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1 Introduction and Relation to NASA STD 7009

1.1 Introduction and Relation to NASA STD 7009

NASA has developed a standard (NASA Standard 7009) for the use of Models and Simulations (M&S), which was recommended by the Diaz Committee in response to the 2003 Space Shuttle Columbia accident. The intent of the standard is to ensure that enough information about the M&S results is communicated to decision makers so that they can properly determine the credibility of those results. The standard is targeted at instances where M&S results have the potential to significantly impact critical decisions regarding human safety or mission success. Note that the standard applies to results, not codes or models, so most research and model development will not fall directly under the scope of the standard. Research and model development efforts are utilized for two classes of problems: development of models that will be used by other organizations for critical decisions, and those that will be used for major acquisition decisions. The latter falls directly under the scope of the standard and implementation is more straight forward. With respect to the former, many models are being developed with the intent to use the finished product in critical decisions that will fall under the scope of the standard. Given such future applicability, it is beneficial for the model development process to be informed by the requirements in the standard to enable a more seamless transition from the research and development stage to use in critical decisions. This section lists documentation that might be useful to users of OLTARIS whose results fall in the scope of NASA STD 7009.

Since the standard applies to high consequence results and not to codes or models themselves, all of the requirements can't be fulfilled by the model developers, so only those pertaining explicitly to the models themselves as well as their verification, validation, and uncertainty quantification are addressed here. OLTARIS runs a series of models to get results. These models are coupled in a linear fashion in the sense that, for example, the environment model output is used by the transport model but the transport results don't effect the environment. Since there is only this simple coupling between models, the focus was on addressing the standard requirements for the models individually with some summary statements about the calculations as a whole listed in the section labeled end-to-end.

2 Galactic Cosmic Ray Environment

2.1 Galactic Cosmic Rays Model

For a given flight condition, the input particles spectra on the space boundary has to be defined to initiate particle(s) march through bulk matter. One such input boundary is the galactic cosmic rays (GCR). The magnitude of GCR event at the space boundary is in differential spectrum form. Individual GCR spectra follow a pre-determined I/O format to make them compatible with the marching algorithm (HZETRN) as implemented in OLTARIS. The input boundary condition is material independent. Detailed model definition of the GCR boundary condition is described in the section below.

2.1.1 Assumptions and Abstractions (NASA-STD-7009 [1] Req. 4.2.1)

The assumptions and abstractions used for the various input GCR particles spectra on the space boundary model has been described by O'Neill et al. [2] and the references therein.

2.1.2 Basic Structure (NASA-STD-7009 Req. 4.2.2)

The basic structure and mathematics used to describe the GCR environment as input to OLTARIS (in which this environment is used) has been described by Badavi et al. [3] O'Neill et al. [2] and the references therin. The GCR environment is based on detailed analysis of space borne measurements.

2.1.3 Data Sets and Supporting Software (NASA-STD-7009 Req. 4.2.3)

The GCR environment modules used by OLTARIS are composed of FORTRAN source code linked with C shell, Ruby and Perl scripts to the main OLTARIS module.

A suitable input energy spectrum is used to ensure proper coverage of the necessary energies seen in this environment.

2.1.4 Units and Coordinate Frames (NASA-STD-7009 Req. 4.2.4)

GCR Environment output flux is in units of particle/(cm^2-A MeV-day).

2.1.5 Limits of Operation (NASA-STD-7009 Req. 4.2.5)

GCR environment is for free space near earth but can be used as a reasonable approximation in the range of 0.3 to 100 astronomical unit (AU).

2.1.6 Uncertainty Quantification (NASA-STD-7009 Req. 4.2.6)

GCR environment are accurate within 10% or less as described by O'Neill et al. [2].

2.1.7 Proper Use (NASA-STD-7009 Req. 4.2.7)

Proper use of the oltaris website is described in the user manual [1] and reference guide [2].

2.1.8 Parameter Calibrations (NASA-STD-7009 Req. 4.2.8)

The calibration and domain of calibration has been described by O'Neill et al. [2] and the references therein.

2.1.9 Model Updates (NASA-STD-7009 Req. 4.2.9)

Model updates are tracked/documented in a version control repository and are then reported to the user via the OLTARIS Change Log.

2.1.10 Obsolescence Criteria (NASA-STD-7009 Req. 4.2.10)

Obsolete models are removed from OLTARIS when appropriate.

2.2 Verification, Validation, and Uncertainty Quantification

2.2.1 Verification

2.2.1.1 Techniques (NASA-STD-7009 Req. 4.4.1)

Verification techniques for the OLTARIS environment modules include automated module and functional tests. The module test is used to track and maintain functionality of the environment modules by themselves. The functional tests are used to track and maintain functionality of several modules working together to output a GCR environment.

2.2.1.2 Error Estimates (NASA-STD-7009 Req. 4.4.2)

Numerical and other verification error estimates have not been documented for the GCR model.

2.2.1.3 Verification Status (NASA-STD-7009 Req. 4.4.3)

The OLTARIS environment modules are regularly executed through an automated suite of module and functional tests. Verification tests have been completed by comparing OLTARIS environment output with stand alone routines.

2.2.2 Validation

2.2.2.1 Techniques (NASA-STD-7009 Req. 4.4.4)

The environment modules are validated by comparing with available measurements has been described by O'Neill et al. [2] and the references therein.

2.2.2.2 Data (NASA-STD-7009 Req. 4.4.5)

The validation metrics, references, and data sets used in model validation are documented and described in the various references given in the next section.

2.2.2.3 Studies (NASA-STD-7009 Req. 4.4.6)

Validation studies for the environment modules have been conducted by O'Neill et al. [2] and the references therein.

2.2.3 Uncertainty Quantification

2.2.3.1 Process (NASA-STD-7009 Req. 4.4.7)

The uncertainty quantification processes has been described by O'Neill et al. [2] and the references therein.

2.2.3.2 Quantified Uncertainties (NASA-STD-7009 Req. 4.4.8)

The uncertainty quantification process has been described by O'Neill et al. [2] and the references therein.

2.2.3.3 Sensitivity Analysis (NASA-STD-7009 Req. 4.4.9)

Sensitivity analysis to quantify the propagated errors induced in the GCR module has not been identified at this time.

2.3 References

1. ? NASA Standard 7009
2. ? [2.0] [2.1] [2.2] [2.3] [2.4] [2.5] [2.6] [2.7] P. M. O'Neill et al., Badhwar-O'Neill Galactic Cosmic Ray Model Update Based on Advanced Composition Explorer (ACE) Energy Spectra from 1977 to Present, Advances in Space Research 37 (2006) 1727-1733.
3. ? , F.F. Badavi et al., A Dynamic/Anisotropic Low Earth Orbit (LEO) Ionizing Radiation Model?, NASA-TP-2006-214533, 2006.

3 Solar Particle Events Environment

3.1 Solar Particle Events Model

For a given flight condition, the input particles spectra on the space boundary has to be defined to initiate particle(s) march through bulk matter. One such boundary can be the solar particle events (SPE). The magnitude of these SPE events at the space boundary is in differential spectrum form. Individual or combination of these SPE spectra follow a pre-determined I/O format to make them compatible with the marching algorithm (HZETRN) as implemented in OLTARIS. The input boundary condition is material independent. Detailed SPE model definition of the boundary condition is described in the section below.

3.1.1 Assumptions and Abstractions (NASA-STD-7009 [1] Req. 4.2.1)

The assumptions and abstractions used for the various input particle spectrum on the SPE space boundary models have been described by Webber [2], Sauer et al. [3], King [4], Wilson et al. [5] [6] [7], Foelsche et al. [8], Townsend et al. [9] and the references therein.

3.1.2 Basic Structure (NASA-STD-7009 Req. 4.2.2)

The basic structure and mathematics used to describe the SPE environment as input to OLTARIS (in which SPE environment is used) has been described by Badavi et al. [10] and the references therein. All SPE enviroments are based on detailed analytical fits to ground based or space borne measurements.

3.1.3 Data Sets and Supporting Software (NASA-STD-7009 Req. 4.2.3)

The SPE environment modules used by OLTARIS are composed of FORTRAN source code linked with C shell, Ruby and Perl scripts to the main OLTARIS module.

A suitable input energy spectrum is used to ensure proper coverage of the necessary energies seen in this environment.

3.1.4 Units and Coordinate Frames (NASA-STD-7009 Req. 4.2.4)

SPE environment output fluence is in units of particle/(cm^2-A MeV-event).

3.1.5 Limits of Operation (NASA-STD-7009 Req. 4.2.5)

SPE environment are analytic fits for historic SPE in free space.

3.1.6 Uncertainty Quantification (NASA-STD-7009 Req. 4.2.6)

The accuracy of the historical fits to the measured SPE data are discussed in Webber [2], Sauer et al. [3], King [4], Wilson et al. [5] [6] [7], Foelsche et al. [8], Townsend et al. [9] and the references therein.

3.1.7 Proper Use (NASA-STD-7009 Req. 4.2.7)

Proper use of the OLTARIS website is described in the user manual [1] and reference guide [2].

3.1.8 Parameter Calibrations (NASA-STD-7009 Req. 4.2.8)

The calibration and domain of calibration have been described by Webber [2], Sauer et al. [3], King [4], Wilson et al. [5] [6] [7], Foelsche et al. [8], Townsend et al. [9] and the references therein.

3.1.9 Model Updates (NASA-STD-7009 Req. 4.2.9)

Model updates are tracked/documented in a version control repository and are then reported to the user via the OLTARIS Change Log.

3.1.10 Obsolescence Criteria (NASA-STD-7009 Req. 4.2.10)

Obsolete models are removed from OLTARIS when appropriate.

3.2 Verification, Validation, and Uncertainty Quantification

3.2.1 Verification

3.2.1.1 Techniques (NASA-STD-7009 Req. 4.4.1)

Verification techniques for the OLTARIS environment modules include automated module and functional tests. The module test is used to track and maintain functionality of the environment modules by themselves. The functional tests are used to track and maintain functionality of several modules working together to putout a SPE environment.

3.2.1.2 Error Estimates (NASA-STD-7009 Req. 4.4.2)

SPE environment is subject to statistical fluctuation and confidence level (CL) dependencies.

3.2.1.3 Verification Status (NASA-STD-7009 Req. 4.4.3)

The OLTARIS environment modules are regularly executed through an automated suite of module and functional tests. Verification tests have been completed by comparing OLTARIS environment output with stand alone routines.

3.2.2 Validation

3.2.2.1 Techniques (NASA-STD-7009 Req. 4.4.4)

The environment modules are validated by comparing with limited available measurements.

3.2.2.2 Data (NASA-STD-7009 Req. 4.4.5)

The validation metrics, referents, and data sets used in model validation are documented and described in the various references given in the next section.

3.2.2.3 Studies (NASA-STD-7009 Req. 4.4.6)

Validation studies, independent of the data used for the fit spectra, for the environment modules have not been idendtified at this time.

3.2.3 Uncertainty Quantification

3.2.3.1 Process (NASA-STD-7009 Req. 4.4.7)

The uncertainty quantification processes in the environment modules have not been identified at this time.

3.2.3.2 Quantified Uncertainties (NASA-STD-7009 Req. 4.4.8)

The uncertainty quantification processes in the environment modules have not been identified at this time.

3.2.3.3 Sensitivity Analysis (NASA-STD-7009 Req. 4.4.9)

Sensitivity analyses have been performed to quantify the impact of uncertainities in the modeled SPE environments on exposure quantities by Cucinotta et al. [11], Townsend et al. [12] [13] [14], and Townsend and Zapp [15].

3.3 References

1. ? NASA Standard 7009
2. ? 2.0 2.1 2.2 W. R. Webber, An Evaluation of the Radiation Hazard due to Solar-Particle Events D2-90469 Aero-Space Div,. Boeing Co. 1963.
3. ? 3.0 3.1 3.2 H. H. Sauer et al., Summary Data for the Solar Energetic Particle Events of August Through December 1989. Space Environment Lab., National Oceanic and Atmospheric Adm., 1990.
4. ? 4.0 4.1 4.2 J. H. King, Solar Proton Fluences for 1977-1983 Space Missions. J. Spacecraft and Rockets, vol. 11, no. 6, pp. 401-408, 1974.
5. ? 5.0 5.1 5.2 J. W. Wilson et al., Preliminary Analysis of the Implications of Natural Radiations on Geostationary Operations. NASA TN D-8290 1976.
6. ? 6.0 6.1 6.2 J. W. Wilson et al., International Space Station: A Testbed for Experimental and Computational Dosimetry. Adv. Space Res. 37: 1656-1663; 2006.

7. ? 7.0 7.1 7.2 J. W. Wilson et al., Cosmic Ray Neutron Albedo Dose in Low Earth Orbit. Health Physics, 57, 1989, pp. 665-668.
8. ? 8.0 8.1 8.2 T. Foelsche et al., Measured and Calculated Neutron Spectra and Dose Equivalent Rates at High Altitudes; Relevance to SST Operations and Space Research. NASA TN D-7715 1974.
9. ? 9.0 9.1 9.2 L. Townsend et al., Carrington Flare of 1859 as a Prototypical Worst-Case Solar Energetic Particle Event; IEEE Transactions on Nuclear Science, vol. 50, NO. 6, Dec. 2003.
10. ? F.F. Badavi et al., A Dynamic/Anisotropic Low Earth Orbit (LEO) Ionizing Radiation Model?, NASA-TP-2006-214533, 2006.
11. ? Cucinotta, F.A., Townsend, L.W., Wilson, J.W., Golightly, M.J., Weyland, M., Analysis of Radiation Risk from Alpha Particle Component of Solar Particle Events. Advances in Space Research, Volume 14 pp. 661-670 (1994).
12. ? Townsend, L.W., Cucinotta, F.A., Bagga, R., Estimates of HZE Particle Contributions to SPE Radiation Exposures on Interplanetary Missions. Advances in Space Research, Volume 14 pp. 671-674 (1994).
13. ? Townsend, L.W., Zapp, E.N., Stephens, D.L., Hoff, J.L., Carrington Flare of 1859 as Prototypical Worse-Case Solar Energetic Particle Event. IEEE Transactions on Nuclear Science, Volume 50 (2003).
14. ? Townsend, L.W., Stephens, D.L., Hoff, J.L., Zapp, E.N., Moussa, H.M., Miller, T.M., Campbell, C.E., Nichols, T.F., The Carrington Event: Possible Doses to Crews in Space from a Comparable Event. Advances in Space Research, Volume 38 pp. 226-231 (2006).
15. ? Townsend, L.W., Zapp, E.N., Dose Uncertainties for Large Solar particle Events: Input Spectra Variability and Human Geometry Approximations. Radiation Measurements, Volume 30 pp. 337-343 (1999).

4 Low Earth Orbit Environment

4.1 Low Earth Orbit Model

For a given Earth orbit flight condition, the input particles spectra on the space boundary has to be defined to initiate particle(s) march through bulk matter. One such boundary is the combination of attenuated galactic cosmic rays (GCR), trapped proton/electron within Earth geomagnetic field and albedo neutrons from the Earth's atmosphere. The magnitude of these events at the space boundary are in differential spectrum form. Individual or combination of these spectra follow a pre-determined I/O format to make them compatible with the transport algorithm. The input boundary condition is material independent. Detailed model definition of the LEO boundary condition(s) are described in the section below.

4.1.1 Assumptions and Abstractions (NASA-STD-7009 [1] Req. 4.2.1)

The assumptions and abstractions used for the various earth orbit input particle spectrum have been summarized Badavi et al. [2] and are described in more detail by Wilson et al. [3] [4] [5], Foelsche et al. [6], O'Neill et al. [7], De Angelis et al. [8], Clem et al. [9], Sawyer et al. [10], Vette [11], Jensen et al. [12], Cain et al. [13] and the references therein.

4.1.2 Basic Structure (NASA-STD-7009 Req. 4.2.2)

The basic structure and mathematics used to describe the LEO environment(s) as input to OLTARIS (in which all these environments are used) has been described by Badavi et al. [2] and the references therin. All enviroments (GCR, trapped, albedo) are based on detailed analytical fits to ground based and space borne measurements.

4.1.3 Data Sets and Supporting Software (NASA-STD-7009 Req. 4.2.3)

The LEO environment modules are composed of FORTRAN source code linked with C shell, Ruby and Perl scripts to generate the output LEO spectra. A number of measured (or predicted) auxiliary files containing information about the Sun activity, ground level neutron counts and variation of geomagnetic field strength are also needed by the LEO environment modules. These auxiliary files are updated annually as they become available.

A suitable input energy spectrum is used to ensure proper coverage of the necessary energies seen in this environment.

4.1.4 Units and Coordinate Frames (NASA-STD-7009 Req. 4.2.4)

LEO environment outputs are particle fluxes in unit of particles/(cm^2-A MeV-day).

4.1.5 Limits of Operation (NASA-STD-7009 Req. 4.2.5)

LEO GCR and albedo environments are valid in the range of 30 km to free space. Trapped are valid in the range of 200-20000 km. Temporal limits are valid in the epoch range of 1950-2020. The OLTARIS website will not allow input that exceeds these limits.

4.1.6 Uncertainty Quantification (NASA-STD-7009 Req. 4.2.6)

Free space GCR environment is accurate within about 10% (see GCR section). The uncertainty of geomagnetic cutoff models is currently unknown. Trapped and albedo are potentially uncertain by at least a factor of 2. Badavi et al. [2] Barth et al. [14]

4.1.7 Proper Use (NASA-STD-7009 Req. 4.2.7)

Proper use of the oltaris website is described in the user manual [1] and reference guide [2]

4.1.8 Parameter Calibrations (NASA-STD-7009 Req. 4.2.8)

The calibration and domain of calibration is described in Badavi et al. [2] and the references therein.

4.1.9 Model Updates (NASA-STD-7009 Req. 4.2.9)

Model updates are tracked/documented in a version control repository and are then reported to the user via the OLTARIS Change Log.

4.1.10 Obsolescence Criteria (NASA-STD-7009 Req. 4.2.10)

Obsolete models are removed from OLTARIS when appropriate.

4.2 Verification, Validation, and Uncertainty Quantification

4.2.1 Verification

4.2.1.1 Techniques (NASA-STD-7009 Req. 4.4.1)

Verification techniques for the OLTARIS environment modules include automated module and functional tests. The module test is used to track and maintain functionality of the environment modules by themselves. The functional tests are used to track and maintain functionality of several modules working together to output a LEO environment as a combination of several environments.

4.2.1.2 Error Estimates (NASA-STD-7009 Req. 4.4.2)

The error estimates in the environment modules have not been identified at this time.

4.2.1.3 Verification Status (NASA-STD-7009 Req. 4.4.3)

The OLTARIS environment modules are regularly executed through an automated suite of module and functional tests. Verification tests have been completed by comparing OLTARIS environment output with stand alone routines.

4.2.2 Validation

4.2.2.1 Techniques (NASA-STD-7009 Req. 4.4.4)

The modulated GCR and trapped proton environment modules are validated by comparing with limited available measurements.

4.2.2.2 Data (NASA-STD-7009 Req. 4.4.5)

The validation metrics, referents, and data sets used in model validation are documented and described in the various references given in the next section.

4.2.2.3 Studies (NASA-STD-7009 Req. 4.4.6)

Validation studies for the environment modules have been conducted by Badavi et al. [15],Badavi et al. [2]. Barth et al. [14]

4.2.3 Uncertainty Quantification

4.2.3.1 Process (NASA-STD-7009 Req. 4.4.7)

The uncertainty quantification processes consisted of graphically comparing validation predictions referenced above with data.

4.2.3.2 Quantified Uncertainties (NASA-STD-7009 Req. 4.4.8)

The uncertainties can be found in validation references above.

4.2.3.3 Sensitivity Analysis (NASA-STD-7009 Req. 4.4.9)

Sensitivity analysis to quantify the propagated errors induced in the environment modules have not been identified at this time.

4.3 References

1. ? NASA Standard 7009
2. ? [2.0] [2.1] [2.2] [2.3] [2.4] F.F. Badavi et al., A Dynamic/Anisotropic Low Earth Orbit (LEO) Ionizing Radiation Model?, NASA-TP-2006-214533, 2006.
3. ? J. W. Wilson et al., Preliminary Analysis of the Implications of Natural Radiations on Geostationary Operations. NASA TN D-8290 1976
4. ? J. W. Wilson et al., International Space Station: A Testbed for Experimental and Computational Dosimetry. Adv. Space Res. 37: 1656-1663; 2006.
5. ? J. W. Wilson et al., Cosmic Ray Neutron Albedo Dose in Low Earth Orbit. Health Physics, 57, 1989, pp. 665-668.
6. ? T. Foelsche et al., Measured and Calculated Neutron Spectra and Dose Equivalent Rates at High Altitudes; Relevance to SST Operations and Space Research. NASA TN D-7715 1974.
7. ? P. M. O'Neill et al., Badhwar-O'Neill Galactic Cosmic Ray Model Update Based on Advanced Composition Explorer (ACE) Energy Spectra from 1977 to Present, Advances in Space Research 37 (2006) 1727-1733.

8. ? G. De Angelis et al., A new Dynamical Atmospheric Ionizing Radiation (AIR) Model for Epidemiological Studies, Adv. Space Res., 32(1), 17-26, 2003.
9. ? J. M. Clem et al., Preliminary Validation of Computational Procedures for a new Atmospheric Ionizing Radiation (AIR) Model, Adv. Space Res., 32(1), 27-33, 2003.
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11. ? J. I. Vette, The NASA/National Space Science Data Center Trapped Radiation Environmental Model Program (1964-1991), NSSDC/WDC-A-R&S 91- 29, 1991.
12. ? D. C. Jensen et al., An Interim Geomagnetic Field, J. Geophys. Res., no. 67, pp. 3568-3569, 1962.
13. ? J.C. Cain et al., A Proposed Model for the International Geomagnetic Reference Field-1965, J. Geomag. Geoelec., no. 19, pp. 335-355, 1967.
14. ? [14.0] [14.1] J. Barth, M. Xapsos, "Radiation environment modeling for spacecraft design: New model developments", RADECS workshop, 28 Sep. 2006, Athens, Greece.
15. ? Badavi, F.F., Stewart-Sloan, C.R., Xapsos, M.A., Shinn, J.L., Wilson, J.W., Hunter, A., Description of a Generalized Analytical Model for the Micro-dosimeter Response. NASA Technical Paper 2007-214886 (2007).

5 Lunar Surface Environment

5.1 Lunar Surface Environment Model

For a given lunar surface flight condition, the input particles spectra on the space boundary has to be defined to initiate particle(s) march through bulk matter. One such boundary at lunar surface is the combination of attenuated galactic cosmic rays (GCR) due to the moon shadow, lunar albedo neutrons from the interaction of GCR with lunar regolith and attenuated solar particle events (SPE) due to the moon shadow. The magnitude of these events at the space boundary are in differential spectrum form. Individual or combination of these spectra follow a pre-determined I/O format to make them compatible with the marching algorithm (HZETRN) as implemented in OLTARIS. The input boundary condition is material independent. Detailed model definition of the lunar surface boundary condition(s) are described in the section below.

5.1.1 Assumptions and Abstractions (NASA-STD-7009 [1] Req. 4.2.1)

The assumptions and abstractions used for the various input particle spectrum on the space boundary models have been described by Webber [2], Sauer et al. [3], King [4], Townsend et al. [5], O'Neill et al. [6], Clowdsley et al. [7] and the references therein.

5.1.2 Basic Structure (NASA-STD-7009 Req. 4.2.2)

The basic structure and mathematics used to describe the lunar surface environment(s) as input to OLTARIS (in which these environments are used) has been described by Clowdsley et al. [7] and the references therin. All enviroments (GCR, SPE, albedo) are based on detailed analysis of ground based or space borne measurements.

5.1.3 Data Sets and Supporting Software (NASA-STD-7009 Req. 4.2.3)

The lunar environment(s) modules used by OLTARIS are composed of FORTRAN source code linked with C shell, Ruby and Perl scripts to the main OLTARIS module.

A suitable input energy spectrum is used to ensure proper coverage of the necessary energies seen in this environment.

5.1.4 Units and Coordinate Frames (NASA-STD-7009 Req. 4.2.4)

Lunar environment output is in units of particle/(cm^2-A MeV-day) for GCR and particle/(cm^2-A MeV-event) for SPE.

5.1.5 Limits of Operation (NASA-STD-7009 Req. 4.2.5)

Lunar GCR, albedo and SPE environments are valid above the lunar surface.

5.1.6 Uncertainty Quantification (NASA-STD-7009 Req. 4.2.6)

Lunar GCR environment is accurate within 10% or less. NEED RERFERENCE. Albedo is the by product of GCR interaction with lunar regolith with unknown level of uncertainty. Lunar SPE environment is subject to statistical fluctuation and confidence level (CL) dependencies.

5.1.7 Proper Use (NASA-STD-7009 Req. 4.2.7)

Proper use of the oltaris website is described in the user manual [1] and reference guide [2].

5.1.8 Parameter Calibrations (NASA-STD-7009 Req. 4.2.8)

The calibration and domain of calibration have not been identified at this time for the environment modules.

5.1.9 Model Updates (NASA-STD-7009 Req. 4.2.9)

Model updates are tracked/documented in a version control repository and are then reported to the user via the OLTARIS Change Log.

5.1.10 Obsolescence Criteria (NASA-STD-7009 Req. 4.2.10)

Obsolete models are removed from OLTARIS when appropriate.

5.2 Verification, Validation, and Uncertainty Quantification

5.2.1 Verification

5.2.1.1 Techniques (NASA-STD-7009 Req. 4.4.1)

Verification techniques for the OLTARIS environment modules include automated module and functional tests. The module test is used to track and maintain functionality of the environment modules by themselves. The functional tests are used to track and maintain functionality of several modules working together to output a low lunar surface environment which is a combination of several environments.

5.2.1.2 Error Estimates (NASA-STD-7009 Req. 4.4.2)

GCR environment is accurate within 10% or less. Lunar albedo as the by product of GCR interaction with lunar regolith has an unknown level of uncertainty. SPE environment is subject to statistical fluctuation and confidence level (CL) dependencies.

5.2.1.3 Verification Status (NASA-STD-7009 Req. 4.4.3)

The OLTARIS environment modules are regularly executed through an automated suite of module and functional tests. Verification tests have been completed by comparing OLTARIS environment output with stand alone routines.

5.2.2 Validation

5.2.2.1 Techniques (NASA-STD-7009 Req. 4.4.4)

The environment modules are validated by comparing with limited available measurements.

5.2.2.2 Data (NASA-STD-7009 Req. 4.4.5)

The validation metrics, references, and data sets used in model validation are documented and described in the various references given in the next section.

5.2.2.3 Studies (NASA-STD-7009 Req. 4.4.6)

Validation studies for the environment modules have been conducted by Badavi et al. [8].

5.2.3 Uncertainty Quantification

5.2.3.1 Process (NASA-STD-7009 Req. 4.4.7)

The uncertainty quantification processes in the environment modules have not been identified at this time.

5.2.3.2 Quantified Uncertainties (NASA-STD-7009 Req. 4.4.8)

The uncertainty quantification processes in the environment modules have not been identified at this time.

5.2.3.3 Sensitivity Analysis (NASA-STD-7009 Req. 4.4.9)

Sensitivity analysis to quantify the propagated errors induced in the environment modules have not been identified at this time.

5.3 References

1. ? NASA Standard 7009
2. ? W. R. Webber, An Evaluation of the Radiation Hazard due to Solar-Particle Events D2-90469 Aero-Space Div,. Boeing Co. 1963.
3. ? H. H. Sauer et al., Summary Data for the Solar Energetic Particle Events of August Through December 1989. Space Environment Lab., National Oceanic and Atmospheric Adm., 1990.
4. ? J. H. King, Solar Proton Fluences for 1977-1983 Space Missions. J. Spacecraft and Rockets, vol. 11, no. 6, pp. 401-408, 1974.
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6 Light Ion Cross Sections

6.1 Light Ion Cross Section Model

Total and differential energy cross sections for nucleon (proton and neutron) and light ion (^{2}H, ^{3}H, ^{3}He, ^{4}He) projectiles are handled by a set of subroutines within OLTARIS. Processes relevant to the nuclear interactions of nucleons and light ions which are used by OLTARIS include elastic scattering, light ion knockout and pickup, light ion projectile fragmentation and target fragmentation. The cross sections for these processes are largely modeled by empirical and semi-empirical parameterizations.

6.1.1 Assumptions and Abstractions (NASA-STD-7009 [1] Req. 4.2.1)

The assumptions and abstractions used for the various cross section models have been described by Wilson et al. [2] [3] [4], Cucinotta et al. [5] [6] [7], Tripathi et al. [8] [9], Norbury [10], and the references therein.

6.1.2 Basic Structure (NASA-STD-7009 Req. 4.2.2)

The basic structure and mathematics used in HZETRN (in which all these cross sections are used) have been described by Wilson et al. [11] and Slaba et al. [12] [13] and the references therin. The cross sections for light particle interactions were largely modeled by empirical and semi-empirical parameterizations. These parameterizations were generally analytic equations and the details of each equation are discussed in Wilson et al. [2] [3] [4], Cucinotta et al. [5] [6] [7], Tripathi et al. [8] [9], and Norbury [10].

6.1.3 Data Sets and Supporting Software (NASA-STD-7009 Req. 4.2.3)

The cross section modules used by OLTARIS are composed of FORTRAN source code linked with C shell, Ruby and Perl scripts to the main OLTARIS module. A cross section database for each material is pre-generated at predetermined energies and step sizes and OLTARIS interpolates on this cross section database for the values needed by the transport.

6.1.4 Units and Coordinate Frames (NASA-STD-7009 Req. 4.2.4)

For total cross sections, inputs required by the various modules are initial energy (A MeV) and material, then the output is a total cross section in units of cm^2/g. For cross sections differential in energy, the inputs required are the initial energy (A MeV) and outgoing particle energy (A MeV) and the material, then the output is the differential cross section in units of $cm^2/(g\ A\ MeV)$.

6.1.5 Limits of Operation (NASA-STD-7009 Req. 4.2.5)

The limits of operation of each model have been described by Wilson et al. [2] [3] [4], Cucinotta et al. [5] [6] [7], Tripathi et al. [8] [9], Norbury [10], and the references therein.

6.1.6 Uncertainty Quantification (NASA-STD-7009 Req. 4.2.6)

Uncertainty quantification has typically not been done at the cross section model level other than plotting the models against select experimental data and possibly stating qualitatively the measure of agreement between model and experiment. This method of uncertainty quantification is partially due to a lack of experimental data for all processes. Graphical comparisons to data can be found in Wilson et al. [2] [3] [4], Cucinotta et al. [5] [6] [7], Tripathi et al. [8] [9], and Norbury [10].

6.1.7 Proper Use (NASA-STD-7009 Req. 4.2.7)

Proper use of the oltaris website is described in the user manual [1] and reference guide [2].

6.1.8 Parameter Calibrations (NASA-STD-7009 Req. 4.2.8)

The parameters and level of calibration used in the empirical and semiempirical formulas used for the light particle cross sections are discussed in Wilson et al. [2] [3] [4], Cucinotta et al. [5] [6] [7], Tripathi et al. [8] [9], Norbury [10], and the references therein.

6.1.9 Model Updates (NASA-STD-7009 Req. 4.2.9)

Model updates are tracked/documented in a version control repository and are then reported to the user via the OLTARIS Change Log.

6.1.10 Obsolescence Criteria (NASA-STD-7009 Req. 4.2.10)

Obsolete models are removed from OLTARIS when appropriate.

6.2 Verification, Validation, and Uncertainty Quantification

6.2.1 Verification

6.2.1.1 Techniques (NASA-STD-7009 Req. 4.4.1)

All cross section modules are configuration controlled and system tests exist to ensure that changes made to any module do not break any other component of OLTARIS.

6.2.1.2 Error Estimates (NASA-STD-7009 Req. 4.4.2)

Numerical error estimates for the models have typically not been performed at the level of the cross section modules.

6.2.1.3 Verification Status (NASA-STD-7009 Req. 4.4.3)

The OLTARIS light particle cross section module is regularly executed through an automated suite of module and functional tests to ensure continued reliability.

6.2.2 Validation

6.2.2.1 Techniques (NASA-STD-7009 Req. 4.4.4)

Validation of the light particle cross section models has consisted of plotting the models against select experimental data and possibly stating qualitatively the measure of agreement between model and experiment. Graphical comparisons to data can be found in Wilson et al. [2] [3] [4], Cucinotta et al. [5] [6] [7], Tripathi et al. [8] [9], and Norbury [10].

6.2.2.2 Data (NASA-STD-7009 Req. 4.4.5)

The experimental data used in the validation of the cross section models can be found in Wilson et al. [2] [3] [4], Cucinotta et al. [5] [6] [7], Tripathi et al. [8] [9], and Norbury [10].

6.2.2.3 Studies (NASA-STD-7009 Req. 4.4.6)

No formal validation studies have been conducted for the light particle cross sections.

6.2.3 Uncertainty Quantification

6.2.3.1 Process (NASA-STD-7009 Req. 4.4.7)

The uncertainty quantification process for the light particle cross section modules has not been identified at this time.

6.2.3.2 Quantified Uncertainties (NASA-STD-7009 Req. 4.4.8)

The uncertainty quantification process for the light particle cross section modules has not been identified at this time.

6.2.3.3 Sensitivity Analysis (NASA-STD-7009 Req. 4.4.9)

Heinbockel et al. [14] performed an analysis of the sensitivity of HZETRN to cross section uncertainty.

6.3 References

1. ? NASA Standard 7009
2. ? 2.0 2.1 2.2 2.3 2.4 2.5 2.6 Wilson, J.W., Townsend, L.W., Nealy, J.E., Chun, S.Y., Hong, B.S., Buck, W.W., Lamkin, S.L., Ganapol, B.D., Khan, F., Cucinotta, F.A., BRYNTRN: A Baryon Transport Model, NASA Technical Paper 2887 (1989).

3. ? 3.0 3.1 3.2 3.3 3.4 3.5 3.6 Wilson, J.W., Townsend, L.W., Schimmerling, W., Khandelwal, G.S., Khan, F., Nealy, J.E., Cucinotta, F.A., Simonsen, L.C., Shinn, J.L., Norbury, J.W., Transport Methods and Interactions for Space Radiations, NASA Reference Publication 1257 (1991).
4. ? 4.0 4.1 4.2 4.3 4.4 4.5 4.6 [Wilson, J.W., Townsend, L.W., Buck, W.W., Chun, S.Y., Hong, B.S., Lamkin, S.L., Nucleon-Nucleon Interaction Data Base: Total Nuclear and Absorption Cross Sections, NASA Technical Memorandum 4053 (1988).]
5. ? 5.0 5.1 5.2 5.3 5.4 5.5 5.6 Cucinotta, F.A., Calculations of Cosmic-Ray Helium Transport in Shielding Materials, NASA Technical Paper 3354 (1993).
6. ? 6.0 6.1 6.2 6.3 6.4 6.5 6.6 [Cucinotta, F.A., Townsend, L.W., Wilson, J.W., Shinn, J.L., Badwar, G.D., Dubey, R.R., Light ion components of the galactic cosmic rays: nuclear interactions and transport theory, Advances in Space Research, Vol. 17, pp. 77-86 (1996).]
7. ? 7.0 7.1 7.2 7.3 7.4 7.5 7.6 [Cucinotta, F.A., Townsend, L.W., Wilson, J.W., Description of alpha-nucleus interaction cross sections for cosmic ray shielding studies, NASA Technical Paper 3285 (1993).]
8. ? 8.0 8.1 8.2 8.3 8.4 8.5 8.6 [Tripathi, R.K., Wilson, J.W., Cucinotta, F.A., New Parameterization of Neutron Absorption Cross Sections, NASA Technical Paper 3354 (1997).]
9. ? 9.0 9.1 9.2 9.3 9.4 9.5 9.6 [Tripathi, R.K., Cucinotta, F.A., Wilson, J.W., Universal Parameterization of Absorption Cross Sections, NASA Technical Paper 209726 (1999).]
10. ? 10.0 10.1 10.2 10.3 10.4 10.5 10.6 [Norbury, J.W., Nucleon-Nucleon Total Cross Sections, NASA Technical Paper 215116 (2008).]
11. ? Wilson, J.W., Townsend, L.W., Schimmerling, W., Khandelwal, G.S., Khan, F., Nealy, J.E., Cucinotta, F.A., Simonsen, L.C., Shinn, J.L., Norbury, J.W., Transport Methods and Interactions for Space Radiations. NASA Reference Publication 1257 (1991).
12. ? Slaba, T.C., Blattnig, S.R., Coupled Neutron Transport for HZETRN. NASA TP 2009-215941 (2009).
13. ? Slaba, T.C., Blattnig, S.R., Badavi, F.F., Faster and More Accurate Transport Procedures for HZETRN. NASA Technical Paper, under review (2009)
14. ? [J. H. Heinbockel, J. W. Wilson, S. R. Blattnig, G. D. Qualls, F. F. Badavi, F. A. Cucinotta, Cross section sensitivity and propagated errors in HZE exposures. Radiation Measurements 41, pp. 1103-1114 (2006)]

7 Heavy Ion Cross Sections

7.1 Heavy Ion Cross Section Model

Nuclear cross sections for the production of all particles from the interactions of heavy nuclei (i.e. all nuclei heavier than ^{4}He) are modeled by NUCFRG2 [1]. NUCFRG2 is an abrasion/ablation model of nuclear fragmentation.

7.1.1 Assumptions and Abstractions (NASA-STD-7009 [2] Req. 4.2.1)

The assumptions and abstractions used in NUCFRG2 are discussed in Wilson et al. [1] and the references therein.

7.1.2 Basic Structure (NASA-STD-7009 Req. 4.2.2)

The basic structure of NUCFRG2 is discussed in Wilson et al. [1].

7.1.3 Data Sets and Supporting Software (NASA-STD-7009 Req. 4.2.3)

The cross section modules used by OLTARIS are composed of FORTRAN source code linked with C shell, Ruby and Perl scripts to the main OLTARIS module. A cross section database is pre-generated for each material at predetermined energies and OLTARIS interpolates on this cross section database for values needed in the transport.

7.1.4 Units and Coordinate Frames (NASA-STD-7009 Req. 4.2.4)

The NUCFRG2 model uses A MeV for the units of energy. The output of NUCFRG2 is a total cross section in units of cm^2/g.

7.1.5 Limits of Operation (NASA-STD-7009 Req. 4.2.5)

NUCFRG2, as implemented in OLTARIS, can take projectiles with charge up to and including nickel.

7.1.6 Uncertainty Quantification (NASA-STD-7009 Req. 4.2.6)

The uncertainty in the data used to calibrate the NUCFRG2 model is discussed in Wilson et al. [1]. The overall uncertainty of NUCFRG2 was analyzed and characterized by Norman and Blattnig [3].

7.1.7 Proper Use (NASA-STD-7009 Req. 4.2.7)

Proper use of the oltaris website is described in the user manual [1] and reference guide [2].

7.1.8 Parameter Calibrations (NASA-STD-7009 Req. 4.2.8)

The parameters and level of calibration used in the NUCFRG2 model of nuclear fragmentation is discussed in Wilson et al. [1]

7.1.9 Model Updates (NASA-STD-7009 Req. 4.2.9)

Model updates are tracked/documented in a version control repository and are then reported to the user via the OLTARIS Change Log.

7.1.10 Obsolescence Criteria (NASA-STD-7009 Req. 4.2.10)

Obsolete models are removed from OLTARIS when appropriate.

7.2 Verification, Validation, and Uncertainty Quantification

7.2.1 Verification

7.2.1.1 Techniques (NASA-STD-7009 Req. 4.4.1)

All cross section modules are configuration controlled and system tests exist to ensure that changes made to any module do not break any other component of OLTARIS.

7.2.1.2 Error Estimates (NASA-STD-7009 Req. 4.4.2)

Numerical error estimates for the models have typically not been performed at the level of the cross section modules.

7.2.1.3 Verification Status (NASA-STD-7009 Req. 4.4.3)

The OLTARIS heavy particle cross section module is regularly executed through an automated suite of module and functional tests to ensure continued reliability.

7.2.2 Validation

7.2.2.1 Techniques (NASA-STD-7009 Req. 4.4.4)

An initial validation of the NUCFRG2 model against experimental data can be found in Wilson et al. [1] which consisted of a ?^{2} analysis. A comprehensive validation study for the heavy ion nuclear cross sections was completed by Norman and Blattnig [3] through comparison to all available nuclear fragmentation data using a novel validation metric based on cumulative absolute uncertainty.

7.2.2.2 Data (NASA-STD-7009 Req. 4.4.5)

The data used in the initial validation of the NUCFRG2 model can be found in Wilson et al. [1] and the references therein. The experimental data used in the comprehensive validation study for the heavy ion nuclear cross sections can be found in Norman and Blattnig [3].

7.2.2.3 Studies (NASA-STD-7009 Req. 4.4.6)

A comprehensive validation study for the heavy ion nuclear cross sections was completed by Norman and Blattnig [3].

7.2.3 Uncertainty Quantification

7.2.3.1 Process (NASA-STD-7009 Req. 4.4.7)

Norman and Blattnig [3] quantified the uncertainty in NUCFRG2 [1] compared to all available experimental nuclear fragmentation cross section data using a cumulative absolute uncertainty distribution which quantified uncertainty as a function the fraction of experimental data.

7.2.3.2 Quantified Uncertainties (NASA-STD-7009 Req. 4.4.8)

Norman and Blattnig [3] developed a cumulative absolute uncertainty distribution as a function of the fraction of experimental data and reported a cumulative absolute uncertainty at .50 fraction of data for NUCFRG2 of 15 millibarn (mb) with an uncertainty due to experiment at .50 fraction of data of 6 mb. In addition, Norman and Blattnig [3] reported a mean absolute error of 16 mb and a mean experimental error of 5 mb for NUCFRG2. Note that the unit of cross section here is a millibarn (mb) which is equal to 10^{-27} cm^2.

7.2.3.3 Sensitivity Analysis (NASA-STD-7009 Req. 4.4.9)

Heinbockel et al. [4] performed an analysis of the sensitivity of HZETRN to heavy ion cross section uncertainty.

7.3 References

1. ? $^{1.0\ 1.1\ 1.2\ 1.3\ 1.4\ 1.5\ 1.6\ 1.7}$ J. W. Wilson et al., NUCFRG2: An evaluation of the semiempirical nuclear fragmentation database. NASA-TP-3533 1995
2. ? NASA Standard 7009
3. ? $^{3.0\ 3.1\ 3.2\ 3.3\ 3.4\ 3.5\ 3.6}$ [R. B. Norman, S. R. Blattnig, A Comprehensive Validation Methodology for Sparse Experimental Data. NASA Technical Paper, submitted.]
4. ? [J. H. Heinbockel, J. W. Wilson, S. R. Blattnig, G. D. Qualls, F. F. Badavi, F. A. Cucinotta, Cross section sensitivity and propagated errors in HZE exposures. Radiation Measurements 41, pp. 1103-1114 (2006)]

8 Stopping Powers and Ranges

8.1 Stopping Powers and Ranges Model

Within OLTARIS, HZETRN solution methods, first use physical perturbations, based on the ordering of the cross sections with the frequent atomic interactions, as the first perturbation. Special methods are used for neutrons for which atomic cross section are zero. The first physical perturbation treated is the highly directed atomic collisions with mean free paths on the order of micrometers. The approximation to treat the atomic interactions is the continuous slowing down approximation (CSDA) which leads to the well specified range-energy relations.

8.1.1 Assumptions and Abstractions (NASA-STD-7009 [1] Req. 4.2.1)

The assumptions and abstractions used for the various atomic cross section approximations have been described by Wilson et al. [2] and the references therein.

8.1.2 Basic Structure (NASA-STD-7009 Req. 4.2.2)

The basic structure and physical formalism used to describe the atomic collisions as input to OLTARIS (in which all these collisions are used) has been described by Wilson. [2] and the references therin.

8.1.3 Data Sets and Supporting Software (NASA-STD-7009 Req. 4.2.3)

The atomic collisions modules used by OLTARIS are composed of FORTRAN source code linked with C shell, Ruby and Perl scripts to the main OLTARIS module. The collision interactions are expressed in terms of energy, range, and stopping power databases for a particular ion in a given material.

8.1.4 Units and Coordinate Frames (NASA-STD-7009 Req. 4.2.4)

Atomic collisions are expressed in terms of range of an ion in g/cm^2, stopping power of an ion in MeV/g/cm^2, and energy in A MeV.

8.1.5 Limits of Operation (NASA-STD-7009 Req. 4.2.5)

Atomic interactions within HZETRN are described by Continuous Slowing Down Approximation (CSDA) where the assumption of ion fragments traveling in essentially the same direction as projectile ion is valid. Neutrons are handled differently. At low projectile energy, CSDA approximation breaks down for light particles such as electrons and photons. Treatment of electrons and photons within OLTARIS will be handled differently to account for scattering mechanism.

8.1.6 Uncertainty Quantification (NASA-STD-7009 Req. 4.2.6)

The uncertainty quantification processes in the atomic interaction modules within OLTARIS have not been identified at this time.

8.1.7 Proper Use (NASA-STD-7009 Req. 4.2.7)

Proper use of the oltaris website is described in the user manual [1] and reference guide [2].

8.1.8 Parameter Calibrations (NASA-STD-7009 Req. 4.2.8)

The parameter calibrations in the atomic interaction modules within OLTARIS have not been identified at this time.

8.1.9 Model Updates (NASA-STD-7009 Req. 4.2.9)

Model updates are tracked/documented in a version control repository and are then reported to the user via the OLTARIS Change Log.

8.1.10 Obsolescence Criteria (NASA-STD-7009 Req. 4.2.10)

Obsolete models are removed from OLTARIS when appropriate.

8.2 Verification, Validation, and Uncertainty Quantification

8.2.1 Verification

8.2.1.1 Techniques (NASA-STD-7009 Req. 4.4.1)

Verification techniques for the OLTARIS atomic modules include automated module and functional tests. The module test is used to track and maintain functionality of the atomic modules by themselves. The functional tests are used to track and maintain functionality of several modules working together to putout a material atomic data base.

8.2.1.2 Error Estimates (NASA-STD-7009 Req. 4.4.2)

The extend of error estimates in the atomic modules have not been identified at this time.

8.2.1.3 Verification Status (NASA-STD-7009 Req. 4.4.3)

The OLTARIS atomic modules are regularly executed through an automated suite of module and functional tests. Verification tests have been completed by comparing OLTARIS atomic output with stand alone routines.

8.2.2 Validation

8.2.2.1 Techniques (NASA-STD-7009 Req. 4.4.4)

The range and stopping power of the atomic modules are validated by comparing with limited available measurements.

8.2.2.2 Data (NASA-STD-7009 Req. 4.4.5)

The validation metrics, referents, and data sets used in model validation are documented and described in the reference given in the next section.

8.2.2.3 Studies (NASA-STD-7009 Req. 4.4.6)

Validation studies for the atomic modules have been conducted by Wilson et al. [2]

8.2.3 Uncertainty Quantification

8.2.3.1 Process (NASA-STD-7009 Req. 4.4.7)

The uncertainty quantification processes in the atomic modules have not been identified at this time.

8.2.3.2 Quantified Uncertainties (NASA-STD-7009 Req. 4.4.8)

The uncertainty quantification processes in the atomic modules have not been identified at this time.

8.2.3.3 Sensitivity Analysis (NASA-STD-7009 Req. 4.4.9)

Sensitivity analysis to quantify the propagated errors induced in the atomic modules have not been identified at this time.

8.3 References

1. ? NASA Standard 7009
2. ? [2.0] [2.1] [2.2] Wilson, J.W., Townsend, L.W., Schimmerling, W., Khandelwal, G.S., Khan, F., Nealy, J.E., Cucinotta, F.A., Simonsen, L.C., Shinn, J.L., Norbury, J.W., Transport Methods and Interactions for Space Radiations, NASA Reference Publication 1257 (1991).

9 Radiation Transport

9.1 Transport Model

The OLTARIS transport module is based on the HZETRN transport code. Unless otherwise stated, all references and statements below pertaining to HZETRN are equally applicable to the OLTARIS transport module.

9.1.1 Assumptions and Abstractions (NASA-STD-7009 [1] Req. 4.2.1)

The assumptions and abstractions used in HZETRN have been described by Wilson et al. [2] and Slaba et al. [3] [4] and the references therein. Further discussions have by given by Wilson et al. [5] [6] [7] [8] [9] [10], Slaba et al. [11] [12] Cucinotta [13], Lamkin et al. [14], and Shinn et al. [15].

9.1.2 Basic Structure (NASA-STD-7009 Req. 4.2.2)

The basic structure and mathematics used in HZETRN have been described by Wilson et al. [2] and Slaba et al. [3] [4] and the references therin. Further discussions have been given by Wilson et al. [5] [6] [7] [8] [9] [10], Slaba et al. [11] [12] [16], Cucinotta et al. [13] [17] , Lamkin et al. [14] [18], and Shinn et al. [15] [19].

9.1.3 Data Sets and Supporting Software (NASA-STD-7009 Req. 4.2.3)

The OLTARIS transport module is comprised of FORTRAN source files connected with Ruby, Perl, and c-shell scripts. The input files include light particle and heavy ion nuclear cross section databases, atomic cross section databases as well as environmental databases for Low Earth Orbit, Solar Particle Events, and Galactic Cosmic Rays. The documentation for these data can be found in their respective sections.

9.1.4 Units and Coordinate Frames (NASA-STD-7009 Req. 4.2.4)

The input variables for the transport module are energy (A MeV, or MeV/amu, or MeV/n), material thickness (g/cm^2), atomic cross sections (MeV-cm^2/g), macroscopic absorption cross sections (cm^2/g), macroscopic differential production cross sections for light particles (cm^2/(g-A MeV)), macroscopic fragmentation cross sections for heavy ions (cm^2/g), and a particle boundary condition (particles/(cm^2-A MeV-time)).

The output variable for the transport module is a differential fluence (particles/(cm^2-A MeV-event)) for an SPE, or a differential flux (particles/(cm^2-A MeV-day)) for all other space environments. Ultimately, the space environment drives the units for the transport output.

9.1.5 Limits of Operation (NASA-STD-7009 Req. 4.2.5)

The transport module is designed to transport space environment boundary conditions through bulk material. The boundary conditions must have a broad energy spectrum. Mono-energetic laboratory boundary conditions cannot be used. The lower energy bound has been set to 0.01 A MeV, and the upper energy bound has been set to 50 000 A MeV. Transport of particles with energies outside these bounds has not been tested, studied, or verified. For slab geometry, there has been no lower or upper bounds placed on the thickness of the bulk materials, and there has been no constraints placed on the number or ordering of bulk materials. For generating an interpolation database of fluxes, there is no lower bound on the thickness of bulk materials. The upper bound has been set at 1000 g/cm^2, and the number of materials has been set to three. The maximum number of particles being transported for any boundary condition is currently set at 59.

9.1.6 Uncertainty Quantification (NASA-STD-7009 Req. 4.2.6)

Heinbockel et al. [20] performed a sensitivity analysis to quantify the propagated errors induced in the transport module by errors or uncertainties in the physical input parameters. Convergence studies have been done by Slaba et al. [4] [16] and Shinn et al. [15] to quantify the numerical uncertainity in the transport module.

9.1.7 Proper Use (NASA-STD-7009 Req. 4.2.7)

The transport module is transparent to the user and is run automatically by the website.

9.1.8 Parameter Calibrations (NASA-STD-7009 Req. 4.2.8)

The calibration and domain of calibration of discretization parameters has been studied and discussed in detail by Slaba et al. [4].

9.1.9 Model Updates (NASA-STD-7009 Req. 4.2.9)

Model updates are tracked/documented in a version control repository and are then reported to the user via the OLTARIS Change Log.

9.1.10 Obsolescence Criteria (NASA-STD-7009 Req. 4.2.10)

Obsolete models are removed from OLTARIS when appropriate.

9.2 Verification, Validation, and Uncertainty Quantification

9.2.1 Verification

9.2.1.1 Techniques (NASA-STD-7009 Req. 4.4.1)

Verification techniques for the OLTARIS transport module include automated module and functional tests, convergence tests, and benchmark comparisons. The module test is used to track and maintain functionality of the transport module by itself. The functional tests are used to track and maintain functionality of several modules working together - this includes the transport module. Convergence tests are used to quantify discretization error in the transport algorithms. Benchmark comparisons are used to track and quantify the accuracy of the transport algorithms through direct comparisons to various other state-of-the-art particle transport codes.

9.2.1.2 Error Estimates (NASA-STD-7009 Req. 4.4.2)

An overview of previous efforts to quantify numerical error as well as a detailed numerical error analysis can be found in Slaba et al. [4] and the references therin. Numerical error estimates have also been made for HZETRN by Wilson et al. [2] [5] [7] [8], Slaba et al. [16], Lamkin et al. [18], and Shinn et al. [19].

9.2.1.3 Verification Status (NASA-STD-7009 Req. 4.4.3)

The OLTARIS transport module is regularly executed through an automated suite of module and functional tests. Convergence tests have been completed by Slaba et al. [4] [16] and Shinn et al. [19]. Benchmark comparisons have been completed by Wilson et al. [10] [21], Heinbockel et al. [22] [23], and Slaba et al. [3] [11] [12].

9.2.2 Validation

9.2.2.1 Techniques (NASA-STD-7009 Req. 4.4.4)

The transport model is validated by comparing to available experimental or measured data.

9.2.2.2 Data (NASA-STD-7009 Req. 4.4.5)

The validation metrics, referents, and data sets used in model validation are documented and described in the various references given in the next section.

9.2.2.3 Studies (NASA-STD-7009 Req. 4.4.6)

Validation studies for the transport module have been conducted by Wilson et al. [21], Nealy et al. [24], and Badavi et al. [25].

9.2.3 Uncertainty Quantification

9.2.3.1 Process (NASA-STD-7009 Req. 4.4.7)

The process of quantifying numerical uncertainties of the M&S data (direct and derived) from the transport moduled have been described by Slaba et al. [4]. The uncertainty quantification processes used for the transport module input data (light particle and heavy ion nuclear cross sections, atomic cross sections, environmental models for Low Earth Orbit, Solar Particle Events, and Galactic Cosmic Rays) can be found in their respective sections of this document. The uncertainty quantification process for the propagation of uncertainties has been described by Heinbockel et al. [20].

9.2.3.2 Quantified Uncertainties (NASA-STD-7009 Req. 4.4.8)

Numerical uncertainties have been quantified for the transport module by Slaba et al. [4]. The quantified uncertainties for the transport module input data (light particle and heavy ion nuclear cross sections, atomic cross sections, environmental models for Low Earth Orbit, Solar Particle Events, and Galactic Cosmic Rays) can be found in their respective sections of this document. Propagated uncertainties have been quantified by Heinbockel et al. [20].

9.2.3.3 Sensitivity Analysis (NASA-STD-7009 Req. 4.4.9)

A direct and comprehensive sensitivity analysis has never been performed for the transport module.

9.3 References

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10 Dose Response

10.1 Dose Response Model

The OLTARIS dose model is based on the HZETRN2005 dose algorithms with the OLTARIS based transport results as the inputs. The dose is calculated at a point in the geometry and not in a volume.

10.1.1 Assumptions and Abstractions (NASA-STD-7009 Req. 4.2.1)

There are two assumptions made in the calculation of dose:

- That neutrons contribute dose through a parametrization of nuclear star data since target fragments for the heavy nuclei are not tracked.
- That particles that are not tracked in the transport code do not contribute to the dose save item 1 above.

10.1.2 Basic Structure (NASA-STD-7009 Req. 4.2.2)

This model is just an integration of all particle's (*j*) stopping power ($S_{j,m}(E)$) in material *m* times the flux ($_{j}(E)$) over the entire energy range (*E*) of the transport results:

$$D_m = \sum_j D_{j,m}$$

where,

$$D_{j,m} = \int_0^\infty dE \; S_{j,m}(E)\phi_j(E) + d^\star(E)$$

10.1.3 Data Sets and Supporting Software (NASA-STD-7009 Req. 4.2.3)

The dose module used by OLTARIS is composed of FORTRAN source code linked with C shell, Ruby and Perl scripts to the main OLTARIS module.

The module uses the Stopping Power data/model for a material as described in the Atomic Physics Section.

10.1.4 Units and Coordinate Frames (NASA-STD-7009 Req. 4.2.4)

The module input units are:

- Flux or fluence in particles per area (cm^2) - energy per nucleon (MeV per A or AMeV) - time (day for flux and event for fluence)
- Energy in AMeV
- Spatial values in g/cm^2
- Stopping power in MeV - g/cm^2

The modules output units are:

- Dose in mGy per time (day for flux input or event for fluence input)

10.1.5 Limits of Operation (NASA-STD-7009 Req. 4.2.5)

The algorithm has no limits, the limits are in the incoming data.

10.1.6 Uncertainty Quantification (NASA-STD-7009 Req. 4.2.6)

There are two places where uncertainty is not documented:

- The parametrizations for neutron nuclear star data
- The numerical algorithm used for integration

Neither of these algorithms have built in uncertainty checks nor can a general uncertainty check be performed outside of the code for all situations capable of being analyzed by this code.

10.1.7 Proper Use (NASA-STD-7009 Req. 4.2.7)

Through the website interface, only the dose box needs to be checked and a target material chosen, which determines the stopping powers used. All other features are automatic.

10.1.8 Parameter Calibrations (NASA-STD-7009 Req. 4.2.8)

The calibration for the neutron star data is undocumented.

The calibration data for the stopping powers used in the dose calculation is discussed in the Atomic Physics section of this document.

10.1.9 Model Updates (NASA-STD-7009 Req. 4.2.9)

Model updates are tracked/documented in a version control repository and are then reported to the user via the OLTARIS Change Log.

10.1.10 Obsolescence Criteria (NASA-STD-7009 Req. 4.2.10)

Obsolete models are removed from OLTARIS when appropriate.

10.2 Verification, Validation, and Uncertainty Quantification

10.2.1 Verification

10.2.1.1 Techniques (NASA-STD-7009 Req. 4.4.1)

Verification techniques for the OLTARIS Dose module include automated module tests, functional tests, and a benchmark comparison for the numerical integration algorithm.

10.2.1.2 Error Estimates (NASA-STD-7009 Req. 4.4.2)

Error estimates for the stopping power data can be found in the Atomic Physics section of this document.

Numerical error for the integration routine are not documented.

As the definition of dose is being used, there are no modeling errors.

10.2.1.3 Verification Status (NASA-STD-7009 Req. 4.4.3)

The numerical implementation of the model has been tested and benchmarked. The OLTARIS dose algorithm passes the module and functional tests.

10.2.2 Validation

10.2.2.1 Techniques (NASA-STD-7009 Req. 4.4.4)

The dose algorithm has not been validated as a separate module, but it is included in other validation scenarios against spacecraft in orbit.

10.2.2.2 Data (NASA-STD-7009 Req. 4.4.5)

N/A

10.2.2.3 Studies (NASA-STD-7009 Req. 4.4.6)

N/A

10.2.3 Uncertainty Quantification

10.2.3.1 Process (NASA-STD-7009 Req. 4.4.7)

Uncertainty quantification processes have not been documented for the dose algorithm.

10.2.3.2 Quantified Uncertainties (NASA-STD-7009 Req. 4.4.8)

Uncertainty quantification has not been documented for the dose algorithm.

10.2.3.3 Sensitivity Analysis (NASA-STD-7009 Req. 4.4.9)

No sensitivity analysis has been performed for the dose algorithm; however, sensitivity analyzes with dose as an end point have been performed.

10.3 References

11 Dose Equivalent Response

11.1 Dose Equivalent Response Model

The OLTARIS dose equivalent model is based on the HZETRN2005 dose equivalent algorithms with the OLTARIS based transport results as the inputs. The dose equivalent is calculated at a point in the geometry and not in a volume.

11.1.1 Assumptions and Abstractions (NASA-STD-7009 Req. 4.2.1)

There are three assumptions made in the calculation of dose equivlent:

- That neutrons contribute through a parametrization of nuclear star data since target fragments for the heavy nuclei are not tracked.
- That particles that are not tracked in the transport code do not contribute to the dose equivalent save item 1 above.
- All values are for human tissue.

11.1.2 Basic Structure (NASA-STD-7009 Req. 4.2.2)

This model is just an integration of all particle's (*j*) stopping powers ($S_{j,T}(E)$) in tissue (*T*) times flux ($_j(E)$) times an LET based Quality Factor[1] ($Q_{\mathrm{ICRP60}}(S_{j,T}(E))$) over the entire energy range (*E*) of the transport results:

$$H_T = \sum_j H_{j,T}$$

where,

$$H_{j,T} = \int_0^\infty dE\ Q_{\mathrm{ICRP60}}\left(S_{j,T}(E)\right) S_{j,T}(E)\phi_j(E) + h^\star(E)$$

and

$$Q_{\mathrm{ICRP60}}\left(S_{j,T}(E)\right) = \begin{cases} 1 & \text{for} \quad 0 < S_{j,T}(E) \leq 10 \\ 0.32 S_{j,T}(E) - 2.2 & \text{for} \quad 10 < S_{j,T}(E) \leq 100 \\ \frac{300}{\sqrt{S_{j,T}(E)}} & \text{for} \quad 100 > S_{,T}j(E) \end{cases} .$$

11.1.3 Data Sets and Supporting Software (NASA-STD-7009 Req. 4.2.3)

The dose equivalent module used by OLTARIS is composed of FORTRAN source code linked with C shell, Ruby and Perl scripts to the main OLTARIS module.

The module uses the Stopping Power data/model for a material as described in the Atomic Physics Section.

11.1.4 Units and Coordinate Frames (NASA-STD-7009 Req. 4.2.4)

The module input units are:

- Flux or fluence in particles per area (cm^2) - energy per nucleon (MeV per A or AMeV) - time (day for flux and event for fluence)
- Energy in AMeV
- Spatial values in $\mathrm{g/cm}^2$
- Stopping power in MeV - $\mathrm{g/cm}^2$

The modules output units are:

- Dose Equivalent in mSv per time (day for flux input or event for fluence input)

11.1.5 Limits of Operation (NASA-STD-7009 Req. 4.2.5)

The algorithm has no limits, the limits are in the incoming data.

11.1.6 Uncertainty Quantification (NASA-STD-7009 Req. 4.2.6)

There are two places where uncertainty is not documented:

- The parametrizations for neutron nuclear star data
- The numerical algorithm used for integration

Neither of these algorithms have built in uncertainty checks nor can a general uncertainty check be performed outside of the code for all situations capable of being analyzed by this code.

11.1.7 Proper Use (NASA-STD-7009 Req. 4.2.7)

Through the website interface, only the dose equivalent box needs to be checked. All other features are automatic.

11.1.8 Parameter Calibrations (NASA-STD-7009 Req. 4.2.8)

The calibration for the neutron star data is undocumented.

The calibration data for the stopping powers used in the dose calculation is discussed in the Atomic Physics section of this document.

11.1.9 Model Updates (NASA-STD-7009 Req. 4.2.9)

Model updates are tracked/documented in a version control repository and are then reported to the user via the OLTARIS Change Log.

11.1.10 Obsolescence Criteria (NASA-STD-7009 Req. 4.2.10)

Obsolete models are removed from OLTARIS when appropriate.

11.2 Verification, Validation, and Uncertainty Quantification

11.2.1 Verification

11.2.1.1 Techniques (NASA-STD-7009 Req. 4.4.1)

Verification techniques for the OLTARIS Dose Equivalent module include automated module tests, functional tests, and a benchmark comparison for the numerical integration algorithm.

11.2.1.2 Error Estimates (NASA-STD-7009 Req. 4.4.2)

Error estimates for the stopping power data can be found in the Atomic Physics section of this document.

Numerical error for the integration routine are not documented.

As the definition of dose equivalent is being used, there are no modeling errors.

11.2.1.3 Verification Status (NASA-STD-7009 Req. 4.4.3)

The numerical implementation of the model has been tested and benchmarked. The OLTARIS dose equivalent algorithm passes the module and functional tests.

11.2.2 Validation

11.2.2.1 Techniques (NASA-STD-7009 Req. 4.4.4)

The dose equivalent algorithm has not been validated as a separate module, but it is included in other validation scenarios against spacecraft in orbit.

11.2.2.2 Data (NASA-STD-7009 Req. 4.4.5)

N/A

11.2.2.3 Studies (NASA-STD-7009 Req. 4.4.6)

N/A

11.2.3 Uncertainty Quantification

11.2.3.1 Process (NASA-STD-7009 Req. 4.4.7)

Uncertainty quantification processes have not been documented for the dose equivalent algorithm.

11.2.3.2 Quantified Uncertainties (NASA-STD-7009 Req. 4.4.8)

Uncertainty quantification has not been documented for the dose equivalent algorithm.

11.2.3.3 Sensitivity Analysis (NASA-STD-7009 Req. 4.4.9)

No sensitivity analysis has been performed for the dose equivalent algorithm; however, sensitivity analyzes with dose equivalent as an end point have been performed.

11.3 References

1. ? International Commission on Radiological Protection (ICRP), The 1990 Recommendations of the International Commission on Radiological Protection, ICRP Publication 60, Elsevier, New York, 1993.

12 Whole Body Effective Dose Equivalent

12.1 Whole Body Effective Dose Equivalent Model

The OLTARIS whole body effective dose equivalent model is based on the dose equivalent model discussed in that section, and is a weighted sum over numerous point dose equivalent calculations to represent the organs and the whole body.

12.1.1 Assumptions and Abstractions (NASA-STD-7009 Req. 4.2.1)

As is recommended in NCRP-132[1] and NCRP-142[2], effective dose equivalent is calculated by first calculating the averaged dose equivalent for the organs and tissues listed in the table below. The remainder organs are listed in NCRP-132 as: adrenals, brain, small intestine, large intestine, kidneys, muscle, pancreas, spleen, thymus, and uterus. A weighted average of these organ or tissue dose equivalent values, as defined in the equation below, is then calculated using the NCRP-132 tissue weighting factors given in the top row of the table.

$$ED = \sum_T w_T \bar{H}_T$$

where w_T are the NCRP-132 tissue weighting factors in the table and $\bar{H}_T$ are the organ or tissue averaged dose equivalents as calculated by OLTARIS.

Table: NCRP 132 Organs and their weights

Tissue Weights	0.01	0.05	0.12	0.20
Tissue Types	Bone Surface	Bladder	Bone Marrow	Gonads
	Skin	Breast	Colon	
		Liver	Lung	
		Esophagus	Stomach	
		Thyroid		
		Remainder		

Organ or tissue averaged dose equivalent is calculated by first calculating the dose equivalent at a large enough number of target points in the organ or tissue to accurately characterize that organ or tissue and then averaging these point values. Currently, the user can select one of four human body models (CAM, CAF, MAX, or FAX) for these calculations. Target point locations for all of the necessary organs and tissues in each of the human body models have been chosen[3] [4] and body thickness distributions are combined with vehicle thickness distributions.

There are a few body model specific details that should be noted. First, there are ten remainder organs for the females, but only nine for the males. For this reason, the tissue weighting factor, w_T, for each of the remainder organs is 0.005 for females and 0.00555556 for the males. Second, in the CAF and CAM models, the colon, large intestine, and small intestine are treated as one organ. This organ labeled intestine is therefore assigned a tissue weighting factor equivalent to the sum of the tissue weighting factor specified for colon, 0.12, and the tissue weighting factors for two remainder organs. Thus the intestine weighting factor is 0.13 for CAF and 0.1311111 for CAM. Similarly, the colon and the large intestine are treated as one organ and labeled "colon" in the FAX and MAX models, but the small intestine is treated as a separate organ in these models. The weighting factor for colon is therefore 0.125 in FAX and 0.12555556 in MAX. Also, the organ averaged dose equivalent is calculated for several organs not included in the effective dose equivalent calculation. These organs are heart, hippocampus, lens, and salivary glands for the CAF model; heart, hippocampus, lens, prostate, and salivary glands for the CAM model; heart, hippocampus, lens, retina, salivary glands, and trachea for the FAX model; and heart, hippocampus, lens, prostate, retina, salivary glands, and trachea for the MAX model. Additional details about the body models are contained in the Body Geometry sections.

12.1.2 Basic Structure (NASA-STD-7009 Req. 4.2.2)

See above section on Assumptions and Abstractions. The input data is the same as for the dose equivalent calculation except that there are many more points to evaluate. Each organ has a set of points that represent that organ, and then the organs are averaged together as denoted above to generate a final value.

To evaluate a human model inside of a vehicle, the human model thickness distributions are added to the vehicles thickness distributions. These distributions are then interpolated on the dose equivalent table generated by the transport and dose equivalent modules. There are up to 5 zones for the vehicle and up to 1500 points for the human model. These are combined together to generate 1500 dose equivalent values. The points are arranged in groups to represent human organs of interest listed in the table above.

12.1.3 Data Sets and Supporting Software (NASA-STD-7009 Req. 4.2.3)

The effective dose modules used by OLTARIS are composed of FORTRAN source code linked with C shell, Ruby and Perl scripts to the main OLTARIS module.

12.1.4 Units and Coordinate Frames (NASA-STD-7009 Req. 4.2.4)

The module input units are:

- Flux or fluence in particles per area (cm^2) - energy per nucleon (MeV per A or AMeV) - time (day for flux and event for fluence)
- Energy in AMeV
- Spatial values in g/cm^2 in the form of thickness distributions
- Stopping power in MeV - g/cm^2

The modules output units are:

- Whole Body Effective Dose Equivalent in mSv per time (day for flux input or event for fluence input)

12.1.5 Limits of Operation (NASA-STD-7009 Req. 4.2.5)

The algorithm has no limits, the limits are in the incoming data.

12.1.6 Uncertainty Quantification (NASA-STD-7009 Req. 4.2.6)

The uncertainty quantification is the same as for dose equivalent.

In addition, numerical uncertainty quantification of the human phantom dose point selection process has also been performed by Slaba et. al. [3] [4]

12.1.7 Proper Use (NASA-STD-7009 Req. 4.2.7)

Through the website interface, only the effective dose equivalent box needs to be checked and the human body model chosen. All other features are automatic.

12.1.8 Parameter Calibrations (NASA-STD-7009 Req. 4.2.8)

The parameter calibration is the same as for dose equivalent.

12.1.9 Model Updates (NASA-STD-7009 Req. 4.2.9)

Model updates are tracked/documented in a version control repository and are then reported to the user via the OLTARIS Change Log.

12.1.10 Obsolescence Criteria (NASA-STD-7009 Req. 4.2.10)

Obsolete models are removed from OLTARIS when appropriate.

12.2 Verification, Validation, and Uncertainty Quantification

12.2.1 Verification

12.2.1.1 Techniques (NASA-STD-7009 Req. 4.4.1)

Verification techniques for the OLTARIS Effective Dose Equivalent module include automated module tests, functional tests, and a benchmark comparison for the numerical integration algorithm.

12.2.1.2 Error Estimates (NASA-STD-7009 Req. 4.4.2)

Same error estimates as in the dose equivalent module.

In addition, Slaba et. al.[3] [4] provided estimates of the errors resulting from the choice of target point distribution in the human phantoms.

12.2.1.3 Verification Status (NASA-STD-7009 Req. 4.4.3)

As the definition of effective dose equivalent is being used, there are no modeling errors.

12.2.2 Validation

12.2.2.1 Techniques (NASA-STD-7009 Req. 4.4.4)

The effective dose equivalent algorithm has not been validated as a separate module, but it is included in other validation scenarios against spacecraft in orbit.

12.2.2.2 Data (NASA-STD-7009 Req. 4.4.5)

N/A

12.2.2.3 Studies (NASA-STD-7009 Req. 4.4.6)

N/A

12.2.3 Uncertainty Quantification

12.2.3.1 Process (NASA-STD-7009 Req. 4.4.7)

Slaba et. al. [3] [4] provided estimates of the errors resulting from the choice of target point distribution in the human phantoms.

Zapp et al. [5] examined the variation in organ averaged dose equivalent values for SPE environments when the body size is varied. This study found that the "dose equivalent may vary by as much as 15% if the body size is varied from the 5th percentile to the 95th percentile in the population used to derive the CAM model data." The CAM model was used for this study, but it should provide insight into size variation in any human model.

The sensitivity of organ averaged dose equivalent calculations to changes in SPE environment models was examined by Prof. Lawrence Townsend and his students at the University of Tennessee. [6] [7] [8]

The sensitivity of effective dose calculations to changes in astronaut orientation was examined by Clowdsley et al. [9]

12.2.3.2 Quantified Uncertainties (NASA-STD-7009 Req. 4.4.8)

Uncertainty quantification has not been documented for the effective dose equivalent algorithm.

12.2.3.3 Sensitivity Analysis (NASA-STD-7009 Req. 4.4.9)

No sensitivity analysis has been performed for the effective dose equivalent algorithm; however, sensitivity analyzes with effective dose equivalent as an end point have been performed. Zapp et al. [5] examined the variation in organ averaged dose equivalent values for SPE environments when the body size is varied. This study found that the "dose equivalent may vary by as much as 15% if the body size is varied from the 5th percentile to the 95th percentile in the population used to derive the CAM model data." The CAM model was used for this study, but it should provide insight into size variation in any human model. The sensitivity of organ averaged dose equivalent calculations to changes in SPE environment models was examined by Prof. Lawrence Townsend and his students at the University of Tennessee. [6] [7] [8] The sensitivity of effective dose calculations to changes in astronaut orientation was examined by Clowdsley et al. [9]

12.3 References

1. ? National Council on Radiation Protection and Measurements (NCRP), "Radiation Protection Guidance for Activities in Low-Earth Orbit," NCRP Report 132, 2000.
2. ? National Council on Radiation Protection and Measurements (NCRP), "Operational Radiation Safety Program for Astronauts in Low-Earth Orbit: A Basic Framework," NCRP Report 142, 2002.
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13 TLD-100 Response

13.1 TLD-100 Response Model

13.1.1 Assumptions and Abstractions (NASA-STD-7009 Req. 4.2.1)

For dosimetry measurement purposes, one of the most widely used phosphors based radiation detection instruments is the lithium fluoride (LiF) thermoluminescence detector (TLD-100). Within OLTARIS, the flux response function for the TLD-100 sensitivity to an incoming ion of charge Z and energy E, is modeled by a functional fit to the available data.

13.1.2 Basic Structure (NASA-STD-7009 Req. 4.2.2)

The assumptions and abstractions used to compute the LET dependent quantities have been described by Badavi et al.[1] and the references therein.

13.1.3 Data Sets and Supporting Software (NASA-STD-7009 Req. 4.2.3)

The TLD modules used by OLTARIS are composed of FORTRAN source code linked with C shell, Ruby and Perl scripts to the main OLTARIS module. A TLD database is post-generated upon the completion of particle transport in a material.

13.1.4 Units and Coordinate Frames (NASA-STD-7009 Req. 4.2.4)

Within OLTARIS, the units of TLD is cGy/day*

- For SPE related work day above is to be replaced with event

13.1.5 Limits of Operation (NASA-STD-7009 Req. 4.2.5)

The TLD modules are limited by the operational limits of the transport runs within OLTARIS.

13.1.6 Uncertainty Quantification (NASA-STD-7009 Req. 4.2.6)

The TLD modules are limited by the uncertainties that may be introduced in the description of environment or transport runs within OLTARIS.

13.1.7 Proper Use (NASA-STD-7009 Req. 4.2.7)

Proper use of the oltaris website is described in the user manual [1] and reference guide [2].

13.1.8 Parameter Calibrations (NASA-STD-7009 Req. 4.2.8)

Parameter calibration within TLD modules have not been identified at this time.

13.1.9 Model Updates (NASA-STD-7009 Req. 4.2.9)

Model updates are tracked/documented in a version control repository and are then reported to the user via the OLTARIS Change Log.

13.1.10 Obsolescence Criteria (NASA-STD-7009 Req. 4.2.10)

Obsolete models are removed from OLTARIS when appropriate.

13.2 Verification, Validation, and Uncertainty Quantification

13.2.1 Verification

13.2.1.1 Techniques (NASA-STD-7009 Req. 4.4.1)

Verification techniques for the OLTARIS TLD modules include automated module and functional tests. The module test is used to track and maintain functionality of the environment modules by themselves. The functional tests are used to track and maintain functionality of several modules working together to putout a TLD response database.

13.2.1.2 Error Estimates (NASA-STD-7009 Req. 4.4.2)

Sensitivity analysis to quantify the propagated errors induced in the TLD modules have not been identified at this time.

13.2.1.3 Verification Status (NASA-STD-7009 Req. 4.4.3)

The OLTARIS TLD modules are regularly executed through an automated suite of module and functional tests. Verification tests have been completed by comparing OLTARIS TLD output with stand alone routines.

13.2.2 Validation

13.2.2.1 Techniques (NASA-STD-7009 Req. 4.4.4)

The TLD modules are validated by comparing with available measurements has been described by Badavi et al.[1] and the references therein.

13.2.2.2 Data (NASA-STD-7009 Req. 4.4.5)

The validation metrics, referents, and data sets used in model validation are documented and described in the various references given in the next section.

13.2.2.3 Studies (NASA-STD-7009 Req. 4.4.6)

Validation studies for the TLD modules have been conducted by Badavi et al.[1] and the references therein.

13.2.3 Uncertainty Quantification

13.2.3.1 Process (NASA-STD-7009 Req. 4.4.7)

The uncertainty quantification processes errors induced in the TLD modules has not been identified at this time.

13.2.3.2 Quantified Uncertainties (NASA-STD-7009 Req. 4.4.8)

The uncertainty quantification processes errors induced in the TLD modules has not been identified at this time.

13.2.3.3 Sensitivity Analysis (NASA-STD-7009 Req. 4.4.9)

The sensitivity analysis quantification processes errors induced in the TLD modules has not been identified at this time.

13.3 References

1. ? [1.0] [1.1] [1.2] F.F. Badavi et al., A Dynamic/Anisotropic Low Earth Orbit(LEO)Ionizing Radiation Model, NASA-TP-2006-214533, 2006.

14 Tissue Equivalent Proportional Counter Response

14.1 Tissue Equivalent Proportional Counter Response Model

14.1.1 Assumptions and Abstractions (NASA-STD-7009 Req. 4.2.1)

In a the section on LET, it was stated that the conversion of GCR, SPE and trap particle energy spectra into LET distributions is a convenient guide in assessing biologically significant components of these spectra. Furthermore, a numerical mapping procedure to convert particle flux from energy to LET domain was described. What was not discussed is the fact that a feature of ionizing radiation is its discontinuous nature of interaction with matter. That is, the deposited energy into a medium consists of discrete events with energy partitioning among ionization and excitation processes. This observation led to the suggestion that the usual LET dependent quality factor (Q) be replaced by a lineal energy (y) dependent Q for use in radiation protection studies.

Furthermore, the usual method of measuring LET is based on passive plastic track detectors with limited LET range. These detectors can not detect electrons, their efficiency for detection of secondaries such as pion or kaon are not well established and they experience detection-resolution limitation above LETs of 250 ~ 300 keV/µm. Finally, because of the passive nature of these detectors, the separation of GCR from trapped particles for LEO flights is difficult. In contrast to the limitations of LET based passive detectors, TEPC detectors simulate a micron size tissue site, and can provide a time resolved dose and y spectra.

Monte Carlo (MC) simulations are the method of choice to model energy deposition by ions in a micro-volume. MC necessitates a complete model of the important components of the TEPC device and depending on the uncertainty wanted, can take some time to execute. In contrast, OLTARIS uses a computationally efficient deterministic method for the numerical representation of stochastic energy deposition and ionization produced by energetic ions passing through absorber sites of submicron dimension. Further details can be found in have been described by Badavi et al.[1] and the references therein.

14.1.2 Basic Structure (NASA-STD-7009 Req. 4.2.2)

The basic structure of the TEPC response model have been described by Badavi et al.[1] and the references therein.

14.1.3 Data Sets and Supporting Software (NASA-STD-7009 Req. 4.2.3)

The TEPC modules used by OLTARIS are composed of FORTRAN source code linked with C shell, Ruby and Perl scripts to the main OLTARIS module. A TEPC response database is post-generated upon the completion of particle transport in a material.

14.1.4 Units and Coordinate Frames (NASA-STD-7009 Req. 4.2.4)

Within OLTARIS, the units of the TEPC response related quantities for tissue as applied to microdosimeter analysis are as follows: LET: keV/µm Differential LET flux: particles/(cm^2-sr-day-keV/µm)* Integral LET flux: particles/(cm^2-sr-day)*

- For SPE related work day above is to be replaced with event

14.1.5 Limits of Operation (NASA-STD-7009 Req. 4.2.5)

Shall document the limits of operation of models.

14.1.6 Uncertainty Quantification (NASA-STD-7009 Req. 4.2.6)

The TEPC modules are limited by the operational limits of the HZETRN transport runs within OLTARIS, the form factor of TEPC and the estimation of sensitive volume within TEPC.

14.1.7 Proper Use (NASA-STD-7009 Req. 4.2.7)

Proper use of the oltaris website is described in the user manual [1] and reference guide [2].

14.1.8 Parameter Calibrations (NASA-STD-7009 Req. 4.2.8)

No parameter calibration within TEPC response modules was performed.

14.1.9 Model Updates (NASA-STD-7009 Req. 4.2.9)

Model updates are tracked/documented in a version control repository and are then reported to the user via the OLTARIS Change Log.

14.1.10 Obsolescence Criteria (NASA-STD-7009 Req. 4.2.10)

Obsolete models are removed from OLTARIS when appropriate.

14.2 Verification, Validation, and Uncertainty Quantification

14.2.1 Verification

14.2.1.1 Techniques (NASA-STD-7009 Req. 4.4.1)

Verification techniques for the OLTARIS TEPC response modules include automated module and functional tests. The module test is used to track and maintain functionality of the environment modules by themselves. The functional tests are used to track and maintain functionality of several modules working together to putout a TEPC differential and integral spectra.

14.2.1.2 Error Estimates (NASA-STD-7009 Req. 4.4.2)

Numerical error estimates have not been made.

14.2.1.3 Verification Status (NASA-STD-7009 Req. 4.4.3)

The OLTARIS TEPC response modules are regularly executed through an automated suite of module and functional tests. Verification tests have been completed by comparing OLTARIS TEPC output with stand alone routines.

14.2.2 Validation

14.2.2.1 Techniques (NASA-STD-7009 Req. 4.4.4)

The TEPC response modules are validated by comparing with available measurements has been described by Badavi et al.[1] and the references therein.

14.2.2.2 Data (NASA-STD-7009 Req. 4.4.5)

The validation metrics, referents, and data sets used in model validation are documented and described in the various references given in Badavi et al.[1] and the references therein.

14.2.2.3 Studies (NASA-STD-7009 Req. 4.4.6)

Validation studies for the TEPC response modules have been conducted by Badavi et al.[1] and the references therein.

14.2.3 Uncertainty Quantification

14.2.3.1 Process (NASA-STD-7009 Req. 4.4.7)

The uncertainty quantification processes errors induced in the TEPC response modules has not been identified at this time.

14.2.3.2 Quantified Uncertainties (NASA-STD-7009 Req. 4.4.8)

Badavi et al.[1] and the references therein.

14.2.3.3 Sensitivity Analysis (NASA-STD-7009 Req. 4.4.9)

The sensitivity analysis quantification processes errors induced in the TEPC response modules has not been identified at this time.

14.3 References

1. ? [1.0] [1.1] [1.2] [1.3] [1.4] [1.5] F. F. Badavi et al., Description of a Generalized Analytical Model for the Micro-dosimeter Response, NASA-TP-2007-214886, 2007

15 Linear Energy Transfer Response

15.1 Linear Energy Transfer Response Model

15.1.1 Assumptions and Abstractions (NASA-STD-7009 Req. 4.2.1)

In analyzing charged particle spectra in space due to Galactic Cosmic Rays (GCR), Solar Particle Events (SPE) and trapped protons/electrons, the conversion of particle energy spectra into Linear Energy Transfer (LET) distributions is a convenient guide in assessing biologically significant components of these spectra. The mapping of LET to energy is triple valued and can be defined only on open energy subintervals where the derivative of LET with respect to energy is not zero. OLTARIS uses a well-defined numerical procedure which allows for the generation of LET spectra on the open energy subintervals that are integrable in spite of their singular nature. Due to the biological significance of tissue and the need for electronics evaluations, all LET related simulations within OLTARIS are done with tissue or with silicon as the target material.

15.1.2 Basic Structure (NASA-STD-7009 Req. 4.2.2)

The assumptions and abstractions used to compute the LET dependent quantities have been described by Badavi et al.[1] [2] and the references therein.

15.1.3 Data Sets and Supporting Software (NASA-STD-7009 Req. 4.2.3)

The LET modules used by OLTARIS are composed of FORTRAN source code linked with C shell, Ruby and Perl scripts to the main OLTARIS module. An LET database is post-generated upon the completion of particle transport in a material.

15.1.4 Units and Coordinate Frames (NASA-STD-7009 Req. 4.2.4)

Within OLTARIS, the units of the LET related quantities for tissue as applied to microdosimeter analysis are as follows: LET: keV/µm Differential LET flux: particles/(cm^2-sr-day-keV/µm)* Integral LET flux: particles/(cm^2-sr-day)*

- For SPE related work day above is to be replaced with event

15.1.5 Limits of Operation (NASA-STD-7009 Req. 4.2.5)

The LET modules are limited by the operational limits of the transport runs within OLTARIS.

15.1.6 Uncertainty Quantification (NASA-STD-7009 Req. 4.2.6)

The LET modules are limited by the uncertainties that may be introduced in the description of environment or transport runs within OLTARIS.

15.1.7 Proper Use (NASA-STD-7009 Req. 4.2.7)

Proper use of the OLTARIS website is described in the user manual [1] and reference guide [2].

15.1.8 Parameter Calibrations (NASA-STD-7009 Req. 4.2.8)

Parameter calibration within LET modules have not been identified at this time.

15.1.9 Model Updates (NASA-STD-7009 Req. 4.2.9)

Model updates are tracked/documented in a version control repository and are then reported to the user via the OLTARIS Change Log.

15.1.10 Obsolescence Criteria (NASA-STD-7009 Req. 4.2.10)

Obsolete models are removed from OLTARIS when appropriate.

15.2 Verification, Validation, and Uncertainty Quantification

15.2.1 Verification

15.2.1.1 Techniques (NASA-STD-7009 Req. 4.4.1)

Verification techniques for the OLTARIS LET modules include automated module and functional tests. The module test is used to track and maintain functionality of the environment modules by themselves. The functional tests are used to track and maintain functionality of several modules working together to putout an LET differential and integral spectra.

15.2.1.2 Error Estimates (NASA-STD-7009 Req. 4.4.2)

Sensitivity analysis to quantify the propagated errors induced in the LET modules have not been identified at this time.

15.2.1.3 Verification Status (NASA-STD-7009 Req. 4.4.3)

The OLTARIS LET modules are regularly executed through an automated suite of module and functional tests. Verification tests have been completed by comparing OLTARIS LET output with stand alone routines.

15.2.2 Validation

15.2.2.1 Techniques (NASA-STD-7009 Req. 4.4.4)

The LET modules are validated by comparing with available measurements has been described by Badavi et al.[3] and the references therein.

15.2.2.2 Data (NASA-STD-7009 Req. 4.4.5)

The validation metrics, referents, and data sets used in model validation are documented and described in the various references given in the next section.

15.2.2.3 Studies (NASA-STD-7009 Req. 4.4.6)

Validation studies for the LET modules have been conducted by Badavi et al.[3] and the references therein.

15.2.3 Uncertainty Quantification

15.2.3.1 Process (NASA-STD-7009 Req. 4.4.7)

The uncertainty quantification processes errors induced in the LET modules has not been identified at this time.

15.2.3.2 Quantified Uncertainties (NASA-STD-7009 Req. 4.4.8)

The uncertainty quantification processes errors induced in the LET modules has not been identified at this time.

15.2.3.3 Sensitivity Analysis (NASA-STD-7009 Req. 4.4.9)

The sensitivity analysis quantification processes errors induced in the LET modules has not been identified at this time.

15.3 References

1. ? F. F. Badavi et al., Numerical study of the generation of linear energy transfer spectra for space radiation applications, NASA-TP-2005-213941, 2005
2. ? F. F. Badavi et al., Radiation Protection Effectiveness of Polymeric Based Shielding Materials at Low Earth Orbit, SAMPE paper 2008-L002, May 2008.
3. ? [3.0] [3.1] F. F. Badavi et al., Description of a Generalized Analytical Model for the Micro-dosimeter Response, NASA-TP-2007-214886, 2007

16 Computerized Anatomical Man and Female Body Models

16.1 CAM and CAF Model

For whole body effective dose calculations, OLTARIS users can choose from several available human body geometry models. Two of these models are the Computerized Anatomical Man (CAM) and the Computerized Anatomical Female (CAF). CAM and CAF were developed for NASA for space radiation analysis in 1973 and 1990 respectively and have been used in a number of NASA studies. A fixed set of target points has been identified for each of the following organs or tissue types in the CAM and CAF models: adrenals, blood forming organs (BFO), bladder, bone, brain, breast, esophagus, gonads (testes for CAM, ovaries for CAF), heart, hippocampus, intestine, kidney, lens, liver, lungs, muscle, pancreas, salivary glands, skin, spleen, stomach, thymus, thyroid, prostate (CAM only), and uterus (CAF only). Thickness distributions utilizing 42, 492, 512, 968, 1002, 4002, 9002, and 10,000 ray distributions have been precalculated and stored for each target point using the CAMERA ray-tracing software that was developed for CAM. The effective dose is calculated by first calculating the organ averaged dose equivalent for each organ or tissue type and then taking a weighted average of these values, as described in the Response Functions section.

16.1.1 Assumptions and Abstractions (NASA-STD-7009 [1] Req. 4.2.1)

The assumptions and abstractions used in the CAM model have been described by Billings and Yucker. [2] The assumptions and abstractions used in the CAF model have been described by Yucker et al. [3] [4] Additional information about the CAM and CAF models has been provided by Atwell. [5] Slaba et al. [6] [7] provide a good analysis of how accurately the CAM and CAF models represent the International Commission on Radiological Protection (ICRP) reference male and female [8] in terms of organ mass and size.

CAMERA version 1.4 was used for the ray-traces. The assumptions and abstractions in CAMERA are described by Billings and Yucker [2] and Yucker et al. [3] [4] The target point thickness distributions output by the CAMERA code and stored on OLTARIS represent the thickness of human tissue along each ray in the distribution from the target point to the outer boundary of the body. These thicknesses are in cm and one generic human tissue definition is used to represent all of the tissues making up the body.

The methodologies utilized for selecting organ or tissue target point distributions adequate for calculating organ averaged dose equivalent and the associated assumptions and abstractions are described by Slaba et al. [6] [7] The coordinates of the target points for all of the target points except those in the lens and the hippocampus are in Slaba et al. [6] In the CAM, the target points for the lens are (8.460, -3.060, 10.980) and (8.460, 3.060, 10.980) in cm and the target points for the hippocampus are (-1.260, 2.340, 10.980), (-3.420, 2.340, 10.620), (-4.500, 1.620, 9.180), (-1.260, -2.340, 10.980), (-3.420, -2.340, 10.620), and (-4.500, -1.620, 9.180), also in cm. In the CAF, the target points for the lens are (7.740, -2.880, 10.080) and (7.740, 2.880, 10.080) in cm and the target points for the hippocampus are (-1.260, 2.340, 9.900), (-3.060, 2.340, 9.540), (-3.780, 1.620, 8.460), (-1.260, -2.340, 9.900), (-3.060, -2.340, 9.540), and (-3.780, -1.620, 8.460), also in cm.

The effective dose calculation is described in the Response Functions section and by Singelterry et al. [9] The OLTARIS effective dose calculation utilizes the NCRP 132 [10] tissue weighting factors. Twelve different organs or tissue types (bone surface, skin, bladder, breast, liver, esophagus, thyroid, bone marrow or BFO, colon, lung, stomach, and gonads which are ovaries for females and testes for males) are assigned individual tissue weighting factors, the sum of which is 0.95, and a list of "remainder" tissues share the remaining 0.05 weighting factor. The remainder organs are listed in NCRP-132 as: adrenals, brain, small intestine, large intestine, kidneys, muscle, pancreas, spleen, thymus, and uterus. As documented by Singleterry et al., [9] there are a few details in the effective dose calculation which are specific to the use of the CAM and CAF models. First, there are ten remainder organs for the females, but only nine for the males. For this reason, the tissue weighting factor for each of the remainder organs is 0.005 for CAF and 0.00555556 for the CAM. Second, in the CAM and CAF models, the colon, large intestine, and small intestine are treated as one organ. This organ labeled intestine is therefore assigned a tissue weighting factor equivalent to the sum of the tissue weighting factor specified for colon, 0.12, and the tissue weighting factors for two remainder organs. Thus the intestine weighting factor is 0.13 for CAF and 0.1311111 for CAM. Also, the organ averaged dose equivalent is calculated for several organs not included in the effective dose equivalent calculation. These organs are heart, hippocampus, lens, prostate, and salivary glands for the CAM model and heart, hippocampus, lens, and salivary glands for the CAF model.

16.1.2 Basic Structure (NASA-STD-7009 Req. 4.2.2)

CAM and CAF are mathematical geometric models of the human body based on second order (quadratic) surfaces. Roughly 1100 unique surfaces are used to create approximately 2450 solid objects. More detail is provided by Billings and Yucker [2] and Yucker et al. [3] [4]

The thickness distributions output from the CAMERA ray-tracer and stored on OLTARIS for each target point model the distribution of human tissue surrounding the target point (the thickness of human tissue along each ray in the distribution from the target point to the outer boundary of the body). These thicknesses are in cm and one generic human tissue definition is used to represent all of the tissues making up the body. More information about CAMERA is also provided by Billings and Yucker [2] and Yucker et al. [3] [4]

16.1.3 Data Sets and Supporting Software (NASA-STD-7009 Req. 4.2.3)

CAMERA version 1.4 requires an input file containting the ray angles for the thickness distribututions and the target point locations. The original CAMERA code was described by Billings and Yucker [2] and Yucker et al. [3] [4] The methodologies utilized to choose the target point locations were described by Slaba et al. [6] [7]

16.1.4 Units and Coordinate Frames (NASA-STD-7009 Req. 4.2.4)

For the CAM and CAF models, the origin is located at the top of the head. The positive x-axis points in the same direction as the nose, the positive y-axis is parallel to the right shoulder, and the positive z-axis points toward the feet. The coordinates for the body target point locations stored on OLTARIS are in cm. However, the scripts used to create the CAMERA input file convert these coordinates to inches. Ray angels can be input into

CAMERA in either of two formats, theta-phi or using the cosines of the angels between the ray and the x-, y-, and z-axes. For OLTARIS, the latter format is used. The thickness distributions output from CAMERA are in cm of tissue. One generic human tissue definition is used to represent all of the tissues making up the body.

16.1.5 Limits of Operation (NASA-STD-7009 Req. 4.2.5)

OLTARIS supports 12 different ray distributions. The number of rays varies from 42 to 10,000. The error associated with effective dose calculations utilizing different ray distributions will depend on vehicle geometry and whether or not the external environment is isotropic. Slaba et al. [6] [7] examined the uncertainty associate with various body target point distributions. The body target point distributions used for OLTARIS were deemed acceptable for aluminum shielding with a minimum thickness of 0.4 g/cm^2. Thinner shields were not examined.

16.1.6 Uncertainty Quantification (NASA-STD-7009 Req. 4.2.6)

Efforts made in the original development of the CAM model to ensure that it does accurately model a 50th percentile Airforce male have been described by Billings and Yucker. [2] Efforts made in the original development of the CAF model to ensure that it does accurately model a 50th percentile Airforce female have been described by Yucker et al. [3] [4]

Slaba et al. [6] [7] provided an analysis of the difference between the organ masses and volumes in the CAM and CAF and the corresponing organ masses and volumes in the ICRP reference male and female. [8] Slaba et al. also showed that the organ masses and volumes in the Male Adult voXel (MAX) phantom [11] and the Female Adult voXel (FAX) phantom [12] are very close to those of the ICRP reference male and female. Slaba et al. also compared the organ averaged dose equivalent and effective dose values for CAM and CAF to those for MAX and FAX. Since MAX and FAX so closely represent the ICRP references, this could be viewed as a measure of the error in the CAM and CAF models.

Numerical uncertainty quantification of the dose point selection process has also been performed by Slaba et al. [6] [7]

16.1.7 Proper Use (NASA-STD-7009 Req. 4.2.7)

OLTARIS users have the opportunity to choose a body model to be utilized for effective dose calculations. Proper use of the OLTARIS website is described in the user manual OLTARIS User Manual and reference guide OLTARIS Reference Guide and by Singleterry et al. [9] The codes needed to produce thickness distributions for CAM or CAF have been prerun and the thickness distributions are stored on OLTARIS.

16.1.8 Parameter Calibrations (NASA-STD-7009 Req. 4.2.8)

The sizes of the CAM and CAF models are calibrated to match 50th percentile U.S. Air Force personnel. [2] [3] [4]

16.1.9 Model Updates (NASA-STD-7009 Req. 4.2.9)

Model updates are tracked/documented in a version control repository and are then reported to the user via the OLTARIS Change Log.

16.1.10 Obsolescence Criteria (NASA-STD-7009 Req. 4.2.10)

Obsolete models are removed from OLTARIS when appropriate.

16.2 Verification, Validation, and Uncertainty Quantification

16.2.1 Verification

16.2.1.1 Techniques (NASA-STD-7009 Req. 4.4.1)

A number of steps were needed to initially incorporate CAM and CAF into OLTARIS. A new version controlled version of CAMERA, CAMERA version 1.4, was created. This version made it easier to input multiple angular distributions and large target point distrubutions. This version of CAMERA was tested by experienced and inexperienced users at NASA Langley Research Center (LaRC) and NASA Johnson Space Center (JSC), ensuring that both teams produced exactly the same shield thickness distributions when the same target point distribution was used. Organ averaged dose equivalent numbers and effective dose numbers were also compared to previously published numbers to ensure that they were in the righ "ballpark." The study performed by Slaba et al. [6] [7] provided further verification. Slaba et al. examined multiple target point location distributions and showed that if enough points were chosen and an appropriate method for distributing them was utilized, then varying the distribution would have little effect on the resulting organ averaged dose equivalent numbers. Slaba et al. also compared organ averaged dose equivalent and effective dose values calculated using the CAM and CAF human body models to corresponding values calculated using the MAX (Male Adult voXel) [11] and FAX (Female Adult voXel) [12] human body models. The fact that most of these values were similar supported the conclusion that both types of models were being utilized correctly.

Ongoing verification techniques for the use of CAM and CAF in the OLTARIS effective dose module include automated module and functional tests. The module test is used to track and maintain functionality of the effective dose module by itself. The functional tests are used to track and maintain functionality of several modules working together to perform an effective dose calculation as a function of the chose environment and shield distribution.

16.2.1.2 Error Estimates (NASA-STD-7009 Req. 4.4.2)

Slaba et al. [6] [7] provided estimates of the errors resulting from the choice of target point distribution.

16.2.1.3 Verification Status (NASA-STD-7009 Req. 4.4.3)

The OLTARIS effective dose module is regularly executed through an automated suite of module and functional tests. Slaba et al. [6] [7] have completed a study which eximines the error resulting from the use of different target point distributions and provides verification that the CAM and CAF models are being used correctly in the effective dose calculation by comparing organ averaged dose equivalent values and effective dose values calculated with these models to corresponding values calculated using other human body models.

16.2.2 Validation

16.2.2.1 Techniques (NASA-STD-7009 Req. 4.4.4)

Efforts made in the original development of the CAM model to ensure that it does accurately model a 50th percentile Airforce male have been described by Billings and Yucker. [2] Efforts made in the original development of the CAF model to ensure that it does accurately model a 50th percentile Airforce female have been described by Yucker et al. [3] [4]

Slaba et al. [6] [7] provided an analysis of the difference between the organ masses and volumes in the CAM and CAF and the corresponing organ masses and volumes in the ICRP reference male and female. [8] Slaba et al. also showed that the organ masses and volumes in the MAX and FAX are very close to those of the ICRP reference male and female. Slaba et al. also compared the organ averaged dose equivalent and effective dose values for CAM and CAF to those for MAX and FAX. Since MAX and FAX so closely represent the ICRP references, this could be viewed as a measure of the error in the CAM and CAF models.

16.2.2.2 Data (NASA-STD-7009 Req. 4.4.5)

The organ masses and volumes in the ICRP reference male and female [8] were used by Slaba et al. [6] [7] to validate the CAM and CAF model. Slaba et al. also used the organ averaged dose equivalent and effective dose numbers calculated for the MAX and FAX human body models to validate the CAM and CAF.

16.2.2.3 Studies (NASA-STD-7009 Req. 4.4.6)

Slaba et al. [6] [7] provided an analysis of the difference between the organ masses and volumes in the CAM and CAF and the corresponing organ masses and volumes in the ICRP reference male and female. [8] Slaba et al. also showed that the organ masses and volumes in the MAX and FAX are very close to those of the ICRP reference male and female. Slaba et al. also compared the organ averaged dose equivalent and effective dose values for CAM and CAF to those for MAX and FAX. Since MAX and FAX so closely represent the ICRP references, this could be viewed as a measure of the error in the CAM and CAF models.

16.2.3 Uncertainty Quantification

16.2.3.1 Process (NASA-STD-7009 Req. 4.4.7)

Slaba et al. [6] [7] provided estimates of the errors resulting from the choice of target point distribution.

Zapp et al. [13] examined the variation in organ averaged dose equivalent values for SPE environments when the body size is varied. This study found that the "dose equivalent may vary by as much as 15% if the body size is varied from the 5th percentile to the 95th percentile in the population used to derive the CAM model data."

16.2.3.2 Quantified Uncertainties (NASA-STD-7009 Req. 4.4.8)

No uncertainty analysis has been performed.

16.2.3.3 Sensitivity Analysis (NASA-STD-7009 Req. 4.4.9)

Zapp et al. [13] examined the variation in organ averaged dose equivalent values for SPE environments when the body size is varied. This study found that the "dose equivalent may vary by as much as 15% if the body size is varied from the 5th percentile to the 95th percentile in the population used to derive the CAM model data."

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17 Male and Female Adult Voxel Body Models

17.1 MAX and FAX Body Models

For whole body effective dose calculations, OLTARIS users can choose from several available human body geometry models. Two of these models are the Male Adult voXel (MAX) phantom and the Female Adult voXel (FAX) phantom. MAX and FAX are CT based models which have been adapted to accurately model the ICRP reference male and female. A fixed set of target points has been identified for each of the following organs or tissue types in the MAX and FAX models: adrenals, blood forming organs (BFO), bladder, bone, brain, breast, colon, esophagus, gonads (testes for MAX, ovaries for FAX), heart, hippocampus, kidney, lens, liver, lungs, muscle, pancreas, retina, salivary glands, skin, small intestine, spleen, stomach, thymus, thyroid, trachea, prostate (MAX only), and uterus (FAX only). Thickness distributions utilizing 42, 492, 512, 968, 1002, 4002, 9002, and 10,000 ray distributions have been precalculated and stored for each target point using a ray-tracing code that was developed at NASA LaRC specifically for this purpose. The effective dose is calculated by first calculating the organ averaged dose equivalent for each organ or tissue type and then taking a weighted average of these values, as described in the Response Functions section.

17.1.1 Assumptions and Abstractions (NASA-STD-7009 [1] Req. 4.2.1)

The assumptions and abstractions used in the MAX model have been described by Kramer et al. [2] The assumptions and abstractions used in the FAX model have been described by Kramer et al. [3] Slaba et al. [4] [5] provide a good analysis of how accurately the MAX and FAX models represent the International Commission on Radiological Protection (ICRP) reference male and female [6] in terms of organ mass and size. It should be noted that the MAX and FAX models were updated in 2006 [7] and that these updates have not yet been incorporated into OLTARIS.

No documentation has been created for the ray-tracing code utilized with MAX and FAX. The target point thickness distributions output by the ray-tracing code and stored on OLTARIS represent the thickness of human tissue along each ray in the distribution from the target point to the outer boundary of the body. These thicknesses are in cm and one generic human tissue definition is used to represent all of the tissues making up the body.

The methodologies utilized for selecting organ or tissue target point distributions adequate for calculating organ averaged dose equivalent and the associated assumptions and abstractions are described by Slaba et al. [4] [5] The coordinates of the target points for all of the target points except those in the lens, hippocampus, retina, and trachea are in Slaba et al. [4] In the MAX, the target points for the lens are (8.100, 3.780, 10.620) and (8.100, -2.340, 10.620) in cm, the target points for the hippocampus are (-2.260, 2.840, 10.480), (-4.420, 2.840, 10.120), (-5.500, 2.120, 8.680), (-2.260, -2.840, 10.480), (-4.420, -2.840, 10.120), and (-5.500, -2.120, 8.680) in cm, the target points for the retina are (6.300, 3.870, 10.890) and (6.300, -2.610, 10.530) in cm, and the target points for the trachea are (2.153, -1.130, 23.051), (2.246, -0.022, 23.170), (0.655, 0.108, 25.614), (0.644, -0.846, 25.225), (0.302, -0.464, 26.570), (0.295, -0.612, 27.774), (0.112, -0.698, 29.214), (-0.011, -0.716, 30.398), (-1.008, -0.536, 32.695), (-1.508, -0.342, 34.247), and (-1.537, -0.194, 35.734), also in cm. In FAX, the target points for the lens are (6.660, 3.060, 9.540) and (6.660, -3.060, 9.540) in cm, the target points for the hippocampus are (-2.760, 2.740, 9.900), (-4.560, 2.740, 9.540), (-5.280, 2.020, 8.460), (-2.760, -2.740, 9.900), (-4.560, -2.740, 9.540), and (-5.280, -2.020, 8.460) in cm, the target point for retina are (5.220, 2.880, 9.540) and (5.220, -2.880, 9.540) in cm, and the target points for trachea are (1.800, -0.180, 22.140), (0.900, -0.180, 23.220), (0.180, -0.180, 24.300), (-0.360, -0.180, 25.380), (-0.360, 0.000, 26.460), (-0.540, -0.180, 27.540), (-0.720, -0.180, 28.620), (-0.720, 0.000, 29.700), and (-0.720, 0.000, 30.780), also in cm.

The effective dose calculation is described in the Response Functions section and by Singelterry et al. [8] The OLTARIS effective dose calculation utilizes the NCRP 132 [9] tissue weighting factors. Twelve different organs or tissue types (bone surface, skin, bladder, breast, liver, esophagus, thyroid, bone marrow or BFO, colon, lung, stomach, and gonads which are ovaries for females and testes for males) are assigned individual tissue weighting factors, the sum of which is 0.95, and a list of "remainder" tissues share the remaining 0.05 weighting factor. The remainder organs are listed in NCRP-132 as: adrenals, brain, small intestine, large intestine, kidneys, muscle, pancreas, spleen, thymus, and uterus. As documented by Singleterry et al., [8] there are a few details in the effective dose calculation which are specific to the use of the MAX and FAX models. First, there are ten remainder organs for the females, but only nine for the males. For this reason, the tissue weighting factor for each of the remainder organs is 0.005 for FAX and 0.00555556 for the MAX. Second, in the MAX and FAX models, the colon and large intestine are treated as one organ. This organ labeled colon is therefore assigned a tissue weighting factor equivalent to the sum of the tissue weighting factor specified for colon, 0.12, and the tissue weighting factors for a remainder organs. Thus the colon weighting factor is 0.13 for FAX and 0.1311111 for FAX. Also, the organ averaged dose equivalent is calculated for several organs not included in the effective dose equivalent calculation. These organs are heart, hippocampus, lens, prostate, salivary glands, muscle, retina, and trachea for the MAX model and heart, hippocampus, lens, salivary glands, muscle, retina, and trachea for the FAX model. An additional detail specific to MAX and FAX is that some of the tissues (muscle, bone, and BFO) have been segmented according to body region to provide more detailed information. The mass averaged dose equivalent is calculated for each of these regions and a fraction of the weighting factor assigned to that tissue is assigned to each region and is used in the effective dose calculation. This segmentation and the methods for deriving weighting factors are described in greater detail by Slaba et al. [4] [5] However, it should be noted that Slaba et al. did not use the NCRP 132 weighting factors, so their weighting factors are not exactly the same as those utilized in OLTARIS. For the muscle, these regions are head and neck, left arm, lower legs, lower torso, middle torso, right arm, upper legs, and upper torso. The weighting factors for these regions are fractions of the muscle weighting factor representing the fractions of the total number of voxels in the muscle in each region. For the bone and BFO, these regions are left arm, left leg, mandible, pelvis, ribs, right arm, right leg, skull, and spine. For bone, the total bone weighting factor is divided evenly amongst the nine regions. For BFO, the total BFO weighting factor is divided according to the non-gender specific mass fraction weighting factors given in ICRP Publication 70. [10]

17.1.2 Basic Structure (NASA-STD-7009 Req. 4.2.2)

MAX and FAX are voxel models of the human body based on CT images. These phantoms have been adapted to closely model the ICRP reference male and female. [6] More detail is provided by Kramer et al. [2] and Kramer et al. [3]

The thickness distributions output from the ray-tracer and stored on OLTARIS for each target point model the distribution of human tissue surrounding the target point (the thickness of human tissue along each ray in the distribution from the target point to the outer boundary of the body). These thicknesses are in cm and one generic human tissue definition is used to represent all of the tissues making up the body.

17.1.3 Data Sets and Supporting Software (NASA-STD-7009 Req. 4.2.3)

The ray-tracing code requires an input file containting the ray angles for the thickness distribututions and the target point locations. The methodologies utilized to choose the target point locations were described by Slaba et al. [4] [5]

17.1.4 Units and Coordinate Frames (NASA-STD-7009 Req. 4.2.4)

For the MAX and FAX models, the origin is located at the top of the head. The positive x-axis points in the same direction as the nose, the positive y-axis is parallel to the right shoulder, and the positive z-axis points toward the feet. The coordinates for the body target point locations stored on OLTARIS are in cm. Ray angels can be input into the ray-tracer using the cosines of the angels between the ray and the x-, y-, and z-axes. The thickness distributions output from the ray-tracer are in cm of tissue. One generic human tissue definition is used to represent all of the tissues making up the body.

17.1.5 Limits of Operation (NASA-STD-7009 Req. 4.2.5)

OLTARIS supports 12 different ray distributions. The number of rays varies from 42 to 10,000. The error associated with effective dose calculations utilizing different ray distributions will depend on vehicle geometry and whether or not the external environment is isotropic. Slaba et al. [4] [5] examined the uncertainty associate with various body target point distributions. The body target point distributions used for OLTARIS were deemed acceptable for aluminum shielding with a minimum thickness of 0.4 g/cm^2. Thinner shields were not examined.

17.1.6 Uncertainty Quantification (NASA-STD-7009 Req. 4.2.6)

Efforts made in the original development of the MAX model to ensure that it does accurately model the ICRP reference male [6] have been described by Kramer et al. [2] Efforts made in the original development of the FAX model to ensure that it does accurately model the ICRP reference female [6] have been described by Kramer et al. [3]

Slaba et al. [4] [5] provided an analysis of the difference between the organ masses and volumes in the MAX and FAX and the corresponing organ masses and volumes in the ICRP reference male and female [6] and showed that the organ masses and volumes in the MAX and FAX are very close to those of the ICRP reference male and female.

Numerical uncertainty quantification of the dose point selection process has also been performed by Slaba et al. [4] [5]

17.1.7 Proper Use (NASA-STD-7009 Req. 4.2.7)

OLTARIS users have the opportunity to choose a body model to be utilized for effective dose calculations. Proper use of the OLTARIS website is described in the user manual OLTARIS User Manual and reference guide OLTARIS Reference Guide and by Singleterry et al. [8] The codes needed to produce thickness distributions for MAX and FAX have been prerun and the thickness distributions are stored on OLTARIS.

17.1.8 Parameter Calibrations (NASA-STD-7009 Req. 4.2.8)

Organ masses were calibrated to match the ICRP standard as described in Kramer et al. [2] [3]

17.1.9 Model Updates (NASA-STD-7009 Req. 4.2.9)

Model updates are tracked/documented in a version control repository and are then reported to the user via the OLTARIS Change Log.

It should be noted that the MAX and FAX models were updated in 2006 [7] and that these updates have not yet been incorporated into OLTARIS.

17.1.10 Obsolescence Criteria (NASA-STD-7009 Req. 4.2.10)

Obsolete models are removed from OLTARIS when appropriate.

17.2 Verification, Validation, and Uncertainty Quantification

17.2.1 Verification

17.2.1.1 Techniques (NASA-STD-7009 Req. 4.4.1)

When MAX and FAX were initially incorporated into OLTARIS, a number of steps were taken. Organ averaged dose equivalent numbers and effective dose numbers were also compared to previously published numbers for CAM and CAF to ensure that they were in the right "ballpark." The study performed by Slaba et al. [4] [5] provided further verification. Slaba et al. examined multiple target point location distributions and showed that if enough points were chosen and an appropriate method for distributing them was utilized, then varying the distribution would have little effect on the resulting organ averaged dose equivalent numbers. Slaba et al. also compared organ averaged dose equivalent and effective dose values calculated using the MAX and FAX human body models to corresponding values calculated using the CAM (Computerized Anatomical Man) and CAF (Computerized Anatomical Femal) human body models. The fact that most of these values were similar supported the conclusion that both types of models were being utilized correctly.

Ongoing verification techniques for the use of MAX and FAX in the OLTARIS effective dose module include automated module and functional tests. The module test is used to track and maintain functionality of the effective dose module by itself. The functional tests are used to track and maintain functionality of several modules working together to perform an effective dose calculation as a function of the chose environment and shield distribution.

17.2.1.2 Error Estimates (NASA-STD-7009 Req. 4.4.2)

Slaba et al. [4] [5] provided estimates of the errors resulting from the choice of target point distribution.

17.2.1.3 Verification Status (NASA-STD-7009 Req. 4.4.3)

The OLTARIS effective dose module is regularly executed through an automated suite of module and functional tests. Slaba et al. [4] [5] have completed a study which eximines the error resulting from the use of different target point distributions and provides verification that the MAX and FAX models are being used correctly in the effective dose calculation by comparing organ averaged dose equivalent values and effective dose values calculated with these models to corresponding values calculated using other human body models.

17.2.2 Validation

17.2.2.1 Techniques (NASA-STD-7009 Req. 4.4.4)

Efforts made in the original development of the MAX model to ensure that it does accurately model the ICRP reference male [6] have been described by Kramer et al. [2] Efforts made in the original development of the FAX model to ensure that it does accurately model the ICRP reference female [6] have been described by Kramer et al. [3]

Slaba et al. [4] [5] provided an analysis of the difference between the organ masses and volumes in the MAX and FAX and the corresponing organ masses and volumes in the ICRP reference male and female [6] and showed that the organ masses and volumes in the MAX and FAX are very close to those of the ICRP reference male and female.

17.2.2.2 Data (NASA-STD-7009 Req. 4.4.5)

The organ masses and volumes in the ICRP reference male and female. [6] were used by Slaba et al. [4] [5] to validate the MAX and FAX model.

17.2.2.3 Studies (NASA-STD-7009 Req. 4.4.6)

Slaba et al. [4] [5] provided an analysis of the difference between the organ masses and volumes in the MAX and FAX and the corresponing organ masses and volumes in the ICRP reference male and female [6] and showed that the organ masses and volumes in the MAX and FAX are very close to those of the ICRP reference male and female.

17.2.3 Uncertainty Quantification

17.2.3.1 Process (NASA-STD-7009 Req. 4.4.7)

Slaba et al. [4] [5] provided estimates of the errors resulting from the choice of target point distribution.

Zapp et al. [11] examined the variation in organ averaged dose equivalent values for SPE environments when the body size is varied. This study found that the "dose equivalent may vary by as much as 15% if the body size is varied from the 5th percentile to the 95th percentile in the population used to derive the CAM model data." The CAM model was used for this study, but it should provide insight into size variation in any human model.

17.2.3.2 Quantified Uncertainties (NASA-STD-7009 Req. 4.4.8)

Slaba et al. [4] [5] provided estimates of the errors resulting from the choice of target point distribution in the human phantoms.

17.2.3.3 Sensitivity Analysis (NASA-STD-7009 Req. 4.4.9)

Zapp et al. [11] examined the variation in organ averaged dose equivalent values for SPE environments when the body size is varied. This study found that the "dose equivalent may vary by as much as 15% if the body size is varied from the 5th percentile to the 95th percentile in the population used to derive the CAM model data." The CAM model was used for this study, but it should provide insight into size variation in any human model.

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18 End-to-End Model

An overview of oltaris including verification is given in Robert C. Singleterry et al. "OLTARIS: On-Line Tool for the Assessment of Radiation In Space" NASA TP under review.

End to end validation and uncertainty quantification is summarized here, https://oltaris.larc.nasa.gov/uncertainty_stmt and reference therin.