Human Rating Requirements for Mars Missions

For Presentation to the Mars Society
August 4th, 2012

Gary V. Stephenson

Linquest Corporation, Los Angeles, CA
425-443-8651, gary.stephenson@linquest.com

Abstract. Human rating requirements are explored for space systems associated with the transport of a human crew for missions to and from Mars. Human rating certification requirements guidance is given by NPR 8705.2B and broadly speaking consists of three parts: part 1, comply with human rating certification processes; part 2, comply with human rating technical requirements; and part 3, prepare and maintain a Human Rating Certification Package (HRCP) that demonstrates compliance with the first two parts.

The design challenges specific to a Missions to Mars (M2M) are described and include long endurance human habitation during interplanetary (IP) space travel, with higher than usual radiation exposure and lower than usual gravitation exposure, crew control requirements with expanded need for autonomous operations and control and operator situational awareness, and contingency operations for survivability. Due to the extreme physical isolation of the crew during missions to Mars there will be the need to trade lifeboat options with in situ survivability options in the case of contingency operations.

These human rating challenges are placed in the context of the design development of mission equipment needed for a Mission to Mars. It is assumed that the M2M equipment suite can be divided into four distinct systems, all of which will require human rating: a launch and LEO operations vehicle, a transhab vehicle for IP travel, a Martian orbital operations vehicle, and a Martian surface habitat. A methodology for flowing human rating requirements to each of these systems is identified and outlined.

Keywords: Human, Rating, Requirements, Certification, NASA, Standards.

PACS: 96.30.Gc, 96.30.Hf, 96.55.+z, 91.62.Fc

Introduction

NASA's NPR8705.2B [1] defines a human-rated system as one that "accommodates human needs, effectively utilizes human capabilities, controls hazards with sufficient certainty to be considered safe for human operations, and provides, to the maximum extent practical, the capability to safely recover the crew from hazardous situations."

Human-rating consists of three fundamental tenets:

(A) The process of assuring that the total system can safely conduct human missions
(B) Design that accommodates human interaction with the system to enhance overall safety and mission success
(C) Incorporation of design that enables a safe recovery of the crew from hazardous situations

Accordingly a summary of human rating certification requirements guidance is given by NPR 8705.2B and is summarized for the purposes of this paper in 4 steps:

Step 1. Comply with human-rating certification requirements
Step 2.Develop a reference mission envelope and comply with ensuing reference mission requirements envelope.
Step 3. Comply with technical requirements for human-rating
Step 4. Prepare and maintain a Human-Rating Certification Package (HRCP)

Overall approach in this paper is therefore follows this four step process:

- The NASA approach to human rating for the Constellation Program
    - How the NASA approach can be adapted to commercial Missions to Mars
- The first step to human rating:
    - Flowing the HSIR guidance into the mission equipment requirements set
- The second step to human rating:
    - Applying the design guidance of NASA's NPR 8705 002B and NASA Std 3000 into the mission equipment design
- The third step to human rating:
    - Collecting all the inputs for the Human Rating Certification Package (HRCP)
- Remaining key trades and design decisions needed to enable human rating for Missions to Mars

A summary of human rating certification requirements is presented in the format of these four steps, and future considerations and recommendations for applying these four steps are also briefly discussed.

Step 1. Comply with human-rating certification requirements

([1], 2.1.1) The Human-Rating Certification requirements are designed to lead the Program Manager through the certification process and define the contents of the HRCP. The certification requirements are divided into five categories:

a. Process and Standards ([1], 2.2)
b. Designing the System ([1], 2.3)
c. Validating the System Capabilities and Performance ([1], 2.4)
d. Flight Testing the System ([1], 2.5)
e. Certifying and Operating the Human-Rated System ([1], 2.6)

Step 1a. Process and Standards ([1], 2.2)

Requirements in this category are as follows:

From [1], 2.2.1: "HRCP. The Program Manager shall develop and maintain an HRCP for crewed space systems that require NASA Human-Rating Certification (Requirement 58373)."

From [1], 2.2.2: "Human-Rating Waivers and Exceptions. The Program Manager shall summarize, in the HRCP, all requests for waivers and exceptions to the certification and technical requirements in this NPR and provide access to the program documentation that contains the waivers and exceptions (Requirement 58376)."

From [1], 2.2.3: "Safety Analysis Processes. Prior to SRR, the Program Manager shall document, implement, and maintain (for the life of the program) a process for identifying hazards, understanding risk implications of the hazards, modeling hazard scenarios, quantifying and ranking risks to crew safety, and mitigating risks or deficiencies as appropriate (Requirement 58378)."

From [1], 2.2.4: "Safety and Mission Assurance Program. Safety and Mission Assurance Program. Prior to SRR, the Program Manager shall summarize, in the HRCP, the safety and mission assurance program established in accordance with paragraph 1.5.2 of NPR 8715.3, NASA General Safety Program Requirements. (This is updated at SDR, PDR, CDR, ORR.) (Requirement 58380)."

From [1], 2.2.5: Applicable Standards. The Program Manager shall comply with the following standards:
a. NASA-Standard-3001 Volume 1, Space Flight Human System Standard: Crew Health.
b. NASA-Standard-3001 Volume 2, Space Flight Human-System Standard: Human Factors,
c. FAA HFDS - Human Factors Design Standard.
d. MIL-STD-1472, Department of Defense Design Criteria Standard - Human Engineering (Requirement 58389).

The historical precedence for applying human rating requirements and standards to crew exploration vehicles – the Constellation Program as shown in figure 1:

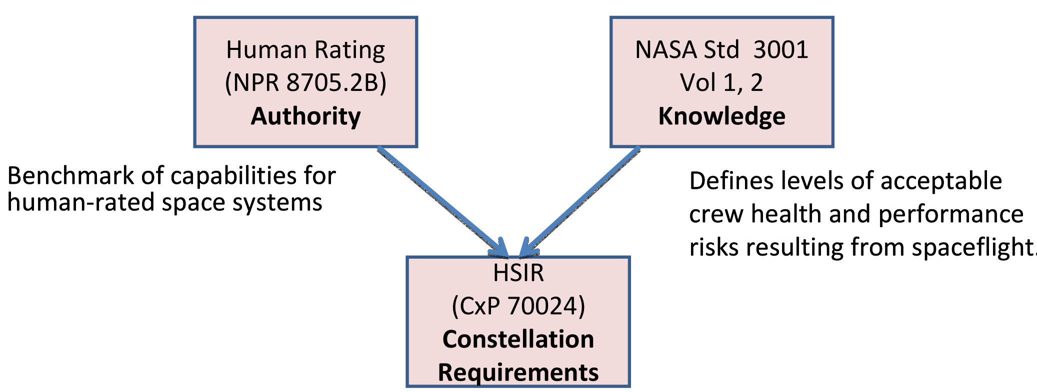

Figure 1, Relationship of NASA Standards to the Constellation Program HSIR

From [1], 2.2.6: Other Standards Mandated by the Technical Authorities. At SRR, the Program Manager shall document, in the HRCP, the list of additional program-level standards mandated by the Technical Authorities as relevant to human-rating, per paragraph 1.4 of this NPR (Requirement 58390).

From [1], 2.2.7: Summarizing Exceptions, Adjustments, and Waivers to Applicable Standards. At SRR, the Program Manager shall summarize, in the HRCP, the exceptions, adjustments, and waivers to the applicable standards listed in paragraph 2.2.5 and provide access to the program documentation that contains the exceptions, adjustments, and waivers. (This is updated at SDR, PDR, CDR, and ORR.) (Requirement 58392).

From [1], 2.2.8: Summarizing Waivers and Exceptions to other Standards Mandated by the Technical Authorities. At SRR, the Program Manager shall summarize, in the HRCP, the waivers and exceptions to the standards from the requirement in paragraph 2.2.6 that are significant to human-rating and provide access to the program documentation that contains the waivers and exceptions. (This is updated at SDR, PDR, CDR, and ORR.) (Requirement 58394).

Human-Systems Integration Requirements – HSIR (CxP 70024 Rev C) [5]

- Defines parameters of a habitable environment, capabilities and limitations of the flight and ground crew that drive the design of the CxP Architecture systems to achieve mission objectives
- Provides the parameters that protect the health and safety of the crew and allows them to perform their functions in an efficient and effective manner
- Focuses on proper integration of human-to-system interfaces for all mission phases through applicable requirements.

Step 1b. Process Requirements for Designing the System ([1], 2.3)

Requirements in this step focus on process guidance for design of the system:

From [1], 2.3.1: "Reference Missions. At SRR, the Program Manager shall document, in the HRCP, a description of the crewed space system, its functional interfaces to other systems, and the reference missions [or range of missions, i.e. mission envelope] that will be certified for human-rating (Requirement 58397)."

In a similar manner to the Constellation Program mission objectives and requirements are injected into the process of developing M2M mission equipment requirements in the form of Human System Interface Requirements, for each mission element, as depicted in figure 2.

This leverages a proven Human-Systems Integration Requirements development process, the same methodology as used for the development of the Constellation HSIR (CxP 70024 Rev C, Ref [5].) Because of the scope of this process it is expanded as a major step in it's own right for the purposes of this paper. It therefore appears Mission to Mars (M2M) Unique requirements applied to applicable mission equipment.

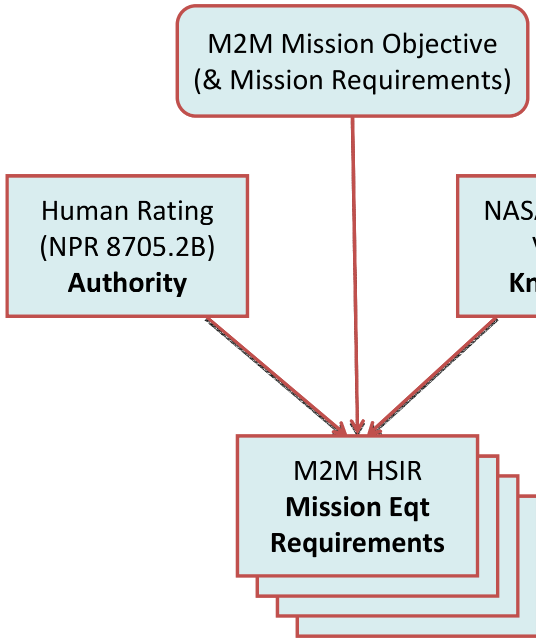

Figure 2, Relationship of NASA Standards to the Constellation Program HSIR

From [1], 2.3.2: "Identifying System Capabilities for Crew Survival. At SDR, the Program Manager shall document, in the HRCP, a description of the crew survival strategy for all phases of the reference missions and the system capabilities required to execute the strategy. (This is updated at PDR, CDR, and ORR.) (Requirement 58399)."

From [1], 2.3.3: "Documenting the Design Philosophy for Utilization of the Crew. At SRR, the Program Manager shall document, in the HRCP, a description of the design philosophy which will be followed to develop a system that utilizes the crew's capabilities to execute the reference missions, prevent aborts, and prevent catastrophic events (Requirement 58401)."

From [1], 2.3.4: "Incorporating Capabilities into the System Design. At SDR, the Program Manager shall document, in the HRCP, a description of the implementation of the survival capabilities identified in the requirement in paragraph 2.3.2 and provide clear traceability to the highest level program documentation. (This is updated and reviewed at PDR and CDR.) (Requirement 58403)."

From [1], 2.3.5: "Implementing the Technical Requirements. At SRR, the Program Manager shall document, in the HRCP, a description of the implementation of the applicable requirements of Chapter 3 of this NPR and provide clear traceability to the highest level program documentation. (This is updated and reviewed at SDR, PDR, and CDR.) (Requirement 58405)."

From [1], 2.3.6: "Allocation of Safety Goals and Thresholds. At SRR, the Program Manager shall document, in the HRCP, probabilistic safety requirements derived from the Agency-level safety goals and safety thresholds, including any allocations to mission phases and system elements (to be updated at PDR and CDR) (Requirement)."

From [1], 2.3.7: "Integration of Design and Safety Analyses.
2.3.7.1 The Program Manager shall *integrate design and safety analyses* to determine the following:
a. A list of the significant risk contributors that together constitute the majority of the total risk to which the crew is subjected (Requirement).
b. The appropriate *hazard controls and mitigations* to reduce the risk to the crew, including the level and implementation of failure tolerance to catastrophic events for the space system (Requirement 58413).
c. Specific *rationale for dynamic flight phases* where dissimilar redundancy, backup systems, or abort capabilities are not available to limit the likelihood of a catastrophic event or the loss of crew.
d. The *effectiveness of crew survival capabilities* under conditions and time constraints to be encountered during high-risk accident conditions and their impact on the risk to the crew (Requirement).
2.3.7.2 At SDR, the Program Manager shall summarize, in the HRCP, and present the current understanding of *risks and uncertainties* and related decisions regarding the system design and application of testing, based on the results of the design and safety analyses performed in accordance with paragraph 2.3.7.1 (this is updated and reviewed at PDR, CDR, and ORR)."

From [1], 2.3.8: "Human-System Integration Team. No later than SRR, the Program Manager shall establish a human-system integration team, consisting of astronauts, mission operations personnel, training personnel, ground processing personnel, human factors personnel, and human engineering experts, with clearly defined authority, responsibility, and accountability to lead the human-system integration (hardware and software) for the crewed space system (Requirement 58419)."

From [1], 2.3.9: "Evaluating Crew Workload. At SRR, the Program Manager shall document, in the HRCP, a description of how the crew workload for the reference mission(s) will be evaluated. (This is updated and reviewed at PDR and CDR.) (Requirement 58421)."

From [1], 2.3.10: "Human-in-the-Loop Integration Evaluation.
2.3.10.1 The Program Manager shall *conduct human-in-the-loop usability evaluation* for the human-system interfaces and integrated human-system performance testing, with human performance criteria, for critical system and subsystem operations involving human performance (Requirement 58423).
2.3.10.2 At PDR and CDR, the Program Manager shall summarize, in the HRCP, and present how the usability evaluations for human system interfaces and integrated human-system performance evaluation results (to date) were *used to influence the system design* and provide access to the detailed evaluation plans and results (Requirement 58424).
2.3.10.3 At ORR, the Program Manager shall summarize, in the HRCP, how the integrated human-system performance test results were used to *validate the system design* and provide access to the detailed test plans and results (Requirement 58425)."

From [1], 2.3.11: "Human Error Analysis. The Program Manager shall conduct a human error analysis for all mission phases to include operations planned for response to system failures (Requirement 58430).
2.3.11.1 At PDR, CDR, and ORR, the Program Manager shall summarize, in the HRCP, and present how the human error analysis (to date) was used to:

a. Understand and *manage potential catastrophic hazards* which could be caused by human errors (Requirement (Requirement 58432).
b. *Understand the relative risks* and uncertainties within the system design (Requirement 48433).
c. *Influence decisions related to the system design*, operational use, and application of testing (Requirement 58434)."

From [1], 2.3.12: "The Program Manager shall design the system to manage human error [via design] according to the following precedence:
a. Design the system to *prevent human error in the operation* and control of the system.
b. Design the system to *reduce the likelihood of human error* and provide the capability for the human to detect and correct or recover from the error.
c. Design the system to *limit the negative effects of errors* (Requirement 58444)."

Three types of guidance must flow to all mission elements via Human Systems Integration Requirements (HSIR): process guidance, mission guidance, and design guidance, as shown in figure 3.

Details of the guidance flow are collected to support the process compliance guidance package. Mission to Mars (M2M) unique requirements are parsed to each mission element during these steps. See section 2 for the details of design guidance.

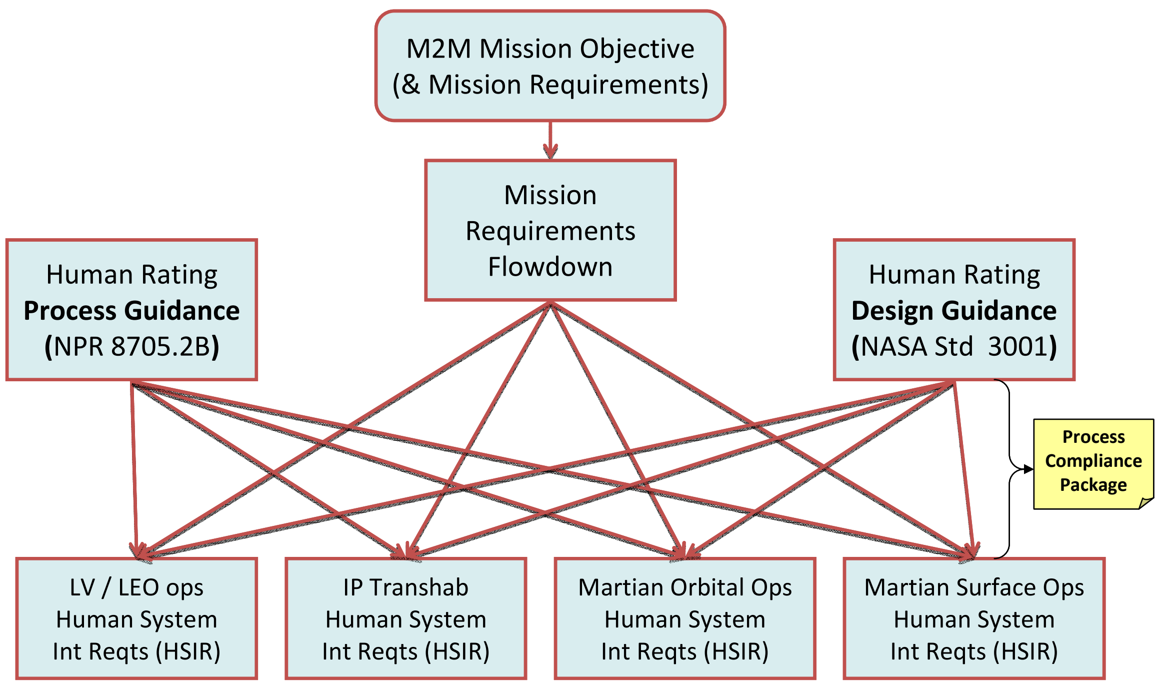

Figure 3, Relationship of Process, Mission, and Design Guidance to a Mars Mission HSIR set

Step 1c. Validating the System Capabilities and Performance ([1], 2.4)

The following requirements are part of this category:

From [1], 2.4.1: "Verifying and Validating Implementation of the Technical Requirements. At SRR, SDR, PDR, and CDR, the Program Manager shall document, as part of the HRCP, how the implementation of the technical requirements in Chapter 3 will be verified and validated (with rationale) (Requirement 58446)."

From [1], 2.4.2: "Verifying and Validating Survival Capabilities. At CDR, the Program Manager shall document, as part of the HRCP, how the implementation of survival capabilities from the requirement contained in paragraph 2.3.4 will be verified and validated (with rationale) (Requirement 58448)."

From [1], 2.4.3: "Verifying and Validating Critical System and Subsystem Performance. At CDR, the Program Manager shall document, as part of the HRCP, how the critical system and subsystem performance will be verified and validated (with rationale) (Requirement 58450)."

From [1], 2.4.4: "Integrated Verification and Validation of Critical Systems and Subsystems. At CDR, the Program Manager shall document, as part of the HRCP, how critical system and subsystem performance will be verified and validated at the integrated system level to ensure that (sub)system interactions will not cause a catastrophic hazard (with rationale) (Requirement 58452)."

From [1], 2.4.5: "Verifying and Validating Critical Software Performance.
2.4.5.1 At CDR, the Program Manager shall document, as part of the HRCP, how testing will be used to verify and validate the performance, security, and safety of all *critical software across the entire performance envelope* (or flight envelope) including mission functions, modes, and transitions (with rationale) (Requirement 58455).
2.4.5.2 At CDR, the Program Manager shall also document, as part of the HRCP, how testing will be used to verify and validate the performance, security, and safety of all *critical software under additional off-nominal, contingency, and stress testing* (with faults injected) (with rationale) (Requirement 58456)."

From [1], 2.4.6: "System Design Verification and Validation Results. At ORR, the Program Manager shall summarize, as part of the HRCP, the results of the verification and validation performed per requirements 2.4.1 and 2.4.2, along with access to the detailed results (Requirement 58458)."

From [1], 2.4.7: "Critical System and Subsystem Performance Verification and Validation. At ORR, the Program Manager shall summarize, as part of the HRCP, the results of the critical system and subsystem verification and validation performed per requirements 2.4.3 and 2.4.4, along with access to the detailed results (Requirement 58459)."

From [1], 2.4.8: "Software Verification and Validation Results. At ORR, the Program Manager shall summarize, as part of the HRCP, the results of the critical software testing performed per requirement 2.4.5, along with access to the detailed results (Requirement 58460)."

From [1], 2.4.9: "Validating Crew Workload. At ORR, the Program Manager shall document, in the HRCP, how the crew workload was validated and determined acceptable for the reference mission(s) (Requirement 58461)."

From [1], 2.4.10: "Updating Safety Models to Support System Validation. At the ORR, the Program Manager shall describe how the safety analysis documented in paragraph 2.2.3 related to loss of crew was updated based on the results of validation/verification testing and used to support validation/verification of the design in circumstances where testing was not accomplished (Requirement 58462)."

Step 1d. Flight Testing the System ([1], 2.5)

The following requirements are part of this section:

From [1], 2.5.1: "Establishing the Flight Test Program. At SDR, the Program Manager shall document, as part of the HRCP, the flight test program, including the type and number of test flights that will be performed. (Requirement 58466)"

From [1], 2.5.2: "At PDR, the Program Manager shall update the flight test program documented in the HRCP to include the flight test objectives with linkage to specific program requirements that are validated by flight test. (This is updated and reviewed at CDR.) (Requirement 58468)"

From [1], 2.5.3: "Flight Test Results. At ORR, the Program Manager shall summarize, as part of the HRCP, the results of the flight test program to date and each test objective, along with access to the detailed test results (Requirement 58473)."

From [1], 2.5.4: "Crewed Test Flights. The Program Manager shall obtain an interim Human-Rating Certification prior to crewed test flights per paragraph 2.6.3. (Requirement 58473)"

Step 1e. Certifying and Operating the Human-Rated System ([1], 2.6)

From [1], 2.6.1: "Maintaining the System and System Configuration Control. At ORR, the Program Manager shall provide, as part of the HRCP, a configuration management and maintenance plan that documents the processes that the program will use to ensure that the space system remains in the "as-certified" condition through the end of the life cycle to include system disposal. (Requirement 58478)"

From [1], 2.6.2: "Data Collection, Management, and Analysis. At ORR, the Program Manager shall provide, as part of the HRCP, a data collection, management, and analysis plan that documents the processes that the program will use to ensure that the appropriate space system data is collected, stored, and analyzed throughout its life cycle in support of the analyses to understand the risks associated with each mission (Requirement 58480)."

From [1], 2.6.3: "System Certification. Prior to the first crewed flight, the Program Manager shall obtain from the NASA Administrator, [or authority for human-rating], a Human-Rating Certification for the crewed space system based on the reference (or test) missions (Requirement 58483)"

From [1], 2.6.4: "Evaluating Changes to the System.
2.6.4.1 After Human-Rating Certification, the Program Manager, along with the Technical Authorities, [and the Director, JSC, if applicable,] shall collectively evaluate design changes, manufacturing (or refurbishment) process changes, and testing changes to the space system.
2.6.4.2 If the Program Manager, any of the Technical Authorities, [or the Director, JSC, if applicable,] determine that a re-rating is required, the Program Manager shall submit a request for Human-Rating Recertification, with a revised HRCP, to the NASA Administrator, as the authority for human rating (Requirement 58486)."

From [1], 2.6.5: "Operating the System within the Certification. As part of each flight or mission readiness review, the Program Manager shall review the Human-Rating Certification to include the following:
a. *Compliance with the Configuration Management* and Maintenance Plan (Requirement 58490).
b. Verification that the human-rated system will be *operated within the certified envelope* of the reference mission(s) (Requirement 48491).
c. *Anomalies from the previous flight/mission* that affect the Human-Rating Certification and their resolution (Requirement 58492).
d. *Design changes*, manufacturing (or refurbishment) process changes, and testing changes that were made as part of the Program's safety upgrade and improvement program that are expected to affect risk to the crew (Requirement)."

Step 2. Develop and comply with reference mission requirements [5]

List all of the reference mission requirements identified in the Constellation literature as a point of departure for the more extensive Missions to Mars suite.

Step 2a. ANTHROPOMETRY, BIOMECHANICS, AND STRENGTH ([5], 3.1)

The following anthropometry and biomechanics defining the reference range of interfaces is defined in these sections of reference [5] for both suited and unsuited astronauts:

"3.1.1 ANTHROPOMETRY
3.1.2 RANGE OF MOTION
3.1.3 MASS PROPERTIES
3.1.4 STRENGTH"

Step 2b. (Regulation of) NATURAL AND INDUCED ENVIRONMENTS ([5], 3.2)

Atmosphere, water, and the entire range of environmental properties needed to sustain life are covered in the following requirements from [5]:

"3.2.1 ATMOSPHERE
3.2.1.1 Atmospheric Quality, Nominal
3.2.1.2 Atmospheric Quality, Contingency, Off-Nominal and Suited
3.2.1.3 Control

3.2.1.4 Display
3.2.1.5 Alerting
3.2.1.6 Contaminants
3.2.1.7 Gaseous Pollutants
3.2.1.8 Rate of Change of Pressure
3.2.1.9 Combustion Products
3.2.1.10 Hazardous Chemicals
3.2.1.11 Crew Protection

3.2.2 POTABLE WATER
3.2.2.1 Quality
3.2.2.2 Quantity
3.2.2.3 Water Temperature
3.2.2.4 Water Sampling

3.2.3 THERMAL ENVIRONMENT
3.2.3.1 Atmospheric Temperature
3.2.3.2 Relative Humidity
3.2.3.3 Ventilation
3.2.3.4 User Control
3.2.3.5 Monitoring

3.2.4 ACCELERATION
3.2.5 VIBRATION
3.2.6 ACOUSTICS
3.2.7 IONIZING RADIATION
3.2.8 NON-IONIZING RADIATION"

See reference [5] for further details. To some extent the notion that "people are people" will allow these types of environmental requirements to be applied to Mars missions directly. The exception will be cumulative effects such as radiation and the effects of weightlessness, both of which will be covered further in Step 3.

Step 2c. (Regulation of equipment design for crew) Safety ([5], 3.3)

The safety requirements covered here extend in scope only to crew exposure to the cabin designs in and of themselves, and not springing from any operational situation. Design aspects covering operational safety in the mission assurance sense are covered in step 3. Here are the safety requirements from a crew interface point of view, from reference [5]:

"3.3.1 GENERAL - Emergency Access
3.3.2 MECHANICAL HAZARDS
3.3.3 ELECTRICAL HAZARDS
3.3.4 TOUCH TEMPERATURES
3.3.5 FIRE PROTECTION"

See reference [5] for further details.

Step 2d. (Regulation of) Architecture ([5], 3.4)

The following requirements areas address architectural requirements of crew living and working spaces in all mission equipment elements:

> "3.4.1 CONFIGURATION - workstation layout
> 3.4.2 TRANSLATION PATHS - ingress, egress
> 3.4.3 RESTRAINTS AND MOBILITY AIDS
> 3.4.4 HATCHES
> 3.4.5 WINDOWS
> 3.4.6 LIGHTING"

See reference [5] for further details.

Step 2e. (Enabling) Crew Functions ([5], 3.5)

All mission elements with living spaces must provide for crew functions as follows:

> "3.5.1 FOOD PREPARATION
> 3.5.2 PERSONAL HYGIENE
> 3.5.3 BODY WASTE MANAGEMENT
> 3.5.4 EXERCISE
> 3.5.5 SPACE MEDICINE
> 3.5.6 STOWAGE
> 3.5.7 TRASH MANAGEMENT"

See reference [5] for further details.

Step 2f. CREW INTERFACES FOR DISPLAYS AND CONTROL ([5], 3.6)

All controls and displays must conform with these requirements in order to facilitate smooth crew control:

> "3.6.1 GENERAL - crew I/F labels
> 3.6.2 CREW PERFORMANCE - crew I/F usability & workload
> 3.6.3 DISPLAY AND CONTROL LAYOUT - arrangement, spacing
> 3.6.4 DISPLAYS - content and viewing
> 3.6.5 HARDWARE AND SOFTWARE CONTROLS - operation, protection
> 3.6.6 CREW NOTIFICATIONS AND CAUTION AND WARNING
> 3.6.7 CREW SYSTEM INTERACTION
> 3.6.8 ELECTRONIC PROCEDURES"

See reference [5] for further details.

Step 2g. MAINTENANCE AND HOUSEKEEPING ([5], 3.7)

The maintenance and housekeeping requirements are provided to enable the crew to more easily perform these functions.

> "3.7.1 MAINTENANCE – failure notification, access, common tools, error proof design
> 3.7.2 HOUSEKEEPING – design for cleanliness, ease of filter replacement"

See reference [5] for further details.

Step 2h. INFORMATION MANAGEMENT ([5], 3.8)

Information management requirements are defined to provide the crew with accurate, timely data that is easy and natural to access:

> "3.8.1 GENERAL -crew operability
> 3.8.2 DATA AVAILABLE
> 3.8.3 DATA DISTRIBUTION
> 3.8.4 DATA BACKUP"

See reference [5] for further details.

Step 2i. GROUND MAINTENANCE AND ASSEMBLY ([5], 3.9)

A system that is not easily maintained and assembled on the ground is at risk when deployed in space. These requirements ensure that all mission systems are designed for ease of ground assembly and maintenance:

> "3.9.1 GROUND ANTHROPOMETRY, BIOMECHANICS, AND STRENGTH
> 3.9.2 GROUND NATURAL AND INDUCED ENVIRONMENTS
> 3.9.3 GROUND SAFETY
> 3.9.4 GROUND ARCHITECTURE
> 3.9.5 GROUND CREW FUNCTIONS
> 3.9.6 GROUND CREW INTERFACES
> 3.9.7 LAUNCH SITE PROCESSING AND GROUND MAINTENANCE
> 3.9.8 GROUND INFORMATION MANAGEMENT"

See reference [5] for further details.

During the verification program all of the requirements called out in step 2 must be verified. The verification of these requirements is dealt with in section 4 of reference [5] for each requirement.

Step 3. Comply with technical requirements for human-rating

The technical requirements for human rating identify capabilities that ensure the safety of the crew and the safe operational conduct of all mission systems. The following substeps are the relevant highlights from references [1], [2] and [4], as indicated.

Step 3a. System Safety ([1], 3.2)

"3.2.1 The space system shall provide the capability to sustain a safe, habitable environment for the crew (Requirement 58503).
3.2.2 The space system shall meet probabilistic safety criteria derived from the Agency-level (NASA) safety goals and safety thresholds with a specified degree of certainty (Requirement).
3.2.3 The space system shall provide failure tolerance to catastrophic events, with specific levels of failure tolerance and implementation (similar or dissimilar redundancy) derived via an integration of the design and safety analysis (per the requirement in paragraph 2.3.7.1) (Requirement).
a. Failure of primary structure, structural failure of pressure vessel walls, and failure of pressurized lines are excepted from the failure tolerance requirement provided the potentially catastrophic failures are controlled through a defined process in which approved standards and margins are implemented that account for the absence of failure tolerance.
b. Other potentially catastrophic hazards that cannot be controlled using failure tolerance are excepted from the failure tolerance requirements with concurrence from the Technical Authorities provided the hazards are controlled through a defined process in which approved standards and margins are implemented that account for the absence of failure tolerance.
3.2.4 The space system shall provide the failure tolerance capability in [1], 3.2.3 without the use of emergency equipment and systems (Requirement 58557).
3.2.5 The space system shall be designed to tolerate inadvertent operator action (minimum of one inadvertent action), as identified by the human error analysis ([1], paragraph 2.3.11), *without causing a catastrophic event* (Requirement 58559).
3.2.6 The space system shall tolerate inadvertent operator action, as described in [1], 3.2.4, *in the presence of any single system failure* (Requirement 58561).
3.2.7 The space system shall provide the capability to mitigate the hazardous behavior of critical software where the hazardous behavior would result in a catastrophic event (Requirement 58563).
3.2.8 The space system shall provide the capability to detect and annunciate faults that affect critical systems, subsystems, and/or crew health (Requirement 58569).
3.2.9 The space system shall provide the capability to isolate and/or recover from faults identified during system development that would result in a catastrophic event (Requirement 58572).
3.2.10 The space system shall provide the capability to utilize health and status data (including system performance data) of critical systems and subsystems to facilitate anomaly resolution during and after the mission (Requirement 58574).
3.2.11 The crewed space system shall provide the capability for autonomous operation of system and subsystem functions which, if lost, would result in a catastrophic event (Requirement 58576).
3.2.12 The space system shall provide the capability for the crew to readily access equipment involved in the response to emergency situations and the capability to gain access to equipment needed for follow-up/recovery operations (Requirement 58578)."

Step 3b. Crew / Human Control of the System-General ([1], 3.3)

"3.3.1 The crewed space system shall provide the capability for the crew to monitor, operate, and control the crewed space system and subsystems, where:
a. The capability is necessary to execute the mission; or
b. The capability would prevent a catastrophic event; or

c. The capability would prevent an abort (Requirement).
3.3.2 The crewed space system shall provide the capability for the crew to manually override higher level software control/automation (such as automated abort initiation, configuration change, and mode change) when the transition to manual control of the system will not cause a catastrophic event (Requirement 58586).
3.3.3 The space system shall provide the capability for humans to remotely monitor, operate, and control the crewed system elements and subsystems, where:
a. The remote capability is necessary to execute the mission; or
b. The remote capability would prevent a catastrophic event; or
c. The remote capability would prevent an abort (Requirement 58598)."

Step 3c. System Control Requirements - Human-Rated Spacecraft ([1], 3.4)

"3.4.1 The crewed space system shall provide the capability for the crew to manually control the flight path and attitude of their spacecraft, with the following exception: during the atmospheric portion of Earth ascent when structural and thermal margins have been determined to negate the benefits of manual control (Requirement).
3.4.2 The crewed spacecraft shall exhibit Level 1 handling qualities (Handling Qualities Rating (HQR) 1, 2 and 3), as defined by the Cooper-Harper Rating Scale [15], during manual control of the spacecraft's flight path and attitude (Requirement)."

Step 3d. System Control Requirements - Proximity Operations with Human-Rated Spacecraft ([1], 3.5)

"3.5.1 The space system shall provide the capability for the crew to monitor, operate, and control an uncrewed spacecraft during proximity operations, where:
a. The capability is necessary to execute the mission; or
b. The capability would prevent a catastrophic event; or
c. The capability would prevent an abort (Requirement 58604).
3.5.2 The crewed space system shall provide the capability for direct voice communication between crewed spacecraft (2 or more) during proximity operations (Requirement 58607)."

Step 3e. Crew Survival / Abort Requirements ([1], 3.6)

"3.6.1 Earth Ascent Systems
3.6.1.1 The space system shall provide the capability for unassisted crew emergency egress to a safe haven during Earth prelaunch activities (Requirement 58611).
3.6.1.2 The space system shall provide abort capability from the launch pad until Earth-orbit insertion to protect for the following ascent failure scenarios (minimum list):
a. Complete loss of ascent thrust/propulsion (Requirement 58613).
b. Loss of attitude or flight path control (Requirement 58614).
3.6.1.3 The crewed space system shall monitor the Earth ascent launch vehicle performance and automatically initiate an abort when an impending catastrophic failure is detected (Requirement 58616).

3.6.1.4 Earth Ascent Abort
3.6.1.4.1 The space system shall provide the capability for the crew to initiate the Earth ascent abort sequence (Requirement 58619).
3.6.1.4.2 The space system shall provide the capability for the ground control to initiate the Earth ascent abort sequence (Requirement 58620).
3.6.1.5 If a range safety destruct system is incorporated into the design, the space system shall automatically initiate the Earth ascent abort sequence when range safety destruct commands are received onboard, with an adequate time delay prior to destruction of the launch vehicle to allow a successful abort (Requirement 58622).

3.6.2 Earth Orbit Systems
3.6.2.1 The crewed space system shall provide the capability to autonomously abort the mission from Earth orbit by targeting and performing a deorbit to a safe landing on Earth (Requirement 58625).

3.6.3 Earth – [Mars] Transit and [Mars] Orbit Systems
3.6.3.1 The crewed space system shall provide the capability to autonomously abort the mission during [Martian] transit and from [Martian] orbit by executing a safe return to Earth (Requirement 58627).

3.6.4 [Mars] Descent Systems
3.6.4.1 The crewed space system shall provide the capability to autonomously abort the [Mars] descent and execute all operations required for a safe return to Earth (Requirement 58629).

3.6.5 [Martian] Surface Systems
3.6.5.1 The space system shall provide the capability for the crew on the [Martian] surface to monitor the descent and landing trajectory of an uncrewed spacecraft and send commands necessary to prevent a catastrophic event (Requirement 58632).
Rationale: This capability assumes the arrival is within the safe zone of the crew or crewed surface systems.

3.6.6 [Martian] Ascent Systems. Reserved for a future version of the NPR.
[Recommended text: The crewed space system shall provide the capability to autonomously abort the Mars ascent and execute all operations required for a safe return to the Martian surface to await contingency and/or rescue operations.]

3.6.7 Earth Reentry Systems
3.6.7.1 The crewed space system shall provide the capability for unassisted crew emergency egress after Earth landing (Requirement 58636).
Rationale: This requirement assumes the crew is able to function in a 1-g environment. Unassisted means without help from ground or rescue personnel or equipment.
3.6.7.2 The crewed space system shall provide a safe haven capability for the crew inside the spacecraft after Earth landing until the arrival of the landing recovery team or rescue forces (Requirement 58638).

3.6.7.3 The space system shall provide recovery forces with the location of the spacecraft after return to Earth (Requirement 58640).”

In practice design requirements (a. – e.) are better summarized by the 16 technical requirements in HSSWG 3-02 [2] (g. – i.): “The spacecraft serves as the crew’s first line of defense against the hazardous space environment. NASA has identified design requirements to ensure the safety and reliability of human-rated exploration vehicles.” [3] The most important requirements, fully addressed in *NASA Human Rating Requirements* [3], are reprinted below.

Step 3g. GENERAL (process requirements) ([2], 3.1), [3], ([14], table 8-1)

“**Requirement 1**: The vehicle shall be designed, built, inspected, tested, and certified specifically addressing the requirements for human rating.
Requirement 2: The vehicle design, manufacture, and test shall comply with JPG 80803 and applicable military standards. Where alternative approaches are employed, verification shall be provided that the alternative approaches meet or exceed the performance of accepted approaches.
Requirement 3: The vehicle crew habitability and life support systems shall comply with NASA Standard-3000 and NASA Space Flight Health Requirements for crew habitability and life support systems design.
Requirement 4: A successful, comprehensive flight test program shall be completed to validate analytical math models, verify the safe flight envelope, and provide a performance database prior to the first operational flight (flights other than for the specific purpose of flight test) with humans on board.
Requirement 5: Spacecraft operations in proximity or docking with a crewed vehicle shall comply with joint vehicle and operational requirements so as to not pose a hazard to either vehicle. Provisions shall be made to enable abort, breakout, and separation by either vehicle without violating the design and operational requirements of either vehicle. Uncrewed vehicles must permit safety critical commanding from the crewed vehicle.”

Step 3h. SAFETY AND RELIABILITY Requirements ([2], 3.2)

“**Requirement 6**: The program shall be designed so that the cumulative probability of safe crew return over the life of the program exceeds 0.99. This will be accomplished through the use of all available mechanisms including mission success, abort, safe haven, and crew escape
Requirement 7: A crew escape system shall be provided on future (e.g., post-Space Shuttle) Earth-to-orbit (ETO) vehicles for safe crew extraction and recovery from in-flight failures across the flight envelope from pre-launch to landing. The escape system shall have a probability of successful crew return of 0.99.
Requirement 8: For ETO vehicles, abort modes shall be provided for all phases of flight to safely recover the crew and vehicle or permit the use of the crew escape system. For beyond-Earth orbit (BEO) missions, spacecraft and propulsion systems shall have sufficient power to fly trajectories with abort capabilities and provide power and critical consumables for crew survival. Trajectories and propulsion systems shall be optimized to provide abort options. When such options are unavailable, safe haven capabilities shall be provided.
Requirement 9: If a flight termination (range safety) system is required for future (e.g., post-Space Shuttle) ETO vehicles, the vehicle design shall provide for safe recovery of the crew.
Requirement 10: All critical systems essential for crew safety shall be designed to be two-fault tolerant. When this is not practical, systems shall be designed so that no single failure shall cause loss of the crew.

For the purposes of this requirement, maintenance can be considered as the third leg of redundancy so long as mission operations and logistics resupply permit it.
Requirement 11: Vehicle reliability shall be verified by test backed up with analysis at the integrated system level prior to the first flight with humans on board and verified by flight-based analysis and system health monitoring for each subsequent flight.
Requirement 12: The performance and reliability of all critical software shall be tested on a flight equivalent avionics testbed across the entire flight envelope. Independent verification and validation methods shall be used to confirm the integrity of the software testing process."

Step 3i. HUMAN-IN-THE-LOOP ([2], 3.3)

"Requirement 13: The vehicle shall provide the flight crew on board the vehicle with proper insight, intervention capability, control over vehicle automation, authority to enable irreversible actions, and critical autonomy from the ground.
Requirement 14: The flight crew shall be capable of taking manual control of the vehicle during all phases of flight. The vehicle shall exhibit Level I handling qualities as defined by the Cooper-Harper Rating Scale.
Requirement 15: The spacecraft displays and controls design shall be based on a detailed function and task analysis performed by an integrated team of human factors engineers with spacecraft displays and controls design experience, vehicle engineers, and crew members. Solutions in this design area shall not be limited to those derived from experience with Shuttle if newer or alternative concepts are applicable.
Requirement 16: The mission design, including task design and scheduling, shall not adversely impact the ability of the crew to operate the vehicle**."**

For long interplanetary missions there is also the need for on-board medical care, including an astronaut trained at the physician level due to the high level of autonomy required, as discussed in (j.) below, and fitness for duty standards as described in (k.) below:

Step 3j. Level of Care Five, ([4], 1.1.1.6, 1.1.1.7, D.8)

Level of Care Five - from ([4], D.8)

Rationale [for this level of care], "The training and caliber of the care giver is at the physician level, due to the autonomous nature of the mission. Advanced and ambulatory care is provided, but expanded. Additional portable diagnostic devices and surgical equipment may be used to augment the advanced and ambulatory support packs but are limited by up-and down-mass, the vehicle, and the ability to pre-deploy such items. Despite the addition of a physician care giver, consumables and survival of the remaining crewmembers dictate what resources can be expended on critical care for the ill or injured crewmember."

Level of Care Five ([4], 4.1.1.6)

From 4.1.1.6.1, "A high level of potential risk exists that personnel may experience medical problems on orbit at some time during the mission. Preventive strategies shall be used to a greater degree to reduce the overall risk."

From 4.1.1.6.2, “The ability to support chronic illness is limited. Intervention strategies shall be used to reduce the risk to an acceptable level and shall include increasing levels of advanced care in the form of medications, equipment, training, or consumables over and above those for previous levels.”

From 4.1.1.6.3, “The training and caliber of the caregiver shall be at the physician level, due to the exclusively autonomous nature of the mission.”

From 4.1.1.6.4, “The scope of medical care available shall be limited or triaged due to availability of supplies, consumables, or mission risk. Return to Earth is not a viable option for more serious illness/injuries. Impact to overall mission is greater.”

From 4.1.1.6.5, “Level of Care Five shall be provided for lunar/planetary missions greater than 210 days.”

Termination of Care, ([4], 4.1.1.7)

From 4.1.1.7.1, **“**NASA shall have a policy and procedures for termination of care, in the event the crewmember cannot be saved, or if continued treatment causes undue risk or peril to the remaining crew.”

From 4.1.1.7.2, “Topics such as disposition of the deceased shall be included in this plan.”

Step3k. Maintaining Crew Health Standards ([4], 4.2)

Standards for Human Performance ([4]. 4.2)

Space Flight Health Standards for Human Performance have been developed in order to support NASA’s exploration vision and to guide and focus efforts to protect the health of space-faring crews. The types of standards are listed below.

Types of Standards [4]

Step 3k1. From 4.2.2.1, a first type of health standard is **“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.”

An important example of an FFD standard for a long duration Mars mission would be “Behavioral Health and Cognition Standard” ([4]. F.3): “The planned nominal number of work hours is 6.5 hours per day. It is recommended not to exceed a 48-hour total workweek. Maintaining the nominal work hours and workload is even more important during critical operations. A critical overload workload is defined as 10-hour work days > 3 days in a week or > 60 hours in a workweek. This performance range requires continued re-evaluation and update.”

Step 3k2. From 4.2.2.2, a second type of health standard is "**<u>Space Permissible Exposure Limits (SPEL)</u>** - Quantifiable limit of exposure to a space flight factor over a given length of time (e.g., lifetime radiation exposure). Physical / chemical agent measured.

An example of a critical SPEL standard for Mars missions would be "Space Permissible Exposure Limit for Space Flight Radiation Exposure," ([4], 4.2.10), stated as follows:

From 4.2.10.1 Planned career exposure for radiation shall not exceed 3 percent risk of exposure induced death (REID) for fatal cancer.
From 4.2.10.2 NASA shall assure 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.
From 4.2.10.3 Exploration Class Mission radiation exposure limits shall be defined by NASA based on National Council on Radiation Protection (NCRP) recommendations.
From 4.2.10.4 Planned radiation dose shall not exceed short-term limits as defined in table 4 in Appendix F supporting material for the radiation standard.
From 4.2.10.5 In-flight radiation exposures shall be maintained using the "as low as reasonably achievable (ALARA) principle."

Table 1 provides an example of the type of dose limit table that will have to be developed for Mars missions.

Table 1 —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), ([4], F.8)

	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)**

Step 3k3. From 4.2.2.3, a third type of health standard is "**<u>Permissible Outcome Limits (POL</u>**)- Acceptable maximum decrement or change in a physiological or behavioral parameter, during or after a space flight mission, as the result of exposure to the space environment. Biological/clinical parameter measured, (e.g., bone density)."

An example of a critical POL standard for Mars missions will be the "Permissible Outcome Limit for Microgravity-Induced Bone Mineral Loss Performance Standard," ([4], 4.2.9), stated as follows:

From 4.2.9.1, **"**Crewmembers' pre-flight bone mass Dual Energy X-ray Absorptiometry (DEXA T) score shall not exceed -1.0 (-1.0 Standard Deviation (SD) below the mean Bone Mineral Density).
From 4.2.9.2, "Countermeasures shall be aimed at maintaining bone mass in-flight consistent with outcome limits."
From 4.2.9.3 The post-flight (end of mission) bone mass DEXA T score shall not exceed -2.0 (-2.0 SD below the mean Bone Mineral Density).
From 4.2.9.4, "Post-flight rehabilitation shall be aimed at returning bone mass to pre-flight baseline."

Permissible Outcome Limit for Microgravity Induced Bone Mineral is graphed in the figure 4 below:

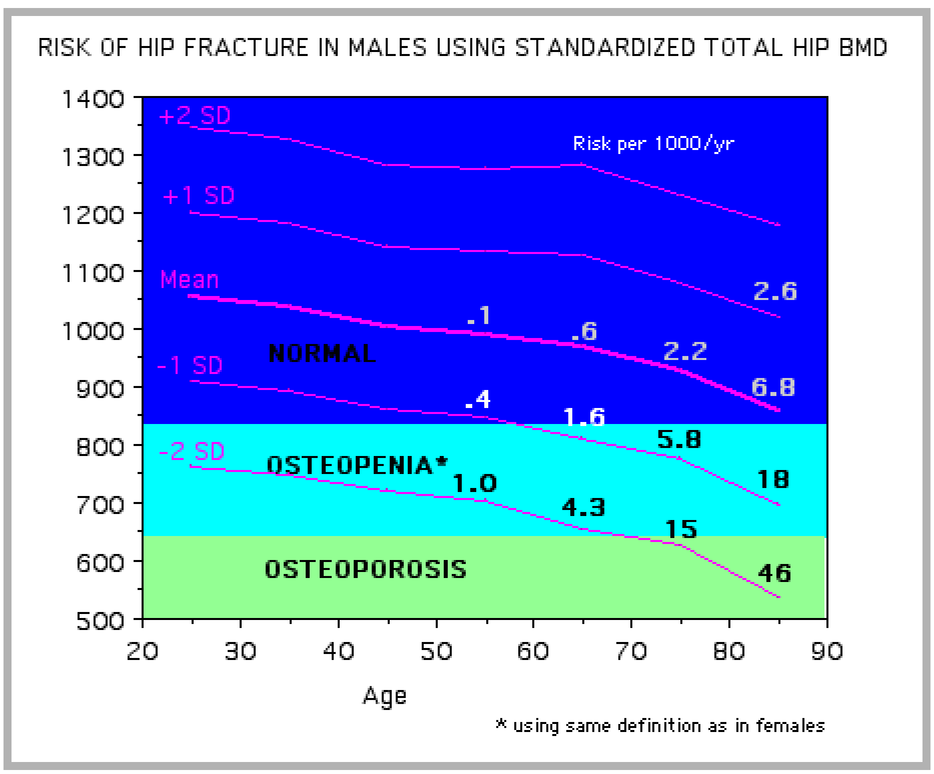

Figure 4 —Risk of Hip Fracture in Males Using Standardized Total Hip BMD ([4], F.7)

Step 4. Preparing and maintaining a Human-Rating Certification Package (HRCP)

From [1], 1.3.1, "the human-rating certification process is based on the certification requirements in Chapter 2 of reference [1], NPR 8705.2B. These certification requirements lead the Program Manager through specific aspects of human-rating and document the results in a Human-Rating Certification Package (HRCP) as called out in Appendix D of [1], NPR 8705.2B."

The key certification elements documented in the HRCP are:
[Step 4a.] "Defining of reference missions for certification."
[Step 4b.] "Incorporating system capabilities to implement crew survival strategies for each phase of the reference missions."
[Step 4c.] "Implementation of capabilities from the applicable technical requirements in Chapter 3 of the NPR."
[Step 4d.] "Utilization of safety analyses to influence system development and design."
[Step 4e.] "Integration of the human into the system and human error management."
[Step 4f.] "Verification, validation, and testing of critical system performance."
[Step 4g.] "Performance of a flight test program and documentation of successfully completed test objectives."
[Step 4h.] "Documented proof of system configuration management over the life of the program and related plans to maintain Human-Rating Certification."

Mission equipment is certified as human rated when the HRCP checklist is completed and the package is approved. Broadly speaking then, in the context of this paper step 4 of achieving a human rating is collecting the HRCP. HRCP components are collected as depicted in figure 5:

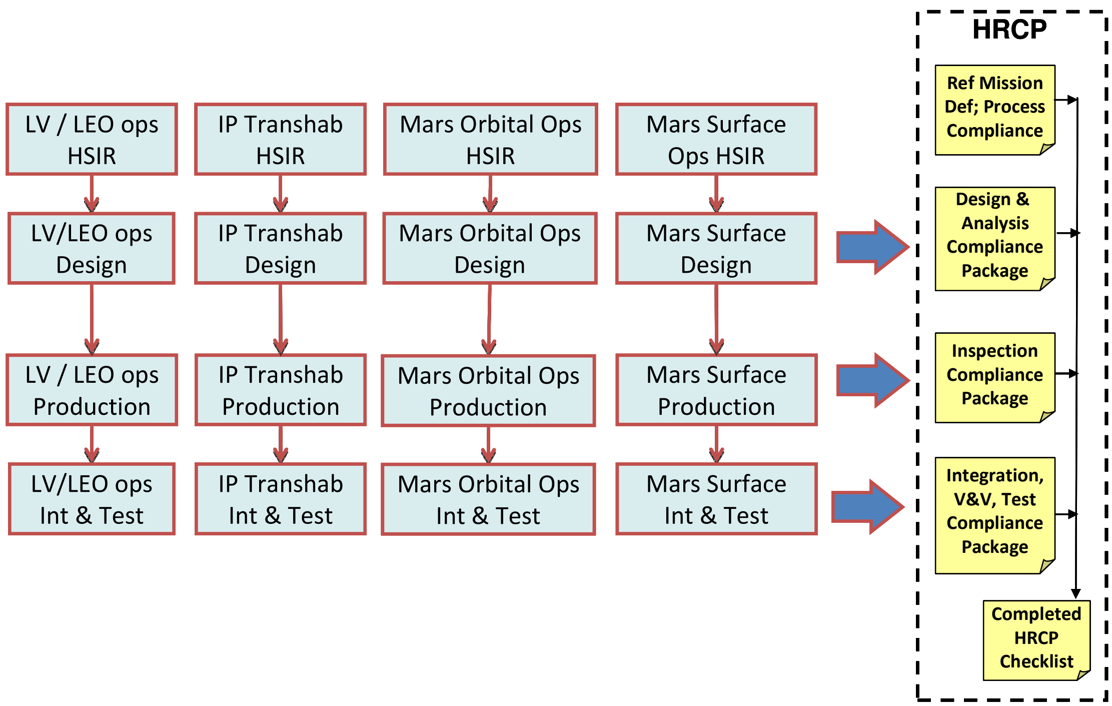

Figure 5, Relationship of NASA Standards to the Constellation Program HSIR

Maintaining a human rating will also require approved configuration management and maintenance processes.

Future Considerations. Specific system design challenges for Missions to Mars

Future work on developing human rating requirements for Mars missions should focus first on the development of reference missions as discussed in step 2. Developing and vetting a reference mission set for Mars missions is currently unresolved but is needed for the resolution of all other follow-on technical design issues as defined in step 3.

Specific impacts system design challenges driven by Missions to Mars (M2M) will need to be addressed for these driving requirements areas:

A. Meeting the Permissible Outcome Limit performance standard for Microgravity-Induced Bone Mineral Loss due to low gravitation as discussed in step 3k3.
B. Meeting the Space Permissible Exposure Limit for Space Flight Radiation Exposure, due to higher than usual radiation as discussed in step 3k2.
C. Crew control – In the context of long distance IP travel, there will be expanded requirements for autonomous operations and control and operator situational awareness per steps 3b, 3c, and 3d.
D. Contingency ops for survivability – Due to the extreme physical isolation of the crew for M2M there will be the need to trade lifeboat options with in situ survivability options in the case of contingency operations as required by step 3e.

Recommendations: Suggested trade space areas to address technical requirements areas for Mars missions

Suggested trade space areas are recommended for each technical requirements area and the trade space dimensions defined in the following cases:

- Radiation Abatement Trades:
  – Energy versus matter shielding trades (Example: EM coil versus H2O shielding)
    - Needed for Interplanetary (IP) Transhab, Mars Orbital Ops, and Mars Surface Ops
- Artificial Gravity Trades:
  – Ship contained rotation vs. tethered systems (Example: “2001” vs. “2010” style)
    - Needed for IP Transhab
- Operations Control Trades:
  – Remote operations versus autonomous operations (manual or automated)
    - Needed for IP Transhab, Mars Orbital Ops, and Mars Surface Ops
- Contingency Operations Trades:
  – Escape pods versus lifeboats versus “in situ” survivability options
    - Needed for all phases of the reference mission (answers may be different for different phases)
    - Specifically called out and required for the HRCP

NASA is already seeking proposals to address these key trades using university research opportunities as noted on its NSPIRES website. The results of these trades should be monitored carefully for useful design inputs.

Post Script: Requirements division between NASA Commercial Crew and FAA Commercial Space Transportation Programs

A Memorandum of Understanding (MOU) was recently signed by NASA and the FAA to establish a policy for manned and unmanned missions to and from the space station. Commercial providers will be required to obtain a license from the FAA ensuring public safety. Crew safety and mission assurance will be NASA's responsibility.

For more information on NASA's Commercial Crew Program, visit:
http://www.nasa.gov/commercialcrew

For more information on the FAA's Office of Commercial Space Transportation, visit:
http://www.faa.gov/about/office_org/headquarters_offices/ast

The agreement does not address any operations beyond ISS orbit.

Conclusions and Recommendations

A four step process has been developed that summarizes human rating requirements for missions to Mars. Existing human rating requirements are applicable to Mars missions but are still evolving, and need to be supplemented in areas unique to Mars missions, especially in the area reference mission development, which will assist in the development of unique Human System Interface Requirements for all mission elements.

New reference missions to Mars must provide for a range of operations to allow greater mission flexibility in real time, given the isolation and lack of immediate ground control authority due to the long delays inherit in interplanetary missions. Recommended future work includes the development and careful vetting of these reference missions, as well as the eventual definition of the radiation abatement approach, the selection of artificial gravity solution, better definition of autonomous control, and a robust definition of contingency operations for each phase of the mission.

Acknowledgements

The author wishes to acknowledge the people of NASA for over a half century of dedication to the safe pursuit of human space flight. This long, sustained effort has made this requirements survey possible.

References

Core human rating references:

[1] NASA Procedural Requirement NPR8705.2B, "Human-Rating Requirements for Space Systems, dated 11/10/2011, at http://nodis3.gsfc.nasa.gov/, accessed 5/20/2012.

[2] NASA Exploration Team Human Subsystem Working Group (HSSWG), "Guidelines and Capabilities for Designing Human Missions," March 2002.

[3] Van Laak, J., et al., NASA JSC 28354, "Human-Rating Requirements," June 1998.

[4] NASA Technical Standard NASA-STD-3001, "NASA Space Flight Human Systems," Volume 1 "Crew Health," 3/5/2007, and Volume 2 "Man-Systems Integration Standards," Rev. B, July 1995.

[5] NASA CxP 70024, "Constellation Program Human-Systems Integration Requirements," 12/15/2006.

[6] Berdich, D., "Human Rating Requirements for NASA's Constellation Program," 80th Annual Scientific Meeting of the Aerospace Medical Association (AsMA), 05 May2009, Los Angeles, California, http://www.nasa.gov/centers/johnson/ppt/499169main_HSI_KB3_3_NASA_HSI_Rqmts_DBerdich.ppt, accessed 6/11/2012.

Space flight worthiness and safety documents and guidance:

[7] USAF Space and Missile Systems Center, SMCI 63-1202, "Space Flight Worthiness," 10/1/2002.

[8] USAF Eastern and Western Range EWR 127-1, "Range Safety Requirements," 8/21/1995.

[9] USAF Instruction AFI 91-202, "Safety," revised 3/20/2012.

[10] Department of Defense MIL-STD-882D, "Standard Practice for System Safety," revised 2/10/2000.

[11] USAF Space and Missile Systems Center, SMCI 63-1205, "Space System Safety Policy, Process, and Techniques," 8/20/2007.

Human factors and engineering references:

[12] FAA HF-STD-01, Human Factors Design Standard (HFDS), 5/3/2012, http://hf.tc.faa.gov/hfds/download.htm, accessed 7/28/12.

[13] Department of Defense MIL-STD-1472F, "Human Engineering," 8/23/1999.

[14] Larson, W.J., and Pranke, L.K., *Human Spaceflight: Mission Analysis and Design*, McGraw Hill, NY, 2007.

[15] NASA TM-2009-215767, Cooper-Harper Experience Report for Spacecraft Handling Qualities Applications, 6/1/2009