# SPACE WEATHER SUPPORT TO NASA OPERATIONS

REQUIREMENTS

STATE OF THE ART

TRENDS

NEEDS AND CONSTRAINTS

ARCHITECTURES

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**Ron Turner, ANSER**
**Chris St. Cyr, NASA**

# Overview

- This report is the first in a series designed to examine space weather support to NASA operations
- The focus is on the requirements for space weather support to NASA operations
  - Subsequent reports will look at how the requirements are met today, trends that may improve future space weather support, and architectures that may be implemented to meet future NASA space weather operational support
- The following topics are covered:
  - A definition of space weather
  - A brief summary of space weather impacts
  - Space weather requirement documents for human space flight (Shuttle, ISS, and Constellation)
  - Space weather requirements for robotic missions (design and operations)
  - Space weather requirements for Launch Support
- Backup material provides additional depth in selected areas to illustrate the requirements

# Space Weather

**For the purpose of this report, "space weather" refers to conditions of the space environment and includes short term fluctuations (meteorology) as well as long term averages and extremes (climatology)**

- **The space environment extends from the Sun through the heliosphere and includes the magnetospheres and ionospheres of planets and moons of the solar system**
- **The space environment is characterized by the magnetic fields, charged and neutral components of the solar wind, and energetic particles superimposed on the solar wind from solar and galactic sources**
- **The space environment changes over time scales ranging from seconds to millennium, but the most common time scales of interest to operations range from minutes to hours or days; for mission planning and design the relevant time scales range from days to years or decades**

# “Space Weather” vs. “Radiation”

- **There is a potential for confusion between the terms “space weather” and “radiation” in a study of operational requirements**
- **Space weather is the broader term and encompasses a wide range of phenomenology with operational impact**
- **The dominant subset of space weather impact is related to the radiation, or energetic particle, environment, including electrons, protons, neutrons, and charged ions with energies from KeV to GeV**
- **The radiation environment inside a spacecraft or habitat is modified by the surroundings (shielding, atmosphere, tissue, etc) and can be enhanced by human-induced radiation sources (power supplies, medical monitoring, invasive radioisotopic tracers)**

# Radiation Risk Mitigation is a Multidiscipline Challenge

- **Effective radiation risk mitigation requires coordinated integration of multiple skills and expertise**
  - **Fundamental biological impact**
  - **Radiation effects and analysis on electronics and components**
  - **Space environment characterization and forecast**
  - **Radiation transport**
  - **Systems design**
  - **Operations impact**

# Space Weather Impact is Felt Across NASA

- **Space weather in general and the radiation environment in particular poses a significant risk to NASA missions across all NASA directorates:**
  - **Science**
  - **Operations**
  - **Exploration**
  - **Aeronautics**

**Radiation impacts much of NASA's mission content including: objectives for Earth and space missions; electronics and materials development and their safe performance; transportation storage and handling of nuclear materials; design of space transportation, life support, and robotic systems; concepts of operations; mission designs; and nuclear power and propulsion and power systems.**

***Report of the NASA Radiation Study Team***
***May 25, 2006***

# Scope of Space Weather Impact

- **Human Space Flight**
  - Radiation exposure increases risk to long term astronaut health, some risk of acute effects
  - Radiation event can damage/disrupt critical electronics or interfere with communications
  - Response to radiation event can temporarily suspend mission operations and/or be mission limiting
- **Robotic Missions**
  - Radiation exposure limits life of some electronics and components
  - Radiation event can damage/disrupt electronics or interfere with communications
  - Response to radiation event can temporarily suspend mission operations
- **Launch Support**
  - Single-event upset risk to avionics can lead to loss of vehicle
  - Response to radiation event can delay launch
- **Aeronautics**
  - Communications interference or loss
  - Risk to avionics
  - Enhanced radiation exposure to crew of high or frequent flier

# Space Weather: "Requirements" and "requirements"

- Many space weather "Requirements" are documented through:
  - Formal NASA Policy Directives (NPD), NASA Procedural Requirements (NPR), or Standards
  - Application of mandated systems engineering processes
  - Contract documents applied to contractors
- Additional space weather "requirements" are applied informally, especially during real time mission operations
  - To meet intent of "ALARA"
  - Mission-specific experience
  - Lessons learned from related programs

# General Findings

- **Human space flight requirements for orbital missions are mature, well-documented, and effectively applied**
  - **50 years of experience, primarily in low Earth orbit**
- **Long-duration human missions to Moon and beyond are outside current experience**
  - **Apollo missions were short, risks were not well understood**
  - **Exploration missions will be characterized by durations of months to years outside the protection of a magnetosphere with a high frequency of EVAs**
- **Robotic design standards are mission unique, not uniform across NASA**
- **Robotic space weather operational support is ad hoc across agency**
- **Launch and Aeronautics space weather requirements and operational response exist but are not well documented**

# Human Space Flight
# Shuttle and ISS

# Human Space Flight Radiation Limits Key Documents

- NASA policy for establishing standards to protect the health and safety of crew, and for providing health and medical programs for crewmembers during all phases of space flight, is authorized by
  - NPD 1000.3, ***The NASA Organization***
  - NPD 8900.5A, ***NASA Health and Medical Policy for Human Space Exploration***
- Specific provision of health and medical programs for crewmembers is authorized by
  - NPR 8900.1 ***NASA Health and Medical Requirements for Human Space Exploration***
  - NPD 8900.3G, ***Astronaut Medical and Dental Observation Study and Care Program***
- Detailed radiation requirements are maintained in
  - NASA Standard 3001, ***NASA Space Flight Human System Standards, Vol 1***

# Radiation Requirements Document Map

**NASA Governance**
NPD 1000.0, NPD1000.3
**Human Rating Requirements**
NPR 8705.2B

**Engineering & Program and Project Management Directives**

**Medical Directives**
NPD 8900.5A, NPR 8900.1
NPD 8900.3G

**Safety & Mission Assurance Directives**
NPD 8700.1C, NPD 8700.3A

**Medical Standards**
NASA STD 3001 Vols I, II

**Program Documentation**

**Concept of Operations**
Shuttle/ISS

**MODD**
Flight Rules, etc

**MORD**
Shuttle: JSC 13956
ISS: SSP 50260

**NPD: NASA Policy Directive**
**NPR: NASA Procedural Requirement**
**MORD: Medical Operations Requirement Document**
**MODD: Mission Operations Directorate Documents**

# NASA Space Flight Human System Standards Vol 1: Crew Health (Nov 2006)

- NASA's policy is to establish standards for providing a healthy and safe environment for crewmembers, and to provide health and medical programs for crewmembers during all phases of space flight
- Standards are established to optimize crew health and performance thus contributing to overall mission success, and prevent negative long-term health consequences due to space flight
- In this document, the Office of the Chief Health and Medical Officer establishes NASA's space flight Crew Health standards for the preflight, in-flight, and postflight phases of human space flight
- These standards apply to all NASA human space flight programs and are not developed for any specific program
  - However, while some of the existing programs, such as the Space Shuttle and International Space Station Programs, meet the intent and purpose of these standards currently, these standards may have implications for longer duration missions and missions with architectures and objectives outside of low Earth orbit
  - While the standards are applicable to the in-flight phase of all space missions, it is anticipated that they will be most relevant during long duration lunar outpost and Mars exploration missions, since the combined ill effects of exposure to the space environment will be of most concern in those mission scenarios

# NASA Space Flight Human System Standards Vol 1: Crew Health (Continued)

## Types of Standards

- Fitness for Duty (FFD) - Minimum measurable capability or capacity for a given physiological or behavioral parameter that allows successful performance of all required duties. Functional capacity measured.
- **Space Permissible Exposure Limits (SPEL) - Quantifiable limit of exposure to a space flight factor over a given length of time (e.g., life time radiation exposure). Physical/chemical agent measured.**
- Permissible Outcome Limits (POL) - Acceptable maximum decrement or change in a physiological or behavioral parameter, during of after a space flight mission, as the result of exposure to the space environment. Biological/clinical parameter measured (e.g., bone density).

# ALARA

"Although specific exposure limits will be identified based on mortality risk, in all cases decisions concerning vehicle, habitat, and mission design will be made such that resulting crew radiation exposures are as low as reasonably achievable (ALARA). As an operating practice, ALARA is a recognized NASA requirement.

The ALARA principle is a legal requirement intended to ensure astronaut safety. An important function of ALARA is to ensure that astronauts do not approach radiation limits and that such limits are not considered as "tolerance values". ALARA is especially important for space missions in view of the large uncertainties in cancer and other risk projection models. Mission programs and terrestrial occupational procedures resulting in radiation exposures to astronauts are required to find cost-effective approaches to implement ALARA."

NASA Space Flight Human System Standard, Vol.1 Crew Health

# Space Permissible Exposure Limit for Space Flight Radiation Exposure

***Career Cancer Risk Limits***

Career exposure to radiation is limited to not exceed 3 percent REID (Risk of Exposure Induced Death) for fatal cancer. NASA assures that this risk limit is not exceeded at a 95 percent confidence level using a statistical assessment of the uncertainties in the risk projection calculations to limit the cumulative effective dose (in units of Sievert) received by an astronaut throughout his or her career.

**NASA Space Flight Human System Standard, Vol.1 Crew Health**

# Space Permissible Exposure Limit for Space Flight Radiation Exposure

## *Dose Limits for Non-Cancer Effects*

**Short-term dose limits are imposed to prevent clinically significant non-cancer health effects including performance degradation, sickness, or death in-flight.** For risks that occur above a threshold dose, a probability of $<10^{-3}$ is a practical limit if more accurate methods than dose limit values are to be implemented. Life-time limits for cataracts, heart disease, and damage to the central nervous system (CNS) are imposed to limit or prevent risks of degenerative tissue diseases (e.g., stroke, coronary heart disease, striatum aging, etc.). Career limits for the heart are intended to limit the REID for heart disease to be below approximately 3 to 5%, and are expected to be largely age and sex independent. Average life-loss from gamma-ray induced heart disease death is approximately 9-years.

**NASA Space Flight Human System Standard, Vol.1 Crew Health**

## *Career Cancer Risk Limits, Example*

**Table I**. Example career effective dose limits in units of Sievert (mSv) for 1-year missions and average Life-loss for an exposure induced death for radiation carcinogenesis (1 mSv= 0.1 rem).

| | E(mSv) for 3% REID (Ave. Life Loss per Death, yr) | |
|---|---|---|
| Age, yr | Males | Females |
| 25 | 520 (15.7) | 370 (15.9) |
| 30 | 620 (15.4) | 470 (15.7) |
| 35 | 720 (15.0) | 550 (15.3) |
| 40 | 800 (14.2) | 620 (14.7) |
| 45 | 950 (13.5) | 750 (14.0) |
| 50 | 1150 (12.5) | 920 (13.2) |
| 55 | 1470 (11.5) | 1120 (12.2) |

## *Dose Limits for Non-Cancer Effects*

**Table II.** Dose limits for Short-term or Career Non-Cancer Effects (in mGy-Eq. or mGy). Note RBE's for specific risks are distinct as described below.

| *Organ* | *30 day limit* | *1 Year Limit* | *Career* |
|---|---|---|---|
| Lens* | 1000 mGy-Eq | 2000 mGy-Eq | 4000 mGy-Eq |
| Skin | 1500 | 3000 | 4000 |
| BFO | 250 | 500 | Not applicable |
| Heart** | 250 | 500 | 1000 |
| CNS*** | 500 | 1000 | 1500 |
| CNS*** ($Z \geq 10$) | - | 100 mGy | 250 mGy |

*Lens limits are intended to prevent early (<5 yr) severe cataracts (e.g. from a solar particle event). An additional cataract risk exists at lower doses from cosmic rays for sub-clinical cataracts, which may progress to severe types after long latency (>5 yr) and are not preventable by existing mitigation measures, however are deemed an acceptable risk to the program.

**Heart doses calculated as average over heart muscle and adjacent arteries.

***CNS limits should be calculated at the hippocampus.

# International Space Station & Shuttle Avionics

| Command & Data Handling, Comm & Track, Environment & Life Support, Power, Robotics, Thermal Control | | |
|---|---|---|
| Prediction and specification of differential energy particle spectra as a function of time inside / outside Magnetosphere | ISS<br>Shuttle<br>Mars Missions | >400 equipment items susceptible to Single Event Latch-up (it is recommended these be powered down during a large proton event) Space Station needs time to prepare to shut down equipment |
| Prediction and Specification of geomagnetic field–<br><br>Geomagnetic index (Kp)<br>- onset and progression | Boeing<br>ISS Partners | Situational Awareness and anomaly assessment on ISS |
| Alerts and Warnings of 50 PFU at > 100 MeV<br>(Accuracy TBD) | Boeing<br>ISS Partners | ISS<br>Shutdown the robotic arm to prevent electronics damage. |
| Alerts and Warnings<br>100 pfu at > 100 MeV | Boeing<br>ISS Partners | Alert the flight team in Mission Control. The Flight Team will start to evaluate a plan to shutdown equipment to prevent damage to electronics. |
| Alerts and Warnings<br>200 pfu > 100 MeV | Boeing<br>ISS Partners | Implemented plan to shutdown equipment to prevent damage to electronics. |

**Human spaceflight radiation requirements extend beyond human health concerns**

# Constellation Radiation Requirements

# Constellation Architecture

- Constellation Architecture is comprised of Spacecraft, Launch Vehicles, Support Systems, and Destination systems as reflected in the Constellation Architecture Hierarchy
- The Constellation spacecraft include Orion and the Lunar Surface Access Module (LSAM)
  - Orion consists of a Crew Module (CM), a Service Module (SM), Spacecraft Adapter (SA) and a Launch Abort System (LAS)
  - The Lunar Surface Access Module (LSAM), provides the capability to insert the crew into Low Lunar Orbit (LLO), carry the crew to the lunar surface, and then return them to LLO.
  - The LSAM also has the capability to deliver significant cargo to the surface along with the crew.
  - While on the surface, the LSAM can serve as the crew's home for up to seven days.
  - In an uncrewed mode, the LSAM can be used to deliver large, monolithic cargo to the lunar surface
- Constellation Architecture destination systems include the habitats, power systems, surface mobility (i.e. rovers), payloads, robotic systems and resource utilization systems that enable the crewmembers to live, work and explore the surface of other worlds
- The Mars Transfer Vehicle (MTV) and Descent Ascent Vehicle (DAV) support the Mars missions and will be added to the Architecture in the future

# Key Documents for Radiation Requirements

- **CxP 7000** Constellation Architecture Requirements Document (CARD)
- **CxP 70007** Design Reference Missions and Operations Concept (DRM)
- **CxP 70023** Constellation Program Design Specification for Natural Environments (DSNE)
- **CxP 70024** Human Systems Integration Requirements (HSIR)
- **CxP 70044** Constellation Natural Environment Definition for Design (NEDD)
- **CxP 70036** Constellation Program Environmental Qualification and Acceptance Testing Requirements (CEQATR)

# Constellation Design Requirements

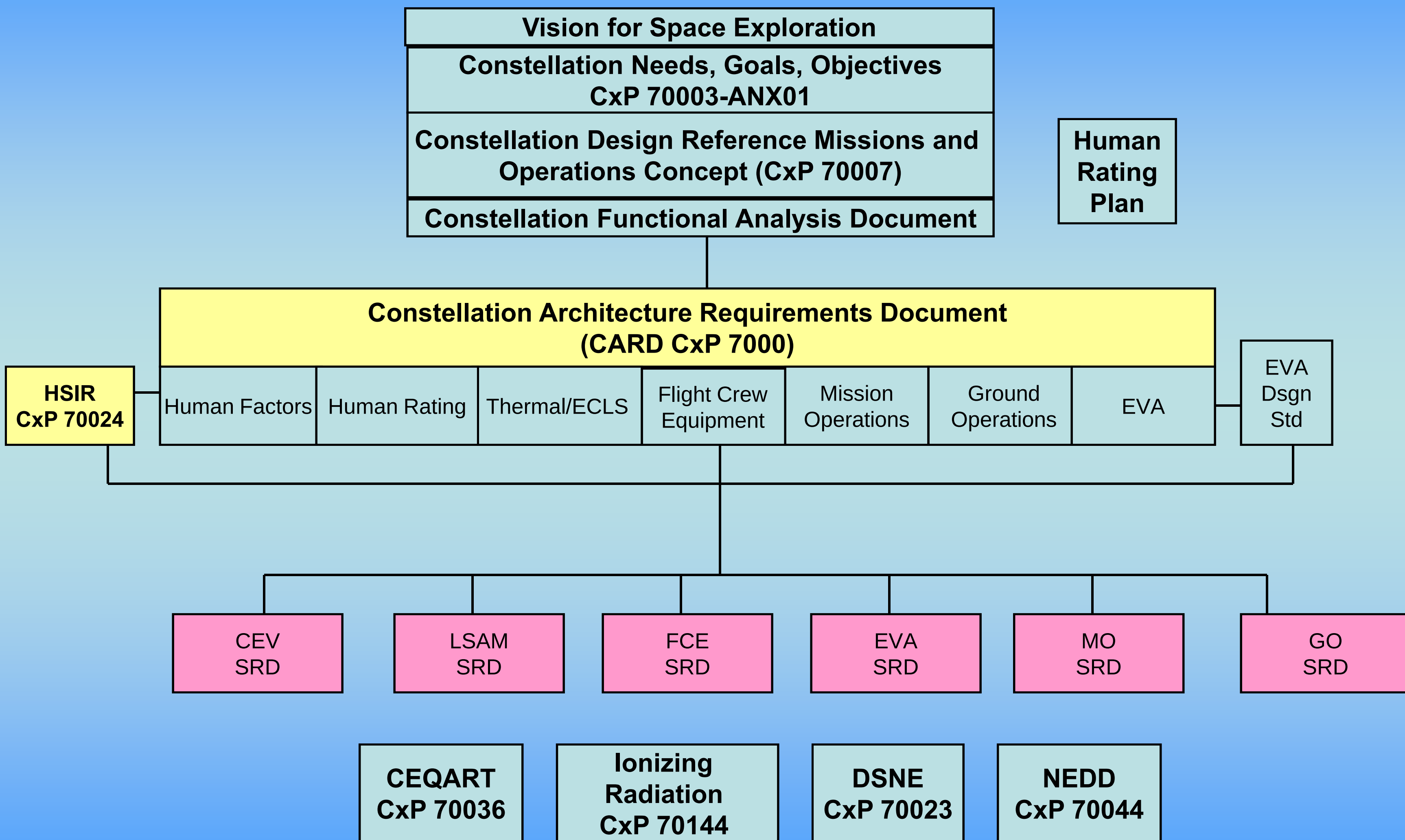



Chart designed after similar chart by Mary Van Baalen

# Constellation Architecture Requirements Document

- The Constellation Architecture Requirements Document (CARD) defines requirements controlled by the Constellation Program for the hardware, software, facilities, personnel and services needed to perform the Design Reference Missions (DRMs)
- The CARD is structured to provide top level design guidance, architecture-wide requirements, and allocations to the systems
- CARD comment on Safety and Mission Success:
  - To be sustainable, future space exploration systems, infrastructure, and missions pursued using them, must be both safe and reliable.
  - Flight crew, ground crew, public safety and mission success should be the primary design consideration.
  - Safety involves the execution of mission activities with the minimal risk of personnel injury.
  - Mission success is defined as the safe return of all crew members after completing the primary mission objectives.
  - Safety, reliability and quality will be designed-in to Constellation Program systems in order to ensure system robustness and mission success.

# CARD Section 3.1.3.6.8
# Environmental Considerations

The vehicle design should minimize environmentally induced constraints on ground and flight operations; minimize sensitivity to extreme variations in both natural and induced environmental conditions. Hardware should be able to survive long periods with no power and be able to return to operation from such a frozen state. Where practical, crewed vehicles should be equipped with space weather sensors to provide radiation event alerts. Space Radiation should be accounted for in the design only to a risk level commensurate with other sources of risk to crew safety. It is program policy that no manned vehicle will attempt landing on a destination surface until certain information essential to system design confirmation has been obtained by measurement of the inflight environment and surface environment of the destination at the proposed landing site. Such information may be obtained from robotic programs, by means of remote observations, surface tests, and meteoroid and radiation experiments, or from early flight tests conducted prior to the first human landing. Design features should ensure that opportunities for both forward and back contamination are minimized in the execution of Constellation missions. In addition to minimizing contamination risks, designs should also focus on accomplishing Constellation requirements in a way that causes the minimal change to the environment being explored. Further, impacts to terrestrial environment (including climate change) and considerations of environmental sustainability shall be incorporated in CxP design and operations

**Space Radiation should be accounted for in the design only to a risk level commensurate with other sources of risk to crew safety.**

# CARD Section 3.2.15
# Environmental Conditions

**[CA0048-PO] The Constellation Architecture shall meet its requirements during and after exposure to the environments defined in CxP 70023, Constellation Architecture Design Specification for Natural Environments (DSNE).**

***Rationale:***

**This requirement assures the Constellation Architecture will meet its requirements in any natural environment which it is likely to encounter. It also minimizes costs and causes all CxP architecture systems and elements to be designed to a consistent set of environment specifications. This assures that operating ranges can be defined and the architecture qualified for operations across those ranges.**

**CxP 70023, Design Specification for Natural Environments (DSNE) specifies the environment parameters that define these design ranges and limits.**

**Integrated vehicle configurations to be considered in the assessment of natural environment effects for the Constellation Architecture include: CEV/CLV/GS, CEV/ISS, CEV/CLV, CEV/CaLV-EDS/LSAM, CEV/LSAM, CaLV/LSAM/GS, and CaLV/LSAM.**

# Human Systems Integration Requirements

- **The HSIR provides requirements to ensure proper integration of human-to-system interfaces. These requirements apply to all Constellation systems and all mission phases, including pre-launch, ascent, Earth orbit, trans-lunar flight, lunar orbit, lunar landing, lunar ascent, Earth return, Earth entry, Earth landing, post-landing, and recovery.**
- **The Constellation Program must meet NASA's Agency-level human rating requirements, which are intended to ensure crew survival without permanent disability.**

# Human Systems Integration Requirements
# Ionizing Radiation Requirements

**3.2.7 Ionizing Radiation**
**3.2.7.1 Radiation Design Requirements**
**3.2.7.1.1 Radiation Design Requirements**
**3.2.7.2 Active Radiation Monitoring**
**3.2.7.2.1 Charged Particle Monitoring**
**3.2.7.2.2 Dose Equivalent Monitoring**
**3.2.7.2.3 Absorbed Dose Monitoring**
**3.2.7.3 Passive Radiation Monitoring**
**3.2.7.3.1 Passive Radiation Monitoring**
**3.2.7.4 Reporting of Radiation Data**
**3.2.7.4.1 Radiation Data Reporting to the Crew - Absorbed Dose**
**3.2.7.4.2 Radiation Data Reporting to the Crew - Dose Equivalent**
**3.2.7.3 Passive Radiation Monitoring**
**3.2.7.3.1 Passive Radiation Monitoring**
**3.2.7.4 Reporting of Radiation Data**
**3.2.7.4.1 Radiation Data Reporting to the Crew - Absorbed Dose**
**3.2.7.4.2 Radiation Data Reporting to the Crew - Dose Equivalent**
**3.2.7.5 Alerting for Radiation Data**
**3.2.7.5.1 Alerting for Radiation Data**

**HSIR has the most detailed “shall” list of Constellation Radiation Requirements**

**CxP 70024 Human Systems Integration Requirements (HSIR)**

# Natural Environment Definition for Design

- **NEDD provides a uniform description of the natural environment to serve as a basic framework for both the crewed and robotic missions of the Exploration Systems Mission Directorate (ESMD)**
- **It is intended to support engineering and analysis, requirements development, and verification involved in the development of exploration concepts and architectures, flight hardware, and new technologies**
  - **It does not support the operational phases of the Program since models and data with different properties are needed for those applications.**
- **By presenting a single benchmark definition of natural environment parameters it provides an easily accessible and uniform baseline for competitive studies, independent analyses, and concept studies**
- **This document is a requirement in the sense that its use is directed by the Program, but it does not contain any requirement "shall" language**
- **It provides a single description of each environment that requirements may be written against, thereby enabling clear definition of contract scope and control**
- **By providing a complete and single source for environment data, the document also reduces system development cost by providing a ready source of required technical data and minimizing the environment related efforts required of the contractor community**

**CxP 70044 Constellation Natural Environment Definition for Design (NEDD)**

# Design Specification for Natural Environments

- **The Design Specification for Natural Environments (DSNE) completes environment-related requirements from architecture, system level, and lower tier documents by specifying the ranges of environmental conditions that must be accounted for by the design of all Constellation Program (CxP) elements**
- **It exists as a separate document to assure clarity and consistency and to prevent the requirements documents from becoming cluttered with extensive amounts of technical material**
- **It is based on the Constellation Design Reference Missions and Operational Concepts Document and the models, data, and environment descriptions in the Natural Environments Definition for Design (NEDD).**

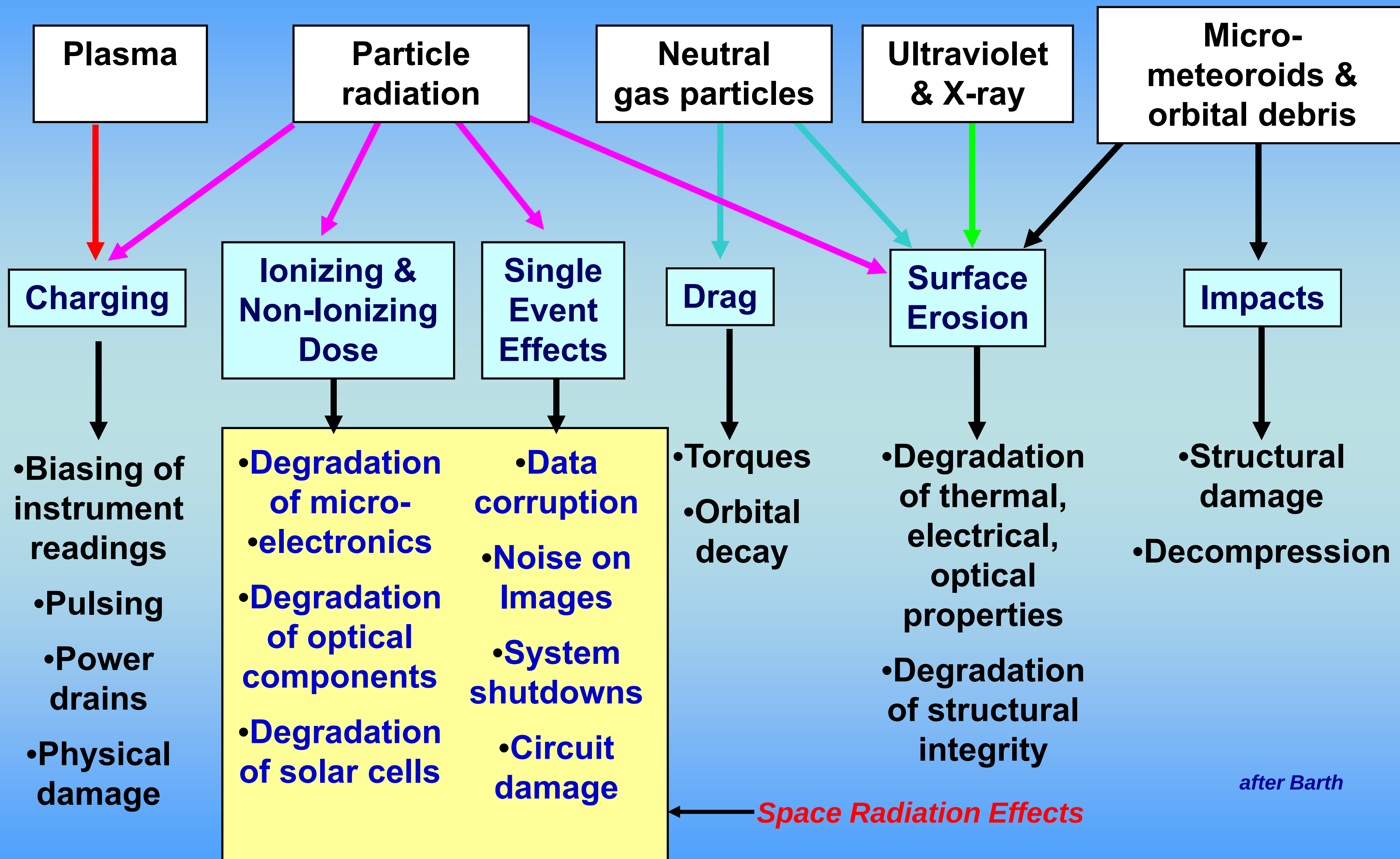
**CxP 70023 Constellation Program Design Specification for Natural Environments (DSNE)**

# Robotic Missions

# Robotic Mission Requirements

- **There are 84 operational NASA missions and 18 more in various stages of development**
- **These missions range from balloon and short-duration low-Earth investigations to long-life deep space exploration**
- **Radiation and reliability needs vary commensurately**
- **The approach for mission design, development, and deployment is guided by NASA NPR 7123.1, *Systems Engineering Processes and Requirements*, as implemented individually by center guidance and mission Principal Investigators**
- **Mission operational space weather requirements are managed individually by projects**

# Space Environments and Related Effects




From: Space Radiation Effects on Electronics: *A Primer for Designers and Managers, by Ken LaBel, NASA GSFC*

# Radiation and Systems Engineering: A Rational Approach for Space Systems

- **Define the Environment**
  - External to the spacecraft
- **Evaluate the Environment**
  - Internal to the spacecraft
- **Define the Requirements**
  - Define criticality factors
- **Evaluate Design/Components**
  - Existing data/Testing/Performance characteristics
- **"Engineer" with Designers**
  - Parts replacement/Mitigation schemes
- **Iterate Process**
  - Review parts list based on updated knowledge

From: Space Radiation Effects on Electronics: *A Primer for Designers and Managers, by Ken LaBel, NASA GSFC*

# Define the Hazard

- **The radiation environment *external* to the spacecraft**
  - **Trapped particles**
    - Protons
    - Electrons
  - **Galactic cosmic rays - GCRs (heavy ions)**
  - **Solar particles (protons and heavy ions)**
- **Based on**
  - **Time of launch and mission duration**
  - **Orbital parameters, …**
- **Provides as a minimum**
  - **GCR fluxes**
  - **Nominal and worst-case trapped particle fluxes**
  - **Peak “operate-through” fluxes (solar or trapped)**
  - **Dose-depth curve of total ionizing dose (TID)**

***Note: We are currently using static models for a dynamic environment***

**From: Space Radiation Effects on Electronics:** ***A Primer for Designers and Managers, by Ken LaBel, NASA GSFC***

# Evaluate the Hazard

- **Utilize mission-specific geometry to determine particle fluxes and Total Ionizing Dose at locations *inside* the spacecraft**
  - **3-D ray trace (geometric sectoring)**
- **Typically multiple steps**
  - **Basic geometry (empty boxes,…) or single electronics box**
  - **Detailed geometry**
    - Include printed circuit boards (PCBs), cables, integrated circuits (ICs), thermal louvers, etc…
- **Usually an iterative process**
  - **Initial spacecraft design**
  - **As spacecraft design changes**
  - **Mitigation by changing box location**

**From: Space Radiation Effects on Electronics:** ***A Primer for Designers and Managers, by Ken LaBel, NASA GSFC***

# Define Requirements

- **Environment usually based on hazard definition with "nominal shielding" or basic geometry**
  - **Using actual spacecraft geometry sometimes provides a "less harsh" radiation requirement**
- **Performance requirements for "nominal shielding" such as 70 mils of Al or actual spacecraft configuration**
  - **Total Ionizing Dose**
  - **Displacement Damage (protons, neutrons)**
  - **Single Event Effects**
    - Specification is more complex
    - Often requires SEE criticality analysis (SEECA) method be invoked
- **Must include radiation design margin (RDM)**
  - **At least a factor of 2**
  - **Often required to be higher due to device issues and environment uncertainties (enhanced low dose rate issues, for example)**

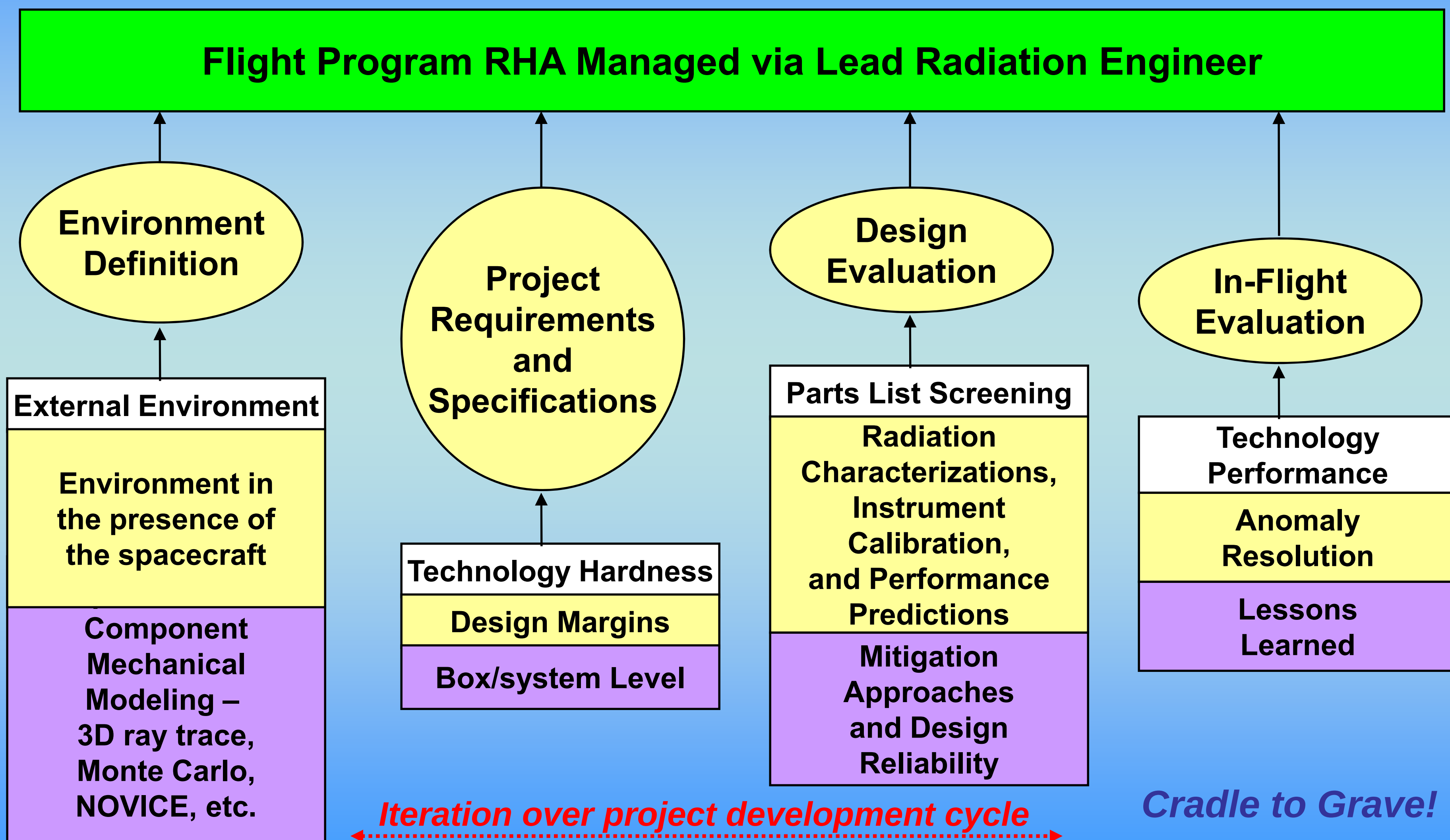
**From: Space Radiation Effects on Electronics:** ***A Primer for Designers and Managers, by Ken LaBel, NASA GSFC***

# A Systematic Approach to Flight Project Radiation Hardness Assurance (RHA)

- **Assign a lead radiation engineer to each spaceflight project**
  - **Treat radiation like other engineering disciplines**
    - Parts, thermal,...
  - **Provides a single point of contact for all radiation issues**
    - Environment, parts evaluation, testing,…
- **Each program follows a systematic approach to RHA**
  - **Develop a comprehensive RHA plan**
  - **RHA active early in program reduces cost in the long run**
    - Issues discovered late in programs can be expensive and stressful
      - What is the cost of reworking a flight board if a device has RHA issues?

**From: Space Radiation Effects on Electronics:** ***A Primer for Designers and Managers, by Ken LaBel, NASA GSFC***

# Flight Program Radiation Hardness Assurance (RHA) Flow




From: Space Radiation Effects on Electronics: *A Primer for Designers and Managers, by Ken LaBel, NASA GSFC*

# Robotic Mission Operations Support

- **NASA has an extensive fleet of robotic explorers and infrastructure**
- **The NASA fleet is widely dispersed**

| DIVISION | Number of Spacecraft Operating | Number of Spacecraft in Development |
|---|---|---|
| | | |
| Astrophysics | 11 | 6 |
| Earth | 18 | 6 |
| Earth (GOES) | 6 | ? |
| Heliophysics | 27 | 4 |
| Planetary | 14 | 2 |
| TDRSS | 7 | ? |
| ISS | 1 | --- |
| | | |
| | **84** | **18** |

**"In Development" includes missions that have been funded and are past the hurdle of Initial Confirmation Review by HQ**

| SPACECRAFT LOCATION | |
|---|---|
| | |
| LEO equatorial | 13 |
| LEO polar or sun-synch | 18 |
| MEO | 9 |
| HEO | 6 |
| GEO | 14 |
| L1 or L2 | 4 |
| Heliocentric $\leq$1 AU | 3 |
| Heliocentric >1 AU | 10 |
| Mars landers/orbiters | 6 |
| Saturn orbiter | 1 |
| | |
| | 84 |

# Robotic Mission Operations Support

- **The Mission Operations Control Centers are also widely dispersed**

| MOCC LOCATION | |
|---|---|
| APL | 5 |
| ESOC | 9 |
| GSFC | 15 |
| JAXA | 4 |
| JPL | 15 |
| JSC (ISS and STS) | 1 |
| LASP | 3 |
| NOAA (GOES) | 7 |
| UCB | 7 |
| USAF | 2 |
| WSC (TDRSS) | 7 |
| Other | 9 |
| | |
| | 84 |

# Radiation Standards for Robotic Space Mission Design/Development (1/2) (From PA&E report)

- Materials radiation testing standards do not exist for material properties at a NASA Agency level. Individual NASA Centers (as well as the Aerospace Corporation and the U.S. Air Force) have test programs, each with its own ISO-9001-like procedures and protocols, but there is no set of NASA standards for radiation testing of materials.
- The coordinating office for radiation testing of materials at NASA was formerly the Space Environment Effects Program at MSFC. However, it has no FY 2006 or ongoing funding. Individual flight programs have very limited materials radiation testing budgets, and the testing being done is highly directed toward individual components, such as cables and multi-layer insulation.
- In addition, there is little or no coordination or communication between the individual radiation testing efforts, so it is difficult or impossible for lessons-learned by one program to be shared Agencywide. Although there exist compilations of the effects of radiation on various space materials properties, there is no one coordinating office for space radiation damage for all NASA Centers.

# Radiation Standards for Robotic Space Mission Design/Development (2/2) (From PA&E report)

*Radiation Hardness Assurance Standards*

- **Standards for radiation hardness of space systems are not adequate. There are multiple standards for testing of electronics and for material properties, but no single standard or group of standards encompasses all issues and many of them are outdated. New standards are needed in some areas (e.g., electrostatic discharge or microprocessor testing) while updates are needed in others (e.g., radiation-induced conductivity of materials or lifetime exposure degradation of electronics). Data for many modern materials and circuits that take into account new mission scenarios are either inadequate or do not exist.**

*Spacecraft Charging Standards*

- **Spacecraft charging guidelines are not consistent with modern electronics. Guidelines associated with issues such as surface/volume resistivity, buried charge, breakdown strength, triboelectric charging, and photoemission are either not current or do not exist.**

# Launch Operations Requirements

- **Launch teams are concerned with the possibility of a proton event causing single-event upsets within the guidance computer**
- **Requirement and specific criteria are established by launch system provider, not NASA**
  - **It applies to west coast polar and high inclination launches**
  - **The launch contractor will monitor the proton flux on the NOAA/GOES website and will hold the launch if the protons flux exceeds threshold**
  - **NASA monitors for insight role**

**Kodiak Star launch was delayed a week due to solar event in Sept 2001**


***Launch commit criteria for Atlas 5***

**Winds:**

- **Maximum allowable launch wind is 30 knots**
- **If winds are from 060-110 degrees or 230 - 340 degrees, then the wind limit is 23 knots**

**Temperature:**

- **Ambient air temperature cannot be cooler than 40 degrees F**

**Solar Radiation:**

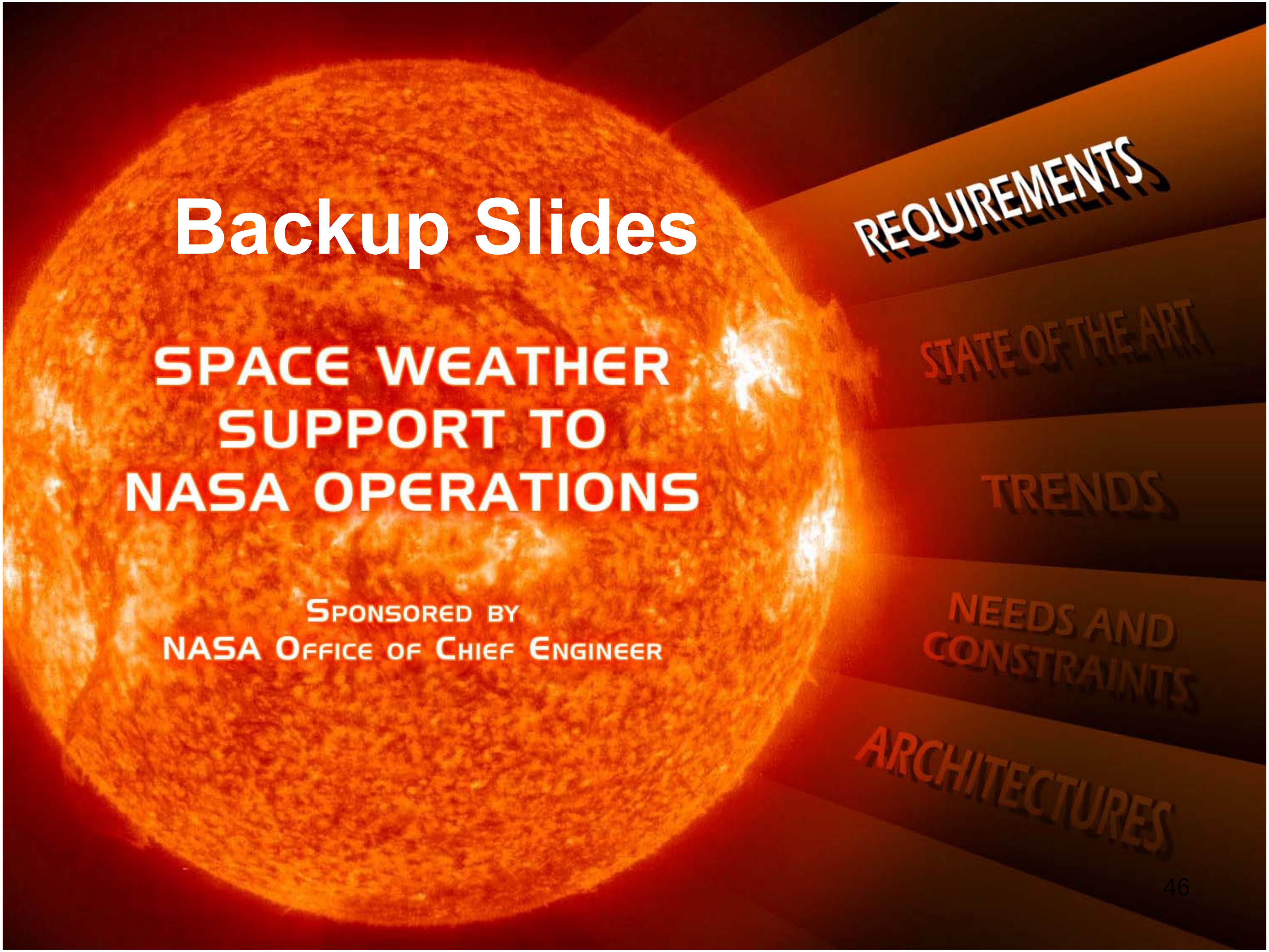
- **50 MeV Proton Flux not greater than 100 pfu**

***"Distribution of SWPC data and products to NASA"***
**Briefing from NOAA SWPC to OCE, June 4, 2008**

# Aeronautics Requirements

- **Space Weather can affect aviation through**
  - **Communications interference or loss**
  - **Risk to avionics**
  - **Crew/passenger radiation exposure**
- **There were no identified NASA Aeronautics requirements as of yet**

# Backup Slides



# NASA Human Health Documents

# NPD 8900.5A *NASA Health and Medical Policy for Human Space Exploration*

**Responsible Office: Office of the Chief Health & Medical Officer**

**It is NASA's policy to:**

**a. Provide a healthy and safe environment for crewmembers to enable successful human space exploration.**

**b. Provide health and medical care systems for crewmembers for all mission phases--prior, during, and after space flights.**

**c. Update crewmember health and medical services based on best supporting evidence and current standards of medical practice, lessons learned, risk management, and expert recommendations.**

**d. Design initial and recurrent medical training for crewmembers, consistent with mission requirements, and commensurate with available resources and priorities.**

**e. Establish space flight health and medical standards that address:**

**(1) Health and medical screening, evaluation, and certification (including medical selection and retention standards).**

**(2) Health and medical diagnosis, intervention, and care (including management and training).**

**(3) Health maintenance, preventive programs, and countermeasures (including permissible exposure limits, permissible outcome limits, and fitness for duty standards).**

**(4) Habitability and environmental health guidelines and standards, as appropriate.**

**f. Sponsor health and clinical research to enable human space exploration.**

**Note: Health is defined as encompassing physiological, psychological, and dental well-being. Medical refers to the treatment of illness and injury.**

**Note: These habitability and environmental health standards are documented in NASA-STD-3000, Man-Systems Integration Standards, which establishes design standards for all space facilities and related equipment that directly interface with crewmembers.**

# NPR 8900.1 *NASA Health and Medical Requirements for Human Space Exploration*

## *Appendix C:* Process for Establishing Health and Medical Standards

Health and medical standards are initiated by the NASA CHMO and are developed under the supervision of the delegated HMTA with participation of other Centers and external experts, as appropriate. Final approval is executed by the NASA CHMO. Health and medical standards are established by the OCHMO per the following process:

a. A recommendation for development of a new standard or revision of an existing standard may originate anywhere in the Agency, such as in the OCHMO, the SOMD, the ESMD, the AMB, or the Space Life Sciences Directorate (SLSD) at JSC, and is forwarded to the NASA CHMO for consideration.

b. The NASA CHMO reviews the recommendations, and if warranted, initiates development or revision of a standard and establishes a standards development team under the supervision of the delegated HMTA. Note: The standards development team includes internal NASA experts and may include external discipline experts, as appropriate.

c. The standards development team drafts the standard which is reviewed according to the process established by the delegated HMTA with the concurrence of the NASA CHMO.

d. The delegated HMTA then reviews the draft standard and provides a recommendation for approval of the new or revised standard to the NASA CHMO.

e. The NASA CHMO determines whether or not independent technical review of the draft standard is required by an external team and convenes a team to conduct the review, where appropriate.

f. The draft/revised standards are distributed to affected and interested parties (e.g., Flight Crew Operations Directorate/Astronaut Office, mission directorates, functional staff offices, Centers, etc.) for review and comment.

g. The draft/revised standards are presented to the NASA MPB, which provides a recommendation for approval to the NASA CHMO.

h. The NASA CHMO considers comments and recommendations, and either rejects, recommends further modifications, or executes final approval of the standard.

i. Implementation of the standards is overseen by the delegated HMTA.

j. Periodic review of the standards occurs every five years, or at more frequent intervals if new data or clinical observations indicate that a standard or standards need to be updated.

# NASA STS and ISS Documents

# STS MORD Radiation Safety (1/2)

## 4.5 Radiation Safety

**Data to support monitoring shall be provided by other government agencies including National Oceanic and Atmospheric Administration (NOAA) and DOD. The SRAG shall negotiate and coordinate support from required agencies for environmental monitoring. The Radiation Health Officer (RHO) provides the overall safety evaluation of crew radiation risks to the FS.**

### 4.5.1 *Preflight*

**The SRAG monitors and evaluates the space environment for conditions that could lead to excessive crew radiation exposure. The RHO determines acute and late- radiation effects probabilities for individual crew members, and maintains the crew exposure data base.**

**The SRAG shall provide an operational dosimetry system to monitor individual crewmember exposures in accordance with federal regulations, and to monitor the radiation environment to assist with operational decision-making.**

**One Crew Passive Dosimeter (CPD) shall be assigned and provided to each crewmember who shall be required to wear the CPD through all phases of the mission, including EVAs.**

**Six Passive Radiation Dosimeters (PRDs) shall be provided for each flight and shall be deployed before launch at fixed locations inside the crew compartment.**

**The Area Passive Dosimeter (APD) and pocket ion chambers shall be supplied in a pouch and stored in a middeck locker with the SOMS Kits. The dosimetry pouch shall be readily available to the crew to support radiation monitoring.**

**The Tissue Equivalent Proportional Counter (TEPC) shall be supplied for high-altitude (greater than or equal to 205 nautical miles) and/or high-inclination flights (greater than or equal to 50 degrees) and hard-mounted in the middeck. The TEPC is nominally activated early on Flight Day (FD) 1, and is deactivated as close to, or during, deorbit prep, as possible. Daily status checks are to be performed and noted.**

**The SRAG shall analyze the safety and projected exposure from all manifested radioisotopes or radiation producing equipment to ensure compliance with radiation exposure guidelines of 10 CFR 20.**

**The SRAG shall maintain the necessary workstations, software, and other equipment to acquire, display, and interpret space environment data or other radiation hazards.**

# STS MORD—Radiation Safety (2/2)

*4.5.2 Crew Exposure Limits*

At L-6 months, the Radiation Health Officer (RHO) shall update each flight crewmember's organ specific cumulative doses and ion specific fluences, organ specific projections of lifetime excess cancer incidence and mortality, and projected probabilities for deterministic effects from occupational radiation exposures. These projections shall be recorded in the medical record by the CS/DCS.

When required, the Radiation Constraints Panel Radioactive Payload Working Group shall assess the experiment protocols using radioisotopes, and shall support crew training in radioisotope handling protocols. The projected exposures and isotope assessments shall be reported to flight management via the SLSD Flight Readiness Review (FRR).

The SRAG shall determine and distribute the criteria for which a recall to MCC will be initiated by personnel in the Biomed MPSR.

At L-10 days, the crew shall be informed of all projected exposures and current and projected space weather conditions.

4.5.3 In-flight Monitoring

The SRAG shall monitor and evaluate the space environment for conditions that can lead to excessive crew radiation exposure.

The SRAG shall provide immediate notification to the FCR Surgeon and RHO of conditions that have the potential to increase crew exposure above nominal levels, and will provide recommendations to manage the crew's exposure in accordance with federal regulations, including the ALARA concept. The SRAG shall provide daily updates of crew exposure status, along with current and forecasted space weather conditions, to the FD through the FCR Surgeon.

The RHO will be on-call to the FCR Surgeon during missions and advise the CS on possible health risks from enhanced exposures above nominal levels.

Space environmental monitoring shall be performed from L-3 days through EOM. During the launch phase, support shall be provided through the beginning of on-orbit operations. During nominal space environment activity, the SRAG shall provide on-console support for 4 hours per day and be available for immediate return to the MCC during other periods. The SRAG shall provide continuous on-console support during all EVAs and during periods of increased space radiation.

*4.5.4 Postflight*

All operational dosimeters shall be retrieved by landing site personnel and returned to JSC in accordance with JSC 17768, Landing Site Disposition Document.

The SRAG shall analyze the dosimeters and provide a dosimetry report to the RHO. All dosimetry data from the mission shall be provided to the RHO by R+30. Results from individual crewmember's CPDs shall be protected under the Privacy Act of 1974; distribution of this information shall be limited to the RHO, CS, the medical records system, and those individuals required to evaluate crew exposures. At R+90, the RHO shall provide a post-mission report of organ specific cumulative doses and ion specific fluences, organ specific projections of lifetime excess cancer incidence and mortality, and projected probabilities for deterministic effects from occupational radiation exposures resulting from the mission.

# ISS MORD—Radiation Safety (1/2)

- This section establishes the medical support requirements for ionizing radiation exposure, including common dose limits, radiation monitoring, record-keeping, and management of radiation exposure through "As Low As Reasonably Achievable" (ALARA) practices through all mission phases. Radiation exposure is limited to prevent short-term effects and to reduce the probability of long-term effects. ALARA practices are mandated or encouraged by the radiation protection authorities of the IPs in order to minimize health risks due to justifiable radiation exposures.
- The dynamic, complex, and unique nature of the radiation environment in low Earth orbit is such that radiation health and protection requirements rely upon analytical modeling and continuous measurements of the on-board environment, as well as personal dosimetry that includes analytical assessments of passive dosimeters worn at all times by each crewmember. During the mission, the ionizing radiation environment is monitored to provide sufficiently comprehensive and timely data to:
  - Maintain crew doses below legal limits and to practice ALARA actions to avoid unnecessary levels of exposure.
  - Collect and record information to assess crewmembers' critical organ and tissue doses for an individual mission and cumulative career records.
  - Initiate immediate countermeasures for transient radiation exposure events, e.g., during EVA, solar particle events, or electron belt enhancements.

# ISS MORD—Radiation Safety (2/2)

# NASA Constellation Documents

# Human Systems Integration Requirement Examples[1]
# 1) SPE Design Limits

**SPE exposure limits**

- **The system shall provide protection from radiation exposure consistent with ALARA principles to ensure that effective dose (tissue averaged) to any crew member does not exceed the relevant value, given in Table 3.2.7.1.1-1, System Specific Radiation Design Requirements, for the design SPE, as specified in (DSNE), Section 3.3.4.**

| System | Radiation Design Requirement |
|---|---|
| Orion | 150 mSv |
| Lander | TBD-007-001 |

**TABLE 3.2.7.1.1-1 SYSTEM SPECIFIC RADIATION DESIGN REQUIREMENTS**

**[1]Examples are for illustration, not for completeness**

# Human Systems Integration Requirement Examples[1]
# 2) Charged Particle Monitoring

**The system shall continuously measure and record the external fluence of particles of $Z<3$, in the energy range 30 to 300 MeV/nucleon and particles of $3 \leq Z \leq 26$, in the energy range 100 to 400 MeV/nucleon and integral fluence measurement at higher energies, as a function of energy and time, from a monitoring location that ensures an unobstructed free space full-angle field of view 1.1345 Radians (65 degrees) (TBR-006-023) or greater.**

**[1]Examples are for illustration, not for completeness**

# Human Systems Integration Requirement Examples[1]
# 3) Data Reporting and Alerting

- The system shall display the measured cumulative absorbed dose/minute averaged dose rate to the crew once per minute, with latency less than five minutes
- The system shall display the measured cumulative dose equivalent/minute averaged dose equivalent rate to the crew once per minute, with latency less than five minutes
- The system shall alert the crew, whenever the absorbed dose rate exceeds a pre-flight programmable threshold in the range 0.02 mGy/min to10 mGy/min for 3 consecutive readings.

[1]Examples are for illustration, not for completeness

# NASA Robotic Design Example
# Single Event Effects

# Sample Single Event Effects Specification (1 of 3)

1. Definitions and Terms

***Single Event Effect (SEE)*** **- any measurable effect to a circuit due to an ion strike. This includes (but is not limited to) SEUs, SHEs, SELs, SEBs, SEGRs, and Single Event Dielectric Rupture (SEDR).**

***Single Event Upset (SEU)*** **- a change of state or transient induced by an energetic particle such as a cosmic ray or proton in a device. This may occur in digital, analog, and optical components or may have effects in surrounding interface circuitry (a subset known as Single Event Transients (SETs)). These are "soft" errors in that a reset or rewriting of the device causes normal device behavior thereafter.**

***Single Hard Error (SHE)*** **- an SEU which causes a permanent change to the operation of a device. An example is a stuck bit in a memory device.**

***Single Event Latchup (SEL)*** **- a condition which causes loss of device functionality due to a single event induced high current state. An SEL may or may not cause permanent device damage, but requires power strobing of the device to resume normal device operations.**

***Single Event Burnout (SEB)*** **- a condition which can cause device destruction due to a high current state in a power transistor.**

***Single Event Gate Rupture (SEGR)*** **- a single ion induced condition in power MOSFETs which may result in the formation of a conducting path in the gate oxide.**

***Multiple Bit Upset (MBU)*** **- an event induced by a single energetic particle such as a cosmic ray or proton that causes multiple upsets or transients during its path through a device or system.**

***Linear Energy Transfer (LET)*** **- a measure of the energy deposited per unit length as a energetic particle travels through a material. The common LET unit is MeV*cm$^2$/mg of material (Si for MOS devices, etc.).**

***Onset Threshold LET ($LET_{th0}$)*** **- the minimum LET to cause an effect at a particle fluence of 1E7 ions/cm$^2$(per JEDEC). Typically, a particle fluence of 1E5 ions/cm$^2$ is used for SEB and SEGR testing.**



From: Space Radiation Effects on Electronics: *A Primer for Designers and Managers, by Ken LaBel, NASA GSFC*

# Single Event Effects Specification (2 of 3)

2. Component SEU Specification

2.1 No SEE may cause permanent damage to a system or subsystem.

2.2 Electronic components shall be designed to be immune to SEE induced performance anomalies, or outages which require ground intervention to correct. Electronic component reliability shall be met in the SEU environment.

2.3 If a device is not immune to SEUs, analysis for SEU rates and effects must take place based on $LET_{th}$ of the candidate devices as follows:

| Device Threshold | Environment to be Assessed |
|---|---|
| $LET_{th}$ < 15* MeV*cm$^2$/mg | Cosmic Ray, Trapped Protons, Solar Proton Events |
| $LET_{th}$ = 15*-100 MeV*cm$^2$/mg | Galactic Cosmic Ray Heavy Ions, Solar Heavy Ions |
| $LET_{th}$ > 100 MeV*cm$^2$/mg | No analysis required |

2.4 The cosmic ray induced LET spectrum which shall be used for analysis is given in Figure TBD.

2.5 The trapped proton environment to be used for analysis is given in Figures TBD. Both nominal and peak particle flux rates must be analyzed.

2.6 The solar event environment to be used for analysis is given in Figure TBD.

2.7 For any device that is not immune to SEL or other potentially destructive conditions, protective circuitry must be added to eliminate the possibility of damage and verified by analysis or test.



From: Space Radiation Effects on Electronics: *A Primer for Designers and Managers, by Ken LaBel, NASA GSFC*

# Single Event Effects Specification (3 of 3)

**2. Component SEU Specification (Cont.)**

**2.8 For SEU, the *criticality* of a device in it's specific application must be defined into one of three categories: error-critical, error-functional, or error-vulnerable. Please refer to the /radhome/papers/seecai.htm Single Event Effect Criticality Analysis (SEECA) document for details. A SEECA analysis should be performed at the system level.**

**2.9 The improper operation caused by an SEU shall be reduced to acceptable levels. Systems engineering analysis of circuit design, operating modes, duty cycle, device criticality etc. shall be used to determine acceptable levels for that device. Means of gaining acceptable levels include part selection, error detection and correction schemes, redundancy and voting methods, error tolerant coding, or acceptance of errors in non-critical areas.**

**2.10 A design's resistance to SEE for the specified radiation environment must be demonstrated.**

**3. SEU Guidelines**

**Wherever practical, procure SEE immune devices. SEE immune is defined as a device having an $LET_{th} > 100$ MeV*cm$^2$/mg.**

**If device test data does not exist, ground testing is required. For commercial components, testing is recommended on the flight procurement lot.**



**From: Space Radiation Effects on Electronics:** ***A Primer for Designers and Managers, by Ken LaBel, NASA GSFC***