Memorandum

Date: March 17, 2005

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To: LEM Group

Cc: F. Pratt, ISIS

Revision of energy loss of muons in C as calculated by TRIM.SP (7 layers version)

F. Pratt noticed that the polystyrene data (LEM beam time 2003) make more sense if the stopping profiles of muons in poystyrene (C_8H_8) are calculated with the stopping.dat input file instead of stopicru.dat.

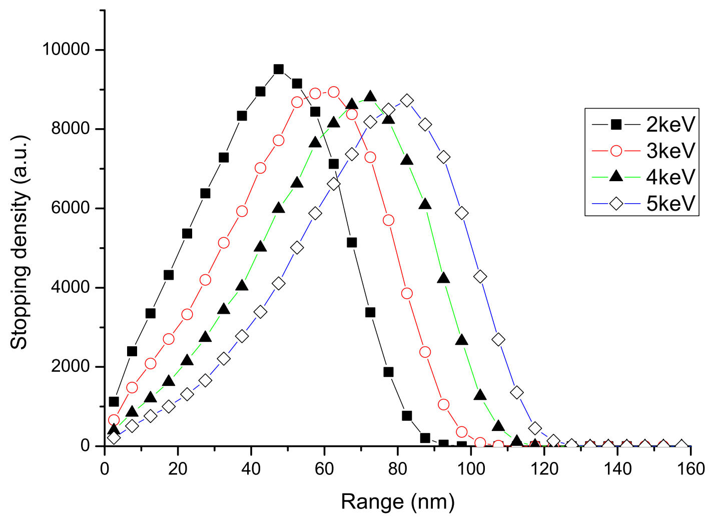


Fig1.:Calculated with stopicru.dat (parametrization for C according to ICRU49)

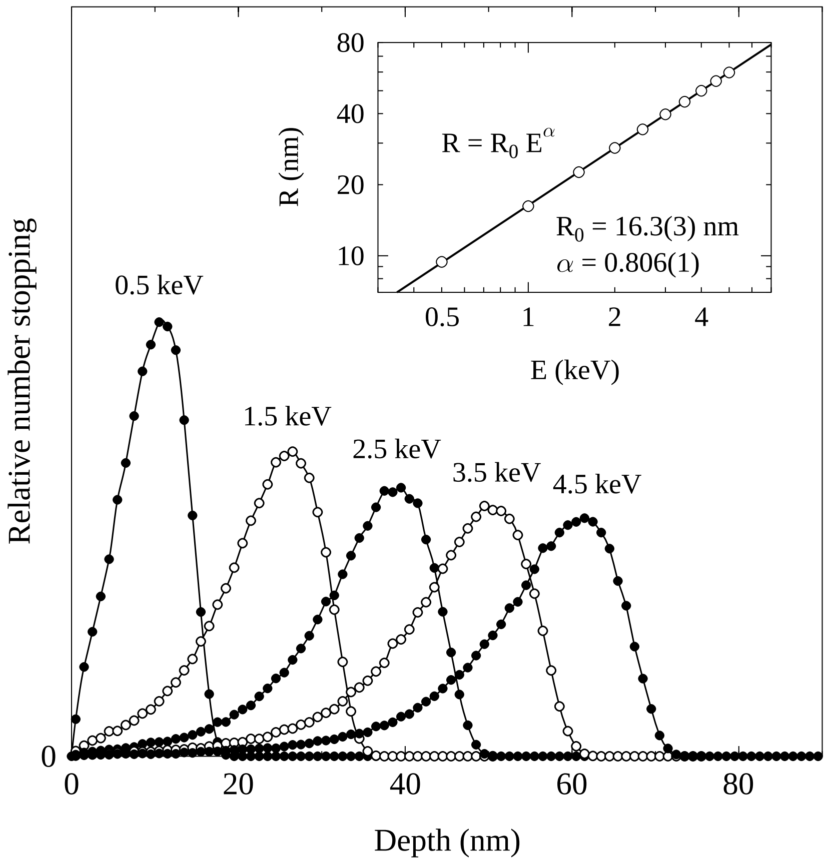


Fig. 2 Calculated with stopping.dat (from Francis) (I do not know whether energy and angular straggling are included here, but it should not make a huge effect).

Stopping.dat is the parametrization according to Anderson and Ziegler book [1]. It uses only the first 5 parameters of the parametrization and it is good for muons up to 100 keV energy (see appendix A).

In stopicru.dat we updated few years ago some of these parameters according to the newer ICRU compilation of 1993 [2] (see appendix B). The program datmak uses as a default stopicru.dat. (You can check in the *.inp file the parameters which are used).

For most of the elements there is not a big difference between stopping.dat and stopicru.dat. The stopping powers in C according to AZ77 and ICRU49 (figure 3) are also very similar although ICRU49 (dashed green curve) tends to slightly underestimated the stopping power as compared to AZ77 (black curve, barely visible).

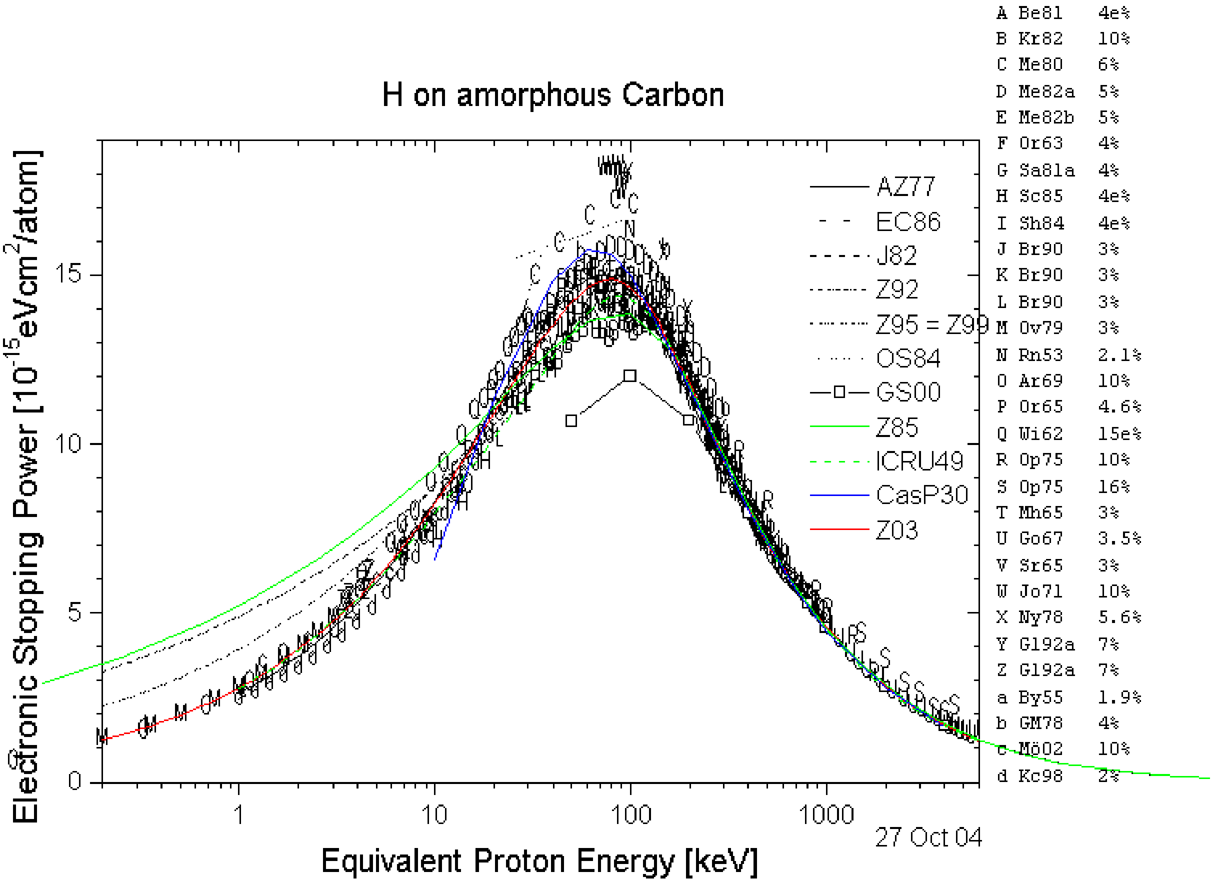
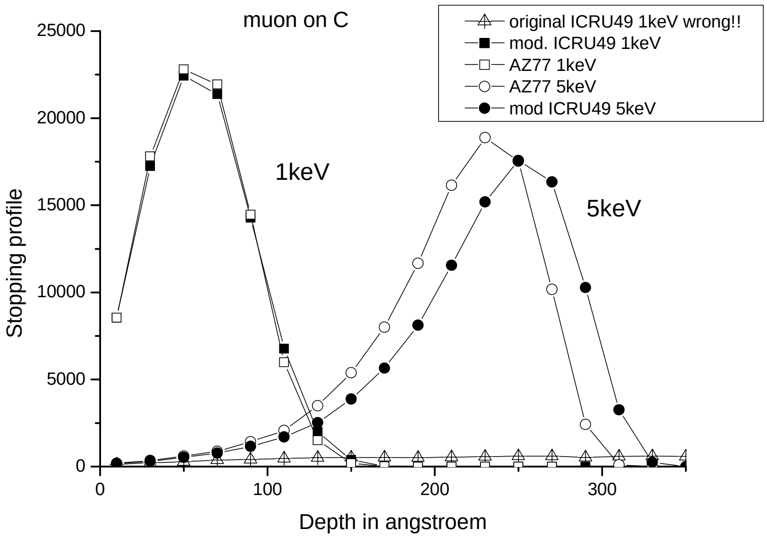


Fig. 3: From Helmut Paul most recent compilation (web). Stopping.dat is according to AZ77 Stopicru.dat is according to ICRU49.

So the stopping profiles should also be similar. (There is a note in ICRU49 that this is valid for proton in amorphous C only for energies between 40 and 600 keV, which means between ~4 and ~60 keV for muons, but see Fig. 3 this can also not explain the difference). The problem is that TRIMSP does not take into account in the proper way the fact that the A1 parameter in ICRU is zero.

To solve the problem A1 in ICRU49 has to be set equal to A2 (i.e. 2.601). Another possibility is to use the AZ77 parameters for C. The difference between the two choices is small (see Fig. 4).



Muon on C 1 keV and 5 keV, DeltaE400eV,
DeltaAng=15 degrees
calculated with trim.sp

100000 particles
comparison of
-AZ77 parametrization
-ICRU parametrization
-modfied ICRU parametrization (i.e. A1 parameter set equal to A2 parameter in order to avoid the wrong dealing in TRIMSP)

Fig. 4: Stopping profiles of muons in Carbon with different parametrizations.

I changed in the stopicru.dat file the A1 parameter from 0.0 to 2.601 for Carbon correspondingly.

Appendix A: from AZ77

Page 16 AZ77

TABLE 1

STOPPING FORMULAE USING TABULATED COEFFICIENTS (TABLE 2)

******* ENERGY: 1-10 keV *******

$$\text{STOPPING} = A_1\, E^{1/2} \qquad \text{eV}/(10^{15}\ \text{atoms/cm}^2)$$

******* ENERGY: 10-999 keV *******

$$(\text{STOPPING})^{-1} = (S_{LOW})^{-1} + (S_{HIGH})^{-1} \qquad \text{eV}/(10^{15}\ \text{atoms/cm}^2)$$

$$S_{LOW} = A_2\, E^{.45}$$

$$S_{HIGH} = (A_3/E)\ ln\,[1 + (A_4/E) + (A_5 E)]$$

******* ENERGY: 1000 keV-100,000 keV *******

$$\text{STOPPING} = (A_6/\beta^2)[ln(\frac{A_7\beta^2}{1-\beta^2}) - \beta^2 - \sum_{i=0}^{4} A_{i+8}(ln E)^i] \qquad \text{eV}/(10_{15}\ \text{atoms/cm}^2)$$

E = HYDROGEN ENERGY/HYDROGEN MASS [keV/amu]

stopping data valid only
up to 100 MeV

TABLE 2

COEFFICIENTS FOR STOPPING OF HYDROGEN

TARGET ELEMENT	A - 1 COEFF.	A - 2 COEFF.	A - 3 COEFF.	A - 4 COEFF.	A - 5 COEFF.	A - 6 COEFF.	A - 7 COEFF.	A - 8 COEFF.	A - 9 COEFF.	A - 10 COEFF.	A - 11 COEFF.	A - 12 COEFF.
H [1]	1.262	1.44	242.6	1.2E4	0.1159	0.0005099	5.436E4	-5.052	2.049	-0.3044	0.01966	-0.0004659
HE [2]	1.229	1.397	484.5	5873	0.05225	0.00102	2.451E4	-2.158	0.8278	-0.1172	0.007259	-0.000166
LI [3]	1.411	1.6	725.6	3013	0.04578	0.00153	2.147E4	-0.5831	0.562	-0.1183	0.009298	-0.0002498
BE [4]	2.248	2.59	966	153.8	0.03475	0.002039	1.63E4	0.2779	0.1745	-0.05684	0.005155	-0.0001488
B [5]	2.474	2.815	1206	1060	0.02855	0.002549	1.345E4	-2.445	1.283	-0.2205	0.0156	-0.000393
C [6]	2.631	2.989	1445	957.2	0.02819	0.003059	1.322E4	-4.38	2.044	-0.3283	0.02221	-0.0005417
N [7]	2.954	3.35	1683	1900	0.02513	0.003569	1.179E4	-5.054	2.325	-0.3713	0.02506	-0.0006109
O [8]	2.652	3	1920	2000	0.0223	0.004079	1.046E4	-6.734	3.019	-0.4748	0.03171	-0.0007669
F [9]	2.085	2.352	2157	2634	0.01816	0.004589	8517	-5.571	2.449	-0.3781	0.02483	-0.0005919
NE [10]	1.951	2.199	2393	2699	0.01568	0.005099	7353	-4.408	1.879	-0.2814	0.01796	-0.0004168
NA [11]	2.542	2.869	2628	1854	0.01472	0.005609	6905	-4.959	2.073	-0.3054	0.01921	-0.0004403
MG [12]	3.792	4.293	2862	1009	0.01397	0.006118	6551	-5.51	2.266	-0.3295	0.02047	-0.0004637
AL [13]	4.154	4.739	2766	164.5	0.02023	0.006628	6309	-6.061	2.46	-0.3535	0.02173	-0.0004871
SI [14]	4.15	4.7	3329	550	0.01321	0.007138	6194	-6.294	2.538	-0.3628	0.0222	-0.0004956
P [15]	3.232	3.647	3561	1560	0.01267	0.007648	5942	-6.527	2.616	-0.3721	0.02267	-0.000504
S [16]	3.447	3.891	3792	1219	0.01211	0.008158	5678	-6.761	2.694	-0.3814	0.02314	-0.0005125
CL [17]	5.047	5.714	4023	878.6	0.01178	0.008668	5524	-6.994	2.773	-0.3907	0.02361	-0.0005209
AR [18]	5.731	6.5	4253	530	0.01123	0.009178	5268	-7.227	2.851	-0.4	0.02407	-0.0005294
K [19]	5.151	5.833	4482	545.7	0.01129	0.009687	5295	-7.44	2.923	-0.4094	0.02462	-0.0005411
CA [20]	5.521	6.252	4710	553.3	0.01112	0.0102	5214	-7.653	2.995	-0.4187	0.02516	-0.0005529
SC [21]	5.201	5.884	4938	560.9	0.009995	0.01071	4688	-8.012	3.123	-0.435	0.02605	-0.0005707
TI [22]	4.862	5.496	5165	568.5	0.009474	0.01122	4443	-8.371	3.251	-0.4513	0.02694	-0.0005886
V [23]	4.48	5.055	5391	952.3	0.009117	0.01173	4276	-8.731	3.379	-0.4676	0.02783	-0.0006064

TARGET ELEMENT | A - 1 COEFF. | A - 2 COEFF. | A - 3 COEFF. | A - 4 COEFF. | A - 5 COEFF. | A - 6 COEFF. | A - 7 COEFF. | A - 8 COEFF. | A - 9 COEFF. | A - 10 COEFF. | A - 11 COEFF. | A - 12 COEFF.

FOR ENERGIES 1 - 10 KEV / AMU USE COEFF. A-1 (VELOCITY PROPORTIONAL STOPPING)
FOR ENERGIES 10 - 999 KEV / AMU USE COEFF. A-2 TO A-5
FOR ENERGIES ABOVE 1000 KEV / AMU USE COEFF. A-6 TO A-12 (BETHE STOPPING)

Appendix B: from ICRU49

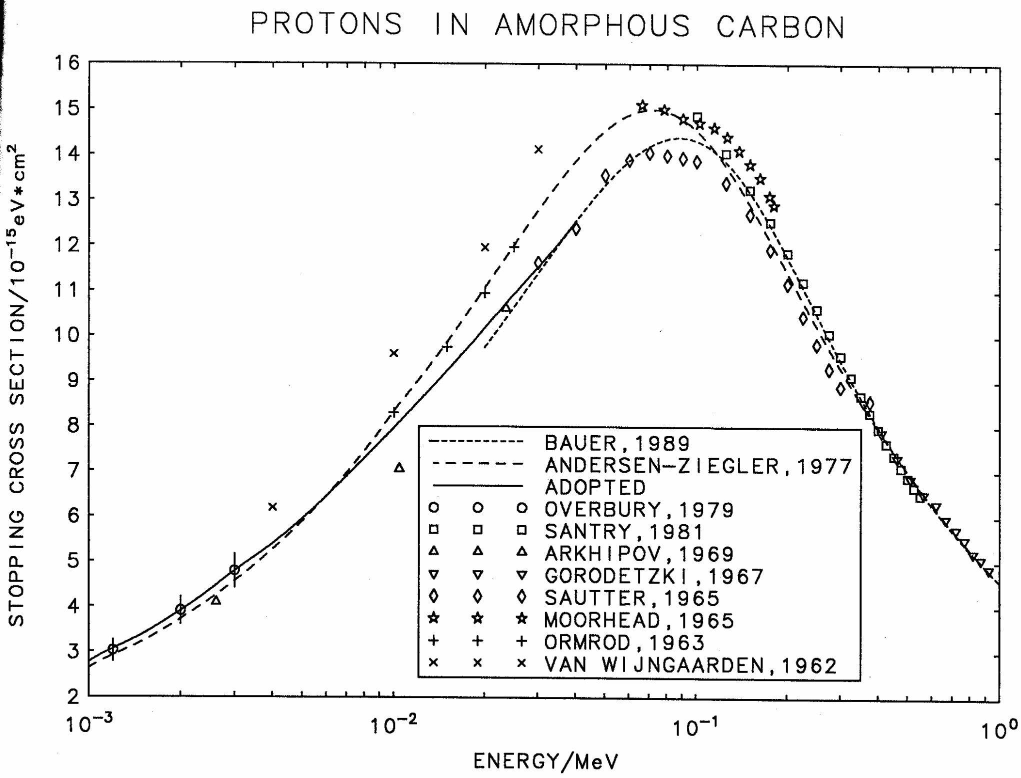


Fig. 3.3. Stopping cross section of amorphous carbon for protons. The experimental points are from Overbury *et al.* (1979), Santry and Werner (1981b), Arkhipov and Gott (1969), Gorodetzky *et al.* (1967), Sautter and Zimmerman (1965), Moorhead (1965), Ormrod and Duckworth (1963), and van Wijngaarden and Duckworth (1962). The short-dashed curve is a Varelas-Biersack fit to his measurements made by Bauer (1990). The long-dashed curve is the fit given by Andersen and Ziegler (1977), and the solid curve represents the cross section adopted in this work.

3.3 Input Data Used for Protons

For the tabulation of stopping powers of elemental substances for protons at energies below 1 MeV, use was made of the empirical formulas of Andersen and Ziegler (1977), originally introduced by Varelas and Biersack (1970). For some materials, the numerical values of the coefficients in the fitting formulas were taken directly from Andersen and Ziegler; for some materials the values of the coefficients were updated to take into account new experimental information. Andersen and Ziegler used as independent variable not the energy, T, but a scaled energy, T_s, which is equal to T (in keV) divided by M_p/u.[7] The stopping cross section (T_s) is fitted by the equations

$$\epsilon = \epsilon_{low} \cdot \epsilon_{high}/(\epsilon_{low} + \epsilon_{high}), \tag{3.1a}$$

where

$$\epsilon_{low} = A_2 T_s^{0.45}, \tag{3.1b}$$

and

$$\epsilon_{high} = (A_3/T_s) \ln(1 + A_4/T_s + A_5 T_s). \tag{3.1c}$$

Varelas and Biersack actually proposed a $T_s^{0.5}$-dependence for ϵ_{low}, as predicted by the free-electron gas theory. Andersen and Ziegler found that the use of an exponent 0.45 gave closer fits to the experimental data. For large values of T_s, Eq. (3.1) implies an energy dependence similar to that of the Bethe theory, and at intermediate energies, around the stopping maximum, it provides satisfactory repre-

[7] M_p/u is the ratio of the proton mass to the atomic mass unit and has the value 1.0073.

TABLE 3.1—*Coefficients of the empirical formulas, Eqs. (3.1) and (3.2), for the electronic stopping cross sections for protons*

Z	A_1	A_2	A_3	A_4	A_5
1	1.254E+00	1.440E+00	2.426E+02	1.200E+04	1.159E−01
2	1.229E+00	1.397E+00	4.845E+02	5.873E+03	5.225E−02
3	1.411E+00	1.600E+00	7.256E+02	3.013E+03	4.578E−02
4	2.248E+00	2.590E+00	9.660E+02	1.538E+02	3.475E−02
5	2.474E+00	2.815E+00	1.206E+03	1.060E+03	2.855E−02
6[a]		2.601E+00	1.701E+03	1.279E+03	1.638E−02
7	2.954E+00	3.350E+00	1.683E+03	1.900E+03	2.513E−02
8	2.652E+00	3.000E+00	1.920E+03	2.000E+03	2.230E−02
9	2.085E+00	2.352E+00	2.157E+03	2.634E+03	1.816E−02
10	1.951E+00	2.199E+00	2.393E+03	2.699E+03	1.568E−02
11	2.542E+00	2.869E+00	2.628E+03	1.854E+03	1.472E−02
12	3.791E+00	4.293E+00	2.862E+03	1.009E+03	1.397E−02
13	4.154E+00	4.739E+00	2.766E+03	1.645E+02	2.023E−02
14	4.914E+00	5.598E+00	3.193E+03	2.327E+02	1.419E−02
15	3.232E+00	3.647E+00	3.561E+03	1.560E+03	1.267E−02
16	3.447E+00	3.891E+00	3.792E+03	1.219E+03	1.211E−02
17	5.301E+00	6.008E+00	3.969E+03	6.451E+02	1.183E−02
18	5.731E+00	6.500E+00	4.253E+03	5.300E+02	1.123E−02
19	5.152E+00	5.833E+00	4.482E+03	5.457E+02	1.129E−02
20	5.521E+00	6.252E+00	4.710E+03	5.533E+02	1.112E−02
21	5.201E+00	5.884E+00	4.938E+03	5.609E+02	9.995E−03
22	4.858E+00	5.489E+00	5.260E+03	6.511E+02	8.930E−03
23	4.479E+00	5.055E+00	5.391E+03	9.523E+02	9.117E−03
24	3.983E+00	4.489E+00	5.616E+03	1.336E+03	8.413E−03
25	3.469E+00	3.907E+00	5.725E+03	1.461E+03	8.829E−03
26	3.519E+00	3.963E+00	6.065E+03	1.243E+03	7.782E−03
27	3.140E+00	3.535E+00	6.288E+03	1.372E+03	7.361E−03
28	3.553E+00	4.004E+00	6.205E+03	5.551E+02	8.763E−03
29	3.696E+00	4.194E+00	4.649E+03	8.113E+01	2.242E−02
30	4.210E+00	4.750E+00	6.953E+03	2.952E+02	6.809E−03
31	5.041E+00	5.697E+00	7.173E+03	2.026E+02	6.725E−03
32	5.554E+00	6.300E+00	6.496E+03	1.100E+02	9.689E−03
33	5.323E+00	6.012E+00	7.611E+03	2.925E+02	6.447E−03
34	5.874E+00	6.656E+00	7.395E+03	1.175E+02	7.684E−03
35	6.658E+00	7.536E+00	7.694E+03	2.223E+02	6.509E−03
36	6.413E+00	7.240E+00	1.185E+04	1.537E+02	2.880E−03
37	5.694E+00	6.429E+00	8.478E+03	2.929E+02	6.087E−03
38	6.339E+00	7.159E+00	8.693E+03	3.303E+02	6.003E−03
39	6.407E+00	7.234E+00	8.907E+03	3.678E+02	5.889E−03
40	6.734E+00	7.603E+00	9.120E+03	4.052E+02	5.765E−03
41	6.901E+00	7.791E+00	9.333E+03	4.427E+02	5.587E−03
42	6.424E+00	7.248E+00	9.545E+03	4.802E+02	5.376E−03
43	6.799E+00	7.671E+00	9.756E+03	5.176E+02	5.315E−03
44	6.109E+00	6.887E+00	9.966E+03	5.551E+02	5.151E−03
45	5.924E+00	6.677E+00	1.018E+04	5.925E+02	4.919E−03
46	5.238E+00	5.900E+00	1.038E+04	6.300E+02	4.758E−03
47	5.345E+00	6.038E+00	6.790E+03	3.978E+02	1.676E−02
48	5.814E+00	6.554E+00	1.080E+04	3.555E+02	4.626E−03
49	6.229E+00	7.024E+00	1.101E+04	3.709E+02	4.540E−03
50	6.409E+00	7.227E+00	1.121E+04	3.864E+02	4.474E−03
51	7.500E+00	8.480E+00	8.608E+03	3.480E+02	9.074E−03
52	6.979E+00	7.871E+00	1.162E+04	3.924E+02	4.402E−03
53	7.725E+00	8.716E+00	1.183E+04	3.948E+02	4.376E−03
54	8.337E+00	9.425E+00	1.051E+04	2.696E+02	6.206E−03
55	7.287E+00	8.218E+00	1.223E+04	3.997E+02	4.447E−03
56	7.899E+00	8.911E+00	1.243E+04	4.021E+02	4.511E−03
57	8.041E+00	9.071E+00	1.263E+04	4.045E+02	4.540E−03
58	7.488E+00	8.444E+00	1.283E+04	4.069E+02	4.420E−03
59	7.291E+00	8.219E+00	1.303E+04	4.093E+02	4.298E−03

References:

[1] ICRU49: Stopping Powers and Ranges for protons and alpha particles, ICRU 1993

[2] AZ77: Andersen H.H., Ziegler J.F., Hydrogen: Stopping powers and ranges in all elements, Vol. 3 of Stopping and ranges of ions in matter , 1977 New York