0.2	3.0
		$\bar{C} \geqslant 5.215$	$0.326\bar{C} - 1.5$	3.0
Gases (NTP)		$\bar{C} < 10.0$	1.6	4.0
		$10.0 \leqslant \bar{C} < 10.5$	1.7	4.0
		$10.5 \leqslant \bar{C} < 11.0$	1.8	4.0
		$11.0 \leqslant \bar{C} < 11.5$	1.9	4.0
		$11.5 \leqslant \bar{C} < 12.25$	2.0	4.0
		$12.25 \leqslant \bar{C} < 13.804$	2.0	5.0
		$\bar{C} \geqslant 13.804$	$0.326\bar{C} - 2.5$	5.0
Special cases		k	X_0	X_1
H_2 (gas)		4.754	1.837	3.0
H_2 (liquid)		5.949	0.425	2.0
He (gas)		3.297	2.191	3.0

nent k in equations (12 and 15) is given the value 3, except for H and He as indicated in Table 9.

The prescription for gases pertains to a density corresponding to normal temperature (0° C) and pressure (1 atm). If results for another gas density ρ' is desired, X_0 and X_1 are chosen from Table 9 for normal temperature and pressure (NTP), but, when evaluating equation (12), $\bar{C}$ is replaced by $\bar{C} - \ln(\rho'/\rho)$, X_0 by $X_0 - \ln(\rho'/\rho)/(2 \ln 10)$, and X_1 by $X_1 - \ln(\rho'/\rho)/(2 \ln 10)$.

The Sternheimer-Peierls algorithm has been adopted in the present work because it can easily be applied to any material and because it permits the simple parameterization of the expression for the collision stopping power including the density-effect correction.*

6. Evaluation of the Collision Stopping Power from Pre-tabulated Quantities

6.1 *Material constants and energy-dependent quantities*

The evaluation of the collision stopping power with the use of pre-tabulated quantities is facilitated if one separates the various quantities into those which depend only on the kinetic energy of the particle (electron or positron), and those which depend only on the stopping properties of the medium (expressed in terms of the mean excitation energy, I, and the plasma energy, $\hbar\omega_p$).

After inserting equation (12) for the density-effect into equation (2), one can combine terms and obtain the following equations:

$$B(T) = \begin{cases} B_0(T) + b_0 \quad \text{for} \quad T \leqslant T_0 & \text{(16a)} \\ B_1(T) + b_1 - b_2\{1 - [2 \ln(p/mc)]/b_3\}^k \\ \quad \text{for} \quad T_0 < T < T_1 & \text{(16b)} \\ B_1(T) + b_1 \quad \text{for} \quad T \geqslant T_1 & \text{(16c)} \end{cases}$$

$k = 3$ (except for H_2 and He; see Table 9).

The quantities $B_0(T)$ and $B_1(T)$ in equation (16) are functions only of the kinetic energy T of the electron (or positron) and are given, together with $\ln(p/mc)$ and β^2, in Table 10 for a fine grid of energies. The quantities Z/A, b_0, b_1, b_2, b_3, T_0 and T_1 are material constants and are given in Table 11a for 95 elemental substances, and in Table 11b for 180 compounds and mixtures.

$B_0(T)$ has been defined by equations (3) and (4). The defining equations for the remaining quantities in equation (16) are:

$$B_1(T) = B_0(T) + 1 - 2 \ln(p/mc), \tag{17}$$

$$b_0 = -2 \ln(I/mc^2), \tag{18}$$

$$b_1 = -2 \ln(\hbar\omega_p/mc^2), \tag{19}$$

$$b_2 = [1 + 2 \ln(I/\hbar\omega_p) - 2 \ln(p_0/mc)] \times \{[\ln(p_1/mc)]/[\ln(p_1/p_0)]\}^k, \tag{20}$$

and

$$b_3 = 2 \ln(p_1/mc). \tag{21}$$

The constants p_0, T_0, p_1 and T_1 are obtained from X_0 and X_1 according to equation (13).

6.2 *Limitations and uncertainties*

An error of $\sim 1\%$ is expected to result from approximations in the derivation of the Bethe stopping-power formula. Additional uncertainties in the evaluation of the collision stopping power arise at low energies (where the theory is no longer fully applicable) and because of uncertainties in the values of the mean excitation energy, I, and the density-effect correction δ.

The Bethe stopping-power formula is derived on the assumption that the velocity of the incident particle is large compared to the velocities of the atomic electrons with which it interacts. When this condition is not satisfied, shell corrections are needed which are available for heavy particles but not for electrons. We have attempted to make a rough estimate of the errors incurred through the use of the uncorrected Bethe formula for electrons at low energies, assuming that the error is twice as large as the shell corrections for protons of the same velocity. Such an error estimate is consistent with the limited evidence from the comparisons in Ref. 7 of other low-energy stopping-power calculations with the results of the Bethe theory. At 100 keV, the error is estimated to be $\sim 0.3\%$ for H_2O, $\sim 0.7\%$ for Al, $\sim 1.3\%$ for Cu, $\sim 2\%$ for Ag and $\sim 3\%$ for Au. At 10 keV, these errors are $\sim 2\%$ for H_2O, $\sim 4\%$ for Al, $\sim 9\%$ for Cu, $\sim 12\%$ for Ag and $\sim 21\%$ for Au. The use of the uncorrected Bethe formula is not recommended at energies below 10 keV except for low-Z materials such as water, air or plastics, for which the error may reach $\sim 3\%$ at 5 keV, $\sim 7\%$ at 2 keV and 10–15% at 1 keV.

The uncertainties of the collision stopping power due to uncertainties of the mean excitation energy can be estimated by combining the information in Table 1 (relative change in stopping power due to 10% change in I) and the error estimates for the I-values given in Table 2 for elements and in Section 4 for compounds. At energies above 1 MeV, in condensed materials, the largest error comes from the evaluation of the density-effect correction. The Sternheimer model is only approximate, and the value of δ is also influenced by the choice of input data for the model.

* Calculations of the density-effect correction using semi-empirical dielectric-response functions have recently been made by INOKUTI and SMITH[66] for aluminum and by ASHLEY[67] for water. These results agree to within 0.2% for aluminum and 0.4% for water with the new numerical results from STERNHEIMER's[5] method used in Ref. 7. The fitting procedure of STERNHEIMER and PEIERLS[6] introduces an additional error of 1–2%. While this manuscript was in press, new fits to the density-effect data have been made[68] for a limited number of materials which could be used in equation (12) instead of the Sternheimer–Peierls fit.

TABLE 10. Energy-dependent quantities for use in equation (16) to calculate the collision stopping power for electrons and positrons

			Electrons		Positrons	
T (MeV)	β^2	$2\ln(p/mc)$	$B_0(T)$	$B_1(T)$	$B_0(T)$	$B_1(T)$
0.00100	3.90241D-03	-5.54225D+00	-1.21688D+01	-5.62657D+00	-1.10962D+01	-4.55396D+00
0.00125	4.87444D-03	-5.31886D+00	-1.17233D+01	-5.40440D+00	-1.06523D+01	-4.33348D+00
0.00150	5.84505D-03	-5.13630D+00	-1.13593D+01	-5.22304D+00	-1.02901D+01	-4.15383D+00
0.00175	6.81425D-03	-4.98190D+00	-1.10518D+01	-5.06986D+00	-9.98424D+00	-4.00234D+00
0.00200	7.78202D-03	-4.84813D+00	-1.07854D+01	-4.93729D+00	-9.71959D+00	-3.87147D+00
0.00250	9.71333D-03	-4.62450D+00	-1.03406D+01	-4.71607D+00	-9.27812D+00	-3.65362D+00
0.00300	1.16390D-02	-4.44169D+00	-9.97736D+00	-4.53567D+00	-8.91827D+00	-3.47659D+00
0.00350	1.35591D-02	-4.28705D+00	-9.67048D+00	-4.38343D+00	-8.61475D+00	-3.32770D+00
0.00400	1.54736D-02	-4.15303D+00	-9.40483D+00	-4.25180D+00	-8.35245D+00	-3.19942D+00
0.00450	1.73825D-02	-4.03476D+00	-9.17067D+00	-4.13591D+00	-8.12163D+00	-3.08687D+00
0.00500	1.92858D-02	-3.92891D+00	-8.96135D+00	-4.03244D+00	-7.91563D+00	-2.98672D+00
0.00550	2.11837D-02	-3.83311D+00	-8.77213D+00	-3.93901D+00	-7.72972D+00	-2.89661D+00
0.00600	2.30760D-02	-3.74562D+00	-8.59949D+00	-3.85388D+00	-7.56039D+00	-2.81478D+00
0.00700	2.68442D-02	-3.59049D+00	-8.29395D+00	-3.70346D+00	-7.26143D+00	-2.67094D+00
0.00800	3.05907D-02	-3.45599D+00	-8.02962D+00	-3.57363D+00	-7.00364D+00	-2.54765D+00
0.00900	3.43156D-02	-3.33724D+00	-7.79675D+00	-3.45952D+00	-6.77727D+00	-2.44004D+00
0.01000	3.80191D-02	-3.23091D+00	-7.58871D+00	-3.35780D+00	-6.57569D+00	-2.34478D+00
0.01250	4.71850D-02	-3.00534D+00	-7.14900D+00	-3.14366D+00	-6.15196D+00	-2.14662D+00
0.01500	5.62206D-02	-2.82061D+00	-6.79078D+00	-2.97018D+00	-5.80948D+00	-1.98887D+00
0.01750	6.51283D-02	-2.66405D+00	-6.48875D+00	-2.82470D+00	-5.52295D+00	-1.85890D+00
0.02000	7.39105D-02	-2.52812D+00	-6.22780D+00	-2.69969D+00	-5.27728D+00	-1.74916D+00
0.02500	9.11076D-02	-2.30019D+00	-5.79331D+00	-2.49312D+00	-4.87265D+00	-1.57247D+00
0.03000	1.07830D-01	-2.11310D+00	-5.43989D+00	-2.32679D+00	-4.54823D+00	-1.43513D+00
0.03500	1.24095D-01	-1.95421D+00	-5.14226D+00	-2.18806D+00	-4.27877D+00	-1.32457D+00
0.04000	1.39920D-01	-1.81596D+00	-4.88536D+00	-2.06940D+00	-4.04922D+00	-1.23327D+00
0.04500	1.55319D-01	-1.69348D+00	-4.65945D+00	-1.96597D+00	-3.84989D+00	-1.15642D+00
0.05000	1.70309D-01	-1.58344D+00	-4.45790D+00	-1.87446D+00	-3.67418D+00	-1.09074D+00
0.05500	1.84903D-01	-1.48348D+00	-4.27599D+00	-1.79251D+00	-3.51739D+00	-1.03391D+00
0.06000	1.99115D-01	-1.39184D+00	-4.11024D+00	-1.71841D+00	-3.37607D+00	-9.84232D-01
0.07000	2.26447D-01	-1.22848D+00	-3.81723D+00	-1.58875D+00	-3.12992D+00	-9.01440D-01
0.08000	2.52403D-01	-1.08584D+00	-3.56389D+00	-1.47806D+00	-2.92097D+00	-8.35136D-01
0.09000	2.77074D-01	-9.59021D-01	-3.34061D+00	-1.38159D+00	-2.73977D+00	-7.80744D-01
0.10000	3.00544D-01	-8.44708D-01	-3.14084D+00	-1.29613D+00	-2.57992D+00	-7.35208D-01
0.12500	3.54452D-01	-5.99528D-01	-2.71673D+00	-1.11721D+00	-2.24711D+00	-6.47585D-01
0.15000	4.02359D-01	-3.95644D-01	-2.36791D+00	-9.72263D-01	-1.97895D+00	-5.83310D-01
0.17500	4.45125D-01	-2.20387D-01	-2.07015D+00	-8.49768D-01	-1.75283D+00	-5.32440D-01
0.20000	4.83460D-01	-6.61854D-02	-1.80926D+00	-7.43077D-01	-1.55582D+00	-4.89638D-01
0.25000	5.49106D-01	1.97060D-01	-1.36496D+00	-5.62020D-01	-1.22024D+00	-4.17295D-01
0.30000	6.02989D-01	4.17936D-01	-9.91990D-01	-4.09926D-01	-9.35849D-01	-3.53785D-01
0.35000	6.47761D-01	6.09210D-01	-6.68094D-01	-2.77304D-01	-6.85131D-01	-2.94341D-01
0.40000	6.85365D-01	7.78536D-01	-3.80305D-01	-1.58842D-01	-4.58535D-01	-2.37072D-01
0.45000	7.17253D-01	9.30877D-01	-1.20406D-01	-5.12827D-02	-2.50364D-01	-1.81241D-01
0.50000	7.44529D-01	1.06964D+00	1.17158D-01	4.75177D-02	-5.69563D-02	-1.26597D-01
0.55000	7.68040D-01	1.19727D+00	3.36331D-01	1.39057D-01	1.24191D-01	-7.30831D-02
0.60000	7.88448D-01	1.31560D+00	5.40025D-01	2.24429D-01	2.94879D-01	-2.07178D-02
0.70000	8.21944D-01	1.52957D+00	9.09400D-01	3.79827D-01	6.09993D-01	8.04197D-02
0.80000	8.48071D-01	1.71955D+00	1.23807D+00	5.18522D-01	8.96146D-01	1.76593D-01
0.90000	8.68843D-01	1.89077D+00	1.53451D+00	6.43740D-01	1.15853D+00	2.67762D-01
1.00000	8.85629D-01	2.04685D+00	1.80465D+00	7.57800D-01	1.40090D+00	3.54050D-01
1.25000	9.15797D-01	2.38657D+00	2.39122D+00	1.00465D+00	1.93658D+00	5.50010D-01
1.50000	9.35431D-01	2.67328D+00	2.88358D+00	1.21030D+00	2.39464D+00	7.21361D-01
1.75000	9.48921D-01	2.92195D+00	3.30785D+00	1.38590D+00	2.79439D+00	8.72441D-01
2.00000	9.58585D-01	3.14183D+00	3.68051D+00	1.53868D+00	3.14872D+00	1.00689D+00
2.50000	9.71198D-01	3.51808D+00	4.31227D+00	1.79419D+00	3.75501D+00	1.23693D+00
3.00000	9.78817D-01	3.83315D+00	4.83536D+00	2.00221D+00	4.26130D+00	1.42815D+00
3.50000	9.83769D-01	4.10448D+00	5.28152D+00	2.17704D+00	4.69557D+00	1.59109D+00
4.00000	9.87168D-01	4.34288D+00	5.67038D+00	2.32750D+00	5.07558D+00	1.73270D+00
4.50000	9.89601D-01	4.55558D+00	6.01493D+00	2.45935D+00	5.41328D+00	1.85771D+00
5.00000	9.91402D-01	4.74762D+00	6.32419D+00	2.57658D+00	5.71709D+00	1.96948D+00
5.50000	9.92773D-01	4.92269D+00	6.60470D+00	2.68202D+00	5.99316D+00	2.07047D+00
6.00000	9.93840D-01	5.08357D+00	6.86134D+00	2.77777D+00	6.24610D+00	2.16253D+00
7.00000	9.95371D-01	5.37086D+00	7.31709D+00	2.94623D+00	6.69607D+00	2.32522D+00
8.00000	9.96395D-01	5.62187D+00	7.71285D+00	3.09098D+00	7.08751D+00	2.46564D+00
9.00000	9.97113D-01	5.84477D+00	8.06256D+00	3.21779D+00	7.43386D+00	2.58910D+00

TABLE 10—*continued*

			Electrons		Positrons	
T (MeV)	β^2	2ln(p/mc)	$B_0(T)$	$B_1(T)$	$B_0(T)$	$B_1(T)$
10.00000	9.97636D-01	6.04524D+00	8.37580D+00	3.33056D+00	7.74443D+00	2.69919D+00
12.50000	9.98457D-01	6.47281D+00	9.04031D+00	3.56750D+00	8.40412D+00	2.93132D+00
15.00000	9.98915D-01	6.82477D+00	9.58412D+00	3.75935D+00	8.94473D+00	3.11996D+00
17.50000	9.99195D-01	7.12392D+00	1.00444D+01	3.92047D+00	9.40272D+00	3.27880D+00
20.00000	9.99379D-01	7.38406D+00	1.04434D+01	4.05933D+00	9.80000D+00	3.41594D+00
25.00000	9.99599D-01	7.82058D+00	1.11106D+01	4.29006D+00	1.04649D+01	3.64428D+00
30.00000	9.99719D-01	8.17865D+00	1.16562D+01	4.47753D+00	1.10088D+01	3.83015D+00
35.00000	9.99793D-01	8.48224D+00	1.21176D+01	4.63541D+00	1.14691D+01	3.98689D+00
40.00000	9.99841D-01	8.74575D+00	1.25175D+01	4.77176D+00	1.18681D+01	4.12238D+00
45.00000	9.99874D-01	8.97854D+00	1.28703D+01	4.89175D+00	1.22202D+01	4.24171D+00
50.00000	9.99898D-01	9.18704D+00	1.31859D+01	4.99889D+00	1.25353D+01	4.34831D+00
55.00000	9.99915D-01	9.37584D+00	1.34715D+01	5.09566D+00	1.28205D+01	4.44464D+00
60.00000	9.99929D-01	9.54834D+00	1.37322D+01	5.18389D+00	1.30809D+01	4.53251D+00
70.00000	9.99947D-01	9.85424D+00	1.41942D+01	5.33996D+00	1.35423D+01	4.68802D+00
80.00000	9.99960D-01	1.01195D+01	1.45945D+01	5.47495D+00	1.39421D+01	4.82257D+00
90.00000	9.99968D-01	1.03537D+01	1.49475D+01	5.59386D+00	1.42948D+01	4.94115D+00
100.00000	9.99974D-01	1.05633D+01	1.52634D+01	5.70013D+00	1.46104D+01	5.04716D+00
125.00000	9.99983D-01	1.10075D+01	1.59324D+01	5.92491D+00	1.52790D+01	5.27146D+00
150.00000	9.99988D-01	1.13708D+01	1.64792D+01	6.10833D+00	1.58254D+01	5.45456D+00
175.00000	9.99992D-01	1.16782D+01	1.69414D+01	6.26327D+00	1.62874D+01	5.60927D+00
200.00000	9.99994D-01	1.19445D+01	1.73419D+01	6.39739D+00	1.66877D+01	5.74322D+00
250.00000	9.99996D-01	1.23898D+01	1.80111D+01	6.62136D+00	1.73567D+01	5.96695D+00
300.00000	9.99997D-01	1.27537D+01	1.85580D+01	6.80424D+00	1.79034D+01	6.14966D+00
350.00000	9.99998D-01	1.30615D+01	1.90203D+01	6.95878D+00	1.83656D+01	6.30410D+00
400.00000	9.99998D-01	1.33282D+01	1.94209D+01	7.09261D+00	1.87661D+01	6.43784D+00
450.00000	9.99999D-01	1.35635D+01	1.97741D+01	7.21063D+00	1.91193D+01	6.55579D+00
500.00000	9.99999D-01	1.37740D+01	2.00902D+01	7.31617D+00	1.94353D+01	6.66128D+00
550.00000	9.99999D-01	1.39645D+01	2.03761D+01	7.41163D+00	1.97211D+01	6.75670D+00
600.00000	9.99999D-01	1.41383D+01	2.06371D+01	7.49877D+00	1.99821D+01	6.84380D+00
700.00000	9.99999D-01	1.44464D+01	2.10995D+01	7.65312D+00	2.04445D+01	6.99809D+00
800.00000	1.00000D+00	1.47133D+01	2.15001D+01	7.78680D+00	2.08450D+01	7.13173D+00
900.00000	1.00000D+00	1.49487D+01	2.18534D+01	7.90470D+00	2.11983D+01	7.24959D+00
1000.00000	1.00000D+00	1.51593D+01	2.21694D+01	8.01015D+00	2.15143D+01	7.35502D+00
1250.00000	1.00000D+00	1.56054D+01	2.28388D+01	8.23346D+00	2.21837D+01	7.57828D+00
1500.00000	1.00000D+00	1.59699D+01	2.33858D+01	8.41590D+00	2.27306D+01	7.76068D+00
1750.00000	1.00000D+00	1.62781D+01	2.38482D+01	8.57013D+00	2.31930D+01	7.91489D+00
2000.00000	1.00000D+00	1.65451D+01	2.42488D+01	8.70372D+00	2.35935D+01	8.04846D+00
2500.00000	1.00000D+00	1.69913D+01	2.49182D+01	8.92694D+00	2.42629D+01	8.27167D+00
3000.00000	1.00000D+00	1.73558D+01	2.54652D+01	9.10932D+00	2.48099D+01	8.45403D+00
3500.00000	1.00000D+00	1.76641D+01	2.59276D+01	9.26351D+00	2.52723D+01	8.60821D+00
4000.00000	1.00000D+00	1.79311D+01	2.63282D+01	9.39707D+00	2.56729D+01	8.74176D+00
4500.00000	1.00000D+00	1.81667D+01	2.66815D+01	9.51488D+00	2.60262D+01	8.85956D+00
5000.00000	1.00000D+00	1.83773D+01	2.69976D+01	9.62026D+00	2.63423D+01	8.96493D+00
5500.00000	1.00000D+00	1.85680D+01	2.72835D+01	9.71558D+00	2.66282D+01	9.06025D+00
6000.00000	1.00000D+00	1.87420D+01	2.75446D+01	9.80261D+00	2.68892D+01	9.14727D+00
7000.00000	1.00000D+00	1.90502D+01	2.80070D+01	9.95678D+00	2.73517D+01	9.30144D+00
8000.00000	1.00000D+00	1.93173D+01	2.84076D+01	1.00903D+01	2.77523D+01	9.43498D+00
9000.00000	1.00000D+00	1.95528D+01	2.87610D+01	1.02081D+01	2.81056D+01	9.55277D+00
10000.00000	1.00000D+00	1.97635D+01	2.90770D+01	1.03135D+01	2.84217D+01	9.65814D+00

Furthermore, the Sternheimer–Peierls global fit for all materials introduces some additional error. STERNHEIMER[6] estimates that the overall effect of these errors will introduce an uncertainty of no more than 1–2% into the collision stopping power.

6.3. *Use of tabulated data*

As an example of the use of equation (16) and the data in Tables 10 and 11, we consider the evaluation of the collision stopping power in polystyrene for electrons with kinetic energy $T = 5$ MeV.

1. From Table 11b, $T_0 = 0.447$ MeV and $T_1 = 50.6$ MeV; these values indicate that equation (16b) must be used.

2. From Table 11b, $b_1 = 20.1286$, $b_2 = 3.2631$, $b_3 = 9.2103$.

3. From Table 10, B_1 (5 MeV) = 2.57658.

4. From equation (12b) with $k = 3$, the stopping number is calculated to be $B = 22.3340$.

TABLE 11a. Material constants for use in equation (16) to calculate the collision stopping power for electrons and positron: elemental substances

Element	Z	Z/A	Density* (g/cm^3)	I (eV)	$\hbar\omega_p$ (eV)	T_0 (MeV)	T_1 (MeV)	b_0	b_1	b_2	b_3
HYDROGEN	1	0.992162	8.375E-05	19.2	0.263	35.865	528.9	20.3784	28.9620	97.6113	13.8862
HYDROGEN, LIQUID	1	0.992162	6.250E-02	21.8	7.176	0.941	50.6	20.1244	22.3469	5.2405	9.2103
HELIUM	2	0.499675	1.663E-04	41.8	0.263	81.671	528.9	18.8225	28.9618	74.9081	13.8862
LITHIUM	3	0.432214	5.340E-01	40.0	13.844	0.447	50.6	18.9105	21.0326	3.0193	9.2103
BERYLLIUM	4	0.443844	1.848E+00	63.7	26.098	0.447	50.6	17.9799	19.7646	2.5565	9.2103
BORON	5	0.462535	2.370E+00	76.0	30.170	0.447	50.6	17.6268	19.4745	2.6430	9.2103
CARBON (GRAPHITE)	6	0.499542	2.265E+00	78.0	30.652	0.447	50.6	17.5748	19.4429	2.6708	9.2103
CARBON (GRAPHITE)	6	0.499542	1.700E+00	78.0	26.555	0.447	50.6	17.5748	19.7298	3.0644	9.2103
NITROGEN	7	0.499761	1.165E-03	82.0	0.695	26.026	5293.3	17.4748	27.0148	14.0501	18.4913
OXYGEN	8	0.500019	1.332E-03	95.0	0.744	32.895	5293.3	17.1805	26.8810	14.2300	18.4913
FLUORINE	9	0.473724	1.580E-03	115.0	0.788	32.895	5293.3	16.7984	26.7637	15.8402	18.4913
NEON	10	0.495565	8.385E-04	137.0	0.587	52.430	5293.3	16.4483	27.3524	21.2268	18.4913
SODIUM	11	0.478474	9.710E-01	149.0	19.641	0.447	510.5	16.2804	20.3330	5.0817	13.8155
MAGNESIUM	12	0.493726	1.740E+00	156.0	26.708	0.447	510.5	16.1886	19.7183	4.4386	13.8155
ALUMINUM	13	0.481811	2.699E+00	166.0	32.860	0.447	510.5	16.0643	19.3038	4.0815	13.8155
SILICON	14	0.498478	2.330E+00	173.0	31.055	0.447	510.5	15.9817	19.4167	4.3221	13.8155
PHOSPHORUS	15	0.484281	2.200E+00	173.0	29.743	0.447	510.5	15.9817	19.5030	4.4282	13.8155
SULFUR	16	0.499064	2.000E+00	180.0	28.789	0.447	510.5	15.9023	19.5683	4.6061	13.8155
CHLORINE	17	0.479508	2.995E-03	174.0	1.092	41.542	5293.3	15.9702	26.1123	16.2297	18.4913
ARGON	18	0.450586	1.662E-03	188.0	0.789	52.430	5293.3	15.8154	26.7633	21.5822	18.4913
POTASSIUM	19	0.485955	8.620E-01	190.0	18.650	0.717	510.5	15.7942	20.4365	5.8481	13.8155
CALCIUM	20	0.499002	1.550E+00	191.0	25.342	0.447	510.5	15.7837	19.8233	5.0656	13.8155
SCANDIUM	21	0.467124	2.989E+00	216.0	34.050	0.447	510.5	15.5377	19.2326	4.6417	13.8155
TITANIUM	22	0.459482	4.540E+00	233.0	41.619	0.447	510.5	15.3862	18.8311	4.3343	13.8155
VANADIUM	23	0.451498	6.110E+00	245.0	47.861	0.447	510.5	15.2857	18.5517	4.1141	13.8155
CHROMIUM	24	0.461574	7.180E+00	257.0	52.458	0.447	510.5	15.1901	18.3682	4.0061	13.8155
MANGANESE	25	0.455058	7.440E+00	272.0	53.022	0.447	510.5	15.0767	18.3469	4.1193	13.8155
IRON	26	0.465558	7.874E+00	286.0	55.172	0.447	510.5	14.9763	18.2674	4.1450	13.8155
COBALT	27	0.458146	8.900E+00	297.0	58.188	0.447	510.5	14.9008	18.1609	4.1069	13.8155
NICKEL	28	0.477083	8.902E+00	311.0	59.385	0.447	510.5	14.8087	18.1202	4.1701	13.8155
COPPER	29	0.456362	8.960E+00	322.0	58.270	0.447	510.5	14.7392	18.1581	4.3023	13.8155
ZINC	30	0.458856	7.133E+00	330.0	52.132	0.447	510.5	14.6901	18.3807	4.6364	13.8155
GALLIUM	31	0.444636	5.904E+00	334.0	46.688	0.447	510.5	14.6660	18.6013	4.9374	13.8155
GERMANIUM	32	0.440832	5.323E+00	350.0	44.141	0.447	510.5	14.5724	18.7135	5.1904	13.8155
ARSENIC	33	0.440460	5.730E+00	347.0	45.779	0.447	510.5	14.5896	18.6406	5.0797	13.8155
SELENIUM	34	0.430598	4.500E+00	348.0	40.112	0.504	510.5	14.5839	18.9049	5.4141	13.8155
BROMINE	35	0.438026	7.072E-03	343.0	1.604	52.430	5293.3	14.6128	25.3435	19.8237	18.4913
KRYPTON	36	0.429594	3.478E-03	352.0	1.114	52.430	52937.6	14.5610	26.0725	15.0942	23.0965
RUBIDIUM	37	0.432912	1.532E+00	363.0	23.467	1.640	510.5	14.4995	19.9771	7.2552	13.8155
STRONTIUM	38	0.433691	2.540E+00	366.0	30.244	1.022	510.5	14.4830	19.4697	6.3738	13.8155
YTTRIUM	39	0.438666	4.469E+00	379.0	40.346	0.602	510.5	14.4132	18.8933	5.6226	13.8155
ZIRCONIUM	40	0.438500	6.506E+00	393.0	48.671	0.447	510.5	14.3406	18.5181	5.2352	13.8155
NIOBIUM	41	0.441304	8.570E+00	417.0	56.039	0.447	510.5	14.2221	18.2362	5.0343	13.8155
MOLYBDENUM	42	0.437774	1.022E+01	424.0	60.951	0.447	510.5	14.1888	18.0681	4.8685	13.8155
TECHNETIUM	43	0.439192	1.150E+01	428.0	64.760	0.447	510.5	14.1700	17.9469	4.7425	13.8155

TABLE 11a—*continued*

RUTHENIUM	44	0.435342	1.241E+01	441.0	66.978	0.447	510.5	14.1102	17.8795	4.7333	13.8155
RHODIUM	45	0.437294	1.241E+01	449.0	67.128	0.447	510.5	14.0742	17.8751	4.7720	13.8155
PALLADIUM	46	0.432250	1.202E+01	470.0	65.683	0.447	510.5	13.9828	17.9186	4.9380	13.8155
SILVER	47	0.435718	1.050E+01	470.0	61.635	0.447	510.5	13.9828	18.0458	5.0944	13.8155
CADMIUM	48	0.427008	8.650E+00	469.0	55.381	0.477	510.5	13.9871	18.2598	5.3530	13.8155
INDIUM	49	0.426755	7.310E+00	488.0	50.896	0.629	510.5	13.9076	18.4287	5.6784	13.8155
TIN	50	0.421265	7.310E+00	488.0	50.567	0.638	510.5	13.9076	18.4417	5.6961	13.8155
ANTIMONY	51	0.418891	6.691E+00	487.0	48.242	0.703	510.5	13.9117	18.5358	5.8220	13.8155
TELLURIUM	52	0.407524	6.240E+00	485.0	45.952	0.772	510.5	13.9200	18.6331	5.9507	13.8155
IODINE	53	0.417637	4.930E+00	491.0	41.348	0.984	510.5	13.8954	18.8442	6.3127	13.8155
XENON	54	0.411303	5.485E-03	482.0	1.369	52.430	52937.6	13.9324	25.6605	16.1063	23.0965
CESIUM	55	0.413828	1.873E+00	488.0	25.370	2.433	510.5	13.9076	19.8212	8.2007	13.8155
BARIUM	56	0.407777	3.500E+00	491.0	34.425	1.408	510.5	13.8954	19.2107	6.9446	13.8155
LANTHANUM	57	0.410351	6.154E+00	501.0	45.792	0.833	510.5	13.8551	18.6400	6.0577	13.8155
CERIUM	58	0.413931	6.657E+00	523.0	47.834	0.831	510.5	13.7691	18.5528	6.0558	13.8155
PRASEODYMIUM	59	0.418714	6.710E+00	535.0	48.301	0.854	510.5	13.7237	18.5334	6.0951	13.8155
NEODYMIUM	60	0.415973	6.900E+00	546.0	48.819	0.871	510.5	13.6830	18.5120	6.1247	13.8155
PROMETHIUM	61	0.420942	7.220E+00	560.0	50.236	0.865	510.5	13.6324	18.4548	6.1146	13.8155
SAMARIUM	62	0.412344	7.460E+00	574.0	50.540	0.899	510.5	13.5830	18.4427	6.1721	13.8155
EUROPIUM	63	0.414583	5.243E+00	580.0	42.484	1.295	510.5	13.5622	18.7900	6.7854	13.8155
GADOLINIUM	64	0.406995	7.900E+00	591.0	51.672	0.912	510.5	13.5246	18.3984	6.1940	13.8155
TERBIUM	65	0.408997	8.229E+00	614.0	52.865	0.941	510.5	13.4483	18.3528	6.2422	13.8155
DYSPROSIUM	66	0.406154	8.550E+00	628.0	53.698	0.954	510.5	13.4032	18.3215	6.2640	13.8155
HOLMIUM	67	0.406232	8.795E+00	650.0	54.467	0.994	510.5	13.3343	18.2931	6.3286	13.8155
ERBIUM	68	0.406553	9.066E+00	658.0	55.322	0.987	510.5	13.3099	18.2619	6.3179	13.8155
THULIUM	69	0.408443	9.321E+00	674.0	56.225	1.003	510.5	13.2618	18.2295	6.3431	13.8155
YTTERBIUM	70	0.404531	6.730E+00	684.0	47.546	1.432	510.5	13.2323	18.5649	6.9766	13.8155
LUTETIUM	71	0.405791	9.840E+00	694.0	57.581	1.014	510.5	13.2033	18.1819	6.3606	13.8155
HAFNIUM	72	0.403384	1.331E+01	705.0	66.770	0.773	510.5	13.1719	17.8858	5.9519	13.8155
TANTALUM	73	0.403431	1.665E+01	718.0	74.692	0.633	510.5	13.1353	17.6615	5.6854	13.8155
TUNGSTEN	74	0.402502	1.930E+01	727.0	80.315	0.554	510.5	13.1104	17.5164	5.5239	13.8155
RHENIUM	75	0.402778	2.102E+01	736.0	83.846	0.518	510.5	13.0858	17.4303	5.4441	13.8155
OSMIUM	76	0.399579	2.257E+01	746.0	86.537	0.497	510.5	13.0588	17.3671	5.3979	13.8155
IRIDIUM	77	0.400583	2.242E+01	757.0	86.357	0.516	510.5	13.0295	17.3713	5.4406	13.8155
PLATINUM	78	0.399836	2.145E+01	790.0	84.389	0.597	510.5	12.9442	17.4174	5.6133	13.8155
GOLD	79	0.401083	1.932E+01	790.0	80.215	0.667	510.5	12.9442	17.5189	5.7524	13.8155
MERCURY	80	0.398823	1.355E+01	800.0	66.977	0.996	510.5	12.9190	17.8796	6.3315	13.8155
THALLIUM	81	0.396315	1.172E+01	810.0	62.104	1.186	510.5	12.8942	18.0307	6.6249	13.8155
LEAD	82	0.395753	1.135E+01	823.0	61.072	1.263	510.5	12.8624	18.0642	6.7391	13.8155
BISMUTH	83	0.397166	9.747E+00	823.0	56.696	1.456	510.5	12.8624	18.2128	7.0103	13.8155
POLONIUM	84	0.401948	9.320E+00	830.0	55.773	1.526	510.5	12.8454	18.2457	7.1047	13.8155
RADON	86	0.387356	9.066E-03	794.0	1.708	52.430	52937.6	12.9341	25.2180	18.7032	23.0965
RADIUM	88	0.389337	5.000E+00	826.0	40.205	2.730	510.5	12.8551	18.9003	8.5227	13.8155
ACTINIUM	89	0.392022	1.007E+01	841.0	57.254	1.489	510.5	12.8191	18.1933	7.0550	13.8155
THORIUM	90	0.387867	1.172E+01	847.0	61.438	1.320	510.5	12.8049	18.0522	6.8205	13.8155

TABLE 11a—*continued*

Element	Z	Z/A	Density* (g/cm^3)	I (eV)	$\hbar\omega_p$ (eV)	T_0 (MeV)	T_1 (MeV)	b_0	b_1	b_2	b_3
PROTACTINIUM	91	0.393878	1.537E+01	878.0	70.901	1.070	510.5	12.7330	17.7657	6.4495	13.8155
URANIUM	92	0.386508	1.895E+01	890.0	77.986	0.908	510.5	12.7058	17.5752	6.1871	13.8155
NEPTUNIUM	93	0.392325	2.025E+01	902.0	81.221	0.859	510.5	12.6790	17.4939	6.1031	13.8155
PLUTONIUM	94	0.393220	1.984E+01	921.0	80.486	0.913	510.5	12.6373	17.5121	6.1954	13.8155
AMERICIUM	95	0.390848	1.367E+01	934.0	66.607	1.364	510.5	12.6093	17.8906	6.8821	13.8155
CURIUM	96	0.388554	1.351E+01	939.0	66.022	1.401	510.5	12.5986	17.9083	6.9342	13.8155
BERKELIUM	97	0.392601	1.400E+01	952.0	67.557	1.376	510.5	12.5711	17.8623	6.9002	13.8155

* Gas densities are for a pressure of 1 atm and a temperature of 20°C. See also footnotes pertaining to density in Table 7.
* Graphite is comprised of crystallite regions (with a density of 2.265 g cm^{-3}) and pores (voids). The density 1.7 g cm^{-3} is a typical bulk density for reactor-grade graphite. The best choice for the density value is not known to us.

TABLE 11b. Material constants for use in equation (16) to calculate the collision stopping power for electrons and positrons: compounds and mixtures

Material	<Z/A>	I (eV)	$\hbar\omega_p$ (eV)	T_0 (MeV)	T_1 (MeV)	b_0	b_1	b_2	b_3
A-150 TISSUE-EQUIVALENT PLASTIC	0.549031	65.1	22.667	0.447	50.6	17.9364	20.0464	3.0027	9.2103
ACETONE	0.550966	64.2	19.010	0.447	50.6	17.9643	20.3983	3.4473	9.2103
ACETYLENE	0.537680	58.2	0.700	20.570	5293.3	18.1609	27.0023	11.2514	18.4913
ADENINE	0.518027	71.4	24.098	0.447	50.6	17.7517	19.9240	3.0882	9.2103
ADIPOSE TISSUE (ICRP)	0.558468	63.2	20.655	0.447	50.6	17.9953	20.2323	3.1770	9.2103
AIR, DRY (NEAR SEA LEVEL)	0.499190	85.7	0.707	32.895	5293.3	17.3873	26.9826	13.5906	18.4913
ALANINE	0.538758	71.9	25.204	0.447	50.6	17.7363	19.8342	2.9861	9.2103
ALUMINUM OXIDE	0.490382	145.2	40.206	0.447	510.5	16.3320	18.9002	3.2559	13.8155
AMBER	0.551776	63.2	22.450	0.447	50.6	17.9965	20.0657	2.9467	9.2103
AMMONIA	0.587185	53.7	0.635	20.570	5293.3	18.3214	27.1977	11.4143	18.4913
ANILINE	0.536895	66.2	21.361	0.447	50.6	17.9029	20.1651	3.2115	9.2103
ANTHRACENE	0.527400	69.5	23.704	0.447	50.6	17.8056	19.9570	3.0594	9.2103
B-100 BONE-EQUIVALENT PLASTIC	0.527397	85.9	25.199	0.447	50.6	17.3815	19.8346	3.4734	9.2103
BAKELITE	0.527919	72.4	23.408	0.447	50.6	17.7246	19.9821	3.2050	9.2103
BARIUM FLUORIDE	0.422069	375.9	41.398	0.558	510.5	14.4294	18.8418	5.5324	13.8155
BARIUM SULFATE	0.445611	285.7	40.805	0.447	510.5	14.9783	18.8706	4.8845	13.8155
BENZENE	0.537680	63.4	19.806	0.447	50.6	17.9893	20.3163	3.3003	9.2103
BERYLLIUM OXIDE	0.479778	93.2	34.629	0.447	50.6	17.2192	19.1989	2.8239	9.2103
BISMUTH GERMANIUM OXIDE	0.420652	534.1	49.904	0.795	510.5	13.7270	18.4680	5.9920	13.8155
BLOOD (ICRP)	0.549952	75.2	22.001	0.447	50.6	17.6492	20.1061	3.4785	9.2103

TABLE 11b—*continued*

BONE, COMPACT (ICRU)	0.530103	91.9	28.536	0.447	50.6	17.2465	19.5859	3.3174	9.2103
BONE, CORTICAL (ICRP)	0.521299	106.4	28.298	0.447	510.5	16.9536	19.6027	3.3554	13.8155
BORON CARBIDE	0.470580	84.7	31.380	0.447	50.6	17.4090	19.3959	2.8339	9.2103
BORON OXIDE	0.488378	99.6	27.107	0.447	50.6	17.0851	19.6886	3.6798	9.2103
BRAIN (ICRP)	0.554227	73.3	21.772	0.447	50.6	17.6983	20.1270	3.4399	9.2103
BUTANE	0.584966	48.3	1.101	20.570	5293.3	18.5334	26.0967	5.2655	18.4913
N-BUTYL ALCOHOL	0.566630	59.9	19.520	0.447	50.6	18.1029	20.3454	3.1845	9.2103
C-552 AIR-EQUIVALENT PLASTIC	0.499687	86.8	27.023	0.447	50.6	17.3611	19.6949	3.3097	9.2103
CADMIUM TELLURIDE	0.416649	539.3	46.314	0.946	510.5	13.7077	18.6174	6.2502	13.8155
CADMIUM TUNGSTATE	0.427472	468.3	52.954	0.526	510.5	13.9902	18.3494	5.4630	13.8155
CALCIUM CARBONATE	0.499554	136.4	34.080	0.447	510.5	16.4571	19.2308	3.5087	13.8155
CALCIUM FLUORIDE	0.486700	166.0	35.849	0.447	510.5	16.0643	19.1296	3.8674	13.8155
CALCIUM OXIDE	0.499292	176.1	36.988	0.447	510.5	15.9456	19.0670	3.9364	13.8155
CALCIUM SULFATE	0.499495	152.3	35.038	0.447	510.5	16.2364	19.1754	3.7119	13.8155
CALCIUM TUNGSTATE	0.437610	395.0	46.934	0.471	510.5	14.3304	18.5908	5.3376	13.8155
CARBON DIOXIDE	0.499889	85.0	0.874	26.026	5293.3	17.4030	26.5566	11.9944	18.4913
CARBON TETRACHLORIDE	0.481072	166.3	25.234	0.447	510.5	16.0607	19.8319	4.7356	13.8155
CELLULOSE ACETATE, CELLOPHANE	0.530399	77.6	25.008	0.447	50.6	17.5839	19.8499	3.2166	9.2103
CELLULOSE ACETATE BUTYRATE	0.532794	74.6	23.041	0.447	50.6	17.6636	20.0137	3.3320	9.2103
CELLULOSE NITRATE	0.514237	87.0	25.224	0.447	50.6	17.3563	19.8327	3.5053	9.2103
CERIC SULFATE DOSIMETER SOLUTION	0.552785	76.7	21.743	0.447	50.6	17.6074	20.1296	3.5682	9.2103
CESIUM FLUORIDE	0.421319	440.7	37.942	0.941	510.5	14.1115	19.0161	6.2423	13.8155
CESIUM IODIDE	0.415689	553.1	39.455	1.363	510.5	13.6572	18.9379	6.8811	13.8155
CHLOROBENZENE	0.515288	89.1	21.752	0.523	50.6	17.3087	20.1289	3.9839	9.2103
CHLOROFORM	0.485852	156.0	24.462	0.447	510.5	16.1886	19.8941	4.6547	13.8155
CONCRETE, PORTLAND	0.502736	135.2	30.986	0.447	510.5	16.4750	19.4212	3.7208	13.8155
CYCLOHEXANE	0.570337	56.4	19.207	0.447	50.6	18.2233	20.3777	3.0635	9.2103
1,2-DICHLOROBENZENE	0.503389	106.5	23.354	0.447	510.5	16.9520	19.9867	3.8298	13.8155
DICHLORODIETHYL ETHER	0.517437	103.3	22.894	0.447	510.5	17.0130	20.0265	3.8036	13.8155
1,2-DICHLOROETHANE	0.505257	111.9	22.764	0.447	510.5	16.8531	20.0379	4.0144	13.8155
DIETHYL ETHER	0.566630	60.0	18.326	0.447	50.6	18.0996	20.4716	3.3622	9.2103
N,N-DIMETHYL FORMAMIDE	0.547238	66.6	20.763	0.447	50.6	17.8913	20.2219	3.3053	9.2103
DIMETHYL SULFOXIDE	0.537574	98.6	22.173	0.627	50.6	17.1067	20.0905	4.2374	9.2103
ETHANE	0.598615	45.4	0.789	20.570	5293.3	18.6572	26.7616	7.7992	18.4913
ETHYL ALCOHOL	0.564373	62.9	19.233	0.447	50.6	18.0052	20.3751	3.3592	9.2103
ETHYL CELLULOSE	0.544046	69.3	22.594	0.447	50.6	17.8115	20.0529	3.1830	9.2103
ETHYLENE	0.570337	50.7	0.746	20.570	5293.3	18.4381	26.8744	9.3543	18.4913
EYE LENS (ICRP)	0.548767	73.3	22.388	0.447	50.6	17.7002	20.0712	3.3606	9.2103
FERRIC OXIDE	0.475916	227.3	45.331	0.447	510.5	15.4359	18.6603	4.0629	13.8155
FERROBORIDE	0.465067	261.0	52.546	0.447	510.5	15.1593	18.3649	4.0399	13.8155

TABLE 11b—*continued*

Material	<Z/A>	I (eV)	$\hbar\omega_p$ (eV)	T_0 (MeV)	T_1 (MeV)	b_0	b_1	b_2	b_3
FERROUS OXIDE	0.473232	248.6	47.327	0.447	510.5	15.2564	18.5741	4.1777	13.8155
FERROUS SULFATE DOSIMETER SOLUTION	0.553282	76.4	21.690	0.447	50.6	17.6175	20.1346	3.5610	9.2103
"FREON-12"	0.479681	143.0	21.121	0.447	510.5	16.3621	20.1877	4.8025	13.8155
"FREON-12B2"	0.448012	284.9	25.877	0.843	510.5	14.9841	19.7816	6.0766	13.8155
"FREON-13"	0.478656	126.6	19.432	0.447	510.5	16.6064	20.3545	4.7071	13.8155
"FREON-13B1"	0.456651	210.5	23.849	0.524	510.5	15.5893	19.9448	5.4582	13.8155
"FREON-13I1"	0.438975	293.5	25.615	0.916	510.5	14.9242	19.8019	6.2001	13.8155
GADOLINIUM OXYSULFIDE	0.422656	493.3	51.099	0.639	510.5	13.8861	18.4207	5.6970	13.8155
GALLIUM ARSENIDE	0.442473	384.9	44.170	0.509	510.5	14.3822	18.7122	5.4255	13.8155
GEL IN PHOTOGRAPHIC EMULSION	0.539734	74.8	24.058	0.447	50.6	17.6583	19.9274	3.2208	9.2103
GLASS, BOROSILICATE ("PYREX", CORNING 7740)	0.497070	134.0	30.339	0.447	510.5	16.4920	19.4634	3.7519	13.8155
GLASS, LEAD	0.421007	526.4	46.631	0.888	510.5	13.7561	18.6037	6.1533	13.8155
GLASS, PLATE	0.497313	145.4	31.481	0.447	510.5	16.3286	19.3895	3.8618	13.8155
GLUCOSE, DEXTROSE	0.534888	77.2	26.153	0.447	50.6	17.5962	19.7603	3.0769	9.2103
GLUTAMINE	0.533714	73.3	25.437	0.447	50.6	17.6985	19.8159	3.0127	9.2103
GLYCEROL	0.542921	72.6	23.846	0.447	50.6	17.7183	19.9451	3.1628	9.2103
GUANINE	0.516121	75.0	26.022	0.447	50.6	17.6533	19.7704	3.0125	9.2103
GYPSUM, PLASTER OF PARIS	0.511128	129.7	31.379	0.447	510.5	16.5584	19.3960	3.5872	13.8155
N-HEPTANE	0.578823	54.4	18.128	0.447	50.6	18.2955	20.4933	3.1231	9.2103
N-HEXANE	0.580204	54.0	17.836	0.447	50.6	18.3103	20.5258	3.1475	9.2103
"KAPTON" POLYIMIDE FILM	0.512644	79.6	24.586	0.447	50.6	17.5347	19.8839	3.3308	9.2103
LANTHANUM OXYBROMIDE	0.425878	439.7	47.125	0.593	510.5	14.1159	18.5826	5.6047	13.8155
LANTHANUM OXYSULFIDE	0.423481	456.2	45.394	0.696	510.5	14.0422	18.6575	5.8096	13.8155
LEAD OXIDE	0.403227	766.7	56.488	1.281	510.5	13.0040	18.2202	6.7647	13.8155
LITHIUM AMIDE	0.522568	55.5	22.609	0.447	50.6	18.2566	20.0516	2.5706	9.2103
LITHIUM CARBONATE	0.487203	87.9	29.217	0.447	50.6	17.3352	19.5388	3.1311	9.2103
LITHIUM FLUORIDE	0.462617	94.0	31.815	0.447	50.6	17.2017	19.3684	3.0805	9.2103
LITHIUM HYDRIDE	0.503214	36.5	18.510	0.447	50.6	19.0942	20.4516	1.9704	9.2103
LITHIUM IODIDE	0.418393	485.1	34.841	1.345	510.5	13.9196	19.1867	6.8562	13.8155
LITHIUM OXIDE	0.468519	73.6	27.984	0.447	50.6	17.6920	19.6250	2.7599	9.2103
LITHIUM TETRABORATE	0.484869	94.6	31.343	0.447	50.6	17.1887	19.3983	3.1393	9.2103
LUNG (ICRP)	0.549652	75.3	21.891	0.447	50.6	17.6448	20.1161	3.4983	9.2103
M3 WAX	0.555116	67.9	22.000	0.447	50.6	17.8514	20.1062	3.2013	9.2103
MAGNESIUM CARBONATE	0.498137	118.0	34.979	0.447	510.5	16.7476	19.1788	3.0874	13.8155
MAGNESIUM FLUORIDE	0.481527	134.3	34.634	0.447	510.5	16.4884	19.1986	3.4305	13.8155
MAGNESIUM OXIDE	0.496224	143.8	38.407	0.447	510.5	16.3510	18.9918	3.3451	13.8155
MAGNESIUM TETRABORATE	0.490139	108.3	32.089	0.447	510.5	16.9182	19.3513	3.0896	13.8155
MERCURIC IODIDE	0.409332	684.5	46.494	1.495	510.5	13.2310	18.6096	7.0633	13.8155
METHANE	0.623340	41.7	0.588	20.570	5293.3	18.8273	27.3516	9.7660	18.4913
METHANOL	0.561763	67.6	19.214	0.447	50.6	17.8610	20.3770	3.5596	9.2103

TABLE 11b—*continued*

MIX D WAX	0.564789	60.9	21.547	0.447	50.6	18.0710	20.1478	2.9570	9.2103
MS20 TISSUE SUBSTITUTE	0.538856	75.1	21.153	0.447	50.6	17.6494	20.1847	3.5861	9.2103
MUSCLE, SKELETAL (ICRP)	0.549378	75.3	21.781	0.447	50.6	17.6445	20.1262	3.5125	9.2103
MUSCLE, STRIATED (ICRU)	0.550051	74.7	21.795	0.447	50.6	17.6606	20.1249	3.4888	9.2103
MUSCLE-EQUIVALENT LIQUID, WITH SUCROSE	0.548281	74.3	22.480	0.447	50.6	17.6715	20.0630	3.3888	9.2103
MUSCLE-EQUIVALENT LIQUID, WITHOUT SUCROSE	0.550136	74.2	22.109	0.447	50.6	17.6750	20.0963	3.4298	9.2103
NAPTHALENE	0.530532	68.4	22.459	0.447	50.6	17.8381	20.0649	3.1629	9.2103
NITROBENZENE	0.519856	75.8	22.747	0.447	50.6	17.6321	20.0394	3.4106	9.2103
NITROUS OXIDE	0.499855	84.9	0.872	26.026	5293.3	17.4053	26.5628	12.0146	18.4913
NYLON, DU PONT "ELVAMIDE 8062M"	0.550625	64.3	22.221	0.447	50.6	17.9616	20.0861	3.0227	9.2103
NYLON, TYPE 6 AND TYPE 6/6	0.547902	63.9	22.774	0.447	50.6	17.9736	20.0370	2.9388	9.2103
NYLON, TYPE 6/10	0.552359	63.2	22.866	0.447	50.6	17.9957	20.0289	2.8975	9.2103
NYLON, TYPE 11 ("RILSAN")	0.556486	61.6	25.661	0.447	50.6	18.0482	19.7983	2.5090	9.2103
OCTANE, LIQUID	0.577781	54.7	18.360	0.447	50.6	18.2846	20.4679	3.1033	9.2103
PARAFFIN WAX	0.572748	55.9	21.031	0.447	50.6	18.2405	20.1963	2.7911	9.2103
N-PENTANE	0.582122	53.6	17.398	0.447	50.6	18.3252	20.5756	3.1953	9.2103
PHOTOGRAPHIC EMULSION	0.454532	331.0	37.946	0.510	510.5	14.6840	19.0160	5.4280	13.8155
PLASTIC SCINTILLATOR (VINYLTOLUENE BASED)	0.541415	64.7	21.540	0.447	50.6	17.9478	20.1485	3.1271	9.2103
PLUTONIUM DIOXIDE	0.405828	746.5	62.143	1.007	510.5	13.0574	18.0294	6.3499	13.8155
POLYACRYLONITRILE	0.527671	69.6	22.642	0.447	50.6	17.8017	20.0487	3.1906	9.2103
POLYCARBONATE, "MAKROLON"	0.526968	73.1	22.915	0.447	50.6	17.7038	20.0247	3.2920	9.2103
POLYCHLOROSTYRENE	0.525176	81.7	23.810	0.447	50.6	17.4833	19.9481	3.4893	9.2103
POLYETHYLENE	0.570337	57.4	21.099	0.447	50.6	18.1882	20.1898	2.8540	9.2103
POLYETHYLENE TEREPTHALATE, "MYLAR"	0.520370	78.7	24.595	0.447	50.6	17.5575	19.8831	3.2985	9.2103
POLYMETHYL METHACRYLATE	0.539369	74.0	23.086	0.447	50.6	17.6801	20.0098	3.3040	9.2103
POLYOXYMETHYLENE	0.532868	77.4	25.110	0.447	50.6	17.5903	19.8417	3.1967	9.2103
POLYPROPYLENE	0.559985	59.2	20.457	0.447	50.6	18.1253	20.2516	3.0251	9.2103
POLYSTYRENE	0.537680	68.7	21.754	0.447	50.6	17.8288	20.1286	3.2631	9.2103
POLYTETRAFLUOROETHYLENE, "TEFLON"	0.479925	99.1	29.609	0.447	50.6	17.0960	19.5121	3.4226	9.2103
POLYTRIFLUOROCHLOROETHYLENE	0.480810	120.7	28.955	0.447	510.5	16.7021	19.5568	3.6082	13.8155
POLYVINYL ACETATE	0.534323	73.7	22.978	0.447	50.6	17.6878	20.0192	3.3064	9.2103
POLYVINYL ALCOHOL	0.544798	69.7	24.251	0.447	50.6	17.7999	19.9114	3.0048	9.2103
POLYVINYL BUTYRAL	0.545366	67.2	22.521	0.447	50.6	17.8737	20.0594	3.1066	9.2103
POLYVINYL CHLORIDE	0.512011	108.2	23.510	0.447	510.5	16.9209	19.9735	3.8517	13.8155
POLYVINYLIDENE CHLORIDE, SARAN	0.495132	134.3	26.437	0.447	510.5	16.4881	19.7387	4.0952	13.8155
POLYVINYLIDENE FLUORIDE	0.499730	88.8	27.024	0.447	50.6	17.3148	19.6948	3.3731	9.2103
POLYVINYL PYRROLIDONE	0.539844	67.7	23.671	0.447	50.6	17.8566	19.9597	2.9932	9.2103
POTASSIUM IODIDE	0.433728	431.9	33.575	1.154	510.5	14.1520	19.2607	6.5773	13.8155
POTASSIUM OXIDE	0.488343	189.9	30.672	0.447	510.5	15.7953	19.4416	4.5819	13.8155
PROPANE	0.589620	47.1	0.959	20.570	5293.3	18.5837	26.3715	6.3168	18.4913
PROPANE, LIQUID	0.589620	52.0	14.509	0.447	50.6	18.3852	20.9387	3.6110	9.2103
N-PROPYL ALCOHOL	0.565765	61.1	19.429	0.447	50.6	18.0632	20.3548	3.2517	9.2103
PYRIDINE	0.530965	66.2	20.807	0.447	50.6	17.9029	20.2177	3.2837	9.2103
RUBBER, BUTYL	0.570337	56.5	20.873	0.447	50.6	18.2191	20.2113	2.8411	9.2103
RUBBER, NATURAL	0.557854	59.8	20.644	0.447	50.6	18.1055	20.2334	3.0273	9.2103

TABLE 11b—*continued*

Material	<Z/A>	I (eV)	$\hbar\omega_p$ (eV)	T_0 (MeV)	T_1 (MeV)	b_0	b_1	b_2	b_3
RUBBER, NEOPRENE	0.519560	93.0	23.036	0.507	50.6	17.2221	20.0142	3.9427	9.2103
SILICON DIOXIDE	0.499298	139.2	31.014	0.447	510.5	16.4164	19.4194	3.7906	13.8155
SILVER BROMIDE	0.436700	486.6	48.448	0.696	510.5	13.9132	18.5273	5.8078	13.8155
SILVER CHLORIDE	0.446550	398.4	45.405	0.517	510.5	14.3132	18.6570	5.4432	13.8155
SILVER HALIDES IN PHOTOGRAPHIC EMULSION	0.436633	487.1	48.433	0.697	510.5	13.9115	18.5279	5.8111	13.8155
SILVER IODIDE	0.425944	543.5	46.105	0.970	510.5	13.6920	18.6264	6.2896	13.8155
SKIN (ICRP)	0.549325	72.7	22.400	0.447	50.6	17.7147	20.0702	3.3394	9.2103
SODIUM CARBONATE	0.490618	125.0	32.117	0.447	510.5	16.6319	19.3495	3.4396	13.8155
SODIUM IODIDE	0.426968	452.0	36.057	1.097	510.5	14.0609	19.1181	6.4903	13.8155
SODIUM MONOXIDE	0.484035	148.8	30.205	0.447	510.5	16.2827	19.4722	4.0201	13.8155
SODIUM NITRATE	0.494149	114.6	30.459	0.447	510.5	16.8046	19.4555	3.3577	13.8155
STILBENE	0.532597	67.7	20.719	0.447	50.6	17.8592	20.2261	3.3551	9.2103
SUCROSE	0.531699	77.5	26.416	0.447	50.6	17.5873	19.7403	3.0618	9.2103
TERPHENYL	0.521485	71.7	23.116	0.447	50.6	17.7434	20.0072	3.2138	9.2103
TESTES (ICRP)	0.551083	75.0	21.815	0.447	50.6	17.6533	20.1231	3.4962	9.2103
TETRACHLOROETHYLENE	0.482410	159.2	25.513	0.447	510.5	16.1479	19.8099	4.6011	13.8155
THALLIUM CHLORIDE	0.408613	690.3	48.749	1.389	510.5	13.2140	18.5149	6.9181	13.8155
TISSUE, SOFT (ICRP)	0.551210	72.3	21.394	0.447	50.6	17.7253	20.1620	3.4509	9.2103
TISSUE, SOFT (ICRU FOUR-COMPONENT)	0.549750	74.9	21.366	0.447	50.6	17.6572	20.1647	3.5479	9.2103
TISSUE-EQUIVALENT GAS (METHANE BASED)	0.549927	62.1	0.697	20.570	5293.3	18.0597	27.0100	11.7611	18.4913
TISSUE-EQUIVALENT GAS (PROPANE BASED)	0.550268	59.5	0.913	20.570	5293.3	18.1178	26.4692	8.9563	18.4913
TITANIUM DIOXIDE	0.475721	179.5	41.022	0.447	510.5	15.9079	18.8601	3.7281	13.8155
TOLUENE	0.542651	62.5	19.764	0.447	50.6	18.0179	20.3205	3.2669	9.2103
TRICHLOROETHYLENE	0.487104	148.1	24.301	0.447	510.5	16.2925	19.9072	4.5431	13.8155
TRIETHYL PHOSPHATE	0.538001	81.2	21.863	0.447	50.6	17.4947	20.1186	3.7078	9.2103
TUNGSTEN HEXAFLUORIDE	0.429760	354.4	29.265	1.024	510.5	14.5473	19.5355	6.3763	13.8155
URANIUM DICARBIDE	0.396869	752.0	60.969	1.062	510.5	13.0427	18.0675	6.4364	13.8155
URANIUM MONOCARBIDE	0.391937	862.0	66.602	1.168	510.5	12.7698	17.8908	6.5983	13.8155
URANIUM OXIDE	0.399959	720.6	60.332	0.996	510.5	13.1281	18.0885	6.3314	13.8155
UREA	0.532841	72.8	24.194	0.447	50.6	17.7140	19.9160	3.1289	9.2103
VALINE	0.546320	67.7	23.622	0.447	50.6	17.8570	19.9639	2.9985	9.2103
"VITON" FLUOROELASTOMER	0.485850	98.6	26.948	0.447	50.6	17.1060	19.7005	3.6672	9.2103
WATER, LIQUID	0.555087	75.0	21.469	0.447	50.6	17.6533	20.1550	3.5401	9.2103
WATER VAPOR	0.555087	71.6	0.590	32.895	5293.3	17.7461	27.3423	13.5961	18.4913
XYLENE	0.546309	61.8	19.866	0.447	50.6	18.0405	20.3102	3.2219	9.2103

5. From Table 11b, Z/A = 0.537680, and from Table 10, $\beta^2 = 0.991402$.

6. From equation (1), the stopping power is calculated to be

$$-\frac{1}{\rho}\left(\frac{dE}{dx}\right)_{coll} = 1.860\,\text{MeV/(g cm}^{-2}\text{)}.$$

Acknowledgements—We gratefully acknowledge the advice and help received from many colleagues, especially H. H. ANDERSEN, J. ASHLEY, H. BICHSEL, M. INOKUTI and R. M. STERNHEIMER. We also thank H. BICHSEL for making available to us his computer program for the analysis of proton and α-particle stopping-power data.

This work was carried out with support from the Department of Energy, the Office of Naval Research and the National Standard Reference Data System.

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