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Solar Cruiser Total Ionizing Dose

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2 Mission Trajectory

The nominal Solar Cruiser location is beyond the Sun-Earth L1 point, called sub-L1, roughly 0.984 AU from the Sun. The sub-L1 location is in interplanetary space with no shielding from any planetary bodies and is exposed to the solar wind. The nominal mission length is 2 years.

3 Materials

The representative material for the Reaction Control Device (RCD) of Solar Cruiser is 150μm of Kapton. Using data from NIST[1], the composition of Kapton is shown in Table 1, where the density of Kapton is 1.42 g/cm^3.

Table 1: Composition of Kapton.

Atomic #	Fraction by Weight	Weight (amu)	Fraction by Number	Stoichiometry
1	0.026362	1.008	0.25639	10
6	0.691133	12.011	0.56412	22
7	0.073270	14.007	0.05128	2
8	0.209235	15.999	0.12821	5

4 Dose-Depth in Kapton

The SRIM (Stopping and Range of Ions in Solids) software is used to compute the dose in thin materials with no prior shielding. The SRIM software package contains TRIM (the Transport of Ions in Matter), with a screenshot of the setup used in this analysis shown in Figure 1.

The dose deposited in Kapton depends on the energy of the incident protons. As the energy increases, the depth of the deposited dose increases. In Figure 2, the colored solid curves show the percentiles of dose deposited less than a particular depth, as a function of energy for normally incident protons. For example, the purple curve shows the depth vs. energy at which 95% of the dose is deposited. From Figure 2, it is clear that the dose is not deposited uniformly. Thicknesses between the green and blue curves, 45% of the dose is deposited, as well as between the green and purple curves. Therefore, 90% of the dose is deposited between the blue and purple curves. In general, the depth vs. energy profile has a double-power-law shape

$$D(E) = \left(\frac{E}{a}\right)^b + \left(\frac{E}{c}\right)^d, \qquad (1)$$

where a is the low-energy scale, c is the high-energy scale, and b & d are the indices for each scale, respectively. As the percentile increases, the values for the energy

[1] https://physics.nist.gov/cgi-bin/Star/compos.pl?matno=179

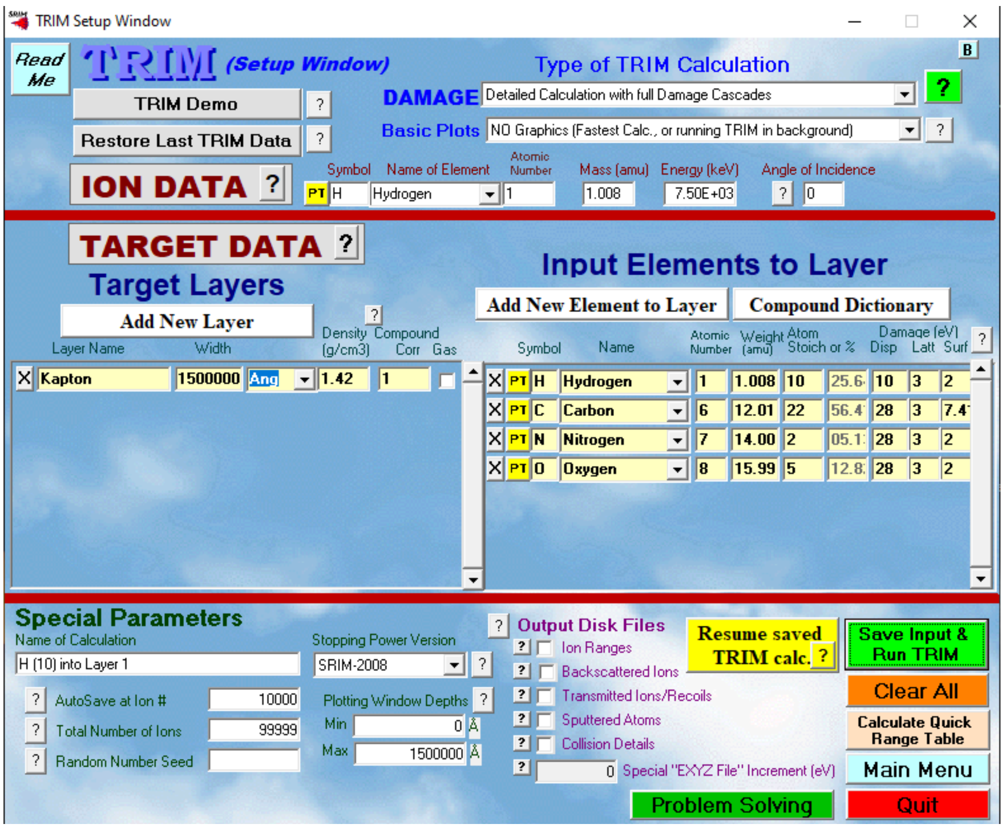

Figure 1: Example of TRIM setup.

scales a and c decreases. For a list of parameter fits, see Table 4 in Appendix A. Observing that $b < d$, the Kapton material is more effective at stopping lower energy protons ($<\sim 100$ keV) than higher energy protons.

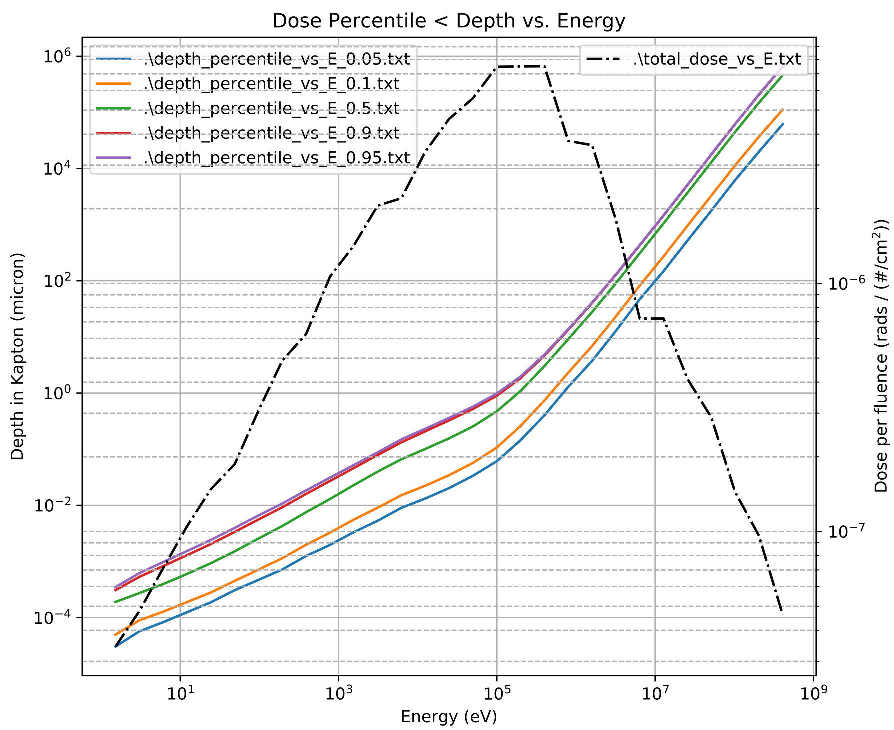

Figure 2: Left axis: Depth in Kapton vs. energy for various dose-depth percentiles. Right axis: Dose per fluence vs. energy.

The dotted-dashed curve in Figure 2 shows the total dose deposited per fluence as a function of energy. Basically, this curve can be thought of as the dose cross-section of Kapton for normally incident protons. One way to find the total dose for a given energy spectrum, one could convolute the dose cross-section with the differential energy spectrum, taking into account the depth percentile for a particular thickness of Kapton material. However, a more direct method to find the total dose is used in the following sections.

5 Natural Environment

The natural environments for the RCD of Solar Cruiser are separated into a mid-energy component (solar energetic particles, Section 5.1) and a low-energy component (background solar wind, Section 5.2). The high-energy component (galactic cosmic rays, $>$ GeV) are omitted because of the thin materials studied in this analysis. In general, for an isotropic proton environment with energies greater than ~ 6.5 MeV (see Equation (1)), the particles do not deposit a significant amount of energy in 150μm Kapton (i.e., the Bragg peak has not been reached yet).

5.1 Solar Particle Events

The solar particle event (SPE) environment for interplanetary space is derived following the same procedure as outlined in the Cross-Program Design Specification for Natural Environments (DSNE) Section 3.3.1 (see the technical notes at the end of the section). A 2-year trajectory is defined in interplanetary space at the sub-L1 location of 0.984 AU in SPENVIS[2] under the Coordinate generators tab. Once this is set, the SPE fluence is computed under the Solar particle mission fluences. The following parameters are set:

- Solar particle model: ESP-PSYCHIC (total fluence)
- Ion range: H to H
- Prediction period: override
- Prediction period [years]: 2.0
- Offset in solar cycle: override
- Offset from solar maximum [years]: 0
- Confidence level [%]: 95.0

Table 2 shows the down-selected energy bins that match DSNE Table 3.3.1.10.2-1. In terms of fluence > 100 keV, the 2-year SPE environment shown in Table 2 is $3.7\times$ greater than the unshielded SPE environment is DSNE Table 3.3.1.10.2-1.This is why it is important to run the ESP-PSYCHIC model for the required mission length and not multiply Table 3.3.1.10.2-1 by the number of years.

[2] https://www.spenvis.oma.be/

Table 2: ESP-PSYCHIC worst event fluence of protons for 2 years during solar maximum at 0.984 AU. The energy center = $\sqrt{\text{bin left edge} \times \text{bin right edge}}$.

Energy Center (keV)	Bin Flux (#/cm^2)	Bin Width (keV)	Bin Left Edge (keV)
1.58E+02	8.04E+11	1.50E+02	1.00E+02
3.54E+02	3.62E+11	2.50E+02	2.50E+02
7.07E+02	2.33E+11	5.00E+02	5.00E+02
1.41E+03	1.50E+11	1.00E+03	1.00E+03
2.65E+03	8.57E+10	1.50E+03	2.00E+03
4.18E+03	4.59E+10	1.50E+03	3.50E+03
5.96E+03	3.85E+10	2.10E+03	5.00E+03
7.54E+03	1.16E+10	9.00E+02	7.10E+03
8.49E+03	1.02E+10	1.00E+03	8.00E+03
9.49E+03	8.09E+09	1.00E+03	9.00E+03
1.26E+04	3.02E+10	6.00E+03	1.00E+04
1.70E+04	5.77E+09	2.00E+03	1.60E+04
1.90E+04	4.45E+09	2.00E+03	1.80E+04
2.24E+04	8.14E+09	5.00E+03	2.00E+04
2.96E+04	8.87E+09	1.00E+04	2.50E+04
3.74E+04	2.56E+09	5.00E+03	3.50E+04
4.24E+04	1.90E+09	5.00E+03	4.00E+04
4.74E+04	1.43E+09	5.00E+03	4.50E+04
5.96E+04	3.36E+09	2.10E+04	5.00E+04
7.54E+04	7.50E+08	9.00E+03	7.10E+04
8.49E+04	5.95E+08	1.00E+04	8.00E+04
9.49E+04	4.28E+08	1.00E+04	9.00E+04
1.26E+05	1.05E+09	6.00E+04	1.00E+05
1.70E+05	1.32E+08	2.00E+04	1.60E+05
1.90E+05	9.10E+07	2.00E+04	1.80E+05
2.24E+05	1.32E+08	5.00E+04	2.00E+05
3.16E+05	1.23E+08	1.50E+05	2.50E+05
4.47E+05	2.12E+07	1.00E+05	4.00E+05

5.2 Low-Energy Solar Wind

To compute the low-energy solar wind plasma contribution of the environment (assumed at 1 AU), the L2-CPE V1.3 software package was used. The proton fluence was computed with the setup shown in Figure 3. Other percentiles that are automatically calculated are 5%, 50%, 95%, and the maximum, mean, and minimum fluxes for each energy bin (see Listing 1 in Appendix B). Table 3 shows the reduced data in the same format as Table 2. The 95% is used in accordance with DSNE (see the technical notes at the end of Section 3.3.1). The sunward facing flux is used and assumed to be isotropic as worst-case.

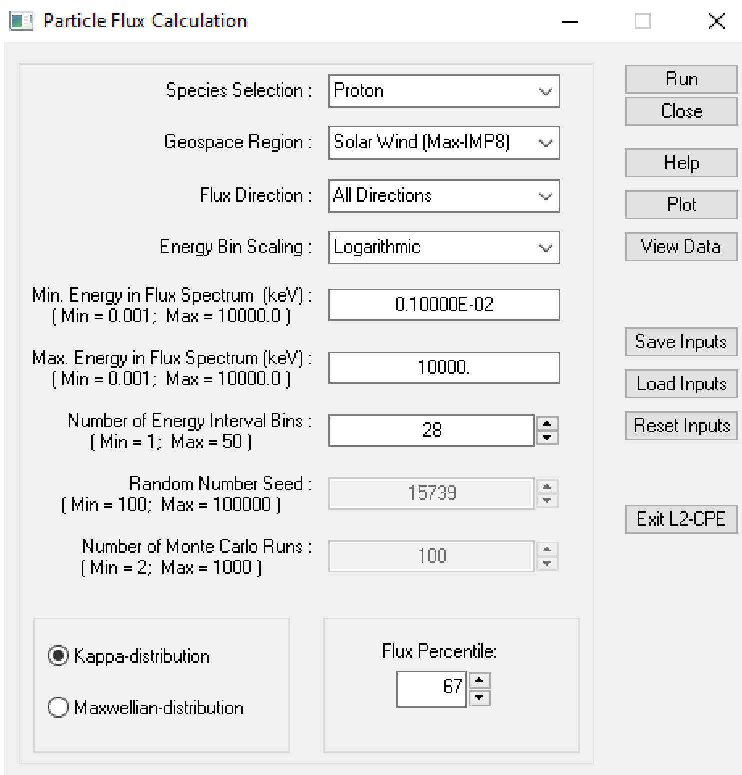

Figure 3: Screen shot of the setup used in computing the low-energy proton flux environment in L2-CPE.

Table 3: The 95% sunward solar wind environment from L2-CPE for 2 years. The energy center $= \sqrt{\text{bin left edge} \times \text{bin right edge}}$.

Energy Center (keV)	Bin Flux (#/cm^2)	Bin Width (keV)	Bin Left Edge (keV)
1.34E-03	4.97E+09	8.00E-04	1.00E-03
2.40E-03	8.36E+09	1.40E-03	1.80E-03
4.23E-03	1.38E+10	2.40E-03	3.20E-03
7.48E-03	2.24E+10	4.40E-03	5.60E-03
1.33E-02	3.50E+10	7.80E-03	1.00E-02
2.37E-02	5.29E+10	1.38E-02	1.78E-02
4.21E-02	7.66E+10	2.46E-02	3.16E-02
7.50E-02	1.05E+11	4.38E-02	5.62E-02
1.33E-01	1.37E+11	7.78E-02	1.00E-01
2.37E-01	1.64E+11	1.38E-01	1.78E-01
4.22E-01	1.86E+11	2.46E-01	3.16E-01
7.50E-01	1.94E+11	4.38E-01	5.62E-01
1.33E+00	1.88E+11	7.78E-01	1.00E+00
2.37E+00	1.68E+11	1.38E+00	1.78E+00
4.22E+00	1.40E+11	2.46E+00	3.16E+00
7.50E+00	1.10E+11	4.38E+00	5.62E+00
1.33E+01	8.21E+10	7.78E+00	1.00E+01
2.37E+01	5.75E+10	1.38E+01	1.78E+01
4.22E+01	3.91E+10	2.46E+01	3.16E+01
7.50E+01	2.56E+10	4.38E+01	5.62E+01
1.33E+02	1.65E+10	7.78E+01	1.00E+02
2.37E+02	1.04E+10	1.38E+02	1.78E+02
4.22E+02	6.43E+09	2.46E+02	3.16E+02
7.50E+02	3.91E+09	4.38E+02	5.62E+02
1.33E+03	2.35E+09	7.78E+02	1.00E+03
2.37E+03	1.43E+09	1.38E+03	1.78E+03
4.22E+03	8.50E+08	2.46E+03	3.16E+03
7.50E+03	5.05E+08	4.38E+03	5.62E+03

6 Total Ionizing Dose

6.1 Solar Particle Events

6.2 Low-Energy Solar Wind

7 Results

A Dose Percentile-Depth vs. Energy Parameters Fits

Table 4: Parameter fits to Equation (1) for various dose percentiles using normally incident protons.

Percentile/100	a	b	c	d
0.05	8.445E+00	6.539E-01	4.543E+03	1.785E+00
0.10	4.414E+00	6.654E-01	3.267E+03	1.786E+00
0.15	2.923E+00	6.729E-01	2.682E+03	1.787E+00
0.20	2.171E+00	6.793E-01	2.339E+03	1.788E+00
0.25	1.723E+00	6.845E-01	2.109E+03	1.789E+00
0.30	1.429E+00	6.894E-01	1.947E+03	1.790E+00
0.35	1.216E+00	6.937E-01	1.826E+03	1.792E+00
0.40	1.057E+00	6.976E-01	1.732E+03	1.793E+00
0.45	9.332E-01	7.013E-01	1.658E+03	1.794E+00
0.50	8.296E-01	7.043E-01	1.598E+03	1.795E+00
0.55	7.407E-01	7.067E-01	1.549E+03	1.796E+00
0.60	6.660E-01	7.089E-01	1.510E+03	1.798E+00
0.65	6.006E-01	7.109E-01	1.479E+03	1.799E+00
0.70	5.423E-01	7.128E-01	1.456E+03	1.800E+00
0.75	4.868E-01	7.140E-01	1.438E+03	1.801E+00
0.80	4.309E-01	7.141E-01	1.423E+03	1.802E+00
0.85	3.744E-01	7.131E-01	1.412E+03	1.803E+00
0.90	3.140E-01	7.104E-01	1.402E+03	1.804E+00
0.95	2.441E-01	7.046E-01	1.396E+03	1.804E+00
0.99	1.554E-01	6.904E-01	1.393E+03	1.805E+00
0.999	9.998E-02	6.752E-01	1.394E+03	1.807E+00
0.9999	7.282E-02	6.638E-01	1.385E+03	1.806E+00

B Raw L2-CPE output of the Interplanetary Proton Environment

Listing 1: The sunward facing flux (worst-case) during solar maximum from IMP8 using L2-CPE.

```
                                           - FLUX SUMMARY -
L2-CPE V1.3            Kappa-distribution
Cartesian (LRAD) Algorithm


Phenomenological Region  =>  Solar Wind at SolMax (IMP-8)



Species  =>  Protons

Positive X direction flux calculated.

Minimum Energy =      0.0010 keV
Maximum Energy = 10000.0000 keV

Number of Energy Bins =    28

50% Total Flux        =   0.6109E+03 (#/cm^2/sec)
95% Total Flux        =   0.2986E+05 (#/cm^2/sec)
 5% Total Flux        =   0.6493E+01 (#/cm^2/sec)
 67% Total Flux       =   0.1896E+04 (#/cm^2/sec)
Maximum Total Flux    =   0.5679E+07 (#/cm^2/sec)
Minimum Total Flux    =   0.1387E-02 (#/cm^2/sec)
Mean Total Flux       =   0.7319E+04 (#/cm^2/sec)
Std. Dev. Total Flux  =   0.4616E+05 (#/cm^2/sec)


                        Differential Energy Flux Table  (#/cm^2/sec/keV)

   E1(keV)   E2(keV)    50%          95%          5%           67%
   Maximum      Minimum      Mean        Std. Dev.
   0.0010     0.0018  0.4228E+04  0.1013E+06  0.8432E+02  0.1078E+05  0.4149E
   +08  0.2333E-01  0.2406E+05  0.1700E+06
   0.0018     0.0032  0.3944E+04  0.9578E+05  0.7729E+02  0.1009E+05  0.3867E
   +08  0.2121E-01  0.2272E+05  0.1597E+06
   0.0032     0.0056  0.3597E+04  0.8902E+05  0.6892E+02  0.9277E+04  0.3526E
   +08  0.1871E-01  0.2109E+05  0.1472E+06
   0.0056     0.0100  0.3200E+04  0.8097E+05  0.5914E+02  0.8297E+04  0.3125E
   +08  0.1588E-01  0.1914E+05  0.1324E+06
   0.0100     0.0178  0.2742E+04  0.7134E+05  0.4856E+02  0.7171E+04  0.2671E
   +08  0.1282E-01  0.1688E+05  0.1155E+06
   0.0178     0.0316  0.2252E+04  0.6065E+05  0.3763E+02  0.5959E+04  0.2182E
   +08  0.9715E-02  0.1437E+05  0.9709E+05
   0.0316     0.0562  0.1746E+04  0.4935E+05  0.2715E+02  0.4692E+04  0.1685E
   +08  0.6801E-02  0.1173E+05  0.7806E+05
   0.0562     0.1000  0.1268E+04  0.3808E+05  0.1798E+02  0.3485E+04  0.1216E
   +08  0.4322E-02  0.9100E+04  0.5960E+05
   0.1000     0.1778  0.8508E+03  0.2786E+05  0.1078E+02  0.2404E+04  0.8108E
   +07  0.2350E-02  0.6656E+04  0.4296E+05
   0.1778     0.3162  0.5214E+03  0.1882E+05  0.5686E+01  0.1526E+04  0.4940E
   +07  0.1078E-02  0.4558E+04  0.2909E+05
   0.3162     0.5623  0.2876E+03  0.1200E+05  0.2641E+01  0.8831E+03  0.2727E
   +07  0.4226E-03  0.2905E+04  0.1846E+05
   0.5623     1.0000  0.1428E+03  0.7016E+04  0.1063E+01  0.4634E+03  0.1357E
   +07  0.1060E-03  0.1717E+04  0.1096E+05
```

```
   1.0000     1.7783   0.6332E+02   0.3824E+04   0.3668E+00   0.2177E+03   0.6088E
   +06  0.2191E-04  0.9409E+03  0.6094E+04
   1.7783     3.1623   0.2496E+02   0.1928E+04   0.1092E+00   0.9264E+02   0.2900E
   +06  0.3786E-05  0.4789E+03  0.3183E+04
   3.1623     5.6234   0.8762E+01   0.9028E+03   0.2810E-01   0.3574E+02   0.1467E
   +06  0.5546E-06  0.2276E+03  0.1569E+04
   5.6234    10.0000   0.2794E+01   0.3977E+03   0.6305E-02   0.1251E+02   0.7069E
   +05  0.7017E-07  0.1018E+03  0.7351E+03
  10.0000    17.7828   0.8167E+00   0.1673E+03   0.1265E-02   0.4048E+01   0.3331E
   +05  0.7825E-08  0.4326E+02  0.3295E+03
  17.7828    31.6228   0.2200E+00   0.6582E+02   0.2297E-03   0.1225E+01   0.1518E
   +05  0.7849E-09  0.1764E+02  0.1422E+03
  31.6228    56.2341   0.5576E-01   0.2516E+02   0.3830E-04   0.3482E+00   0.6881E
   +04  0.7220E-10  0.6967E+01  0.5949E+02
  56.2341   100.0000   0.1341E-01   0.9267E+01   0.5868E-05   0.9401E-01   0.2985E
   +04  0.6195E-11  0.2690E+01  0.2427E+02
 100.0000   177.8279   0.3090E-02   0.3361E+01   0.8546E-06   0.2441E-01   0.1249E
   +04  0.5030E-12  0.1023E+01  0.9707E+01
 177.8279   316.2278   0.6874E-03   0.1191E+01   0.1201E-06   0.6135E-02   0.5097E
   +03  0.3913E-13  0.3849E+00  0.3827E+01
 316.2278   562.3413   0.1495E-03   0.4141E+00   0.1598E-07   0.1510E-02   0.2056E
   +03  0.2944E-14  0.1441E+00  0.1493E+01
 562.3413  1000.0000   0.3152E-04   0.1416E+00   0.2079E-08   0.3623E-03   0.8160E
   +02  0.2159E-15  0.5386E-01  0.5782E+00
1000.0000  1778.2794   0.6590E-05   0.4795E-01   0.2656E-09   0.8677E-04   0.3197E
   +02  0.1552E-16  0.2013E-01  0.2229E+00
1778.2794  3162.2776   0.1354E-05   0.1634E-01   0.3325E-10   0.2047E-04   0.1240E
   +02  0.1100E-17  0.7536E-02  0.8573E-01
3162.2776  5623.4131   0.2765E-06   0.5473E-02   0.4064E-11   0.4813E-05   0.4777E
   +01  0.6855E-19  0.2829E-02  0.3294E-01
5623.4131  10000.0000   0.5583E-07   0.1828E-02   0.4980E-12   0.1122E-05   0.1829E
   +01  0.3413E-20  0.1066E-02  0.1266E-01


                         Particle Flux per Energy Bin Table  (#/cm^2/sec)

   E1(keV)   E2(keV)    50%          95%          5%          67%
   Maximum      Minimum      Mean        Std. Dev.
   0.0010     0.0018   0.3291E+01   0.7883E+02   0.6563E-01   0.8387E+01   0.3229E
   +05  0.1815E-04  0.1873E+02  0.1323E+03
   0.0018     0.0032   0.5458E+01   0.1326E+03   0.1070E+00   0.1397E+02   0.5352E
   +05  0.2935E-04  0.3145E+02  0.2211E+03
   0.0032     0.0056   0.8853E+01   0.2191E+03   0.1696E+00   0.2283E+02   0.8678E
   +05  0.4606E-04  0.5190E+02  0.3623E+03
   0.0056     0.0100   0.1400E+02   0.3544E+03   0.2588E+00   0.3631E+02   0.1368E
   +06  0.6950E-04  0.8375E+02  0.5794E+03
   0.0100     0.0178   0.2134E+02   0.5552E+03   0.3779E+00   0.5581E+02   0.2079E
   +06  0.9978E-04  0.1314E+03  0.8989E+03
   0.0178     0.0316   0.3117E+02   0.8393E+03   0.5209E+00   0.8248E+02   0.3019E
   +06  0.1345E-03  0.1989E+03  0.1344E+04
   0.0316     0.0562   0.4296E+02   0.1215E+04   0.6682E+00   0.1155E+03   0.4147E
   +06  0.1674E-03  0.2887E+03  0.1921E+04
   0.0562     0.1000   0.5549E+02   0.1666E+04   0.7870E+00   0.1525E+03   0.5322E
   +06  0.1891E-03  0.3983E+03  0.2608E+04
   0.1000     0.1778   0.6622E+02   0.2169E+04   0.8392E+00   0.1871E+03   0.6310E
   +06  0.1829E-03  0.5180E+03  0.3343E+04
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```
    0.1778      0.3162   0.7216E+02   0.2605E+04   0.7869E+00   0.2113E+03   0.6837E
    +06   0.1492E-03   0.6308E+03   0.4026E+04
    0.3162      0.5623   0.7079E+02   0.2952E+04   0.6500E+00   0.2173E+03   0.6712E
    +06   0.1040E-03   0.7149E+03   0.4543E+04
    0.5623      1.0000   0.6250E+02   0.3071E+04   0.4650E+00   0.2028E+03   0.5941E
    +06   0.4638E-04   0.7516E+03   0.4797E+04
    1.0000      1.7783   0.4928E+02   0.2976E+04   0.2854E+00   0.1694E+03   0.4738E
    +06   0.1705E-04   0.7323E+03   0.4743E+04
    1.7783      3.1623   0.3454E+02   0.2669E+04   0.1511E+00   0.1282E+03   0.4014E
    +06   0.5240E-05   0.6628E+03   0.4405E+04
    3.1623      5.6234   0.2156E+02   0.2222E+04   0.6916E-01   0.8797E+02   0.3611E
    +06   0.1365E-05   0.5602E+03   0.3862E+04
    5.6234     10.0000   0.1223E+02   0.1741E+04   0.2760E-01   0.5475E+02   0.3094E
    +06   0.3071E-06   0.4456E+03   0.3217E+04
   10.0000     17.7828   0.6356E+01   0.1302E+04   0.9842E-02   0.3150E+02   0.2593E
    +06   0.6090E-07   0.3367E+03   0.2564E+04
   17.7828     31.6228   0.3045E+01   0.9110E+03   0.3178E-02   0.1696E+02   0.2101E
    +06   0.1086E-07   0.2441E+03   0.1968E+04
   31.6228     56.2341   0.1372E+01   0.6192E+03   0.9425E-03   0.8571E+01   0.1693E
    +06   0.1777E-08   0.1715E+03   0.1464E+04
   56.2341    100.0000   0.5868E+00   0.4056E+03   0.2568E-03   0.4114E+01   0.1306E
    +06   0.2711E-09   0.1177E+03   0.1062E+04
  100.0000    177.8279   0.2405E+00   0.2616E+03   0.6651E-04   0.1900E+01   0.9719E
    +05   0.3915E-10   0.7958E+02   0.7555E+03
  177.8279    316.2278   0.9513E-01   0.1649E+03   0.1662E-04   0.8491E+00   0.7055E
    +05   0.5415E-11   0.5327E+02   0.5296E+03
  316.2278    562.3413   0.3678E-01   0.1019E+03   0.3933E-05   0.3717E+00   0.5061E
    +05   0.7245E-12   0.3547E+02   0.3674E+03
  562.3413   1000.0000   0.1380E-01   0.6197E+02   0.9101E-06   0.1586E+00   0.3571E
    +05   0.9447E-13   0.2357E+02   0.2531E+03
 1000.0000   1778.2794   0.5129E-02   0.3732E+02   0.2067E-06   0.6753E-01   0.2488E
    +05   0.1208E-13   0.1567E+02   0.1735E+03
 1778.2794   3162.2776   0.1874E-02   0.2261E+02   0.4601E-07   0.2833E-01   0.1717E
    +05   0.1522E-14   0.1043E+02   0.1186E+03
 3162.2776   5623.4131   0.6804E-03   0.1347E+02   0.1000E-07   0.1185E-01   0.1176E
    +05   0.1687E-15   0.6963E+01   0.8106E+02
 5623.4131  10000.0000    0.2443E-03   0.8000E+01   0.2180E-08   0.4910E-02   0.8007E
    +04   0.1494E-16   0.4665E+01   0.5541E+02

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            TOTALS:      0.5836E+03   0.2937E+05   0.6244E+01   0.1811E+04   0.6977E
    +07   0.1260E-02   0.7319E+04   0.5040E+05
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