DH CONSULTANCY BVBA

Interplanetary and Planetary Radiation Model for Human Spaceflight (IPRAM)

Executive Summary Report

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This is the Executive Summary Report for the Interplanetary and Planetary Radiation Model for Human Spaceflight, ESA Contract No 4000106133/12/NL/AF.

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<tr><td colspan="4">ABSTRACT:

Gaps in existing radiation environment and effects standards adversely affect human spaceflight developments. The most important drivers in the domain of interplanetary and planetary radiation environments were investigated, identifying appropriate data sources and modelling methods to address the needs of future interplanetary manned mission design and operation.

New radiation estimates have been compiled for missions to the Moon, Mars, and near-Earth asteroids, combining a comprehensive set of spacecraft and neutron monitor data with statistical models. A roadmap for future developments is presented, as well as a gap analysis of environment data and models of the radiation environment and effects on humans and spacecraft components.</td></tr>
<tr><td colspan="4">The work described in this report was done under ESA Contract. Responsibility for the contents resides in the author or organisation that prepared it.</td></tr>
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1.1	07/01/2015	Circulation among team members for comments.
1.2	21/01/2015	Final version.

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1 REFERENCES AND ACRONYMS

1.1 APPLICABLE AND REFERENCE DOCUMENTS

1.1.1 APPLICABLE DOCUMENTS

[**AD 1**] "Interplanetary and planetary radiation model for human spaceflight," ESA Statement of Work, TEC-EES/2011.820/ED, Issue 1, Rev 2, ITT AO 1-7009/11/NL/NA 10 October 2011.

[**AD 2**] ESA Contract No 4000106133/12/NL/AF.

1.1.2 REFERENCE DOCUMENTS

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1.2 ACRONYMS AND ABBREVIATIONS

ACE	Advanced Composition Explorer
AD	Applicable Document
AU	Astronomical Unit
BFO	Blood Forming Organs
CNS	Central Nervous System
CREME	Cosmic Ray Effects on Micro-Electronics
ESA	European Space Agency
ESP	Emission of Solar Protons
EVA	ExtraVehicular Activity
GCR	Galactic Cosmic Ray
GLE	Ground Level Enhancement
GME	Goddard Medium Energy
GOES	Geostationary Operational Environmental Satellites
GRAS	Geant4 Radiation Analysis for Space
HEPAD	High Energy Proton and Alpha Detector
ICRP	International Commission on Radiological Protection
IMP	Interplanetary Monitoring Platform
IPRAM	Interplanetary and Planetary Radiation Model for Human Spaceflight
IRIS	Interplanetary Radiation Information System
ISO	International Organization for Standardization

JPL	Jet Propulsion Laboratory
LET	Linear Energy Transfer
N/A	Not Applicable
NEA	Near Earth Asteroid
NASA	National Aeronautics and Space Administration
NCRP	National Council on Radiation Protection and Measurements
NM	Neutron Monitor
ODI	Open Data Interface
RD	Reference Document
REID	Risk of Exposure Induced Death
SEM	Space Environment Monitor
SEP	Solar Energetic Particle
SEPEM	Solar Energetic Particle Environment Modelling
SoW	Statement of Work
SPENVIS	SPace ENVironment Information System
SPE	Solar Proton Event
SRD	System Requirements Document
SSA	Space Situational Awareness
SSAT	Sector Shielding Analysis Tool
TEPC	Tissue Equivalent Proportional Counters
TV	Transfer Vehicle
WP	Work Package

2 INTRODUCTION

This document is the Executive Summary Report for the Interplanetary and Planetary Radiation Model for Human Spaceflight, ESA Contract No 4000106133/12/NL/AF.

2.1 CONTEXT

The principal objectives of the IPRAM study were:

1. To specify the systems requirements for the definition of interplanetary and planetary radiation environments relevant to human spaceflight in the context of future missions beyond LEO.
2. To perform a review of the available state of the art models and software to predict the interplanetary and planetary environment, and the influence of shielding and effects.
3. Review the available data which may be used to validate models of the environment, or which could be used to develop empirical models and ingest relevant datasets in ODI.
4. Based on current models, develop a specification for the interplanetary and planetary environments (for missions to the Moon, Mars, and near-Earth asteroids).
5. Identify the gaps in our current knowledge preventing the development of accurate environment models and limitations of effects tools.
6. Define a strategy for the improvement in that knowledge and model development.

2.2 PROJECT OVERVIEW

The IPRAM project was divided into 5 Work Packages, in accordance with the Statement of Work [AD 1]. Detailed technical reports were produced for each of the WPs, as well as extensive simulation results for the radiation environment specification. A brief summary of the WPs is presented in the sections below, including references to the detailed technical reports and to sections in this Executive Summary Report.

2.2.1 WP 1000: Requirements Specification

The requirements review identified the requirements for the assessment and protection measures for future human spaceflight associated with interplanetary and planetary missions. The technical report [RD 1] produced during this phase of the work defines the model and data requirements to predict the risk to future human space missions beyond LEO. This specification includes a review and validation of requirements specified by ESA, a comparison with standards and NASA documentation, system requirements for prediction and monitoring of the environment, and information on results from previous relevant studies.

2.2.2 WP 2000: Review of State of the Art Models and Tools

In this WP, a review was performed of the state of the art models and tools available for predicting the interplanetary radiation environment at distances relevant to possible future manned missions. The main emphasis was on distances between 1 and 1.7 AU, covering missions to Moon, Mars and near-Earth asteroids. In addition, theoretical activities concerning the transport and acceleration of SEPs were reviewed, which provides guidelines for future development of models, data and tools to fill the gaps in our capabilities for environment specification. This review was limited to helioradial distances between 0.3 AU and 5 AU.

2.2.3 WP 3000: Review of Available Data and Data Analysis

WP 3000 encompassed a comprehensive review of available datasets relevant for the specification of the interplanetary radiation environment. The output of this part of the WP is the Dataset Review [RD 5]. In addition, a number of interplanetary spacecraft datasets were acquired and ingested into ODI for future analyses.

2.2.4 WP 4000: Gap Analysis and Future Model Development Strategy

The purpose of this WP was to review and compare the state of the art models and the requirements as identified in the SRD from WP 1000 and identify the gaps in current knowledge that prevent more accurate predictions of the radiation environments for human missions beyond Earth's orbit. At the same time, the instrumentation, data quality and data analysis requirements were assessed in the context of the SRD. The main output of this WP was the Gap Analysis document [RD 6].

2.2.5 WP 5000: Environment Specification

This WP was split into two tasks:

1. The establishment of the primary environment spectra (i.e. SEP and GCR particle spectra) for a Martian and for a lunar mission scenario, and for a near-Earth asteroid mission. Two types of spectra were produced: total fluence spectra, and worst case peak flux spectra.
2. The derivation of secondary environment spectra (including albedo spectra) and the calculation of the radiation effects as identified in WP 1000.

The analyses performed for both tasks are described in Section 5. Given the large volume of particle spectra and dose results, only a sample of the results can be presented in this document. More details are provided in the Environment Specification document [RD 7], and all simulation results were provided in digital form to the Agency (although this was not required by the SoW). The results for the Mars simulations were compared to results from the literature.

As part of a CCN activity, the instantaneous dose rates and cumulative doses were calculated as a function of time over the two reference SEP events for solar minimum and solar maximum conditions, respectively. The results are shown in Section 5.4.

3 REQUIREMENTS SPECIFICATION

The IRIS [RD 8] was defined within the IPRAM study as a system intended for use to quantify ionising radiation risks to interplanetary and planetary human missions. The SoW [AD 1] required that the analysis undertaken within the IPRAM Project address potential human missions from 0.3 to 5 AU (i.e. Mercury to Jupiter), with the priority given to consideration of missions the Moon, near-Earth asteroids, and Mars and its moons.

3.1 OUTLINE OF CALCULATION APPROACH AND SCOPE OF THE REQUIREMENTS ASSESSMENT PERFORMED

Figure 1 shows a flow-diagram which summarises the processes involved in assessing the radiation risk to the crew and critical equipment of human space missions. Note that whilst the diagram displays a series of processes going from left to right, in reality these processes are iterative, with stages repeated if the requirements for the radiation protection systems are not met. For clarity, these iterative stages are omitted in the figure. A series of 105 System Requirements were defined to address the calculation process summarised by Figure 1, and also the requirements for a monitoring infrastructure.

3.2 RADIOBIOLOGICAL PROTECTION LIMITS

Radiobiological effects are subdivided into two categories, stochastic and deterministic effects, and each has different dose quantities and associated protection limits. Stochastic effects are associated with radiation induced cancer and the increase dose results in a corresponding increase risk of cancer. Deterministic effects are long term low-level, or short-term high-level radiation exposure resulting in disruption to the central nervous system (CNS), suppression of haematopoiesis in bone marrow, cataracts and other vision impairment, and acute radiation sickness. For deterministic effects, a key concern is the potential exposure of astronauts during solar particle events, especially when in low-shielding conditions such as during EVA.

The radiobiological limits for European missions should, in principle, be defined within the ECSS standards, and indeed engineering standards and handbook ECSS-E-ST-10-12C, ECSS-E-HB-10-12 and ECSS-E-ST-34 [RD 9][RD 10][RD 11] all define stochastic and deterministic radiological protection limits for human spaceflight, but these are in conflict with each other and in any case are out of date.

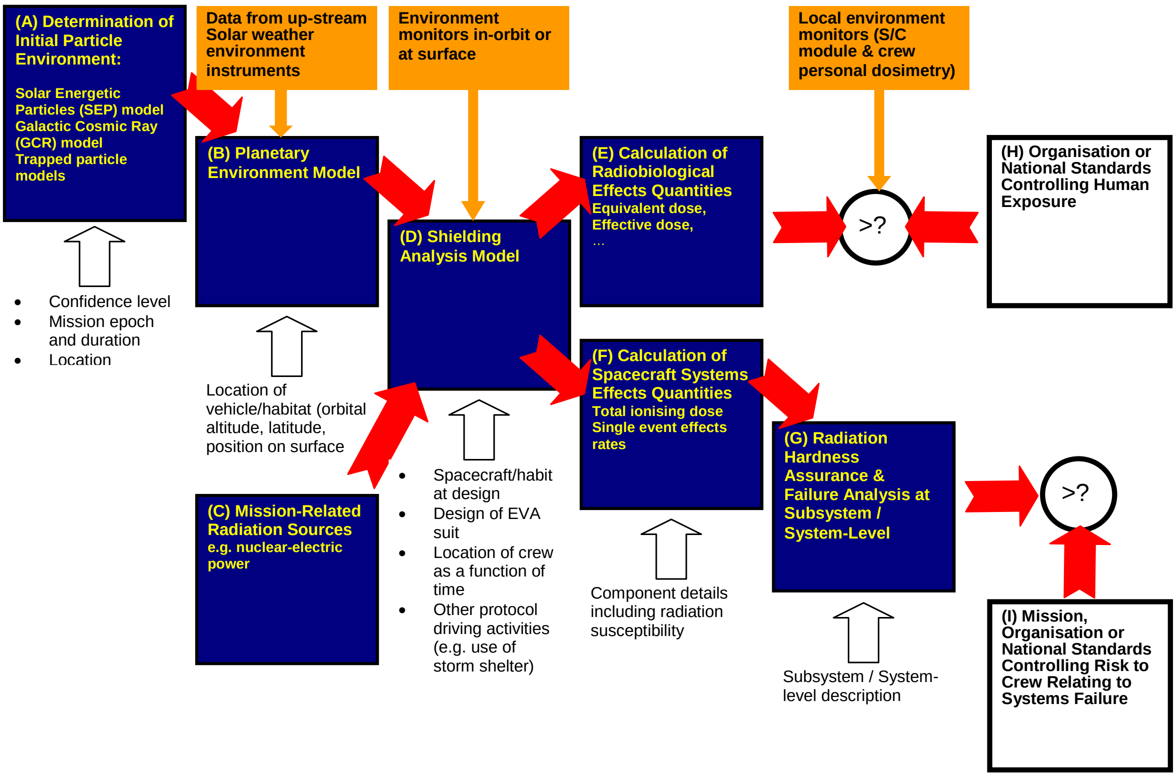

FIGURE 1 PROCESS FLOW FOR ASSESSMENT OF RADIATION EXPOSURE OF CREW AND EQUIPMENT

For stochastic radiation effects, both ECSS and NASA/NCRP standards or recommendations use effective dose, *E*. The dose constraints are intended to limit the additional risk from fatal cancer resulting from career exposure, in this case a 3% excess lifetime risk on fatal cancer during lifetime. The effective dose career limits which are age and gender-dependent are shown in Table 1.

TABLE 1 EXAMPLE AGE- AND GENDER-DEPENDENT CAREER EFFECTIVE DOSE (*E*) LIMITS IN SV, ASSUMING A TEN-YEAR CAREER. THESE VALUES ORIGINATE FROM NRCP 132 [RD 16] AND ARE IDENTIFIED IN ECSS-E-ST-34C [RD 11].

Age	Male	Female
25	0.7	0.4
35	1.0	0.6
45	1.5	0.9
55	3.0	1.7

During the course of the IPRAM Project, a draft document was issued by the ICRP for consultation that attempted to address radiation exposure of astronauts when in space [RD 14]. This draft was updated and issued formally by the ICRP as Publication 123 in August 2013 [RD 15]. For the purposes of the IPRAM project simulation studies, since the work undertaken in WP5000 commenced prior to the release of the ICRP 123 document, the deterministic radiobiological protection limits were defined as shown in Table 2 **but interpreted as dose equivalent in tissue/organ**.

TABLE 2 RECOMMENDED DOSE LIMITS FOR SHORT-TERM OR CAREER NON-CANCER EFFECTS. UNTIL THE RESULTS OF DISCUSSION BY EUROPEAN RADIATION EFFECTS EXPERTS, THESE VALUES SHOULD BE TREATED AS GRAY-EQUIVALENT DOSE IN ORGAN OR TISSUE (IN SV).

Organ	30 day	1 year	Career
BFO	0.25	0.5	Not applicable
Eye	1.0	2.0	4.0
Skin	1.5	3.0	4.0
Heart	0.25	0.5	1.0
CNS (Z≤10)	0.5	1.0	1.5
(Z>10)	0.5	0.1	0.25

3.3 REVIEW AND VALIDATION OF IRIS REQUIREMENTS

The purpose of IRIS and its associated work was to develop a set of reference standards which can be used to assist with mission studies and the development of software tools and methodologies that support mission studies. The requirements identified in the IRIS document cover [RD 1] the risk to crew from the perspective of an exploration-class mission and the requirements placed on the Interplanetary Radiation Information System from the user/operator perspective.

A review was conducted of the IRIS requirements, which led to the following recommendations:

- Section 2 of the IRIS document specifies that the exposure limit is defined as an annual equivalent dose of 0.5 Sv/year. This is presumed to come from ECSS-E-ST-34C, which is one of the *deterministic effects exposure limits* for BFOs. IRIS should base the exposure limits on both the gray-equivalent doses defined in Table 2 for deterministic effects, and the effective dose equivalent limits of 1.0 Sv for a lifetime, and 0.5 Sv for a year.
- A confidence level should also be defined in association with these values, e.g. the maximum exposure limit for BFOs within a 30 day period is 0.25 Sv with a 95% CL that this dose will not be exceeded.
- It is possible that European radiobiological effects experts will ultimately define protection limits for stochastic effects, based either on a maximum percentage increased REID that is age- and gender-dependent (i.e. equivalent to Table 2 in the WP 1000 review document but in H_E), or more general limits.
- The gender-dependent tissue-weighting factors defined in ICRP 103 should be used, or if more appropriate (and available data permit) gender- and age-dependent weighting factors used (e.g. see Table A.4.19 of ICRP 103 and ICRP 123 recommendations [RD 12][RD 15]). The ICRP Publication 60 values for W_T provided in ECSS-E-ST-10-12C should **not** be used.
- Requirement 3.2.1 originally specifies a single threshold dose at which action is to be taken, with the threshold left TBD. It was recommended that this requirement be

altered to define thresholds at which crews should: cease EVA activities and return to spacecraft/habitat; retreat to storm shelter except for brief periods where critical operations are necessary; were permitted to leave the storm shelter.

3.4 RECOMMENDATIONS

The principal recommendations of the review conducted within WP1000 are:

- The IRIS requirements should be updated as recommended in Section 3.3, taking into consideration broader exposure limits and the more up-to-date radiation protection quantities.
- The ECSS documentation (particularly ECSS-E-ST-34C and ECSS-E-HB-10-12A) should be reviewed by radiobiological effects experts in the context of the ICRP Publication 123 recommendations [RD 15], and changes made to specify protection limits in terms of gray-equivalent in organ/tissue and effective dose equivalent (instead of equivalent dose and effective dose currently used). In addition, updated protection limits are required to treat human spaceflight in interplanetary space and not just LEO.
- The systems requirements identified here associated with the radiation monitoring infrastructure should be reviewed in the context of on-going work in Space Situational Awareness (SSA) activities, and potentially incorporated into the latter.
- There is a need to develop a system or practice to regularly update the environment specifications as new radiation data and models become available.
- Parallel activities should be undertaken to: permit more accurate assessment of the risk from radiation damage in humans from high-LET radiation, i.e. from heavy ions; better understand radiation damage to humans in the space environment where synergistic effects are important; generate fluence-to-radiological-dose conversion coefficients for all relevant ion species for quantities such as gray-equivalent in organ/tissue, effective dose equivalent, dose equivalent in organ/tissue, etc.

4 GAP ANALYSIS, PROPOSED FUTURE STUDIES AND ROADMAP

The objective of WP4000 of the project was to review and compare the state of the art models with respect to the requirements as identified in the SRD from WP1000 [RD 1] and identify the gaps in current knowledge that prevent a more accurate prediction of the radiation environments for human missions beyond Earth's orbit. At the same time, the instrumentation, data quality and data analysis requirements were assessed in the context of the SRD. As part of the analysis, the study assessed the minimum set of instruments required to provide sufficient awareness of the environment for human missions to the Moon, a near-Earth asteroid, and missions to Mars and its moons.

4.1 GAP ANALYSIS AND STRATEGY FOR DEVELOPMENT

Within WP4000, the results of the model and data reviews conducted within [RD 2][RD 3][RD 4][RD 5] were assessed and compared with the Systems Requirements in reference [RD 1]. The principal developments needed in order to provide the necessary modelling capability in an IRIS were identified as:

- Treatment of uncertainties in the calculations in interplanetary, planetary and shielded environments—primarily for SEP environments, but also for GCR, and improved understanding of trade-off between model fidelity and accuracy.
- Treatment of SEP model energies to 300 MeV (extrapolated to 1 GeV) and of SEP anisotropies.
- Incorporation of relevant dose radiological conversion coefficients.

The key improvements required to help future model development are:

- Better coverage is needed of the high energy range for solar H and He, and with adequate energy resolution.
- Further data are required to aid our understanding of and validate models treating helioradial dependence of the SEP environment.
- If modelling of SEP anisotropies is to be explored further, there is a need for relevant particle data with accurate corresponding magnetometer data.

The modelling gaps are listed in [RD 6], which also identifies potential solutions.

4.2 MINIMUM SSA SYSTEM FOR INTERPLANETARY AND PLANETARY HUMAN MISSIONS

WP4000 also briefly examined the minimum IRIS system of detectors that is considered necessary to support interplanetary missions to the Moon, to Mars and its moons, and a near Earth asteroid. The analysis looked at the principal sensor types discussed within the SRD but is presented as a first iteration. Therefore, a more detailed analysis is required to examine more carefully the required sensor performance, the availability of communications infrastructure and overall system availability/reliability—these aspects remain the subject of future work.

For missions to the Moon, it is recommended that solar monitoring and upstream particle detection be performed at the Sun-Earth L1 Lagrange point (approximately 1.5×10^6 km from Earth). The minimum sensor payload for the L1 sentinel would be: a simple X-ray imager; an X-ray flux monitor, as a trigger for the imager to reduce the telemetry burden; a radio spectrograph or a multi-channel receiver to detect type III bursts; an energetic electron-proton instrument; a magnetometer.

It is assumed that as a baseline, communications links via Earth will be used provided operations are on the Earth-facing side of the Moon. Potentially direct links to the L1 Lagrange point could also be made provided the L1 point is above the lunar horizon. Obviously, given the proximity of the Earth and L1 point the signal path length delays are negligible, i.e. a few seconds. If surface operations also take place on the far side of the Moon, methods to forward information on the environment condition need to be considered, e.g. using the TV or other spacecraft.

To monitor the local radiation environment, as a minimum, radiation monitors should include: ctive in-situ detectors within different areas of the spacecraft and habitat, measuring the dose both internally and externally (based on TEPC and solid state detectors); similar, but perhaps more compact active monitors on ground vehicles and EVA suits; personal dosimeters providing active detector warning of the radiation dose are necessary (based on solid state detectors or TEPC), and possibly passive detectors such as thermoluminescent dosimeters should be considered for regular dose monitoring.

For a near Earth asteroid mission, the minimum space situational awareness system includes the same solar monitoring equipment as for lunar missions. The location of the relativistic electron and proton detectors to measure the near-Earth particle environment and connectivity to the solar event depends upon the trajectory of the spacecraft relative to Earth and the L1 Lagrange point. Assuming the mission operates within 0.1 AU of Earth, signal path length delays are <1 minute and therefore negligible.

For missions to Mars and its moons, the dependence of the environment on solar longitude and communications delays means one must consider having the necessary infrastructure to monitor the environment from solar longitudes magnetically connected to Mars, and to communicate this information directly to the mission's command spacecraft/transfer vehicle. For early warning of solar activity, it is recommended that a sentinel spacecraft be located at the L4 Lagrange point for the Sun-Mars system, providing greater visibility of the relevant solar longitudes. In addition, electron-proton instruments are required in Mars orbit, primarily to use the relativistic electron flux to warn if the event is magnetically connected with Mars—by default it is assumed that the crew TV has such a system. The potential latencies in the information returned to the Mars ground site have been examined for a variety of general systems, including no communications relay, relaying the communications from the crew TV via Earth.

To provide a robust system which, if necessary, is independent of communications via Earth, it is proposed that the minimum system include an areosynchronous communications spacecraft constantly visible from the ground site. In addition, if the communications satellite also has the same relativistic electron and proton monitoring equipment, then this would reduce the delay between detecting an enhancement in the relativistic electrons near Mars and alerting the ground site.

The minimum local environment monitoring requirement for the NEA and Mars missions is considered to be identical to that for lunar missions, i.e. active area monitoring both internal and external to the spacecraft, smaller active systems for EVA equipment, and personal dosimeters.

5 ENVIRONMENT SPECIFICATION

In order to quantify the radiation environment for interplanetary and planetary missions, the following steps need to be taken:

1. Establish the SEP and GCR components of the primary radiation spectrum; this involves:
   a. Selection of a number of representative ion species for radiation effects
   b. Calculate GCR ion flux and fluence spectra for the outbound, surface and inbound mission phases.
   c. Repeat step b for SEP ions. This step involves a mixture of statistical model runs and usage of peak flux and fluence spectra for representative events. The energy ranges of the statistical models need to be extended to GeV energies.
2. Define shielding configurations: a series of Al slab shield thicknesses, and a spacecraft/habitat geometry model for which a sector shielding analysis is performed.
3. Perform GRAS simulations for the selected shielding configurations and nominal ion spectra to produce response functions which can be folded with the primary environment spectra. The response functions include the shielded primary radiation spectrum, the secondary radiation spectra (including planetary albedo), and dose quantities relevant for biological effects.
4. Fold the response functions with the primary environment spectra derived in step 1.

The derivation of the primary environment spectra is described in [RD 7]. In particular, the extension of the energy range of the SEP models using GLE data is discussed in detail, as well as the extension of the SEPEM reference proton dataset energies using GOES/HEPAD data, helioradial distance scaling and the use of abundance ratios to obtain representative ion spectra.

Three mission scenarios, provided by the Agency, were analysed in detail:

1. A Moon mission consisting of short cruise phases and a surface stay of 6 months (Section 5.3.1).
2. A mission to Mars with a surface stay of 15.5 months and a combined cruise phase length of 16.5 months (Section 5.3.2).
3. A near Earth asteroid mission (Apophis) with a total cruise phase of 9.5 months and a surface phase of 1.5 months (Section 5.3.3).

The Mars and Apophis scenarios use trajectory simulations provided by the Agency.

As the three mission profiles are very different, the radiation analyses needed to be tailored to capture the variety in mission phase lengths and their combination into a total mission analysis. The analyses yielded a very large number of output files and plots for the primary and secondary radiation environment spectra and the derived dose quantities. A representative selection of dose plots and tables is presented in [RD 7]. All output generated during this phase of the project was delivered on DVD as an unsolicited delivery.

Section 5.4 presents the instantaneous dose rates and cumulative doses as a function of time over the two reference SEP events for solar minimum and solar maximum conditions.

5.1 Definition of the Primary Environment

The primary environment for all mission scenarios consists of SEP and GCR ions representing the whole periodic table of elements up to U (Z=92). In principle, all 92 elements should be taken into account in the definition of the primary and secondary radiation environments, and in the calculation of radiation doses. Such an approach is, however, far outside the scope of the project, so that instead a limited set of ions was selected for the environment and dose estimates: H, He, C, O, Mg, Si and Fe. Treatment of these ions should result in a representative estimate of radiation doses.

The SEPEM statistical models that were used to compute the SEP environment take into account the solar cycle dependence of the environment by dividing a mission scenario in contiguous periods of minimum and maximum solar activity. As the mission scenarios in this study are relatively short, it was decided to perform two separate sets of simulations: one in which the whole mission falls into a single period of solar maximum activity, and a similar set in conditions of solar minimum activity. This was achieved for the SEPEM analysis by artificially shifting the solar cycle start and end dates. For the GCR analysis, it was assumed that the environment is constant over each mission scenario, so that only two runs of the GCR ISO Standard 15390 model [RD 20] were needed for the selected ions: one for epoch 1996.4 (representative of solar minimum), and one for epoch 1989.5 (representative of solar maximum).

5.1.1 THE SEP ENVIRONMENT

The SEPEM application server [RD 21] provides access to a number of statistical models which can be run on a number of spacecraft datasets, in particular on the SEPEM reference proton dataset (http://dev.sepem.oma.be/help/data_pref.html). The dataset is based on GOES/SEM proton data that were cross-calibrated with IMP-8/GME data for common time periods, cleaned from unphysical spikes and re-binned into energy channels that are logarithmically spaced between 5 and 200 MeV. The dataset covers the years 1973–2013 and contains 250 proton events (http://dev.sepem.oma.be/help/event_ref.html). The SEPEM proton energy channels are listed in Table 3.

TABLE 3 PROTON ENERGY CHANNELS USED FOR THE ENVIRONMENT SPECIFICATION. THE FIRST TEN CHANNELS ARE THE REFERENCE SEPEM CHANNELS, THE LAST FOUR CONSTITUTE THE ENERGY EXTENSION OBTAINED WITH THE GLE DATA ANALYSIS.

Channel	E_l	E_u	E_c
P1	5.000	7.231	6.013
P2	7.231	10.46	8.695
P3	10.46	15.12	12.57
P4	15.12	21.87	18.18
P5	21.87	31.62	26.30
P6	31.62	45.73	38.03
P7	45.73	66.13	54.99
P8	66.13	95.64	79.53
P9	95.64	138.3	115.0
P10	138.3	200.0	166.3
P11	200.0	300.0	244.9
P12	300.0	450.0	367.4
P13	450.0	675.0	551.1
P14	675.0	1012.5	826.7

One of the tasks of the IPRAM project was to extend the energy range of the SEPEM proton environment specification beyond 200 MeV. The modelling of the proton environment at these energies was performed using the results of Tylka and Dietrich [RD 24] on Ground Level Enhancements (GLEs). The results of their analysis offer a unique resource on high energy particle events, as the analysis covers all GLEs from 1956 till present, for which a statistical analysis can be performed. 58 GLEs from Feb 1956 to Dec 2006, combined into 43 GLE episodes, were used.

Tylka & Dietrich analysed the GLEs in the dataset by fitting the time-integrated increase of the World Network of Neutron Monitors (NM) together with low-energy observations from spacecraft to Band functions [RD 25]. The Band function represents a spectrum which smoothly rolls over from one power law (in rigidity R) at low energies to another at high energies. Band fits were used to generate differential GLE event fluences of the 43 events in the 10 SEPEM reference energy channels plus an additional four energy channels between 200 MeV and 1 GeV (see Table 3).

The SEPEM tools were used to perform a statistical analysis of the 43 GLE energy spectra, using the (exponentially) cut-off power law distribution and a JPL-type Monte Carlo simulation with a fixed mean event rate of 0.953/yr. Applying a confidence level of 95% (i.e. a probability of exceeding of 5%), the fluence distributions of channels P3–P14 were then used to derive mission-integrated fluence spectra resulting from the GLE episodes.

Next, the same analysis was applied to the SEPEM reference dataset of 250 events observed in energy channels P1–P10. The resulting spectra were compared to the GLE analysis over the common energy channels (P3–P10), and a very good coincidence of the results was found. In the overlapping energy range, the two datasets show very similar results. In order to combine the results of the GLE and SEPEM dataset analyses, a weighting function was defined to smoothly join the spectra into a single fluence spectrum. This weighting function is used for all mission analyses in the project, for solar maximum conditions. For solar minimum conditions, the high energy part of the spectrum (channel P11 and above) is defined by the GLE fluences scaled by the ratio of the SEPEM to GLE fluence ratio in channel P10.

The statistical analysis of the GLE fluence data could in principle be repeated for the peak fluxes. However, GLE peak flux spectra are only available for a few events, so that this approach is not possible. Instead, it was decided to use the peak flux spectra observed during two representative SEP events, one during solar maximum (the large GLE of 29 Sep 1989) and one during solar minimum (the 13 Dec 2006 GLE). The flux values were obtained by applying spectrum fit functions to a combination of the SEPEM reference proton dataset and GOES/HEPAD data. The HEPAD instrument measures protons in three energy bands, listed in Table 4.

TABLE 4 GOES/HEPAD PROTON ENERGY CHANNELS

Channel	GOES-6			GOES-11		
	E_l	E_u	E_c	E_l	E_u	E_c
H8	355.0	430.0	390.7	320.0	420.0	366.6
H9	430.0	505.0	466.0	420.0	510.0	462.8
H10	505.0	685.0	588.2	510.0	700.0	597.5

Data spikes were removed from the HEPAD data before applying Sauer's correction algorithm, as reported in Appendix C of Shea & Smart [RD 26].

The fluence and peak flux proton environments described above represent the environment in the vicinity of Earth, i.e. at a distance of 1 AU from the Sun. As the asteroid and Mars mission scenarios cover helioradial distances between 1.0 and 1.6 AU, the dependence of the SEP fluence and flux on distance needs to be taken into account.

SEPEM incorporates a mechanism for performing a statistical analysis of the SEP proton environment encountered during a spacecraft mission with a helioradial distance range between 0.3 and 1.6 AU. The analysis uses a list of synthetic events for which distance scaling parameters were derived ([RD 17][RD 18]) and a virtual timeline method whereby the mission profile is used to obtain the helioradial distance for each randomly generated event.

During the IPRAM project, a new set of distance scaling parameters was derived to better represent the high energy end of the event spectra. The new parameter set is only valid for distances between 1.0 and 1.6 AU, but this is sufficient to cover the asteroid and Mars mission scenarios treated in this study.

The final scaling procedure for the fluence spectra can be summarised as follows:

1. Compute the fluence spectrum for a given trajectory using the new radial dependence coefficients.
2. Repeat the calculation for a fixed distance of 1 AU (actually, the SEPEM code provides this as a secondary output when running the distance scaled analysis).
3. Compute the ratio of the two spectra (scaled and unscaled) for each channel.
4. Interpolate the GLE statistical model spectra for the mission duration.
5. For solar maximum, extend the SEPEM spectrum at 1 AU using the GLE spectrum and the weighting function. For solar minimum, scale the high energy GLE fluences by the ratio of GLE to SEPEM fluences in channel P10.
6. Scale the extended SEPEM spectrum using the ratios obtained in step 3; for channels P11-P14, use the ratio for channel P10.

This procedure needs to be executed separately for solar maximum and solar minimum conditions. In order to scale the peak flux spectra, steps 1–3 should be executed in the same way. Steps 4 and 5 are replaced by instead using the analytical fit functions for the reference event spectra. The resulting extended spectrum at 1 AU should then be scaled as described in step 6.

The SEP spectra derived in the preceding sections are limited to protons. In the current implementation of SEPEM, statistical analysis of ion fluxes using a reference dataset is not supported. Also, no GLE ion data are available. The only option left to obtain SEP ion spectra for the various mission scenarios is to apply abundance ratio scaling factors to the proton fluences and fluxes. The ECSS-E-ST-10-04C standard [RD 27] prescribes the use of the CREME-96 [RD 19] solar ion worst 5 minute fluxes for describing the SEP peak flux ion environment. Table B-9 in the standard document lists the energy spectrum for the ion species H, He, C, N, O and Fe. As this set of species does not correspond with the ion set used in this study, the original spectrum file for all ions was downloaded from the CREME-MC web site. The ratios of the individual ion fluxes to the H flux for each of the energies in the CREME spectrum were calculated and interpolated to the energies used in IPRAM. These ratios are then used to scale the proton spectra obtained for the different mission scenarios.

5.2 Calculation of albedo, radiation shielding and radiation dose

The albedo, secondary particles and radiation dose after shielding are calculated using pre-calculated response functions. The primary environment spectra used in this study consist of proton and He, C, O, Mg, Si, Fe spectra from SPEs and GCRs. Corresponding response functions to these radiation sources have been generated in 13 energy channels for the albedo of the Moon, Mars and asteroid surfaces, and for various aluminium shielding thickness. Specifically, GRAS v3.3 [RD 23] and Geant4 v9.6.p02 [RD 22] have been used for the simulations generating these response functions.

Three shielding configurations were considered:

- Nominal Al slab shielding in free space, for a number of discrete shielding thicknesses in the range 0.05–70.0 g cm^{-2}. The slab shield results were converted to spherical shield configurations using the method established by Seltzer in the development of SHIELDOSE [RD 28].
- Habitat shielding on a planetary body, using representative surface compositions for the creation of albedo radiation response functions. For Mars, atmospheric shielding is (crudely) taken into account by adding a nominal Al shielding thickness.
- A simple aluminium cylindrical spacecraft and shelter model (primarily for the Mars mission) with overall dimensions of 6 m in diameter and 10 m in length. It is divided into 3 sections along the length: at the two ends are two cylinders 6 m in diameter and 4 m in height, with 5 cm thick walls; in the centre is a smaller cylinder, 3 m in diameter and 2 m in height. The lateral wall of the centre cylinder is 10 cm thick while its two ends are of 5 cm thickness (see Figure 2). The total mass of the shelter is over 41 tonnes. The shielding distribution of this model was calculated using the Sector Shielding Analysis Tool (SSAT) available in SPENVIS.

Simulations were performed with the following incident particle parameters: particle type: H, He, C, O, Mg, Si, Fe; energies: 1–100,000 MeV/nuc in 13 channels. From each simulation the following tallies/response functions were generated: protons and backscattered primaries; neutrons; electrons and gamma rays; dose equivalent and equivalent dose in skin tissue; effective dose and ambient dose equivalent, calculated using the fluence-to-dose conversion coefficients from [RD 12][RD 13]; effective dose equivalent, calculated using the fluence-to-dose conversion coefficients from [RD 15]; Gray equivalent dose in red bone marrow, skin and eye for males and females, calculated using the fluence-to-dose conversion coefficients from [RD 15].

Once the generated response functions have been created, the expected albedo and secondary particle radiation, as well as other radiation dose quantities can be calculated rapidly by folding the primary incident radiation spectra with the response functions.

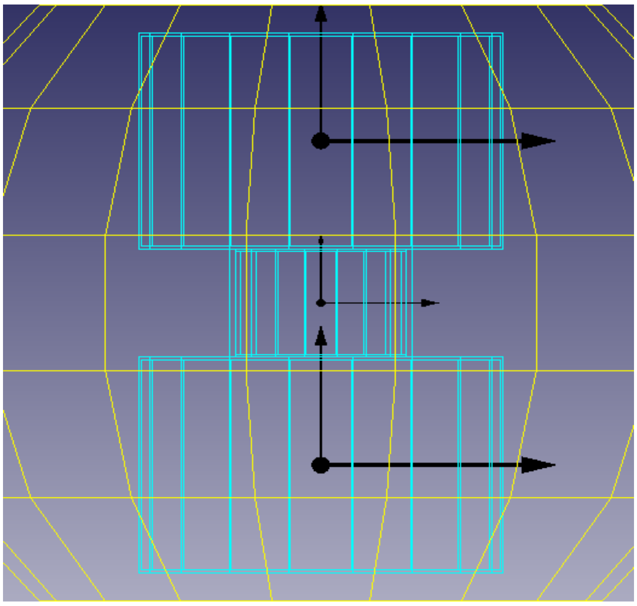

FIGURE 2 SCHEMATIC OF THE SIMPLE SPACECRAFT HABITAT GEOMETRY MODEL. THE DESIGN IS PRIMARILY INTENDED FOR THE MARS MISSION SCENARIO.

5.3 MISSION SCENARIOS

SEP and GCR fluence and peak flux spectra were generated for the three mission scenarios and folded with the dose response functions in order to obtain total and peak dose quantities. The radiation doses for each mission phase were obtained by separately running the GCR and SEP ion fluence spectra through the shielding analysis described above, for the 5 shielding thicknesses used in the study, and for the habitat shielding distribution. Detailed results are presented in [RD 7], here only a summary of the main results is shown.

5.3.1 *THE MOON SCENARIO*

The lunar mission scenario consists of three phases:

1. An outbound trajectory lasting 5 days
2. A surface habitat stay of 6 months
3. An inbound trajectory lasting 5 days

The doses for the individual shielding thicknesses (i.e. excluding the habitat) were summed over the mission phases to also obtain the total mission dose. Figure 3 and Figure 4 show the total GCR and SEP mission doses (per ion species and for all ions combined) for 10.0 g cm^{-2} Al shielding in solar maximum conditions.

5.3.2 *THE MARS SCENARIO*

The Mars mission scenario consists of three phases:

1. An outbound trajectory lasting 9.5 months
2. A surface habitat stay of 15.5 months
3. An inbound trajectory lasting 7 months

The scenario is based on a trajectory simulation provided as text files by the Agency, with start and end dates of 5 Jan 2031 and 7 Sep 2033, respectively, and a total duration of 32 months. The helioradial distance during the mission varies in the range 0.98–1.6 AU.

The SEP doses for the cruise phases cannot be simply summed as the underlying environment spectra were obtained with a confidence level. Figure 5 and Figure 6 show the SEP and GCR surface doses for 10.0 g cm^{-2} shielding in solar maximum conditions.

5.3.3 *THE ASTEROID SCENARIO*

The asteroid (Apophis) mission scenario consists of three phases:

1. An outbound trajectory lasting 8.5 months
2. A surface habitat stay of 1.5 months
3. An inbound trajectory lasting 1 month

The scenario is based on a trajectory simulation provided as text files by the Agency, with start and end dates of 15 May 2028 and 14 Apr 2029, respectively, and a total duration of 11 months. The helioradial distance during the mission varies in the range 0.9–1.1 AU.

The doses for the individual shielding thicknesses (i.e. excluding the habitat) were summed over the free space and surface mission phases to also obtain the total mission dose. Figure 7 and Figure 8 show the total SEP and GCR habitat doses (per ion species and for all ions combined) for the free space simulation in solar maximum conditions.

5.4 SEP DOSE RATES DURING WORST EVENTS

As a guideline for establishing alert procedures, we calculated the instantaneous dose rates and the cumulative doses over the two reference SEP events for solar maximum and solar minimum. The instantaneous proton spectrum for each 5 minute interval in the SEPEM reference dataset (i.e. channels P1–P10) was scaled to ion fluxes using abundance. The resulting proton and ion spectra were then fed into the dose calculation suite, resulting in a dose rate for each of the simulated dose quantities, for each 5 minute interval in the event time series. It should be noted that the proton spectra (and hence the ion spectra) were not extended beyond channel P10.

The dose calculations were performed for the following shielding configurations:

1) 0.2 g cm^{-2} shielding in free space to simulate an EVA;
2) 10 g cm^{-2} shielding on the Martian surface to simulate an activity outside the habitat (0.2 g cm^{-2} for the space suit and 9.8 g cm^{-2} for the Martian atmosphere);
3) 10 g cm^{-2} shielding in free space to simulate a location in the vehicle;
4) 20 g cm^{-2} shielding on the Martian surface to simulate a location in the habitat (10 g cm^{-2} for the habitat and 10 g cm^{-2} for the Martian atmosphere).

Figure 9 and Figure 10 show the instantaneous dose rates and the cumulative doses for case 1, for solar minimum conditions. Similar sets of figures for the remaining cases are shown in [RD 7].

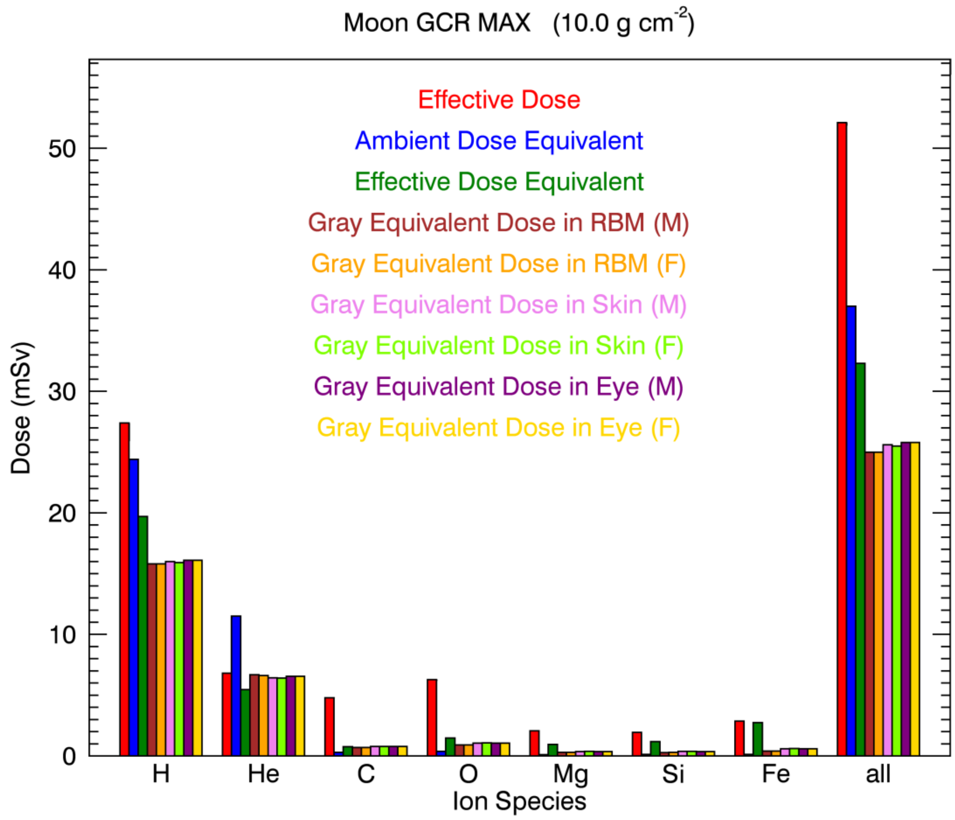

FIGURE 3 GCR SOLAR MAX DOSES FOR THE WHOLE LUNAR MISSION (10.0 G CM^{-2} AL SHIELDING)

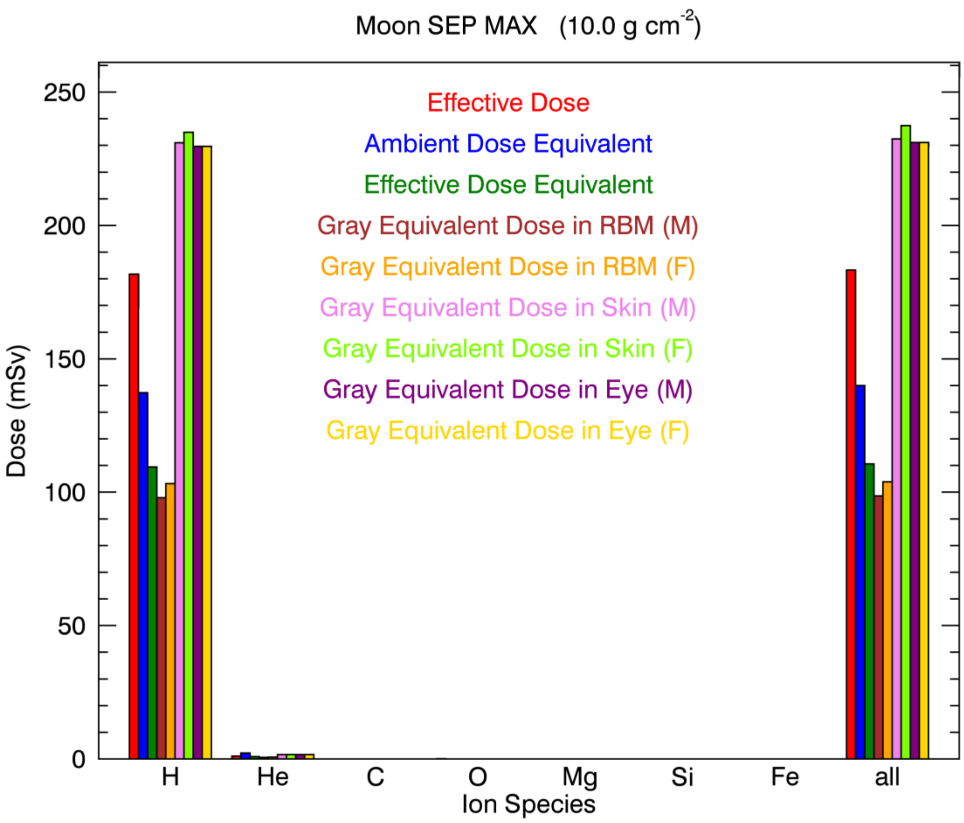

FIGURE 4 SEP SOLAR MAX DOSES FOR THE WHOLE LUNAR MISSION (10.0 G CM^{-2} AL SHIELDING)

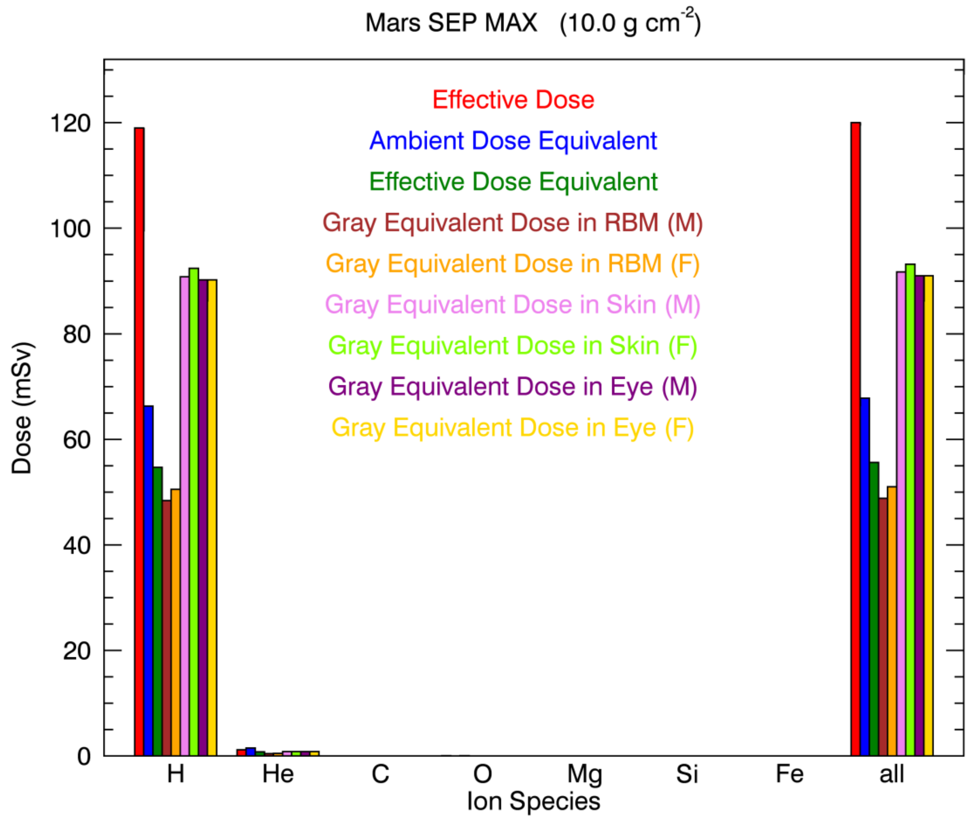

FIGURE 5 SEP SOLAR MAX DOSES FOR THE SURFACE PHASE OF THE MARS MISSION (10.0 G CM^{-2} SHIELDING)

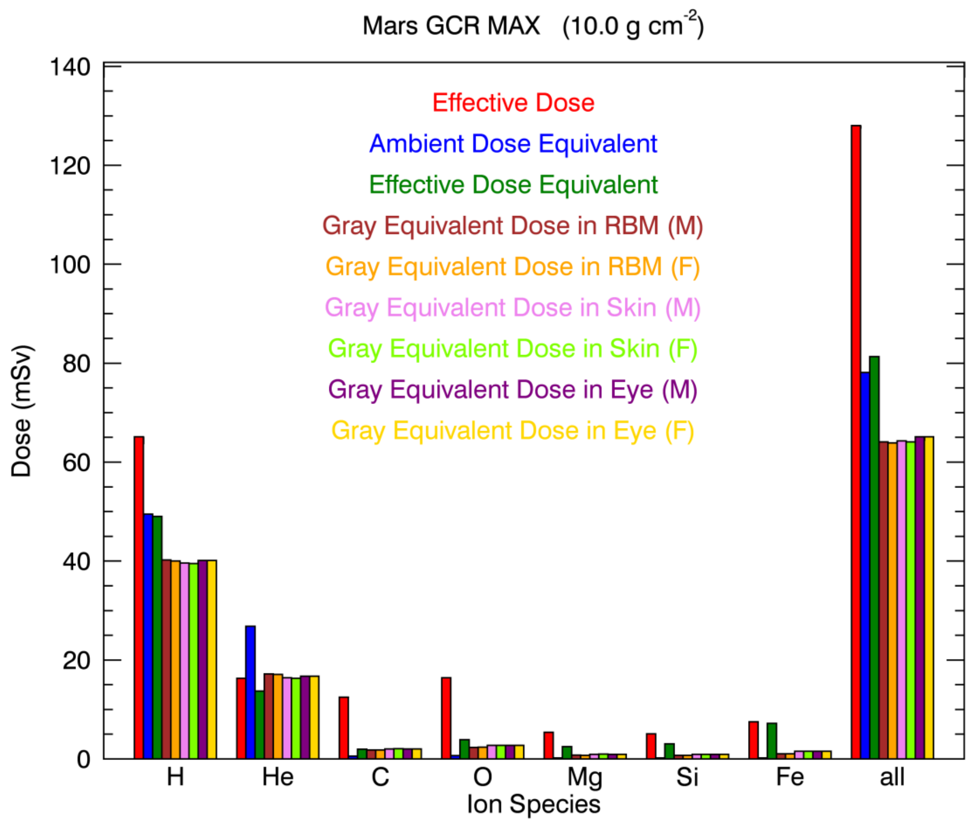

FIGURE 6 GCR SOLAR MAX DOSES FOR THE SURFACE PHASE OF THE MARS MISSION (10.0 G CM^{-2} AL SHIELDING)

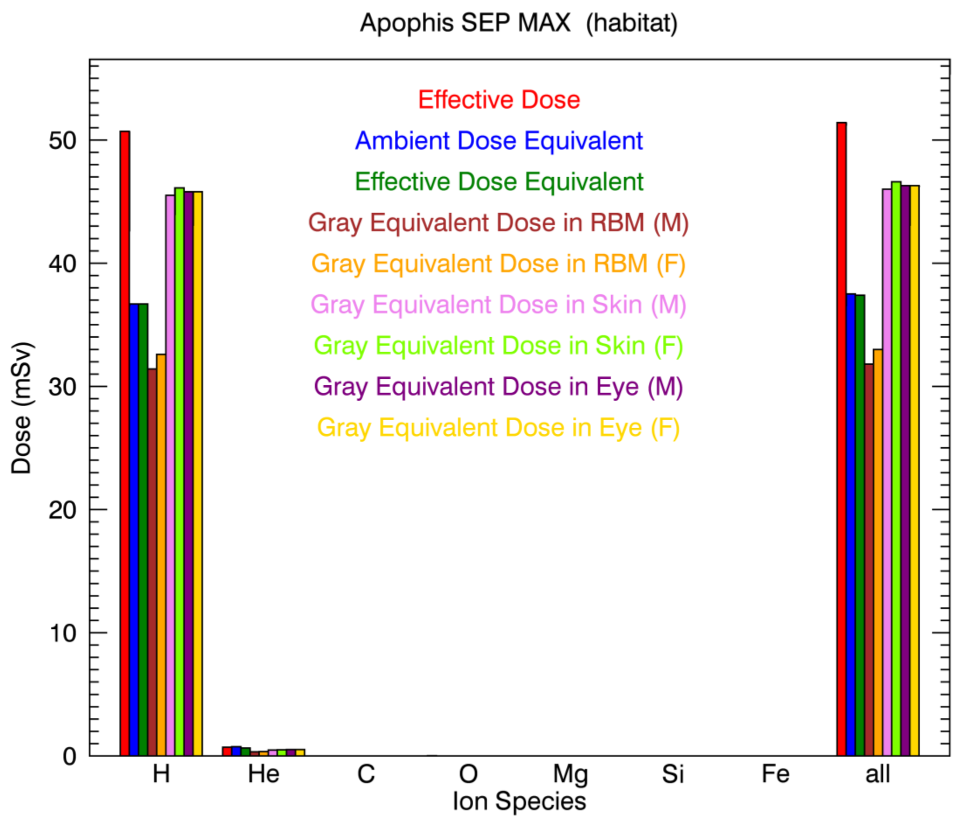

FIGURE 7 SEP SOLAR MAX HABITAT DOSES FOR THE FREE SPACE SIMULATION OF THE APOPHIS MISSION

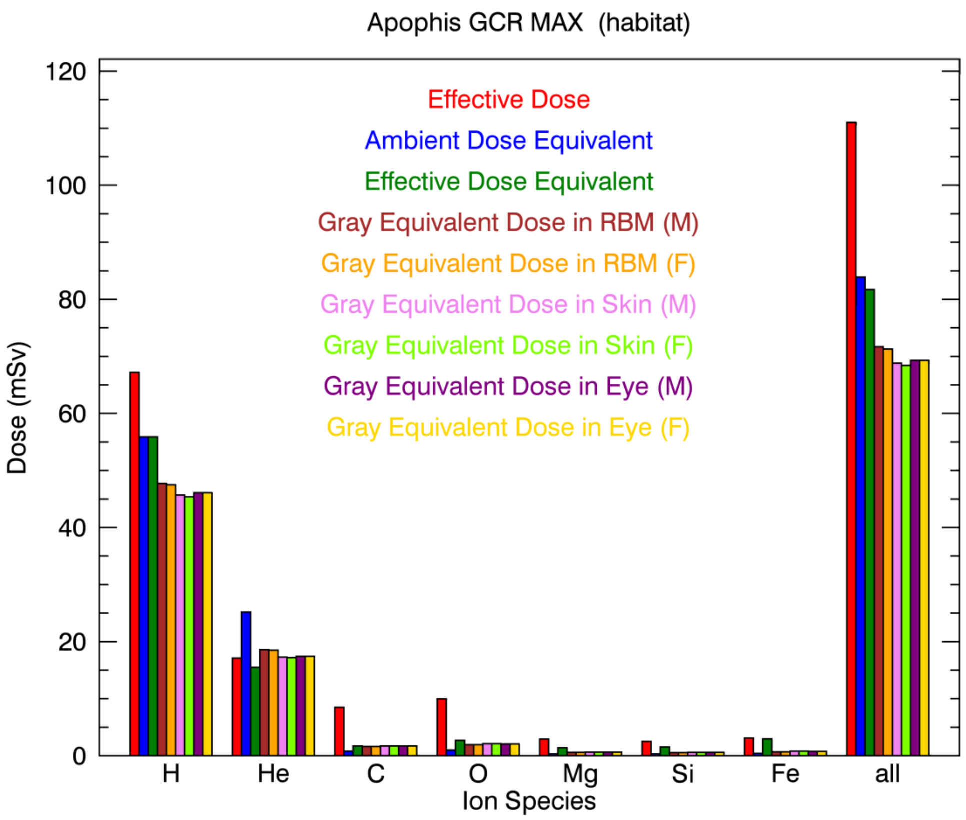

FIGURE 8 GCR SOLAR MAX HABITAT DOSES FOR THE FREE SPACE SIMULATION OF THE APOPHIS MISSION

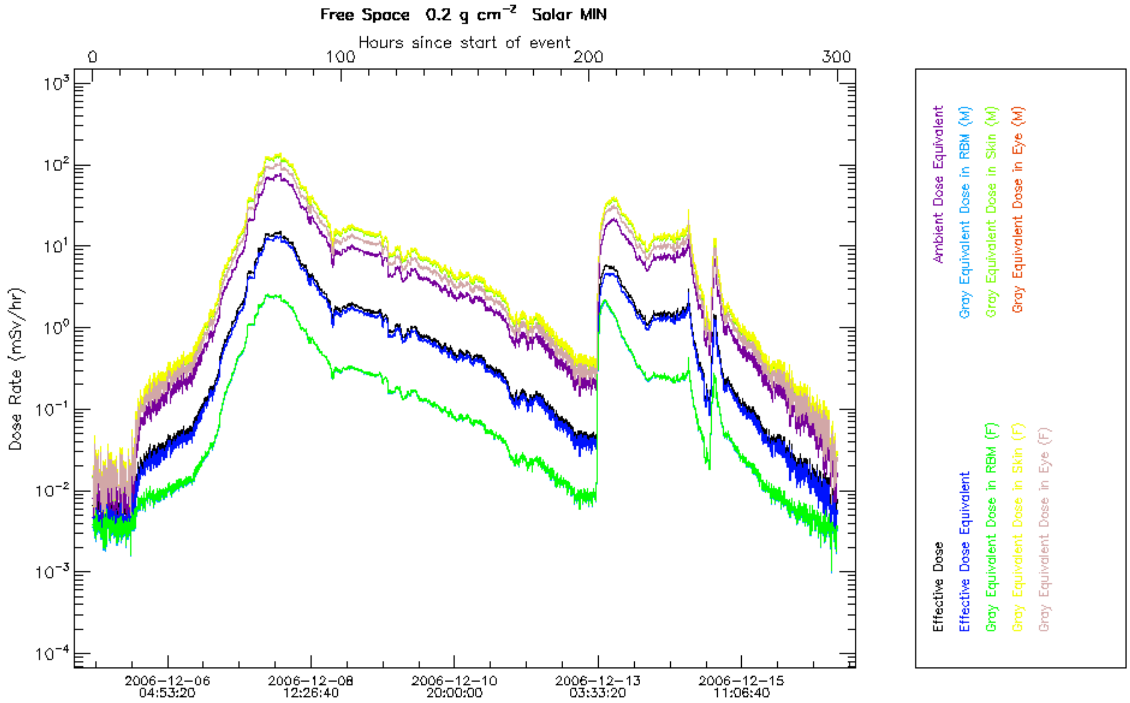

FIGURE 9 INSTANTANEOUS DOSE RATES FOR THE EVA SIMULATION IN FREE SPACE DURING THE SOLAR MINIMUM EVENT

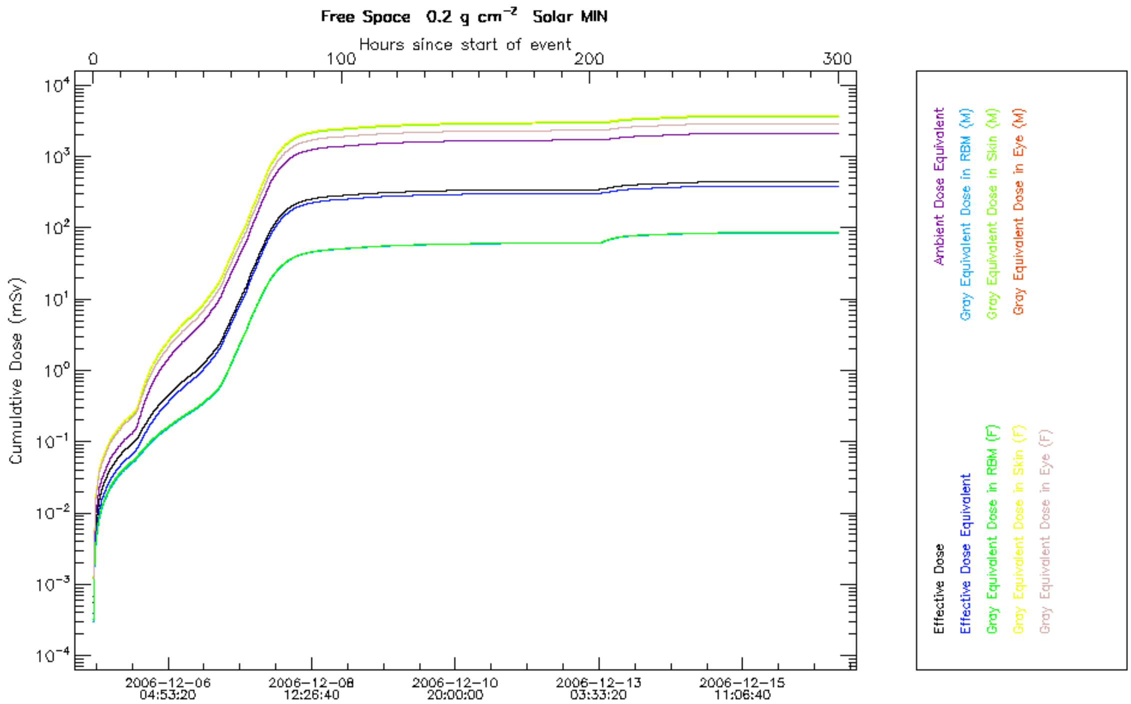

FIGURE 10 CUMULATIVE DOSES FOR THE EVA SIMULATION IN FREE SPACE DURING THE SOLAR MINIMUM EVENT