

Radiation Dose in Composites

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1 Executive Summary

2 Introduction

3 Material Properties

Basic material properties that are essential in the estimation of dose are material density and thickness. For higher fidelity calculations of dose, the material stoichiometry is required. If a particular material is layered, the material properties of each layer would be needed. Each layer would assumed to be homogeneous in a particular elemental composition.

In Sections 3.1 and 3.2, we discuss assumptions in material properties of composites and multi-layered insulation.

3.1 Composites

To first order, composites are typically composed of a fiber material and a matrix that is dominated by a resin bonding material with additives as a minor component.

3.1.1 Density

In this analysis, three fiber materials were considered:

Table 1: List of approximate fiber densities.

Fiber Type	Density [g cm^{-3}]
Glass	1.9
Aramid	1.4
Carbon	1.6

In composites of interest, the mass percentage of resin is approximately 33 – 35% (e.g., for composite overwrapped pressure vessels (COPVs)). An example density for epoxy resin is about 1.3 g cm^{-3} [Joven, 2013]. Therefore, we can approximate the three composite materials as:

Table 2: List of approximate composite densities using fiber densities from Table 1, an epoxy resin density of 1.3 g cm^{-3} , and an epoxy resin mass percentage of 33 – 35%.

Composite Type	Density [g cm^{-3}]
Glass + epoxy	1.70
Aramid + epoxy	1.37
Carbon + epoxy	1.50

3.1.2 Thickness

For a given environment, radiation damage to composites is widely dependent on composition, manufacturing processes, size/thickness, and if any shielding is present. In this analysis, a range of thicknesses are considered based on the following components:

Table 3: List of representative materials made of composites with a range of thicknesses.

Composite Component	Min Thickness [mm]	Max Thickness [mm]
COPV	1.5	19
Landing struts	1.5	19
Sandwich panels/Face sheets	0.8	6.5
Solid laminate	1	19

3.1.3 Stoichiometry

At the time of writing, no representative material stoichiometric information has been given. Therefore, placeholder values are assumed that are used in this analysis.

In the SRIM software package, there is a list of common compounds, one of which is epoxy. For the three fiber types shown in Table 1, we assume the most basic elemental composition. Stoichiometry for the epoxy and the fiber materials are shown in Table 4.

Table 4: The epoxy resin composition is taken from the common compound table in SRIM. Glass fiber is assumed to be strictly made of silicon-based glass. The aramid fiber is assumed to be a Nomex or Kevlar type aramid. Carbon fiber is assumed to be made of only carbon.

Material	Stoichiometry [element-count]
Epoxy resin	H-19, C-18, O-3
Glass fiber	O-2, Si-1
Aramid fiber	H-2, C-14, N-2, O-2
Carbon fiber	C-1

If a homogenized substance composed of the epoxy and fiber material is assumed, a net stoichiometry list (see Table 5) can be built using the assumption that the epoxy is 33 – 35% of the total weight of the composite. Densities from Table 2 should be used for each of the composites.

3.1.4 Proton Stopping Distance

The effective stopping (shielding) capabilities for a given proton energy of a composite material can be estimated using SRIM. Using the ion stopping and range table calculator in SRIM, we plug in the stoichiometry (Table 5) and density (Table 2) for each

Table 5: Stoichiometry for each composite is given where the epoxy weight is 33 – 35% of the total mass.

Material	Stoichiometry [element-count]
Glass composite	H-19, C-18, O-21, Si-9
Aramid composite	H-23, C-46, N-4, O-7
Carbon composite	H-19, C-62, O-3

composite material. The generated output provides the projected range, longitudinal and lateral straggling as a function of ion energy. To estimate the maximum stopping distance of the proton, we take the projected range and add half of the lateral straggling, since we are assuming a normally incident beam. The proton energy range used to generate the stopping distance tables is 10 keV to 1 GeV, completely encompassing the typical energy range of solar energetic particles (SEPs). See Listings 1-4 in Appendix A for the stopping distance tables.

The maximum stopping distance as a function of ion energy can be fit by a double power law given by

$$E[\text{keV}] = \frac{a}{\left(\frac{x[\text{mm}]}{c}\right)^{-b} + x[\text{mm}]^{-d}}, \quad (1)$$

where the ion energy E is in keV and the maximum stopping distance x is in mm. The constant a can be thought of as the largest ion energy (in keV) that roughly 1 mm of material can stop completely. The constant c defines the length scale (in mm) at which low energy ions are affected. The index b is the power law relation that dominates for thin materials (i.e., on the order of c and smaller) and the index d is the power law relation that dominates for thick materials (i.e., much greater than c).

For a given material, keeping the stoichiometry the same, changing the density only changes the constants a and c . If the initial density is ρ_0 and the new density is ρ_1 , where $\alpha = \rho_1/\rho_0$, the ion energy is then given by

$$E[\text{keV}] = \frac{a\alpha^d}{\left(\frac{x[\text{mm}]}{c\alpha^{\frac{d}{b}-1}}\right)^{-b} + x[\text{mm}]^{-d}}, \quad (2)$$

where new constants a' and c' can be defined as

$$a' = a\alpha^d, \quad (3)$$

$$c' = c\alpha^{\frac{d}{b}-1}, \quad (4)$$

Fitting Listings 1-4 with Equation 1, the parameters a , b , c , and d are given in Table 6.

In order to compare the stopping distance of equal density materials, we rescale the composites to that of aluminum at 2.702 g cm⁻³ using Equation 2. The rescaled parameters are given in Table 7.

Examining Table 7, for the list of composites in this analysis, the large thickness range (i.e., much greater than c) is independent of material type and density. The

Table 6: Parameters to the double power law fit of the proton energy as a function of maximum stopping distance of composites compared to aluminum of density 2.702 g cm^{-3} .

Material	a [keV]	b	c [mm]	d
Glass composite	1.068E4	1.668	1.31E-2	0.5759
Aramid composite	9.89E3	1.706	1.23E-2	0.5721
Carbon composite	1.039E4	1.699	1.16E-2	0.5717
Aluminum	1.270E4	1.529	1.49E-2	0.5794

Table 7: Parameters to the double power law fit of the proton energy as a function of maximum stopping distance of composites rescaled to the density of aluminum compared to aluminum of density 2.702 g cm^{-3} .

Material	a [keV]	b	c [mm]	d
Glass composite	1.395E4	1.668	9.67E-3	0.5759
Aramid composite	1.46E4	1.706	7.83E-3	0.5721
Carbon composite	1.455E4	1.699	7.85E-3	0.5717
Aluminum	1.270E4	1.529	1.49E-2	0.5794

small-scale range c for the composites is on the order of $8 - 10 \text{ } \mu\text{m}$ and smaller, whereas the small-scale range for aluminum is roughly $15 \text{ } \mu\text{m}$ and smaller. The index parameter for small scales b seems to be strongly material dependent, which in turn implies the maximum stopped energy to be strongly dependent on materials for thin materials. Observing the a parameter, the composites tend to have greater stopping capability of protons compared to aluminum. This may have to do with the large number of hydrogen atoms present in the composites themselves, since the collision cross section between hydrogen atoms and protons is higher than large-Z materials.

For larger thicknesses $x \gg c$ (i.e., thicknesses greater than roughly 0.5 mils), we can approximate Equation 1 as

$$E[\text{keV}] \sim ax[\text{mm}]^d. \quad (5)$$

In order to use the material density to scale the equivalent thickness, a correction factor is needed if data on aluminum is used to estimate stopping power of composites. These scale factors κ can be computed as

$$\kappa_{\text{composite}} = \left(\frac{a_{\text{composite}}}{a_{\text{Al}}} \right)^{1/d}. \quad (6)$$

Therefore, when rescaling the composites to aluminum equivalent thicknesses, the true scaling is given by (taking $d \approx 0.575$)

$$x_{\text{Al equiv}} = \kappa_{\text{composite}} \frac{\rho_{\text{composite}}}{\rho_{\text{Al}}} x_{\text{composite}}, \quad (7)$$

where $x_{\text{composite}}$ is the composite thickness and $x_{\text{Al equiv}}$ is the corrected aluminum

equivalent thickness. The correction factors for the composites studied in this analysis are given in Table 8.

Table 8: Length scale correction factors to aluminum equivalent modeling of composites.

Material	$k_{\text{composite}}$
Glass composite	1.177
Aramid composite	1.272
Carbon composite	1.266

With the correction factors greater than one, an interpretation can be that for a composite and aluminum coupon of similar areal density, more energy will be absorbed (i.e., more ionizing dose) by the composite per areal density since higher energy protons can be stopped in the composite compared to the aluminum equivalent (i.e., the a parameters for the composites are greater than that for aluminum in Table 7). For example, in order to have the same limiting energy as glass composite, the aluminum equivalent thickness must be increased by 17.7%, according to Table 8.

3.2 Multi-layered Insulation (MLI)

Multi-layered insulation, or MLI, is used on spacecraft to aid in thermal management and certain types of radiation and contamination protection. In Chapter 5 of the Spacecraft Thermal Control Handbook [Donabedian and Gilmore, 2003], details about MLI applications are described. Table 9 lists separate components of MLI taken from Donabedian and Gilmore [2003].

Table 9: Various components and layers of MLI and their average densities and thicknesses.

Name	Layer	Density [g cm^{-3}]	Thickness [mils]
Beta cloth	outer	1.185	8
Aluminized beta cloth	outer	1.355	8
Kapton	outer	1.50	0.5 - 5
Teflon	outer	2.17	0.5 - 5
Aluminized Kapton	interior	1.50	0.3 - 5
Goldized Kapton	interior	1.50	0.3 - 5
Aluminized mylar	interior	1.38	0.25 - 5
Dacron netting	separator	0.04	6.5
Nomex netting	separator	0.04	6.5
Aluminized polyimide	inner	3.96	0.5 - 3
Double-goldized	inner	5	0.45
Glass-reinforced	inner	5	0.45

Two versions of MLI are constructed to simulate a finite amount of shielding in front of the composite material. In this analysis, aluminized beta cloth - mylar - Nomex is

used which amounts to a density of 1.328 g cm^{-3} and a thickness of 22.5 mils. A thin version of this MLI gives a density of 1.435 g cm^{-3} and a thickness of 5.75 mils. The aluminum equivalent is given in Table 10.

Table 10: Aluminum equivalent thicknesses for placeholder MLIs, assuming an aluminum density of 2.702 g cm^{-3} .

Material	Density g cm^{-3}	Thickness [mils]	Al-equiv thickness [mils,mm]
Thick MLI	1.328	22.5	11.1, 2.81E-1
Thin MLI	1.435	5.75	3.05, 7.76E-2

4 Radiation Environment

The leading radiation environment in interplanetary space is often due to solar energetic particles (SEPs) from solar particle events (SPEs). The geomagnetically unshielded SPE environment is used from SLS-SPEC-159 Design Specification for Natural Environments (DSNE), found in Table 3.3.1.10.2-1. The environment is generated using SPENVIS, employing the ESP/PSYCHIC model. The worst case SPE option is used for an override of 1 year with only protons. Output generated from SPENVIS can be found in Listing 5 of Appendix B.

The SPE integral flux can be fit using a Weibull function, given by

$$\Phi(> E[\text{MeV}])[\# \text{cm}^{-2}] = 9.278 \times 10^{11} \exp(-1.821 E^{0.298}), \quad (8)$$

or by a double power law,

$$\Phi(> E[\text{MeV}])[\# \text{cm}^{-2}] = \frac{1.248 \times 10^{11}}{\left(\frac{E}{13.5}\right)^{2.587} + E^{0.6244}}. \quad (9)$$

Shorter time periods than 1 year should not be scaled linearly. Most of the SPE flux is dominated by a few large SPEs, each occurring over at most 1 week.

5 Dose Estimation

Given the limited information available, the total ionizing dose (TID) is estimated in composites. The zeroth order estimation uses the DSNE SPE TID tables, which must assume a finite shielding thickness, shown in Section 5.1. A first order approximation is done by computing dose-depth curves in composites for various energies and incident angles, shown in Section 5.2.

Interestingly, using the DSNE tables, the conservative dose estimate assuming at least 3 mils of aluminum shielding is $7.59E4$ rads (which 3 mils of shielding is outside the validity range of SHIELDOSE2, and the dose is in silicon), whereas the dose estimate with no shielding in a carbon composite is $6.94E4$ rads. Half of the TID is deposited in the first ~ 15 mils of composite material.

5.1 DSNE with Shielding

5.2 SRIM without Shielding

6 SRIM Comparison with DSNE (SHIELDOSE2)

A Ion Stopping and Range Tables

Listing 1: Ion stopping and range tables of protons in glass composite.

1	=====
2	SRIM version —> SRIM-2013.00
3	Calc. date —> July 29, 2020
4	=====
5	
6	Disk File Name = SRIM Outputs\Hydrogen in Glass Composite.txt
7	
8	Ion = Hydrogen [1] , Mass = 1.008 amu
9	
10	Target Density = 1.7000E+00 g/cm3 = 8.3236E+22 atoms/cm3
11	===== Target Composition =====
12	Atom Atom Atomic Mass
13	Name Numb Percent Percent
14	-----
15	H 1 028.36 002.32
16	C 6 026.87 026.24
17	O 8 031.34 040.77
18	Si 14 013.43 030.67
19	=====
20	Bragg Correction = -3.61%
21	Stopping Units = MeV / (mg/cm2)
22	See bottom of Table for other Stopping units
23	
24	Ion dE/dx dE/dx Projected Longitudinal Lateral
25	Energy Elec. Nuclear Range Straggling Straggling
26	-----
27	10.00 keV 3.417E-01 5.866E-03 1809 A 578 A 572 A
28	11.00 keV 3.573E-01 5.508E-03 1952 A 597 A 598 A
29	12.00 keV 3.721E-01 5.197E-03 2092 A 614 A 622 A
30	13.00 keV 3.863E-01 4.924E-03 2227 A 629 A 645 A
31	14.00 keV 3.998E-01 4.681E-03 2359 A 643 A 666 A
32	15.00 keV 4.126E-01 4.464E-03 2488 A 656 A 685 A
33	16.00 keV 4.249E-01 4.269E-03 2614 A 668 A 704 A
34	17.00 keV 4.365E-01 4.092E-03 2737 A 679 A 721 A
35	18.00 keV 4.476E-01 3.931E-03 2858 A 690 A 738 A
36	20.00 keV 4.683E-01 3.648E-03 3093 A 709 A 768 A
37	22.50 keV 4.914E-01 3.352E-03 3375 A 731 A 803 A
38	25.00 keV 5.119E-01 3.106E-03 3648 A 749 A 835 A
39	27.50 keV 5.301E-01 2.897E-03 3913 A 766 A 864 A
40	30.00 keV 5.462E-01 2.717E-03 4170 A 781 A 890 A
41	32.50 keV 5.605E-01 2.560E-03 4422 A 795 A 915 A
42	35.00 keV 5.732E-01 2.422E-03 4668 A 808 A 938 A
43	37.50 keV 5.844E-01 2.300E-03 4911 A 820 A 960 A
44	40.00 keV 5.944E-01 2.190E-03 5150 A 831 A 981 A
45	45.00 keV 6.110E-01 2.003E-03 5618 A 852 A 1020 A

46	50.00 keV	6.238E-01	1.848E-03	6078 A	871 A	1056 A
47	55.00 keV	6.334E-01	1.717E-03	6531 A	888 A	1089 A
48	60.00 keV	6.403E-01	1.605E-03	6980 A	904 A	1121 A
49	65.00 keV	6.449E-01	1.508E-03	7425 A	920 A	1150 A
50	70.00 keV	6.475E-01	1.423E-03	7869 A	934 A	1179 A
51	80.00 keV	6.480E-01	1.281E-03	8757 A	965 A	1233 A
52	90.00 keV	6.436E-01	1.166E-03	9650 A	994 A	1285 A
53	100.00 keV	6.357E-01	1.072E-03	1.06 um	1021 A	1334 A
54	110.00 keV	6.254E-01	9.934E-04	1.15 um	1048 A	1383 A
55	120.00 keV	6.136E-01	9.262E-04	1.24 um	1074 A	1430 A
56	130.00 keV	6.008E-01	8.682E-04	1.34 um	1101 A	1477 A
57	140.00 keV	5.875E-01	8.175E-04	1.43 um	1127 A	1525 A
58	150.00 keV	5.741E-01	7.729E-04	1.53 um	1153 A	1572 A
59	160.00 keV	5.607E-01	7.332E-04	1.64 um	1179 A	1620 A
60	170.00 keV	5.476E-01	6.978E-04	1.74 um	1205 A	1668 A
61	180.00 keV	5.348E-01	6.658E-04	1.85 um	1232 A	1716 A
62	200.00 keV	5.104E-01	6.105E-04	2.07 um	1306 A	1815 A
63	225.00 keV	4.826E-01	5.539E-04	2.37 um	1413 A	1944 A
64	250.00 keV	4.576E-01	5.076E-04	2.68 um	1522 A	2078 A
65	275.00 keV	4.353E-01	4.689E-04	3.00 um	1634 A	2218 A
66	300.00 keV	4.153E-01	4.360E-04	3.35 um	1749 A	2364 A
67	325.00 keV	3.973E-01	4.078E-04	3.71 um	1867 A	2516 A
68	350.00 keV	3.811E-01	3.832E-04	4.08 um	1988 A	2675 A
69	375.00 keV	3.665E-01	3.616E-04	4.47 um	2112 A	2839 A
70	400.00 keV	3.532E-01	3.424E-04	4.88 um	2238 A	3010 A
71	450.00 keV	3.298E-01	3.100E-04	5.73 um	2638 A	3369 A
72	500.00 keV	3.100E-01	2.835E-04	6.65 um	3033 A	3750 A
73	550.00 keV	2.930E-01	2.614E-04	7.62 um	3426 A	4154 A
74	600.00 keV	2.782E-01	2.428E-04	8.64 um	3820 A	4577 A
75	650.00 keV	2.653E-01	2.267E-04	9.72 um	4215 A	5021 A
76	700.00 keV	2.538E-01	2.128E-04	10.85 um	4613 A	5483 A
77	800.00 keV	2.345E-01	1.898E-04	13.25 um	5919 A	6461 A
78	900.00 keV	2.188E-01	1.715E-04	15.83 um	7151 A	7503 A
79	1.00 MeV	2.060E-01	1.566E-04	18.59 um	8345 A	8604 A
80	1.10 MeV	1.971E-01	1.442E-04	21.50 um	9507 A	9752 A
81	1.20 MeV	1.883E-01	1.337E-04	24.54 um	1.06 um	1.09 um
82	1.30 MeV	1.795E-01	1.248E-04	27.73 um	1.18 um	1.22 um
83	1.40 MeV	1.716E-01	1.170E-04	31.06 um	1.29 um	1.34 um
84	1.50 MeV	1.644E-01	1.102E-04	34.55 um	1.41 um	1.48 um
85	1.60 MeV	1.578E-01	1.041E-04	38.19 um	1.52 um	1.61 um
86	1.70 MeV	1.517E-01	9.876E-05	41.98 um	1.64 um	1.75 um
87	1.80 MeV	1.460E-01	9.395E-05	45.92 um	1.76 um	1.90 um
88	2.00 MeV	1.357E-01	8.568E-05	54.25 um	2.16 um	2.21 um
89	2.25 MeV	1.249E-01	7.728E-05	65.51 um	2.75 um	2.61 um
90	2.50 MeV	1.157E-01	7.045E-05	77.70 um	3.30 um	3.05 um
91	2.75 MeV	1.079E-01	6.478E-05	90.83 um	3.85 um	3.52 um
92	3.00 MeV	1.011E-01	6.000E-05	104.86 um	4.40 um	4.01 um
93	3.25 MeV	9.527E-02	5.591E-05	119.80 um	4.96 um	4.54 um
94	3.50 MeV	9.012E-02	5.236E-05	135.62 um	5.51 um	5.09 um
95	3.75 MeV	8.555E-02	4.926E-05	152.32 um	6.08 um	5.67 um
96	4.00 MeV	8.146E-02	4.653E-05	169.89 um	6.65 um	6.27 um
97	4.50 MeV	7.447E-02	4.191E-05	207.55 um	8.68 um	7.57 um
98	5.00 MeV	6.869E-02	3.817E-05	248.56 um	10.60 um	8.96 um
99	5.50 MeV	6.382E-02	3.507E-05	292.86 um	12.49 um	10.47 um
100	6.00 MeV	5.966E-02	3.245E-05	340.40 um	14.37 um	12.07 um
101	6.50 MeV	5.605E-02	3.022E-05	391.13 um	16.26 um	13.77 um
102	7.00 MeV	5.290E-02	2.829E-05	445.00 um	18.17 um	15.57 um

103	8.00 MeV	4.764E-02	2.510E-05	561.90 um	24.95 um	19.45 um
104	9.00 MeV	4.341E-02	2.259E-05	690.95 um	31.32 um	23.71 um
105	10.00 MeV	3.993E-02	2.056E-05	831.91 um	37.57 um	28.33 um
106	11.00 MeV	3.702E-02	1.887E-05	984.55 um	43.81 um	33.31 um
107	12.00 MeV	3.454E-02	1.745E-05	1.15 mm	50.10 um	38.64 um
108	13.00 MeV	3.240E-02	1.624E-05	1.32 mm	56.47 um	44.31 um
109	14.00 MeV	3.053E-02	1.519E-05	1.51 mm	62.94 um	50.32 um
110	15.00 MeV	2.889E-02	1.428E-05	1.71 mm	69.52 um	56.66 um
111	16.00 MeV	2.743E-02	1.347E-05	1.92 mm	76.21 um	63.33 um
112	17.00 MeV	2.612E-02	1.275E-05	2.14 mm	83.02 um	70.32 um
113	18.00 MeV	2.495E-02	1.211E-05	2.37 mm	89.96 um	77.63 um
114	20.00 MeV	2.292E-02	1.101E-05	2.86 mm	115.11 um	93.19 um
115	22.50 MeV	2.085E-02	9.900E-06	3.53 mm	151.04 um	114.37 um
116	25.00 MeV	1.915E-02	8.999E-06	4.26 mm	185.25 um	137.40 um
117	27.50 MeV	1.774E-02	8.255E-06	5.06 mm	218.88 um	162.25 um
118	30.00 MeV	1.654E-02	7.628E-06	5.92 mm	252.44 um	188.88 um
119	32.50 MeV	1.551E-02	7.094E-06	6.83 mm	286.21 um	217.22 um
120	35.00 MeV	1.462E-02	6.632E-06	7.81 mm	320.31 um	247.26 um
121	37.50 MeV	1.383E-02	6.228E-06	8.84 mm	354.84 um	278.96 um
122	40.00 MeV	1.314E-02	5.873E-06	9.93 mm	389.84 um	312.28 um
123	45.00 MeV	1.197E-02	5.276E-06	12.27 mm	517.07 um	383.67 um
124	50.00 MeV	1.101E-02	4.793E-06	14.83 mm	636.98 um	461.20 um
125	55.00 MeV	1.021E-02	4.394E-06	17.59 mm	754.06 um	544.65 um
126	60.00 MeV	9.541E-03	4.058E-06	20.57 mm	870.29 um	633.81 um
127	65.00 MeV	8.965E-03	3.772E-06	23.74 mm	986.65 um	728.50 um
128	70.00 MeV	8.466E-03	3.525E-06	27.11 mm	1.10 mm	828.55 um
129	80.00 MeV	7.644E-03	3.120E-06	34.41 mm	1.53 mm	1.04 mm
130	90.00 MeV	6.993E-03	2.801E-06	42.44 mm	1.92 mm	1.28 mm
131	100.00 MeV	6.465E-03	2.543E-06	51.18 mm	2.30 mm	1.53 mm
132	110.00 MeV	6.028E-03	2.330E-06	60.58 mm	2.67 mm	1.80 mm
133	120.00 MeV	5.659E-03	2.151E-06	70.64 mm	3.05 mm	2.09 mm
134	130.00 MeV	5.344E-03	1.999E-06	81.31 mm	3.42 mm	2.39 mm
135	140.00 MeV	5.073E-03	1.867E-06	92.59 mm	3.80 mm	2.71 mm
136	150.00 MeV	4.835E-03	1.752E-06	104.45 mm	4.17 mm	3.05 mm
137	160.00 MeV	4.626E-03	1.651E-06	116.87 mm	4.55 mm	3.39 mm
138	170.00 MeV	4.441E-03	1.562E-06	129.82 mm	4.94 mm	3.75 mm
139	180.00 MeV	4.275E-03	1.482E-06	143.30 mm	5.32 mm	4.12 mm
140	200.00 MeV	3.992E-03	1.345E-06	171.74 mm	6.72 mm	4.90 mm
141	225.00 MeV	3.706E-03	1.206E-06	209.92 mm	8.68 mm	5.92 mm
142	250.00 MeV	3.476E-03	1.095E-06	250.83 mm	10.50 mm	7.01 mm
143	275.00 MeV	3.287E-03	1.002E-06	294.27 mm	12.23 mm	8.15 mm
144	300.00 MeV	3.130E-03	9.250E-07	340.05 mm	13.91 mm	9.33 mm
145	325.00 MeV	2.996E-03	8.591E-07	388.01 mm	15.55 mm	10.55 mm
146	350.00 MeV	2.881E-03	8.022E-07	437.99 mm	17.16 mm	11.81 mm
147	375.00 MeV	2.782E-03	7.526E-07	489.86 mm	18.74 mm	13.10 mm
148	400.00 MeV	2.696E-03	7.090E-07	543.48 mm	20.30 mm	14.42 mm
149	450.00 MeV	2.552E-03	6.357E-07	655.48 mm	25.90 mm	17.13 mm
150	500.00 MeV	2.438E-03	5.766E-07	773.25 mm	30.94 mm	19.91 mm
151	550.00 MeV	2.346E-03	5.278E-07	896.07 mm	35.63 mm	22.75 mm
152	600.00 MeV	2.271E-03	4.869E-07	1.02 m	40.07 mm	25.63 mm
153	650.00 MeV	2.208E-03	4.521E-07	1.15 m	44.31 mm	28.54 mm
154	700.00 MeV	2.155E-03	4.220E-07	1.29 m	48.39 mm	31.47 mm
155	800.00 MeV	2.071E-03	3.728E-07	1.57 m	62.63 mm	37.35 mm
156	900.00 MeV	2.009E-03	3.341E-07	1.86 m	74.98 mm	43.23 mm
157	1.00 GeV	1.962E-03	3.029E-07	2.15 m	86.12 mm	49.06 mm
158						
159	Multiply Stopping by for Stopping Units					

```

160
161 1.6999E+01          eV / Angstrom
162 1.6999E+02          keV / micron
163 1.6999E+02          MeV / mm
164 1.0000E+00          keV / (ug/cm2)
165 1.0000E+00          MeV / (mg/cm2)
166 1.0000E+03          keV / (mg/cm2)
167 2.0423E+01          eV / (1E15 atoms/cm2)
168 1.0643E+01          L.S.S. reduced units
169 =====
170 (C) 1984,1989,1992,1998,2008 by J.P. Biersack and J.F. Ziegler

```

Listing 2: Ion stopping and range tables of protons in aramid composite.

```

1  =====
2  SRIM version  —> SRIM-2013.00
3  Calc. date   —> July 29, 2020
4  =====
5
6  Disk File Name = SRIM Outputs\Hydrogen in Aramid Composite.txt
7
8  Ion = Hydrogen [1] , Mass = 1.008 amu
9
10 Target Density = 1.3700E+00 g/cm3 = 8.8746E+22 atoms/cm3
11 ===== Target Composition =====
12   Atom   Atom   Atomic   Mass
13   Name   Numb   Percent  Percent
14   -----
15   H       1     028.75    003.12
16   C       6     057.50    074.29
17   O       8     008.75    015.06
18   N       7     005.00    007.53
19   =====
20 Bragg Correction = -3.61%
21 Stopping Units = MeV / (mg/cm2)
22 See bottom of Table for other Stopping units
23
24   Ion      dE/dx   dE/dx   Projected   Longitudinal   Lateral
25   Energy   Elec.    Nuclear Range     Straggling     Straggling
26   -----
27 10.00 keV  4.205E-01  6.757E-03  1987 A      524 A          545 A
28 11.00 keV  4.388E-01  6.327E-03  2139 A      538 A          567 A
29 12.00 keV  4.560E-01  5.955E-03  2286 A      552 A          588 A
30 13.00 keV  4.721E-01  5.628E-03  2429 A      564 A          607 A
31 14.00 keV  4.874E-01  5.340E-03  2568 A      575 A          625 A
32 15.00 keV  5.017E-01  5.083E-03  2704 A      585 A          641 A
33 16.00 keV  5.154E-01  4.852E-03  2837 A      594 A          657 A
34 17.00 keV  5.283E-01  4.644E-03  2967 A      602 A          672 A
35 18.00 keV  5.405E-01  4.454E-03  3094 A      611 A          686 A
36 20.00 keV  5.631E-01  4.123E-03  3343 A      626 A          712 A
37 22.50 keV  5.885E-01  3.779E-03  3642 A      642 A          742 A
38 25.00 keV  6.109E-01  3.492E-03  3932 A      657 A          768 A
39 27.50 keV  6.309E-01  3.251E-03  4213 A      670 A          793 A
40 30.00 keV  6.487E-01  3.043E-03  4487 A      682 A          815 A
41 32.50 keV  6.646E-01  2.863E-03  4754 A      693 A          836 A
42 35.00 keV  6.789E-01  2.705E-03  5017 A      703 A          856 A
43 37.50 keV  6.918E-01  2.565E-03  5274 A      712 A          874 A

```

44	40.00 keV	7.033E-01	2.440E-03	5528 A	721 A	892 A
45	45.00 keV	7.229E-01	2.226E-03	6026 A	738 A	924 A
46	50.00 keV	7.384E-01	2.049E-03	6514 A	754 A	954 A
47	55.00 keV	7.504E-01	1.901E-03	6994 A	769 A	982 A
48	60.00 keV	7.594E-01	1.775E-03	7468 A	782 A	1008 A
49	65.00 keV	7.656E-01	1.665E-03	7938 A	795 A	1033 A
50	70.00 keV	7.694E-01	1.569E-03	8405 A	806 A	1056 A
51	80.00 keV	7.710E-01	1.410E-03	9339 A	834 A	1101 A
52	90.00 keV	7.662E-01	1.282E-03	1.03 um	860 A	1143 A
53	100.00 keV	7.567E-01	1.177E-03	1.12 um	884 A	1183 A
54	110.00 keV	7.440E-01	1.089E-03	1.22 um	909 A	1223 A
55	120.00 keV	7.291E-01	1.014E-03	1.32 um	932 A	1261 A
56	130.00 keV	7.130E-01	9.496E-04	1.42 um	956 A	1300 A
57	140.00 keV	6.962E-01	8.934E-04	1.52 um	980 A	1338 A
58	150.00 keV	6.792E-01	8.440E-04	1.62 um	1004 A	1377 A
59	160.00 keV	6.624E-01	8.001E-04	1.73 um	1029 A	1415 A
60	170.00 keV	6.458E-01	7.608E-04	1.84 um	1053 A	1454 A
61	180.00 keV	6.298E-01	7.255E-04	1.96 um	1078 A	1494 A
62	200.00 keV	5.993E-01	6.645E-04	2.19 um	1154 A	1575 A
63	225.00 keV	5.647E-01	6.022E-04	2.51 um	1267 A	1681 A
64	250.00 keV	5.339E-01	5.512E-04	2.84 um	1382 A	1792 A
65	275.00 keV	5.064E-01	5.087E-04	3.19 um	1499 A	1908 A
66	300.00 keV	4.820E-01	4.727E-04	3.55 um	1620 A	2029 A
67	325.00 keV	4.601E-01	4.417E-04	3.94 um	1743 A	2157 A
68	350.00 keV	4.404E-01	4.148E-04	4.34 um	1868 A	2290 A
69	375.00 keV	4.226E-01	3.912E-04	4.76 um	1996 A	2429 A
70	400.00 keV	4.065E-01	3.702E-04	5.20 um	2126 A	2573 A
71	450.00 keV	3.784E-01	3.348E-04	6.13 um	2566 A	2878 A
72	500.00 keV	3.546E-01	3.060E-04	7.12 um	2993 A	3205 A
73	550.00 keV	3.343E-01	2.819E-04	8.18 um	3415 A	3551 A
74	600.00 keV	3.166E-01	2.616E-04	9.30 um	3835 A	3918 A
75	650.00 keV	3.012E-01	2.442E-04	10.47 um	4255 A	4302 A
76	700.00 keV	2.875E-01	2.290E-04	11.71 um	4677 A	4704 A
77	800.00 keV	2.646E-01	2.041E-04	14.35 um	6121 A	5559 A
78	900.00 keV	2.460E-01	1.842E-04	17.20 um	7470 A	6475 A
79	1.00 MeV	2.308E-01	1.681E-04	20.25 um	8773 A	7449 A
80	1.10 MeV	2.200E-01	1.547E-04	23.49 um	1.00 um	8469 A
81	1.20 MeV	2.094E-01	1.434E-04	26.88 um	1.13 um	9530 A
82	1.30 MeV	1.990E-01	1.337E-04	30.44 um	1.25 um	1.06 um
83	1.40 MeV	1.897E-01	1.253E-04	34.19 um	1.38 um	1.18 um
84	1.50 MeV	1.813E-01	1.180E-04	38.12 um	1.50 um	1.30 um
85	1.60 MeV	1.736E-01	1.115E-04	42.22 um	1.63 um	1.42 um
86	1.70 MeV	1.666E-01	1.057E-04	46.50 um	1.76 um	1.55 um
87	1.80 MeV	1.601E-01	1.005E-04	50.96 um	1.89 um	1.68 um
88	2.00 MeV	1.486E-01	9.161E-05	60.40 um	2.35 um	1.96 um
89	2.25 MeV	1.363E-01	8.257E-05	73.20 um	3.01 um	2.34 um
90	2.50 MeV	1.261E-01	7.523E-05	87.09 um	3.64 um	2.74 um
91	2.75 MeV	1.174E-01	6.914E-05	102.05 um	4.26 um	3.17 um
92	3.00 MeV	1.099E-01	6.401E-05	118.08 um	4.88 um	3.63 um
93	3.25 MeV	1.034E-01	5.962E-05	135.17 um	5.50 um	4.11 um
94	3.50 MeV	9.772E-02	5.582E-05	153.28 um	6.13 um	4.62 um
95	3.75 MeV	9.267E-02	5.250E-05	172.42 um	6.76 um	5.16 um
96	4.00 MeV	8.816E-02	4.957E-05	192.57 um	7.40 um	5.73 um
97	4.50 MeV	8.046E-02	4.463E-05	235.82 um	9.72 um	6.93 um
98	5.00 MeV	7.410E-02	4.063E-05	283.00 um	11.92 um	8.24 um
99	5.50 MeV	6.876E-02	3.731E-05	334.04 um	14.07 um	9.64 um
100	6.00 MeV	6.420E-02	3.451E-05	388.88 um	16.21 um	11.14 um

101	6.50 MeV	6.025E-02	3.213E-05	447.46 um	18.36 um	12.74 um
102	7.00 MeV	5.681E-02	3.006E-05	509.73 um	20.53 um	14.42 um
103	8.00 MeV	5.106E-02	2.667E-05	645.05 um	28.37 um	18.08 um
104	9.00 MeV	4.646E-02	2.399E-05	794.67 um	35.72 um	22.09 um
105	10.00 MeV	4.269E-02	2.182E-05	958.31 um	42.91 um	26.46 um
106	11.00 MeV	3.953E-02	2.002E-05	1.14 mm	50.09 um	31.17 um
107	12.00 MeV	3.684E-02	1.851E-05	1.33 mm	57.33 um	36.22 um
108	13.00 MeV	3.453E-02	1.722E-05	1.53 mm	64.65 um	41.60 um
109	14.00 MeV	3.251E-02	1.610E-05	1.75 mm	72.08 um	47.31 um
110	15.00 MeV	3.074E-02	1.513E-05	1.98 mm	79.64 um	53.34 um
111	16.00 MeV	2.917E-02	1.427E-05	2.22 mm	87.33 um	59.69 um
112	17.00 MeV	2.776E-02	1.351E-05	2.48 mm	95.15 um	66.35 um
113	18.00 MeV	2.650E-02	1.283E-05	2.75 mm	103.10 um	73.31 um
114	20.00 MeV	2.432E-02	1.166E-05	3.32 mm	132.44 um	88.16 um
115	22.50 MeV	2.210E-02	1.048E-05	4.11 mm	174.40 um	108.40 um
116	25.00 MeV	2.028E-02	9.520E-06	4.97 mm	214.28 um	130.44 um
117	27.50 MeV	1.877E-02	8.730E-06	5.90 mm	253.43 um	154.25 um
118	30.00 MeV	1.749E-02	8.065E-06	6.91 mm	292.48 um	179.78 um
119	32.50 MeV	1.639E-02	7.498E-06	7.98 mm	331.72 um	206.99 um
120	35.00 MeV	1.544E-02	7.008E-06	9.13 mm	371.34 um	235.84 um
121	37.50 MeV	1.460E-02	6.581E-06	10.34 mm	411.43 um	266.31 um
122	40.00 MeV	1.386E-02	6.204E-06	11.62 mm	452.05 um	298.36 um
123	45.00 MeV	1.261E-02	5.572E-06	14.38 mm	601.58 um	367.09 um
124	50.00 MeV	1.160E-02	5.060E-06	17.40 mm	742.19 um	441.81 um
125	55.00 MeV	1.075E-02	4.637E-06	20.66 mm	879.34 um	522.30 um
126	60.00 MeV	1.004E-02	4.282E-06	24.17 mm	1.02 mm	608.37 um
127	65.00 MeV	9.428E-03	3.980E-06	27.92 mm	1.15 mm	699.84 um
128	70.00 MeV	8.899E-03	3.718E-06	31.89 mm	1.29 mm	796.54 um
129	80.00 MeV	8.028E-03	3.289E-06	40.52 mm	1.79 mm	1.01 mm
130	90.00 MeV	7.340E-03	2.952E-06	50.02 mm	2.25 mm	1.23 mm
131	100.00 MeV	6.782E-03	2.680E-06	60.35 mm	2.69 mm	1.48 mm
132	110.00 MeV	6.320E-03	2.455E-06	71.49 mm	3.14 mm	1.74 mm
133	120.00 MeV	5.931E-03	2.266E-06	83.40 mm	3.58 mm	2.02 mm
134	130.00 MeV	5.599E-03	2.105E-06	96.05 mm	4.02 mm	2.31 mm
135	140.00 MeV	5.312E-03	1.966E-06	109.42 mm	4.46 mm	2.62 mm
136	150.00 MeV	5.062E-03	1.845E-06	123.48 mm	4.90 mm	2.95 mm
137	160.00 MeV	4.841E-03	1.738E-06	138.21 mm	5.35 mm	3.28 mm
138	170.00 MeV	4.646E-03	1.644E-06	153.58 mm	5.79 mm	3.63 mm
139	180.00 MeV	4.471E-03	1.559E-06	169.58 mm	6.24 mm	3.99 mm
140	200.00 MeV	4.173E-03	1.415E-06	203.34 mm	7.90 mm	4.75 mm
141	225.00 MeV	3.872E-03	1.269E-06	248.70 mm	10.23 mm	5.75 mm
142	250.00 MeV	3.630E-03	1.151E-06	297.33 mm	12.38 mm	6.81 mm
143	275.00 MeV	3.431E-03	1.054E-06	349.00 mm	14.43 mm	7.92 mm
144	300.00 MeV	3.264E-03	9.724E-07	403.48 mm	16.42 mm	9.07 mm
145	325.00 MeV	3.124E-03	9.029E-07	460.57 mm	18.36 mm	10.27 mm
146	350.00 MeV	3.003E-03	8.430E-07	520.10 mm	20.26 mm	11.50 mm
147	375.00 MeV	2.898E-03	7.907E-07	581.89 mm	22.13 mm	12.76 mm
148	400.00 MeV	2.807E-03	7.448E-07	645.81 mm	23.98 mm	14.05 mm
149	450.00 MeV	2.656E-03	6.677E-07	779.38 mm	30.65 mm	16.70 mm
150	500.00 MeV	2.535E-03	6.055E-07	919.93 mm	36.65 mm	19.43 mm
151	550.00 MeV	2.438E-03	5.542E-07	1.07 m	42.24 mm	22.21 mm
152	600.00 MeV	2.358E-03	5.111E-07	1.22 m	47.53 mm	25.04 mm
153	650.00 MeV	2.291E-03	4.745E-07	1.38 m	52.58 mm	27.90 mm
154	700.00 MeV	2.235E-03	4.428E-07	1.54 m	57.44 mm	30.78 mm
155	800.00 MeV	2.146E-03	3.911E-07	1.87 m	74.51 mm	36.58 mm
156	900.00 MeV	2.079E-03	3.505E-07	2.22 m	89.31 mm	42.37 mm
157	1.00 GeV	2.028E-03	3.177E-07	2.57 m	102.68 mm	48.14 mm

```

158
159 Multiply Stopping by          for Stopping Units
160
161 1.3700E+01          eV / Angstrom
162 1.3700E+02          keV / micron
163 1.3700E+02          MeV / mm
164 1.0000E+00          keV / (ug/cm2)
165 1.0000E+00          MeV / (mg/cm2)
166 1.0000E+03          keV / (mg/cm2)
167 1.5437E+01          eV / (1E15 atoms/cm2)
168 7.6339E+00          L.S.S. reduced units
169 =====
170 (C) 1984,1989,1992,1998,2008 by J.P. Biersack and J.F. Ziegler

```

Listing 3: Ion stopping and range tables of protons in carbon composite.

```

1 =====
2 SRIM version —> SRIM-2013.00
3 Calc. date —> July 29, 2020
4 =====
5
6 Disk File Name = SRIM Outputs\Hydrogen in Carbon Composite.txt
7
8 Ion = Hydrogen [1] , Mass = 1.008 amu
9
10 Target Density = 1.5000E+00 g/cm3 = 9.3466E+22 atoms/cm3
11 ===== Target Composition =====
12 Atom Atom Atomic Mass
13 Name Numb Percent Percent
14
15 H 1 022.62 002.36
16 C 6 073.81 091.73
17 O 8 003.57 005.91
18 =====
19 Bragg Correction = -3.61%
20 Stopping Units = MeV / (mg/cm2)
21 See bottom of Table for other Stopping units
22
23 Ion Energy dE/dx dE/dx Projected Longitudinal Lateral
24 Energy Elec. Nuclear Range Range Straggling Straggling
25
26 10.00 keV 4.274E-01 6.617E-03 1799 A 467 A 488 A
27 11.00 keV 4.458E-01 6.196E-03 1936 A 480 A 507 A
28 12.00 keV 4.629E-01 5.832E-03 2068 A 492 A 526 A
29 13.00 keV 4.790E-01 5.512E-03 2197 A 502 A 542 A
30 14.00 keV 4.942E-01 5.230E-03 2323 A 512 A 558 A
31 15.00 keV 5.085E-01 4.978E-03 2446 A 521 A 573 A
32 16.00 keV 5.219E-01 4.752E-03 2566 A 529 A 587 A
33 17.00 keV 5.347E-01 4.548E-03 2684 A 536 A 600 A
34 18.00 keV 5.467E-01 4.363E-03 2799 A 543 A 612 A
35 20.00 keV 5.689E-01 4.038E-03 3024 A 557 A 636 A
36 22.50 keV 5.936E-01 3.701E-03 3295 A 571 A 662 A
37 25.00 keV 6.154E-01 3.421E-03 3558 A 584 A 686 A
38 27.50 keV 6.346E-01 3.184E-03 3813 A 596 A 707 A
39 30.00 keV 6.517E-01 2.981E-03 4063 A 607 A 727 A
40 32.50 keV 6.670E-01 2.804E-03 4306 A 616 A 746 A
41 35.00 keV 6.806E-01 2.649E-03 4545 A 625 A 764 A

```

42	37.50 keV	6.929E-01	2.512E-03	4781 A	634 A	780 A
43	40.00 keV	7.038E-01	2.390E-03	5013 A	641 A	796 A
44	45.00 keV	7.224E-01	2.180E-03	5468 A	657 A	825 A
45	50.00 keV	7.372E-01	2.007E-03	5914 A	671 A	852 A
46	55.00 keV	7.487E-01	1.862E-03	6353 A	684 A	877 A
47	60.00 keV	7.573E-01	1.738E-03	6787 A	696 A	901 A
48	65.00 keV	7.633E-01	1.631E-03	7218 A	708 A	923 A
49	70.00 keV	7.669E-01	1.537E-03	7647 A	719 A	944 A
50	80.00 keV	7.684E-01	1.381E-03	8502 A	744 A	985 A
51	90.00 keV	7.635E-01	1.256E-03	9362 A	767 A	1023 A
52	100.00 keV	7.541E-01	1.153E-03	1.02 um	790 A	1059 A
53	110.00 keV	7.414E-01	1.067E-03	1.11 um	812 A	1095 A
54	120.00 keV	7.267E-01	9.934E-04	1.20 um	834 A	1130 A
55	130.00 keV	7.107E-01	9.302E-04	1.29 um	856 A	1165 A
56	140.00 keV	6.941E-01	8.751E-04	1.39 um	878 A	1200 A
57	150.00 keV	6.774E-01	8.267E-04	1.48 um	900 A	1234 A
58	160.00 keV	6.607E-01	7.837E-04	1.58 um	922 A	1270 A
59	170.00 keV	6.444E-01	7.452E-04	1.68 um	945 A	1305 A
60	180.00 keV	6.285E-01	7.107E-04	1.79 um	968 A	1341 A
61	200.00 keV	5.985E-01	6.509E-04	2.00 um	1038 A	1414 A
62	225.00 keV	5.644E-01	5.898E-04	2.29 um	1141 A	1510 A
63	250.00 keV	5.339E-01	5.399E-04	2.59 um	1247 A	1610 A
64	275.00 keV	5.068E-01	4.983E-04	2.91 um	1354 A	1714 A
65	300.00 keV	4.826E-01	4.630E-04	3.25 um	1464 A	1824 A
66	325.00 keV	4.609E-01	4.326E-04	3.60 um	1576 A	1939 A
67	350.00 keV	4.414E-01	4.063E-04	3.97 um	1691 A	2058 A
68	375.00 keV	4.238E-01	3.831E-04	4.35 um	1807 A	2183 A
69	400.00 keV	4.078E-01	3.626E-04	4.75 um	1925 A	2312 A
70	450.00 keV	3.798E-01	3.280E-04	5.59 um	2325 A	2586 A
71	500.00 keV	3.561E-01	2.997E-04	6.50 um	2714 A	2878 A
72	550.00 keV	3.358E-01	2.761E-04	7.46 um	3096 A	3188 A
73	600.00 keV	3.182E-01	2.562E-04	8.47 um	3477 A	3515 A
74	650.00 keV	3.027E-01	2.392E-04	9.54 um	3858 A	3859 A
75	700.00 keV	2.891E-01	2.243E-04	10.67 um	4240 A	4218 A
76	800.00 keV	2.660E-01	1.999E-04	13.06 um	5550 A	4980 A
77	900.00 keV	2.473E-01	1.805E-04	15.66 um	6774 A	5798 A
78	1.00 MeV	2.319E-01	1.647E-04	18.43 um	7956 A	6666 A
79	1.10 MeV	2.203E-01	1.515E-04	21.37 um	9109 A	7578 A
80	1.20 MeV	2.089E-01	1.405E-04	24.47 um	1.02 um	8530 A
81	1.30 MeV	1.982E-01	1.310E-04	27.74 um	1.14 um	9524 A
82	1.40 MeV	1.888E-01	1.227E-04	31.18 um	1.25 um	1.06 um
83	1.50 MeV	1.803E-01	1.155E-04	34.78 um	1.37 um	1.16 um
84	1.60 MeV	1.725E-01	1.092E-04	38.55 um	1.48 um	1.28 um
85	1.70 MeV	1.655E-01	1.035E-04	42.49 um	1.60 um	1.39 um
86	1.80 MeV	1.590E-01	9.845E-05	46.59 um	1.72 um	1.51 um
87	2.00 MeV	1.474E-01	8.973E-05	55.28 um	2.15 um	1.77 um
88	2.25 MeV	1.353E-01	8.087E-05	67.06 um	2.76 um	2.11 um
89	2.50 MeV	1.251E-01	7.368E-05	79.84 um	3.34 um	2.47 um
90	2.75 MeV	1.165E-01	6.772E-05	93.61 um	3.91 um	2.86 um
91	3.00 MeV	1.091E-01	6.270E-05	108.37 um	4.48 um	3.28 um
92	3.25 MeV	1.027E-01	5.840E-05	124.08 um	5.05 um	3.72 um
93	3.50 MeV	9.702E-02	5.468E-05	140.75 um	5.63 um	4.18 um
94	3.75 MeV	9.202E-02	5.142E-05	158.35 um	6.21 um	4.67 um
95	4.00 MeV	8.755E-02	4.855E-05	176.89 um	6.80 um	5.18 um
96	4.50 MeV	7.990E-02	4.371E-05	216.67 um	8.93 um	6.28 um
97	5.00 MeV	7.359E-02	3.979E-05	260.07 um	10.95 um	7.46 um
98	5.50 MeV	6.829E-02	3.654E-05	307.01 um	12.93 um	8.74 um

99	6.00 MeV	6.376E-02	3.381E-05	357.44 um	14.90 um	10.10 um
100	6.50 MeV	5.985E-02	3.147E-05	411.31 um	16.87 um	11.55 um
101	7.00 MeV	5.642E-02	2.944E-05	468.57 um	18.87 um	13.08 um
102	8.00 MeV	5.072E-02	2.612E-05	593.00 um	26.07 um	16.40 um
103	9.00 MeV	4.615E-02	2.349E-05	730.58 um	32.82 um	20.04 um
104	10.00 MeV	4.240E-02	2.137E-05	881.06 um	39.44 um	24.00 um
105	11.00 MeV	3.926E-02	1.961E-05	1.04 mm	46.03 um	28.28 um
106	12.00 MeV	3.659E-02	1.813E-05	1.22 mm	52.68 um	32.86 um
107	13.00 MeV	3.430E-02	1.687E-05	1.41 mm	59.41 um	37.74 um
108	14.00 MeV	3.229E-02	1.577E-05	1.61 mm	66.24 um	42.92 um
109	15.00 MeV	3.053E-02	1.482E-05	1.82 mm	73.18 um	48.39 um
110	16.00 MeV	2.897E-02	1.398E-05	2.04 mm	80.24 um	54.15 um
111	17.00 MeV	2.758E-02	1.323E-05	2.28 mm	87.42 um	60.19 um
112	18.00 MeV	2.632E-02	1.256E-05	2.53 mm	94.73 um	66.51 um
113	20.00 MeV	2.416E-02	1.142E-05	3.05 mm	121.70 um	79.98 um
114	22.50 MeV	2.195E-02	1.026E-05	3.78 mm	160.28 um	98.34 um
115	25.00 MeV	2.015E-02	9.324E-06	4.57 mm	196.93 um	118.33 um
116	27.50 MeV	1.864E-02	8.550E-06	5.43 mm	232.91 um	139.93 um
117	30.00 MeV	1.737E-02	7.899E-06	6.35 mm	268.80 um	163.09 um
118	32.50 MeV	1.628E-02	7.344E-06	7.34 mm	304.86 um	187.77 um
119	35.00 MeV	1.533E-02	6.864E-06	8.40 mm	341.27 um	213.95 um
120	37.50 MeV	1.450E-02	6.445E-06	9.51 mm	378.11 um	241.59 um
121	40.00 MeV	1.377E-02	6.077E-06	10.69 mm	415.43 um	270.66 um
122	45.00 MeV	1.253E-02	5.457E-06	13.22 mm	552.91 um	333.01 um
123	50.00 MeV	1.152E-02	4.956E-06	16.00 mm	682.17 um	400.79 um
124	55.00 MeV	1.068E-02	4.542E-06	19.00 mm	808.24 um	473.81 um
125	60.00 MeV	9.970E-03	4.194E-06	22.22 mm	933.28 um	551.88 um
126	65.00 MeV	9.364E-03	3.898E-06	25.67 mm	1.06 mm	634.86 um
127	70.00 MeV	8.839E-03	3.642E-06	29.33 mm	1.18 mm	722.58 um
128	80.00 MeV	7.973E-03	3.222E-06	37.26 mm	1.64 mm	911.73 um
129	90.00 MeV	7.290E-03	2.892E-06	46.00 mm	2.07 mm	1.12 mm
130	100.00 MeV	6.735E-03	2.625E-06	55.50 mm	2.48 mm	1.34 mm
131	110.00 MeV	6.276E-03	2.404E-06	65.74 mm	2.88 mm	1.58 mm
132	120.00 MeV	5.890E-03	2.219E-06	76.70 mm	3.29 mm	1.83 mm
133	130.00 MeV	5.560E-03	2.062E-06	88.33 mm	3.69 mm	2.10 mm
134	140.00 MeV	5.275E-03	1.926E-06	100.63 mm	4.10 mm	2.38 mm
135	150.00 MeV	5.026E-03	1.807E-06	113.56 mm	4.51 mm	2.67 mm
136	160.00 MeV	4.807E-03	1.703E-06	127.11 mm	4.91 mm	2.98 mm
137	170.00 MeV	4.613E-03	1.610E-06	141.25 mm	5.33 mm	3.29 mm
138	180.00 MeV	4.439E-03	1.527E-06	155.97 mm	5.74 mm	3.62 mm
139	200.00 MeV	4.143E-03	1.386E-06	187.03 mm	7.27 mm	4.31 mm
140	225.00 MeV	3.844E-03	1.243E-06	228.76 mm	9.41 mm	5.22 mm
141	250.00 MeV	3.603E-03	1.127E-06	273.51 mm	11.39 mm	6.18 mm
142	275.00 MeV	3.405E-03	1.032E-06	321.05 mm	13.27 mm	7.18 mm
143	300.00 MeV	3.240E-03	9.523E-07	371.19 mm	15.10 mm	8.23 mm
144	325.00 MeV	3.100E-03	8.843E-07	423.73 mm	16.89 mm	9.32 mm
145	350.00 MeV	2.980E-03	8.256E-07	478.52 mm	18.64 mm	10.43 mm
146	375.00 MeV	2.876E-03	7.744E-07	535.41 mm	20.36 mm	11.58 mm
147	400.00 MeV	2.785E-03	7.295E-07	594.25 mm	22.06 mm	12.75 mm
148	450.00 MeV	2.634E-03	6.539E-07	717.24 mm	28.20 mm	15.16 mm
149	500.00 MeV	2.514E-03	5.930E-07	846.67 mm	33.73 mm	17.64 mm
150	550.00 MeV	2.417E-03	5.428E-07	981.79 mm	38.88 mm	20.17 mm
151	600.00 MeV	2.337E-03	5.006E-07	1.12 m	43.76 mm	22.74 mm
152	650.00 MeV	2.271E-03	4.647E-07	1.27 m	48.41 mm	25.34 mm
153	700.00 MeV	2.214E-03	4.337E-07	1.42 m	52.89 mm	27.97 mm
154	800.00 MeV	2.125E-03	3.830E-07	1.72 m	68.64 mm	33.24 mm
155	900.00 MeV	2.059E-03	3.432E-07	2.04 m	82.30 mm	38.52 mm

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156      1.00 GeV   2.008E-03  3.111E-07   2.37 m   94.64 mm   43.77 mm
157
158      Multiply Stopping by          for Stopping Units
159
160      1.5000E+01          eV / Angstrom
161      1.5000E+02          keV / micron
162      1.5000E+02          MeV / mm
163      1.0000E+00          keV / (ug/cm2)
164      1.0000E+00          MeV / (mg/cm2)
165      1.0000E+03          keV / (mg/cm2)
166      1.6048E+01          eV / (1E15 atoms/cm2)
167      8.0274E+00          L.S.S. reduced units
168      =====
169      (C) 1984,1989,1992,1998,2008 by J.P. Biersack and J.F. Ziegler

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Listing 4: Ion stopping and range tables of protons in aluminum.

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1      =====
2      SRIM version —> SRIM-2013.00
3      Calc. date  —> July 29, 2020
4      =====
5
6      Disk File Name = SRIM Outputs\Hydrogen in Aluminum.txt
7
8      Ion = Hydrogen [1] , Mass = 1.008 amu
9
10     Target Density = 2.7020E+00 g/cm3 = 6.0305E+22 atoms/cm3
11     ===== Target Composition =====
12     Atom    Atom    Atomic    Mass
13     Name    Numb    Percent    Percent
14
15     Al      13      100.00    100.00
16     =====
17     Bragg Correction = 0.00%
18     Stopping Units = MeV / (mg/cm2)
19     See bottom of Table for other Stopping units
20
21
22     Ion      dE/dx    dE/dx    Projected    Longitudinal    Lateral
23     Energy   Elec.     Nuclear  Range        Straggling      Straggling
24
25     10.00 keV  2.797E-01  4.085E-03  1277 A        501 A           471 A
26     11.00 keV  2.924E-01  3.861E-03  1382 A        518 A           493 A
27     12.00 keV  3.044E-01  3.664E-03  1484 A        534 A           514 A
28     13.00 keV  3.155E-01  3.489E-03  1583 A        549 A           534 A
29     14.00 keV  3.260E-01  3.332E-03  1681 A        563 A           552 A
30     15.00 keV  3.359E-01  3.190E-03  1776 A        575 A           570 A
31     16.00 keV  3.451E-01  3.062E-03  1869 A        587 A           586 A
32     17.00 keV  3.537E-01  2.945E-03  1961 A        598 A           602 A
33     18.00 keV  3.618E-01  2.838E-03  2052 A        608 A           617 A
34     20.00 keV  3.766E-01  2.648E-03  2229 A        628 A           645 A
35     22.50 keV  3.925E-01  2.448E-03  2444 A        649 A           678 A
36     25.00 keV  4.062E-01  2.279E-03  2653 A        668 A           708 A
37     27.50 keV  4.178E-01  2.135E-03  2858 A        685 A           735 A
38     30.00 keV  4.276E-01  2.010E-03  3059 A        701 A           761 A
39     32.50 keV  4.360E-01  1.900E-03  3257 A        716 A           786 A
40     35.00 keV  4.430E-01  1.803E-03  3453 A        729 A           809 A
41     37.50 keV  4.489E-01  1.717E-03  3647 A        742 A           831 A

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41	40.00 keV	4.538E-01	1.639E-03	3839 A	754 A	852 A
42	45.00 keV	4.612E-01	1.505E-03	4220 A	777 A	893 A
43	50.00 keV	4.658E-01	1.394E-03	4599 A	798 A	931 A
44	55.00 keV	4.685E-01	1.299E-03	4977 A	818 A	967 A
45	60.00 keV	4.695E-01	1.218E-03	5354 A	837 A	1002 A
46	65.00 keV	4.692E-01	1.147E-03	5733 A	855 A	1035 A
47	70.00 keV	4.680E-01	1.085E-03	6113 A	872 A	1068 A
48	80.00 keV	4.636E-01	9.803E-04	6880 A	907 A	1131 A
49	90.00 keV	4.573E-01	8.958E-04	7660 A	941 A	1192 A
50	100.00 keV	4.499E-01	8.259E-04	8453 A	973 A	1252 A
51	110.00 keV	4.420E-01	7.670E-04	9262 A	1005 A	1311 A
52	120.00 keV	4.338E-01	7.166E-04	1.01 um	1036 A	1370 A
53	130.00 keV	4.256E-01	6.730E-04	1.09 um	1067 A	1429 A
54	140.00 keV	4.175E-01	6.348E-04	1.18 um	1098 A	1487 A
55	150.00 keV	4.095E-01	6.011E-04	1.27 um	1128 A	1546 A
56	160.00 keV	4.017E-01	5.711E-04	1.36 um	1159 A	1604 A
57	170.00 keV	3.941E-01	5.442E-04	1.45 um	1189 A	1664 A
58	180.00 keV	3.868E-01	5.199E-04	1.54 um	1220 A	1723 A
59	200.00 keV	3.730E-01	4.777E-04	1.73 um	1295 A	1844 A
60	225.00 keV	3.571E-01	4.345E-04	1.98 um	1399 A	1998 A
61	250.00 keV	3.427E-01	3.989E-04	2.24 um	1503 A	2155 A
62	275.00 keV	3.297E-01	3.691E-04	2.51 um	1608 A	2317 A
63	300.00 keV	3.178E-01	3.438E-04	2.80 um	1714 A	2483 A
64	325.00 keV	3.069E-01	3.219E-04	3.09 um	1822 A	2652 A
65	350.00 keV	2.969E-01	3.029E-04	3.39 um	1930 A	2826 A
66	375.00 keV	2.877E-01	2.862E-04	3.71 um	2040 A	3004 A
67	400.00 keV	2.792E-01	2.713E-04	4.03 um	2151 A	3186 A
68	450.00 keV	2.640E-01	2.460E-04	4.70 um	2469 A	3561 A
69	500.00 keV	2.508E-01	2.254E-04	5.42 um	2783 A	3952 A
70	550.00 keV	2.392E-01	2.081E-04	6.16 um	3095 A	4358 A
71	600.00 keV	2.289E-01	1.935E-04	6.95 um	3407 A	4777 A
72	650.00 keV	2.197E-01	1.809E-04	7.77 um	3719 A	5211 A
73	700.00 keV	2.115E-01	1.700E-04	8.62 um	4033 A	5657 A
74	800.00 keV	1.972E-01	1.518E-04	10.42 um	4996 A	6588 A
75	900.00 keV	1.852E-01	1.374E-04	12.34 um	5916 A	7566 A
76	1.00 MeV	1.749E-01	1.256E-04	14.38 um	6815 A	8590 A
77	1.10 MeV	1.654E-01	1.158E-04	16.54 um	7707 A	9659 A
78	1.20 MeV	1.558E-01	1.075E-04	18.83 um	8608 A	1.08 um
79	1.30 MeV	1.478E-01	1.004E-04	21.26 um	9522 A	1.20 um
80	1.40 MeV	1.408E-01	9.421E-05	23.81 um	1.04 um	1.32 um
81	1.50 MeV	1.346E-01	8.879E-05	26.48 um	1.14 um	1.44 um
82	1.60 MeV	1.289E-01	8.399E-05	29.27 um	1.23 um	1.58 um
83	1.70 MeV	1.238E-01	7.971E-05	32.19 um	1.33 um	1.71 um
84	1.80 MeV	1.191E-01	7.587E-05	35.22 um	1.43 um	1.86 um
85	2.00 MeV	1.108E-01	6.927E-05	41.63 um	1.75 um	2.15 um
86	2.25 MeV	1.021E-01	6.254E-05	50.28 um	2.21 um	2.55 um
87	2.50 MeV	9.486E-02	5.707E-05	59.64 um	2.65 um	2.98 um
88	2.75 MeV	8.868E-02	5.253E-05	69.67 um	3.08 um	3.43 um
89	3.00 MeV	8.336E-02	4.869E-05	80.38 um	3.51 um	3.91 um
90	3.25 MeV	7.871E-02	4.540E-05	91.75 um	3.95 um	4.41 um
91	3.50 MeV	7.461E-02	4.255E-05	103.77 um	4.39 um	4.95 um
92	3.75 MeV	7.097E-02	4.006E-05	116.42 um	4.83 um	5.50 um
93	4.00 MeV	6.771E-02	3.785E-05	129.71 um	5.29 um	6.08 um
94	4.50 MeV	6.210E-02	3.413E-05	158.13 um	6.82 um	7.32 um
95	5.00 MeV	5.744E-02	3.111E-05	188.98 um	8.29 um	8.65 um
96	5.50 MeV	5.350E-02	2.860E-05	222.22 um	9.73 um	10.07 um
97	6.00 MeV	5.013E-02	2.649E-05	257.80 um	11.17 um	11.58 um

98	6.50 MeV	4.719E-02	2.468E-05	295.69 um	12.62 um	13.19 um
99	7.00 MeV	4.462E-02	2.311E-05	335.85 um	14.08 um	14.88 um
100	8.00 MeV	4.031E-02	2.053E-05	422.78 um	19.13 um	18.51 um
101	9.00 MeV	3.683E-02	1.849E-05	518.46 um	23.90 um	22.48 um
102	10.00 MeV	3.396E-02	1.684E-05	622.71 um	28.58 um	26.77 um
103	11.00 MeV	3.155E-02	1.547E-05	735.35 um	33.27 um	31.38 um
104	12.00 MeV	2.949E-02	1.431E-05	856.24 um	37.99 um	36.29 um
105	13.00 MeV	2.771E-02	1.333E-05	985.24 um	42.77 um	41.51 um
106	14.00 MeV	2.615E-02	1.247E-05	1.12 mm	47.64 um	47.03 um
107	15.00 MeV	2.478E-02	1.173E-05	1.27 mm	52.58 um	52.84 um
108	16.00 MeV	2.355E-02	1.107E-05	1.42 mm	57.62 um	58.94 um
109	17.00 MeV	2.246E-02	1.048E-05	1.58 mm	62.74 um	65.33 um
110	18.00 MeV	2.147E-02	9.958E-06	1.75 mm	67.96 um	71.99 um
111	20.00 MeV	1.976E-02	9.060E-06	2.11 mm	86.39 um	86.15 um
112	22.50 MeV	1.801E-02	8.150E-06	2.59 mm	112.65 um	105.35 um
113	25.00 MeV	1.658E-02	7.412E-06	3.13 mm	137.73 um	126.20 um
114	27.50 MeV	1.538E-02	6.803E-06	3.71 mm	162.44 um	148.63 um
115	30.00 MeV	1.436E-02	6.289E-06	4.33 mm	187.12 um	172.61 um
116	32.50 MeV	1.348E-02	5.851E-06	4.99 mm	211.97 um	198.10 um
117	35.00 MeV	1.271E-02	5.472E-06	5.69 mm	237.08 um	225.06 um
118	37.50 MeV	1.204E-02	5.141E-06	6.44 mm	262.53 um	253.48 um
119	40.00 MeV	1.145E-02	4.850E-06	7.23 mm	288.35 um	283.31 um
120	45.00 MeV	1.044E-02	4.359E-06	8.91 mm	380.32 um	347.11 um
121	50.00 MeV	9.619E-03	3.962E-06	10.75 mm	467.27 um	416.26 um
122	55.00 MeV	8.934E-03	3.634E-06	12.74 mm	552.34 um	490.56 um
123	60.00 MeV	8.354E-03	3.358E-06	14.88 mm	636.88 um	569.82 um
124	65.00 MeV	7.857E-03	3.122E-06	17.16 mm	721.60 um	653.89 um
125	70.00 MeV	7.425E-03	2.919E-06	19.57 mm	806.87 um	742.61 um
126	80.00 MeV	6.713E-03	2.585E-06	24.80 mm	1.11 mm	933.43 um
127	90.00 MeV	6.148E-03	2.321E-06	30.55 mm	1.39 mm	1.14 mm
128	100.00 MeV	5.689E-03	2.109E-06	36.79 mm	1.67 mm	1.37 mm
129	110.00 MeV	5.309E-03	1.933E-06	43.50 mm	1.94 mm	1.60 mm
130	120.00 MeV	4.988E-03	1.785E-06	50.68 mm	2.21 mm	1.86 mm
131	130.00 MeV	4.714E-03	1.659E-06	58.29 mm	2.48 mm	2.12 mm
132	140.00 MeV	4.477E-03	1.550E-06	66.33 mm	2.75 mm	2.40 mm
133	150.00 MeV	4.269E-03	1.456E-06	74.77 mm	3.02 mm	2.70 mm
134	160.00 MeV	4.087E-03	1.372E-06	83.61 mm	3.30 mm	3.00 mm
135	170.00 MeV	3.925E-03	1.298E-06	92.82 mm	3.57 mm	3.31 mm
136	180.00 MeV	3.780E-03	1.232E-06	102.41 mm	3.85 mm	3.64 mm
137	200.00 MeV	3.532E-03	1.118E-06	122.62 mm	4.85 mm	4.32 mm
138	225.00 MeV	3.282E-03	1.004E-06	149.74 mm	6.25 mm	5.22 mm
139	250.00 MeV	3.080E-03	9.110E-07	178.77 mm	7.54 mm	6.16 mm
140	275.00 MeV	2.915E-03	8.345E-07	209.58 mm	8.78 mm	7.16 mm
141	300.00 MeV	2.776E-03	7.703E-07	242.04 mm	9.98 mm	8.19 mm
142	325.00 MeV	2.659E-03	7.156E-07	276.02 mm	11.16 mm	9.25 mm
143	350.00 MeV	2.558E-03	6.684E-07	311.42 mm	12.31 mm	10.35 mm
144	375.00 MeV	2.471E-03	6.272E-07	348.14 mm	13.44 mm	11.47 mm
145	400.00 MeV	2.395E-03	5.910E-07	386.09 mm	14.56 mm	12.62 mm
146	450.00 MeV	2.269E-03	5.301E-07	465.32 mm	18.53 mm	14.97 mm
147	500.00 MeV	2.169E-03	4.810E-07	548.58 mm	22.11 mm	17.39 mm
148	550.00 MeV	2.088E-03	4.404E-07	635.37 mm	25.44 mm	19.85 mm
149	600.00 MeV	2.022E-03	4.064E-07	725.26 mm	28.60 mm	22.35 mm
150	650.00 MeV	1.967E-03	3.774E-07	817.90 mm	31.62 mm	24.87 mm
151	700.00 MeV	1.920E-03	3.524E-07	912.96 mm	34.52 mm	27.41 mm
152	800.00 MeV	1.847E-03	3.114E-07	1.11 m	44.57 mm	32.50 mm
153	900.00 MeV	1.793E-03	2.792E-07	1.31 m	53.29 mm	37.58 mm
154	1.00 GeV	1.752E-03	2.532E-07	1.52 m	61.17 mm	42.63 mm

	Multiply Stopping by	for Stopping Units
155		
156		
157		
158	2.7019E+01	eV / Angstrom
159	2.7019E+02	keV / micron
160	2.7019E+02	MeV / mm
161	1.0000E+00	keV / (ug/cm2)
162	1.0000E+00	MeV / (mg/cm2)
163	1.0000E+03	keV / (mg/cm2)
164	4.4804E+01	eV / (1E15 atoms/cm2)
165	2.8899E+01	L.S.S. reduced units
166	=====	
167	(C) 1984,1989,1992,1998,2008 by J.P. Biersack and J.F. Ziegler	

B SPENVIS Output

Listing 5: ESP PSYCHIC SPE worst case 1 year.

```

1  '* ', 54, 1, 25, 22, 5, 5, 75, 1
2  'SPENVIS_4.6.10.3408_23-Jul-2020_00:20:04 '
3  'PRJ_DEF ', -1, 'TEST_PROJECT '
4  'PRJ_HDR ', -1, 'My_Test_Project '
5  'MOD_ABB ', -1, 'SEP '
6  'MIS_PLA ', 1, -3, ' '
7  'MIS_NTR ', 1, 1, ' '
8  'MIS_STA ', 1, 9862.00000000, ' '
9  'MIS_END ', 1, 15337.00000000, ' '
10 'MIS_DUR ', 1, 5.475000E+03, 'days '
11 'SEP_IEL ', 1, 1, ' '
12 'SEP_JEL ', 1, 1, ' '
13 'SEP_MOD ', -1, 'ESP-PSYCHIC_worst_event_fluence '
14 'SEP_TMI ', 1, 1.0, 'years '
15 'SEP_TMA ', 1, 0.0, 'years '
16 'SEP_DUR ', 1, 1.0, 'years '
17 'SEP_NCY ', 1, 1, ' '
18 'SEP_NOR ', 1, 0, ' '
19 'SEP_NAL ', 1, 0, ' '
20 'SEP_PRB ', 1, 95.0, '%'
21 'SEP_OMN ', 1, 1, ' '
22 'SEP_ABS ', -1, 'Energy '
23 'SEP_IGC ', 1, 0, ' '
24 'SEP_IGV ', 1, 1, ' '
25 'SEP_IST ', 1, 0, ' '
26 'PLT_HDR ', -1, 'ESP-PSYCHIC_worst_event_fluence: solar_protons '
27 'SPECIES ', -1, 'proton '
28 'PS_Annotation ', 8, 1
29 'Mission_start: 01/01/1977_00:00:00 '
30 0.05, 0.00, 0.00
31 'Mission_end: 29/12/1991_00:00:00 '
32 0.95, 0.00, 1.00
33 'Nr. of segments: 1 '
34 0.05, 1.50, 0.00
35 'Duration: 5475.00 days '
36 0.95, 0.00, 1.00

```

```
37 'PS_Annotation', 12, 0
38 'Solar_particle_model': 'ESP-PSYCHIC_worst_event_fluence'
39 0.05, 2.00, 0.00
40 'Mission_duration': '1.00_years, spanning 1 solar cycles'
41 0.10, 1.50, 0.00
42 '1.00_years_in_solar_maximum'
43 0.15, 1.50, 0.00
44 '0.00_years_in_solar_minimum'
45 0.15, 1.50, 0.00
46 'Confidence_level': '95.000%'
47 0.10, 1.50, 0.00
48 'Magnetic_shielding': 'off'
49 0.10, 1.50, 0.00
50 'Energy', 'MeV', 1, 'Energy'
51 'IFlux', 'cm!u-2!n', 1, 'Integral_Fluence'
52 'DFlux', 'cm!u-2!n!MeV!u-1!n', 1, 'Differential_Fluence'
53 'Attenuation', 'u', 1, 'Orbit_Averaged_Proton_Attenuation_Factor'
54 'Exposure', 'hrs', 1, 'Proton_Exposure_Time'
55 1.0000E-01, 4.9253E+11, 2.8327E+12, 1.0000, 1.3140E+05
56 1.1000E-01, 4.6599E+11, 2.4764E+12, 1.0000, 1.3140E+05
57 1.2000E-01, 4.4301E+11, 2.1650E+12, 1.0000, 1.3140E+05
58 1.4000E-01, 4.0504E+11, 1.7055E+12, 1.0000, 1.3140E+05
59 1.6000E-01, 3.7479E+11, 1.3763E+12, 1.0000, 1.3140E+05
60 1.8000E-01, 3.4999E+11, 1.1398E+12, 1.0000, 1.3140E+05
61 2.0000E-01, 3.2919E+11, 9.6334E+11, 1.0000, 1.3140E+05
62 2.2000E-01, 3.1145E+11, 8.2966E+11, 1.0000, 1.3140E+05
63 2.5000E-01, 2.8915E+11, 6.7898E+11, 1.0000, 1.3140E+05
64 2.8000E-01, 2.7071E+11, 5.6775E+11, 1.0000, 1.3140E+05
65 3.2000E-01, 2.5050E+11, 4.5880E+11, 1.0000, 1.3140E+05
66 3.5000E-01, 2.3778E+11, 3.9807E+11, 1.0000, 1.3140E+05
67 4.0000E-01, 2.2002E+11, 3.2318E+11, 1.0000, 1.3140E+05
68 4.5000E-01, 2.0546E+11, 2.6766E+11, 1.0000, 1.3140E+05
69 5.0000E-01, 1.9326E+11, 2.2622E+11, 1.0000, 1.3140E+05
70 5.5000E-01, 1.8284E+11, 1.9492E+11, 1.0000, 1.3140E+05
71 6.3000E-01, 1.6896E+11, 1.5763E+11, 1.0000, 1.3140E+05
72 7.1000E-01, 1.5762E+11, 1.3030E+11, 1.0000, 1.3140E+05
73 8.0000E-01, 1.4706E+11, 1.0787E+11, 1.0000, 1.3140E+05
74 9.0000E-01, 1.3732E+11, 8.9447E+10, 1.0000, 1.3140E+05
75 1.0000E+00, 1.2917E+11, 7.5598E+10, 1.0000, 1.3140E+05
76 1.1000E+00, 1.2220E+11, 6.4944E+10, 1.0000, 1.3140E+05
77 1.2000E+00, 1.1618E+11, 5.6777E+10, 1.0000, 1.3140E+05
78 1.4000E+00, 1.0622E+11, 4.4726E+10, 1.0000, 1.3140E+05
79 1.6000E+00, 9.8287E+10, 3.6093E+10, 1.0000, 1.3140E+05
80 1.8000E+00, 9.1783E+10, 2.9892E+10, 1.0000, 1.3140E+05
81 2.0000E+00, 8.6331E+10, 2.5264E+10, 1.0000, 1.3140E+05
82 2.2000E+00, 8.1678E+10, 2.1758E+10, 1.0000, 1.3140E+05
83 2.5000E+00, 7.5829E+10, 1.7806E+10, 1.0000, 1.3140E+05
84 2.8000E+00, 7.0994E+10, 1.5325E+10, 1.0000, 1.3140E+05
85 3.2000E+00, 6.5285E+10, 1.3442E+10, 1.0000, 1.3140E+05
86 3.5000E+00, 6.1439E+10, 1.1998E+10, 1.0000, 1.3140E+05
87 4.0000E+00, 5.6125E+10, 9.6194E+09, 1.0000, 1.3140E+05
88 4.5000E+00, 5.1820E+10, 7.8751E+09, 1.0000, 1.3140E+05
89 5.0000E+00, 4.8250E+10, 7.2806E+09, 1.0000, 1.3140E+05
90 5.5000E+00, 4.4539E+10, 6.8738E+09, 1.0000, 1.3140E+05
91 6.3000E+00, 3.9740E+10, 5.4586E+09, 1.0000, 1.3140E+05
92 7.1000E+00, 3.5806E+10, 4.9353E+09, 1.0000, 1.3140E+05
93 8.0000E+00, 3.1347E+10, 4.4340E+09, 1.0000, 1.3140E+05
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94 9.0000E+00, 2.7491E+10, 3.4506E+09, 1.0000, 1.3140E+05
95 1.0000E+01, 2.4445E+10, 2.6797E+09, 1.0000, 1.3140E+05
96 1.1000E+01, 2.2131E+10, 2.1174E+09, 1.0000, 1.3140E+05
97 1.2000E+01, 2.0210E+10, 1.7809E+09, 1.0000, 1.3140E+05
98 1.4000E+01, 1.7208E+10, 1.2866E+09, 1.0000, 1.3140E+05
99 1.6000E+01, 1.5064E+10, 9.3293E+08, 1.0000, 1.3140E+05
100 1.8000E+01, 1.3476E+10, 7.1663E+08, 1.0000, 1.3140E+05
101 2.0000E+01, 1.2198E+10, 6.5060E+08, 1.0000, 1.3140E+05
102 2.2000E+01, 1.0874E+10, 6.0432E+08, 1.0000, 1.3140E+05
103 2.5000E+01, 9.3205E+09, 4.5508E+08, 1.0000, 1.3140E+05
104 2.8000E+01, 8.1431E+09, 3.6265E+08, 1.0000, 1.3140E+05
105 3.2000E+01, 6.8515E+09, 2.9247E+08, 1.0000, 1.3140E+05
106 3.5000E+01, 6.0426E+09, 2.5867E+08, 1.0000, 1.3140E+05
107 4.0000E+01, 4.8408E+09, 2.0982E+08, 1.0000, 1.3140E+05
108 4.5000E+01, 3.9443E+09, 1.5897E+08, 1.0000, 1.3140E+05
109 5.0000E+01, 3.2512E+09, 1.2647E+08, 1.0000, 1.3140E+05
110 5.5000E+01, 2.6796E+09, 1.0417E+08, 1.0000, 1.3140E+05
111 6.3000E+01, 1.9761E+09, 7.2882E+07, 1.0000, 1.3140E+05
112 7.1000E+01, 1.5135E+09, 5.1021E+07, 1.0000, 1.3140E+05
113 8.0000E+01, 1.1232E+09, 3.7228E+07, 1.0000, 1.3140E+05
114 9.0000E+01, 8.1915E+08, 2.4763E+07, 1.0000, 1.3140E+05
115 1.0000E+02, 6.2791E+08, 1.5663E+07, 1.0000, 1.3140E+05
116 1.1000E+02, 5.0590E+08, 1.0628E+07, 1.0000, 1.3140E+05
117 1.2000E+02, 4.1534E+08, 8.1466E+06, 1.0000, 1.3140E+05
118 1.4000E+02, 2.8879E+08, 5.1594E+06, 1.0000, 1.3140E+05
119 1.6000E+02, 2.0896E+08, 3.3143E+06, 1.0000, 1.3140E+05
120 1.8000E+02, 1.5621E+08, 2.2258E+06, 1.0000, 1.3140E+05
121 2.0000E+02, 1.1993E+08, 1.5600E+06, 1.0000, 1.3140E+05
122 2.2000E+02, 9.3814E+07, 1.1385E+06, 1.0000, 1.3140E+05
123 2.5000E+02, 6.7186E+07, 7.4414E+05, 1.0000, 1.3140E+05
124 2.8000E+02, 4.9165E+07, 5.0590E+05, 1.0000, 1.3140E+05
125 3.2000E+02, 3.3986E+07, 3.0472E+05, 1.0000, 1.3140E+05
126 3.5000E+02, 2.6526E+07, 2.1683E+05, 1.0000, 1.3140E+05
127 4.0000E+02, 1.8336E+07, 1.3287E+05, 1.0000, 1.3140E+05
128 4.5000E+02, 1.3239E+07, 8.4433E+04, 1.0000, 1.3140E+05
129 5.0000E+02, 9.8930E+06, 4.9413E+04, 1.0000, 1.3140E+05
130 'End_of_Block'
131 '*', 52, 1, 25, 22, 3, 3, 75, 0
132 'SPENVIS_4.6.10.3408_23-Jul-2020_00:20:04'
133 'PRJ_DEF', -1, 'TEST_PROJECT'
134 'PRJ_HDR', -1, 'My_Test_Project'
135 'MOD_ABB', -1, 'SEP'
136 'MIS_PLA', 1, -3, ' '
137 'MIS_NTR', 1, 1, ' '
138 'MIS_STA', 1, 9862.00000000, ' '
139 'MIS_END', 1, 15337.00000000, ' '
140 'MIS_DUR', 1, 5.475000E+03, 'days'
141 'SEP_IEL', 1, 1, ' '
142 'SEP_JEL', 1, 1, ' '
143 'SEP_MOD', -1, 'ESP-PSYCHIC_worst_eventfluence'
144 'SEP_TMI', 1, 1.0, 'years'
145 'SEP_TMA', 1, 0.0, 'years'
146 'SEP_DUR', 1, 1.0, 'years'
147 'SEP_NCY', 1, 1, ' '
148 'SEP_NOR', 1, 0, ' '
149 'SEP_NAL', 1, 0, ' '
150 'SEP_PRB', 1, 95.0, '%'

```

```

151 'SEP_OMN', 1, 1, '_'
152 'SEP_ABS', -1, 'Energy'
153 'SEP_IGC', 1, 0, '_'
154 'SEP_IGV', 1, 1, '_'
155 'SEP_IST', 1, 0, '_'
156 'PLT_HDR', -1, 'ESP-PSYCHIC_worst_event_fluence:solar_ions'
157 'SPECIES', -1, 'H'
158 'PS_Annotation', 8, 1
159 'Mission_start:_01/01/1977_00:00:00'
160 0.05, 0.00, 0.00
161 'Mission_end:_29/12/1991_00:00:00'
162 0.95, 0.00, 1.00
163 'Nr_of_segments:1'
164 0.05, 1.50, 0.00
165 'Duration:_5475.00_days'
166 0.95, 0.00, 1.00
167 'PS_Annotation', 12, 0
168 'Solar_particle_model:_ESP-PSYCHIC_worst_event_fluence'
169 0.05, 2.00, 0.00
170 'Mission_duration:_1.00_years,_spanning_1_solar_cycles'
171 0.10, 1.50, 0.00
172 '1.00_years_in_solar_maximum'
173 0.15, 1.50, 0.00
174 '0.00_years_in_solar_minimum'
175 0.15, 1.50, 0.00
176 'Confidence_level:_95.000%'
177 0.10, 1.50, 0.00
178 'Magnetic_shielding:off'
179 0.10, 1.50, 0.00
180 'Energy','MeV/n', 1, 'Energy'
181 'IFlux','cm!u-2!n', 1, 'Integral_Fluence_of','SPECIES'
182 'DFlux','cm!u-2!n!(MeV/n)!u-1!n', 1, 'Differential_Fluence_of','SPECIES'
183 1.0000E-01, 4.9253E+11, 2.8327E+12
184 1.1000E-01, 4.6599E+11, 2.4764E+12
185 1.2000E-01, 4.4301E+11, 2.1650E+12
186 1.4000E-01, 4.0504E+11, 1.7055E+12
187 1.6000E-01, 3.7479E+11, 1.3763E+12
188 1.8000E-01, 3.4999E+11, 1.1398E+12
189 2.0000E-01, 3.2919E+11, 9.6334E+11
190 2.2000E-01, 3.1145E+11, 8.2966E+11
191 2.5000E-01, 2.8915E+11, 6.7898E+11
192 2.8000E-01, 2.7071E+11, 5.6775E+11
193 3.2000E-01, 2.5050E+11, 4.5880E+11
194 3.5000E-01, 2.3778E+11, 3.9807E+11
195 4.0000E-01, 2.2002E+11, 3.2318E+11
196 4.5000E-01, 2.0546E+11, 2.6766E+11
197 5.0000E-01, 1.9326E+11, 2.2622E+11
198 5.5000E-01, 1.8284E+11, 1.9492E+11
199 6.3000E-01, 1.6896E+11, 1.5763E+11
200 7.1000E-01, 1.5762E+11, 1.3030E+11
201 8.0000E-01, 1.4706E+11, 1.0787E+11
202 9.0000E-01, 1.3732E+11, 8.9447E+10
203 1.0000E+00, 1.2917E+11, 7.5598E+10
204 1.1000E+00, 1.2220E+11, 6.4944E+10
205 1.2000E+00, 1.1618E+11, 5.6777E+10
206 1.4000E+00, 1.0622E+11, 4.4726E+10
207 1.6000E+00, 9.8287E+10, 3.6093E+10

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208 1.8000E+00, 9.1783E+10, 2.9892E+10
209 2.0000E+00, 8.6331E+10, 2.5264E+10
210 2.2000E+00, 8.1678E+10, 2.1758E+10
211 2.5000E+00, 7.5829E+10, 1.7806E+10
212 2.8000E+00, 7.0994E+10, 1.5325E+10
213 3.2000E+00, 6.5285E+10, 1.3442E+10
214 3.5000E+00, 6.1439E+10, 1.1998E+10
215 4.0000E+00, 5.6125E+10, 9.6194E+09
216 4.5000E+00, 5.1820E+10, 7.8751E+09
217 5.0000E+00, 4.8250E+10, 7.2806E+09
218 5.5000E+00, 4.4539E+10, 6.8738E+09
219 6.3000E+00, 3.9740E+10, 5.4586E+09
220 7.1000E+00, 3.5806E+10, 4.9353E+09
221 8.0000E+00, 3.1347E+10, 4.4340E+09
222 9.0000E+00, 2.7491E+10, 3.4506E+09
223 1.0000E+01, 2.4445E+10, 2.6797E+09
224 1.1000E+01, 2.2131E+10, 2.1174E+09
225 1.2000E+01, 2.0210E+10, 1.7809E+09
226 1.4000E+01, 1.7208E+10, 1.2866E+09
227 1.6000E+01, 1.5064E+10, 9.3293E+08
228 1.8000E+01, 1.3476E+10, 7.1663E+08
229 2.0000E+01, 1.2198E+10, 6.5060E+08
230 2.2000E+01, 1.0874E+10, 6.0432E+08
231 2.5000E+01, 9.3205E+09, 4.5508E+08
232 2.8000E+01, 8.1431E+09, 3.6265E+08
233 3.2000E+01, 6.8515E+09, 2.9247E+08
234 3.5000E+01, 6.0426E+09, 2.5867E+08
235 4.0000E+01, 4.8408E+09, 2.0982E+08
236 4.5000E+01, 3.9443E+09, 1.5897E+08
237 5.0000E+01, 3.2512E+09, 1.2647E+08
238 5.5000E+01, 2.6796E+09, 1.0417E+08
239 6.3000E+01, 1.9761E+09, 7.2882E+07
240 7.1000E+01, 1.5135E+09, 5.1021E+07
241 8.0000E+01, 1.1232E+09, 3.7228E+07
242 9.0000E+01, 8.1915E+08, 2.4763E+07
243 1.0000E+02, 6.2791E+08, 1.5663E+07
244 1.1000E+02, 5.0590E+08, 1.0628E+07
245 1.2000E+02, 4.1534E+08, 8.1466E+06
246 1.4000E+02, 2.8879E+08, 5.1594E+06
247 1.6000E+02, 2.0896E+08, 3.3143E+06
248 1.8000E+02, 1.5621E+08, 2.2258E+06
249 2.0000E+02, 1.1993E+08, 1.5600E+06
250 2.2000E+02, 9.3814E+07, 1.1385E+06
251 2.5000E+02, 6.7186E+07, 7.4414E+05
252 2.8000E+02, 4.9165E+07, 5.0590E+05
253 3.2000E+02, 3.3986E+07, 3.0472E+05
254 3.5000E+02, 2.6526E+07, 2.1683E+05
255 4.0000E+02, 1.8336E+07, 1.3287E+05
256 4.5000E+02, 1.3239E+07, 8.4433E+04
257 5.0000E+02, 9.8930E+06, 4.9413E+04
258 'End_of_File'

```

Listing 6: Dose in silicon as a function of aluminum shielding thickness of a sphere.

```

1 '* ', 25, 1, 11, 10, 2, 2, 23, 0
2 'SPENVIS_4.6.10.3386_23-Jul-2020_00:09:00'
3 'PRJ_DEF', -1, 'TEST_PROJECT'

```

```

4 'PRJ.HDR', -1, 'My_Test_Project'
5 'MOD.ABB', -1, 'SH2'
6 'MIS.PLA', 1, -3, '_'
7 'MIS.NTR', 1, 1, '_'
8 'MIS.STA', 1, 9862.00000000, '_'
9 'MIS.END', 1, 15337.00000000, '_'
10 'MIS.DUR', 1, 5.475000E+03, 'days'
11 'PLT.TYP', -1, 'SUMMARY'
12 'PLT.HDR', -1, '4pi_Dose_at_Centre_of_Al_Spheres'
13 'PLT.LEG', -1, 'Solar_Protons'
14 'PS.Annotation', 8, 1
15 'Mission_start:_01/01/1977_00:00:00'
16 0.05, 0.00, 0.00
17 'Mission_end:_29/12/1991_00:00:00'
18 0.95, 0.00, 1.00
19 'Nr_of_segments:1'
20 0.05, 1.50, 0.00
21 'Duration:_5475.00_days'
22 0.95, 0.00, 1.00
23 'PS.Annotation', 0, 0
24 'Thick', 'mm', 1, 'Aluminium_Absorber_Thickness'
25 'Dose', 'rad', 1, 'Dose_in_Si'
26 1.0000E-02, 3.3911E+05
27 3.0000E-02, 1.4785E+05
28 5.0000E-02, 1.0308E+05
29 1.0000E-01, 6.4313E+04
30 2.0000E-01, 4.0112E+04
31 3.0000E-01, 3.0030E+04
32 4.0000E-01, 2.3338E+04
33 5.0000E-01, 1.8449E+04
34 6.0000E-01, 1.5023E+04
35 8.0000E-01, 1.1070E+04
36 1.0000E+00, 8.8504E+03
37 2.5000E+00, 3.7988E+03
38 5.0000E+00, 1.9959E+03
39 1.0000E+01, 8.8531E+02
40 1.2000E+01, 7.0294E+02
41 1.4000E+01, 5.5720E+02
42 1.6000E+01, 4.5273E+02
43 1.8000E+01, 3.7664E+02
44 2.0000E+01, 3.1782E+02
45 3.0000E+01, 1.4978E+02
46 5.0000E+01, 5.9685E+01
47 7.5000E+01, 2.9417E+01
48 1.0000E+02, 1.7294E+01
49 'End_of_File'

```

Listing 7: Dose in silicon as a function of aluminum shielding thickness of a slab.

```

1 '*' , 25, 1, 11, 10, 2, 2, 23, 0
2 'SPENVIS_4.6.10.3386_23-Jul-2020_00:12:47'
3 'PRJ.DEF', -1, 'TEST_PROJECT'
4 'PRJ.HDR', -1, 'My_Test_Project'
5 'MOD.ABB', -1, 'SH2'
6 'MIS.PLA', 1, -3, '_'
7 'MIS.NTR', 1, 1, '_'
8 'MIS.STA', 1, 9862.00000000, '_'

```

```
9 'MIS.END', 1, 15337.00000000,' '
10 'MIS.DUR', 1, 5.475000E+03,'days'
11 'PLT.TYP', -1,'SUMMARY'
12 'PLT.HDR', -1,'Dose at Transmission Surface of Al Slab Shields '
13 'PLT.LEG', -1,'Solar Protons '
14 'PS.Annotation', 8, 1
15 'Mission.start: 01/01/1977 00:00:00 '
16 0.05, 0.00, 0.00
17 'Mission.end: 29/12/1991 00:00:00 '
18 0.95, 0.00, 1.00
19 'Nr. of segments: 1 '
20 0.05, 1.50, 0.00
21 'Duration: 5475.00 days '
22 0.95, 0.00, 1.00
23 'PS.Annotation', 0, 0
24 'Thick', 'mm', 1, 'Aluminium Absorber Thickness '
25 'Dose', 'rad', 1, 'Dose in Si '
26 1.0000E-02, 9.7044E+04
27 3.0000E-02, 4.3388E+04
28 5.0000E-02, 3.0446E+04
29 1.0000E-01, 1.8643E+04
30 2.0000E-01, 1.0959E+04
31 3.0000E-01, 7.6311E+03
32 4.0000E-01, 5.6987E+03
33 5.0000E-01, 4.5062E+03
34 6.0000E-01, 3.7338E+03
35 8.0000E-01, 2.8126E+03
36 1.0000E+00, 2.2703E+03
37 2.5000E+00, 9.5753E+02
38 5.0000E+00, 4.5323E+02
39 1.0000E+01, 1.7843E+02
40 1.2000E+01, 1.3491E+02
41 1.4000E+01, 1.0461E+02
42 1.6000E+01, 8.3682E+01
43 1.8000E+01, 6.8164E+01
44 2.0000E+01, 5.6500E+01
45 3.0000E+01, 2.6389E+01
46 5.0000E+01, 1.0762E+01
47 7.5000E+01, 5.1030E+00
48 1.0000E+02, 2.9528E+00
49 'End of File '
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References

Donabedian, M., and D. G. Gilmore, *Spacecraft thermal control handbook*, Aerospace Press, 2003.

Joven, R., Characterization and modeling of shear stress during manufacturing and thermal properties of structural composite materials, Ph.D. thesis, Wichita State University, 2013.