

SPENVIS

SPace ENVironment Information System

Technical Note 13

Generation of shielded flux look-up tables using MULASSIS

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Preface

This document describes the approach followed for developing a tool that generates automatically MULASSIS Geant4 macros and by analysing the resulting outputs creates appropriate look-up tables.

A second application, has been implemented in the World Wide Web (WWW) based SPace ENVironment Information System (SPENVIS), employs those data in order to evaluate the flux/fluence behind some shielding for a number of user provided inputs (total shield thickness, Tantalum to Aluminium ratio and incident particle source).

Chapter 1

Introduction

The interaction of the space radiation with the satellite shielding can cause reduction of the fluxes of primary particles, creation and subsequent absorption of secondary particles and changes in the energy spectra [2]. Thus, calculating the effects of space radiation on spacecraft components is a particularly complex problem.

A number of methods have been developed in the recent years ranging from simplified approaches like dose look-up table methods (e.g. SHIELDOSE [4], [5] and its undocumented SHIELDOSE-2 upgrade) to more detailed sector shielding calculations and full Monte-Carlo (MC) simulations of the interaction of space radiation with matter (e.g. MULASSIS [12], [3]). For an extensive review of these methods see [7] and [2].

The main idea for this work package was the creation of look-up tables using data generated by multiple MULASSIS runs. A second application, that has been implemented in the World Wide Web (WWW) based SSpace ENVironment Information System (SPENVIS), utilises those data in order to evaluate the fluence/flux behind some shielding for a number of user provided inputs (e.g. total shield thickness, Tantalum to Aluminium ratio and incident particle source).

For the generation of the appropriate data, multiple runs of MULASSIS were required. Hence, some simplifying assumptions have been made for the generation of the MULASSIS macro files:

- **Geometry:** Planar slab with three layers (Al shielding, Ta shielding and Si target). Shielding could vary while target is assumed to be a thin detector of $0.023 \text{ [g/cm}^2\text{]}$ ($100 \text{ [}\mu\text{m}]$).
- **Source:** Incident particles are almost mono-energetic (constant energy spectrum over a very small energy range) protons or electrons, following an omnidirectional angular distribution.
- **Analysis:** Fluence/flux (choosing an intelligent way for defining the energy binning).

The basic geometry is shown in **figure 1.1**.

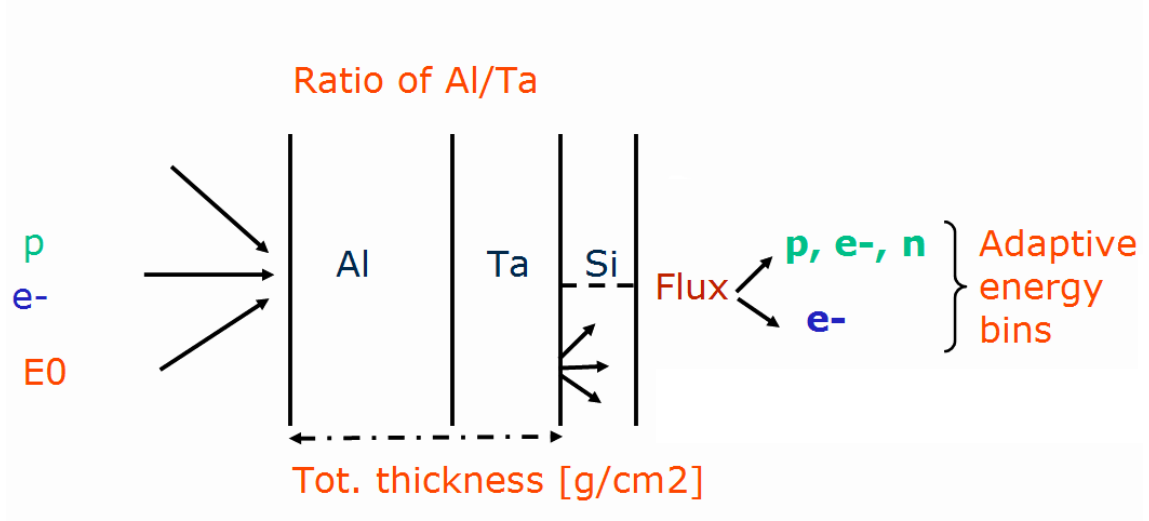


Figure 1.1. Basic geometry adopted for the MULASSIS simulations.

Given the initial energy E_0 , the total shielding and the Tantalum to Aluminium ratio, our basic strategy was the following:

1. Find appropriate energy binning schemes by calculating the energy of primaries after passing through shield (make use of NIST Al stopping power [10]).
2. Generate MULASSIS macro files following the above simplifying assumptions.
3. Make the MULASSIS runs and process the results in order to create the look-up tables.

For the first step, when calculating the maximum energy deposited for a given incident energy and shielding thickness the PSTAR/ESTAR NIST data are used [9],[8]. This information was then used for specifying the energy binning scheme for the MULASSIS fluence/flux analysis.

Next, we present some basic definitions and describe the physical principles of the interaction of energetic particles (protons and electrons) with matter. After that we illustrate the preliminary calculations using the PSTAR/ESTAR NIST data. Finally, we describe in detail how the MULASSIS macro files were created and how the look-up tables were generated using the output of the corresponding MULASSIS runs.

Chapter 2

Interaction of energetic particles with material

Energetic particles (i.e. electrons and protons) passing through material can undergo a variety of interactions leading to energy-loss, scattering and possible generation of secondary particles [2],[7].

In the following, we give a brief description of the physical principles that govern the transfer of energy from the incoming radiation flux to the device materials.

2.1 Basic concepts

When a stream of mono-energetic particles passes through a material, the energy and particle flux are both reduced. **Number transmission coefficient** (*NTC*) [2] is defined as the ratio of total emergent particle fluence, N_{out} over the total incident particle fluence, N_{in} ,

$$NTC = \frac{N_{out}}{N_{in}}. \quad (2.1)$$

The **Stopping power** of the material is defined as the rate of energy loss of the incident particles with distance crossed and is given by [2],

$$-\frac{dE}{dx} = \frac{ne^4z^2N_AZ}{mv^2A}B, \quad (2.2)$$

where n is an integer (2 for electron and 4 for ion), N_A/A is the number of atoms of atomic number Z per unit volume (N_A is the Avogadro's number equal to 6×10^{23} atoms per mole), A is the atomic mass of the absorber, z and v are the charge number (1 for electron) and the velocity of the incident particle, e and m are the charge and mass of the electron and x is the path length or distance measured along the track of a particle. Finally, B (B_e for electron and B_i for ion) is a function of the incident particle energy (rises slowly with E) known as the **stopping**

number of the material. The stopping power is often measured in units of energy loss per unit mass thickness along the particle path i.e. $[\text{MeVg}^{-1}\text{cm}^2]$.

The **total stopping power** for electrons is assumed to be the sum of the collision and radiative stopping powers while for protons and helium ions the sum of collision and nuclear stopping powers [10].

The **range** of a charged particle in a material is defined as the thickness of material penetrated before the particle losses all its energy. Range can be expressed in units of depth (length) or more often in units of $[\text{g/cm}^2]$ (product of depth and density) [2]. The latter unit is equivalent to mass per unit area and is frequently used in radiation studies as a measure of absorber or shield thickness. Note that the range of a charged particle at a given incident particle energy when expressed in $[\text{g/cm}^2]$ is closely similar for all materials. Second order effects that depend on excitation potential and atomic number can be ignored for the energies likely to be encountered in the space environment.

One can also use the term **practical range** for the most probable range of a particle of a given incident energy [2]. Finally, **maximum range** takes into account the fact that some particles (e.g. straggling electrons) can clearly penetrate thicknesses greater than the practical range.

A particularly useful concept is the **CSDA range** [10]. This is a very close approximation to the average path length traveled by a charged particle as it slows down to rest, calculated in what is known as the **continuous-slowing-down approximation**. In this approximation, the rate of energy loss at every point along the track is assumed to be equal to the total stopping power. Energy-loss fluctuations are neglected. The CSDA range is obtained by integrating the reciprocal of the total stopping power with respect to energy.

Dose is the energy deposited per unit mass of material (physical absorbed dose) and it is the basic parameter for evaluating ionisation-induced damage [2], [7]. The dose deposited in a target depends on

- the incident particle type and
- the energy that the particle retains after passing through any surrounding absorber.

The dose is computed from the product of the **particle fluence** at a particular point and the **restricted stopping power** of the particle (generation of secondaries that can travel some distance before depositing their energy is excluded).

The evaluation of biological effects of radiation is more complex and involves the use of an empirical factor known as **dose equivalent** [7]. This factor attempts to account for the differences in the effects of the same absorber dose of different radiation types. This can be a highly complex procedure and it is outside the scope of this work.

2.2 Space radiation environment particles

Energetic charged particles with energies in the MeV range and above are encountered throughout the magnetosphere of Earth, in the interplanetary space and the magnetospheres of other planets. For the purpose of this report we are focusing only on the interaction of electrons, protons and ions with the matter. These can be either trapped particles (electrons or protons/ions) forming the radiation belts, solar energetic particles (SEP) ejected from the Sun or galactic cosmic rays (GCR) [6].

2.2.1 Electrons

The main interaction of electrons with material occurs mainly at the atomic level. Thus, they produce excitation and ionisation when losing energy and being scattered. Because of their low mass relative to nuclei, electrons are readily scattered through angles. Hence, complete backscattering of electrons from materials can be significant, especially in high- Z materials. In addition, electron acceleration in the strong electric fields of the atom result in the generation of energetic photons in a process known as bremsstrahlung.

The degree of scattering depends on the shielding material, the incident electron energy and angle. For example, when mono-energetic electrons pass through a material the energy spectrum behind the shield is broadened and somewhat asymmetric. Nevertheless, a clearly dominant energy peak is preserved with a value that is less than the incident energy.

For electrons in the energy range less than 5 [MeV] (typical of the Earth's trapped radiation belts) almost all energy loss during passage through material is by interaction mechanisms that result in ionisation of the material, i.e. the creation of electron-hole pairs with no momentum transfer to the atoms.

From equation (2.2) one can see that the electron stopping power first falls rapidly with increasing E due to the $1/v^2$ dependence until it reaches a minimum as v approaches the speed of light in vacuum. At higher energies, dE/dx rises slowly since v is limited and B_e dependence is dominant. The minimum stopping power for electrons occurs at energies in the range of 1-2 [MeV]. Hence, electrons at this energy are said to be minimum ionising [2].

Besides the energy loss by collision, there is an additional contribution to stopping power due to radiation loss from bremsstrahlung. At energies below 1 [MeV] the energy loss from collisions is the main mechanism and radiation loss becomes dominant only at energies well above 10 [MeV]. Thus, for a typical near-Earth electron spectrum only a very small fraction of the energy passes into bremsstrahlung. Nevertheless, this radiation is so much more penetrating that it emerges as a significant remaining "background" when all electrons have been stopped.

2.2.2 Bremsstrahlung

Bremsstrahlung radiation is produced by the slowing down of energetic electrons in the atomic electric field of materials.

Photons produced by the bremsstrahlung mechanism pose a significant danger in space applications because the ranges of the photons are generally greater than those of the primary electrons.

The production of bremsstrahlung is higher in materials of high atomic number, Z . Attenuation due to bremsstrahlung depends strongly on the energy [2]:

- Photoelectric absorption usually dominates below 0.1 [MeV]
- Compton scattering around 1 [MeV]
- Pair-production above 10 [MeV].

Note that all the above processes result in the production of further electrons.

2.2.3 Protons and ions

Energetic protons and ions because they are heavier particles follow normally virtually straight paths (they are not subject to the high degree of scattering experienced by electrons). Therefore, they have well defined ranges and it is relatively easy to compute their slowing and their energy deposition in materials. Protons and other ions can also interact with atomic nuclei, causing fragmentation of the nucleus or generation of secondary neutrons or protons (the probability of such event is small but not negligible). Unlike protons, neutrons are slowed down by the nuclei of atoms. Therefore, the process varies with the individual tendencies of nuclei to capture or be excited by the neutrons.

It is obvious, from equation (2.2) that fully ionised energetic ions such as cosmic rays deposit their energy very rapidly in a material. This in turn gives rise to single-event phenomena (SEU, latch-up and radiobiological) [2].

Chapter 3

Preliminary calculations

In this section we describe how we calculate the maximum energy of particles after passing through the shielding and how we use this information to find an appropriate energy binning scheme for the MULASSIS fluence analysis.

The total stopping power and the CSDA range for Aluminium used here have been calculated as a function of the kinetic energy of the incident protons and electrons using the NIST PSTAR [9] and ESTAR [8] programs respectively (appendices A and B). Note that for the following calculations we use the total shielding value but assuming that the shielding material is Aluminium.

3.1 Calculation of particle energy behind shielding

Suppose that the energy for the incident particle is E_0 , measured in [MeV] and the Al shielding thickness is D_{Al} , given in units of [g/cm²]. The first step is to calculate the range, R , using the CSDA NIST data [9] included in appendices A and B.

If E_0 corresponds to an already existing energy value, then the range value is simply taken from the NIST table and $R = R(E_0)$. Otherwise, we find where E_0 is situated, i.e. $E_1 < E_0 < E_2$ where E_1 and E_2 are existing values from the table. Then, a power law interpolation is used for calculating the corresponding range,

$$R(E_0) = \exp \left[\frac{(\ln E_0 - \ln E_1) \ln R(E_2) + (\ln E_2 - \ln E_0) \ln R(E_1)}{\ln E_2 - \ln E_1} \right] \quad (3.1)$$

Next, we calculate the energy loss (E_{abs}) of the particles after passing through the shielding. First, we compare the given Al thickness, D_{Al} , with the calculated range, $R(E_0)$. If the thickness is greater than the range then no protons are assumed to go through the shielding ($E_{abs} = E_0$ and $E_{out} = 0$).

If the thickness is less than the range then we have to calculate the stopping power, $S(E_0)$, corresponding to the energy E_0 . As before, if E_0 corresponds to an already existing energy

value, then the range value is simply taken from the NIST table, Otherwise we use a power law interpolation,

$$S(E_0) = \exp \left[\frac{(\ln E_0 - \ln E_1) \ln S(E_2) + (\ln E_2 - \ln E_0) \ln S(E_1)}{\ln E_2 - \ln E_1} \right] \quad (3.2)$$

where $E_1 < E_0 < E_2$.

Remember that the stopping power is defined as the energy loss per unit length [2],

$$S(E) = -\frac{dE}{dx} \iff E_{abs} = \int_0^{D_{Al}} S(E(x))dx \quad (3.3)$$

Therefore, the absorbed energy can be calculated by

$$E_{abs} = \int_0^{D_{Al}} S(E(x))dx \quad (3.4)$$

In order to solve the above integral numerically we define,

$$\Delta x = \frac{R(E_0)}{N}, \quad (3.5)$$

where N is an arbitrary constant (we have assumed $N = 15$). Hence, we define the following discretisation

$$x_i = x_{i-1} + \Delta x, \quad x_0 = 0 \quad (3.6)$$

The energy loss for $E_0(x_i)$ is calculated using,

$$\begin{aligned} \Delta E_i &= S(E_0(x_i))dx, & dx &= \Delta x & \text{if } x_i + \Delta x < D_{Al} \\ & & dx &= D_{Al} - x_i & \text{otherwise} \end{aligned} \quad (3.7)$$

with

$$\Delta E_0 = S(E_0)dx, \quad E_0(x_0) = E_0, \quad (3.8)$$

where $S(E_0(x_i))$ is calculated using (3.2) for the appropriate energy. Finally, a new energy is calculated using

$$E_0(x_{i+1}) = E_0(x_i) - \Delta E_i. \quad (3.9)$$

While x_i smaller than the Aluminium thickness, D_{Al} , we repeat the above procedure for each energy given by equation (3.9), calculating always the appropriate stopping power i.e. $S(E_0(x_{i+1}))$.

The total absorbed energy by the shielding is given by

$$E_{abs}(E_0) = \sum_i \Delta E_i \quad (3.10)$$

and therefore the energy of the escaping incident particles (protons or electrons) after passing through the shielding is simply,

$$E_{out} = E_0 - E_{abs}(E_0). \quad (3.11)$$

Finally, note that this approach works better for incident protons where equation (3.11) provides the mean energy of the escaping protons. When the incident particles are electrons this is only a rough approximation since we expect to have additional secondary electrons from bremsstrahlung (1D approximation not very good). In this case, (3.11) provides only an order of magnitude for the mean energy of the escaping electrons.

3.2 Calculation of the energy binning scheme

We can now use E_{out} calculated by equation (3.11) to define appropriate reference energies in order to bin the results of MULASSIS. Note that this is an empirical approach following some very simple approximations. We define,

$$\begin{aligned} E_{0max} &= E_0 + E_0 \cdot dE_0 \\ E_{0min} &= E_0 - E_0 \cdot dE_0, \end{aligned} \quad (3.12)$$

where we assume $dE_0 = 0.01$. We can then use equation (3.11) and write

$$\begin{aligned} E_{out}(E_{0max}) &= E_{0max} - E_{abs}(E_{0max}) \\ E_{out}(E_{0min}) &= E_{0min} - E_{abs}(E_{0min}), \end{aligned} \quad (3.13)$$

where $E_{abs}(E_{0max})$ and $E_{abs}(E_{0min})$ are given by (3.10).

We first assume that the incident particles are protons. In this case, we expect to have escaping protons and secondary electrons and neutrons behind the shielding.

We define the energy of secondary electrons behind the shielding as

$$E_{out}^{e-} = 2 \frac{\left[\max(E_{0max}, E_{0min}) - \min(E_{abs}(E_{0max}), E_{abs}(E_{0min})) \right]}{n}, \quad (3.14)$$

where n is the proton to electron mass ratio, $m_p/m_{e-} \simeq 1836$. The max, min are used in order to avoid potential problems when incident energy is absorbed completely by the shielding.

Hence, the energy step for the electron can binning scheme be expressed as

$$\Delta E_{e^-} = \frac{E_{out}^{e^-}}{N_1}, \quad (3.15)$$

where N_1 is another arbitrary constant.

In a similar way, we can define the energy of escaping protons behind the shielding as

$$E_{out}^p = \max(E_{0max}, E_{0min}) - \min(E_{abs}(E_{0max}), E_{abs}(E_{0min})) \quad (3.16)$$

and energy step for protons as

$$\Delta E_p = \frac{E_{out}^p}{N_1}. \quad (3.17)$$

Finally, for the neutrons we simply assume that the energy step is the same as for the protons,

$$\Delta E_n = \Delta E_p. \quad (3.18)$$

The three energy steps calculated above (ΔE_{e^-} , ΔE_p and ΔE_n) are used for defining an appropriate energy binning scheme that in turn will be used as an input for the MULASSIS macro file. We assume $5N_1/4$ energy bins for each particle species (proton, neutron and electron). Thus, the maximum number of energy bins considered can not be larger than $n_{bins} = 15N_1/4$. We also make the additional assumption that the difference between two successive energy bin values must be smaller than 10^{-6} [MeV].

When the incident particles are assumed to be electrons, we are interested mostly on the escaping (incident plus secondary) electrons. We define the energy of the electrons behind the shielding as

$$E_{out}^{e^-} = \max(E_{0max}, E_{0min}) - \min(E_{abs}(E_{0max}), E_{abs}(E_{0min})) \quad (3.19)$$

and thus the energy step for the electron energy binning scheme as

$$\Delta E_{e^-} = \frac{E_{out}^{e^-}}{N_1}. \quad (3.20)$$

Chapter 4

Creation of the look-up tables

In this chapter we describe the generation of the MULASSIS macro files, the processing of the resulting output files and finally the creation of the look-up tables.

The macro files were generated using different values for the incident particle energy, E_0 , the total thicknesses and the ratios of Tantalum to Aluminium (see **table 4.1**). In total, three hundred and eighty four runs of MULASSIS were performed in order to produce the corresponding look-up tables.

E_0 [MeV]		Total Shielding [g/cm ²]	Ta/Al Ratio [%]
proton	electron		
10.0	0.1	0.1	0
30.0	1.0	0.5	5
50.0	3.0	1.0	15
80.0	10.0	2.0	35
100.0	30.0	3.0	
300.0	100.0	5.0	
500.0	300.0		
800.0			
1000.0			

Table 4.1. Different values for the incident particle energy, E_0 , total thicknesses and Ta/Al ratios used for the generation of MULASSIS macro files.

4.1 MULASSIS macro file generation

In this section we describe the generation of the MULASSIS Geant4 macros. Each macro file consists of a header and five distinct macro command sections for specifying the geometry, anal-

ysis, physics, source and the run control. A FORTRAN program was created for the automated generation of the macro files.

4.1.1 Header

The header includes a short summary that describes the type of the incident particle, its maximum energy and range. Information is also provided about the total shielding, the Aluminium shielding, the percentage of Tantalum shielding and the number of events requested for the simulation. Moreover, the energy bin steps for electron, neutron and proton calculated (see chapter 3) are displayed. Finally, the arbitrary variable used for specifying the energy steps and the number of the energy bins calculated are also provided.

4.1.2 Geometry

In the geometry section we have modeled the basic geometry described in **figure 1.1**. Therefore, we assumed a slab geometry with a layer representing the Aluminium shielding, a second shielding layer of Tantalum when required and finally a target layer of Silicon. All layer thicknesses were given in units of $[g/cm^2]$. The Silicon layer was taken to be equal to $0.023 [g/cm^2]$.

4.1.3 Analysis

The first entry for this section concerns the specification of a normalisation factor. For more details about how this factor was calculated see the MULASSIS documentation [3], [12]. Next, the type of analysis was specified, namely the fluence analysis for MULASSIS.

More specifically, the omnidirectional fluence of secondary particles (protons, electrons and neutrons) behind the total shielding was requested. Note that when the incident particles are electrons the analysis refers to secondary electrons only. The units of fluence used in the MULASSIS output was defined as $[particles/cm^2]$ per bin.

Remember that the histogram binning scheme for the fluence analysis can be defined in energy and angle. In addition, one has the possibility to define arbitrary energy and angle schemes by specifying the edges of each bin.

For the purpose of this work, we utilised the calculations presented in the previous chapter for defining an appropriate energy binning scheme in an automated way. This in turn, was registered as an arbitrary energy binning scheme in the MULASSIS macro file. Note that the lower-edge of the lowest bin and the upper-edge of the highest energy binning scheme is given by equation (3.12). The energy bins were given in units of $[MeV]$.

Finally, the default binning scheme for angles was considered i.e. linear from 0 to 180 $[deg]$. More specifically, it consisted of two bins, one for monitoring forward (0 to 90 $[deg]$) and one for monitoring backward (90 to 180 $[deg]$) propagation at a specific boundary.

4.1.4 Physics scenario and cut values

For the physics scenario we assume standard electromagnetic (EM) processes but also hadronic nuclear interactions. The latter includes low energy neutrons and lepton-gamma processes. **Figures 4.2 and 4.3** show the effect of the choice of physics scenario (EM or EM with hadronic processes) can have on the MULASSIS runs when all other variables are kept the same and the incident particles are protons. Finally, value for the global production cut-offs is assumed to be the MULASSIS default value.

4.1.5 Source particle type and energy distribution

The incident particle can be either proton or electron. For the energy distribution we assumed a linear distribution, i.e. $y = AE + B$. The energy E is expressed in [MeV] and A and B are assumed to be equal to 1.0 and 0.0 respectively. The minimum and the maximum energy range were specified as follows:

$$E_{0\min} = 0 \quad (4.1)$$

$$E_{0\max} = E_0 + \frac{E_0}{5}, \quad (4.2)$$

where E_0 is the energy of the incident particle in [MeV]. Finally an omnidirectional angular distribution with $\theta_{\min} = 0$ [deg] and $\theta_{\max} = 90$ [deg] was also assumed (MULASSIS default values).

For more information about the particular macro commands used here refer to the Geant4 General Particle Source (gps) user manual [11].

4.1.6 Run

For the run we first assumed a number of events equal to 40000. However, after inspecting the initial results (see for example **figures 4.1 - 4.3**) we realised that more particles were needed for the MC simulations. Therefore, the number of events was increased from the initial 40000 to 10^7 . Remember that the MC methods display $1/\sqrt{N}$ convergence, where N is the number of sampled points (i.e. quadrupling the number of sampled points will halve the error). Thus, the error of 5×10^{-3} corresponding to the 40000 events becomes only 3.16×10^{-4} when the sampled points increase to 10^7 .

Finally, the CPU time was set high enough in order for all the simulations to run until the end.

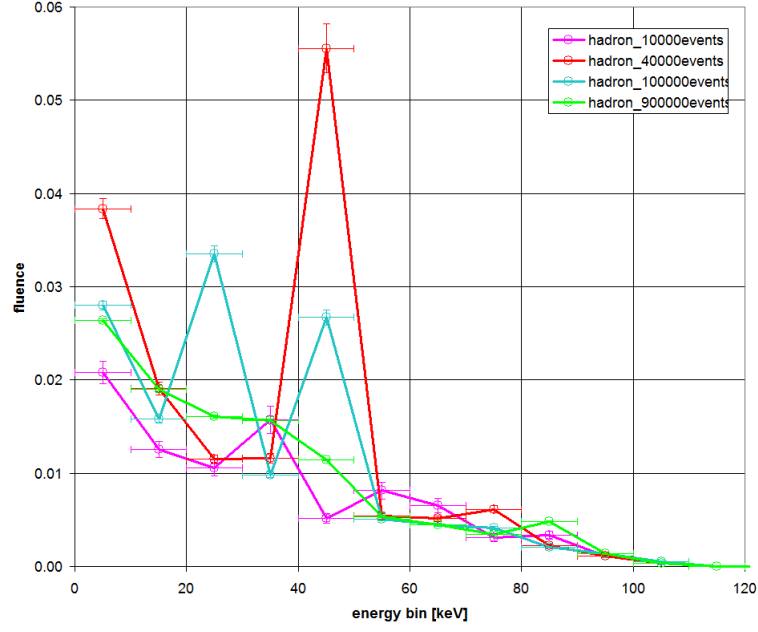


Figure 4.1. Electron flux spectra behind an Aluminium shielding of $0.1 \text{ [g/cm}^2\text{]}$ irradiated by almost monochromatic 50 [MeV] omnidirectional proton flux from various MULASSIS runs where the only variable was the number of initial events (10^4 , 4×10^4 , 10^5 and 9×10^5)

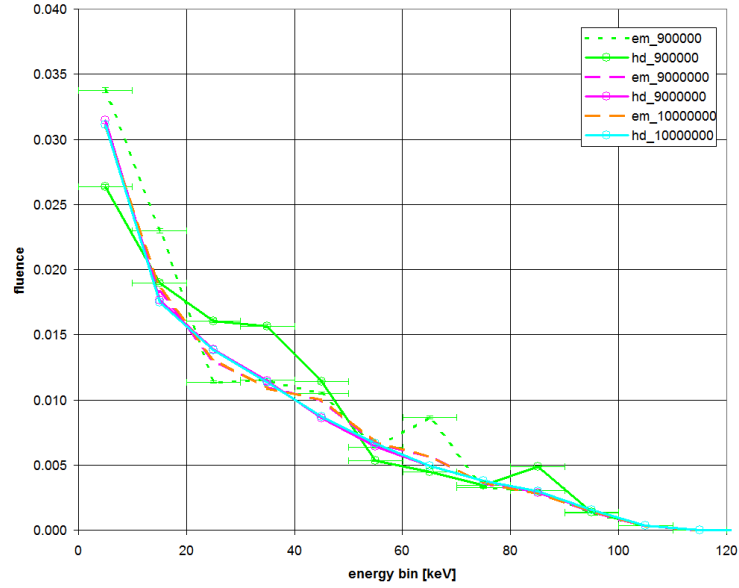


Figure 4.2. Electron flux spectra behind an Aluminium shielding of $0.1 \text{ [g/cm}^2\text{]}$ irradiated by almost monochromatic 50 [MeV] omnidirectional proton flux from various MULASSIS runs for EM and Hadronic physics and various initial events (9×10^5 , 9×10^6 and 10^7)

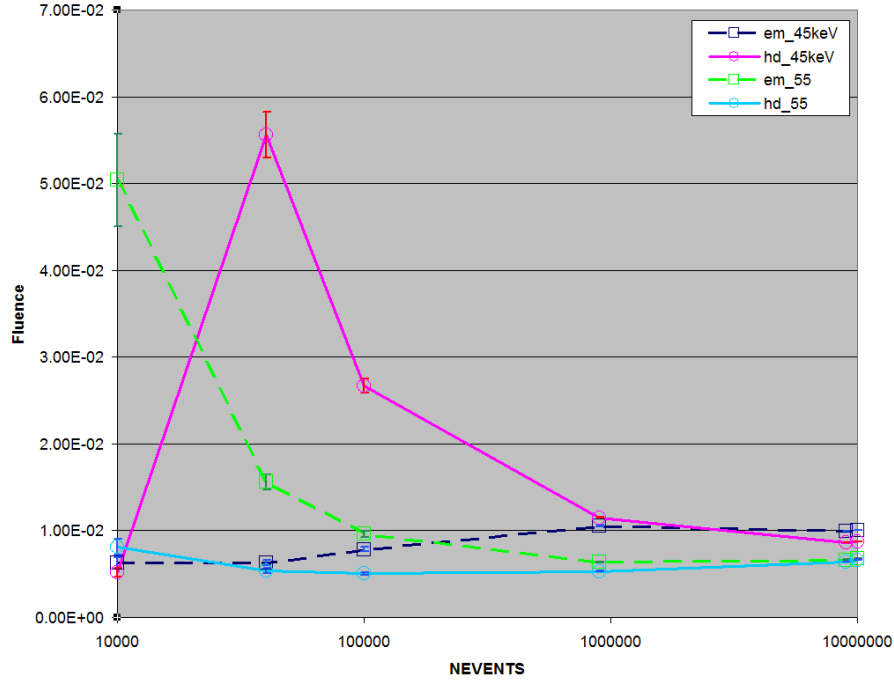


Figure 4.3. 45 and 55 [keV] electron flux behind an Aluminium shielding of 0.1 [g/cm²] irradiated by almost monochromatic 50 [MeV] omnidirectional proton flux as a function of the number of initial events for different MULASSIS runs either with or without Hadronic physics

4.2 MULASSIS runs and generation of the look-up tables

The MULASSIS runs were executed on various machines at BIRA-IASB. To give an indication of the computing power, each machine (all have similar properties) consists of eight processors with Intel(R) Xeon(R) CPU X5450 at 3.00 GHz, 8 GB RAM, SUSE LINUX Enterprise Server 10 (x86_64).

Once the runs were completed, the output files were processed by a FORTRAN application and the appropriate data were saved in a form of a NAMELIST. Note that two separate NAMELISTS have been created for incident protons and electrons (PTABLES and ETABLES respectively).

The variables included in the PTABLES NAMELIST were the following:

E0.PRO(K) Energy values used for creating the almost mono-energetic incident proton spectra in [MeV]

PRO_PFLU(N,I,J,K) Proton fluence/flux behind the total shielding in [particles cm⁻² bin⁻¹]

PRO_PFERROR(N,I,J,K) Proton fluence/flux error in [particles cm⁻² bin⁻¹]

PRO_PEMEAN(N,I,J,K) Mean energy in [keV], corresponding to the registered protons in each energy bin.

PRO_PEUP(N,I,J,K) Upper edges of proton energy bins in [keV]

PRO_PELow(N,I,J,K) Lower edges of proton energy bins in [keV]

PRO_NFLU(N,I,J,K) Neutron fluence/flux behind the total shielding

PRO_NFERROR(N,I,J,K) Neutron fluence/flux error in [particles cm⁻² bin⁻¹]

PRO_NEMEAN(N,I,J,K) Mean energy in [keV], corresponding to the registered neutrons in each energy bin

PRO_NEUP(N,I,J,K) Upper edges of neutron energy bins in [keV]

PRO_NELow(N,I,J,K) Lower edges of neutron energy bins in [keV]

PRO_EFLU(N,I,J,K) Electron fluence/flux behind the total shielding

PRO_EFERROR(N,I,J,K) Electron fluence/flux error in [particles cm⁻² bin⁻¹]

PRO_EEMEAN(N,I,J,K) Mean energy in [keV], corresponding to the registered electrons in each energy bin

PRO_EEUP(N,I,J,K) Upper edges of electron energy bins in [keV]

PRO_EELow(N,I,J,K) Lower edges of electron energy bins in [keV]

where **I** = 6, **J** = 4, **K** = 9 and **N** = 21. Also, the following variables were included in the ETABLES NAMELIST:

E0_ELE(L)

ELE_EFLU(N,I,J,L) Electron fluence/flux behind the total shielding (particles per cm² counted for each bin)

ELE_EFERROR(N,I,J,L) Electron fluence/flux error in [particles cm⁻² bin⁻¹]

ELE_EEMEAN(N,I,J,L) Mean energy in [keV], corresponding to the registered electrons in each energy bin

ELE_EEUP(N,I,J,L) Upper edges of electron energy bins in [keV]

ELE_EELow(N,I,J,L) Lower edges of electron energy bins in [keV]

with **I** = 6, **J** = 4, **L** = 7 and **N** = 21. Note that **N** is the number of energy bins specified for the MULASSIS fluence analysis.

In addition, the following variables are common for both NAMELISTS:

THICK_TOT(I) Possible values of the total shielding in $[\text{g}/\text{cm}^2]$

RATIO_TA2AL(J) Possible values of the Tantalum to Aluminium ratio ($[\%]$)

As an example we assume that the incident particle is a proton of 50 [MeV] and the spacecraft shielding has 2 $[\text{g}/\text{cm}^2]$ thickness with 5% Tantalum to Aluminium ratio. **Figure 4.4** shows the various particle (proton, neutron and electron) fluence/flux behind the shielding as a function of the mean energy deposited in each energy bin. Next, **figure 4.5** demonstrates the effect on the particle fluence/flux behind the shielding of the different Tantalum concentrations in the shielding (various Ta to Al ratios). Then, various shielding thicknesses are considered and the resulting fluences/fluxes are shown in **figure 4.6**. Finally, the effect of different incident proton energies on the above shielding is shown in **figure 4.7**.

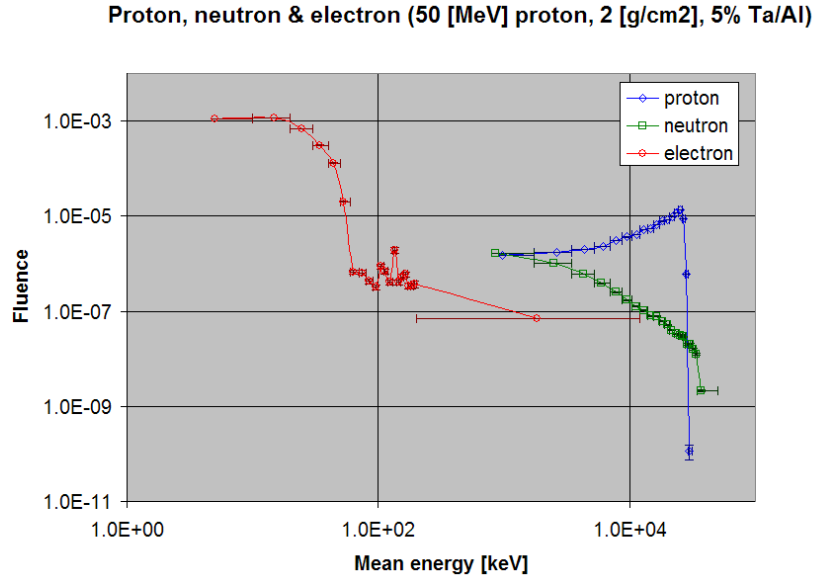
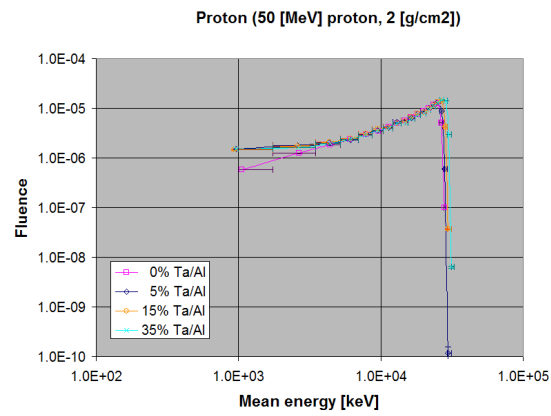
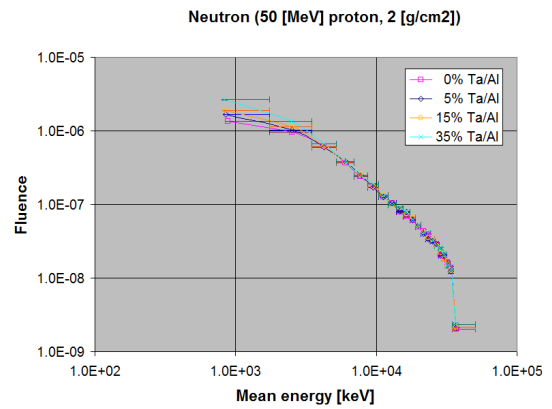


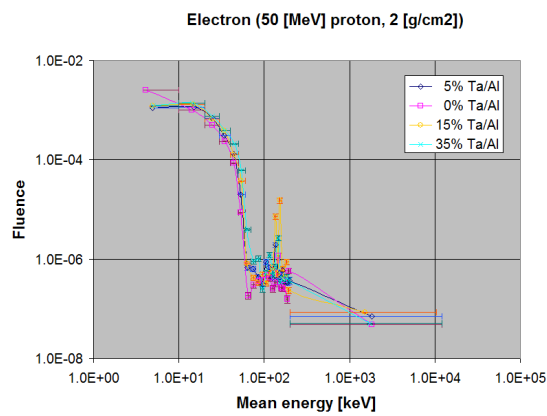
Figure 4.4. Proton, neutron and electron fluence/flux as a function of the mean energy deposited in each energy bin for an incident 50 MeV proton, 2 $[\text{g}/\text{cm}^2]$ shield thickness and Ta to Al ratio of 5%



(a)



(b)



(c)

Figure 4.5. Proton (a), neutron (b) and electron (c) fluence/flux behind 2 [g/cm²] shielding as a function of the mean energy deposited in each energy bin, produced by 50 [MeV] incident protons, for various Ta to Al ratios.

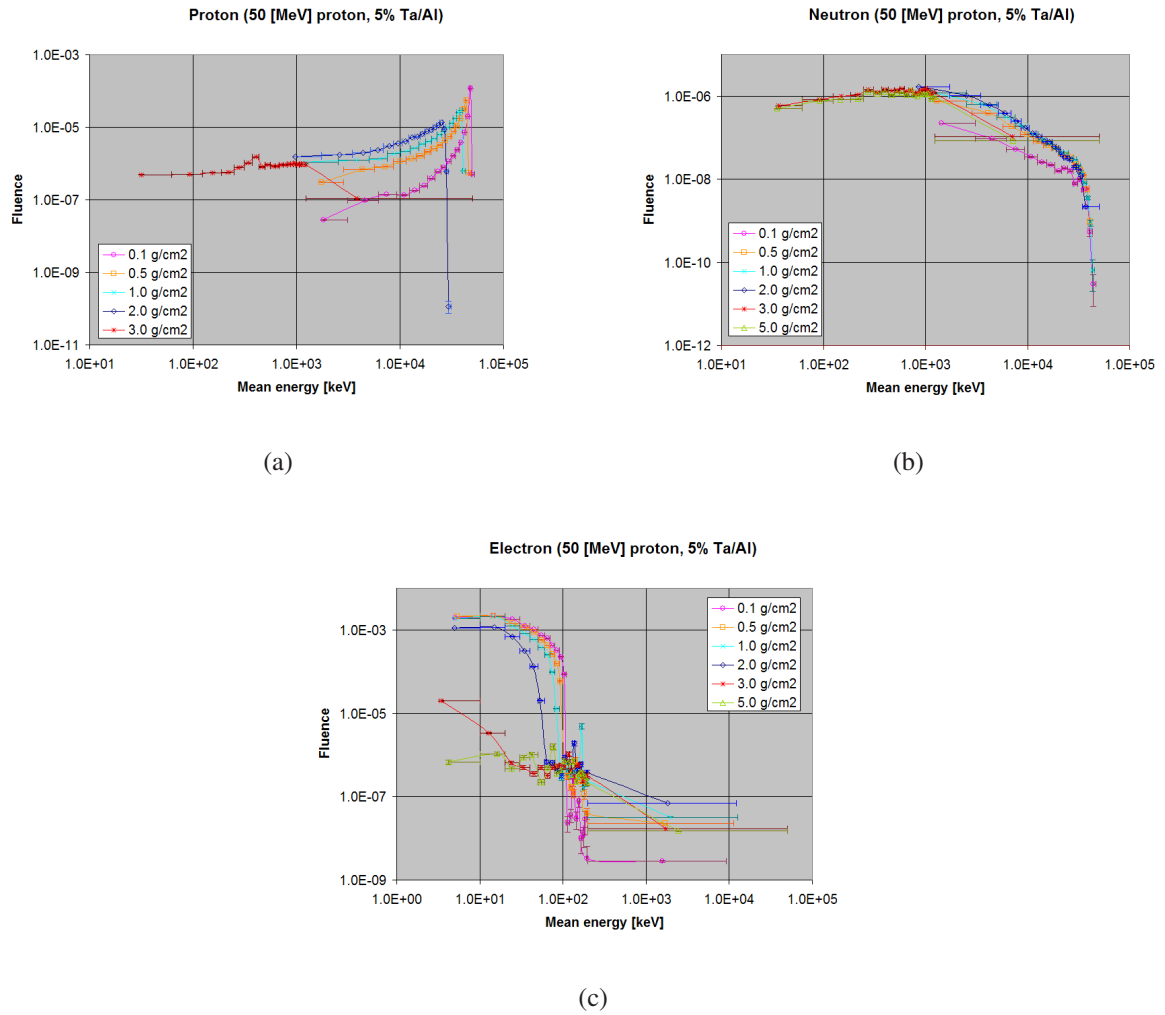


Figure 4.6. Proton (a), neutron (b) and electron (c) fluence/flux as a function of the mean energy deposited in each energy bin for various shielding thicknesses (incident particles are 50 [MeV] protons and Ta to Al ratio is assumed to be 5%).

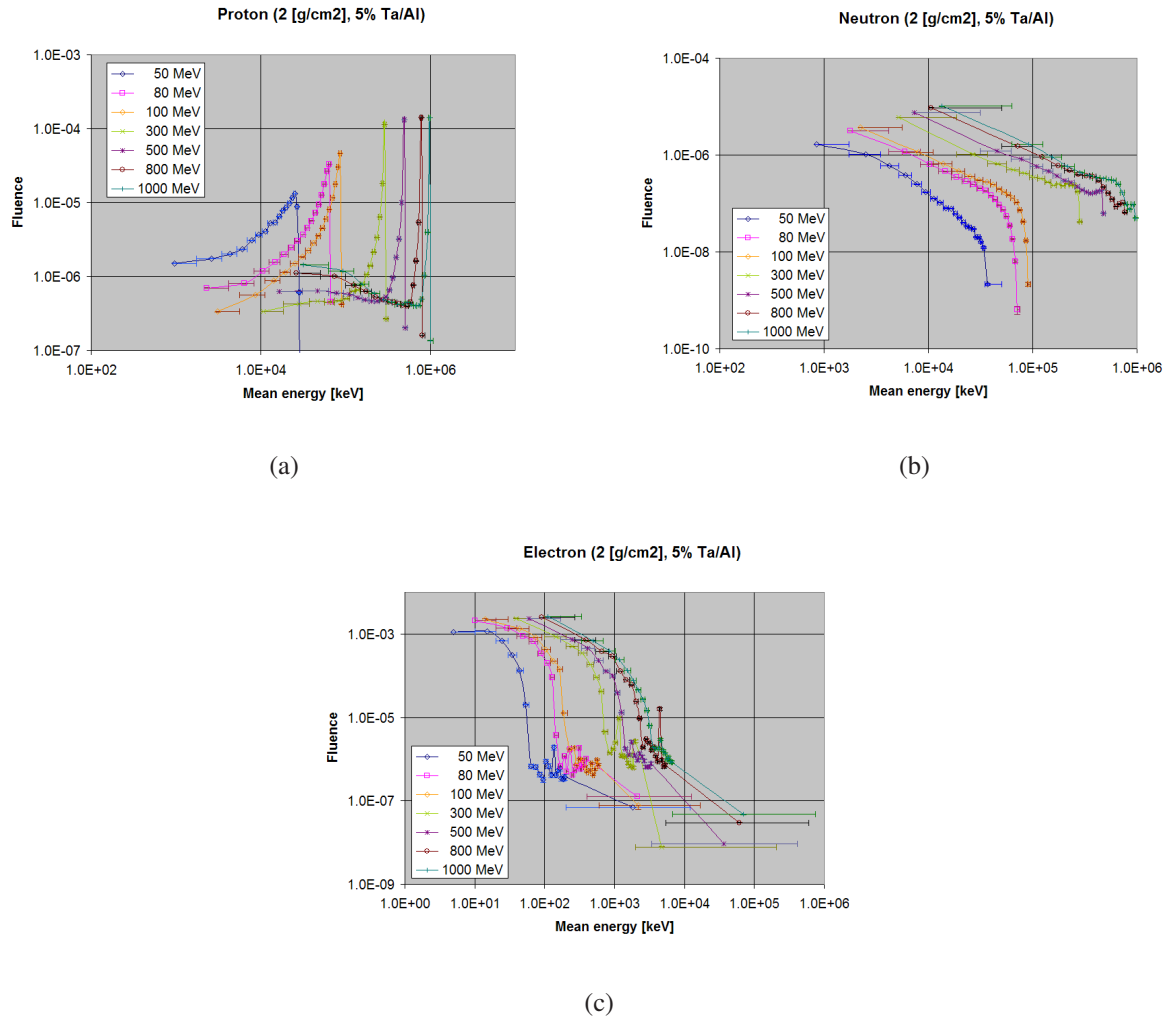


Figure 4.7. Proton (a), neutron (b) and electron (c) fluence/flux behind 2 [g/cm²] shielding with 5% Ta to Al ratio as a function of the mean energy deposited in each energy bin for various incident energy values (incident particles are protons).

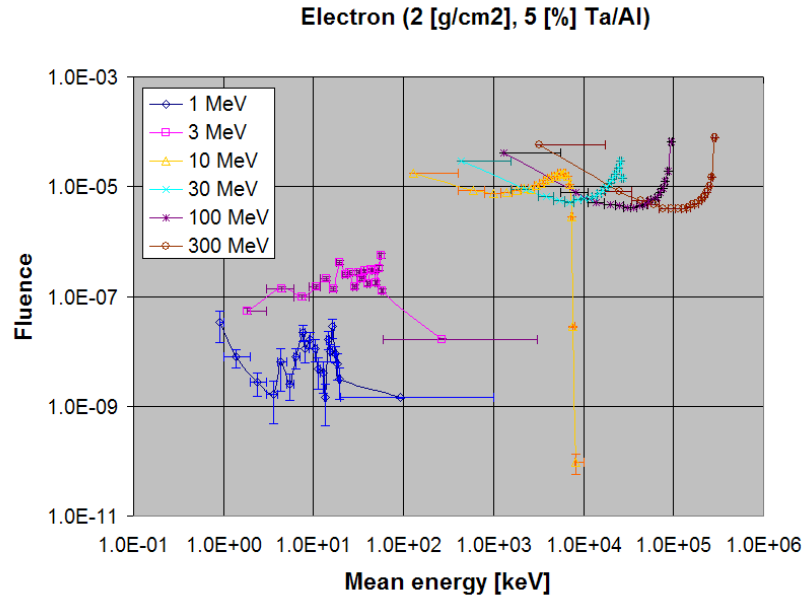


Figure 4.8. Electron fluence/flux behind 2 [g/cm²] shielding with 5% Ta to Al ratio as a function of the mean energy deposited in each energy bin for various incident energy values (incident particles are protons).

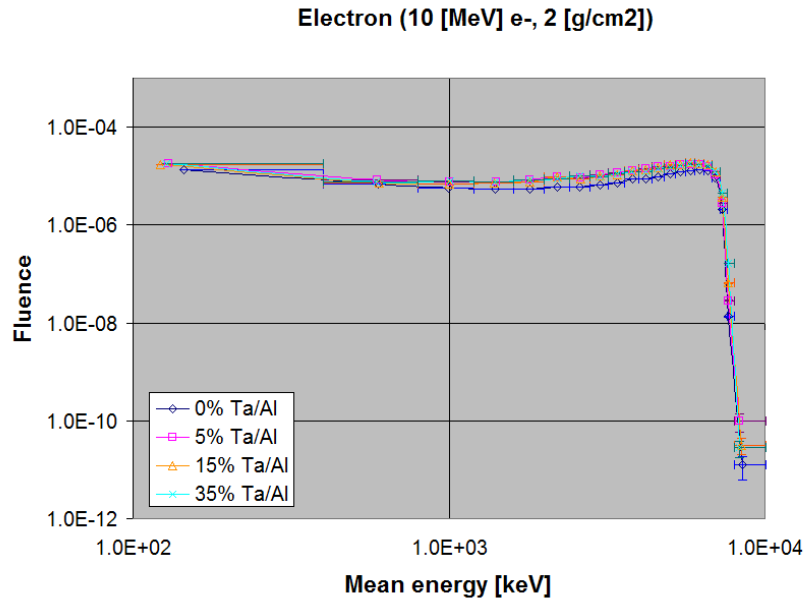


Figure 4.9. Electron fluence/flux behind 2 [g/cm²] shielding as a function of the mean energy deposited in each energy bin, produced by 10 [MeV] incident electrons, for various Ta to Al ratios.

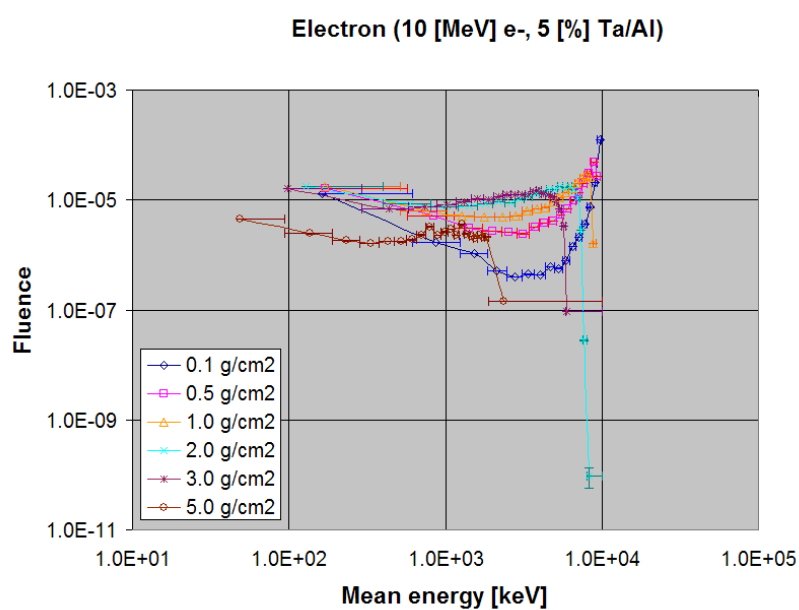


Figure 4.10. Electron fluence/flux as a function of the mean energy deposited in each energy bin for various shielding thicknesses (incident particles are 10 [MeV] electrons and Ta to Al ratio is assumed to be 5%).

Chapter 5

SPENVIS Implementation

As we have already mentioned the aim of this work was to provide a new application in SPENVIS that uses the data generated from the MULASSIS runs. Therefore, a dedicated FORTRAN program has been created (MFLUX) that utilises the two NAMELISTs (PTABLES and ETABLES) described in the previous chapter. This program has been fully integrated into SPENVIS and is available for planet Earth, Mars and Jupiter.

5.1 The SPENVIS interface

SPENVIS users are able to access this application by selecting the **Shielded flux** option included in the **Radiation sources** section of the main template of SPENVIS (**Model packages**).

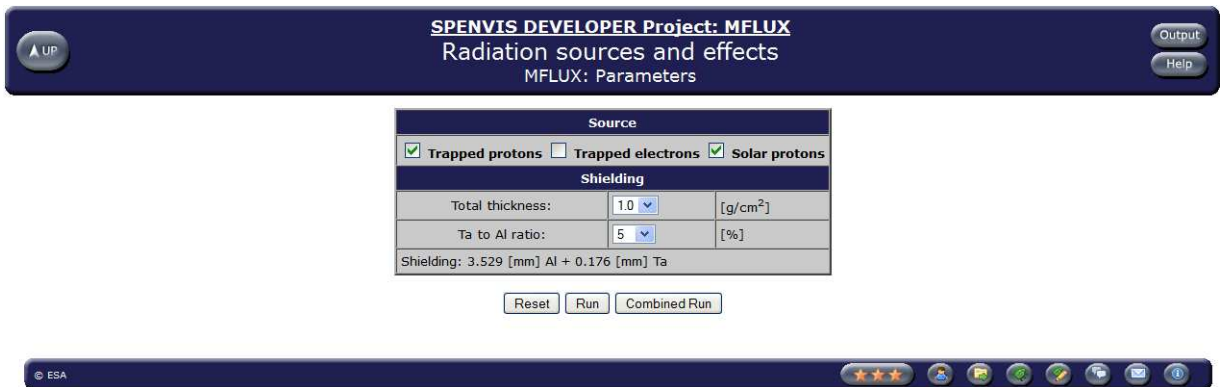


Figure 5.1. Main template of the SPENVIS implementation (MFLUX)

From the model template (**Figure 5.1**), a user is able to define an incident particle spectrum, the total shielding and the Tantalum to Aluminium ratio. For the definition of the incident particle spectrum a run of the Trapped radiation models (TREP) or the Long-term solar particle fluences model (SEP) is required. A user can select (depending on which model has run),

incident trapped particles (proton and/or electron) and/or solar protons as the incident particles. However, the only available values for the total shielding and the Tantalum to Aluminium ratio are the ones used for the generation of the look-up data (see **table 4.1**). The thicknesses of Aluminium and Tantalum shielding are also displayed in units of [mm].

When a user hit the run button the FORTRAN program calculates the fluence/flux behind the user defined shielding and the user is directed to the model output page (**Figure 5.2**). The output includes a report HTML file (`spenvis_mfr.html`), a SPENVIS TREP-like CSV file with the average proton, electron and neutron integral and differential fluxes (`spenvis_mfo.txt`), and finally a CSV file with MULASSIS-like binned proton, electron and neutron fluxes (`spenvis_mfm.txt`). Note that the upper and lower edges of the energy bins have been fixed in order to cover the energy spectra computed by the SPENVIS Trapped radiation and Long-term solar particle fluences models. Hence, the MULASSIS-like output is presented in terms of forty six bins covering an energy range from 0.04 to 1000 [MeV].

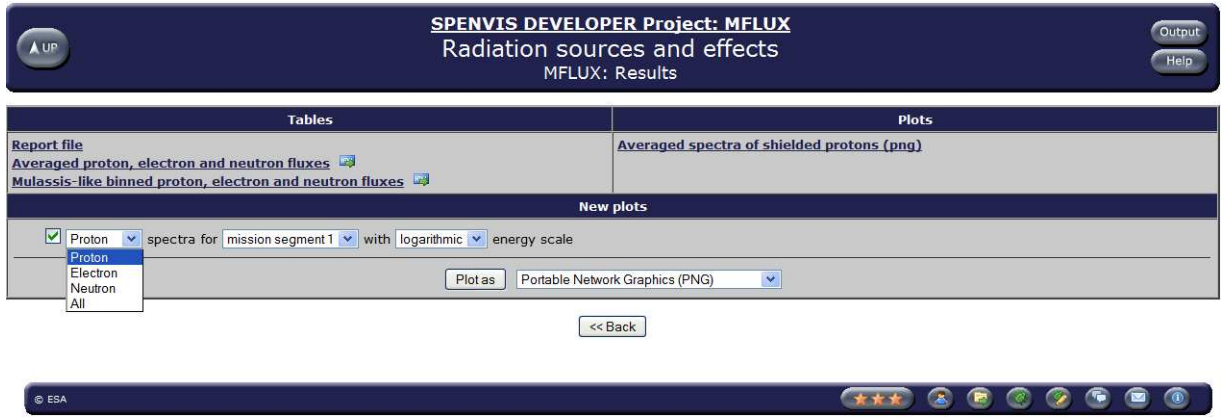


Figure 5.2. Output template of the SPENVIS implementation (MFLUX)

Finally, the SPENVIS implementation provides the possibility to plot the proton, electron and neutron orbit average spectra (using the `spenvis_mfo.txt` file) in various graphical formats (see **figure 5.2**). An example of a SPENVIS generated plot using the MFLUX TREP-like output is shown in **figure 5.3**.

5.2 The main application

The developed FORTRAN program (MFLUX) makes use of the two NAMELISTs `PTABLES` and `ETABLES`. As we have already mentioned, the inputs provided by the user are the incident particle spectrum, the total thickness of the shielding in [g/cm²] and the Tantalum to Aluminium ratio in terms of [%]. Note that more than one incident particle types can be selected. In this case, the output will be the cumulating effect of all selected incident particle types.

Remember that the look-up table variables reside on a three dimensional grid i.e. $I \times J \times K$ for `PTABLES` and $I \times J \times L$ for `ETABLES`, where $I = 6$, $J = 4$, $K = 9$ and $L = 7$ (see **table**

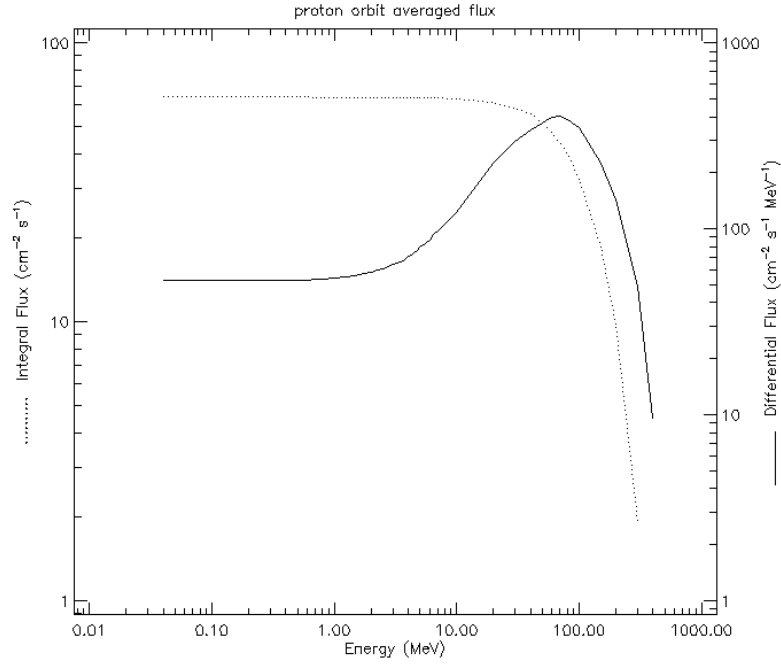


Figure 5.3. SPENVIS generated plot showing the proton orbit average flux behind a shield of 1.0 [g/cm²] with 5% Ta to Al ratio for PROBA2 orbit. The incident particle spectrum has been generated by the AP-8 model.

4.1). So, the fluence/flux (binned into N energy bins) of a particular particle type would be $F(n, i, j, q)$ where $i = 1 \dots I$, $j = 1 \dots J$, $q = 1 \dots K$ or $q = 1 \dots L$ and $n = 1 \dots N$. Also, $N = 21$ for both incident proton and electron.

First, the given values for the shielding thickness and the Tantalum to Aluminium ratio are used to specify the values of the grid indices i and j . Let $i = a$ and $j = b$, then

$$\tilde{F}(n, q) = F(n, a, b, q) \quad (5.1)$$

is the binned fluence/flux for specific values of the shielding and the Tantalum to Aluminium ratio. At this point, the program selects the appropriate variable values from the two NAMELISTs, PTABLES and ETABLES. In principle, one could consider shielding and Tantalum to Aluminium ratio values others than the ones forming the grid. In this case, interpolation or extrapolation would be needed in order to calculate $F(n, a', b', q)$.

Next, the incident particle spectrum is considered. Assume that $e(r)$, $r = 1, \dots, R$ are the spectrum energy values. Then, we define:

$$\begin{aligned} \hat{E}_1(1) &= e(1) \\ \hat{E}_2(m) &= \frac{1 + \delta \hat{E}}{1 - \delta \hat{E}} \hat{E}_1(m) \end{aligned}$$

$$\hat{\mathbf{E}}_1(\mathbf{m}) = \hat{\mathbf{E}}_2(\mathbf{m} - 1), \quad \mathbf{m} = 1, \dots, \mathbf{M} \quad (5.2)$$

so that

$$\hat{\mathbf{E}}_0(\mathbf{m}) = \frac{\hat{\mathbf{E}}_1(\mathbf{m}) + \hat{\mathbf{E}}_2(\mathbf{m})}{2}, \quad \mathbf{m} = 1, \dots, \mathbf{M} \quad (5.3)$$

and $\delta\hat{\mathbf{E}}$ is an arbitrary constant chosen to be equal to 0.05. We also assume that $\hat{\mathbf{E}}_2(\mathbf{M}) \leq \mathbf{e}(\mathbf{r})$.

Remember that the normalisation factor used in MULASSIS [12] is calculated by taking into consideration:

- a geometric factor (converting incident flux to a current through a surface)
- the number of particles in the energy range under consideration

Therefore, for generating our MULASSIS-like output we have to calculate the appropriate normalisation factor. This is where $\hat{\mathbf{E}}_1(\mathbf{m})$ and $\hat{\mathbf{E}}_2(\mathbf{m})$ come into play. We first locate the $\hat{\mathbf{E}}_1(\mathbf{m})$ and $\hat{\mathbf{E}}_2(\mathbf{m})$ with respect to the spectrum energy values, $\mathbf{e}(\mathbf{i})$. Assume that,

$$\mathbf{e}(\mathbf{r}) \leq \hat{\mathbf{E}}_1(\mathbf{m}) \leq \mathbf{e}(\mathbf{r} + 1), \quad \mathbf{l} = 1, 2 \quad (5.4)$$

with $\mathbf{r} = 1, \dots, \mathbf{R}$ and $\mathbf{m} = 1, \dots, \mathbf{M}$. Then, the integral flux, Φ , from $\hat{\mathbf{E}}_1(\mathbf{m})$ to infinity is calculated using a power law interpolation:

$$\Phi \Big|_{\hat{\mathbf{E}}_1(\mathbf{m})}^{\infty} = \exp \left\{ \frac{\left[\ln \hat{\mathbf{E}}_1(\mathbf{m}) - \ln \mathbf{e}(\mathbf{r}) \right] \ln \Phi \Big|_{\hat{\mathbf{e}}(\mathbf{r}+1)}^{\infty} + \left[\ln \mathbf{e}(\mathbf{r} + 1) - \ln \hat{\mathbf{E}}_1(\mathbf{m}) \right] \ln \Phi \Big|_{\hat{\mathbf{e}}(\mathbf{r})}^{\infty}}{\ln \mathbf{e}(\mathbf{r} + 1) - \ln \mathbf{e}(\mathbf{r})} \right\}. \quad (5.5)$$

Finally, the normalisation factor is given by [12]:

$$\mathbf{N}(\mathbf{m}) = \frac{1}{4} \left(\Phi \Big|_{\hat{\mathbf{E}}_1(\mathbf{m})}^{\infty} - \Phi \Big|_{\hat{\mathbf{E}}_2(\mathbf{m})}^{\infty} \right) \quad (5.6)$$

where $\Phi \Big|_{\hat{\mathbf{E}}_1(\mathbf{m})}^{\infty}$ and $\Phi \Big|_{\hat{\mathbf{E}}_2(\mathbf{m})}^{\infty}$ are calculated using equation (5.5).

Note that the trapped particle spectra contain integral fluxes i.e. particles $[\text{cm}^{-2}\text{s}^{-1}]$ while the solar energetic proton spectra contain integral fluences i.e. particles $[\text{cm}^{-2}]$. Hence, when a trapped particle spectrum is used, the normalisation factor needs to be multiplied by the mission duration in seconds.

Also, we need to take into consideration that the look-up tables were created by assuming an almost mono-energetic spectrum with a specific $\Delta\mathbf{E} = \frac{2\mathbf{E}_0}{100}$ (see equation 3.12). However, when we are using the incident particle spectrum we are considering a different $\Delta\hat{\mathbf{E}} = 2\hat{\mathbf{E}}_0(\mathbf{m})\delta\hat{\mathbf{E}}$. Thus, we still need a scaling factor to take into consideration this difference. If we assume that $\mathbf{E}_0 = \hat{\mathbf{E}}_0(\mathbf{m})$ we can write,

$$\mathbf{S} = \frac{\Delta\mathbf{E}}{\Delta\hat{\mathbf{E}}} = \frac{1}{100\delta\hat{\mathbf{E}}} \quad (5.7)$$

Note that this scaling factor is independent of the incident energy value.

The next step is to use the energy values, $\hat{E}_0(\mathbf{m})$ to calculate the binned fluence/flux from the look-up tables. Thus, each $\hat{E}_0(\mathbf{m})$ is located with respect to the appropriate NAMELIST energy values denoted E_0 ($E0_PRO(K)$ and $E0_ELE(L)$ included in `PTABLES` and `ETABLES` respectively). Note that $M \gg K, L$. If,

$$E_0(\mathbf{q}) < \hat{E}_0(\mathbf{m}) < E_0(\mathbf{q} + 1) \quad (5.8)$$

then a power-law interpolation is used to calculate the binned fluence/flux for each energy value, $\hat{E}_0(\mathbf{m})$. Hence,

$$\begin{aligned} \tilde{F}(\mathbf{n}, \mathbf{m}) = \exp \left\{ \left[[\ln \hat{E}_0(\mathbf{m}) - \ln E_0(\mathbf{q})] \ln F(\mathbf{n}, \mathbf{q} + 1) + [\ln E_0(\mathbf{q} + 1) - \right. \right. \\ \left. \left. - \ln \hat{E}_0(\mathbf{m})] \ln F(\mathbf{n}, \mathbf{q}) \right] / \left[\ln E_0(\mathbf{q} + 1) - \ln E_0(\mathbf{q}) \right] \right\}. \end{aligned} \quad (5.9)$$

If $\hat{E}_0(\mathbf{m}) = E_0(\mathbf{q})$ then $\tilde{F}(\mathbf{n}, \mathbf{m}) = F(\mathbf{n}, \mathbf{q})$ and is simply taken from the look-up tables. Finally, if $\hat{E}_0(\mathbf{m}) \leq E_0(1)$ or $\hat{E}_0(\mathbf{m}) > E_0(K), E_0(L)$ then equation (5.9) can not be used and an extrapolation technique is required. The upper and lower energy values defining the binning scheme, the mean energy of each bin and the error on the binned fluence/flux are calculated in a similar way.

Note that when $\tilde{F}(\mathbf{n}, \mathbf{m}) \neq F(\mathbf{n}, \mathbf{q})$ the energy binning is different. In principle, this has to be taken into consideration by considering an additional scaling factor, $S_1(\mathbf{m})$. This is done here by calculating the total surface for the two fluence/flux histograms (i.e. $\sum \tilde{F}(\mathbf{i}, \mathbf{m}) \Delta E_{\text{bin}}(\mathbf{i})$ and $\sum F'(\mathbf{i}, \mathbf{q}) \Delta E'_{\text{bin}}(\mathbf{i})$, $\mathbf{i} = 1, \dots, \mathbf{n}$ where $F'(\mathbf{i}, \mathbf{q})$ is calculated by interpolating between $F(\mathbf{i}, \mathbf{q})$ and $F(\mathbf{i}, \mathbf{q} + 1)$).

Having calculated the F we need to apply the normalisation and scaling factors calculated by (5.6) and (5.7) respectively. Thus,

$$\tilde{F}_1(\mathbf{n}, \mathbf{m}) = S \times S_1(\mathbf{m}) \times N(\mathbf{m}) \times \tilde{F}(\mathbf{n}, \mathbf{m}), \quad (5.10)$$

with $\mathbf{n} = 1, \dots, 21$ and $\mathbf{m} = 1, \dots, M$.

In the end, the calculated variables (e.g. $\tilde{F}_1(\mathbf{n}, \mathbf{m})$) are combined together (merged) in order to compute the final results. Note that this process could also introduce some additional errors, especially when $\tilde{F}_1(\mathbf{n}, \mathbf{m})$ corresponds to a large energy bin and it has to be distributed over a number of smaller energy bins.

A MULASSIS-like output of the particle fluence/flux behind the total shielding binned into forty six energy bins is provided (i.e. $\tilde{F}_2(\mathbf{p})$, $\mathbf{p} = 1, \dots, 46$). Note that a fixed binning scheme has been assumed for calculating this output. Using the MULASSIS-like output a SPENVIS TREP-like output (i.e. integral and differential fluxes) is also generated.

5.3 Testing the SPENVIS implementation

First, an orbit was generated by providing SPENVIS with the following two line elements for the PROBA-2 satellite:

- 1*36037U*09059B***11104.61534143*-.00000045**00000-0**00000+0*0**4394
- 2*36037**98.3100*294.5084*0014427**73.1184*287.1584*14.52012262*76694

where each (*) represents a white space (when providing these two-line elements to SPENVIS the spacing must be respected).

In turn, the **Trapped radiation** and **Long-term solar particle fluences** models were executed using the default values in order to generate the appropriate data files. More specifically, we have used the averaged proton and electron fluxes and the solar particle fluence spectra (`spenvis_tri.txt` and `spenvis_sef.tex` respectively) shown in **Appendix C**.

The MULASSIS data were generated using a stand alone version of MULASSIS and the runs were executed locally on various machines at BIRA-IASB. This was done in order to have the same accuracy as the data included in the look-up tables (10^7 events to simulate) and at a reasonable time.

For the comparison, the MULASSIS output was binned into the same energy bins as in the MFLUX output. In **figure 5.4** we compare the particle fluence (proton, electron and neutron) calculated by MFLUX and MULASSIS for the incident particle spectrum produced by trapped protons. Three different values for the total shielding (0.1, 1.0 and 3.0 [g cm⁻²]) were considered, while the Tantalum to Aluminium ratio was assumed to be zero.

Next, we have compared the effect of the presence of Tantalum in the shielding of the spacecraft. **Figure 5.5** shows the particle fluence (proton, electron and neutron) behind a shielding of 1.0 [g cm⁻²] for the same incident spectrum but for three different Tantalum to Aluminium ratios (0, 5 and 15 [%]).

Also, biased and unbiased MULASSIS outputs were compared with the MFLUX results. Note that the trapped radiation and the solar proton spectra vary by several orders of magnitude over their energy range. This could lead to an over-sampling of non-effectual low-energy particles on the expense of the high energy ones [12]. Thus, it is interesting to consider MULASSIS results where energy biasing of spectra has been applied. **Figure 5.6** shows MULASSIS biased and unbiased particle fluence/flux behind 1.0 [g cm⁻²] shielding (no Tantalum) produced by incident trapped protons and the corresponding MFLUX outputs.

Similar tests were carried out using the incident particle spectrum generated by the trapped electrons and solar protons. In general, MFLUX gives good results for the protons and relatively good outputs for the neutrons. However, the electron outputs are less satisfactory. As we have already mentioned, the approximation we have used is too simplistic for the more complex electron interactions with matter e.g. bremsstrahlung. This becomes more evident as the shielding is increasing.

Finally, we have tested the conversion of MULASSIS-like output into TREP-like output and compared our results with the output of MULASSIS using the same configurations. The total

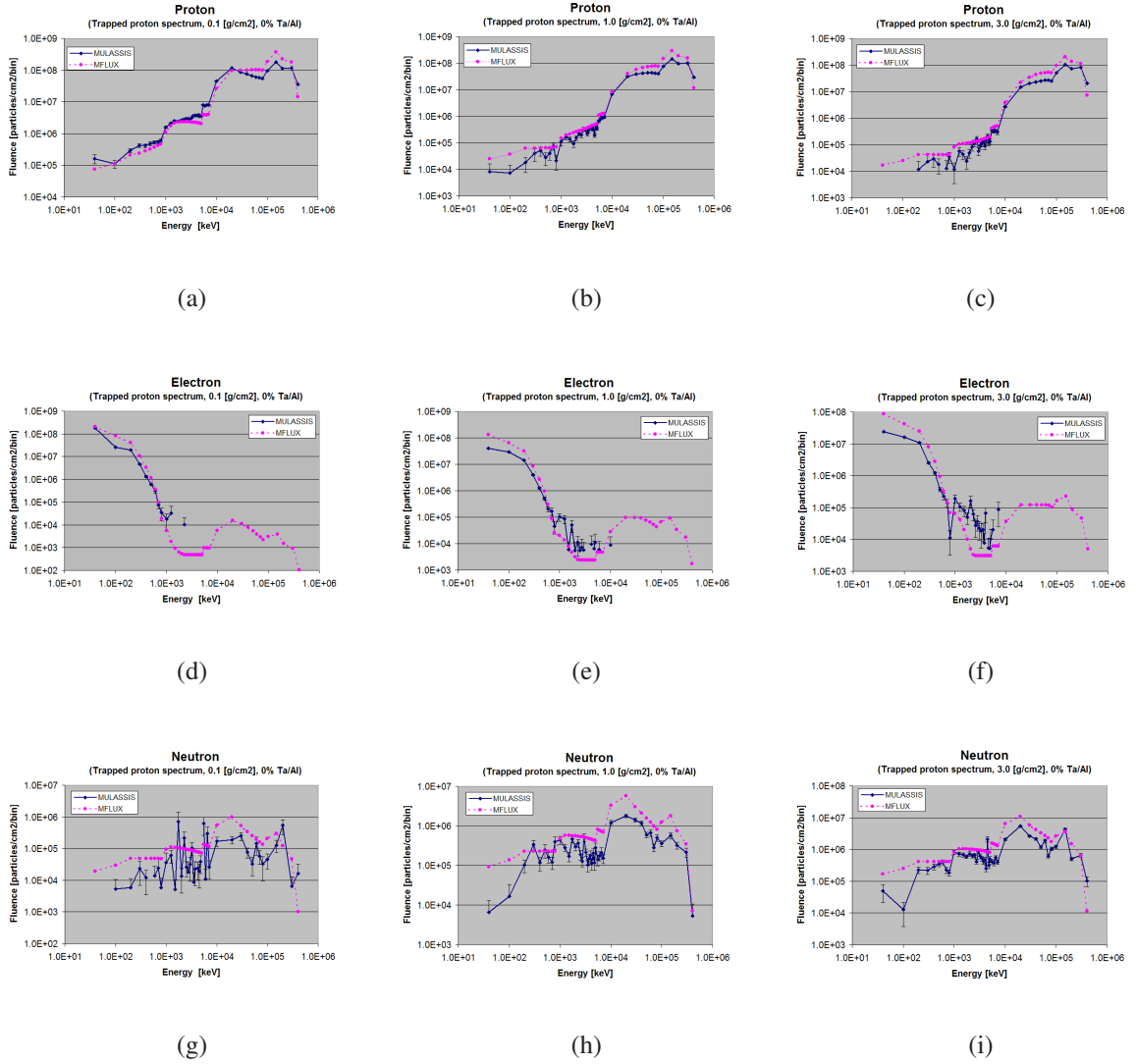
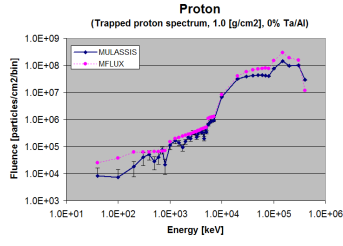


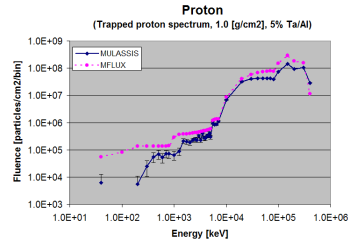
Figure 5.4. Proton (a-c), electron (d-f) and neutron (g-i) fluence/flux behind 0.1, 1.0 and 3.0 $[\text{g cm}^{-2}]$ shielding with 0 [%] Ta to Al ratio produced by incident trapped protons.

shielding was assumed to be equal to of 1.0 $[\text{g/cm}^2]$ with 5% Tantalum to Aluminium ratio. In addition, the trapped proton spectrum calculated by the AP-8 model along the PROBA2 orbit was used as the incident particle spectrum.

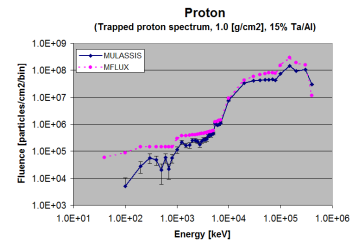
In **figure 5.7** we can see that the MFLUX outputs are in a rather good agreement with the MULASSIS results. Also, note that the MULASSIS run was done assuming 10^5 events while the look-up table data were generated using 10^7 events.



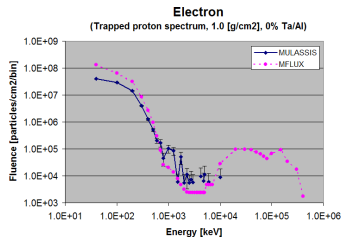
(a)



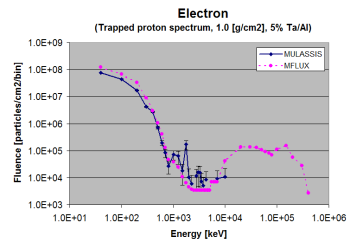
(b)



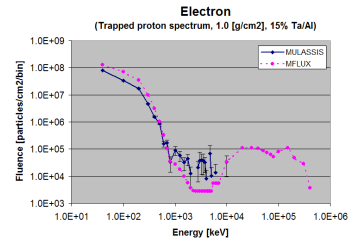
(c)



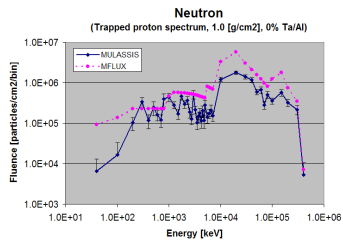
(d)



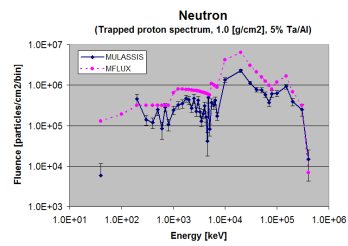
(e)



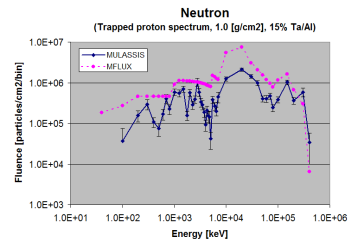
(f)



(g)



(h)



(i)

Figure 5.5. Proton (a-c), electron (d-f) and neutron (g-i) fluence/flux behind 1.0 [g cm⁻²] shielding for different Ta to Al ratios (0, 5 and 15 [%]) produced by incident trapped protons.

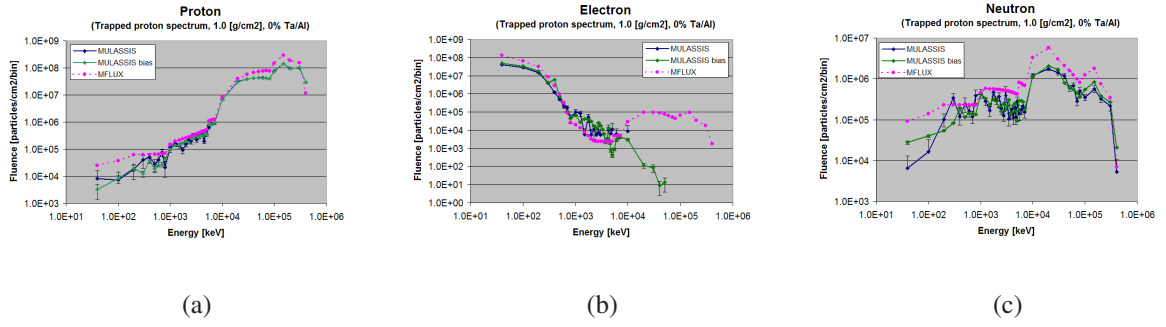


Figure 5.6. Proton (a), electron (b) and neutron (c) fluence/flux behind $1.0 \text{ [g cm}^{-2}\text{]}$ shielding with 0 [%] Ta to Al ratio produced by incident trapped protons. MULASSIS biased and unbiased outputs are compared against the corresponding MFLUX results.

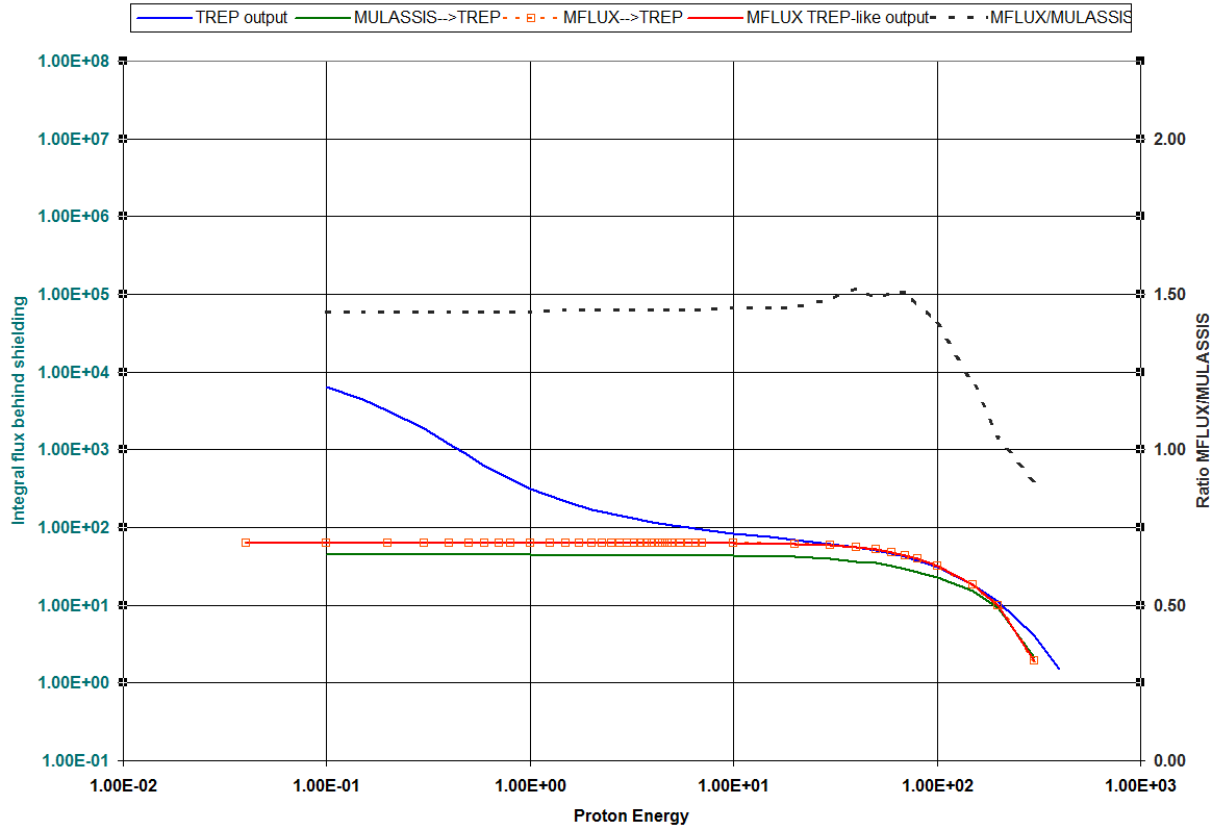


Figure 5.7. Comparing the MFLUX MULASSIS-like and TREP-like outputs with the SPENVIS generated MULASSIS output for the same geometry and source. The total shielding was assumed to be $1.0 \text{ [g/cm}^2\text{]}$ with 5% Ta to Al ratio. The incident particle spectrum has been calculated along the PROBA2 orbit using the AP-8 model.

Chapter 6

Conclusions

We have described the approach followed for generating look-up tables for calculating fluences/fluxes behind some shielding using MULASSIS data. The generation of the look-up tables is automated so the tables can be easily updated if necessary. The only time consuming process required would be the time needed for completing the appropriate MULASSIS simulations. Also, the SPENVIS application (MFLUX) that uses the look-up data can be easily adapted when new data are added.

For the SPENVIS application we have considered only total shielding and Tantalum to Aluminium ratio values that coincide with the ones included in the look-up tables. In principle, one could consider also other values. However, this could introduce some additional errors since this would involve additional interpolations.

The SPENVIS application seems to provide rather good results when the incident particle is proton (trapped proton or solar energetic proton spectra), especially for the proton output. On the other hand, it is less successful when electrons are considered. This has been expected because of the more complex interactions of the electrons with the shielding. Therefore, some more work might be required for improving the MFLUX application.

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Appendix A

PSTAR total stopping power and CSDA range for Al

Table A.1. Proton total stopping power and CSDA range in Al as a function of their kinetic energy.

Kinetic energy [MeV]	Stop. power [MeVcm ² /g]	CSDA range [g/cm ²]	Kinetic energy [MeV]	Stop. power [MeVcm ² /g]	CSDA range [g/cm ²]
1.00E-03	1.04E+02	1.47E-05	5.00E-02	4.75E+02	1.56E-04
1.50E-03	1.24E+02	1.91E-05	5.50E-02	4.77E+02	1.67E-04
2.00E-03	1.40E+02	2.29E-05	6.00E-02	4.76E+02	1.77E-04
2.50E-03	1.55E+02	2.62E-05	6.50E-02	4.75E+02	1.88E-04
3.00E-03	1.68E+02	2.93E-05	7.00E-02	4.72E+02	1.98E-04
4.00E-03	1.92E+02	3.49E-05	7.50E-02	4.69E+02	2.09E-04
5.00E-03	2.13E+02	3.98E-05	8.00E-02	4.65E+02	2.19E-04
6.00E-03	2.32E+02	4.43E-05	8.50E-02	4.61E+02	2.30E-04
7.00E-03	2.50E+02	4.85E-05	9.00E-02	4.57E+02	2.41E-04
8.00E-03	2.66E+02	5.23E-05	9.50E-02	4.52E+02	2.52E-04
9.00E-03	2.82E+02	5.60E-05	1.00E-01	4.48E+02	2.63E-04
1.00E-02	2.97E+02	5.94E-05	1.25E-01	4.25E+02	2.63E-04
1.25E-02	3.25E+02	6.75E-05	1.50E-01	4.05E+02	3.21E-04
1.50E-02	3.48E+02	7.49E-05	1.75E-01	3.87E+02	3.81E-04
1.75E-02	3.69E+02	8.19E-05	2.00E-01	3.72E+02	4.44E-04
2.00E-02	3.87E+02	8.85E-05	2.25E-01	3.57E+02	5.10E-04
2.25E-02	4.02E+02	9.48E-05	2.50E-01	3.44E+02	5.79E-04
2.50E-02	4.16E+02	1.01E-04	2.75E-01	3.33E+02	6.50E-04
2.75E-02	4.27E+02	1.07E-04	3.00E-01	3.22E+02	7.24E-04
3.00E-02	4.37E+02	1.13E-04	3.50E-01	3.02E+02	8.00E-04
3.50E-02	4.53E+02	1.24E-04	4.00E-01	2.84E+02	9.61E-04
4.00E-02	4.64E+02	1.35E-04	4.50E-01	2.69E+02	1.13E-03
4.50E-02	4.71E+02	1.46E-04	5.00E-01	2.55E+02	1.31E-03

Kinetic energy	Stop. power	CSDA range	Kinetic energy	Stop. power	CSDA range
5.50E-01	2.43E+02	1.50E-03	4.50E+01	1.04E+01	1.97E+00
6.00E+01	8.33E+00	3.47E+00	5.00E+01	9.59E+00	2.43E+00
6.50E+01	7.84E+00	4.05E+00	5.50E+01	8.91E+00	2.93E+00
6.00E-01	2.32E+02	1.70E-03	7.00E+01	7.41E+00	4.67E+00
6.50E-01	2.22E+02	1.92E-03	7.50E+01	7.03E+00	5.33E+00
7.00E-01	2.13E+02	2.14E-03	8.00E+01	6.70E+00	6.02E+00
7.50E-01	2.04E+02	2.37E-03	8.50E+01	6.40E+00	6.75E+00
8.00E-01	1.97E+02	2.61E-03	9.00E+01	6.14E+00	8.31E+00
8.50E-01	1.90E+02	2.86E-03	9.50E+01	5.90E+00	9.14E+00
9.00E-01	1.84E+02	3.11E-03	1.00E+02	5.68E+00	1.00E+01
9.50E-01	1.78E+02	3.38E-03	1.25E+02	4.84E+00	1.48E+01
1.00E+00	1.72E+02	3.66E-03	1.50E+02	4.26E+00	2.03E+01
1.25E+00	1.50E+02	3.95E-03	1.75E+02	3.84E+00	2.65E+01
1.50E+00	1.33E+02	5.51E-03	2.00E+02	3.53E+00	3.33E+01
1.75E+00	1.20E+02	7.29E-03	2.25E+02	3.28E+00	4.07E+01
2.00E+00	1.10E+02	9.27E-03	2.50E+02	3.08E+00	4.86E+01
2.25E+00	1.01E+02	1.15E-02	2.75E+02	2.91E+00	5.69E+01
2.50E+00	9.38E+01	1.38E-02	3.00E+02	2.77E+00	6.57E+01
2.75E+00	8.78E+01	1.64E-02	3.50E+02	2.56E+00	8.45E+01
3.00E+00	8.25E+01	1.92E-02	4.00E+02	2.39E+00	1.05E+02
3.50E+00	7.39E+01	2.21E-02	4.50E+02	2.27E+00	1.26E+02
4.00E+00	6.71E+01	2.85E-02	5.00E+02	2.17E+00	1.49E+02
4.50E+00	6.15E+01	3.56E-02	5.50E+02	2.09E+00	1.72E+02
5.00E+00	5.70E+01	4.34E-02	6.00E+02	2.02E+00	1.97E+02
5.50E+00	5.31E+01	5.19E-02	6.50E+02	1.97E+00	2.22E+02
6.00E+00	4.97E+01	6.10E-02	7.00E+02	1.92E+00	2.48E+02
6.50E+00	4.68E+01	7.07E-02	7.50E+02	1.88E+00	2.74E+02
7.00E+00	4.43E+01	8.11E-02	8.00E+02	1.85E+00	3.01E+02
7.50E+00	4.21E+01	9.21E-02	8.50E+02	1.82E+00	3.28E+02
8.00E+00	4.00E+01	1.04E-01	9.00E+02	1.79E+00	3.56E+02
8.50E+00	3.82E+01	1.16E-01	9.50E+02	1.77E+00	3.84E+02
9.00E+00	3.66E+01	1.29E-01	1.00E+03	1.75E+00	4.12E+02
9.50E+00	3.51E+01	1.42E-01	1.50E+03	1.65E+00	7.09E+02
1.00E+01	3.38E+01	1.56E-01	2.00E+03	1.62E+00	1.02E+03
1.25E+01	2.84E+01	1.71E-01	2.50E+03	1.61E+00	1.33E+03
1.50E+01	2.47E+01	2.52E-01	3.00E+03	1.62E+00	1.64E+03
1.75E+01	2.19E+01	3.46E-01	4.00E+03	1.64E+00	2.25E+03
2.00E+01	1.97E+01	4.54E-01	5.00E+03	1.67E+00	2.85E+03
2.50E+01	1.65E+01	5.75E-01	6.00E+03	1.69E+00	3.45E+03
2.75E+01	1.53E+01	8.53E-01	7.00E+03	1.71E+00	4.04E+03
3.00E+01	1.43E+01	1.01E+00	8.00E+03	1.73E+00	4.62E+03
3.50E+01	1.27E+01	1.18E+00	9.00E+03	1.75E+00	5.19E+03
4.00E+01	1.14E+01	1.55E+00	1.00E+04	1.77E+00	5.76E+03

Appendix B

ESTAR total stopping power and CSDA range for Al

Table B.1. Electron total stopping power and CSDA range in Al as a function of their kinetic energy.

Kinetic energy [MeV]	Stop. power [MeVcm ² /g]	CSDA range [g/cm ²]	Kinetic energy [MeV]	Stop. power [MeVcm ² /g]	CSDA range [g/cm ²]
1.00E-03	9.73E+02	1.09E-06	5.00E-02	3.82E+03	1.85E-05
1.50E-03	1.09E+03	1.57E-06	5.50E-02	3.83E+03	1.98E-05
2.00E-03	1.20E+03	2.01E-06	6.00E-02	3.83E+03	2.11E-05
2.50E-03	1.30E+03	2.41E-06	6.50E-02	3.82E+03	2.24E-05
3.00E-03	1.40E+03	2.78E-06	7.00E-02	3.79E+03	2.37E-05
4.00E-03	1.58E+03	3.46E-06	7.50E-02	3.75E+03	2.51E-05
5.00E-03	1.74E+03	4.06E-06	8.00E-02	3.71E+03	2.64E-05
6.00E-03	1.89E+03	4.61E-06	8.50E-02	3.66E+03	2.78E-05
7.00E-03	2.03E+03	5.12E-06	9.00E-02	3.61E+03	2.91E-05
8.00E-03	2.16E+03	5.60E-06	9.50E-02	3.55E+03	3.05E-05
9.00E-03	2.28E+03	6.05E-06	1.00E-01	3.49E+03	3.19E-05
1.00E-02	2.40E+03	6.47E-06	1.25E-01	3.19E+03	3.94E-05
1.25E-02	2.62E+03	7.47E-06	1.50E-01	2.90E+03	4.77E-05
1.50E-02	2.81E+03	8.39E-06	1.75E-01	2.63E+03	5.67E-05
1.75E-02	2.97E+03	9.25E-06	2.00E-01	2.41E+03	6.67E-05
2.00E-02	3.11E+03	1.01E-05	2.25E-01	2.21E+03	7.75E-05
2.25E-02	3.23E+03	1.09E-05	2.50E-01	2.03E+03	8.93E-05
2.50E-02	3.34E+03	1.16E-05	2.75E-01	1.88E+03	1.02E-04
2.75E-02	3.43E+03	1.24E-05	3.00E-01	1.76E+03	1.16E-04
3.00E-02	3.51E+03	1.31E-05	3.50E-01	1.55E+03	1.46E-04
3.50E-02	3.63E+03	1.45E-05	4.00E-01	1.39E+03	1.81E-04
4.00E-02	3.72E+03	1.58E-05	4.50E-01	1.26E+03	2.18E-04
4.50E-02	3.78E+03	1.72E-05	5.00E-01	1.16E+03	2.60E-04

Kinetic energy	Stop. power	CSDA range	Kinetic energy	Stop. power	CSDA range
5.50E-01	1.08E+03	3.05E-04	5.50E+01	2.45E+01	1.23E+00
6.00E-01	1.01E+03	3.53E-04	6.00E+01	2.29E+01	1.44E+00
6.50E-01	9.48E+02	4.04E-04	6.50E+01	2.14E+01	1.67E+00
7.00E-01	8.95E+02	4.58E-04	7.00E+01	2.02E+01	1.91E+00
7.50E-01	8.49E+02	5.15E-04	7.50E+01	1.91E+01	2.16E+00
8.00E-01	8.07E+02	5.76E-04	8.00E+01	1.82E+01	2.43E+00
8.50E-01	7.70E+02	6.39E-04	8.50E+01	1.73E+01	2.71E+00
9.00E-01	7.36E+02	7.06E-04	9.00E+01	1.66E+01	3.01E+00
9.50E-01	7.05E+02	7.75E-04	9.50E+01	1.59E+01	3.31E+00
1.00E+00	6.77E+02	8.48E-04	1.00E+02	1.53E+01	3.63E+00
1.25E+00	5.67E+02	1.25E-03	1.25E+02	1.30E+01	5.42E+00
1.50E+00	4.90E+02	1.73E-03	1.50E+02	1.14E+01	7.49E+00
1.75E+00	4.33E+02	2.27E-03	1.75E+02	1.02E+01	9.81E+00
2.00E+00	3.89E+02	2.88E-03	2.00E+02	9.33E+00	1.24E+01
2.25E+00	3.53E+02	3.56E-03	2.25E+02	8.65E+00	1.52E+01
2.50E+00	3.24E+02	4.30E-03	2.50E+02	8.10E+00	1.82E+01
2.75E+00	3.00E+02	5.10E-03	2.75E+02	7.65E+00	2.13E+01
3.00E+00	2.79E+02	5.97E-03	3.00E+02	7.27E+00	2.47E+01
3.50E+00	2.46E+02	7.88E-03	3.50E+02	6.68E+00	3.19E+01
4.00E+00	2.20E+02	1.00E-02	4.00E+02	6.24E+00	3.96E+01
4.50E+00	1.99E+02	1.24E-02	4.50E+02	5.90E+00	4.79E+01
5.00E+00	1.83E+02	1.51E-02	5.00E+02	5.63E+00	5.66E+01
5.50E+00	1.69E+02	1.79E-02	5.50E+02	5.41E+00	6.57E+01
6.00E+00	1.57E+02	2.10E-02	6.00E+02	5.23E+00	7.51E+01
6.50E+00	1.47E+02	2.43E-02	6.50E+02	5.08E+00	8.48E+01
7.00E+00	1.38E+02	2.78E-02	7.00E+02	4.96E+00	9.47E+01
7.50E+00	1.30E+02	3.16E-02	7.50E+02	4.85E+00	1.05E+02
8.00E+00	1.23E+02	3.55E-02	8.00E+02	4.76E+00	1.15E+02
8.50E+00	1.17E+02	3.97E-02	8.50E+02	4.68E+00	1.26E+02
9.00E+00	1.11E+02	4.41E-02	9.00E+02	4.61E+00	1.37E+02
9.50E+00	1.07E+02	4.87E-02	9.50E+02	4.55E+00	1.48E+02
1.00E+01	1.02E+02	5.35E-02	1.00E+03	4.50E+00	1.59E+02
1.25E+01	8.44E+01	8.05E-02	1.50E+03	4.21E+00	2.74E+02
1.50E+01	7.24E+01	1.13E-01	2.00E+03	4.13E+00	3.95E+02
1.75E+01	6.36E+01	1.50E-01	2.50E+03	4.11E+00	5.16E+02
2.00E+01	5.68E+01	1.91E-01	3.00E+03	4.12E+00	6.38E+02
2.50E+01	4.71E+01	2.88E-01	4.00E+03	4.17E+00	8.79E+02
2.75E+01	4.35E+01	3.44E-01	5.00E+03	4.24E+00	1.12E+03
3.00E+01	4.04E+01	4.04E-01	6.00E+03	4.31E+00	1.35E+03
3.50E+01	3.55E+01	5.36E-01	7.00E+03	4.37E+00	1.58E+03
4.00E+01	3.18E+01	6.85E-01	8.00E+03	4.43E+00	1.81E+03
4.50E+01	2.89E+01	8.50E-01	9.00E+03	4.49E+00	2.03E+03
5.00E+01	2.65E+01	1.03E+00	1.00E+04	4.54E+00	2.25E+03

Appendix C

SPENVIS generated proton and electron spectra used for testing MFLUX

C.1 Averaged proton and electron fluxes (spenvis_tri.txt)

```
'*', 74, 1, 32, 37, 3, 3, 29, 1
'SPENVIS 4.y.z.win32 - 6-May-2011 14:26:11'
'PRJ\_DEF', -1, 'MFLUX'
'PRJ\_HDR', -1, ' '
'MOD\_ABB', -1, 'TRP'
'MIS\_PLA', 1, 3, ' '
'MIS\_NTR', 1, 1, ' '
'MIS\_STA', 1, 22383.61534143, ' '
'MIS\_END', 1, 22748.61534143, ' '
'MIS\_DUR', 1, 3.650000E+02, 'days'
'ORB\_HDR', -1, ' '
'ORB\_TYP', -1, 'TLE'
'ORB\_MJD', 1, 22383.61534143, ' '
'ORB\_YEA', 1, 2011, ' '
'ORB\_MON', 1, 4, ' '
'ORB\_DAY', 1, 14, ' '
'ORB\_HOU', 1, 14, ' '
'ORB\_MIN', 1, 46, ' '
'ORB\_SEC', 1, 5.5, ' '
'ORB\_APO', 1, 7.506968E+02, 'km'
'ORB\_PER', 1, 7.140985E+02, 'km'
'ORB\_INC', 1, 98.30, 'deg'
'ORB\_RAA', 1, 294.51, 'deg'
'ORB\_ARG', 1, 70.29, 'deg'
'ORB\_TRA', 1, 289.71, 'deg'
'ORB\_PRD', 1, 1.655031E+00, 'hrs'
'ORB\_DUR', 1, 6.895963E-01, 'days'
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'ORB\_MJR', -1, '1 Jan 1950, 00:00 UT'
'ORB\_GDR', -1, 'Astron. J. 66, 15, 1961'
'TRP\_MOD', -1, 'AP-8 MAX'
'TRP\_OMN', 1, 1, ' '
'PLT\_HDR', -1, 'AP-8 MAX Orbit averaged flux'
'PS Annotation', 8, 2
'Mission start: 14/04/2011 14:46:05'
0.05, 0.00, 0.00
'Mission end: 13/04/2012 14:46:05'
```

```

0.95, 0.00, 1.00
'Nr. of segments: 1'
0.05, 1.50, 0.00
'Duration: 365.00 days'
0.95, 0.00, 1.00
'PS Annotation', 24, 1
'Segment 1:'
0.05, 2.00, 0.00
'Apogee: 750.7 km'
0.05, 1.50, 0.00
'Perigee: 714.1 km'
0.50, 0.00, 0.50
'Inclination: 98.3 deg'
0.95, 0.00, 1.00
'R.A. Asc. Node: 294.5 deg'
0.05, 1.50, 0.00
'Arg. Per.: 70.3 deg'
0.50, 0.00, 0.50
'True Anomaly: 289.7 deg'
0.95, 0.00, 1.00
'Period: 1.66 hrs'
0.05, 1.50, 0.00
'Duration: 0.69 days'
0.50, 0.00, 0.50
'10.00 Orbits'
0.95, 0.00, 1.00
'Orbit start: 14/04/2011 14:46:05'
0.05, 1.50, 0.00
'Orbit end: 15/04/2011 07:19:06'
0.95, 0.00, 1.00
'PS Annotation', 2, 0
'Trapped proton model: AP-8 MAX'
0.05, 2.00, 0.00
'Energy', 'MeV', 1, 'Energy'
'IFlux', 'cm!u-2!n s!u-1!n', 1, 'Integral Flux'
'DFlux', 'cm!u-2!n s!u-1!n MeV!u-1!n', 1, 'Differential Flux'
1.0000E-01, 6.3488E+03, 4.3947E+04
1.5000E-01, 4.4631E+03, 3.1483E+04
2.0000E-01, 3.2005E+03, 2.1225E+04
3.0000E-01, 1.8832E+03, 1.0147E+04
4.0000E-01, 1.1712E+03, 5.2746E+03
5.0000E-01, 8.2825E+02, 2.7995E+03
6.0000E-01, 6.1130E+02, 1.6774E+03
7.0000E-01, 4.9277E+02, 1.0421E+03
1.0000E+00, 3.0901E+02, 4.5395E+02
1.5000E+00, 2.1421E+02, 1.3949E+02
2.0000E+00, 1.6952E+02, 7.0720E+01
3.0000E+00, 1.3614E+02, 2.6120E+01
4.0000E+00, 1.1728E+02, 1.4383E+01
5.0000E+00, 1.0737E+02, 8.7293E+00
6.0000E+00, 9.9817E+01, 6.4926E+00
7.0000E+00, 9.4386E+01, 4.9818E+00
1.0000E+01, 8.3485E+01, 2.9220E+00
1.5000E+01, 7.4807E+01, 1.4448E+00
2.0000E+01, 6.9037E+01, 1.0155E+00
3.0000E+01, 6.1654E+01, 6.6995E-01
4.0000E+01, 5.5638E+01, 5.6522E-01
5.0000E+01, 5.0349E+01, 4.8942E-01
6.0000E+01, 4.5849E+01, 4.3986E-01
7.0000E+01, 4.1552E+01, 4.1107E-01
1.0000E+02, 3.0897E+01, 3.1572E-01
1.5000E+02, 1.8399E+01, 1.9710E-01
2.0000E+02, 1.1187E+01, 1.1997E-01
3.0000E+02, 4.0443E+00, 4.8427E-02
4.0000E+02, 1.5016E+00, 2.4259E-03

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'End of Block'
'*', 74, 1, 32, 37, 3, 3, 30, 0
'SPENVIS 4.y.z.win32 - 6-May-2011 14:26:11'
'PRJ_DEF', -1, 'MFLUX'
'PRJ_HDR', -1, ' '
'MOD_ABB', -1, 'TRP'
'MIS_PLA', 1, 3, ' '
'MIS_NTR', 1, 1, ' '
'MIS_STA', 1, 22383.61534143, ' '
'MIS_END', 1, 22748.61534143, ' '
'MIS_DUR', 1, 3.650000E+02, 'days'
'ORB_HDR', -1, ' '
'ORB_TYP', -1, 'TLE'
'ORB_MJD', 1, 22383.61534143, ' '
'ORB_YEA', 1, 2011, ' '
'ORB_MON', 1, 4, ' '
'ORB_DAY', 1, 14, ' '
'ORB_HOU', 1, 14, ' '
'ORB_MIN', 1, 46, ' '
'ORB_SEC', 1, 5.5, ' '
'ORB_APO', 1, 7.506968E+02, 'km'
'ORB_PER', 1, 7.140985E+02, 'km'
'ORB_INC', 1, 98.30, 'deg'
'ORB_RAA', 1, 294.51, 'deg'
'ORB_ARG', 1, 70.29, 'deg'
'ORB_TRA', 1, 289.71, 'deg'
'ORB_PRD', 1, 1.655031E+00, 'hrs'
'ORB_DUR', 1, 6.895963E-01, 'days'
'ORB_TSE', 1, 22748.61534143, ' '
'ORB_AXM', 1, 2, ' '
'ORB_MJR', -1, '1 Jan 1950, 00:00 UT'
'ORB_GDR', -1, 'Astron. J. 66, 15, 1961'
'TRP_MOD', -1, 'AE-8 MAX'
'TRP_OMN', 1, 1, ' '
'PLT_HDR', -1, 'AE-8 MAX Orbit averaged flux'
'PS Annotation', 8, 2
'Mission start: 14/04/2011 14:46:05'
0.05, 0.00, 0.00
'Mission end: 13/04/2012 14:46:05'
0.95, 0.00, 1.00
'Nr. of segments: 1'
0.05, 1.50, 0.00
'Duration: 365.00 days'
0.95, 0.00, 1.00
'PS Annotation', 24, 1
'Segment 1:'
0.05, 2.00, 0.00
'Apogee: 750.7 km'
0.05, 1.50, 0.00
'Perigee: 714.1 km'
0.50, 0.00, 0.50
'Inclination: 98.3 deg'
0.95, 0.00, 1.00
'R.A. Asc. Node: 294.5 deg'
0.05, 1.50, 0.00
'Arg. Per.: 70.3 deg'
0.50, 0.00, 0.50
'True Anomaly: 289.7 deg'
0.95, 0.00, 1.00
'Period: 1.66 hrs'
0.05, 1.50, 0.00
'Duration: 0.69 days'
0.50, 0.00, 0.50
'10.00 Orbits'
0.95, 0.00, 1.00

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```

'Orbit start: 14/04/2011 14:46:05'
0.05, 1.50, 0.00
'Orbit end: 15/04/2011 07:19:06'
0.95, 0.00, 1.00
'PS Annotation', 2, 0
'Trapped electron model: AE-8 MAX'
0.05, 2.00, 0.00
'Energy', 'MeV', 1, 'Energy'
'IFlux', 'cm!u-2!n s!u-1!n', 1, 'Integral Flux'
'DFlux', 'cm!u-2!n s!u-1!n MeV!u-1!n', 1, 'Differential Flux'
4.0000E-02, 4.1630E+05, 3.1093E+06
1.0000E-01, 2.5674E+05, 2.2094E+06
2.0000E-01, 1.1080E+05, 1.0167E+06
3.0000E-01, 5.3392E+04, 4.0687E+05
4.0000E-01, 2.9427E+04, 1.7814E+05
5.0000E-01, 1.7764E+04, 8.2148E+04
6.0000E-01, 1.2998E+04, 4.0338E+04
7.0000E-01, 9.6962E+03, 2.7013E+04
8.0000E-01, 7.5950E+03, 1.8212E+04
1.0000E+00, 5.0724E+03, 1.0168E+04
1.2500E+00, 3.2944E+03, 5.8287E+03
1.5000E+00, 2.1580E+03, 3.7647E+03
1.7500E+00, 1.4121E+03, 2.4617E+03
2.0000E+00, 9.2718E+02, 1.5879E+03
2.2500E+00, 6.1817E+02, 1.0266E+03
2.5000E+00, 4.1386E+02, 7.2755E+02
2.7500E+00, 2.5439E+02, 5.1143E+02
3.0000E+00, 1.5814E+02, 3.1450E+02
3.2500E+00, 9.7137E+01, 1.9586E+02
3.5000E+00, 6.0210E+01, 1.2479E+02
3.7500E+00, 3.4740E+01, 8.0082E+01
4.0000E+00, 2.0169E+01, 4.7589E+01
4.2500E+00, 1.0946E+01, 2.8419E+01
4.5000E+00, 5.9598E+00, 1.5654E+01
4.7500E+00, 3.1188E+00, 8.6441E+00
5.0000E+00, 1.6378E+00, 4.8098E+00
5.5000E+00, 3.4734E-01, 1.5924E+00
6.0000E+00, 4.5325E-02, 3.4734E-01
6.5000E+00, 0.0000E+00, 4.5325E-02
7.0000E+00, 0.0000E+00, 0.0000E+00
'End of File'

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C.2 Solar particle fluence spectra (spenvis_sef.tex)

```

'*, 50, 1, 21, 22, 5, 5, 75, 1
'SPENVIS 4.y.z.win32 - 18-May-2011 16:22:12'
'PRJ_DEF', -1, 'MFLUX'
'PRJ_HDR', -1, ' '
'MOD_ABB', -1, 'SEP'
'MIS_PLA', 1, 3, ' '
'MIS_NTR', 1, 1, ' '
'MIS_STA', 1, 22383.61534143, ' '
'MIS_END', 1, 22748.61534143, ' '
'MIS_DUR', 1, 3.650000E+02, 'days'
'SEP_IEL', 1, 1, ' '
'SEP_JEL', 1, 1, ' '
'SEP_MOD', -1, 'JPL-91'
'SEP_TMI', 1, 1.0, 'years'
'SEP_TMA', 1, 0.0, 'years'
'SEP_DUR', 1, 1.0, 'years'
'SEP_NCY', 1, 1, ' '
'SEP_NOR', 1, 0, ' '

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'SEP_NAL', 1, 0, ''
'SEP_PRB', 1, 95.0, '%'
'SEP_OMN', 1, 1, ''
'SEP_ABS', -1, 'Energy'
'PLT_HDR', -1, 'JPL-91 : solar protons'
'PS Annotation', 8, 1
'Mission start: 14/04/2011 14:46:05'
0.05, 0.00, 0.00
'Mission end: 13/04/2012 14:46:05'
0.95, 0.00, 1.00
'Nr. of segments: 1'
0.05, 1.50, 0.00
'Duration: 365.00 days'
0.95, 0.00, 1.00
'PS Annotation', 12, 0
'Solar particle model: JPL-91'
0.05, 2.00, 0.00
'Mission duration: 1.00 years, spanning 1 solar cycles'
0.10, 1.50, 0.00
'1.00 years in solar maximum'
0.15, 1.50, 0.00
'0.00 years in solar minimum'
0.15, 1.50, 0.00
'Confidence level: 95.000%'
0.10, 1.50, 0.00
'Magnetic shielding: quiet magnetosphere'
0.10, 1.50, 0.00
'Energy', 'MeV', 1, 'Energy'
'IFlux', 'cm!u-2!n', 1, 'Integral Fluence'
'DFlux', 'cm!u-2!n MeV!u-1!n', 1, 'Differential Fluence'
'Attenuation', ' ', 1, 'Orbit Averaged Attenuation Factor'
'Exposure', 'hrs', 1, 'Exposure Time'
1.0000E-01, 7.1784E+10, 1.2265E+11, 0.2057, 2.4962E+03
1.1000E-01, 7.0593E+10, 1.1549E+11, 0.2057, 2.4962E+03
1.2000E-01, 6.9471E+10, 1.0891E+11, 0.2057, 2.4962E+03
1.4000E-01, 6.7402E+10, 9.7955E+10, 0.2057, 2.4962E+03
1.6000E-01, 6.5533E+10, 8.9008E+10, 0.2057, 2.4962E+03
1.8000E-01, 6.3826E+10, 8.1677E+10, 0.2057, 2.4962E+03
2.0000E-01, 6.2254E+10, 7.5537E+10, 0.2057, 2.4962E+03
2.2000E-01, 6.0795E+10, 7.0357E+10, 0.2057, 2.4962E+03
2.5000E-01, 5.8782E+10, 6.3843E+10, 0.2057, 2.4962E+03
2.8000E-01, 5.6947E+10, 5.8448E+10, 0.2057, 2.4962E+03
3.2000E-01, 5.4728E+10, 5.2506E+10, 0.2057, 2.4962E+03
3.5000E-01, 5.3209E+10, 4.8806E+10, 0.2057, 2.4962E+03
4.0000E-01, 5.0896E+10, 4.3706E+10, 0.2057, 2.4962E+03
4.5000E-01, 4.8816E+10, 3.9490E+10, 0.2057, 2.4962E+03
5.0000E-01, 4.6929E+10, 3.5991E+10, 0.2057, 2.4962E+03
5.5000E-01, 4.5202E+10, 3.3073E+10, 0.2057, 2.4962E+03
6.3000E-01, 4.2710E+10, 2.9224E+10, 0.2057, 2.4962E+03
7.1000E-01, 4.0498E+10, 2.6088E+10, 0.2057, 2.4962E+03
8.0000E-01, 3.8279E+10, 2.3227E+10, 0.2057, 2.4962E+03
9.0000E-01, 3.6086E+10, 2.0633E+10, 0.2057, 2.4962E+03
1.0000E+00, 3.4129E+10, 1.8497E+10, 0.2057, 2.4962E+03
1.1000E+00, 3.2369E+10, 1.6714E+10, 0.2057, 2.4962E+03
1.2000E+00, 3.0771E+10, 1.5235E+10, 0.2057, 2.4962E+03
1.4000E+00, 2.7962E+10, 1.2853E+10, 0.2057, 2.4962E+03
1.6000E+00, 2.5579E+10, 1.0982E+10, 0.2057, 2.4962E+03
1.8000E+00, 2.3529E+10, 9.5123E+09, 0.2057, 2.4962E+03
2.0000E+00, 2.1745E+10, 8.3306E+09, 0.2057, 2.4962E+03
2.2000E+00, 2.0175E+10, 7.3743E+09, 0.2057, 2.4962E+03
2.5000E+00, 1.8135E+10, 6.2254E+09, 0.2057, 2.4962E+03
2.8000E+00, 1.6403E+10, 5.3227E+09, 0.2057, 2.4962E+03
3.2000E+00, 1.4461E+10, 4.3842E+09, 0.2057, 2.4962E+03
3.5000E+00, 1.3228E+10, 3.8337E+09, 0.2057, 2.4962E+03
4.0000E+00, 1.1574E+10, 2.7825E+09, 0.2057, 2.4962E+03

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4.5000E+00, 1.0383E+10, 1.9813E+09, 0.2057, 2.4962E+03
5.0000E+00, 9.4605E+09, 1.7106E+09, 0.2057, 2.4962E+03
5.5000E+00, 8.6591E+09, 1.4948E+09, 0.2057, 2.4962E+03
6.3000E+00, 7.5715E+09, 1.2243E+09, 0.2057, 2.4962E+03
7.1000E+00, 6.6753E+09, 1.0162E+09, 0.2057, 2.4962E+03
8.0000E+00, 5.8408E+09, 8.3810E+08, 0.2057, 2.4962E+03
9.0000E+00, 5.0784E+09, 6.8673E+08, 0.2057, 2.4962E+03
1.0000E+01, 4.4902E+09, 4.8964E+08, 0.2057, 2.4962E+03
1.1000E+01, 4.0771E+09, 3.3663E+08, 0.2057, 2.4962E+03
1.2000E+01, 3.7598E+09, 2.9797E+08, 0.2057, 2.4962E+03
1.4000E+01, 3.2239E+09, 2.3788E+08, 0.2057, 2.4962E+03
1.6000E+01, 2.7935E+09, 1.9259E+08, 0.2057, 2.4962E+03
1.8000E+01, 2.4423E+09, 1.5859E+08, 0.2057, 2.4962E+03
2.0000E+01, 2.1513E+09, 1.3240E+08, 0.2057, 2.4962E+03
2.2000E+01, 1.9068E+09, 1.1209E+08, 0.2057, 2.4962E+03
2.5000E+01, 1.6054E+09, 8.8831E+07, 0.2057, 2.4962E+03
2.8000E+01, 1.3718E+09, 6.6941E+07, 0.2057, 2.4962E+03
3.2000E+01, 1.1570E+09, 4.0450E+07, 0.2057, 2.4962E+03
3.5000E+01, 1.0505E+09, 3.0543E+07, 0.2057, 2.4962E+03
4.0000E+01, 9.1183E+08, 2.4920E+07, 0.2057, 2.4962E+03
4.5000E+01, 7.9810E+08, 2.0574E+07, 0.2057, 2.4962E+03
5.0000E+01, 7.0363E+08, 1.7214E+07, 0.2057, 2.4962E+03
5.5000E+01, 6.2407E+08, 1.4610E+07, 0.2057, 2.4962E+03
6.3000E+01, 5.1986E+08, 1.1444E+07, 0.2057, 2.4962E+03
7.1000E+01, 4.3771E+08, 9.0930E+06, 0.2057, 2.4962E+03
8.0000E+01, 3.6458E+08, 7.1577E+06, 0.2057, 2.4962E+03
9.0000E+01, 3.0090E+08, 5.5780E+06, 0.2057, 2.4962E+03
1.0000E+02, 2.5096E+08, 4.4099E+06, 0.2057, 2.4962E+03
1.1000E+02, 2.1125E+08, 3.5327E+06, 0.2057, 2.4962E+03
1.2000E+02, 1.7917E+08, 2.8827E+06, 0.2057, 2.4962E+03
1.4000E+02, 1.3063E+08, 1.9712E+06, 0.2057, 2.4962E+03
1.6000E+02, 9.7283E+07, 1.3640E+06, 0.2057, 2.4962E+03
1.8000E+02, 7.3775E+07, 9.8685E+05, 0.2101, 2.5491E+03
2.0000E+02, 5.6632E+07, 7.2737E+05, 0.2144, 2.6020E+03
2.2000E+02, 4.3875E+07, 5.4838E+05, 0.2188, 2.6549E+03
2.5000E+02, 3.0224E+07, 3.6164E+05, 0.2217, 2.6902E+03
2.8000E+02, 2.1133E+07, 2.4444E+05, 0.2261, 2.7431E+03
3.2000E+02, 1.3278E+07, 1.4832E+05, 0.2326, 2.8225E+03
3.5000E+02, 9.4926E+06, 1.0403E+05, 0.2377, 2.8843E+03
4.0000E+02, 5.3909E+06, 6.0043E+04, 0.2449, 2.9725E+03
4.5000E+02, 3.0407E+06, 3.3964E+04, 0.2478, 3.0078E+03
5.0000E+02, 1.8040E+06, 1.5503E+04, 0.2522, 3.0607E+03
'End of Block'
'*', 49, 1, 22, 22, 3, 3, 75, 0
'SPENVIS 4.y.z.win32 - 18-May-2011 16:22:12'
'PRJ_DEF', -1, 'MFLUX'
'PRJ_HDR', -1, ' '
'MOD_ABB', -1, 'SEP'
'MIS_PLA', 1, 3, ' '
'MIS_NTR', 1, 1, ' '
'MIS_STA', 1, 22383.61534143, ' '
'MIS_END', 1, 22748.61534143, ' '
'MIS_DUR', 1, 3.650000E+02, 'days'
'SEP_IEL', 1, 1, ' '
'SEP_JEL', 1, 1, ' '
'SEP_MOD', -1, 'JPL-91'
'SEP_TMI', 1, 1.0, 'years'
'SEP_TMA', 1, 0.0, 'years'
'SEP_DUR', 1, 1.0, 'years'
'SEP_NCY', 1, 1, ' '
'SEP_NOR', 1, 0, ' '
'SEP_NAL', 1, 0, ' '
'SEP_PRB', 1, 95.0, '%'
'SEP_OMN', 1, 1, ' '
'SEP_ABS', -1, 'Energy'

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'PLT_HDR', -1, 'JPL-91 : solar ions'
'SPECIES', -1, 'H '
'PS Annotation', 8, 1
'Mission start: 14/04/2011 14:46:05'
0.05, 0.00, 0.00
'Mission end: 13/04/2012 14:46:05'
0.95, 0.00, 1.00
'Nr. of segments: 1'
0.05, 1.50, 0.00
'Duration: 365.00 days'
0.95, 0.00, 1.00
'PS Annotation', 12, 0
'Solar particle model: JPL-91'
0.05, 2.00, 0.00
'Mission duration: 1.00 years, spanning 1 solar cycles'
0.10, 1.50, 0.00
'1.00 years in solar maximum'
0.15, 1.50, 0.00
'0.00 years in solar minimum'
0.15, 1.50, 0.00
'Confidence level: 95.000%'
0.10, 1.50, 0.00
'Magnetic shielding: quiet magnetosphere'
0.10, 1.50, 0.00
'Energy', 'MeV/n', 1, 'Energy'
'IFlux', 'cm!u-2!n', 1, 'Integral Fluence of ', 'SPECIES'
'DFlux', 'cm!u-2!n (MeV/n)!u-1!n', 1, 'Differential Fluence of ', 'SPECIES'
1.0000E-01, 7.1784E+10, 1.2265E+11
1.1000E-01, 7.0593E+10, 1.1549E+11
1.2000E-01, 6.9471E+10, 1.0891E+11
1.4000E-01, 6.7402E+10, 9.7955E+10
1.6000E-01, 6.5533E+10, 8.9008E+10
1.8000E-01, 6.3826E+10, 8.1677E+10
2.0000E-01, 6.2254E+10, 7.5537E+10
2.2000E-01, 6.0795E+10, 7.0357E+10
2.5000E-01, 5.8782E+10, 6.3843E+10
2.8000E-01, 5.6947E+10, 5.8448E+10
3.2000E-01, 5.4728E+10, 5.2506E+10
3.5000E-01, 5.3209E+10, 4.8806E+10
4.0000E-01, 5.0896E+10, 4.3706E+10
4.5000E-01, 4.8816E+10, 3.9490E+10
5.0000E-01, 4.6929E+10, 3.5991E+10
5.5000E-01, 4.5202E+10, 3.3073E+10
6.3000E-01, 4.2710E+10, 2.9224E+10
7.1000E-01, 4.0498E+10, 2.6088E+10
8.0000E-01, 3.8279E+10, 2.3227E+10
9.0000E-01, 3.6086E+10, 2.0633E+10
1.0000E+00, 3.4129E+10, 1.8497E+10
1.1000E+00, 3.2369E+10, 1.6714E+10
1.2000E+00, 3.0771E+10, 1.5235E+10
1.4000E+00, 2.7962E+10, 1.2853E+10
1.6000E+00, 2.5579E+10, 1.0982E+10
1.8000E+00, 2.3529E+10, 9.5123E+09
2.0000E+00, 2.1745E+10, 8.3306E+09
2.2000E+00, 2.0175E+10, 7.3743E+09
2.5000E+00, 1.8135E+10, 6.2254E+09
2.8000E+00, 1.6403E+10, 5.3227E+09
3.2000E+00, 1.4461E+10, 4.3842E+09
3.5000E+00, 1.3228E+10, 3.8337E+09
4.0000E+00, 1.1574E+10, 2.7825E+09
4.5000E+00, 1.0383E+10, 1.9813E+09
5.0000E+00, 9.4605E+09, 1.7106E+09
5.5000E+00, 8.6591E+09, 1.4948E+09
6.3000E+00, 7.5715E+09, 1.2243E+09
7.1000E+00, 6.6753E+09, 1.0162E+09

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8.0000E+00,	5.8408E+09,	8.3810E+08
9.0000E+00,	5.0784E+09,	6.8673E+08
1.0000E+01,	4.4902E+09,	4.8964E+08
1.1000E+01,	4.0771E+09,	3.3663E+08
1.2000E+01,	3.7598E+09,	2.9797E+08
1.4000E+01,	3.2239E+09,	2.3788E+08
1.6000E+01,	2.7935E+09,	1.9259E+08
1.8000E+01,	2.4423E+09,	1.5859E+08
2.0000E+01,	2.1513E+09,	1.3240E+08
2.2000E+01,	1.9068E+09,	1.1209E+08
2.5000E+01,	1.6054E+09,	8.8831E+07
2.8000E+01,	1.3718E+09,	6.6941E+07
3.2000E+01,	1.1570E+09,	4.0450E+07
3.5000E+01,	1.0505E+09,	3.0543E+07
4.0000E+01,	9.1183E+08,	2.4920E+07
4.5000E+01,	7.9810E+08,	2.0574E+07
5.0000E+01,	7.0363E+08,	1.7214E+07
5.5000E+01,	6.2407E+08,	1.4610E+07
6.3000E+01,	5.1986E+08,	1.1444E+07
7.1000E+01,	4.3771E+08,	9.0930E+06
8.0000E+01,	3.6458E+08,	7.1577E+06
9.0000E+01,	3.0090E+08,	5.5780E+06
1.0000E+02,	2.5096E+08,	4.4099E+06
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1.2000E+02,	1.7917E+08,	2.8827E+06
1.4000E+02,	1.3063E+08,	1.9712E+06
1.6000E+02,	9.7283E+07,	1.3640E+06
1.8000E+02,	7.3775E+07,	9.8685E+05
2.0000E+02,	5.6632E+07,	7.2737E+05
2.2000E+02,	4.3875E+07,	5.4838E+05
2.5000E+02,	3.0224E+07,	3.6164E+05
2.8000E+02,	2.1133E+07,	2.4444E+05
3.2000E+02,	1.3278E+07,	1.4832E+05
3.5000E+02,	9.4926E+06,	1.0403E+05
4.0000E+02,	5.3909E+06,	6.0043E+04
4.5000E+02,	3.0407E+06,	3.3964E+04
5.0000E+02,	1.8040E+06,	1.5503E+04

'End of File'