NASA/TP-2014-218556

Human Integration Design Processes (HIDP)

Human Health and Performance Directorate

National Aeronautics and Space Administration
International Space Station Program
Johnson Space Center
Houston, Texas

September 2014

NASA STI Program ... in Profile

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA scientific and technical information (STI) program plays a key part in helping NASA maintain this important role.

The NASA STI program operates under the auspices of the Agency Chief Information Officer. It collects, organizes, provides for archiving, and disseminates NASA's STI. The NASA STI program provides access to the NASA Aeronautics and Space Database and its public interface, the NASA Technical Reports Server, thus providing one of the largest collections of aeronautical and space science STI in the world. Results are published in both non-NASA channels and by NASA in the NASA STI Report Series, which includes the following report types:

- TECHNICAL PUBLICATION. Reports of completed research or a major significant phase of research that present the results of NASA Programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA counterpart of peer-reviewed formal professional papers but has less stringent limitations on manuscript length and extent of graphic presentations.

- TECHNICAL MEMORANDUM. Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.

- CONTRACTOR REPORT. Scientific and technical findings by NASA-sponsored contractors and grantees.

- CONFERENCE PUBLICATION. Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or co-sponsored by NASA.

- SPECIAL PUBLICATION. Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.

- TECHNICAL TRANSLATION. English-language translations of foreign scientific and technical material pertinent to NASA's mission.

Specialized services also include organizing and publishing research results, distributing specialized research announcements and feeds, providing information desk and personal search support, and enabling data exchange services.

For more information about the NASA STI program, see the following:

- Access the NASA STI program home page at http://www.sti.nasa.gov

- E-mail your question to help@sti.nasa.gov

- Fax your question to the NASA STI Information Desk at 443-757-5803

- Phone the NASA STI Information Desk at 443-757-5802

- Write to:
  STI Information Desk
  NASA Center for AeroSpace Information
  7115 Standard Drive
  Hanover, MD 21076-1320

NASA/TP-2014-218556

Human Integration Design Processes (HIDP)

Human Health and Performance Directorate

National Aeronautics and Space Administration
International Space Station Program
Johnson Space Center
Houston, Texas

September 2014

Available from:

NASA Center for AeroSpace Information
7121 Standard Drive
Hanover, MD 21076-1320

National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161

This report is also available in electronic form at http://ston.jsc.nasa.gov/collections/TRS

REVISION AND HISTORY

REV.	DESCRIPTION	PUB. DATE
-	Initial Release	9/2014

ACKNOWLEDGMENTS

The following individuals comprised the team, subject matter experts, and authors who contributed to the HIDP. Their hard work on this document is very much appreciated and clearly reflected in the high quality of the content.

Jurine Adolf
Abbe Barr
Janet Barzilla
Debbie Berdich
Jennifer Boyer
Jeff Beno
Paul Campbell
Johnny Conkin
Jonathan Dory
Grace Douglas
Scott England
Neta Ezer
Mike Ferrer
Yamil Garcia
Lauren Harvill
Kritina Holden
Keith Holubec
John Keller
Jane Krauhs
Kate Kubicek
Chip Litaker
Sarah Margerum
Kerry McGuire
Lauren Merkle
Deborah Neubek
Jason Norcross
Christopher Reid
Aniko Sandor
Susan Schuh
Ellen Snook
Jeff Somers
Gordon Vos
David Welsh

TABLE OF CONTENTS

PARAGRAPH **PAGE**

APPENDIX

TABLE

FIGURE

1.0 INTRODUCTION

1.1 PURPOSE

The purpose of the Human Integration Design Processes (HIDP) document is to provide human-systems integration design processes, including methodologies and best practices that NASA has used to meet human systems and human rating requirements for developing crewed spacecraft. HIDP content is framed around human-centered design methodologies and processes in support of human-system integration requirements and human rating.

NASA-STD-3001, Space Flight Human-System Standard, is a two-volume set of National Aeronautics and Space Administration (NASA) Agency-level standards established by the Office of the Chief Health and Medical Officer, directed at minimizing health and performance risks for flight crews in human space flight programs. Volume 1 of NASA-STD-3001, Crew Health, sets standards for fitness for duty, space flight permissible exposure limits, permissible outcome limits, levels of medical care, medical diagnosis, intervention, treatment and care, and countermeasures. Volume 2 of NASA-STD-3001, Human Factors, Habitability, and Environmental Health, focuses on human physical and cognitive capabilities and limitations and defines standards for spacecraft (including orbiters, habitats, and suits), internal environments, facilities, payloads, and related equipment, hardware, and software with which the crew interfaces during space operations. The NASA Procedural Requirements (NPR) 8705.2B, Human-Rating Requirements for Space Systems, specifies the Agency’s human-rating processes, procedures, and requirements.

The HIDP was written to share NASA’s knowledge of processes directed toward achieving human certification of a spacecraft through implementation of human-systems integration requirements. Although the HIDP speaks directly to implementation of NASA-STD-3001 and NPR 8705.2B requirements, the human-centered design, evaluation, and design processes described in this document can be applied to any set of human-systems requirements and are independent of reference missions.

1.2 APPLICABILITY

The HIDP is a reference document that is intended to be used during the development of crewed space systems and operations to guide human-systems development process activities.

1.3 HOW TO USE THE HIDP

The HIDP and NASA/SP-2010-3407 Human Integration Design Handbook (HIDH) are complementary reference documents. The HIDH provides background information on the rationale for human-system design standards, while HIDP describes the “how-to” processes, including methodologies and best practices that NASA has used during the development of crewed space systems and operations. Select processes included in the HIDP are based on NASA’s experiences and expertise in spacecraft design, particularly those that are complex processes, have notable lessons learned, or have important considerations. Many program-specific examples are used throughout the HIDP to illustrate processes, methodologies, and/or best practices; they are not intended to prescribe design solutions. Program-specific examples are used to illustrate the processes, but the chapters can be adapted for any mission.

Although the HIDP does not levy design requirements, the relevant standards, example program requirements, and/or NPR requirements are referenced in each process. Additionally, suggested technical work products are identified to provide program managers, technical authorities, and stakeholders with insight and assessment throughout the systems engineering life cycle. In subject areas where NASA has previously documented background or supplementary information, references are made to the HIDH.

The HIDP is organized into stand-alone sections, which should be referenced as needed. Relevant information is purposely repeated in various sections, with cross-references provided.

Chapter 3 provides over-arching information, beginning with a discussion of NASA's Human Systems Integration and human-centered design (HCD) philosophies and their approach to space system development. The HCD approach is captured in NASA-STD-3001, Volume 2 as a requirement for each human space flight program. Section 3.2 describes human-centered design activities in the context of spacecraft design and the NASA systems engineering process. The HCD activities serve as the framework for each process in the HIDP document. For each milestone review, relevant technical products (e.g., concepts of operation, analyses and evaluations, design descriptions) are identified with the intent of minimizing engineering life cycle development costs through iterative assessment of concepts and designs. Section 3.3 describes the Human-Systems Integration (HSI) Team concept and the role of an HSI Team in the HCD process and development of crewed space vehicles. Section 3.4 summarizes the generic technical products that would be typical outputs of HCD activities, and their associated milestones.

Section 4 contains separate, stand-alone subsections describing different spacecraft design processes related to requirements in NASA-STD-3001 and/or NPR 8705.2B. Each process is explicitly tied to a requirement(s) in NASA-STD-3001 and/or NPR 8705.2B, and is written with the intent of enabling space systems development and certification. Each process contains a background section intended to provide just enough background information to understand the content of the process, with pointers to other documents (such as the HIDH) for more information as appropriate. To facilitate successful development and the ultimate achievement of requirement compliance and human-rating certification, each process also suggests key technical products that should be assessed throughout the engineering development life cycle.

A list of the sections follows. Sections 3.1 through 3.4 should be read by all audiences, as they are a companion to each section. For convenience, each title is a hyperlink to that section.

- 3.4 Summary of HIDP Technical Products
- 4.1 User Task Analysis
- 4.2 Usability Evaluation
- 4.3 Workload Evaluation
- 4.4 Human Error Analysis
- 4.5 Design for Crewmember Physical Characteristics and Capabilities
- 4.6 Handling Qualities Evaluation
- 4.7 Acoustic Noise Control Design
- 4.8 Radiation Shielding Design
- 4.9 Functional Volume Design
- 4.10 Crew Survivability Assessment
- 4.11 Metabolic Loads and Environmental Control Life Support System Design
- 4.12 Display Format Design
- 4.13 User Interface Labeling Design
- 4.14 Occupant Protection Design
- 4.15 Design for Deconditioned Crewmember
- 4.16 Design for Mitigation of DCS Risk
- 4.17 Space Food System Design
- 4.18 Legibility Evaluation

As defined in NPR 8705.2B, a crewed space system consists of all the system elements that are occupied by the crew during the mission and provide life-support functions for the crew. The crewed space system also includes all system elements that are physically attached to the crew-occupied element during the mission, while the crew is in the vehicle or system. Throughout HIDP, the terms “spacecraft” and “vehicle” are used synonymously to mean the system elements (e.g., orbiters, habitats, or suits) that are occupied by crew during any mission phase and that provide life-support functions for the crew. Acronyms and definitions can be found in Appendix A and Appendix B, respectively.

It is important to note that the processes described in HIDP do not cover all activities necessary to ensure effective system design. Appendix C contains a list of possible additional HIDP chapters. This process document may be used in addition to existing design methods to apply a human-centered design perspective to various subsystems in a way that is appropriate to the particular aspect and the overall system. All human-centered design activities identified in this document are applicable, in varying degrees, at any stage in system development.

2.0 DOCUMENTS

2.1 APPLICABLE DOCUMENTS

Document Number	Document Revision	Document Title
NASA-STD-3001	March 5, 2007	NASA Space Flight Human-System Standard Volume 1: Crew Health
NASA-STD-3001	January 10, 2011	NASA Space Flight Human-System Standard Volume 2: Human Factors, Habitability, and Environmental Health
NPR 8705.2B	May 6, 2008	Human-Rating Requirements for Space Systems (w/change 4 dated 8/21/2012)

2.2 REFERENCE DOCUMENTS

The list of reference documents is extensive and can be found in Appendix C.

3.0 HUMAN-SYSTEMS INTEGRATION PROCESS

3.1 HUMAN-SYSTEMS INTEGRATION (HSI)

Human-Systems Integration (HSI) is a process by which knowledge of human capabilities and limitations is integrated within the systems engineering life cycle. A key component of HSI is the concept of a human as a system, which should be integrated throughout the life cycle. The HSI process has a broad scope that includes a wide variety of technical domains and specialties, such as personnel, training, safety, environments, toxicology, medicine, human factors, and many more. Because HSI requires the integration of multiple technical processes, a Human-Systems Integration Plan is a deliverable at the major design milestones defined in NPR 7123.1 NASA Systems Engineering Processes and Requirements (pending) and its supporting handbook (NASA-SP-2007-6105; pending).

A key component of the HSI process that is borrowed from the human factors domain is "human-centered design." Human-centered design is a methodology used to ensure that a design accommodates human capabilities and limitations. The following sections explain HCD in greater detail and provide guidance on how to implement the HCD approach in systems design.

3.2 HUMAN-CENTERED DESIGN

3.2.1 RATIONALE FOR HUMAN-CENTERED DESIGN

This section provides an overview of a human-centered design approach based on the International Standards Organization (ISO) 13407: Human-Centered Design Processes for Interactive Systems. Human-centered design (HCD) is an approach to development of interactive systems that focuses on making systems usable by ensuring that the needs, abilities, and limitations of the human user are met. HCD is a multidisciplinary activity that involves a range of skills and stakeholders who collaborate on design. Most importantly, HCD is an iterative activity that intentionally uses data gathered from users and evaluations to inform designs. The benefits of the HCD approach can be realized in terms of cost control, mission success, and user satisfaction.

Development costs of an engineering life cycle are controlled through the iterative calibration of designs based on structured analyses and evaluations, which involve the user / customer and are measured against applicable requirements. Taking these iterative steps eliminates the occurrence of late design changes or rework during production, which have costly impacts.

Mission success is optimized when attention is paid to human interfaces that provide operational clarity and consistency and reduce potential for human error, performance failure, injury, or illness. Though not designed, the human user may be viewed as a functional subsystem of the greater system. Therefore, the designs that are created for the mission and the system must accommodate the human, within the additional constraints of the natural environments.

User satisfaction is increased by involving the user in the HCD process so that users understand and participate in design decisions. This is especially important when the human user will have critical control responsibilities over the system or when user interaction is important to mission goals.

3.2.2 PRINCIPLES OF HUMAN-CENTERED DESIGN

The human-centered design approach is characterized by 4 principles:

- Active involvement of users and a clear understanding of user and task requirements
- Function allocation between users and technology
- Design iteration
- Multidisciplinary design

3.2.2.1 ACTIVE INVOLVEMENT OF USERS AND A CLEAR UNDERSTANDING OF USER AND TASK REQUIREMENTS

Users provide valuable knowledge about the context of use, the tasks, and how users are likely to work with the future product or system. NASA users include astronauts who function as commanders, pilots, or technical specialists (e.g., mission specialist or payload specialist); ground operations personnel; mission operations personnel; scientists with a wealth of knowledge collected from research and studies; and engineers with extensive knowledge and data collected over years of experience with human space flight and space habitation. It is important that the user(s) be included in the development of a product or system. Active involvement of users allows for increased understanding of user needs, feedback on how they will use the product or system, and the demands imposed by a task. This understanding leads to the inclusion of proper task and system requirements, and results in improved design decisions.

3.2.2.2 FUNCTION ALLOCATION BETWEEN USERS AND TECHNOLOGY

One of the most important human-centered design principles concerns the appropriate allocation of function – the specification of which functions should be performed by the users and which by the system. These design decisions determine the extent to which a given job, task, function or responsibility is to be automated or assigned to human performance.

Designers making the decision should weigh the relative capabilities and limitations of the human vs. technology, and the decision should be based on many factors such as reliability, speed, accuracy, strength, flexibility of response, financial cost, the importance of successful or timely accomplishment of tasks, and user well-being. Decisions should not simply be based on determining which functions the technology is capable of performing and then simply allocating the remaining functions to users, relying on their flexibility to make the system work. The resulting human functions should form a meaningful set of tasks. Representative users should be involved in these decisions.

3.2.2.3 DESIGN ITERATION

In addition to results from modeling, analyses, and tests, feedback from the users is a critical source of information for iterating design solutions. Iteration, when combined with active user involvement, provides an effective means of minimizing the risk that a system does not meet user or mission requirements, including requirements that are hidden or difficult to specify explicitly. Iteration allows preliminary design solutions to be tested against “real-world” scenarios, with the results being fed back into progressively refined solutions.

3.2.2.4 MULTIDISCIPLINARY DESIGN

Human-centered design involves the application of a range of technical expertise to adequately address the human aspects of the design. This means that multidisciplinary teams should be involved in a human-centered design process. The composition of the teams should reflect the relationship between the organization responsible for technical development and the customer. The roles can include the following:

- Customer (e.g., users such as scientists, engineers, or operations managers)
- Systems analysts, systems engineers, programmers, scientists, subject matter experts
- User interface designers, visual designers
- Human factors and ergonomics experts, human-computer interaction specialists
- Technical writers, trainers, and support personnel

Individual team members can cover a number of different skill areas and viewpoints. Multidisciplinary teams do not have to be large, but the team should be sufficiently diverse to make appropriate design tradeoff decisions.

3.2.3 HUMAN-CENTERED DESIGN ACTIVITIES

This section describes human-centered design activities tailored for NASA spacecraft design. In these activities, the user may be referred to as “crew” or “crewmember.” The HCD process comprises 3 main activities that are performed iteratively in a feedback loop as represented in Figure 3.2.3-1. The HCD process is conducted and iterated throughout the overall systems engineering life cycle. The HCD activities are shown in the context of the systems engineering milestones in section 3.4. The HIDP processes in section 4 are either structured around or a part of these activities, which are described in paragraphs below.

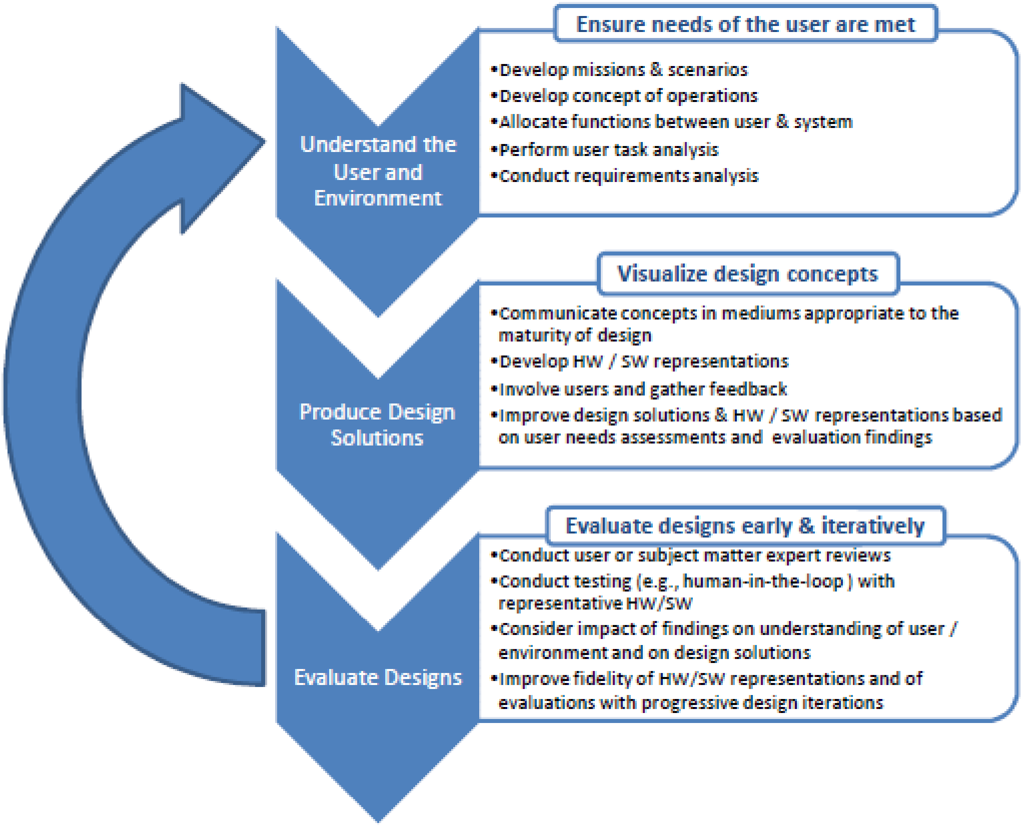


FIGURE 3.2.3-1 HUMAN-CENTERED DESIGN ACTIVITIES

3.2.3.1 UNDERSTAND THE USER AND ENVIRONMENT

Understanding the user and the operating environment is important to ensuring that design solutions meet the needs of the user within constraints of the operating environment. “Understanding the user and environment” means gaining a full awareness of the user (i.e., capabilities and limitations, skills and expertise), the work environment’s constraints and challenges (e.g., microgravity, isolation, small enclosed volumes), and the tasks that will be performed to accomplish the mission (e.g., piloting, maintenance, eating, and sleeping). Understanding is gained through conducting the following activities:

- Develop missions and scenarios
- Develop concept of operations
- Allocate functions between user and system
- Perform user task analysis
- Conduct requirements analysis

3.2.3.1.1 DEVELOP MISSIONS AND SCENARIOS

In accordance with NPR 8705.2B, human-rating certifications are based on program-defined reference missions, which establish the objectives and scope of the program and space system. Reference missions are established during the early phases of spacecraft development. From these, the nominal, off-nominal, and emergency scenarios are defined.

For example, the reference mission that the commercial crewed spacecraft and JSC 65993 Commercial Human-Systems Integration Requirement (CHSIR) are based on is to provide ISS increment crew rotation for up to 4 NASA crewmembers. The example nominal scenario includes the following events, which are illustrated in Figure 3.2.3.1.1-1.

- Vehicle maintenance and processing at launch site
- Launch
- Up to a 3-day transit to International Space Station (ISS)
- Quiescent vehicle-docked phase of up to 210 days
- Less than 2 days for return to Earth from ISS
- Post-landing operations no greater than 2 hours

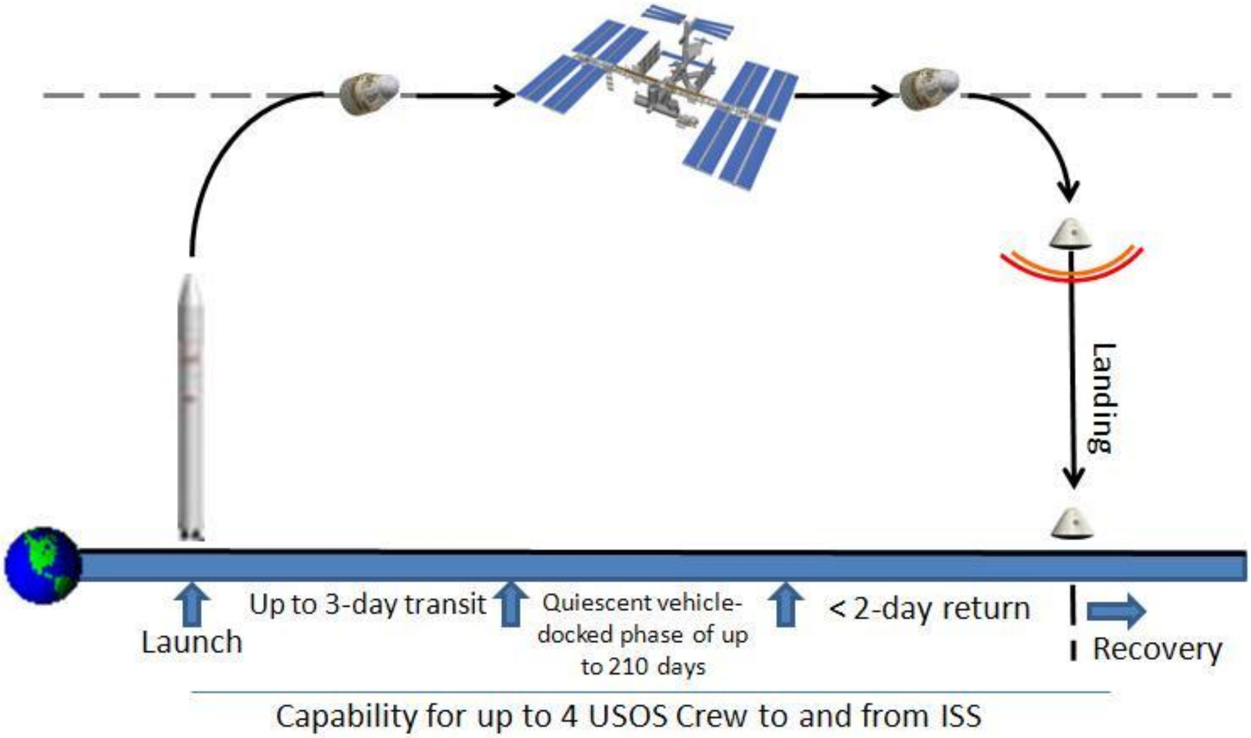


FIGURE 3.2.3.1.1-1 NOMINAL COMMERCIAL CREW TRANSPORT MISSION (ASSUMED FOR CHSIR)

The off-nominal and emergency scenarios addressed in CHSIR include, but are not limited to:

- Emergency evacuation from ISS if it becomes uninhabitable
- Medical evacuation if one crewmember becomes ill or injured with a life-threatening, time-critical condition beyond the medical capability to treat on ISS
- Safe haven capability for 4 United States Orbital Segment crewmembers

3.2.3.1.2 DEVELOP CONCEPT OF OPERATIONS

The Concept of Operations (ConOps) is developed for all scenarios to describe how mission objectives will be accomplished using planned resources, including crew and system. The ConOps gives an overall picture of the operation from the perspective of the users who will operate the system.

As a tool for developing ConOps, it may be useful to visualize each scenario in a table such as the example shown in Table 3.2.3.1.2-1. The example takes a notional scenario for travel to ISS and identifies, initially at a high level, the planned crew activities for each phase of the mission. The table also identifies subsystems that may be influenced by crew activities associated with the notional scenario, which may influence subsystems design. Similar tables should be created for other segments of the mission (e.g., quiescent vehicle docked, return to Earth, post landing) and for the off-nominal and emergency scenarios. As design matures, more detailed tables are created to break up and clearly define the mission phases. ConOps should evolve to cover the end-to-end system as the system capabilities, including the user, become better defined through the conduct of activities in the iterative human-centered design process.

TABLE 3.2.3.1.2-1 EXAMPLE NOMINAL SCENARIO - TRAVEL TO ISS (NOTIONAL)

Mission Phase	Crew Activities					Subsystems Affected
	Crew 1	Crew 2	Crew 3	Crew 4	Crew 5	
Vehicle Boarding	Ingress in suit	Ingress in suit	Ingress in suit	Ingress in suit	Ingress in suit	Architecture ECLSS* Lighting
Launch Prep	Checklist procedures	Checklist procedures	N/A	N/A	N/A	ECLSS Lighting Windows Controls, displays
Launch	Checklist procedures	N/A	N/A	N/A	N/A	ECLSS Lighting Controls, displays
Ascent	Checklist procedures	Eat Waste Sleep	Eat Waste Sleep	Eat Waste Sleep	Eat Waste Sleep	ECLSS Lighting Controls, displays
Orbit	Eat Waste Sleep	Eat Waste Sleep	Eat Waste Sleep	Eat Waste Sleep	Eat Waste Sleep	ECLSS Hygiene Stowage & trash Lighting
Proximity Operations	Checklist procedures	Checklist procedures	N/A	N/A	N/A	ECLSS Lighting Windows Controls, displays
Rendezvous	Checklist procedures	Checklist procedures	N/A	N/A	N/A	ECLSS Lighting Windows Controls, displays
Dock/Berth	Checklist procedures	Checklist procedures	N/A	N/A	N/A	ECLSS Lighting Windows Controls, displays Architecture

*Environmental Control and Life Support System (ECLSS)

3.2.3.1.3 ALLOCATE FUNCTIONS BETWEEN USER AND SYSTEM

Function allocation significantly influences design decisions by establishing which functions are to be performed by the users and which by the system. Based on the ConOps, function allocation determines the extent to which a given activity, task, function, or responsibility is to be automated or assigned to humans. Function allocation is based on many factors, such as relative capabilities and limitations of humans and technology in terms of reliability, speed, accuracy, strength, flexibility of response, financial cost, the importance of successful or timely accomplishment of tasks, and user well-being. Decisions should not be based simply on determining which functions technologies are capable of performing and then allocating the remaining functions to users, relying on their flexibility to make the system work. The resulting human functions should form a meaningful set of tasks. Task analyses and tests may be useful in evaluating performance to help to determine allocations. Representative users should be involved in these decisions. According to NPR 8705.2B paragraph 2.3.3, documenting the design philosophy for utilization of the crew is an important step in improving safety and mission success. When unexpected conditions or failures occur, the capability of the crew to control the system can be used to prevent catastrophic events and aborts.

Function allocations evolve as the system capabilities, including the user, become better defined through the conduct of activities in the iterative human-centered design process.

3.2.3.1.4 PERFORM USER TASK ANALYSIS

The purpose of task analysis is to analyze how the user interacts with the space system and to define the tasks, which direct design concepts and decisions. Task analyses should be performed for all functions allocated to human users for the established mission objectives, scenarios, and ConOps. For each function allocated to human users, define the physical and cognitive tasks that must be accomplished and describe pertinent task attributes such as

- User roles and responsibilities
- Task sequence
- Task durations and frequencies
- Environmental conditions
- Necessary clothing and equipment
- Constraints or limiting factors
- Necessary user knowledge, skills, abilities, or training

Representative users should be involved in task analysis activities. HIDP section 4.1 provides additional details and guidance on performing user task analysis. Task analyses also contribute to the development of operational task procedures, which should be evaluated with design concepts.

Task definitions should evolve as the system capabilities, including the user, become better defined through the conduct of activities in the iterative human-centered design process.

3.2.3.1.5 CONDUCT REQUIREMENTS ANALYSIS

As operating scenarios, function allocations, and tasks become better defined, design requirements should be revisited and refined, and documentation updated. A comparison of analyzed task requirements to program requirements may reveal discrepancies or gaps, perhaps due to incorrect assumptions that were made early-on during concept development and the establishment of program requirements. To direct refinement and maturity of system design, the developer may find it useful to document results of requirements analyses as system-interface requirements.

3.2.3.2 VISUALIZE AND PRODUCE DESIGN SOLUTIONS

In this activity, candidate design solutions should be visualized through graphical or physical representations based on information gathered in the activities described in section 3.2.3.1 Understanding the User and Environment. Design concepts may be communicated in many forms, depending on the maturity of the design, and may range from paper and pencil sketches to interactive prototypes to high-fidelity mockups or computer-based simulations. It is important during this activity to communicate ideas and involve the user in focused design reviews to gather feedback. Designs and their physical representations should be iteratively improved based on user feedback until acceptable solutions are achieved. Consider the use of available NASA design data, models, and equipment when producing design solutions.

3.2.3.3 EVALUATE DESIGNS AND ITERATE SOLUTIONS

This activity evolves designs by identifying areas for design improvement through the gathering of quantitative and qualitative data. Intentional design iteration is a fundamental principle of human-centered design that contributes to control of life-cycle development cost by helping to identify risks and issues early in the design cycle when they are relatively inexpensive to fix. Evaluation of design concepts and alternatives is crucial to achieving optimal design solutions. Evaluations begin early and continue throughout system design. Evaluations can include a wide variety of activities, such as informal reviews with subject matter experts (SMEs) or users, formal usability tests for gathering quantitative performance data or qualitative observations, assessments of design based on human-in-the-loop (HITL) evaluation (required by NPR 8705.2B paragraph 2.3.10), and flight simulations to assess vehicular handling qualities and vehicle controllability by pilots. NASA expects all evaluations with human test subject participation to have institutional review board (IRB) approval.

Fidelity and integration increase with maturation of the design. As the design matures, high-fidelity evaluations are used, progressing from computer-aided design (CAD) analyses to HITL evaluations in a flight simulator. Likewise, integration of the system in the evaluation also increases as design matures. Early in design, single-system or even single-component evaluations are performed. As the design matures, evaluations include entire subsystems, systems, and eventually integrated systems. HIDP sections

4.2 and 4.3 provide additional detail and guidance on usability and workload evaluations, respectively.

Evaluations focus on specific objectives, and plans are developed to include details such as

- Human-centered design goals
- Responsibility for evaluation
- Parts of the system to be evaluated and how they'll be evaluated (e.g., by use of computer simulations, mockups or prototypes, or test scenarios)
- How the evaluation is to be performed (e.g., test setup, methodology)
- The procedures to be used in the evaluation
- Resources required for evaluation and analysis, including users and test subjects
- Scheduling evaluation activities and resources, including users/test subjects and concrete design proposals (e.g., models, simulations, mockups)
- Intended use of results/feedback

Evaluation findings are used to reassess understanding of the user and environment and to re-plan design solutions in an iterative, feedback loop. Therefore, as designs mature each successive evaluation should be performed with more complete and flight-representative inputs, simulations, or hardware (e.g., mockups, qualification units, etc.). Intentional design iteration is a fundamental principle of human-centered design that contributes to control of life-cycle development cost by helping to identify risks and issues early in the design cycle when they are relatively inexpensive to fix.

3.3 ROLES AND RESPONSIBILITIES

3.3.1 THE HUMAN-SYSTEMS INTEGRATION (HSI) TEAM

The Human-Systems Integration (HSI) Team is the group that holds authority, responsibility, and accountability for implementing human-centered design principles and processes during development of new crewed space systems. These systems may include integrated space vehicle systems with human interfaces for diagnostics and control, habitable environments, or solutions that protect crew from hostile or extreme environments. Ensuring effective human-systems integration across the design is particularly important for crewed space system design because of the increased risk, associated with space flight, to human health and performance, as well as the reliance on human capability as part of total system performance. HSI considers all aspects of human interaction with the design. It is the role of the HSI Team to guarantee that this integration occurs, beginning with the earliest design concepts and continuing iteratively during the engineering life cycle through operations and decommission.

3.3.2 HSI TEAM BASIS IN NASA REQUIREMENTS

An HSI Team is required for NASA human rating and is described in NPR 8705.2B Human-rating Requirements for Space Systems paragraph 2.3.8, which states:

> 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).

> *Rationale: Past experience with cockpit development in spacecraft and military aircraft has shown that when a correctly staffed human-system integration team is given the authority, responsibility, and accountability for cockpit design and human integration, the best possible system is achieved within the schedule and budget constraints. This team focuses on all human system interfaces (crew, launch control, and ground processing) that can cause a catastrophic failure.*

For a given NASA program, the managing program office establishes the NASA HSI Team, which is composed of NASA members representing various stakeholder disciplines, and representation from the space system developer.

3.3.3 TECHNICAL SCOPE OF THE HSI TEAM

To integrate a design across multiple disciplines, an HSI Team must have significant depth and breadth of technical expertise to review and evaluate a significant majority of design considerations. Areas of technical expertise necessary for proper HSI include, but are not limited to:

- Human factors and human engineering (including crew workload and usability, human-in-the-loop evaluation, and human error analysis)
- Crew health and countermeasures
- Environmental health (including radiation, toxicology, and other areas)
- Safety
- Systems engineering
- Architecture
- Crew functions and habitability functions (including nutrition, acoustics, water quality and quantity, etc.)
- Crew interfaces and information management
- Maintenance and housekeeping
- Ground maintenance and assembly
- Extravehicular activity physiology
- Mission operations
- Training

3.3.4 THE ROLE OF THE HSI TEAM

The NASA HSI Team provides guidance in human-centered design practices throughout the design process. This includes reviewing deliverables that are due at each Program milestone to ensure that iterative and adequate HSI design considerations are taking place throughout the engineering life cycle. Appropriate subject matter experts from the HSI Team interact with system designers between milestone reviews to provide guidance and expertise, ensuring that human-centered design issues are identified early to avoid cost and schedule impacts. The HSI Team has the authority to elevate issues directly to Program Management for resolution and to document formal acceptance or lack of acceptance of the deliverables provided. It is important that the NASA HSI Team include participation by the space system developer for effective human-centered design (HCD) implementation. Membership on the NASA HSI Team ensures that the developer is involved in discussions of design reviews, stakeholder reviews, evaluations, and other activities such as system analyses and design trades, to communicate information to and from appropriate subject matter experts within the developing group or company and provide design insight as needed. Note that the developer may also choose to form an internal HSI Team as an interface with the NASA HSI Team. The mechanism by which the developer chooses to handle this internally would be left up to their discretion. The NASA HSI Team serves as the official representative body for HSI and HCD implementation, providing official positions to any and all developers and NASA oversight boards and panels. This level of authority is necessary for an HSI Team to fulfill its responsibility.

3.3.5 HSI TEAM REVIEW OF DELIVERABLES

The NASA HSI Team is involved in review of all human-rating deliverables, as detailed in a program’s Human-Rating Certification Plan (HRCP). The deliverables due at each stage of the engineering life cycle are multiple and varied. The technical products presented in sections 3.4 and 4 of the HIDP may or may not be required deliverables. The determination will be made by the managing program. The NASA HSI Team should have insight into design progress between milestones to facilitate review of applicable materials at each milestone. This reinforces the concept of *early and often* inclusion of the HSI Team as part of an HCD process. For specific details of the HRCP requirements and other human-rating requirements, refer to NPR 8705.2B Human-rating Requirements for Space Systems.

3.4 SUMMARY OF HIDP TECHNICAL PRODUCTS

To facilitate successful development and the ultimate achievement of requirement compliance and human-rating certification, each HIDP process suggests key technical products that should be assessed by the NASA HSI Team throughout the engineering development life cycle. The technical products are identified on the basis of experiences with other NASA programs and projects. Subject matter experts have determined these products to be important indicators of progress toward verification and certification achievement.

3.4.1 GENERIC TECHNICAL PRODUCTS

A summary of generic technical products and the life cycle review by which they should be provided is presented in Table 3.4.1-1. Definitions for the products are provided below the table. Individual processes may have unique product details or schedules. Refer to the individual process sections for specific details.

TABLE 3.4.1-1 SUMMARY OF GENERIC TECHNICAL PRODUCTS

Technical Products		Phase A		Phase B	Phase C	Phase D	
		SRR	SDR	PDR	CDR	SAR	FRR
A description of each reference mission for which human rating is being pursued. Required per NPR 8705.2B paragraph 2.3.1.		X	---	---	---	---	---
A description of the Human-Systems Integration Team and their authority within the program. Required per NPR 8705.2B paragraph 2.3.8.		X	---	---	---	---	---
A description of the ConOps, function allocation, and associated crew task lists.		I	U	U	U	---	---
A summary of modeling/analysis/evaluation performed to date and the influence on system design with links to the detailed analysis results. Required per NPR 8705.2B, and HITL evaluations required per paragraph 2.3.10.		---	---	I	U	U	---
System architecture drawings (structures, equipment, etc.), material specifications, interface requirements.		---	---	I	U	U	---
Verification plan.		---	---	I	U	U	---
X = one-time release of item I = initial release of item U = updated release of item							

3.4.2 DEFINITIONS OF GENERIC TECHNICAL PRODUCTS

Reference Missions

Before System Requirements Review (SRR), NASA will provide a description of each reference mission for which human rating is being pursued. Defining reference missions establishes the scope of the program to be human rated and also provides a framework that supports, among other things, identification of crew survival strategies and establishment of scenarios to be used for hazard analysis and risk assessments. The reference missions also define the interfaces with other systems, such as mission control centers, that functionally interact with the crewed space systems. This information is required by NPR 8705.2B paragraph 2.3.1, and it is essential as input for products such as Concept of Operations and crew task lists.

Human-Systems Integration Team

No later than SRR, NASA programs will provide a description of the NASA HSI Team and their authority within the program (required by NPR 8705.2B paragraph 2.3.8). The description will also include how the NASA HSI Team will interface with NASA Program boards and the developing company’s boards, if applicable. Past experience with cockpit development in spacecraft and military aircraft has shown that when HSI teams have the expertise, authority, responsibility, and accountability for cockpit design and human integration throughout the project life cycle, the best possible system is achieved. The HSI Team focuses on human-system interfaces (crew, launch control, and ground processing) that can lead to a catastrophic failure if they do not work properly.

Concept of Operations and Crew Task Lists

The ConOps, described in paragraph 3.2.3.1.2, provides information such as identification of crew activities and determination of which subsystems are influenced by crew activities. Function allocation, described in paragraph 3.2.3.1.3, establishes the extent to which an activity is to be automated or assigned to humans. The crew task list, described in section 4.1 User Task Analysis, documents details including allocation of function between crew and systems, definition of the crew activities sequence, and identification of critical tasks. As the crew task list evolves through the design cycle, its final iteration should become crew procedures.

Summaries of Modeling, Analyses, and Evaluations

Iterative summaries of modeling, analyses, and evaluations provide NASA with insight into human-system integration technical details throughout the design process. As designs mature, modeling, analyses, and evaluations should use inputs and mockups of increasingly higher fidelity, as discussed in paragraph 3.2.3.3 Evaluate Designs and Iterate Solutions. It is important that summaries address how key and critical design decisions were assessed. In accordance with NPR 8705.2B, updated summaries are to be provided at each design review through SAR. Also, in paragraph 2.3.10, the use of human-in-the-loop evaluation is a required method to progressively demonstrate that the operational concept meets system requirements for operational safety, efficiency, and user interface design.

Architecture, Materials, and Interface Specifications

Specifications for drawings, materials, and interfaces provide NASA with insight into human-systems integration technical details throughout the design process.

Verification Plan

The verification plan is a formal document describing the specific methodologies to be used to show compliance with each requirement. For some aspects of spacecraft design, such as radiation shielding, the program’s approach to verification is developed at SRR and reflected in the verification plan.

4.0 HIDP PROCESSES

4.1 USER TASK ANALYSIS

4.1.1 INTRODUCTION

Task analysis is a methodology used to break an event down into tasks and break tasks down into components. It is used to understand and thoroughly document how tasks are accomplished. This section explains the process for conducting a task analysis, and the associated decomposition of physical and mental (i.e., cognitive) activities, activity frequency and duration, task allocation, inter-task dependencies, task criticality and complexity, environmental conditions, necessary clothing and equipment, and any other unique factors involved in or required for one or more people to perform a given task.

A task analysis identifies system-level and subsystem-level tasks, to determine operator needs for established mission objectives and concepts of operation. The focus is on humans and how they perform the task, rather than on the system. When performed throughout the vehicle iterative design process, task analysis can be used to help drive the design of optimal human-system interfaces and to ensure that the design of vehicle components supports the needs of the human for all mission tasks that must be performed. Additional information on using task analysis in the human-systems integration design process can be found in chapter 3 of the NASA/SP-2010-3407 Human Integration Design Handbook (HIDH).

This section details the task analysis process that should be used for identification of critical crew and space system tasks necessary for vehicle, system, and hardware design and verification. When used in conjunction with human factors guidelines, human-in-the-loop testing, and other analysis methods, task analysis can help to ensure that all crew-to-vehicle interfaces and operational environments provide the necessary physical or informational affordances for nominal and contingency tasks. HIDP section 3.2 discusses the human-centered design approach and activities, highlighting the importance of task analysis throughout the design life cycle.

4.1.1.1 PURPOSE

Task analysis is an essential component of human-centered design, focused on providing usable systems for humans throughout a system’s entire life cycle. Although it is recognized as a critical function in design, task analysis is often overlooked until late in design phases when hardware, system, and software designs are too mature to allow for changes that could increase crew efficiency and task performance. Therefore, it is imperative that task analysis begins as early in the design process as possible and continues to be done frequently as design matures. An iterative approach allows the identification of current and future task demands that can aid in decisions, such as which tasks should be allocated to a human instead of an automated system, or how system components should be used. Task analysis also results in the identification of critical crew tasks, which are tasks that are absolutely required and necessary for crews to successfully accomplish operations and meet mission objectives. Critical crew tasks may occur nominally or off-nominally and include tasks that are essential to crew health or, if done incorrectly, may lead to loss of crew, loss of mission, or undesirable vehicle states. Identifying these tasks early, can enable efforts to be made to implement designs that reduce the probability of mishaps or errors and allow crews to perform tasks within expected time limits and environmental conditions. Thus, errors can be avoided, safety can be improved, and crew time can be optimized.

4.1.1.2 SCOPE

Task analysis is a fundamental design activity necessary for implementing many human system requirements. In support of verification, task analysis assists in scoping the specific scenarios for which the verification should be performed. It is used to ensure that provided design solutions meet the needs of associated crew and system tasks. Early and iterative task analyses are recommended to avoid late and costly changes. A single task analysis activity may concurrently address multiple requirements.

4.1.2 TASK ANALYSIS PROCESS OVERVIEW

Task analysis refers to a family of techniques (see Ainsworth, 2004) that involve the systematic identification of the tasks and subtasks involved in a process or system and the analysis of those tasks (e.g., who performs them, what equipment is used, under what conditions, the priority of the task, and dependence on other tasks). A high-level task analysis is one of the first steps in vehicle design. Initial definition of a task occurs during the Concept and Technology Development Phase, when mission, operations, and requirements are refined and clarified. Task definition and descriptions should continue to evolve as designs and plans are developed and crew utilization and functional allocation are defined. At later stages, the focus should be on capturing the lower-level crew and system interactions required for successful mission completion. Interactions include physical and cognitive activities, the latter of which includes perceptual (e.g., visual, tactile, and auditory), decision-making, comprehension, and monitoring activities.

As designs materialize into proposed solutions during the Preliminary Design Phase, evaluation of these designs should be performed using identified crew tasks. Findings from evaluations should be used to improve designs and to evolve and refine crew tasks. Thus task analysis informs the selection of tasks for other analysis methods, which in turn results in modified designs and enhanced knowledge that can be captured in subsequent task analyses. The process of iterative design, task analysis, and evaluation of the needs of the users should continue until a design is achieved that allows the user to perform all necessary tasks and operations during the course of a defined mission.

4.1.2.1 TASK ANALYSIS APPROACH

Both physical and cognitive tasks are addressed in a user task analysis, which is performed with subject matter experts (SMEs) throughout the vehicle design process. To provide structure to the analysis, tasks are often grouped by subsystem so that they are related to concepts such as food, hygiene, vehicle control and monitoring, crew safety and health, environment, maintenance, and other concepts that affect mission objectives, vehicle architecture, and interfaces. For data collected at a subsystem or component level, considerations need to be made for how crew and system-level tasks may be affected by or have an effect on each component and the fully integrated vehicle. Understanding these inter-dependencies may make it possible for knowledgeable designers and engineers to influence the subsequent development of mission-related task sequences or concepts of operation. Such influence will be needed throughout the process of designing systems and hardware.

It is recommended that task analysis sessions be conducted, not only at the component or hardware level, but also by mission phase. Task analyses by mission phase can help determine that all of the necessary hardware and software is available to crewmembers when it is needed throughout the mission. The analysis should generally focus on interfaces (hardware and software) and locations within the spacecraft with which crewmembers have direct interaction during a mission.

4.1.2.1.1 TASK ANALYSIS EXECUTION

The task analysis execution process involves group interviews with SMEs. In preparation for the task analysis session, the specific objectives of the session should be defined. For example, the mission phase and relevant systems should be specified. The level of task detail (e.g., high-level tasks and goals versus low-level crew activities) most appropriate to the phase of design should also be determined. Objectives that are concise and detailed will help to ensure that consistent data are captured from session to session.

After the objectives are specified, the conductors of the task analysis should review appropriate reference documents (such as requirements, standards, and engineering drawings) and identify currently understood tasks, mission operations, scenarios, related systems, and possible operational constraints from crew, system, and vehicle perspectives. Task analysis conductors should also identify any specific areas of uncertainty or questions that specifically need to be addressed by the SMEs during the task analysis session.

Formal task analysis should be conducted with appropriate SMEs for each individual topic area based on the objectives of the task analysis. SMEs may be system engineers, safety representatives, mission operations experts, crewmembers, or other individuals with specialized knowledge about the tasks of interest. Before the task analysis session is conducted, briefings on related system hardware and interfaces, vehicle constraints, mission objectives, assumptions, relevant requirements, and other details should be compiled and provided to the SMEs. This should be done to ensure that all involved parties have a common and clear baseline understanding of the topic area being assessed and the objectives of the task analysis session. Providing SMEs with a preliminary task list is sometimes recommended to allow efficient use of time and resources.

During the task analysis session, one member of the task analysis team should serve as the moderator, while other members serve as co-moderators or note takers. The moderator should begin the session by reminding the participants about the objectives of the session and the scenario or topic area being addressed. It may be helpful to provide reference material, such as hardware drawings or preliminary task lists, for participants to refer to. Throughout the session, the moderator’s role is to ensure (through appropriate queries) that the objectives of the session are met and all SMEs have an equal opportunity to provide input.

Data collected during the session should address multiple aspects of the task. For example, when conducting a task analysis regarding hygiene, it is critical to address not only the tasks required to perform hygiene such as unstowing crew provisioning items and setting up the hygiene area, but also other considerations such as the mission phases when hygiene should occur; how many crewmembers can conduct the hygiene tasks at one time; the type of hardware (restraints, mobility aids, or crew provisioning equipment) necessary for hygiene; and any environmental constraints. Task analysis data collection should include, but not be limited to, the following items for each scenario and individual task:

- Tasks that are required to achieve mission objectives
- Tasks that are required for each mission phase
- Task priority and criticality
- Nominal and off-nominal crew tasks
- Integrated human-system tasks and system interactions
- Crew monitoring activities
- Potential impacts on and impedances to crew tasks
- Vehicle, environmental, safety, operational, and crew constraints on tasks
- All human interfaces (hardware and software) with which the crew will interact to accomplish tasks, including tools and equipment needed to accomplish tasks
- Required communication with the ground
- Function allocation for manual and automated crew and system tasks
- Vehicle information and resources required to perform tasks
- Vehicle/system state
- Expected results of task errors or failures in task completion
- Required operator inputs
- Performance expectations
- Data related to task time (e.g., duration, frequency, limits)
- Task sequences (parallel, serial, multiple crewmembers and/or systems, individual crewmembers and/or systems)
    - Identify when tasks are initiated, concluded, or terminated (i.e., “trigger” conditions)
    - Identify how decisions are made within a task (e.g., decision trees)

The moderator should ensure that the data collected for each scenario and task is complete with regard to these aspects. Any aspects about which SMEs disagree or in which knowledge is incomplete should be documented.

On completion of SME interviews, members of the task analysis team should compare notes and then compile all crew and systems task data identified during the task analysis SME activities. All results from the sessions should be documented in a similar fashion to promote consistency and efficiency across sessions. Separate reports, task lists, and documentation can, and should be, maintained for individual task analysis sessions; however, it is preferred that all critical crew and systems task analysis data be consolidated and maintained in a Master Task List (MTL). Figure 4.1.2.1.1-1 depicts the task analysis execution process involving group interviews with SMEs.

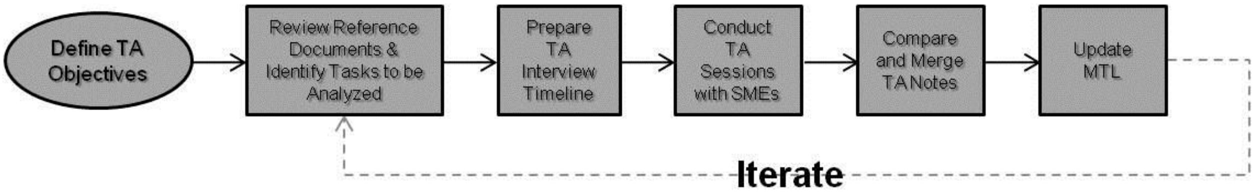


FIGURE 4.1.2.1.1-1 TASK ANALYSIS EXECUTION PROCESS

4.1.2.1.2 TASK ANALYSIS RESULTS AND DESIGN IMPLICATIONS

Task analysis data collection should yield an understanding of critical crew and systems tasks, inter-task interactions, and vehicle interactions. These task data can be used for system, hardware, and vehicle design; development of modeling and simulation products; concept of operations development; procedure development; human reliability assessment; and vehicle verification.

4.1.2.1.3 TASK ANALYSIS PRODUCTS

It is suggested that data collected during all task analysis sessions be documented individually per topic area (in the form of a summary report and task list) and in the form of a completed MTL, which serves as a compilation of all task analyses and their findings. The MTL serves a vital role in facilitating verification because so many verification activities rely on task requirements identified by means of task analyses. The MTL provides a common document for designers and test/verification personnel to find task analysis data.

The summary reports and MTL products should address and document the aforementioned data collection objectives, including the degree to which these objectives were met in the task analysis and the sources for the data collected, which can be used for future reference. It is assumed that as part of the iterative human-centered design process, the individual task lists, summary reports per topic area, and an updated MTL will be provided for each major milestone within the design life cycle. NASA will iteratively review task analysis products to ensure that identified tasks and design solutions provided meet the needs of the reference mission.

4.1.3 TASK ANALYSIS TECHNICAL PRODUCTS

For each of the major milestones of the design life cycle, the technical products in Table 4.1.3-1 are recommended.

TABLE 4.1.3-1 TASK ANALYSIS TECHNICAL PRODUCTS

Technical Products	Phase A		Phase B	Phase C	Phase D	
	SRR	SDR	PDR	CDR	SAR	FRR
Completion of "Round 1" of all task analysis sessions and related individual summary reports and task list. Master Task List (MTL) Rev A complete.	X	---	---	---	---	---
Completion of "Round 2" of all task analysis sessions and updates to related individual summary reports and task list. MTL Rev B complete.	---	X	---	---	---	---
Completion of "Round 3" of all task analysis sessions and updates to related individual summary reports and task list. MTL Rev C complete.	---	---	X	---	---	---
Task analysis sessions are complete and final versions of individual summary reports and task list are complete. Final MTL.	---	---	---	X	---	---
Hardware- and vehicle-based review of task analysis verification based on defined crew tasks and system tasks. Final review of any existing concerns or needs for task data.	---	---	---	---	X	---
Final hardware- and vehicle-based analysis based on defined critical crew tasks and systems tasks.	---	---	---	---	---	X

X = one-time release of item
I = initial release of item
U = updated release of item

4.1.4 REFERENCES

Ainsworth, L.K. (2004). Task analysis. In C. Sandom, R. Harvey (Eds.), *Human factors for engineers* (pp. 81–112). London: Institution of Engineering and Technology.

Loukopoulos, L. D., Dismukes, R. K., & Barshi, I. (2009). *The Multitasking myth: handling complexity in real-world operations*. Farnham, Surrey, England: Ashgate Publishing Limited.

Woolford, B. J., & Bond, R. L. (1999). Human factors of crewed spaceflight. In W. J. Larson & L. K. Pranke (Eds.), *Human spaceflight: mission analysis and design* (Chapter 6). New York, NY: McGraw-Hill.

4.2 USABILITY EVALUATION

4.2.1 INTRODUCTION

4.2.1.1 DEFINITION OF USABILITY

The International Standards Organization (ISO) defines usability as “the extent to which a product can be used by specified users to achieve specified goals” (ISO-9241-11, 1998). Usability is a key element of the human-centered design (HCD) approach, and it has been shown to increase efficiency, effectiveness, and user satisfaction. Furthermore, designs with good usability can reduce errors, fatigue, training time, and overall life cycle costs.

4.2.1.2 HUMAN-CENTERED DESIGN

Usability is a key component of human-centered design. Human-centered design focuses on users’ needs to design the system based on users’ capabilities. Usability testing and evaluation methods provide user performance measures and subjective (qualitative and quantitative) comments that can be used to improve the system in question throughout the engineering design life cycle.

Using the HCD process provides designers and engineers with direct feedback from the earliest stages of design, all the way through product use and distribution. Whether in the conceptual phase or in final prototyping, usability evaluations can elucidate design optimizations for increasing functional efficiency as well as determine potential design issues that could cause increased error rates and potential system failures.

4.2.1.3 ITERATIVE NATURE

Usability testing and evaluation is an iterative process. Usability evaluations should be conducted several times during the life cycle of the system, and results should have a direct influence on system design, providing continuous feedback for the designers of the system. Usability should be part of the system development life cycle from the earliest stages, to make sure that users’ needs, capabilities, and limitations are considered from the start of design and development.

4.2.1.4 APPLICABLE REQUIREMENTS

Usability requirements are specified in NASA-STD-3001 Volume 2 section 10.0 Crew Interfaces. The principal requirements are the 3 listed below:

- Usability Acceptance Criteria [V2 10001]
- Crew Interface Provision [V2 10002]
- Provision of Usable Interfaces [V2 10003]

NPR 8705.2B paragraph 2.3.10 requires human-in-the-loop usability evaluations for human-system interfaces. The NPR-required deliverables at PDR and CDR include summaries of how these evaluations should be used to influence system design.

4.2.2 CONDUCTING A USABILITY STUDY

A variety of methods and metrics may be used for the purpose of conducting a usability study; some of them are described in detail later in this section. Whichever methods and metrics are selected, a structured iterative approach based on human-centered design is to be used. This section provides a high-level, step-by-step approach that may be tailored to fit each usability study.

1. Define the purpose of the study
    - Decide what features of the system are to be tested during the design phase (e.g., features that may be problematic or frequently used features). For example, the purpose of the study may be to provide a basis for selecting between 2 cursor control device prototypes, or it may be to evaluate a specific display implementation.

2. Define tasks
    - Develop a list of crew and system tasks that are related to the tested features and define conditions that are relevant to these tasks. This procedure may include defining task criticality and frequency, identifying task dependencies and interactions, and defining operating environments (e.g., vibration, acceleration, lighting, suit conditions), as well as planning for associated resources such as personnel and equipment. For usability testing, the identification of potential errors that may be encountered for each task is also important.
    - Not all tasks can always be selected for usability testing if the number of possible tasks is large; therefore a subset of possible tasks may be selected. It is wise to select tasks that are frequently performed, tasks that are critical due to time constraints or potential for error, and tasks that involve a unique or novel type of interaction or understanding.

3. Define user sample
    - The users in the usability test should be a sample of the expected user group for the system. Factors to take into account may include age, gender, anthropometry, visual acuity, or special skill sets (e.g., trained pilots).

4. Select methods and metrics to be used
    - Possible methods and metrics for usability studies are discussed later in this section. The selection of methods and metrics depends on the purpose of the study, the number of subjects available, and the fidelity of prototypes or mockups. Gathering measures that will give you the relevant feedback for the design is critical; for example, if the design criteria of highest concern are time and errors, usability error rates would be an appropriate measure, whereas if user perceptions of simplicity are of highest concern, then ease of use, satisfaction, or aesthetics as evaluated by a survey or questionnaire may be more appropriate.

5. Plan evaluation design
   - Determine the appropriate number of subjects for the study. This may vary with the method selected. A minimum of 8-10 subjects is typically recommended. More subjects are needed to find less frequent design issues. Subjects should be representative of the user population in terms of experience, training, age, and other factors.

6. Collect data
   - Complete the collection of data according to previous planning steps. When mockup hardware or prototype software is used, the level of fidelity should be documented and taken into consideration when analyzing results.

7. Analyze data
   - The types of analyses conducted on data from usability tests depend on the objectives of the study. A quantitative analysis can help compare interfaces, determine whether error rates decreased with a new design, or compare efficiency of and satisfaction with the various designs. A qualitative analysis can point to reasons behind any usability issues and can provide information about user needs and preferences. The qualitative analysis looks at comments and observations provided by the users (e.g., the frequency with which different issues were mentioned).
   - Depending on the measures recorded, decide what descriptive and statistical methods can be used. Consult Sauro and Lewis (2005) about data from a small sample size (*n*) and statistical methods for user testing. Sometimes only descriptive statistics are appropriate (e.g., range, mean, median, standard deviation), whereas at other times it is appropriate to look at pairwise comparisons of performance measures.

4.2.3 USABILITY EVALUATION METHODS

Many usability evaluation methods exist. Some are conducted by human factors experts alone (e.g., heuristic evaluation, cognitive walkthrough) and others are conducted with the participation of users or test subjects (e.g., user testing, knowledge elicitation). Which method should be selected depends on the purpose and needs of the evaluation.

4.2.3.1 HEURISTIC EVALUATION

Heuristic analysis is an assessment of how a device or system conforms to well-established user interface design rules, and is performed by a human factors expert or group of experts.

Heuristic analysis is particularly useful early in the design process for identifying problematic aspects of the user interface. Also, it is useful for comparing potential interface designs because the assessments for each rule can be compared across products. This analysis method is usually quick and inexpensive. The weaknesses of heuristic analysis methods are that, generally, they are not applied in the actual use environment, and typical or expected device users are usually not involved in the evaluation. Heuristic analysis often yields good design insights early in the development process. However, it should be used in conjunction with other techniques that acquire input from expected users, especially when heuristic analysis is used later in the design process.

Based on the ten heuristic rules (listed below) developed by Jacob Nielsen (1993), the method provides a high-level evaluation of a system. Such evaluations are often completed by only one reviewer, although having multiple reviewers is recommended. Furthermore, expert reviewers usually find more issues than a novice usability analyst. When a heuristic evaluation is performed, the following heuristics can be used to evaluate the design:

1. Use simple and natural dialogue
2. Speak the user’s language
3. Minimize the user’s memory load
4. Maintain consistency
5. Provide feedback
6. Clearly mark exits
7. Provide shortcuts
8. Use good error messages
9. Prevent errors
10. Provide useful help and documentation

4.2.3.2 COGNITIVE WALKTHROUGH

Cognitive walkthrough involves a structured review of user actions for performing a sequence of predefined tasks. It involves working through the cognitive and motor actions a user would take for each step, to identify the steps in which the usability of the interface is not optimal. This method focuses on user tasks and user goals rather than evaluating the interface based on general guidelines. A cognitive walkthrough early in the design process permits evaluation of different preliminary design concepts. Later in the design process, when designs have become better defined, a cognitive walkthrough may still be productive.

4.2.3.3 CONTEXTUAL INQUIRY AND OBSERVATION

Contextual inquiry generally involves unobtrusive observation of users performing relevant tasks associated with the devices or similar devices in the actual use environment. Observing and working with users in their actual use environment permits a better understanding of the relevant tasks and workflow. This method is typically used early in the design process (i.e., during conceptual design and requirements analysis) to understand users and their tasks. This technique generally does not reveal cognitive processes, attitudes, or opinions.

4.2.3.4 DESIGN AUDITS

In a design audit, the proposed attributes and components of the user interface are compared against a checklist of good design practices. The checklist itemizes characteristics that the user interface should possess along with some method of recording whether or not the interface meets the listed standards and it can be built based on general standards documents such as ISO standards or the Human Integration Design Handbook (NASA/SP-2010-3407). Design audits are relatively quick and cost-effective but may yield only a superficial understanding of user interface issues.

4.2.3.5 DEVICE COMPARISONS AND FUNCTIONAL ANALYSIS

Alternative devices or alternative device concepts can be compared by arranging a list of devices and their attributes in a matrix format. The attributes of each of the device alternatives are assigned ratings or scored on a series of criteria. These comparisons can be useful for understanding which design approach best meets the user needs.

4.2.3.6 EXPERT REVIEWS

Expert reviews depend on the knowledge and experience of human factors specialists to identify design strengths and weaknesses and to recommend opportunities for improvement. Expert reviews combine the basics of heuristic evaluation and cognitive walkthrough. Depending on the expertise level of the evaluator, they can be very effective. To catch the majority of design issues, a minimum of 2 experts should evaluate a given interface. Expert reviews can be performed on design concept sketches as well as on working prototypes. Many serious design flaws can be detected early, without incurring costs for user testing. However, if used in isolation, this technique is unlikely to detect all of the design flaws.

4.2.3.7 FUNCTIONAL ANALYSIS

A functional analysis provides a representation of the functions and events required to meet system objectives. This type of analysis is used to determine the appropriate allocation of functions amongst humans and machines or automated systems. Numerous types of functional analyses can be performed, including operational sequence diagrams, the Functional Analysis Systems Technique (FAST), and computer simulation and modeling techniques (e.g., Systems Analysis of Integrated Network of Tasks [SAINT]).

4.2.3.8 INTERVIEWS

Often, it is useful to discuss design issues with a small group of users, especially when the goal is to generate ideas or reach consensus. Interviews can also be conducted individually. This method is for information gathering, not for evaluation. Structured or directed interviews are useful in circumstances in which the goal is to uncover answers to specific questions, often when designers are fairly well along in the design process. In contrast, unstructured interviews are useful for gaining initial insights about designs under conditions in which the designer wants to avoid biasing the interviewee in any particular direction.

4.2.3.9 PARTICIPATORY DESIGN

Participatory design provides potential users with tools that allow them to become ad-hoc design team members. Examples of the many tools available include 3-dimensional models of components that users might be asked to arrange in a preferred configuration, or 2-dimensional representations that users arrange to represent their ideas about a product’s design. Similarly, users could be asked to direct the efforts of an illustrator to represent their ideas, or to manipulate options on a computer screen.

4.2.3.10 USER TESTING METHODOLOGY

Usability testing and human-in-the-loop (HITL) evaluations are methods that evaluate a system by testing it with its users. The testing consists of asking users to complete tasks related to the system and capture their performance (e.g., error, deviation from optimal path, time) and subjective comments.

4.2.4 USABILITY METRICS

4.2.4.1 EFFECTIVENESS, EFFICIENCY, AND SATISFACTION

Many usability metrics exist that can be used in usability studies. The most relevant ones are the measures of effectiveness, efficiency, and satisfaction:

Effectiveness:	The accuracy and completeness with which users achieve certain goals. Indicators of effectiveness include the quality of the user’s solution and error rates.
Efficiency:	The relation between (1) accuracy and completeness with which users achieve certain goals and (2) resources expended in achieving them. Indicators of efficiency include task completion time and learning time.
Satisfaction:	Users' comfort with and positive attitudes toward the use of the system. Indicators of satisfaction include survey results and scores on standardized scales.

It is important to consider that efficiency, effectiveness, and satisfaction have been found to have low correlation among them (Hornbæk & Law, 2007; Sauro & Lewis, 2009). Therefore, it is advisable to measure all 3 factors to get an appropriate measure of usability.

4.2.4.1.1 METRICS OF EFFECTIVENESS

The most frequently used metrics of effectiveness are error rates and task/step success:

- Error rates
    - Error rates can be calculated in multiple ways: total number of errors on every step (possibly divided by the number of steps; e.g., out of 8 subjects, 5 committed an error on a given step), total number of errors on every task (e.g., 50 errors), or mean number of errors (e.g., 50 errors divided by 100 steps equals 0.5 error rate). The use of error *counts* across all task steps versus *rates* (where the number of steps is in the denominator, resulting in a ratio of errors to steps or a percentage) is at the discretion of the analyst, and should be guided by the specifics of the test.

- Task/step success
    - Task/step completion rates, e.g., 9 out of 10 tasks have been completed successfully.

4.2.4.1.2 METRICS OF EFFICIENCY

The most frequently used metrics of efficiency:

- Step/task completion time: The time needed to complete a step or a task.
- Deviation from the optimal path: The number of times users do not use the most efficient path to reach their goals

4.2.4.1.3 METRICS OF SATISFACTION

The most frequently used metrics of satisfaction include:

- Ratings of satisfaction with the interface.
- Survey addressing satisfaction with specific aspects of the interface
- Specific attitudes toward the interface, as measured on a standardized attitude questionnaire.
    - Users' satisfaction can be measured by attitude rating scales such as Software Usability Measurement Inventory (SUMI) or System Usability Scale (SUS) (Bangor, Kortum, & Miller, 2008; Kirakowski & Corbett, 1993).

4.2.4.2 SUBJECTIVE COMMENTS

Subjective comments are collected during usability studies by asking subjects to think aloud while completing the tasks, unless task completion time is recorded, in which case subjects should be asked to comment about their experience after the trial/step/task is complete. Subjective comments should be recorded and analyzed according to how many subjects mentioned each of the issues and also ranked according to severity. These comments help to identify various types of errors and their design implications.

4.2.5 INTERPRETING AND USING THE RESULTS

The results of usability testing should be analyzed and related usability issues flagged for follow-up with the designers. These issues usually identify design problems such as unclear labeling or control identification, unintuitive task flow, and interface element locations that do not optimize the task flow. Such problems may result in low efficiencies or high error rates, or issues with physical interface design factors such as control sizing or orientation of movement. Use of usability results to further the design’s maturation can increase the efficiency and effectiveness of the interface while reducing errors and fatigue.

4.2.6 USABILITY EVALUATION TECHNICAL PRODUCTS

For each of the major milestones of the design life cycle, the technical products in Table 4.2.7-1 are recommended.

TABLE 4.2.7-1 USABILITY EVALUATION TECHNICAL PRODUCTS

Technical Products	Phase A		Phase B	Phase C	Phase D	
	SRR	SDR	PDR	CDR	SAR	FRR
A description of the ConOps, function allocation, and associated crew task lists. Includes identification of potential errors that can be encountered for each task.	I	U	U	U	---	---
A summary of modeling/analysis/evaluation performed to date and the influence on system design with links to the detailed analysis results. Required per NPR 8705.2B, and HITL evaluations required per paragraph 2.3.10.	---	---	I	U	U	---
Verification plan.	---	---	I	U	U	---

X = one-time release of item
I = initial release of item
U = updated release of item

Concept of Operations and Crew Task Lists

The ConOps, described in paragraph 3.2.3.1.2, provides information such as identification of crew activities and determination of which subsystems are affected by crew activities. Function allocation, described in paragraph 3.2.3.1.3, establishes the extent to which an activity is to be automated or assigned to humans. The crew task list, described in section 4.1 User Task Analysis, documents details including allocation of function between crew and systems, definition of crew activities sequence, and identification of critical tasks. As the crew task list evolves through the design cycle, its final iteration should become crew procedures.

For usability testing, task analysis must include an analysis of potential errors that can be encountered for each task. This information is necessary for the calculation of error rates, which is a required objective measure of usability.

Summaries of Modeling, Analyses, and Evaluations

Iterative summaries of modeling, analyses, and evaluations provide NASA with insight into human-system integration technical details throughout the design process. As designs mature, modeling, analyses, and evaluations should use inputs and mockups with increasingly higher fidelity, as discussed in paragraph 3.2.3.3 Evaluate Designs and Iterate Solutions. It is important that summaries address how key and/or critical design decisions were assessed. Per the NPR 8705.2B, updated summaries are to be provided at each design review through the SAR. Also in paragraph 2.3.10, the use of HITL evaluation is a required method to progressively demonstrate that the operational concept meets system requirements for operational safety, efficiency, and user interface design.

For usability, this should include the evaluation of metrics for effectiveness, efficiency, and satisfaction as well as subjective data.

Verification Plan

The verification plan is a formal document describing the specific methodologies to be used to show compliance with each requirement.

4.2.7 REFERENCES

Bangor, A., Kortum, P. T., & Miller, J. A. (2008). An empirical evaluation of the System Usability Scale (SUS). *International Journal of Human-Computer Interaction, 24*(6), 574-594.

Hornbæk, K., & Law, E. L.-C. (2007). *Meta-analysis of correlations among usability measures.* Paper presented at the Proceedings of the SIGCHI conference on human factors in computing systems, April 28-May 03, 2007, San Jose, CA, USA.

ISO-9241-11. (1998). ISO/IEC 9241-11:1998. Ergonomic requirements for office work with visual display terminals (VDTs), *Part 11: Guidance on usability*.

Kirakowski, J., & Corbett, M. (1993). SUMI: the Software Usability Measurement Inventory. *British Journal of Educational Technology, 24*(3), 210-212.

Nielsen, J. (1993). *Usability engineering*. San Francisco, CA: Morgan Kauffman Publishers Inc.

Sauro, J., & Lewis, J. R. (2005). *Estimating completion rates from small samples using binomial confidence intervals: Comparisons and recommendations.* Paper presented at the Human Factors and Ergonomics Society Annual Meeting, Orlando, FL.

Sauro, J., & Lewis, J. R. (2009). *Correlations among prototypical usability metrics: Evidence for the construct of usability.* Paper presented at the Computer Human Interaction (CHI), Boston, MA.

4.3 WORKLOAD EVALUATION

4.3.1 INTRODUCTION

Historically workload has been defined in a variety of ways. Workload has been defined alternately as the set of test or task demands, the effort that the subject must exert to meet those demands, and the resulting performance based on the task demands. However, in a survey of pilots, Roscoe and Ellis (1990) found that most pilots think of workload in terms of the effort required to meet the demands of the task. In other words, it is the mental and physical effort exerted by subjects to satisfy the requirements of a given task or scenario.

Workload is an important component of crew interaction with systems, and designers must consider it when designing hardware and software with crew interfaces, procedures, and operations. Designers need to consider the workload of the user when designing and producing an interface or designing a task, as low workload levels have been associated with boredom and decreased attention to task, whereas high workload levels have been associated with increased error rates and the narrowing of attention to the possible detriment of other information or tasks (Sheridan, 2002).

Evaluation of crew workload is required by NPR 8705.2B paragraph 2.3.9, which requires a description of how crew workload will be evaluated; and paragraph 2.4.9, which requires documentation of how crew workload was validated and determined acceptable. In space flight, the primary concern is avoiding unnecessarily high workload levels, given that space flight is generally a high-stress environment. Therefore, the process described below focuses on measuring workload with the goal of keeping workload at a level that does not negatively affect performance. For additional details on workload measures, predictors, and limits, please refer to section 5.7 in the NASA/SP-2010-3407 Human Integration Design Handbook (HIDH).

Note that workload is closely linked with other human factors concepts such as *handling qualities* and *usability*, and that significant usability or handling qualities issues will often drive high workload ratings. These topics are covered in complementary HIDP sections along with this one, and the reader is strongly advised to review all 3 sections. The reader should also review the HIDP section on task analysis, as task analysis is required for identifying workload tasks.

4.3.1.1 APPLICABLE REQUIREMENTS

Workload requirements are specified in NASA-STD-3001, Volume 2, and further refined in program-level requirements documents. Volume 2 specifies in V2 5007 that “Cognitive workload **shall** be accommodated (to avoid overload or underload) in the design of all system elements that interface with the crew for all levels of crew capability and all levels of task demands”.

NPR 8705.2B requires the evaluation of crew workload (paragraph 2.3.9) and a description of how workload evaluation methods were validated (paragraph 2.4.9). Additionally, NPR 8705.2B requires human-in-the-loop (HITL) usability evaluations for human-system interfaces (paragraph 2.3.10). In addition, NPR-required deliverables at

PDR and CDR include presentations of how these evaluations were used to influence system design.

4.3.2 WORKLOAD ASSESSMENT PROCESS

The process of assessing the crew workload induced by the system involves the following:

1. Task analysis to identify the tasks and associated hardware and systems that are relevant to workload
2. Testing early and often in the engineering design life cycle: Testing of those tasks, hardware, and systems that task analysis identified as relevant to workload
3. Component-level through system-level testing
4. Verification

It is easier and more cost-effective to correct deficiencies in hardware or procedures that produce high crew workload during the early design phases rather than just before vehicle certification. For these reasons, workload assessments are best integrated early and often through the engineering design life cycle so that related design decisions can be made from a data-driven perspective and ensure crew safety and efficiency.

Consistent with core human-centered design philosophy, the consideration of workload can be done from the very earliest stages of design, though evaluation of workload does require a certain minimum level of design maturity. At the earliest stages of the design life cycle, integration of crew workload should focus on defining the various tasks that are relevant to workload. Task analysis is the method for identifying which crew and system tasks will be performed during each mission phase, the hardware associated with the task, and whether the task is expected to contribute to crew workload. Many of these considerations can be defined very early on during the vehicle specification stage, even before a request for proposal is released or before procurement activity. However, task analysis should continue to mature as the design progresses. Also, early in the design cycle, comparative measures of workload are effective in deciding between design solutions, selecting the design that does not inflict high levels of workload.

After task definitions, the next stage would be to start assessing crew workload in a series of simulated vehicle tasks. NASA has determined that for the current space flight programs (Multi Purpose Crew Vehicle Program and Commercial Crew Program), workload should be assessed using the Bedford scale. The reasons this scale was chosen are numerous, but arguably the most important is the ability to use the scale to determine whether workload is tolerable for the task. Many other types of scales (e.g., NASA Task Load Index, or TLX) are diagnostic or multi-dimensional, meaning that they allow the source of the workload to be localized. These types of scales are advantageous to use during the design phase, where modifications based on workload evaluations are possible. However, during the verification phase, the Bedford scale is most appropriate. The Bedford scale is appropriate for verification because it provides anchors for every rating, is familiar to the crew population, and provides a decision gate in which ratings above this gate indicate that workload is not satisfactory without a reduction in spare capacity or is not tolerable. Given NASA's decision to require that the Bedford scale be used for verification of current spacecraft, this section will focus on the Bedford scale. For a discussion of other types of scales, please refer to the HIDH, Chapter 5. How to assess workload is described below in paragraph 4.3.2.2 Assessing Workload Using the Bedford Scale, and in HIDH paragraph 5.7.3 Measures of Workload.

Eventually, as vehicle design maturity increases, the simulation fidelity also increases, and ratings achieved by means of simulation become more consistent. The value of this early and frequent evaluation of workload is really its direct interaction with design decisions, related to both hardware and procedures.

4.3.2.1 THE BEDFORD SCALE

The Bedford scale (Roscoe, 1987) was developed for and with the help of test pilots at the Royal Aircraft Establishment in Bedford, England. The Bedford scale is organized in a decision-tree format (see Figure 4.3.2-1) in which the subject starts at the bottom left corner and answers each question in order, to move to the next node. In this document, each box with a number (e.g., WL10) is called a level, and each grouping of 3 levels (e.g., WL7, WL8, and WL9) is called a group. For example, the subject first answers the question, "Was it possible to complete the task?" If the answer is "No," the subject follows the branch to the right on the decision tree and reports a workload level of 10. If the answer is "Yes," the subject follows the branch up to answer the next question, "Was workload tolerable for the task?" When the decision tree guides the subject to a group containing multiple workload levels, the subject selects the appropriate level on the basis of the descriptions. For example, if the subject answered "No" to the question "Was workload tolerable for the task?" he or she would evaluate their workload against the descriptions such as "Very little spare capacity, but maintenance of effort in the primary tasks not in question." If this statement best reflects the workload, the subject selects WL7 for that task.

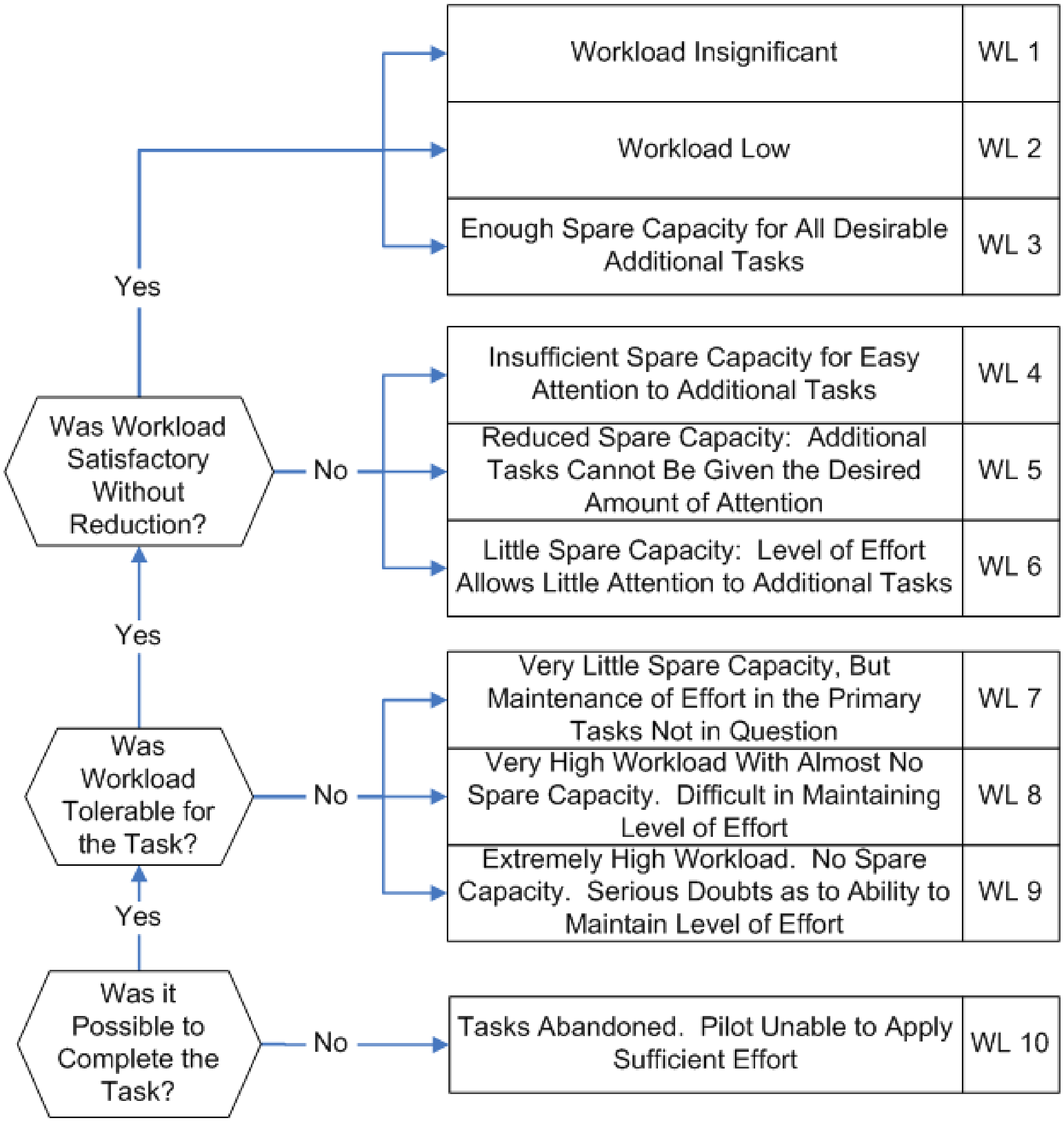


FIGURE 4.3.2-1 THE BEDFORD SCALE

4.3.2.1.1 SPARE CAPACITY

The Bedford scale uses the concept of “spare capacity” to determine the workload level. The concept of “spare capacity” comes from the information processing approach to cognition, in which the brain is analogous to a computer with limited resources. If a computer has 100 MB of RAM and a task is using 50 MB, then the spare capacity of the system to perform another task is 50 MB. The same is true of the human system. The human brain has a limited capacity to perform tasks. If the primary task is using a certain amount of resources, then the resources left over (i.e., unused) are thought of as the spare capacity available to perform additional tasks. This explanation applies to both mental and physical resources. The workload to complete the task is the effort required or the amount of resources used out of the limited supply of resources available. The use of the concept of spare capacity in the application of the Bedford scale is discussed further in the next paragraph on assessing workload.

4.3.2.2 ASSESSING WORKLOAD USING THE BEDFORD SCALE

Workload is assessed as part of a HITL evaluation. A HITL evaluation involves having one or more subjects perform a representative task while data are gathered from the subject(s) to meet an objective (e.g., task performance is measured or subjective feedback is provided by the subject). Workload should be assessed iteratively throughout the design cycle, allowing design changes to be made as necessary, in addition to the final verification testing. There are multiple ways to assess the workload of the task: physiological, performance, and subjective measures. Current NASA programs, MPCV and Commercial Crew program, have a requirement to assess workload using subjective measures. In a HITL evaluation aimed at assessing workload, each subject will be asked to perform a task and have an identified secondary task (whether mocked up for the test or just described to the subject), and the Bedford scale will be administered after completion of the task. Paragraph 4.3.2.2.1, below, discusses how to administer the Bedford scale during a HITL evaluation.

It is critically important that before administering the Bedford scale in an evaluation, the test conductor **defines the task, task steps, task duration, and what secondary tasks the subjects need to judge their spare capacity against**. This ensures that each subject is exposed to the same information, which decreases the measurement error and leads to a more accurate measure of task workload. Additionally, each subject needs to understand the test setup, task, and expectations. The definition of a task is important because multiple steps are often required to complete a scenario, with possibly multiple tasks in each scenario, so subjects need to be very clear on which steps they should use to judge their workload. For example, if the task involves egressing the vehicle, subjects may be instructed that the task begins when they loosen their restraints to egress the seat and ends when their feet reach the floor exterior to the vehicle. This allows subjects to constrain the assessment of workload and exclude tasks that may have occurred before or after those instructed boundary points. Also, in defining the task steps for each subject, the test conductor is reducing the amount of subject variability that is introduced into the measure. Each subject in the test will base their workload rating on the same steps.

The Bedford scale has been **validated for administration at the end of a task** and at specified intervals during a task. Administering Bedford at intervals during a task is primarily used when the Bedford scores will be correlated with some other measure of workload, such as heart rate, or with performance metrics. For space flight tasks, the Bedford scale should be administered at the end of the entire task, resulting in one score/rating for each subject for each task. During a task there may be peaks of high workload followed by periods of lower workload. It is best to advise the subject to either take the mental “average” or “weighted average” across those peaks and valleys to decide on the most representative level of workload, spanning the entire task duration. If task-specific testing (such as dry-run testing or development testing) has been done that shows short peaks of high workload, the test conductor may use the results of that testing to advise the subject to use some predetermined method of weighting the peaks of high workload when determining their overall Bedford level.

Every attempt should be made to make the assessment of tasks as **high-fidelity and flight-like as possible**. The test setup influences the subjects' workload levels, and to get a representative measure of workload for a given task, the task setup must be as representative as possible. Making the setup representative includes using high-fidelity hardware, software, test procedures, timelines, and environments, and including multiple subjects for multiple crew scenarios. For example, if the subject's task is to perform a piloting task using a display and a control, the content of the display needs to include everything that would be there in flight, accurately representing all details such as color, spacing, and labeling, and the control must be an accurate representation of the flight hardware, having an accurate tactile feel and shape, control characteristics (e.g., torque), and interaction with the display. In this example, deviations from the flight-like scenario such as too little display content or an inaccurate control would lead to an inaccurate measure of the workload associated with the task. Too little display content may lead to lower than actual workload ratings because extraneous information that could interfere with the task is absent, or it could lead to higher than actual workload ratings because not enough information is presented for the subject to complete the task without mental compensation. Just as the assessment of workload is contingent on the test setup, an accurate depiction of the workload induced by a design is contingent on having a high-fidelity design.

Subjects need to **maintain error rates and task completion times** commensurate with the performance requirements of the particular task. Without this stipulation, a subject may decide to compromise performance or the time it takes to complete the task so that their workload level does not increase. If this happens, the resulting workload rating will be an artificial representation of the actual workload necessary to complete the task. To maintain task performance across individuals and get a representative measure of workload, it is important to instruct each subject how much time they have to perform the task and what performance level they need to achieve.

It is important when administering the Bedford scale to identify and describe to subjects **what the secondary tasks may be** since the Bedford scale is designed to assess spare capacity. Many studies have shown that people have difficulty judging their capacity (mental and physical) without a reference to judge that capacity against. One type of reference that has been shown to be helpful in making the judgment is for the subject to determine whether they have the capacity to perform an additional task. For example, if the primary task is piloting and the secondary task is talking to the copilot, subjects may have sufficient spare capacity to perform this secondary task and a low workload rating is provided (e.g., WL3). However, if the primary task is piloting and the secondary task is tracking a visual item around a crowded display, subjects may not have the spare capacity necessary to perform both tasks without a detriment in performance, and thus a high workload rating may be provided (e.g., WL6), even though the primary task demands were the same. In the latter case, the visual tracking task is not a good secondary task because the purpose of the secondary task is to aid the subject in assessing whether there is spare capacity to perform that task while performing the primary task. If the secondary task is so difficult that it interferes with the primary task, then it is not serving the purpose of assessing spare capacity, but is affecting performance. If the subject is judging whether they have the capacity to perform an additional task, it is essential that they understand the requirements of the additional task. A clear understanding of the secondary task demands allows the subject to make the best possible decision as to his/her spare capacity. If a subject only has limited knowledge of the secondary task demands, then he/she may misjudge the amount of spare capacity because of failure to consider all of the task steps or mental requirements in the task and the mental/physical resources necessary to complete the task. Also, it is advisable to make the secondary task a realistic task identified in the task analysis, as these tasks may be more familiar and applicable to the user in a given scenario.

In space flight, **both piloting and non-piloting tasks** need to be assessed to ensure that they do not introduce unnecessary workload. Although the Bedford scale was created for and has been validated with pilots and piloting tasks, NASA believes that the Bedford scale is appropriate for verification of all space flight designs because the scale "*provides anchors for every rating, is familiar to the crew population, and provides a decision gate in which ratings above this gate are indicative of workload that is not satisfactory without a reduction in spare capacity*" (e.g., CH10003V and CH10004V). Even though the Bedford scale can be applied to non-piloting tasks, there are certain factors that may need extra attention from the test conductor when preparing for an evaluation of a non-piloting task, simply because there is no precedent to refer to. Among those factors are identifying the task steps and secondary tasks for non-piloting primary tasks, such as vehicle egress. In a vehicle egress task, a crewmember may need to talk to another crewmember to successfully egress the vehicle. The test conductor needs to decide and advise the subject whether talking to another crewmember is part of the primary task or is considered the secondary task. To do this, the test conductor should run through the task with the help of appropriate stakeholders (e.g., crew, ops, hardware designers, human engineering) before the evaluation to determine each task step in the primary task, and what the appropriate secondary task should be. Often iterative testing during the design phase serves this purpose for a verification test. NASA has experts who can help determine appropriate secondary tasks.

Several differences are expected between a nominal and an off-nominal situation, including new or increased troubleshooting tasks, time pressure due to an emergency situation, increased communication between crewmembers and/or the ground, performing less frequently or minimally trained actions, and so on. All of these off-nominal factors have the potential to increase task workload. Thus, there should be 2 workload requirements with different acceptance criteria -- one for a nominal task and one for an off-nominal task (e.g., CHSIR nominal and off-nominal workload requirements). An off-nominal workload requirement allows higher workload ratings to be given for the task (up to and including WL6) than a nominal workload requirement allows (up to and including WL3), because workload is expected to be higher for the off-nominal task than for the nominal task, due to the differences highlighted above. However, for the off-nominal task, a Bedford rating of WL6 or less should be required because ratings greater than WL6 indicate that the workload is not tolerable for the task.

The second question in the Bedford decision tree is “Was workload tolerable for the task?” and if the answer is “no,” then the subject is required to provide a rating of WL7 or above. When designing for space flight, it is unacceptable for the workload to be intolerable for the subject. Even for an off-nominal task, the design should support a tolerable workload level.

4.3.2.2.1 ADMINISTERING BEDFORD

Any person administering the Bedford scale in a HITL evaluation needs to be trained on the parameters of the scale and be able to describe workload and the scale properties to the subjects.

At a HITL evaluation to measure workload, the subject will arrive at the test site, give informed consent, and then be briefed on:

1. The definition of workload. The experimenter needs to provide the subject with a definition of workload so that he/she has a concept of which mental and physical faculty they are judging.

2. The Bedford scale will be used to assess the amount of workload induced by the task, hardware, software, or procedures. Subjects should be shown a copy of the scale and this copy should be available throughout the entire test session for the subject to refer to as needed.

3. The Bedford scale assesses a combination of mental and physical workload. Because the Bedford scale does not dictate how those factors are combined, subjects need to make their own determinations of how they should be combined for an overall workload rating, or the experimenter can advise the subject (if there is some rationale why more weight should be given to either the mental or physical aspect).

4. The concept of spare capacity and how it relates to workload and the Bedford scale.

5. The primary task to be completed and the secondary task to judge spare capacity against. If a piece of hardware or part of a procedure should be given more emphasis or weight (based on some rationale), then that needs to be described to the subject.

6. The decision tree. It is important that the subject always walk through the decision tree starting on the bottom left side and answering each question to move up or to the right. Subjects who have experience with the scale may want to jump to an answer without walking through the entire tree. However, to make sure that the response is an accurate representation of the subjects’ workload and that they have not had a memory failure regarding the level wording, and to

keep consistency across subjects, it is important that all subjects follow the same procedure and walk through the entire tree before responding. The differences between some of the levels are subtle, so the experimenter should walk through the tree with the subject during the briefing to make sure that the subject understands the content, or what each level means, and answer any questions the subject may have.

7. Acceptable ratings. The Bedford scale allows the use of half ratings, even between groups (such as levels 3 and 4, or 6 and 7). A half rating between levels should be given if the subject's workload fell somewhere between the descriptors. A half rating between groups should be given only if the subject cannot determine an answer to the question on the left distinguishing those groups.

After the briefing, the subject will perform the primary task. At the conclusion of the task, the subject should be shown the Bedford scale and asked to walk through the decision tree until he/she decides on a workload level. The experimenter should be present with the subject to answer any questions he/she may have. The subject should verbally provide the rating to the experimenter, who will record it. The experimenter should then ask the subject to verbally explain why he/she provided that rating (i.e., what is the rationale?). It is important to understand why each subject provides the rating that they do, especially in the design phase, so that changes to the design can be made as necessary. A Bedford workload rating alone cannot tell a designer what needs to be improved in a design (the Bedford scale is not diagnostic), only that the design imparted a certain level of workload on the subject. The dialogue with the subject is critical in understanding what may have induced the workload level.

Because the Bedford scale is not diagnostic, it can be beneficial, especially early in the design phase, to use a more diagnostic or multi-dimensional workload scale along with the Bedford. An example of a multi-dimensional scale is the NASA Task Load Index (TLX). NASA-TLX provides an estimate of overall workload based on a weighted average of 6 subscale ratings: Mental Demand, Physical Demand, Temporal Demand, Own Performance, Effort, and Frustration (Hart & Staveland, 1988). Subscale ratings, which range from 1 to 100 in 5-point increments, are given verbally or by selecting a position along a scale presented on a rating form or computer screen. In addition, raters quantify the relative importance of each factor in creating the workload they experienced. The relative importance values, which range from 0 to 5, are used to weight the magnitude ratings when computing the overall workload score. Diagnostic information is provided by variations in subscale ratings as well as the weight given to each factor.

4.3.2.2.2 ANALYZING AND INTERPRETING RESULTS OF THE BEDFORD SCALE

When thinking about choosing an appropriate level of workload on the Bedford scale, the mental distance between the levels is not predicted to be equal. In other words, the difference between levels 1 and 2 may not be the same as the difference between levels 9 and 10; workload rated level 10 is not twice as much as workload rated level 5. Therefore the scale is not linear. Also, the distribution of level responses does not follow a standard, predictable pattern; and therefore the underlying distribution is not known. Because the distribution of responses is not known and the scale is not linear, the use of probability distribution descriptive statistics (such as mean or median) or the use of parametric statistics (which assume a known distribution) are not appropriate methods for describing or analyzing Bedford data. The most effective way of describing the data is using frequency tables or plots (e.g., histograms, frequency weighted scatter plots). The most meaningful presentation of the data shows the number of subjects who gave any particular rating. For example, an evaluation with 6 subjects who rated their workload a 1 and 2 subjects who rated their workload a 2 on the Bedford scale would suggest that the design induces low levels of workload.

4.3.2.2.3 INCORPORATING WORKLOAD THROUGHOUT THE PROJECT LIFE CYCLE

To identify the tasks that are relevant to the workload requirement, a task analysis must be performed outlining all tasks the crew will be performing during all mission phases. Once the task analysis is complete, representative nominal and off-nominal tasks may be selected for evaluation. The task analysis should begin at the beginning of the program and be refined through CDR. After SDR, the developer is expected to begin generation of the verification task list. The verification task list should be delivered at PDR and CDR.

A workload requirement needs to be flowed from the system level down to the component level. At the system level, NASA wants to ensure that the vehicle is usable by the crew without inducing unnecessary workload. Each component that makes up the system needs to be designed well, with crew workload in mind, in order for the vehicle to support adequate crew workload levels.

NASA expects the Bedford scale (along with an additional diagnostic scale, if desired) to be used during developmental testing of tasks (i.e., HITL evaluations) that are predicted to be relevant to crew workload. These tasks may not ultimately be selected for verification testing, but the administration of the Bedford scale during development allows a better understanding of the workload associated with a given task, familiarity with the administration of the Bedford scale, potential redesign of hardware or software based on scale ratings, and crew feedback for associated tasks.

Products associated with workload should always include these items:

- Task analyses
- Component, subsystem, and system requirements traceability
- Implementation of the above best practices for administering and analyzing the Bedford scale in test plans and analysis (for developmental and verification testing)

4.3.3 WORKLOAD EVALUATION TECHNICAL PRODUCTS

For each of the major milestones of the design life cycle, the technical products in Table 4.3.3-1 are recommended.

TABLE 4.3.3-1 WORKLOAD EVALUATION TECHNICAL PRODUCTS

Technical Product	Phase A		Phase B	Phase C	Phase D	
	SRR	SDR	PDR	CDR	SAR	FRR
A description of the ConOps, function allocation, and associated crew task lists.	I	U	U	U	---	---
An explanation of how crew workload will be evaluated for the reference missions. Required per NPR 8705.2B paragraph 2.3.9.	---	I	U	U	---	---
A summary of modeling/analysis/evaluation performed to date and the influence on system design with links to the detailed analysis results. Required per NPR 8705.2B, and HITL evaluations required per paragraph 2.3.10.	---	---	I	U	U	---
Verification plan.	---	---	I	U	U	---
A description of how crew workload for the reference mission was validated and determined to be acceptable. Required per NPR 8705.2B paragraph 2.4.9.	---	---	---	---	X (ORR)	---

X = one-time release of item
I = initial release of item
U = updated release of item

Concept of Operations and Crew Task Lists

The ConOps, described in paragraph 3.2.3.1.2, provides information such as identification of crew activities and determination of which subsystems are affected by crew activities. Function allocation, described in paragraph 3.2.3.1.3, establishes the extent to which an activity is to be automated or assigned to humans. The crew task list, described in section 4.1 User Task Analysis, documents details including allocation of function between crew and systems, definition of the crew activities sequence, and identification of critical tasks. As the crew task list evolves through the design cycle, its final iteration should become crew procedures.

Explanation of Workload Evaluation Plans

As required by NPR 8705.2B paragraph 2.3.9, an explanation of how crew workload will be evaluated for the reference missions is required at SDR, and then updated at PDR and CDR. Documentation of plans for workload evaluation will provide NASA with insight into this important aspect of human-system integration.

Summaries of Modeling, Analyses, and Evaluations

Iterative summaries of modeling, analyses, and evaluations provide NASA with insight into human-system integration technical details throughout the design process. As designs mature, modeling, analyses, and evaluations should use inputs and mockups of increasingly higher fidelity, as discussed in paragraph 3.2.3.3 Evaluate Designs and

Iterate Solutions. It is important that summaries address how key or critical design decisions were assessed. In accordance with NPR 8705.2B, updated summaries are to be provided at each design review through SAR. Also in paragraph 2.3.10 of that document, the use of HITL evaluation is a required method to progressively demonstrate that the operational concept meets system requirements for operational safety, efficiency, and user interface design.

The use of iterative testing throughout the design is a necessary part of designing for workload. It is expected that the Bedford scale (along with additional metrics, as needed) will be used during developmental testing. NASA will provide input as needed concerning testing details such as appropriate secondary tasks.

Verification Plan

The verification plan is a formal document describing the specific methodologies to be used to show compliance with each requirement.

Workload Validation

As required by NPR 8705.2B paragraph 2.4.9, a description of how crew workload for the reference mission was validated and determined to be acceptable is required at SAR.

4.3.4 REFERENCES

Hart, S. G., & Staveland, L. E. (1988) Development of NASA-TLX (Task Load Index): Results of empirical and theoretical research. In P. A. Hancock & N. Meshkati (Eds.), *Human mental workload* (pp. 139-183). Amsterdam: North Holland.

Roscoe, A. H. (1987). Inflight assessment of workload using pilot ratings and heart rate. In A. H. Roscoe (Ed.) *The practical assessment of pilot workload* (AGARD-AG-282) (pp. 78-82). Neuilly-sur-Seine, France: Advisory Group for Aerospace Research and Development.

Roscoe, A.H., & Ellis, G.A. (1990). *A subjective rating scale for assessing pilot workload in flight: A decade of practical use* (Technical Report TR 90019). Farnborough, UK: Royal Aerospace Establishment.

Sheridan, T. (2002). *Humans and automation: Systems design and research issues.* New York: Wiley.

4.4 HUMAN ERROR ANALYSIS

4.4.1 INTRODUCTION

Human error is a broad classification of effects that may be the result of action or inaction by a pilot or human operator in the control of a vehicle or vehicle system. Errors of this sort can be the result of many different causes, which may range from inadvertent actions or usability- or interface-induced errors to errors related to fatigue and various forms of confusion, to name just a few. The intent of conducting the Human Error Analysis (HEA) is to determine the likely or possible errors that could occur in the operation or use of a vehicle, system, or component, so that the design can be modified to reduce or eliminate errors and reduce their likelihood to an acceptable threshold.

4.4.2 APPLICABLE REQUIREMENTS

NASA’s philosophy behind HEA for spacecraft systems requires that iterative human error analyses be conducted, the results of which are to be used for making design decisions. These analyses are supposed to cover all mission phases, including operations planned as responses to system failures. This philosophy is best represented by NPR 8705.2B Human-Rating Requirements for Space Systems, most notably in paragraphs 2.3.11 and 2.3.11.1 (the primary HEA sections), as well as in paragraphs 2.2.3, 2.3.1, 2.3.6, 2.3.12, and 3.2.4. Additional requirements associated with HEA are included in NPR 8715.3 NASA General Safety Program Requirements and NPR 8705.5 Technical Probabilistic Risk Assessment (PRA) Procedures for Safety and Mission Success for NASA Programs and Projects.

4.4.3 HUMAN ERROR ANALYSIS METHODS

This document is intended to join together industry standard methods for HEA within the framework of human-system integration (HSI). The use of HSI processes in aviation is well established, as is the implementation of human error analysis. Many HEA approaches are described in the literature, and the vehicle, system, or component developer must consider the most appropriate method for any given analysis. Numerous tools are associated with the analysis of human error and are driven by a variety of factors including the inherent variation in individual performance capabilities from person to person, the difficulties in forecasting possible errors and probabilities before they occur, and the needs of accident investigators to retroactively deduce the factors associated with an incident.

Note that human error analysis is closely linked with other human factors concepts such as ***workload*** and ***usability***, and that significant usability issues or excessive workload demands will often be associated with an increased incidence of human errors. Indeed *usability errors* are a specific subset of human error referred to as “interface induced errors,” alluding to the fact that poor interface design was a direct cause of an error. Usability and workload considerations are covered in complementary HIDP sections as well as this one, and the reader is strongly advised to review all 3 processes.

4.4.4 RESERVED

4.4.5 HUMAN ERROR ANALYSIS TECHNICAL PRODUCTS

Reserved

4.5 DESIGN FOR CREWMEMBER PHYSICAL CHARACTERISTICS AND CAPABILITIES

4.5.1 INTRODUCTION

The NASA-STD-3001, Volume 2 NASA Spaceflight Human-System Standard section 4 Physical Characteristics and Capabilities includes requirements to ensure that the entire crew population can physically be accommodated within the spacecraft and integrated human-systems interfaces. This process document describes the philosophy and approach of including the parameters of anthropometry, range of motion, strength, body surface area, body volume, and body mass in the design process, and to evaluate the spacecraft design against requirements. The process also details the various factors that will affect successful accommodation of the population within the design and how to account for their effects. The anticipated technical products needed to assess whether the design is on track during the course of the engineering life cycle are also discussed in the context of this design process. The purpose of the process for each parameter of anthropometry, range of motion, strength, body surface area, body volume, and body mass for any space vehicle design is to ensure accommodation and physical incorporation of the crew within the design so that the entire crew population can fit, reach, and perform tasks while maintaining a safe and successful mission. Additional information on anthropometry, biomechanics, and strength can be found in chapter 4 of the NASA/SP-2010-3407 Human Integration Design Handbook (HIDH).

4.5.1.1 HOW TO USE THESE GUIDELINES

Section 4.5 describes processes for critically evaluating a proposed design by using approaches based on anthropometry, range of motion, body surface area, body volume, body mass, and strength. Each approach’s methodology is outlined from initial design concept to final verification. Most of the processes are iterative, using a combination of analytical, computer-based, and/or physical human-in-the-loop (HITL) task evaluations. The end goal is to provide a basic framework that space flight programs and developers can use as a guide to identify population characteristics, set appropriate assumptions, conduct testing and analysis, and outline the expected technical products in the engineering design life cycle.

4.5.1.2 THE INTEGRATED APPROACH

An integrated approach examines the design across all possible physical characteristics and evaluation methodologies at various stages in the design process. It is recommended that an integrated approach is used to understand how the primary physical characteristics and capability aspects relate to each other within a design to ensure that, for each aspect and across aspects, the entire population meets design compliance. More information on design using the integrated approach is given in paragraph 4.5.7.

4.5.1.3 ADDITIONAL CONSIDERATIONS AND NASA ASSISTANCE

NASA has unique experience in suit design and accommodation for space missions. It is anticipated that spacecraft developers who include use of Launch, Entry, Abort (LEA) suits for crewmembers may have questions about suit implementation and design criteria, specifically on how to incorporate or account for suit effects in their design. Additionally, needs may arise for designs to place the crew in postures or dynamic activities that differ from standard conventions. For these circumstances or questions on the application of requirements, suit factors, or accommodation due to suit usage, NASA is available to facilitate interpretation and work with developers to assist their successful design efforts.

4.5.2 DESIGN FOR ANTHROPOMETRY

4.5.2.1 INTRODUCTION

The purpose of the design requirements is to ensure that all vehicle, vehicle-suit hardware, and interfaces are operable by the entire anticipated crew population. NASA requires and expects that all crewmembers are provided with hardware that they all can handle, operate, and use for mission success and crew safety. Thus it is necessary that the designers and developers verify and validate, by means of analysis, modeling, and physical testing, each design against the anthropometric requirements set forth in NASA-STD-3001, Volume 2 section 4.

4.5.2.2 APPLICABLE REQUIREMENTS

The following NASA-STD-3001, Volume 2 requirements are applicable to anthropometry:

- Data Sets [V2 4001]
- Data Set Characteristics [V2 4002]
- Population Definition [V2 4003]
- Data Set Assumptions [V2 4004]
- Body Lengths Data [V2 4005]
- Changes in Body Lengths [V2 4006]

4.5.2.3 SELECTION OF AN ANTHROPOMETRIC DATA SET

The NASA-STD-3001 NASA Spaceflight Human-System Standard Requirement V2 4001 specifies that an anthropometric data set for the crewmember population must be selected and implemented in the design, and V2 4004 specifies that age, gender, and physical condition shall also be included in this data set. Furthermore, Requirement V2 4003 requires that the definition of the population ranges for the physical dimensions that the system is intended to accommodate shall also be included.

Proper selection of the data set to represent the crewmember population is of critical importance. First, the data set itself must reflect the physical range of the anticipated crew population. If the general public will be expected to be accommodated in the design, then a data set that reflects a general population should be selected. For the NASA astronaut crew, the anticipated population is akin to a military population, which is more restrictive over a comparable measurement range than a general population. The NASA anthropometry data set for Space Shuttle, Space Station, Constellation, and

Commercial Crew is based on military Anthropometric Survey (ANSUR) data. Requirements (e.g., anthropometry limits, strength limits) for each of those programs were selected using the NASA data set and modified according to program needs such as changes in selection criteria for future crew populations. Secondly, the selected data set must include the measurements that are critical to the design to ensure proper accommodation. Requirement V2 4005 specifically names body lengths as critical to be incorporated into an anthropometric data set. If the data set consists of only height and weight, it does not capture the critical design parameters or the variation present in the population. For example, individuals may have nearly identical stature but some may have long torsos and short legs whereas others have short torsos and long legs. Including body segment parameters and their variations is critical when examining the way the human fits into a complex, confined space. With proper data set selection, one can ensure that the critical dimensions integral to the design of a vehicle and suit are representative of the range of anthropometry within the crewmember population.

This crewmember population data set is not only used to select measurements and accommodation ranges, but it is also used for all aspects of population analysis. One cannot always have the full range of the population represented in test subjects; thus the data set is used for analyses to determine the extent of the population accommodated and to place test subjects within the population to classify and quantify their clearance and accommodation within the space.

4.5.2.4 ANTHROPOMETRY GENERAL OVERVIEW

The evaluation of designs is a multiphase process that depends on the stages of the design life cycle. In the preliminary stages of design, robust analytical and computer-aided design (CAD) modeling should be used at a minimum, to identify the worst-case scenarios and the critical dimensions of interest, and to determine accommodation of the design. The assumptions of posture, suit effects, and other human interface variables must be documented so they can be verified with future HITL testing. HITL testing will either validate those assumptions or disprove them. If the assumptions are disproven, the analytical and CAD modeling work can be reanalyzed with the corrected information and the design can be iteratively analyzed and verified using HITL testing. As the design matures within the design cycle, the evaluation of the design against the selected anthropometric data set must move from the theoretical to the physical using HITL testing.

Additional discussion of HITL testing for anthropometry, biomechanics, and strength assessments can be found in HIDH section 4.2.4.2 Enhancement of Human-in-the-Loop Testing.

In general, the flow of any anthropometric design evaluation for space flight-related designs, whether low-fidelity analytical analysis or high-fidelity HITL testing, contains the same backbone of required steps:

1. Identify test objectives – which include but are not limited to accounting for unsuited and suited operations, gravity condition (1*g*, micro-*g*, hyper-*g*, etc.), group effects, test configuration fidelity, and so on.

2. Identify the critical measurements from the crewmember population that influence the ability of a human to interact with the design and the surrounding environment. These critical measurements can be population-based and/or derived dimensions.
3. Account for suit, posture, and microgravity factors.
4. Identify worst-case scenarios involving dimensions based on the critical tasks.
5. Evaluate the design using analytical analysis, CAD modeling, and/or HITL testing at the appropriate stage of the design cycle, and determine what segments of the population are not accommodated and what adjustments are necessary to accommodate the entire user population.
6. Make changes to the design to increase anthropometric accommodation
7. Repeat Steps 1-6 until the design meets the requirements set forth for the selected population data set and the design is in the final stages of the design cycle.

4.5.2.5 METHODOLOGY

4.5.2.5.1 IDENTIFY TEST OBJECTIVES

Preparation for evaluations starts with a very clear idea of the test objectives; these are critical to a successful evaluation of the design. Test objectives are developed by identifying the tasks crewmembers are expected to perform, assumptions owing to the design fidelity and/or the concepts of operations, the context of the surrounding environment, and any areas of concern. For instance, if the focus of the design evaluation is on a hypothetical seated crewmember at a console, the primary objectives would be to ensure that the seat can fit all crewmembers and the console can be reached by all crewmembers, both suited and unsuited. Secondary objectives could examine whether the seat can accommodate the population within the overall vehicle context, such as the ability of all crewmembers to ingress and egress the seat for a given seat configuration, with other vehicle components acting as obstacles. It is critical to examine the design as both an individual piece and part of the larger overall vehicle and interface design at all steps of the design cycle.

4.5.2.5.2 IDENTIFY CRITICAL MEASUREMENTS

Various anthropometric measurements should be evaluated throughout the design's lifecycle, as dictated by design and evaluation needs. Measurements that are unique to a particular design may be critical to a proper evaluation. Examples of such measurements are functional measurements used to reconstruct a body posture, unique measurements derived from the combination of 2 or more established measurements, or clearances between the human and hardware. The measurements selected should include those specifically tailored to the task; these incorporate all critical subject body posture configurations for proper subject classification within the population. At a minimum, one should select task-specific measurements for unsuited crewmembers, to place measurements in the context of the population and to understand the impact of posture. Task-specific measurements for suited crewmembers should be selected as appropriate to understand the impact of the suit.

Compliance requires that a design meet the minimum and maximum as defined by the limits selected from the data set range of dimensions for a given design. However, measurements may not be available for every task-specific and posture-specific design. Measurements may have to be derived analytically and then verified through HITL testing. For example, if the focus of the design evaluation is on a hypothetical seated, unsuited crewmember at a console, the seated posture will influence the hip angle of the person. The chair itself must still accommodate the maximum to minimum buttock-to-knee distance; however, when the distance of the chair from the console is evaluated, the hip angle's impact on buttock-to-knee length must be accounted for to accurately predict the clearance between the human and interface.

4.5.2.5.3 ACCOUNTING FOR SUIT, POSTURE, AND MICROGRAVITY FACTORS

4.5.2.5.3.1 SUIT FACTORS

Changes to overall suited body shape caused by the suit, called suit factors, have ramifications across all levels of design and must be accounted for, if applicable, when allotting and interpreting the space needed to fit the expected population. NASA-STD-3001 Requirement V2 4002 includes the spacesuits and suit pressurization as characteristics that must be included in the definition of a data set. Suit factors are classified as the ratio between the unsuited and suited anthropometric measurements of an individual, and take into account not only the added material of the suit and its components but also the small changes in posture that are inherent in the body-to-suit interface.

The estimated suit anthropometry is obtained by modifying the unsuited measurement using a suit factor to result in a derived suited measurement. Each individual measurement taken for a subject will have a corresponding suit factor since the suit affects different parts of the body in different ways and each suit may have different design attributes that affect posture, stature, and other aspects of body shape. Ideally, suit factors are derived for a specific suit, in a specific configuration, in a standardized baseline posture, and are applicable only under the same or very similar conditions. For example, the suit factor determined for a subject's stature in an Extravehicular Mobility Unit (EMU) suit will be different from the stature suit factor for an ACES suit. Likewise the hardware will affect the suit factors; the suit factor for stature in an ACES suit with a bailer bar will be different from the stature suit factor for an ACES suit without a bailer bar. A bailer bar is an external locking mechanism of the helmet that rotates to the top of the head when the face shield of the helmet is open, and latches near the chin when closed and locked.

The suit will have an impact on the overall body size and posture of individuals and must be incorporated into a design to ensure that the population is accommodated. These suit factors allot a certain amount of clearance for the suit and provide a standard that the suit designers must adhere to and the vehicle and hardware designers must account for within their respective designs. Ideally, a suit factor would be a known element, clearly defined for every dimension of interest. However, this is not the case, and suit factors must be quantified and the design must demonstrate incorporation of suit effects before full verification can occur.

Questions have previously arisen about how to handle suit factors for subjects falling in the middle range between the maximum and minimum values. These questions are based on scenarios in which the worst-case body configurations do not occur at the extremes but rather near the middle of the population or during human-based testing with subjects of varied anthropometry.

Take for example, a hypothetical test subject who has a 25th-percentile male stature value or the equivalent 96th-percentile female stature value: should the suit factor used to derive the minimum anthropometry value or the suit factor used to derive the maximum anthropometry value be used to evaluate the subject's accommodation within the vehicle? If the subject is male, the analyst should apply the suit factor used to derive the maximum value. If the subject is female, the analyst should apply the suit factor used to derive the minimum value, with the exception of hip breadth where the situation is reversed. For more complicated cases between the minimum and maximum values in an anthropometry data set, the developer is advised to seek support from NASA.

4.5.2.5.3.2 POSTURAL FACTORS

Measurements will also be influenced during testing by posture effects, induced by the hardware, that change the standard body position of the human. NASA-STD-3001 Requirement V2 4002 includes external-interfacing equipment and gravity environments as characteristics that must be included in the definition of a data set, and V2 4006 specifies that changes to body posture be included in reduced-gravity environments. Essentially posture factors account for the variation between the baseline, unsuited posture and the unsuited task-specific posture. The measurements in the NASA crewmember anthropometric data set were collected in a laboratory environment with distinct, standardized anthropometric data collection postures. Vehicle or system design and the effects of gravity may necessitate that crewmembers assume postures that differ significantly from the prescribed and standardized measurement postures reflected in the requirements. These postural effects need to be quantified and accounted for, to analyze the impact of the design on the entire population.

In the preliminary stages of design, the posture factors can be estimated using assumptions about body posture for the analytical or CAD modeling methods. The posture factor can be initially calculated by using trigonometry to quantify the impact of body joint angles on anthropometry and then determining the ratio between the adjusted and standardized posture. The suit and posture factors can be combined at that stage to provide a preliminary impact of the suited human interacting with the interface of interest. An error will be associated with this estimation of the posture factors, as well as a secondary error of the interaction effects between the suit and posture that will also negatively influence the robustness of the results. The assumptions of the impact of posture effects on the human body unequivocally must be verified during HITL testing to ensure that the assumptions are valid or to modify the analysis as appropriate. At the stage of HITL testing, the ratio of a standard unsuited body measurement to the posture-based unsuited body measurement in the human-system interface can be determined, compared to the previous estimated factors, and integrated into the overall analysis in a fashion similar to the suit factors.

4.5.2.5.3.3 COMBINED POSTURAL AND SUIT EFFECTS

In the preliminary stages of design, the posture and suit factors can be estimated using anthropometric data set values and assumptions about body posture for the analytical or CAD modeling methods. These estimates can be used to determine the accommodation of the design, but they have inherent error, which must be verified during HITL testing. As the design process moves into HITL testing, it follows that if a combination of posture and suit is influencing the human-system interface, the actual values must be collected and compared to the assumed effects. The easiest way to do this is to measure subjects in the unsuited standard configuration and the suited subjects in the posture-specific position. The ratio between the suited, posture-specific value and the unsuited standard value becomes a combined suit factor, incorporating the effects of both posture and suit. When this factor is iteratively applied back into analytical or CAD modeling, this combined effect automatically accounts for both the posture and suit and can be applied directly to the unsuited standard value. Alternatively, the combined factor can be broken down into its respective values, but that requires additional data gathering to capture the unsuited standard, unsuited posture-specific, and suited posture-specific values to quantify each piece of the puzzle.

4.5.2.5.3.4 MICROGRAVITY SPINAL ELONGATION

When analyzing tasks that will be performed in microgravity or will be influenced by microgravity effects, spinal elongation must be incorporated into the assessment. NASA-STD-3001 Requirement V2 4006 specifies that changes to lengths be included in reduced-gravity environments. The most prominent and well-documented change in length due to reduced gravity is spinal elongation. Spinal elongation is the straightening of the spinal curve due to the lack of vertebral compression, bone loss, and body fluid shifts in microgravity. Historically, it has been found that the spine straightens in microgravity, resulting in a 3% growth in stature. This elongation affects anthropometric dimensions involving the spine (such as seated height and eye height). These dimensions must be increased by 3% for spinal elongation due to microgravity exposure. For example, spinal elongation needs to be included when analyzing fit or accommodation to determine whether a crewmember will properly fit within the seat for landing after being exposed to microgravity. To properly determine whether the crewmember is accommodated, 3% of the stature needs to be added to the seated height or any other measurement that incorporates the length of the spine (Equation 1). This holds true for all crewmembers returning from a low Earth orbit mission, such as a mission to the International Space Station.

$$Measurement_{0g} = (Stature_{1g} * 0.03) + Measurement_{1g}$$

Equation 1

Spinal elongation must be calculated on an individual subject basis for the population. It cannot be applied mathematically to the maximum/minimum values of the selected anthropometric data set, as those values are set limits that have been mathematically derived from the entire population. From a mathematical perspective, the maximum stature and maximum sitting height cannot be input into Equation 1 to derive the maximum sitting height with spinal elongation because it is not representative of a "realistic" human; it must be done on an individual basis. Designers are advised to apply spinal elongation on a per-subject basis for the measurement of interest, and then statistically examine the resulting impact on population values to evaluate compliance.

4.5.2.5.3.5 MICROGRAVITY FLUID SHIFT

Crewmembers experience significant changes to their body, especially in the regions of hands, legs, torso, and face, as a result of the shifting of body fluid distribution. To date, no empirical data exist on the amount of fluid shift in these regions and how it may affect crew anthropometry. Since NASA-STD-3001 Requirement V2 4006 specifies that changes to circumferences be included for reduced-gravity environments, designers are advised to take into consideration the possibility that changes in circumference could occur that may negatively affect the design.

4.5.2.5.4 IDENTIFY WORST-CASE SCENARIOS

Identification of the worst-case scenarios essentially focuses the analysis to highlight the segments of the population affected most by the design. The worst case is not always the largest male value or smallest female value, and the multivariate nature of anthropometry may obscure the ability to determine the worst case with only a cursory overview of the design. The best approach is to analytically model the problem at hand using the entire population from the selected anthropometric data set to identify individuals within the population who have issues with the restrictions imposed by design or who are an "at risk" group with respect to anthropometric compliance. The range of anthropometry of those individuals indicates the worst-case scenarios. Identification of worst cases is important for 3 reasons: 1) it quickly highlights the changes that need to be made to the design by examining or accounting for the population as a whole; 2) It identifies the segments of the population to be focused on during modeling and testing who are "at risk," who potentially may have clearance or fit issues; and 3) it helps to define the problematic measurements that can be verified with modeling or HITL testing, given the current stage of the design.

Note: Often the alternative to the derivation of realistic worst cases presented above is to use a "large" male or "small" female manikin representation. It is inappropriate to use the largest male in all dimensions or smallest female in all dimensions for an analysis. For example, it is physiologically and numerically impossible for a single person to have the maximal crotch height, maximal sitting height, and maximum stature of the population. The percentile values of specific attributes of the expected user population cannot be mathematically manipulated. For example, if you add maximum segment lengths together to derive a stature value, that stature value will exceed the maximum population stature. Such a configuration is unrealistic, skews the results of the analysis, and masks the portions of the population who are truly affected by the design. Although modeling a “large” male or “small” female could be useful for visualization purposes, verification should use the anthropometric values identified by the worst-case analysis to feed into modeling or analytical analyses.

4.5.2.6 EVALUATE THE DESIGN USING POPULATION ANALYSIS

Several factors go into the interpretation of results from anthropometric data collection, and the method of interpretation is heavily dependent on the ultimate end goals of the test. A key principle of the interpretation phase for any anthropometric analysis is the following:

Population analysis, which minimally means placing the design factors under consideration within the context of the entire population of interest, should be applied to all anthropometric evaluations.

Population analysis may consist of defining test subjects based on a percentile analysis, comparing to the extremes of the expected population, or comparing hardware dimensions with a large sample from a population data set of potential users. Whichever approach is used, the end result is quantification of subject accommodation for the purposes of compliance evaluation. No one-size-fits-all population analysis method applies to all situations; therefore, it is important to select a method that is appropriate to the problem being solved. The following sections provide details on various population analysis methods, associated pros and cons, and the benefits of combining more than one method to use during various life-cycle phases.

4.5.2.6.1 ANALYTICAL EVALUATION

The analytical evaluation method is the simplest “on paper” analysis used to compare the human requirements against the design. The complexity of the analytical method is driven by the number of measurements involved, the posture, and the specific focus of the analysis. The benefits of this analysis are that it provides a quick analysis of the data to ensure that the design meets the criteria, it identifies the worst-case scenarios, and it is relatively quick and simple to do before any other analysis. To understand this method further, take an example of a basic seat.

For individual measurements with a direct one-to-one match between the requirement dimensions and an identical posture, the analysis is very simple: meet the maximum and minimum for the design for the unsuited and suited conditions, as applicable. Using the example of a seat, the seat pan depth must not exceed the minimum buttock-to-popliteal length, the seat pan width must meet the maximum hip breadth sitting value, and the seat back length must meet the maximum sitting height to fully accommodate the entire population for the ranges as defined with the requirements. Thus, the recommended analytical method for a simplistic measurement case is to compare the design’s measurements against the maximum and minimum, as applicable, to ensure that the entire population can fit within the design specifications. This is the most simplistic scenario one would encounter, and does not account for anticipated changes in posture due to the vehicle/suit interface.

For singular measurements influenced by posture, the analytical method must be adjusted to account for the difference in posture for the body measurement of interest. The measurement must be mathematically adjusted to reflect the change in body posture. The recommended analytical method is to break the body into body planes (sagittal, frontal, and transverse), use trigonometry to mathematically adjust the body posture to the anticipated postural changes, and evaluate the resulting measurement. Using the example of a seat design, if the hip angle of the chair is adjusted from 90 degrees to 75 degrees, the seat pan depth must still not exceed the minimum buttock-to-popliteal length; however, the clearance of the human in relation to the surrounding environment has changed. In this case, the knee distance from the seat back is no longer the buttock-to-knee length; it is the buttock-to-knee length adjusted by an estimated hip angle of 75 degrees. For singular measurements and simple body posture changes, these transformations can be applied directly to the maximum and minimum values and the resulting derived measurement can be compared with the design. The proviso to this analytical analysis is that the estimation of the actual body angle must be verified through HITL testing to achieve confidence in the results.

For multivariate measurements influenced by posture, a whole-body-posture-based analysis (WBPBA) should be used (Rajulu, 2010; Gonzalez, 2003). The analysis is used to determine a derived measurement composed of several other measurements spanning body segments. The methodology behind the WBPBA involves using fixed joint angles or body segment locations and the multiple measurements that compose the posture of interest to run a simulation with each member of the selected anthropometric data set to calculate the range of the derived body dimension needed to accommodate the population. A hypothetical example is the total length a seated person spans from foot to top of head, or “seated clearance” for the purposes of this example. The worst-case scenarios are the smallest (1st-percentile female) and largest (99th-percentile male) calculated seated clearance values. The recommended way to perform this analysis is to first determine the correct seated posture, including hip and knee angles, for the seated position. Using the combination of the hip and knee angles, knee height, upper thigh length, and sitting height, the geometry of the seated individual can be examined in the 2-D sagittal plane, and the seated clearance can be calculated analytically for all members of the selected population. Determination of the mean and standard deviation values of that calculated measurement will yield the percentile values and allow verification that the design constraints can accommodate the NASA crew population.

The analytical models discussed above can also be used to determine group effects. Group effects are the impact of the surrounding environment on the ability to accommodate multiple crewmembers. Ideally, a designer would account for the space that multiple crewmembers occupy in a design, but often design constraints are prohibitive. For example, the minimum spacing between 2 seats can be set using the maximum suited male forearm-to-forearm breadth, as this would ensure that there will be enough elbow room for any seated crewmember. In less-than-ideal states, where total space and free volume are at a premium, design constraints may force that spacing to be smaller than ideal. This can be justified with assertions that instances are rare where 2 males with maximum forearm-to-forearm breadth will fly together. The quantification of group effects using a Monte Carlo simulation can be used to determine statistically just how much of the resulting population is accommodated in the less-than-ideal spacing as well as evaluate the probability that random selection of any 2 crewmembers would result in an accommodation issue. A Monte Carlo simulation is a numerical simulation technique that relies on large numbers of repeated random samplings to compute results. In the context of human factors design, the Monte Carlo can provide information about multi-crew, single anthropometric measurement design issues (Margerum, 2008). A standard or derived dimension can be used to fuel a Monte Carlo simulation, and the output of a Monte Carlo is essentially a new population of the grouped measurement of interest. For the above example of forearm-to-forearm breadth, one can randomly sample 2 people from a gender-weighted population and total the combined forearm-to-forearm breadth. Repeating this random sampling over thousands of iterations yields a new population of derived total forearm-to-forearm breadth for 2 people. The design constraints can be compared with the new population to determine what percentiles are not accommodated and how much more space is required to accommodate the majority, and even to evaluate the probability that crewmembers will have to be reselected based on the measurement constraints. It is also important to note that although the Monte Carlo can assess accommodation of the population in a restricted space, it does not account for performance, and HITL testing should be used to assess the impacts of the restricted environment in conjunction with group effects (Thaxton, 2008).

4.5.2.6.2 CAD MODELING AND SIMULATION

Modeling is the 3-D representation of the human in the surrounding environment. The utility of modeling for verification is driven by the configurability of the human model and the operator’s ability to accurately represent the real-life postures of the models of interest. The benefits of modeling are that it is an extremely useful tool for visualizing a particular scenario and for determining initial limitations of the design. The major drawback of modeling is that it provides only a snippet of the entire spectrum of the population and the multivariate interplay of all the measurements. Modeling follows the old programming axiom of “garbage in, garbage out,” and caution must be used in evaluations based on modeling to ensure that the entire population spectrum is accounted for. Modeling is similar to preliminary analytical analyses; both involve assumptions for suit factors, postures, and body measurement configurations. Like analytical analyses, the assumptions and conclusions drawn from the CAD model must be validated with HITL testing.

Ideally, a CAD program would have the capability of adjusting any measurement of the human model to any value set by the user, allow modeling of clothing effects, and account for variations in anthropometry caused by changes in posture. Unfortunately, off-the-shelf CAD modeling programs are not advanced enough to be the sole tool used for a human factors analysis. Thus, it is important to recognize the limitations of CAD programs and use proper analysis methods. The CAD model must account for the actual impact of the suit on the anthropometry, not by modifying the human model dimensions, but by adding on the suit effect as an external shell or clothing effect to the model. If the model is unable to add on the suit effects, then they must be accounted for mathematically when calculating clearance or interference issues from the CAD model. In addition the model must account for differences in postural changes between the analytical analysis method and the model, as well as differences in body measurements.

It is recommended that designers use the analytical analysis method to identify the worst-case scenarios and preliminary issues with the design before moving to a CAD-based analysis. By the time modeling is used, the concept of how the design fits or does not fit the population should be understood. In this regard, the CAD modeling becomes a preliminary visualization tool for the results witnessed in the analytical method and allows a 3-D overview of the design's impact on the surrounding structure.

The test methodology for CAD modeling should consist of identifying the worst-case scenarios using the analytical analysis and developing manikins that match the identified measurements. For individual measurements, a manikin that matches just the measurement of interest is sufficient. The group effects of multiple crewmembers can be modeled similarly to individual measurements by just adding a second manikin. However, when the analysis involves multivariate measurements influenced by posture, the WBPBA should be used to capture the worst-case individual's anthropometry (Rajulu, 2010; Gonzalez, 2003) and the corresponding values should be used to drive the CAD manikin sizing. In this manner, the modeling will use realistic custom-tailored manikins that have been identified as problematic to analyze in 3 dimensions against the design. As previously noted in paragraph 4.5.2.5.4 Identify Worst-Case Scenarios, one should not use a "large" or "small" manikin, which has all the maximum or minimum measurements entered for all the possible customizable manikin dimensions, for verification purposes. The percentile values are not additive or subtractive, and the maximum and minimum manikins do not represent realistic configurations of a human. Relying on 1 or 2 erroneous manikins to show that the entire population spectrum is accommodated is not the proper method for evaluating the design.

By entering the worst-case manikins identified from the analytical analysis, designers can initially use the CAD representation of the human-to-design interface to verify the analysis assumptions. For example, the distances from hardware to hardware or human to hardware can be examined and compared to the analytical analysis, which may or may not have fully captured or explored the complexity of the design. Once the potential interference or clearance issues identified by the analytical analysis have been confirmed, the CAD model can then be used to mitigate those issues, either through design changes to the surrounding structure or postural changes to the human model. If changes are made, the analytical analysis should be re-run to ensure that a different segment of the population is not influenced by the modified design.

This iterative process results in an optimized methodology, in which the analytical model is used to identify problem areas, the modeling is used to explore those problems and make design changes, and the process starts over until a design is ready for the prototype stage. By not relying solely on 1 method, a designer can ensure that the entire population is mathematically accommodated within the complexity of the overall human-systems interface while accounting for the assumptions used in both methods. Modeling only the worst-case scenarios reduces the cost associated with developing and tweaking each human model while ensuring that no segments of the population remain unaccounted for in the design.

4.5.2.6.3 HUMAN-IN-THE-LOOP TESTING

NPR 8705.2B paragraph 2.3.10 requires HITL evaluations for human-system interfaces. In the context of this document, HITL testing is a physical simulation involving a human operator. The benefits of HITL testing are that it allows a designer to test a mockup or prototype with a human and determine whether the assumptions about the posture and/or hardware issues are consistent. The major drawbacks of HITL testing are the time consumption, limited subject pool availability, and reliance on mockups of appropriate fidelity. HITL testing should be performed iteratively throughout design and as the final step in verification of the design against the requirements. Technical products provided for PDR and CDR should include presentations of how HITL evaluations were used to influence system design.

The value of HITL testing depends on the fidelity of the mockup to the proposed design. The lower the mockup fidelity, the more mathematical assumptions will have to be incorporated into the analysis to account for the differences between the mockup and the actual design. HITL testing for anthropometric evaluation requires a concrete plan for the measurements that will be collected, quantification of test subjects' anthropometry, and the data analysis that will be done to verify the design.

Analytical analysis and modeling should be used as previously discussed to identify worst-case-scenario body configurations and drive specific data collection during the HITL testing. These previous methods should also inform the posture, suit, and microgravity factors to be addressed in the analysis.

Ideally, the subjects selected for HITL testing should cover the full spectrum of the population for each critical measurement of interest. In practice, however, subjects are usually limited to a select group that does not represent the entire anthropometric range. Regardless, anthropometry corresponding to the identified task-specific critical dimensions must be gathered from each subject.

The data analysis associated with HITL testing for anthropometric evaluation has several basic goals. The first goal is simply validation of the assumptions used for analytical and CAD modeling. Facets of this validation include whether the actual posture is the same as the assumed posture, whether the actual restrictions and limitations on the dimensions of the human are the same as those previously anticipated based on analytical and modeled scenarios, and whether any additional issues are faced by a person at the human-system interface. If differences are found between the actual and the previously calculated or modeled work, then the previous analytical analysis and CAD model must be updated to reflect the observed differences and once again tested for population accommodation. For example, in a scenario with knee clearance between the seat back and the kneecap, the hip angle of the seat hardware is angled at 85 degrees. During HITL testing, it is observed that the hip angle of the human does not match the seat hardware angle, and instead it ranges from 80 to 90 degrees. The previous work must then be updated to determine the impact on the population as a whole of using this new number range.

Ideally, during HITL testing the subject will have no observed issues with clearance or restrictions with the interface based on the background analytical and modeling work. Situations will occur where this is not the case. Thus, a second goal of the data analysis is to identify these unanticipated restrictions and quantify them with respect to the population as a whole to determine the root of the problem, be it subject-specific, posture-specific, or design-specific. One method of quantifying the subject in terms of the population uses percentile analysis. The basic steps for this analysis are to identify the subject's percentile value in the gender-specific population, evaluate where the subject falls within the population, and then determine how much of the population is affected by the particular issue for a given measurement. Each measurement's mean (μ), standard deviation (σ), and z-score (k) can be used to determine each subject's percentile value (X) using Equation 2 below.

$$X = \boldsymbol{\mu} + \mathbf{k} * \boldsymbol{\sigma}$$

Equation 2

If one subject has an issue where another does not, evaluation of the percentiles can help identify the root cause of the problem and the impact on accommodation of the population (Rajulu, 2010: Population Analysis). Take as an example an individual seated in a chair. The analytical analysis and CAD modeling both indicate that all subjects should be accommodated within the seat; however, during HITL testing one female subject complains that the edge of the seat pan is painfully digging into the back of her knee. On subsequent percentile analysis you determine that she has a 20th-percentile female buttock-to-popliteal length and has the smallest value of all subjects in the HITL test. This indicates that women ranging from the 1st to the 20th percentile may have a similar issue with the edge of the seat pan. Perhaps the impingement is caused by postural differences between small women and the rest of the population, perhaps the ability to conform to the seat pan is different for smaller women, or perhaps the foot rest adjustability dropped the thigh closer than ideal to the seat pan. Regardless, a segment of the population is now identified as "at risk," a designation that requires further follow-up and analysis.

The third goal of the HITL data analysis is to classify whether the worst-case scenarios pass or fail the anthropometric requirements, by extrapolating from HITL test subjects who may not be the worst cases from both an accommodation and performance perspective. In the ideal situation, where the subjects tested in the HITL study have no observed issues with clearance or restrictions with the interface, the subjects must still be classified in terms of the overall population using percentiles. The basis for this classification is to determine the human-to-hardware clearance values, and extrapolate to determine whether individuals who were identified as the "worst cases" of that measurement will have an issue. As an example of an extrapolation population analysis scenario, consider the task of walking through an entryway while wearing a suit.

Hypothetically speaking, the critical dimensions of interest would be identified as bideltoid breadth and stature, and the 2 worst-case scenarios would be the largest values (i.e., 99th-percentile male in both bideltoid breadth and stature). Before testing, the scenario is analytically examined and the entryway seems to accommodate a suited 99th-percentile male in both bideltoid breadth and stature, but it is not yet verified as meeting the requirements at this stage. The motion of walking involves 2 aspects that must be accounted for in the population analysis: a swinging motion of the arms, resulting in a higher width requirement, and the height variations observed during walking, which may increase the amount of head clearance required. For this example, a group of subjects ranges from 20th- to 80th-percentile male bideltoid breadth and 60th- to 95th-percentile male stature. During testing, all subjects were able to walk through the door, but the total clearance was only about 2 inches for the men who had the largest bideltoid breadth and 1 inch for stature. Collecting unsuited data from the subject pool and comparing each subject's values and the actual observed clearance will cause the analysis to yield the anticipated postural effects (see paragraph 4.5.2.5.3.2 Postural Factors). By extrapolating the observed postural effects to the 99th-percentile male values for both dimensions, designers can determine the required entryway dimensions and compare them to the actual mockup or design. As a result, this hypothetical population analysis identifies the necessary requirements the design must meet, given the worst-case scenario for this selected task.

The HITL test will be used to examine the worst-case manikins identified from the analytical analysis and CAD modeling, validate the assumptions from the previous analysis, and identify any unforeseen issues in the design. If the previous analysis assumptions are determined to be incorrect, the analytical analysis and CAD modeling must be re-run with the updated assumptions in place to evaluate compliance of the design. If the design is determined to be noncompliant with the anthropometric requirements, the issues must be mitigated by making appropriate design changes. If changes are made, the analytical analysis and CAD modeling should be re-run to ensure that a different segment of the population is not affected by the modified design. Finally, if the design is compliant according to the HITL test, designers should continue conducting HITL testing using mockups at a higher fidelity level until the final stage of design is reached. Strategically placed iterative HITL tests will ensure that differences between the low-fidelity and high-fidelity stages of the design will not result in accommodation issues and that seemingly minor changes to a design will not result in major issues in the end product.

This iterative process results in an optimized methodology, in which the HITL test is used to validate design assumptions and identify problem areas, the modeling and analytical analyses are used to explore those problems, evaluate the population, and make design changes, and the process repeats until a design is ready for the prototype stage. By not relying solely on one method, a designer can ensure that the entire population is both mathematically and functionally accommodated within the complexity of the overall human-systems interface while validating the assumptions by using actual human data.

Additional discussion of HITL testing for anthropometry, biomechanics, and strength assessments can be found in HIDH section 4.2.4.2 Enhancement of Human-in-the-Loop Testing.

4.5.2.6.4 PERCENTILE ANALYSIS

Percentile analysis can be used at all levels of analytical, modeling, and HITL analyses. In the most simplistic terms, anthropometric verification and validation is a comparison of the design against the maximum and minimum critical dimensions. As the complexity of the analysis increases, the percentile analysis becomes a critical tool for evaluation of the design. As discussed throughout this section, the selected anthropometric data set in conjunction with percentiles can be used to derive atypical measurements, and evaluate multivariate posture-based body configurations and group effects. The percentile analysis can be used to place the design constraints in the context of the population, evaluate HITL subjects in relation to worst-case subjects, assist with extrapolation of the results to the worst cases, and even yield the accommodation restrictions of the design. It is highly recommended that designers use this tool during the design process, using the basic mathematical equation (Equation 2) or using the more complex variations, adding in the microgravity aspect (Equation 1) or the suited aspect (Margerum, 2008: Case Study #2) to assist with validation and verification of the design.

4.5.2.6.5 USE OF THE MINIMUM AND MAXIMUM POPULATION ACCOMMODATION VALUES

A design may not specifically require both the maximum and minimum values, but care must be taken to account for both of them in the context of the overall vehicle design. Both the maximum and minimum values must be considered even if a design specifically uses only one of the critical values. Using a basic seat example, the seat pan width must meet the maximum hip breadth value to ensure that all crewmembers are supported, but examination of the minimum should be considered in terms of crew safety or comfort. If the crew is jostled on launch and landing, the smaller women may shift around on the seat plan, which could cause discomfort and potential injury. Thus, although the seat pan width is driven by the maximum and supports the entire population range, a factor of adjustability for that dimension is driven by the combination of the maximum and minimum. Consideration of this adjustability factor is essential for crew comfort and safety.

4.5.2.7 ANTHROPOMETRY TECHNICAL PRODUCTS

Verification and validation of a given design requires that the entire population range is accounted for in the design. At a minimum, the design must meet the relevant maximum and minimum ranges for the selected set of critical dimensions set forth by Requirement V2 4003 and tied to the data set used for satisfaction of V2 4001. The design must prove through analytical, modeling, and HITL methods that the entire population spectrum between the maximum and minimum values has been accounted for within the design. Designs in which multiple critical dimensions interact, such as posture-based clearance measurements, must use the relevant analysis methods to accommodate the population as a whole. Successful verification for these multi-variable scenarios would mean that the design accounts for the entire range between the minimum and maximum values for the given measurements of interest using the entire selected anthropometric data set.

For each of the major milestones of the design life cycle, the technical products in Table 4.5.2.7-1 are recommended for review by the NASA customer.

TABLE 4.5.2.7-1 ANTHROPOMETRY TECHNICAL PRODUCTS

Technical Products	Phase A		Phase B	Phase C	Phase D	
	SRR	SDR	PDR	CDR	SAR	FRR
A description of the ConOps, function allocation, associated crew task lists, and the selected anthropometric data set and its associated critical measurement ranges. Includes list of tasks considered to be design-driving for anthropometry requirements as well as definition of factors influencing anthropometry.	I	U	U	U	---	---
A summary of modeling/analysis/evaluation (i.e., CAD, human modeling, and population analysis) performed to date and the influence on system design with links to the detailed analysis results. Required per NPR 8705.2B, and HITL evaluations required per paragraph 2.3.10.	---	---	I	U	U	---
System architecture drawings (structures, equipment, etc.), material specifications, interface requirements.	---	---	I	U	U	---
Verification plan.	---	---	I	U	U	---

X = one-time release of item
I = initial release of item
U = updated release of item

Concept of Operations and Crew Task Lists

The ConOps, described in paragraph 3.2.3.1.2, provides information such as identification of crew activities and determination of which subsystems are affected by crew activities. Function allocation, described in paragraph 3.2.3.1.3, establishes the extent to which an activity is to be automated or assigned to humans. The crew task list, described in section 4.1 User Task Analysis, documents details including allocation of function between crew and systems, definition of the sequence of crew activities, and identification of critical tasks. As the crew task list evolves through the design cycle, its final iteration should become crew procedures.

For anthropometry requirements, it is important to determine what tasks may be design-driving. Tasks or uses of hardware that represent challenges for anthropometric extremes will be particularly important for system-level analysis and testing. Factors that may influence anthropometry include suit conditions, posture, gravity conditions, and group effects.

Modeling, Analysis, and Evaluation Summaries

Iterative summaries of modeling, analyses, and evaluations provide NASA with insight into technical details of human-systems integration throughout the design process. As designs mature, modeling, analyses, and evaluations should use inputs and mockups of increasingly higher fidelity, as discussed in paragraph 3.2.3.3 Evaluate Designs and Iterate Solutions. It is important that summaries address how key and critical design decisions were assessed. According to the NPR 8705.2B, updated summaries are to be provided at each design review through SAR. Also, in paragraph 2.3.10, the use of HITL evaluation is a required method to progressively demonstrate that the operational concept meets system requirements for operational safety, efficiency, and user interface design.

For anthropometric analyses, as appropriate for each design phase, reports should detail CAD model work and progressively higher fidelity human model work in addition to analysis of HITL evaluations. Population analysis ensures that findings extend to the entire crew population and consider worst-case scenarios.

Architecture, Materials, and Interface Specifications

Drawings, materials, and interface specifications provide NASA with insight into human-systems integration technical details throughout the design process.

Verification Plan

The verification plan is a formal document describing the specific methodologies to be used to show compliance with each requirement.

System Requirements Review (SRR)

Suggested developer technical products:

- Selected anthropometric data set and its associated critical measurement ranges
- Overall plan for meeting anthropometric design compliance
- Definition of human-related major systems and what anthropometric requirements are applicable
- High-level analytical analyses examining the impact of anthropometric requirements on the design
- Plans for mitigation efforts if high-level analyses indicate that design does not meet requirements

NASA Involvement:

- Review overall plan, give feedback
- Review major systems and applicable requirements, give feedback
- Review analytical analysis results for consistency and methodology and plans for mitigation, give feedback

System Definition Review (SDR)

Suggested developer technical products:

- Reports detailing analytical analyses for all major subsystems, to prove that concept designs meet anthropometric requirements and account for assumptions

- If available, reports detailing preliminary CAD model work based on previous analytical analyses to prove that concept designs meet anthropometric requirements and account for assumptions
- Plans for mitigation efforts if analyses indicate that design does not meet requirements

NASA Involvement:

- Review reports and mitigation plans, provide feedback

Preliminary Design Review (PDR)

Suggested developer technical products:

- Reports on detailed analyses (analytical, modeling, and HITL) examining the impact of anthropometric requirements on the human-systems interface design, with any limitations and assumptions addressed
- Plans for mitigation efforts if analyses indicate that design does not meet requirements
- Plan for verification of requirements

NASA Involvement:

- Review detailed analysis results for consistency and methodology, provide feedback
- Review plans, provide feedback

Critical Design Review (CDR)

Suggested developer technical products:

- Reports detailing HITL testing to examine the impact of anthropometric requirements on the design; plans for mitigation efforts if analyses indicate that design does not meet requirements
- Reports on updated analyses (analytical and modeling) based on results of HITL testing to examine the impact of anthropometric requirements on the human-systems interface design; plans for mitigation efforts if analyses indicate that design does not meet requirements
- Final plans for anthropometric verification testing

NASA Involvement:

- Review reports, provide feedback
- Review verification plan, provide feedback
- Review design for consistency and methodology, provide feedback on final prototype design

Test Readiness Review (TRR)

Suggested developer technical products:

- Demonstration of adherence to overall plan for meeting human-systems design compliance and justification for necessary plan changes
- All testing completed and mitigation efforts incorporated into the design

NASA Involvement:

- Review report, give feedback

System Acceptance Review (SAR)

Suggested developer Company technical products:

- Demonstration of design compliance and all anthropometric requirements met

NASA Involvement:

- Review of design relative to levied anthropometric requirements

4.5.2.8 ANTHROPOMETRY REFERENCES

Churchill, E. & McConville, J. (1976). Sampling and data gathering strategies for future USAF anthropometry, Appendix II-A. Air Force Systems Command, Wright Patterson Air Force Base, OH.

Gonzalez, L. J., & Rajulu, S. L. (2003, June) *Posture-based whole body anthropometric analysis – A case study*, Paper presented at the meeting Digital Human Modeling for Design and Engineering Conference and Exhibition, Montreal, Canada.

Gordon, C. C., Bradtmiller, B., Churchill, T., Clauser, C. E., McConville, J. T., Tebbetts. I., & Walker, R. A. (1989, September). 1988 Anthropometric Survey of U.S. Army Personnel (ANSUR): Methods and summary statistics (NATICK/TR-89/044). Natick, MA: U.S. Army Natick RD&E Center.

Margerum, S., & Rajulu, S. (2008). Human factors analysis of crew height and weight limitations in space vehicle design. *Human Factors and Ergonomics Society Annual Meeting Proceedings*, *52*(1), 114-118.

McConville, J., & Tillman, B. (1991). Year 2015 astronaut population anthropometric calculations for NASA-STD-3000. Houston, TX: Johnson Space Center.

U.S. Department of Health and Human Services. (2004, October). NHANES (National Health and Nutrition Examination Survey) Mean Body Weight, Height, and Body Mass Index, United States 1960–2002. Rockville, MD: Author.

Rajulu, S., Margerum, S., Young, K., & Blackledge, C. (2010). Anthropometric processes for population analysis, suit factor generation, and a NASA recommended set of practices essential for data collection and analysis for verification and validation of vehicle, suit, and vehicle-suit interface requirements. (JSC 65851). Houston, TX: Johnson Space Center.

Thaxton, S., & Rajulu, S. (2008). Population analysis: Communicating about anthropometry in context. *Human Factors and Ergonomics Society Annual Meeting Proceedings, 52*(1), 119-123(5).

4.5.3 DESIGN FOR RANGE OF MOTION

4.5.3.1 INTRODUCTION

The NASA-STD-3001, Volume 2 NASA Spaceflight Human-System Standard, section 4 Physical Characteristics and Capabilities, includes requirements to accommodate crew ranges of motion (ROM) and reach. The purpose of mobility design requirements is to ensure that all developed hardware is operable by all potential NASA crewmembers. Accordingly, all designers and developers of space systems will need to demonstrate compliance with the verification requirement using a variety of methodologies including analysis, modeling, and HITL testing.

4.5.3.2 APPLICABLE REQUIREMENTS

The following NASA-STD-3001, Volume 2 requirements are applicable to range of motion:

- Data Sets [V2 4001]
- Data Set Characteristics [V2 4002]
- Population Definition [V2 4003]
- Data Set Assumptions [V2 4004]
- Range of Motion Data [V2 4007]
- Reach Data [V2 4008]

4.5.3.3 SELECTION OF A RANGE-OF-MOTION DATA SET

The NASA-STD-3001 NASA Spaceflight Human-System Standard Requirement V2 4001 specifies that a biomechanics data set for the crewmember population must be selected and implemented in the design for range of motion (V2 4007) and reach (V2 4008) Requirement V2 4004 specifies that age, gender, and physical condition shall also be included in this data set. Furthermore, Requirement V2 4003 requires the definition of the population ranges for the physical dimensions that the system is intended to accommodate, and V2 4002 requires these values to include suited conditions.

ROM of a joint is measured by using the maximum observed angle of a joint during a specified task or posture. ROM is referenced in terms of rotation of a child entity with respect to a parent entity, and the exact rotation definitions depend on what type of coordinate system (e.g.., Cartesian, spherical) or transformation (e.g., Euler, fixed) is used by a program. Proper representation of the crewmember population with ROM for both unsuited and suited tasks can be done with a combination of literature surveys and data collection. No data set of ROM values is available as there is with anthropometry; however, a variety of technical papers detail ROM values for particular tasks. The particular joints selected for each requirement would be those identified as important through a task analysis, for example, only upper body, only lower body, or entire body for certain tasks. If the program uses data collection to gather the ROM data, the limits should be determined by using the minimum of the maximum ROM data of the test subject pool. Using information that is in the public domain and data collected from unsuited and suited subjects, a designer can determine the anticipated ROM of the population, as well as the impact of the suit on ROM values, using a crew task to drive the selection of the requirement limits. The ROM requirements specified in HSIR and CHSIR were determined through a study of tasks, specific to suited crewmembers, that focused on the functional ROM. The unsuited and suited motion data were compared across multiple subjects and were summarized first by task; then the tasks were compiled into an overall set of requirements delineated by joint.

4.5.3.4 RANGE OF MOTION GENERAL OVERVIEW

Unfortunately there is no single, simple test to verify that a design will meet mobility requirements for any crewmember. A systematic approach must be taken to conduct progressively more vigorous testing to ensure that a crewmember in the worst-case configuration (see section 4.5.3.5.2 ROM in the worst-case configuration) (e.g., restrained, seated, and suited at various gravitational states with a full contingent of crew in place) can still perform all required operations. Analytical and CAD-based modeling may be implemented as a part of initial concept testing to identify key areas of concern. HITL testing may then be conducted with progressively higher fidelity hardware and tests to ensure that all mobility requirements are met. Initial HITL testing may involve a single test subject in a low-fidelity hardware mockup at 1*g*. Final phases of testing should involve a full complement of test subjects in flight configuration (including high-fidelity flight hardware and pressure suits, if planned), performing all required operations, and when feasible and appropriate, at simulated relevant gravitational states. Relevant nominal and contingency operations should be tested as well. As test hardware progresses to more closely resemble flight hardware, greater efforts must be made to include test subjects that represent the entire crewmember population with associated crew protection devices (e.g., pressure suits, seat restraints)

As with other human factors-driven evaluations, a logical and iterative progression should be made from low-fidelity to high-fidelity test conditions. Generally these steps are involved:

1. State objectives – depending on the phase of the project life cycle, objectives may focus on evaluating hardware, crew accommodation, contingency operations, or other highly specialized tests.
2. Identify critical metrics – these key measurements dictate how the test should be set up and may be related to specific requirements.
3. Identify and compensate for appropriate test conditions – initial tests may be acceptable with a single modeled test subject to demonstrate that hardware can be operated within an accepted ROM of the test subject, whereas final testing should consider gravitational state, suited condition (if appropriate), possibly deconditioned crewmembers, and any other relevant conditions.

4. Recognize critical operations – some comprehensive testing may require testing every possible configuration of the hardware, or earlier testing may be acceptable with just worst-case scenarios.
5. Evaluate the design – evaluate the hardware design using the appropriate fidelity of testing.
6. Review and redesign as necessary – interpret the results of the test to verify that the design met the designated requirements, and improve the design to increase accommodation if necessary.

Repeat and finalize - Repeat steps 1-6 with progressively higher fidelity hardware and more representative subject range until all requirements are met and the design is finalized.

4.5.3.5 METHODOLOGY

4.5.3.5.1 IDENTIFY OBJECTIVES

Evaluating mobility constraints on designs of flight hardware for human accommodation can be a difficult process that depends highly on maturity of the hardware being evaluated. Early in the project life cycle the design may exist only as CAD models, but as the design matures, low- to high-fidelity mockups become available, and eventually flight hardware is available for testing. Initial objectives should focus on ensuring that the tasks(s) can be successfully performed, judging by human-system interaction with respect to the ROM. Initial objectives should also incorporate common problems associated with mobility in human-systems integration such as operability of hardware and use of translation paths by a generic crewmember. Eventual human testing with hardware mockups allows identification of issues associated with a diverse population of test subjects. Human models typically create an idealized test subject, but inclusion of live human test subjects introduces idiosyncrasies such as bilateral asymmetry (dominant limbs may have different ROM than non-dominant limbs), subject motivation, and training. Use of models may be appropriate to save time early in the design cycle, but HITL testing is necessary to verify that a mature design satisfies all requirements.

4.5.3.5.2 IDENTIFY CRITICAL METRICS

Before designing an experiment, it is important to consider what the goals of the study are and to design the test accordingly. Typical motion is described in terms of joint-angle ROMs tied to specific tasks. A task analysis must be performed to ensure that the ROM is relevant to planned operations. The results of the task analysis should be compared and aligned with the corresponding ROM requirements determined from the selected ROM data set. Ultimately, the goal is to prove that the design configuration satisfactorily allows a mission to succeed for all tasks rather than to verify that body movements fall just within required ranges. Recognizing these critical mobility metrics that influence the ability of a crewmember to successfully complete the mission enables the design of tests to prove that requirements are met.

4.5.3.5.3 IDENTIFY TEST CONDITIONS

As the scope of the test becomes clear, it is important to anticipate issues that may affect the accuracy and fidelity of testing. Mobility and other biomechanical investigations can become complex, and therefore the issues detailed in this document are not all-inclusive. New issues may be identified and novel solutions may be developed to account for test factors that otherwise would negatively affect the fidelity of testing.

4.5.3.5.4 HUMAN MODELING

If the goal of the test is, for example, to determine whether a seated and restrained crewmember can reach an emergency control, a carefully crafted human model may work adequately. However, care must be taken to ensure that all constraints are realistically applied and that no obvious errors exist in the model, such as surface penetration, or postures that may be physically possible for some subjects but not others. For example, care must be taken in applying generic ROM limits on human models. As shown in Figure 4.5.3.3.4-1, 2 human models with identical ROM limits but different anthropometry yield a feasible arm position for a larger man (left) but surface penetration of the arm into the chest for a smaller woman (right).

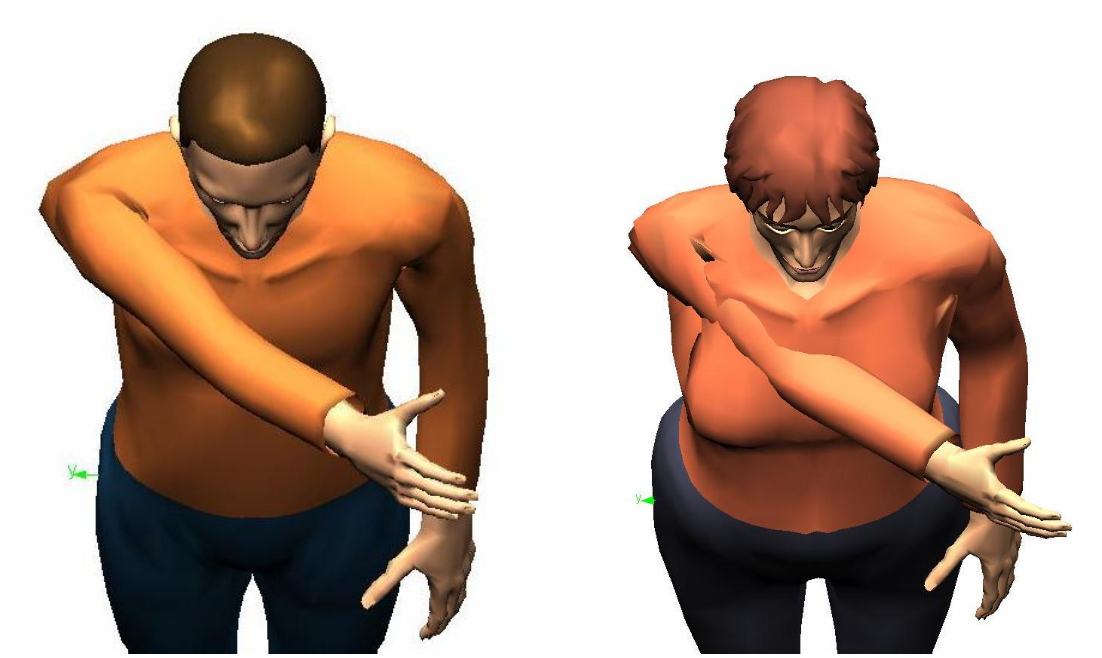


FIGURE 4.5.3.5.4-1 EXAMPLE OF SURFACE PENETRATION IN RAMSIS AS DEPENDENT ON SUBJECT ANTHROPOMETRY

Although most human modeling packages come with the ability to control subject sizes and limitations on ROM, it can be prohibitively time-consuming to check large numbers of simulated operations with many sizes of test subjects. A critical issue that must be addressed for any suited operation is that most human modeling packages have no way of dealing with restrictions to motion, visibility, and comfort stemming from the presence of spacesuits. Some software permits editing of certain parameters, and this editing may partially permit an attempt at simulating a spacesuit, but the fidelity of such simulations currently is questionable, at best. Despite these specific limitations, human modeling holds the most promise early in the design cycle, when designs are immature and it may be prohibitively expensive to build physical mockups of all design permutations. Additionally, once some HITL data are acquired, human modeling may be an appropriate intermediary step after acquisition of preliminary input and before physical fabrication of new hardware.

4.5.3.5.5 HUMAN-IN-THE-LOOP TESTING

After the initial evaluation of hardware designs with human modeling, generally the next step would be to create physical mockups of the vehicle and hardware with appropriate fidelity to determine capabilities and accommodation of the design. These mockups may be simple simulations made out of foam core and cardboard, or they may be elaborate prototypes constructed of flight-grade materials capable of interfacing with reduced-gravity analogs.

Relatively late in the design cycle, as HITL testing of higher fidelity is being performed, it may be necessary to use a variety of means for simulating altered-gravity states. These simulators, which include NASA’s parabolic flight Reduced-Gravity Aircraft, the Neutral Buoyancy Lab (NBL), the hydraulically offloading partial gravity simulator (POGO), the precision air-bearing floor (PABF) and others, represent various degrees of microgravity simulation fidelity and associated restrictions in cost and custom hardware needed for testing. Each simulator carries very unique conditions and as such should be dealt with on a case-by-case basis.

Once physical mockups or components of flight hardware have been fabricated for testing, HITL testing may proceed at 2 levels of detail. The first may call for discrete yes/no answers to the question, “Could the subject satisfactorily complete the task?” with possible subjective feedback from the test subject. The second level of detail provides for the collection of quantitative data, primarily through the use of motion capture or some analogous technology as an objective means of determining if requirements have been met. This quantitative approach for HITL testing allows very clear verification of requirements compliance, but the process of collecting and analyzing the data may be rather involved.

Mobility data can be acquired through a wide variety of methods, which differ in markers, analysis techniques, and even principles of physics that influence how the motion data are collected. For instance there are picture-based methods (stereophotogrammetry), simple video analysis tools, multi-camera video-based systems, passive marker motion systems, active marker motion systems, electrogoniometry systems, and even systems based on accelerometers and inertia. Each system has benefits and limitations depending on the surrounding environment, the test setup, occlusion issues, and on what motion data are output from the specific method. When collecting mobility data, care must be taken to ensure that the data collection hardware can operate in the required test settings. Many active and passive, camera-based motion-capture systems have minimal operable volume requirements that prevent data collection in small, enclosed spaces like some crew capsule mockups.

Systems based on electrogoniometry often run into problems with drift and interference from electrical or magnetic fields. These problems can often be mitigated with appropriate planning, but they may add to the technical difficulties of validating mobility requirements for flight systems.

The number of subjects to be used in a mobility study is always an issue, and the answer depends on the maturity of the system being studied and the degree of verification being sought. Early in the project life cycle, when proof-of-concept studies are more prevalent than final requirements validation, having a relatively small number of subjects may be appropriate to demonstrate the effectiveness of the hardware or system, either through modeling or HITL testing. Human modeling opens the door for evaluating specifically crafted test subjects designed to verify against some anthropometric extreme; however, care must be taken to ameliorate the concerns presented previously. For HITL testing, one must balance the time investment of collecting many test subjects with confidence in the determined results. The relevant population must be considered; if verification includes the need to accommodate the full range of crewmembers, then every effort should be made to include test subjects who represent the full spectrum of crewmembers. In unsuited tests this may be difficult, but when suits are involved, it may be nearly impossible to include subjects of extreme dimensions for whom spacesuit sizes may not be available until the design is verified. In these cases, it may be necessary to develop a metric of performance difference, for example some percentage of unsuited mobility that a spacesuit permits. Applying this ratio to unsuited data for extremes of anthropometry may be a necessary step in initially verifying a design’s success. However, the system would still need to be reviewed with the final design of the spacesuit for these extreme test subjects, as the metric of performance difference may change with suit size.

Additional discussion of HITL testing for anthropometry, biomechanics, and strength assessments can be found in HIDH section 4.2.4.2 Enhancement of Human-in-the-Loop Testing.

4.5.3.5.6 RECOGNIZE CRITICAL OPERATIONS

Recognizing critical operations essentially involves identifying what crew tasks with which subjects are likely to result in a failure to complete the mission. Although additional conditions should be investigated, it is important to ensure that the most likely modes of failure are specifically verified and explored. It is important to note that the worst-case mobility scenario with the smallest subject is not always the point of failure. The worst-case mobility is not synonymous with the worst-case anthropometry; they are 2 distinct scenarios. Points of interference are likely to be discovered with large or intermediately sized subjects performing tasks in ways not anticipated. An analysis should examine a range of anthropometry matched to the “worst-case” mobility to verify the design.

4.5.3.6 EVALUATE THE DESIGN

In the initial stages of design, the anticipated ROM values from the requirements data set can be entered into the CAD model to assess the ability of the modeled crewmember to reach the various devices and controls. This first step ensures that the theoretical crewmember's motions fall within the ROM requirements. The CAD model can be iteratively updated with the results of HITL testing, capturing the differences between the modeled and actual performance as development progresses, and improving the design progressively as needed.

To assess that a mobility requirement has been met, kinematic data for multiple subjects must be collected across the entire population for all conditions through HITL testing. As the design fidelity increases, HITL testing should be used to gather subjects' unsuited ROM outside of the design, the unsuited ROM within the design, and suited ROM, as applicable. The evaluation of a hardware design through initial HITL testing may provide a preliminary assessment of mobility information before the data are even processed. For example, if a test subject can successfully complete a task, the level of mobility used by the test subject should be acceptable. However, one must be cautious about the scope of that assessment, because it applies only to the subset of the population represented by the specific subjects who completed the test.

In preliminary design stages, it is acceptable to have a smaller representative subject range for HITL testing and extrapolate to the entire population. To extrapolate collected data to other conditions and test subjects, it is necessary to collect many test subjects and determine the performance degradation due to the test conditions (assuming unsuited, 1*g* mobility is ideal) using a performance difference metric. This metric is the percentage of unrestrained, unsuited mobility relative to the ROM required to use the designed hardware or system in completion of a specific task. Applying this performance metric to unsuited data for extremes of anthropometry may be a necessary step in initially assessing a design's success.

For example, if cockpit design is verified to meet mobility requirements for unsuited crewmembers of all sizes and the design is then tested with average-sized crewmembers in pressurized suits, a fair first step would be to apply the same ratio of degradation in mobility that was experienced by average crewmembers wearing suits to the mobility exhibited by very small test subjects. However, the cockpit design would not be verified for all sizes of test subjects in pressurized suited conditions until a pressure suit is available to test with very small or very large subjects and the requirement is verified experimentally through HITL testing.

As the hardware moves into the final design stages, the range of test subjects should be increased to fully encompass the entire population, specifically including those who have been identified as problematic by the CAD modeling work. Performance degradation ratios may be applied to data input into various human models to help ensure a design is on track, but verification must come down to successful performance of HITL testing in relevant conditions across the entire anticipated population.

4.5.3.6.1 REVIEW AND REDESIGN AS NECESSARY

As the evaluation of the design is completed, the opportunity exists to enact positive change on the design to increase accommodation of the hardware based on the results of mobility testing. Additional risks to successful verification of the hardware should be identified and any necessary extra analysis of the collected data should be completed before following through to the next step in the process. Special attention should be paid to potential performance limitations in the evaluation of the design. For example, significant effort may be needed to test hardware in a micro- or hypergravity environment (such as on the reduced-gravity aircraft or in a centrifuge) to assess the performance limitations of a reduced-gravity state. Likewise, issues presented with contingency conditions may require extra attention to be paid to critical operations of the hardware.

4.5.3.6.2 REPEAT AND FINALIZE

With the iterative process identified earlier, continue the cycle of designing and testing with progressively higher fidelity hardware, test subjects, and testing environments until the hardware is verified to satisfy all requirements.

4.5.3.7 RANGE-OF-MOTION TECHNICAL PRODUCTS

Developer companies must be able to demonstrate that they have satisfactorily met mobility requirements as identified through careful selection of the data set and associated test conditions and critical operations. Initially, the designer may report what mobility was required to operate the hardware based on human modeling, but final verification will necessitate high-fidelity HITL tests.

For each of the major milestones of the design life cycle, the technical products in Table 4.5.3.7-1 are recommended for review by the NASA customer.

TABLE 4.5.3.7-1 RANGE OF MOTION TECHNICAL PRODUCTS

Technical Products	Phase A		Phase B	Phase C	Phase D	
	SRR	SDR	PDR	CDR	SAR	FRR
A description of the ConOps, function allocation, associated crew task lists, and the selected range-of-motion data set critical limits. Includes list of tasks considered to be design-driving for range-of-motion requirements as well as definition of test conditions and critical operations affecting range of motion.	I	U	U	U	---	---
A summary of modeling/analysis/evaluation (i.e., CAD, human modeling, and population analysis) performed to date and the influence on system design with links to the detailed analysis results. Required per NPR 8705.2B, and HITL evaluations required per paragraph 2.3.10.	---	---	I	U	U	---
System architecture drawings (structures, equipment, etc.), material specifications, interface requirements.	---	---	I	U	U	---
Verification plan.	---	---	I	U	U	---
X = one-time release of item I = initial release of item U = updated release of item						

Concept of Operations and Crew Task Lists

The ConOps, described in paragraph 3.2.3.1.2, provides information such as identification of crew activities and determination of which subsystems are affected by crew activities. Function allocation, described in paragraph 3.2.3.1.3, establishes the extent to which an activity is to be automated or assigned to humans. The crew task list, described in section 4.1 User Task Analysis, documents details including allocation of function between crew and systems, definition of crew activities sequence, and identification of critical tasks. As the crew task list evolves through the design cycle, its final iteration should become crew procedures.

For ROM requirements, it is important to determine what tasks may be design-driving. Tasks that require large ranges of motion will be particularly important for system-level analysis and testing. Factors that may influence ROM include suit conditions, posture, gravity conditions, and group effects.

Summaries of Modeling, Analysis, and Evaluation

Iterative summaries of modeling, analyses, and evaluations provide NASA with insight into human-systems integration technical details throughout the design process. As designs mature, modeling, analyses, and evaluations should use inputs and mockups of increasingly higher fidelity, as discussed in paragraph 3.2.3.3 Evaluate Designs and Iterate Solutions. It is important that summaries address how key and critical design decisions were assessed. According to the NPR 8705.2B, updated summaries are to be provided at each design review through SAR. Also in paragraph 2.3.10, the use of HITL evaluation is a required method to progressively demonstrate that the operational concept meets system requirements for operational safety, efficiency, and user interface design.

For ROM analyses, as appropriate for each design phase, reports should detail CAD model work and progressively higher fidelity human model work in addition to analysis of HITL evaluations. Population analysis ensures that findings extend to the entire crew population and consider worst-case scenarios.

Architecture, Materials, and Interface Specifications

Drawings, materials, and interface specifications provide NASA with insight into human-systems integration technical details throughout the design process.

Verification Plan

The verification plan is a formal document describing the specific methodologies to be used to show compliance with each requirement.

System Requirements Review (SRR)

Suggested developer technical products:

- Selected ROM limits for an applicable task list.
- Overall plan for meeting human-systems design compliance for mobility

- Definition of human-related major systems and which mobility requirements are applicable
- High-level analytical analyses examining the impact of mobility requirements on the design
- Plans for mitigation efforts if high-level analyses identify risks of design not meeting requirements for all conditions

NASA Involvement:

- Review overall plan, provide feedback
- Review major systems and applicable requirements, provide feedback
- Review analytical methodologies, analysis results, and plans for mitigation, provide feedback

System Definition Review (SDR)

Suggested developer technical products:

- Reports detailing analytical analyses for all major subsystems to prove that concept designs meet designated mobility requirements and account for assumptions
- If available, reports detailing preliminary CAD model work or low-fidelity human model work based on previous analytical analyses to prove that concept designs meet designated mobility requirements and account for assumptions
- Plans for mitigation efforts if analyses indicate that design does not meet requirements

NASA Involvement:

- Review reports and mitigation plans, provide feedback on areas of concern, especially any anticipated impingements on crewmember mobility

Preliminary Design Review (PDR)

Suggested developer technical products:

- Reports on detailed analyses (analytical, human modeling, and HITL) examining the impact of designated mobility requirements on the human-system interface design, with any limitations and assumptions addressed
- Plans for mitigation efforts if analyses indicate that design does not meet requirements for all crewmember configurations (i.e., the entire population, under all design constraints)
- Plan for verification of requirements

NASA Involvement:

- Review detailed analysis results for accommodation and issues with integration of results, provide feedback
- Review plans, provide feedback

Critical Design Review (CDR)

Suggested developer Company technical products:

- Reports detailing advanced human modeling and HITL testing examining the impact of mobility requirements on the design; plans for mitigation efforts if analyses indicate that design does not meet requirements
- Reports on updated analyses (analytical and modeling) based on results of HITL testing examining the impact of designated mobility requirements on the human-system interface design; plans for mitigation efforts if analyses indicate that design does not meet requirements
- Final Plans for verification of mobility requirements

NASA Involvement:

- Review reports, provide feedback
- Review verification plan, provide feedback
- Review design for accommodation and issues with integration of results, provide feedback on final prototype design

Test Readiness Review (TRR)

Suggested developer technical products:

- Demonstration of adherence to overall plan for meeting human-systems design compliance and justification for necessary plan changes
- Demonstration of readiness to perform HITL testing to verify that mobility requirements are met for contingency operations and multi-point failures, or suitable plans are in place
- All required testing completed and mitigation efforts incorporated into the design

NASA Involvement:

- Review overall report, provide feedback
- Review potential contingency plans, provide feedback

System Acceptance Review (SAR)

Suggested developer Company technical products:

- Demonstration of design compliance and all mobility requirements met for all crewmembers in all conditions

NASA Involvement:

- Review of design relative to levied requirements

4.5.3.8 RANGE OF MOTION REFERENCES

England, S. A., Benson, E. A. and Rajulu, S. L. (2010, May) Functional mobility testing: Quantification of functionally utilized mobility among unsuited and suited subjects (NASA/TP-2010-216122). Houston, TX: Johnson Space Center.

4.5.4 DESIGN FOR STRENGTH

4.5.4.1 INTRODUCTION

The NASA-STD-3001, Volume 2 NASA Spaceflight Human-System Standard section 4 Physical Characteristics and Capabilities includes requirements to accommodate crewmember strength and deconditioning. See HIDP section 4.15 Deconditioned Crewmember for discussion of muscle deconditioning and its impact on strength. The purpose of the human strength requirements is to ensure that hardware is operable by all potential crewmembers. Accordingly, all designers and developers of space systems must demonstrate by means of analysis, modeling, and HITL testing that verification and validation of the design has been satisfactorily achieved against the requirements.

The intent of this design process is to provide users with methodologies and best practices that should be implemented to ensure that adherence to the human-systems integration requirements set forth by NASA with respect to strength is satisfactory. The hardware design should involve careful consideration for interactions between humans and interfaces when humans are performing tasks, including consideration for the weakest crewmember, hardware integrity, and performance decrements due to physiological adaptations to space flight.

4.5.4.2 APPLICABLE REQUIREMENTS

The following NASA-STD-3001, Volume 2 requirements are applicable to strength:

- Data Sets [V2 4001]
- Data Set Characteristics [V2 4002]
- Population Definition [V2 4003]
- Data Set Assumptions [V2 4004]
- Strength Data [V2 4012]
- Muscle Effects [V2 4013]
- Operational Strength [V2 4014]

4.5.4.3 SELECTION OF STRENGTH DATA SET

The NASA-STD-3001 NASA Spaceflight Human-System Standard Requirement V2 4001 specifies that a strength data set for the crewmember population must be selected and V2 4012 states that this strength data set must be applied to the design. In addition, requirement V2 4004 specifies that age, gender, and physical condition shall also be included within this data set, specifically V2 4013 requires that the effects of deconditioning of the astronaut are included in the system design and V2 4002 requires that characteristics unique to space travel also be factored into the design. Furthermore, requirement V2 4003 requires definition of the population ranges for the strength values that the system is intended to accommodate, and V2 4014 requires that the system is operable at the lowest anticipated strength.

No data set of strength values is available as are values for anthropometry; however, a variety of technical papers detail strength values for particular tasks. Using information in the public domain, a designer can determine the anticipated strength limits of the population. Specific crew operational loads associated with movements could be identified by matching the movement to the design using a task analysis. The strength requirements in HSIR and CHSIR were determined by conducting a task analysis to determine the anticipated motions that would be important to crew strength, and then literature surveys were performed to identify existing unsuited strength data. The suit's effects on strength were estimated by comparing unsuited to suited strength for a range of functional tasks. Deconditioning effects depend on the duration of exposure to reduced gravity and prescribed countermeasures. Because of limited data availability, deconditioning in HSIR and CHSIR was applied by taking a minimum strength limit during a specified movement and applying a safety factor of 2.

4.5.4.3.1 DEFINITION OF HUMAN STRENGTH

Strength refers to a person's ability to generate force. Applying strength requirements will result in a minimum and a maximum applied crew load to be used for operational and hardware design. The minimum load pertains to operational strength that accommodates the weakest person whereas the maximum load represents the force the hardware must be able to withstand without failure. It is important to note that these definitions apply to intentional forces applied by the crewmember. Hardware design should be performed in a human-centered manner, with analysis of expected crew operations used to drive the design of such human-machine interfaces. Analyses should evaluate and define activities and tasks in terms of criticality and required postures. The strength limits established by each program must consider physiological deconditioning effects on crewmembers of extended space flight, which could affect their ability to perform necessary tasks.

4.5.4.3.2 APPLICABILITY TO SPACE FLIGHT SCENARIOS

Launch, Flight, and Reentry

Higher gravitational forces, as would be experienced during launch and reentry, will affect the successful application of human strength to perform a given task (that is, higher gravitational forces may result in a decrement in the force a crewmember is able to apply for completion of a given task). Strength value selection should be carefully considered when designing hardware and tasks for scenarios with higher gravitational force, as the inability to perform a given task under these conditions may result in loss of life, vehicle, or mission. Similarly, tasks that are performed under microgravity conditions (i.e., during flight) may be subject to decreased application forces by users. This may be the result of crewmembers being unable to attain a posture that allows compensation for any reaction forces applied back on the human by the tool or interface used (e.g., torque reaction force from a wrench). Therefore, the posture used, as well as available braces or handholds, should be taken into consideration to ensure successful completion of tasks performed under microgravity conditions. This subject is further addressed in paragraph 4.5.4.5.3.2 Posture Variability.

Decrement Caused by Space Flight

Decrement(s) that reflect the deconditioning effects of space adaptation on crewmembers must be applied to strength limits. Deconditioning includes bone loss, muscle atrophy (including loss of strength and mass), and other physiological decrements associated with long-duration space flight. It can have notable effects on a crewmember's ability to apply the necessary force or torque to complete a given mission task or operation. As deconditioning will affect each human in different ways, values for muscle strength decrements will vary. See HIDP section 4.15 for discussion of crewmember deconditioning.

4.5.4.4 STRENGTH GENERAL OVERVIEW

The evaluation of the design is a multi-phase process that depends on the stages of the design life cycle. In the preliminary stages of design, robust analytical analysis and modeling at a minimum should be used to identify the worst-case scenarios and the postures of interest, and to determine accommodation of the design. Any assumptions of posture, fatigue, and other human interface variables must be documented to verify them by future HITL testing. As the design matures within the design cycle, the evaluation of the design against the limits set forth by the requirements must move from the theoretical to the actual use of HITL.

In general, any design evaluation, whether it is low-fidelity analytical analysis or high-fidelity HITL testing, contains the same basic sequence of required steps in the flow of the design process:

1. Identify test objectives, which include but are not limited to accounting for the following: unsuited and suited operations, gravity condition (e.g., 1*g*, micro-*g*, hyper-*g*), postural effects, muscle fatigue effects, and test configuration fidelity.
2. Identify factors that influence the ability of a human to interact with the design and the surrounding environment.
3. Account for applicable factors affecting human strength, such as posture variability across the population, muscle fatigue, and gravity conditions.
4. Identify worst-case scenarios (i.e., criticalities, weakest crewmembers, and deconditioning effects on ability to generate force/strength).
5. Evaluate the design using analytical analysis, modeling techniques, or HITL testing at the appropriate stage of the design cycle and determine what segments of the population are not accommodated and what adjustments are necessary to accommodate the entire user population.
6. Make changes to the design based on evaluation findings to ensure accommodation of those using hardware to perform tasks or operations.
7. Repeat steps 1-6 until the design meets the limits set forth by the requirements, and the design is in the final stages of the design cycle.

4.5.4.5 METHODOLOGY

4.5.4.5.1 IDENTIFY TEST OBJECTIVES

Evaluation of the strength characteristics of a design is highly dependent on hardware maturity and requires very clear test objectives; these are critical to a successful evaluation of the design. Initial objectives in the early stages of the design life cycle must focus on ensuring operability of the design by the full range of crewmembers. As the design life cycle progresses, the objectives focused on human-centered testing allow identification of issues associated with a diverse population of test subjects and postures. For example, if the focus of a particular design evaluation is on a hatch lever that requires hand grip and elbow flexion to operate, the primary objective would be to ensure that the lever can be successfully operated by all crewmembers, from strongest to weakest, and the required force to actuate the lever allows all deconditioned crewmembers to still successfully operate it in both nominal and emergency situations. Secondary objectives may examine whether the hatch lever can accommodate the population of strengths given a set location within the overall vehicle context, such as the ability of larger crewmembers to bend down and actuate the lever or smaller crewmembers to reach up and operate the lever, with other vehicle components acting as obstacles. It is critical to examine the design as both an individual piece and part of the larger overall vehicle-human-interface design at all steps of the design cycle.

4.5.4.5.2 IDENTIFY INFLUENCING FACTORS

Using the defined test objectives, the next step would be to match the assumed posture needed to perform the task (e.g., a pushing motion at an oblique angle using a handle, hand grip, and elbow flexion) to corresponding postures determined from the strength requirements data set and resolve the posture into all necessary and applicable strength components. This analysis will aid in the identification of postural factors that may affect the subject’s ability to apply the necessary force or torque to perform a given task or operation. These steps will help determine whether the requirements for an assumed posture are reasonable and applicable to the human-system interface in question, while identifying the necessary test metrics and accounting for any assumptions or influencing factors associated with the design.

4.5.4.5.3 ACCOUNT FOR SUIT, POSTURE, AND GRAVITY EFFECTS

4.5.4.5.3.1 SUIT EFFECTS

For the Constellation Program and the Commercial Crew Program, NASA has measured and/or estimated suit effects on crewmember strength. The crewmember strength datasets for those programs can be found in HSIR Appendix B4 and CHSIR Appendix D4. Strength data are provided for unsuited, suited pressurized, and suited unpressurized conditions. The forces required to operate a given designed human-system interface must be within the strength range of the weakest anticipated crewmember for the worst-case pressure differential anticipated (e.g., unsuited, suited-unpressurized, or suited-pressurized). The HSIR and CHSIR set forth very specific postures for application of human strength and it is possible that a posture required to perform a specific, yet-to-be-determined task, may not directly correspond with any one posture in the strength data tables. Under such circumstances, programs should consult with NASA for direction on how to apply the appropriate combination of postures and associated strength values, or whether an additional validation is necessary for a particular posture and strength combination. This will ensure that the appropriate measures are implemented to protect both crewmembers and vehicle.

4.5.4.5.3.2 POSTURE VARIABILITY

During testing, strength measurements will be directly influenced by posture effects, and therefore the strength requirements compiled and set forth in the strength requirements data set are valid at only at the postures given. The assumption of a specific posture is highly dependent on the population and the location of the hardware design within the environment. If the design is placed in a location where smaller individuals will adopt a posture different from that of larger individuals, this variability must be accounted for and should be validated separately. Although data for the analytical and modeling stages of design are limited, the performance changes can be identified through HITL testing. Thus, it is critical to perform HITL testing on a wide variety of subject types to address postural variability in the population and determine its impacts on strength performance. The assumptions for the impact of posture effects on the human body must be unequivocally verified during HITL testing to ensure that the assumptions are valid or to modify the analysis as appropriate.

4.5.4.5.3.3 GRAVITY EFFECTS

Microgravity conditions present an interesting challenge to crewmembers when they are actuating a hardware interface or performing a task or operation requiring the application of force or torque. In this environment, it is much more difficult to apply the necessary force or torque because reaction forces (i.e., the forces acting back on the body when a human force is applied) are lacking, and therefore tasks performed under such conditions should be evaluated carefully and the appropriate strength values should be applied for the other conditions applicable to the situation (e.g., suited or unsuited conditions). For instance, the posture used by the crewmember, as well as any available braces or handholds, should be accounted for and the appropriate strength values applied. This will work to ensure that human operators are able to successfully perform any in-flight tasks requiring the application of force or torque.

For conditions involving hypergravity (e.g., launch, reentry), worst-case scenarios (e.g., deconditioning effects, safety factors, weakest crewmember) should be applied to ensure safe operation of human-system interfaces and the avoidance of any failures that may lead to loss of crew, vehicle, or mission. The task should be carefully analyzed and the appropriate strength value be applied.

4.5.4.5.4 IDENTIFY WORST-CASE SCENARIOS

Identification of the worst-case scenarios for human strength focuses the minimum strength values for a given population in a given posture for a selected criticality to protect all members of that population who will be affected by the design.

4.5.4.6 EVALUATE THE DESIGN

Several factors go into the interpretation of results from human strength data collection, and the method of interpretation is heavily dependent on the ultimate end goals of the test. For example, comparison of the strength requirements associated with a design to the strength levied in a specific posture will require analyses of adopted posture(s) during force production, as well as a determination of the scenarios in which the designed hardware will be used. For example, if a given piece of hardware is used in all phases of flight and potentially under any circumstances, nominal or contingency/emergency, then the appropriate space flight-related factors must be considered. A comparison of the force or torque values of the hardware to the standardized strength values for a given posture will determine compliance of the design.

4.5.4.6.1 PRELIMINARY ANALYSIS

The preliminary analytical analysis method is a simplistic “on paper” analysis to compare the human strength requirements against the strength demands of the hardware design. The use of free-body diagrams can be implemented to account for the force or torque requirements of the hardware design. These can then be compared to human strength requirements found in the strength requirements data set to determine whether further examination, analysis, and/or testing are warranted.

4.5.4.6.2 MODELING

As the design matures, more than likely the design will be placed into a CAD model. The designer should use dynamic models or other defendable, validated modeling techniques to determine the force or torque requirements of the hardware design. Compare the results to the human strength requirements to determine whether the weakest crewmember can apply the necessary force or torque to the hardware interface to successfully perform a task or operation.

4.5.4.6.3 HITL TESTING

HITL testing in the context of this document is a physical simulation involving a human operator. The benefits of HITL testing are that it allows a designer to test a mockup or prototype with a human and determine whether the assumptions about the posture, strength required to perform a task, and/or hardware issues are consistent. Some challenges associated with HITL testing are cost, time consumption, subject availability and participation, and the need for mockups of appropriate fidelity. HITL testing is the final step in validation of the design against the requirements. When HITL testing is conducted for evaluation of strength, multiple subjects will be needed to validate the posture assumptions, and if a variation occurs, the performance improvement or degradation can be determined by comparing subjects. Testing must include a range of subject sizes to properly scope the population. Ideally, a mockup of the human-system interface would be used with instrumentation capable of measuring human-applied forces and torques. This would allow a one-to-one comparison of actual hardware forces and torques to those being estimated, as well as to applicable strength requirements. Other scenarios, though less than ideal, may include obtaining unsuited strength data for the functional posture in question using a strength dynamometer to see where subjects fall in the population, and comparing performance on that dynamometer to actuating the hardware. However, if no dynamometer is available, it may be feasible to test the designed hardware in "ideal" configuration (i.e., outside a mockup, shirt-sleeved, unencumbered, in the location matching the posture selected from the strength requirements), and compare test results from this configuration with results from performing the task in the mockup given the postural issues and identifying all other influencing factors. The appropriate performance metrics (e.g., quantification of force decrement, postural analyses) should be used to characterize any differences between the 2 conditions and to provide recommendations on how to proceed with the human-system interface design.

Additional discussion of HITL testing for anthropometry, biomechanics, and strength assessments can be found in HIDH section 4.2.4.2 Enhancement of Human-in-the-Loop Testing.

4.5.4.6.4 FINALIZE THE DESIGN

Evaluate the design using analytical analysis, modeling techniques, or HITL testing at the appropriate stage of the design cycle and determine what segments of the population are not accommodated and what adjustments are necessary to accommodate the entire user population (i.e., the weakest crewmember). If overall failure of the user-interface interaction (i.e., inability of the weakest crewmember to actuate or operate hardware for task completion) occurs, then re-evaluation of the design is required and the appropriate testing steps must be taken to ensure accommodation of the entire user population.

4.5.4.7 STRENGTH TECHNICAL PRODUCTS

The reporting of human strength values should involve incorporation of worst-case scenarios as identified through careful selection of the data set and associated test conditions. These should be implemented to ensure the protection of all crewmembers, and of the hardware, vehicle, and mission completion. In the realm of human strength testing, worst-case scenarios manifest in the form of minimum values. Mean strength values can provide valuable information about the strength of a group of individuals, but do not provide end-users with information about the protection of weaker subjects (i.e., those with strength values lower than the mean). Inclusion of minimum strength values (i.e., strength values of the weakest individual) ensures that all other members of that tested population are able to effectively apply the force of the weakest subject. In sum, the reporting of minimum values provides users with guidelines for system design to protect the weakest crewmember who may operate a given hardware component or interface. This information will apply to HITL testing as well, and it is crucial for any developer's HITL testing to include an appropriate number of subjects so as to provide the necessary statistical confidence in results and testing-derived strength requirements and recommendations.

Reporting maximum strength values for human-system interfaces provides users guidelines for protecting hardware from the strongest crewmembers who may operate a given hardware component or interface.

For each of the major milestones of the design life cycle, the technical products in Table 4.5.4.7-1 are recommended for review by the NASA customer.

TABLE 4.5.4.7-1 STRENGTH TECHNICAL PRODUCTS

Technical Products	Phase A		Phase B	Phase C	Phase D	
	SRR	SDR	PDR	CDR	SAR	FRR
A description of the ConOps, function allocation, associated crew task lists, and the selected strength critical limits. Includes list of tasks considered to be design-driving for strength requirements as well as definition of factors that influence strength.	I	U	U	U	---	---
A summary of modeling/analysis/evaluation (i.e., CAD, human modeling, and population analysis) performed to date and the influence on system design, with links to the detailed analysis results. Required per NPR 8705.2B, and HITL evaluations required per paragraph 2.3.10.	---	---	I	U	U	---
System architecture drawings (structures, equipment, etc.), material specifications, interface requirements.	---	---	I	U	U	---
Verification plan.	---	---	I	U	U	---

X = one-time release of item
I = initial release of item
U = updated release of item

Concept of Operations and Crew Task Lists

The ConOps, described in paragraph 3.2.3.1.2, provides information such as identification of crew activities and determination of which subsystems are influenced by crew activities. Function allocation, described in paragraph 3.2.3.1.3, establishes the extent to which an activity is to be automated or assigned to humans. The crew task list, described in section 4.1 User Task Analysis, documents details including allocation of function between crew and systems, definition of crew activities sequence, and identification of critical tasks. As the crew task list evolves through the design cycle, its final iteration should become crew procedures.

For strength requirements, it is important to determine what tasks may be design-driving. Tasks or uses of hardware that represent challenges for weaker individuals will be particularly important for system-level analysis and testing. Factors that may affect strength include suit conditions, posture, gravity conditions, and group effects.

Modeling, Analysis, and Evaluation Summaries

Iterative summaries of modeling, analyses, and evaluations provide NASA with insight into technical details of human-systems integration throughout the design process. As designs mature, modeling, analyses, and evaluations should use inputs and mockups of increasingly higher fidelity, as discussed in paragraph 3.2.3.3 Evaluate Designs and Iterate Solutions. It is important that summaries address how key and critical design decisions were assessed. According to NPR 8705.2B, updated summaries are to be provided at each design review through SAR. Also, in paragraph 2.3.10, the use of HITL evaluation is a required method to progressively demonstrate that the operational concept meets system requirements for operational safety, efficiency, and user interface design.

For strength analyses, as appropriate for each design phase, reports should detail CAD model work and progressively higher fidelity human model work in addition to analysis of HITL evaluations. CAD and HITL analyses are necessary to define postures and actions used for each task. Population analysis ensures that findings extend to the entire crew population and consider worst-case scenarios.

Architecture, Materials, and Interface Specifications

Drawings, materials, and interface specifications provide NASA with insight into human-system integration technical details throughout the design process.

Verification Plan

The verification plan is a formal document describing the specific methodologies to be used to show compliance with each requirement.

System Requirements Review (SRR)

Suggested developer technical products:

- Selected strength limits for an applicable task list.
- Overall plan for meeting human-systems design compliance
- Definition of human-related major systems and what strength requirements are applicable
- High-level analytical analyses examining the impact of requirements on the design

NASA Involvement:

- Review overall plan, give feedback
- Review major systems and applicable requirements, give feedback
- Review analytical analysis results for consistency and methodology, give feedback

System Definition Review (SDR)

Suggested developer technical products:

- Reports detailing analytical analyses for all major subsystems, to prove that concept designs meet designated strength requirements and any assumptions are accounted for

NASA Involvement:

- Review reports, give feedback on strength requirements as well as any assumptions made about human strength in the design process

Preliminary Design Review (PDR)

Suggested developer technical products:

- Continued development of overall plan for meeting human-systems design compliance
- Detailed analyses (e.g., modeling) examining the impact of designated strength requirements on the human-system interface design, with any limitations and assumptions addressed

NASA Involvement:

- Review overall plan, provide feedback
- Review major systems and applicable requirements, provide feedback
- Review detailed analysis results for consistency and methodology, provide feedback

Critical Design Review (CDR)

Suggested developer technical products:

- Continued development of overall plan for meeting human-systems design compliance
- Demonstration of design maturity and readiness for fabrication of final design prototype

NASA Involvement:

- Review overall plan, provide feedback
- Review design for consistency and methodology, provide feedback on final prototype design

Test Readiness Review (TRR)

Suggested developer technical products:

- Demonstration of adherence to overall plan for meeting human-systems design compliance and justification for necessary plan changes
- Demonstration of readiness to perform HITL testing to verify and validate strength requirements
- Definition of human-related major systems and designated strength requirements applicable to the HITL testing to be performed

NASA Involvement:

- Review overall plan, give feedback
- Review major systems and applicable requirements, give feedback
- Review analytical analysis results for consistency and methodology, give feedback

System Acceptance Review (SAR)

Suggested developer technical products:

- Demonstration of design compliance

NASA Involvement:

- Review of design relative to levied requirements

4.5.4.8 STRENGTH REFERENCES

Chaffin, D. B., Andersson, G. B. J., Martin, B. J. (1999). *Occupational biomechanics*. New York: J. Wiley & Sons.

MIL-STD-1472. (1968 and *ff.)* Department of Defense human engineering design criteria for military systems, equipment, and facilities.(initial, with revisions through F). Washington, D.C.: U.S. Department of Defense.

4.5.5 DESIGN FOR MASS PROPERTIES, VOLUME, AND SURFACE AREA

4.5.5.1 INTRODUCTION

Requirements for ROM, anthropometry, and strength are provided to ensure that any crewmember can safely operate and manipulate the selected human-system interface of interest, but considerations for mass properties, volume, and surface area differ in their direct applicability to the design. The contributions of mass properties, volume, and surface area serve as inputs for other design factors, such as dynamic calculations of mass and moment of inertia of the vehicle, the functional volume design of the cabin, and radiation exposure calculations. The intent of this process is to provide designers with methodologies and best practices for implementing crew body mass properties, volume, and surface area requirements.

4.5.5.2 APPLICABLE REQUIREMENTS

The following NASA-STD-3001, Volume 2 requirements are applicable to mass properties, volume, and surface area:

- Data Sets [V2 4001]
- Data Set Characteristics [V2 4002]
- Population Definition [V2 4003]
- Data Set Assumptions [V2 4004]
- Body Surface Area Data [V2 4009]
- Body Volume Data [V2 4010]
- Body Mass Data [V2 4011]

4.5.5.3 SELECTION OF VOLUME, MASS, AND AREA DATA SETS

The NASA-STD-3001 NASA Spaceflight Human-System Standard Requirement V2 4001 specifies that a biomechanics data set for the crewmember population must be selected, and specifically that volume (V2 4010), mass (V2 4011) and surface area (V2 4009) must be applied to the design. In addition, requirement V2 4004 specifies that age, gender, and physical condition shall also be included in this data set, and V2 4002 requires that characteristics unique to space travel also be factored into the design. And V2 4003 requires the definition of the population ranges for the associated values of volume, mass, and area that the system is intended to accommodate.

No data set of volume, mass, and area values is available as one is for anthropometry; however, a variety of technical papers detail those values for different populations. Using information in the public domain, a designer can determine the anticipated limits of the population for volume, mass, and area respectively.

4.5.5.3.1 WHOLE-BODY AND BODY-SEGMENT MASS PROPERTIES

The requirement in NASA-STD-3001 for whole-body and body-segment mass properties data sets (V2 4011) is included specifically for the purposes of propulsion calculations and to ensure the structural integrity of human-system interfaces. Accurate data regarding the full range of crewmember mass is critical in analyzing potential forces imparted by a crewmember under all acceleration and gravity environments. Forces exerted by the whole body or body segment create reactions that depend on the mass properties. The mass, center of mass (COM) position, and moment of inertia (MOI) of the body and/or segments greatly affect the degree and severity of possible injuries during acceleration. Thus, accounting for mass properties of the crewmembers is a critical component of crew safety.

4.5.5.3.2 WHOLE-BODY AND BODY-SEGMENT VOLUME

The requirement in NASA-STD-3001 for development and implementation of whole-body and body-segment volume data (V2 2010) is included as a resource for analysis, potentially applicable to cabin or suit volume displacement. Quantifiable volumetric values for the users may also be useful in determining the functional volume design estimates.

4.5.5.3.3 WHOLE-BODY SURFACE AREA

The requirement in NASA-STD-3001 for development and implementation of a whole-body surface area data set (V2 4009) is included as a resource for analysis, potentially applicable to estimating radiation or thermal exposure. For example, body surface area may aid in the estimation of body heat production for thermal environmental control or in the estimation of radiation dosimetry.

4.5.5.4 MASS PROPERTIES, VOLUME, AND SURFACE AREA GENERAL OVERVIEW

Unfortunately, the exact mass properties, volume, and surface area of a given human body are not directly measurable by conventional means. Historically, cadaver studies were performed to quantify the exact physical characteristics of mass, volume, and surface area (DuBois and DuBois, 1916; Gehan et al., 1970; Martin et al., 1984). The regression equations used by the cited references (McConville et al., 1980, and Young et al., 1983) all compromise to this fact and are a means of determining the estimated specific volume, area, and mass properties of a unique individual. The lack of readily available measurement tools places heavy emphasis on the analytical and modeling aspects of design with respect to mass properties, volume, and surface area, with limited value to HITL testing. Below is a suggested approach that places focus on analytical and modeling aspects for the majority of design work, using human-based testing to verify assumptions made in the earlier stages of design. In general, the flow of any design evaluation, whether low-fidelity analytical analysis or high-fidelity HITL testing, contains the same basic sequence of steps:

1. Determine the objectives of the analysis
2. Account for any impacts of suit, posture, group, and gravitational effects
3. Identify possible worst-case scenarios for the proposed objectives

4. Evaluate the design: use the volume, surface area, and mass properties information in the relevant analysis. Evaluate and revise the design to ensure accommodation of the user population.
5. Repeat steps 1-4 until the design meets the requirements set forth and the design is in the final stages of the design cycle.

4.5.5.5 METHODOLOGY

4.5.5.5.1 IDENTIFY ANALYSIS OBJECTIVES

The necessity for an evaluation of the volume, surface area, and/or mass properties of the design is based on their applicability to the design, given the relevant vehicle conditions and exposure concerns of the crewmember. Not every human-system interface design will require such an analysis, so the first step is to identify the relevance of an analysis of volume, surface area, or mass properties to the design, given the stage of the design cycle. For example, launch and landing scenarios will focus heavily on the mass properties data related to the seat. The evaluators will require a solid understanding of the proposed seat design and structural properties of the seat components to perform an evaluation. Low Earth orbit (LEO) scenarios may involve body volume and body surface area characteristics, but inclusion of these in analysis may not be required until the layout of the vehicle design has been fully determined.

After analysis of relevance, the second step in utilization of the volume, surface area, and mass properties information is to scope the contingency scenarios and the associated safety impact on the crewmembers. For example, an off-nominal landing scenario will require a separate dynamic analysis involving the mass properties information. Essentially, consider the various situations that a crewmember may be exposed to and where the mass properties, volume, and surface area requirements are applicable, to ensure crew safety and health.

4.5.5.5.2 ACCOUNT FOR SUIT, POSTURE, GROUP, AND GRAVITY EFFECTS

4.5.5.5.2.1 SUIT EFFECTS

Information about spacesuits and their impact on humans in relation to volume, surface area, and mass properties is limited, but if possible, include suit effects in the analysis.

For example, in a dynamic evaluation of landing, if a crewmember is wearing a suit, the helmet, boots, crew survival equipment, and other gear will affect the mass and inertia profiles of the analysis. This addition of any mass to the body of the user will adversely influence the mass properties and must be accounted for in the analysis. Previous NASA studies have shown how to account for suit mass and subject anthropometry on the whole-body center of mass of a seated crewmember (Blackledge, 2010), and the same principles can be applied to body moment-of-inertia analyses.

The suit will also affect the analyses related to the volume and body surface area. The addition of the suit components adds to the total body volume, influencing functional volume design calculations. The addition of the suit components also influences the surface area of the body in relation to radiation dosimetry and associated protection and shielding. All of these examples are potential applications of suit effects. If possible, attempt to incorporate aspects of the suit into the analysis when they are applicable.

4.5.5.5.2.2 POSTURE EFFECTS

Whereas volume and body surface area values are, for the most part, independent of posture, analysis of mass properties requires posture information to perform dynamic calculations. The whole-body mass properties in most existing literature are related only to a standing position, and deviation from this body position requires recalculation of the whole-body mass properties. For given task posture, the user's body segment positions must be factored in calculating segmental mass effects on whole-body mass properties, such as center of mass and moment of inertia. If the developer needs to derive posture-based mass properties, they are advised to use the anthropometric data set developed from section 4.5.2 Design for Anthropometry coupled with the regression equations from literature. For example, NASA explored the combination of suit and posture effects on the location of the center of mass for a given set of seated recumbent postures in a Blackledge (2010) paper. In this study, regression equations from McConville (1980) and Young (1983) coupled with a suited center of mass (COM) methodology yielded information on the COM changes across the entire population. After this analysis is performed, the assumptions of posture and associated body angles must be evaluated through HITL testing to ensure that the calculations are accurate.

4.5.5.5.2.3 GROUP EFFECTS

A group of users may influence the analyses associated with mass properties and volume, specifically group mass and functional volume design. Group effects reflect a mixture of multiple users across the user population and need to be accounted for to identify any scenarios that may have a negative impact on the system's capability for complying with requirements.

Group effects for mass have been addressed in the past using a Monte Carlo simulation. As previously discussed in the anthropometry section, a Monte Carlo simulation is a numerical simulation technique that relies on repeated random samplings to compute results. In the context of mass, the total mass of the crew may preclude taking other objects into space, because of restrictions in the total mass that can be flown. For example, there is a low likelihood that multiple men in the 99th percentile for mass will fly simultaneously. Instead, random sampling of the weight or mass of the entire selected population can be used to derive whole-body crew mass. The details on the derivation of these values are given in Margerum and Rajulu (2008). A total crew mass value may be used to establish individual mass limits for selecting crew, within the range of allowable individual mass limits. The Monte Carlo simulation can also be expanded for calculations requiring distributions of crew mass during launch and landing and the associated impacts on the vehicle dynamics.

Group effects also need to be accounted for in the functional volume provided to all users for performing their tasks. As users vary in body size, their body volume also varies and the group effects compound this variation in volume. Consideration for a multi-sized crew is essential to functional volume calculations; for example, consider the volume of a crew of 4 that is composed of 3 large crewmembers and one small crewmember instead of the volume of 3 medium crewmembers and one small crewmember. The variances apparent in the population will influence these calculations, and thus the designer should consider group effects in their analyses.

4.5.5.5.2.4 GRAVITY EFFECTS

Gravity deconditioning affects crew body volume, mass properties, and surface area. However, no empirical data exists on the amount of change in these body parameters.

4.5.5.5.3 IDENTIFY WORST-CASE SCENARIOS

Typically for radiation exposure analyses or functional volume design calculations, the worst-case whole-body values are typically the largest and smallest values available in the dataset. However, it is recommended that designers critically evaluate the design and the analysis objectives to determine whether these values should be used for worst-case scenarios. Caution must be used in determining the worst-case scenario, and designers should not assume that applying all maximum or minimum values to the given body segments will produce the worst case. For example, examination of the worst-case dynamic profiles using mass properties will be influenced by posture and anthropometry, and adding suit or crew survival equipment will affect it further. It is suggested that, to properly determine a posture-specific COM, designers should identify worst cases by the procedure specified in the Blackledge (2010) paper.

4.5.5.6 EVALUATE THE DESIGN

The suggested approach is to focus on analytical and modeling aspects for the majority of design work, using human-based testing to verify assumptions made in the earlier stages of design. Using the defined objectives of the analysis, incorporating the suit, posture, group and gravity effects, and focusing on the worst-case scenarios will assist designers in evaluating their design with respect to mass properties, volume, and surface area. The end goal is to ensure that the full population has been considered in the design.

4.5.5.6.1 ANALYTICAL EVALUATION

Early in the design process, the mass properties, body volume, and body surface area can be incorporated into the designs using a simplistic analytical analysis.

Mass properties representing the worst-case scenarios can be incorporated into free-body diagrams of the design to evaluate its kinetic behavior. For example, the forces at the hip joint of a recumbent chair during hypergravity situations are influenced by the mass properties of the seat pan, seat legs, crewmember legs and feet, and their associated positioning with respect to the loading forces. Thus the mass properties of the section of the population with the heaviest and longest legs will drive the maximal loading at the hip joint of the seat. Estimations of COM locations and moment of inertia can be coupled with anthropometry and a whole-body posture-based analysis (WBPBA) to derive the leg mass properties and the forces imparted to the hip joint of the chair for the entire population (Blackledge, 2010).

Volume can provide information about anticipated space required by the crewmember in relation to the design. Similarly, area and volume can be used in initial calculations for radiation dosimetry or other related analyses. Group and suit effects can be factored into the analysis as well, to ensure that the entire user population is considered in the design.

4.5.5.6.2 CAD MODELING AND SIMULATION

As the design stage shifts toward modeling the worst-case scenarios identified in the analytical analysis, models can be loaded into the relevant CAD modeling tool for estimation and visualization. These individually based, anthropometrically based values for mass properties, volume, and surface area can be incorporated into the applicable design for further analysis. The entire population should be factored into the analysis utilizing the available tools at hand, whether the analysis relates to the evaluation of dynamic loading or to estimations of radiation dosimetry.

4.5.5.6.3 HUMAN-IN-THE-LOOP TESTING

HITL for mass properties, volume, and surface area can be used to verify assumptions used in the analytical and CAD modeling analyses. Specifically this pertains to the mass properties work that depends on posture. HITL testing can be used to verify that the assumed postures used in the previous analyses are correct, and if not, those analyses can be updated with the actual values. For volume, body surface area, and mass properties, the HITL testing can be used to tie an actual subject’s data into previous analysis work, and by doing so account for potential variations not accounted for in the previous analyses. The assumptions of group, suit, or postural effects can also be confirmed through HITL testing, ensuring that the entire population has been considered for the analysis that uses these parameters and that all assumptions have been validated. In scenarios where HITL testing is required but unsafe, mannequins or crash test dummies should be used as substitutes for the human body (i.e., mannequin-in-the-loop testing). Mannequin-in the loop testing would follow HITL testing parameters and methodology, except that the data would be collected from mannequins instead of humans. An example of this is flight testing the center of gravity of the manned vehicle using representative mannequins instead of actual crewmembers.

4.5.5.6.4 ADDITIONAL INFORMATION

The developer is advised to acquire copies of the McConville (1980), Young (1983), and Gehan and George (1970) papers for access to the regression equations for calculation of volume, surface area, and mass properties on a per-subject basis.

4.5.5.7 MASS PROPERTIES, VOLUME, AND SURFACE AREA TECHNICAL PRODUCTS

Evaluating a design requires unique phases that depend on the various stages of the design life cycle. As previously mentioned, during the preliminary stages of design, analytical and CAD modeling should be used to identify worst-case scenarios, the critical human dimensions of interest, and a general accommodation level of the design. HITL testing can be valuable for verifying assumptions about the body properties of mass, volume, or body surface area used in analytical and modeling analyses.

For each of the major milestones of the design life cycle, the technical products in Table 4.5.5.7-1 are recommended for review by the NASA customer.

TABLE 4.5.5.7-1 MASS PROPERTIES, VOLUME, AND SURFACE AREA TECHNICAL PRODUCTS

Technical Products	Phase A		Phase B	Phase C	Phase D	
	SRR	SDR	PDR	CDR	SRR	SDR
A description of the ConOps, function allocation, associated crew task lists, and the selected mass, volume, and area critical limits. Includes list of tasks considered to be design-driving for mass properties, volume, and surface area requirements as well as definition of factors affecting these properties.	I	U	U	U	---	---
A summary of modeling/analysis/evaluation (i.e., CAD, human modeling, and population analysis) performed to date and its influence on system design with links to the detailed analysis results. Required per NPR 8705.2B, and HITL evaluations required per paragraph 2.3.10.	---	---	I	U	U	---
System architecture drawings (structures, equipment, etc.), material specifications, interface requirements.	---	---	I	U	U	---
Verification plan.	---	---	I	U	U	---

X = one-time release of item
I = initial release of item
U = updated release of item

Concept of Operations and Crew Task Lists

The ConOps, described in paragraph 3.2.3.1.2, provides information such as identification of crew activities and determination of which subsystems are affected by crew activities. Function allocation, described in paragraph 3.2.3.1.3, establishes the extent to which an activity is to be automated or assigned to humans. The crew task list, described in section 4.1 User Task Analysis, documents details including allocation of function between crew and systems, definition of crew activities sequence, and identification of critical tasks. As the crew task list evolves through the design cycle, its final iteration should become crew procedures.

For mass properties, volume, and surface area requirements, it is important to determine what tasks may be design-driving. Factors that may influence these properties include suit conditions, posture, gravity conditions, and group effects.

Summaries of Modeling, Analysis, and Evaluation

Iterative summaries of modeling, analyses, and evaluations provide NASA with insight into technical details of human-systems integration throughout the design process. As designs mature, modeling, analyses, and evaluations should use inputs and mockups of increasingly higher fidelity, as discussed in paragraph 3.2.3.3 Evaluate Designs and Iterate Solutions. It is important that summaries address how key and critical design decisions were assessed. According to NPR 8705.2B, updated summaries are to be provided at each design review through SAR.

For mass properties, volume, and surface area analyses, as appropriate for each design phase, reports should detail CAD model work and progressively higher fidelity human model work in addition to analysis of human-in-the-loop evaluations. Population analysis ensures that findings extend to the entire crew population and consider worst-case scenarios.

Architecture, Materials, and Interface Specifications

Drawings, materials, and interface specifications provide NASA with insight into technical details of human-systems integration throughout the design process.

Verification Plan

The verification plan is a formal document describing the specific methodologies to be used to show compliance with each requirement.

System Requirements Review (SRR)

Suggested developer technical products:

- Selected mass, volume, and area limits
- Definition of human-related systems and what mass property, body volume, and body surface area requirements are applicable
- Overall plan for meeting mass property, body volume, and body surface area design compliance
- High-level analytical analysis depicting method and implementation for meeting requirements based on mass property, body volume, and body surface area

NASA Involvement:

- Review overall plan, give feedback
- Review analytical analysis methods and results for consistency, give feedback

System Definition Review (SDR)

Suggested developer technical products:

- Reports detailing analytical analyses and/or modeling work (area, volume, mass) for all major subsystems, detailing compliance with the specifications given in the designated requirements.
- Plans for mitigation efforts if analyses indicate that design does not meet requirements

NASA Involvement:

- Review reports, give feedback

Preliminary Design Review (PDR)

Suggested developer technical products:

- Reports detailing analytical analyses and/or modeling work (area, volume, mass) for the design, detailing compliance with the specifications given in the designated requirements.

- Plans for mitigation efforts if analyses indicate that design does not meet requirements
- Plan for verification of requirements

NASA Involvement:

- Review detailed analysis results for consistency and methodology, provide feedback
- Review plans, provide feedback

Critical Design Review (CDR)

Suggested developer technical products:

- Reports detailing analytical, modeling, and HITL analyses (area, volume, mass) for all major subsystems, detailing compliance with the specifications given in the designated requirements; plans for mitigation efforts if analyses indicate that design does not meet requirements
- Reports on updated analyses (analytical and modeling) based on results of HITL testing examining the impact of anthropometric requirements on the human-system interface design; plans for mitigation efforts if analyses indicate that design does not meet requirements
- Final plans for body surface area, volume, and mass properties verification testing

NASA Involvement:

- Review reports, give feedback
- Review final verification plan, give feedback

Test Readiness Review (TRR)

Suggested developer technical products:

- Demonstration of adherence to overall plan for meeting human-systems design compliance and justification for necessary plan changes
- All testing completed and mitigation efforts incorporated into the design

NASA Involvement:

- Review reports, give feedback

System Acceptance Review (SAR)

Suggested developer technical products:

- Demonstration of design compliance and all anthropometric requirements met for area, volume, and mass

NASA Involvement:

- Review of design relative to levied requirements

4.5.5.8 MASS PROPERTIES, VOLUME, AND SURFACE AREA REFERENCES

Blackledge, C., Margerum, S., Ferrer, M., Morency, R., & Rajulu, S. (2010). Modeling the impact of space suit components and anthropometry on the center of mass of a seated crewmember. *Applied Human Factors and Ergonomics, Electronic Proceedings*.

DuBois, D., & DuBois, E. F. (1916). A formula to estimate the approximate surface area if height and weight be known. *Archives of Internal Medicine, 17*, 863–871.

Gehan, E. A., & George, S. L. (1970). Estimation of human body surface area from height and weight. *Cancer Chemotherapy Reports Part I, 54*(4), 225-235.

Margerum, S., & Rajulu, S. (2008). Human factors analysis of crew height and weight limitations in space vehicle design. *Human Factors and Ergonomics Society Annual Meeting Proceedings*, *52*(1), 114-118(5).

Martin, A. D., Drinkwater, D. T., & Clarys, J. P. (1984). Human body surface area: validation of formulae based on cadaver study. *Human Biology*, *56*(3), 475-485.

McConville, J., et al. (1980). *Anthropometric relationships of body and body segment moments of inertia* (AFAMRL-TR-80-119). Wright-Patterson Air Force Base, Ohio: Air Force Aerospace Medical Research Laboratory, Aerospace Medical Division, Air Force Systems Command.

Young, J.W., et al. (1983). *Anthropometrics and mass distribution characteristics of the adult female (*AD-A143096). Oklahoma City, Oklahoma: FAA Civil Aeromedical Institute, Federal Aviation Administration.

4.5.6 BACKGROUND OF CHSIR REQUIREMENT VALUES

4.5.6.1 ANTHROPOMETRY

The anthropometric measurements and limits selected for inclusion in the Commercial Human Systems Integration Requirements (CHSIR) were determined through work with NASA cockpit, seat, and suit teams to generate a consolidated list of dimensions integral to the design of hardware for the space program. The CHSIR anthropometric data set is based on the Natick Anthropometry Survey of Army Personnel (ANSUR), an Army-based anthropometric data set (Gordon et al., 1989). This data set represents the anticipated body type of the astronaut corps more closely than more general population data sets that are available. The data set was age-truncated to between 30 and 51 years to encompass the representative age range of the astronaut corps. It was also height-adjusted to align with Air Force population height and to correspond to projected growth trends to the year 2015 (Churchill et al., 1976; McConville et al., 1991; NHANES 2004). This truncated data set is more appropriate than a more generalized population data set because it minimizes the anticipated anthropometric ranges while ensuring that the astronaut corps can be accommodated.

The minimum and maximum values in CHSIR represent the 1st-percentile-female to 99th-percentile-male range for each critical dimension. This percentile range was selected to accommodate the astronaut corps (as of 2004) as well as minimize the impact on future crew selection and accommodation. Although a 1st- to 99th-percentile range may initially seem high, it is an age-truncated, specifically tailored population as opposed to corresponding values from a generic population data set. Analyses were performed to investigate reducing this 1st-percentile female to 99th-percentile male range to a smaller range of values, but it was determined that blanket reductions in the anthropometric ranges would result in a large detriment to crew accommodation with low payoff for the design, because of the relatively poor correlations between anthropometric dimensions and the large number of dimensions. This truncated and height-adjusted CHSIR anthropometric data set should be the data set used by the Commercial Crew Transportation (CCT) Company for the majority of population analyses that rely on a data set. Generation of the suited anthropometric values in CHSIR is discussed in a later section (see paragraph 4.5.3.2.2.3.1 Suit Factors).

Additional examples of HITL testing and population analysis methods as they have been applied to the space program can be found in the process document JSC 65851 Anthropometric Processes for Population Analysis, Suit Factor Generation, and a NASA Recommended set of Practices Essential for Data Collection and Analysis for Verification and Validation of Vehicle, Suit, and Vehicle-Suit Interface Requirements.

4.5.6.2 RANGE OF MOTION

The details of testing from which the CHSIR ROM tables were generated can be found in NASA Technical Paper 2010-216122 (England et al., 2010). Data interpreted from that report provides a single value for each suited state.

4.5.6.3 STRENGTH

The strength limit values in the CHSIR were developed from extensive review of literature as well as from human strength testing performed at NASA facilities under unsuited, suited unpressurized, and suited pressurized conditions. The literature review included an extensive collection of journal articles associated with human strength data. In addition, other references, such as the MIL-STD-1472 and the *Occupational Biomechanics* textbook (Chaffin et al., 1999), were used to set a standard for very specific strength data such as lifting, pushing, and pulling strengths. The strength data in the tables of CHSIR Appendix D5 represent static (i.e., isometric) force applied by subjects in specific postures (involving segment postures as well as whole-body postures) that were determined to be relevant and applicable to a wide range of possible mission tasks that may include both suited (e.g., launch, entry, extravehicular activities) and unsuited operations.

4.5.6.4 WHOLE-BODY AND BODY-SEGMENT MASS PROPERTIES

To calculate whole-body and body-segment mass properties for the CHSIR, regression equations were used that were based on 2 anthropometric dimensions, stature and weight. Both female and male anthropometric parameters for stature and weight were used from the CHSIR anthropometric data set. These regression equations are sourced from McConville et al. (1980) and Young et al. (1983). These studies have been historically used to compute the whole-body and body-segment volumes. Whole-body and body-segment mass were calculated from these equations by assuming that the density of human flesh was homogeneous and had a density value of 1 g/cm^3. With a value of unity for the density, the mass values were numerically equal to their corresponding volume values. The COM and moment of inertia (MOI) were also captured from the McConville et al. (1980) and Young et al. (1983) studies.

The COM locations for the whole body and body segments were also determined from McConville et al. (1980) and Young et al. (1983). Determination of the COM in those studies was based on the assumption that human flesh is homogeneous and the assumption that the center of volume is at the COM location. Both McConville et al. (1980) and Young et al. (1983) provided ranges for the location of the center of volume for men and women, respectively, in their studies. Unique values for the locations of the center of mass with respect to the anatomical axes were captured from each study for the range in CHSIR. Specifically, the upper range value was specific to the male 95th-percentile stature and weight upper range values, and the lower range value was specific to the female 5th-percentile stature and weight lower range values.

Whole-body and body-segment MOI values were captured from regression equations in McConville et al. (1980) and Young et al. (1983). Each of these studies contained regression equations based on using the stature and weight parameters. The data in the CHSIR anthropometric data set was used for identifying the lower (i.e., 5th-percentile) and upper (i.e., 95th-percentile) range values for the MOI locations. However, the MOIs presented are about the principal axes, X_P, Y_P, and Z_P.

4.5.6.5 WHOLE-BODY AND BODY-SEGMENT MASS VOLUME

Regression equations from the McConville et al. (1980) and Young et al. (1983) studies were used to compute the whole-body and body-segment volumes. As previously mentioned, the regression equations used 2 independent parameters, stature and weight. The whole-body and body-segment volumes were determined for each gender by using the input parameters from the entire CHSIR population. An average and standard deviation was acquired from each set of data to calculate the minimum and maximum values. The maximum whole-body and body-segment values pertained to the acquired maximum value from the male data and the minimum whole-body and body-segment values from the minimum female data calculated from the regression equations.

4.5.6.6 WHOLE-BODY SURFACE AREA

Historically, whole-body surface area was calculated as a function of stature and weight. DuBois and DuBois (1916) devised an algorithm for determining the whole-body surface area and Martin et al. (1984) validated the results. The minimum and maximum whole-body surface area values pertain to the values calculated using this algorithm in conjunction with the CHSIR female and male stature and weight data. The minimum and maximum whole-body surface area values in CHSIR were captured from the female data and from the male data, respectively.

4.5.7 DESIGN USING INTEGRATED APPROACH

4.5.7.1 INTRODUCTION

An integrated approach examines the design across all possible physical characteristics using evaluation methodologies at various stages in the design process. Early in the design process, assessments often focus on univariate concerns (e.g., just strength, just ROM, or just anthropometry). As the design matures, it is beneficial to begin examining the design from a multivariate perspective. The individual process sections in this document and their methodologies are univariate but can be leveraged in unison once the design has matured adequately. It is this multivariate approach that is referred to as the *integrated approach*.

It is recommended that developers use an integrated approach as soon as possible in the design life cycle, to understand how the primary physical characteristics and capabilities interact with one another. At a minimum, the integrated approach should be performed for PDR and CDR to ensure that the individual methodologies, when combined, will still accommodate the entire population. The main benefit of the integrated approach is an understanding of how the 3 primary aspects—anthropometry, strength, and ROM—relate to each other within a design, because they interrelate in the execution of static and dynamic tasks. Such a multivariate approach can uncover unanticipated problems that are not identified in early univariate assessments. Each aspect may have different issues, meaning that a larger segment of the population is “at risk” for accommodation, and this overall picture would otherwise go unnoticed. These accommodation and performance issues may possibly be coupled together, indicating that a general flaw exists in the design if the design is used by a certain segment of the population. If the 3 aspects are evaluated together, overall design compliance can be assessed. A secondary benefit of the integrated approach is the cost benefit. Testing multiple aspects at once will reduce overall subject time, evaluator time, and test time relative to the time and costs required to assess each factor in multiple, independent tests.

4.5.7.2 IDENTIFY WORST-CASE SCENARIOS

The identification of worst-case scenarios uses the same methodologies outlined in the strength, ROM, and anthropometry sections. Similar to the individual sections, identification of the worst-case scenarios essentially focuses the analysis to highlight the segments of the population most affected by the design. For example, a larger individual may fit, anthropometrically speaking, in the seat and reach all the controls; however, a small person seated next to a larger person may have a portion of their ROM blocked by the bulk of the person sitting next to them. Similarly, a larger individual may be able to articulate a lever at their extreme range of motion, but a similarly positioned small person would be unable to both grasp the device fully and induce enough leverage to fully operate the device. Designers should consider how the combination of various factors can place segments of the population at risk.

4.5.7.3 EVALUATE THE DESIGN

The integrated approach involves looking at multiple design variables simultaneously, in analytical analyses, CAD modeling or simulation, or HITL testing, and placing the results in the context of the population for each design variable of interest. This might be thought of as a multidimensional evaluation that examines all relevant design variables for all possible combinations of the population based design factors. For example, this could involve examining the impact of the suit, posture, gravity, and group on the ability of a crew to perform a given task across an entire population spectrum. The integrated approach assists in the evaluation of apparently conflicting requirements (e.g., a need for application of high force combined with reduced clearance—a situation where a larger individual may have a challenge due to clearance concerns, but the high-force requirement would challenge low-strength individuals). This combined approach will highlight design issues and challenges that may otherwise be missed after a strictly univariate evaluation path.

4.6 HANDLING QUALITIES EVALUATION

4.6.1 INTRODUCTION

This section is intended to join together industry standard methods for assessment of vehicle handling qualities (HQ) within the framework of human-systems integration (HSI). The use of HSI processes in aviation is well established, as is the implementation of HQ assessment, though present documentation in the public domain leaves some ambiguity regarding a strict start-to-finish methodology for HQ assessment planning and execution, and integration of HQ assessment within an HSI process. The evaluation of handling qualities is required in accordance with NPR 8705.2B paragraph 3.4.2, which specifies minimal ratings on the Cooper-Harper Rating Scale during manual control of the spacecraft's flight path and attitude.

Note that HQ are closely linked with other human factors concepts such as ***usability*** and ***workload*** and that significant usability issues or excessive workload demands will often drive poor HQ. These topics are covered in HIDP sections 4.2 and 4.3, respectively. Review of all 3 processes is strongly recommended.

4.6.1.1 APPLICABLE HANDLING QUALITIES REQUIREMENTS

The evaluation of HQ is required by NASA per NPR 8705.2B paragraph 3.4.2, which specifies minimal ratings on the Cooper-Harper Rating Scale during manual control of the spacecraft's flight path and attitude. HQ standards are also specified in the NASA-STD-3001 Volume 2 section 10.1.2 Handling Qualities. These standards set minimum criteria for vehicle HQ as measured by the Cooper-Harper Scale.

- V2 10004 Controllability and Maneuverability

NPR 8705.2B paragraph 2.3.10.1 requires human-in-the-loop (HITL) usability evaluations for human-system interfaces. In addition, NPR-required technical products at PDR and CDR include summaries of how these evaluations were used to influence system design.

4.6.1.2 HISTORY OF HANDLING QUALITIES ASSESSMENT

The history of pilot evaluation and the study of aircraft HQ goes back to the very first flights of the Wright brothers. From then until now, the evaluation of HQ and the tweaking and modification of vehicle design parameters to ensure better handling has been an area of both active research and applied engineering solutions.

Early assessment of HQ by pilots was highly subjective and lacked formality. Efforts to examine aircraft performance characteristics and pilot opinion increased from the 1930s through the 1960s, resulting in the development of various tools to standardize the assessment of HQ. These efforts culminated in the 1969 publication of the Cooper-Harper rating scale (NASA TND-5153) by George C. Cooper of the Ames Research Center and Robert P. Harper Jr. from the Cornell Aeronautical Laboratory.

The concept of levels of HQ, as embodied by the Cooper-Harper rating scale, was adopted by the U.S. military (MIL-F-8785C). Though efforts have been made to create new scales and derivatives of the Cooper-Harper, the original Cooper-Harper scale continues to be used as the industry standard for HQ assessment.

4.6.1.3 OVERVIEW OF THE COOPER-HARPER HANDLING QUALITIES SCALE

4.6.1.3.1 DEFINITION OF HANDLING QUALITIES

"Handling Qualities" are defined by Cooper and Harper in their seminal 1969 publication as "those qualities or characteristics of an aircraft that govern the ease and precision with which a pilot is able to perform the tasks required in support of an aircraft role." What the pilot feels (vehicle response), what the pilot sees (out the window and on displays), and what the pilot touches (input devices) are all factors that influence and are related to HQ. The goal of handling-quality assessment is to categorize the performance of the vehicle and determine what, if any, changes may be warranted to improve vehicle performance. These changes may include engineering design revision, task simplification, control parameter tuning, and improved user interface design.

4.6.1.3.2 COOPER-HARPER HANDLING QUALITIES SCALE

The Cooper-Harper Rating Scale is the most commonly used metric in the assessment of aircraft HQ. The scale associates subjective ratings of 1 through 10 on HQ to one of 3 levels of performance through use of a decision gate chart, as shown in Figure 4.6.1.3.2-1.

Cooper-Harper Scale Levels:

- Level 1 (ratings of 1, 2, 3): Satisfactory without improvement
- Level 2 (ratings of 4, 5, 6): Deficiencies warrant improvement
- Level 3 (ratings of 7, 8, 9): Improvement is required
- Rating 10: Handling qualities are worse than Level 3; vehicle is uncontrollable

The Cooper-Harper decision tree begins with an assessment of the vehicle’s “Adequacy for Selected Tasks or Required Operation,” in which the test subject decides whether the performance achieved in a piloting run was desired, adequate, or uncontrolled. These adjectives are associated with the objective or quantitative performance of the flight phase or specific task and are used as anchors at various locations in the scale.

As these adjectives are involved in the core decision logic of the scale, the objective performance criteria associated with their definition are key drivers of the rating process. The phrase “**desired performance**” refers to the best possible objective performance attainable in a flight phase or in a specific flight-related task. “**Adequate performance**” is used to describe a level of success within the needs of the flight phase or specific task for successful completion, though better performance might have been possible had the vehicle handled better. The lack of desired or adequate performance suggests that the flight phase or task was not completed successfully or that the vehicle was uncontrollable.

After the initial determination of performance adequacy, the subject proceeds to the right of the scale into the defined categories of Level 1, 2 or 3. Next, the subject reviews the aircraft characteristics and the demands on the pilot, and determines the final rating.

On a fundamental level the scale relies on the concept of *pilot compensation*, which is based on the pilot's ability to compensate for inadequacies in the vehicle design that result in less than ideal HQ—up to a point. Beyond a certain mental and physical threshold (based on human capability), the pilot is no longer able to compensate and the vehicle is rated as uncontrollable.

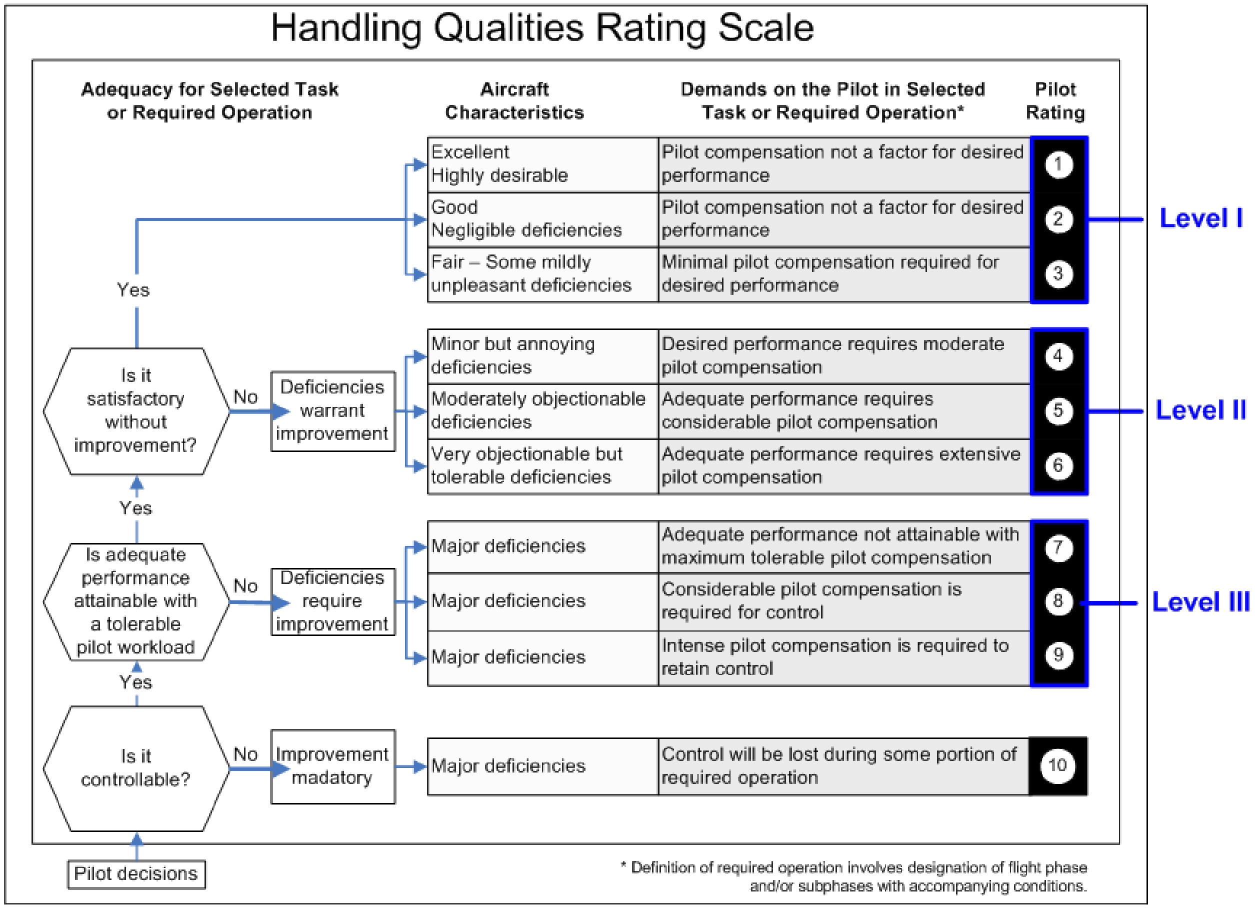


FIGURE 4.6.1.3.2-1 COOPER-HARPER HANDLING QUALITIES RATING SCALE

4.6.2 HANDLING QUALITIES DESIGN PROCESS

4.6.2.1 WHEN TO INTEGRATE HANDLING QUALITIES IN AN HSI ENGINEERING LIFE CYCLE

Generally speaking it is easier and more cost-effective to correct deficiencies in HQ during the early design phases rather than just before vehicle certification. For these reasons, handling-quality assessments are best integrated early and often throughout the engineering life cycle so that design decisions related to handling qualities can be made from a data-driven perspective and ensure safe and effective control of the vehicle.

4.6.2.2 EARLY AND OFTEN

Consistent with core human-centered design philosophy, the consideration of HQ can be done from the very earliest stages of design, though actual evaluation of HQ does require a certain minimum level of design maturity. At the earliest stages of the design life cycle, integration of HQ should focus on activities such as these:

- defining the various operational flight phases of the vehicle (e.g., what actions will the vehicle be expected to perform, particularly from the standpoint of manual control versus automation);
- identifying different control modes (e.g., pulse vs. continuous thrust);
- determining available pitch, yaw, and roll capabilities combined with available translational modes; and
- listing potential failure modes in which manual control will be available or required.

Each of the flight phases will also need to be associated with a required rating or level of handling quality (e.g., ratings of 1-10 or Levels 1-3). These factors will be driven by the vehicle’s intended mission and operational theatres. Many of these considerations can be defined very early during the vehicle specification stage, even pre-request for proposal or before procurement activity.

After flight definition, the next stage would be to start testing early aerodynamic- or control scheme-based prototypes by computer simulation. These simulations may simply be aerodynamic models of the craft with rudimentary control algorithms, and may benefit the program by exposing any potentially inherent aerodynamic instability that might drive flight-control development. This is also a good stage in which to start evaluating relevant early display prototypes for each flight phase, including primary flight displays and associated displays used for secondary piloting tasks (e.g., communications, navigation, or systems monitoring).

Eventually, as vehicle design maturity increases, the simulation fidelity also increases, and ratings achieved through simulation become more consistent. The value of early and iterative evaluation of HQ is realized through direct input to design decisions related to both physical layout and conformation and control methodologies and algorithms. This also allows exposure of any flight phases in which manual control may not be feasible because of either system demands (e.g., required response times may be below the human threshold for reaction time) or environmental constraints (e.g., *g*-loading or vehicle vibration may make manual control impractical).

4.6.3 HANDLING QUALITIES METHODOLOGY

A key note here is that a handling-quality evaluation is an assessment of the vehicle's performance related to its design and control capabilities, and not an assessment of the pilot's ability. Therefore, experienced test pilots are strongly recommended as test subjects. Experienced test pilots have achieved a high level of proficiency in vehicle operation and handling, and with this experience can identify faults with the vehicle. For spacecraft design, the test subject pool should include test pilots or crewmembers trained as operators who have also flown in space or rarefied atmosphere environments (e.g., Space Shuttle pilots and extreme-altitude reconnaissance aircraft pilots) and trained spacecraft pilots.

The general methodology of conducting a Cooper-Harper-based HQ evaluation includes the following components, each of which is discussed in more detail in the sections to follow:

- Definition of flight phases, specific flight scenarios, and composite tasks to be tested
- Definition of adequate versus desired performance criteria for each flight scenario to be tested
- Selection of test conductor
- Selection of test subject(s)
- Preparation of briefing materials
- Test execution and data collection
- Data analysis and interpretation

4.6.3.1 DEFINING PARAMETERS: FLIGHT PHASES, SUBPHASES, SCENARIOS

The first step in the assessment of HQ is definition of the vehicles' required flight phases, subphases, scenarios, and crew tasks. These will be based on the design reference mission prescribed by NASA. The detailed identification of flight phases, subphases, scenarios, and crew tasks may occur as part of the development of the overall Concept of Operations. The Concept of Operations (ConOps) specifies crew activities for each mission phase and scenario and determines which subsystems are affected by crew activities.

The term "flight phase" is commonly used to refer to a portion of an entire flight (i.e., launch to landing), and may include phases such as "launch," "ascent," "orbit," "docking," "entry," and "landing." Each of these phases is frequently divided further into more detailed components, referred to as "subphases." Example subphases for a docking phase might include "initial approach" and "final docking." These distinctions are important, as a handling-quality evaluation provides the most meaningful data when each subphase is rated separately, or at the even more granular level of the specific subphase piloting tasks. Under almost no circumstances would an entire flight be associated with a single rating because separate subphases (a) place different degrees of workload or attention on the pilot, and (b) elicit different performance characteristics from the vehicle according to characteristics of the flight envelope (where flight envelope refers to the operational “envelope” of a vehicle based upon acceptable levels of variables such as airspeed, altitude, and *g*-loading).

The term “scenario” is often used when a subphase has multiple conditions that might be evaluated. For example, consider a spacecraft in an “entry” flight phase and the “initial deceleration” subphase in which the craft must use aerodynamic maneuvers to shed velocity as it reenters the atmosphere. For this example, several scenarios might be tested: one in which the entry profile is flown as a “ballistic” entry; another scenario in which it is flown as a “loads managed” return; and a final scenario referred to as “skip-return.” Under the ballistic-entry scenario, the craft may simply be falling into the atmosphere at an angle preset by the pilot or autopilot (with pilot concurrence) from orbit. Under the loads-managed scenario, the pilot may be engaged in placing the craft into a rolling maneuver. The third scenario would be the “skip-return” whereby the pilot, after the craft initially enters the atmosphere, manages the lift vector of the craft to loft back out of the atmosphere for a short period, and reenter with additional roll reversals before a final landing. All 3 of these situations are associated with the “initial deceleration” subphase of an entry phase, but represent different scenarios to be tested.

Additionally, different initial conditions, or starting parameters, should be used for each test run so that the pilot does not see exactly the same starting point and conditions when he or she pilots a given scenario. Otherwise the lack of variability may skew the ratings due to a learning effect associated with repeatedly flying exactly the same simulation. These differing initial conditions may be as subtle as a slightly different coordinate starting point in the simulation, different environmental conditions (e.g., day or night), aero properties (density, temperature, humidity), or percentage of fuel remaining. These differing initial conditions keep the scenarios fresh for the pilot and require that the pilot approach each test in a slightly different manner, but should not be such a significant source of variability that they present a totally different scenario to the pilot. These slight differences help to maintain the integrity of the ratings while also eliciting potential handling issues that may exist at different parameter values in the scenario.

4.6.3.2 DEFINING PARAMETERS: ADEQUATE VERSUS DESIRED PERFORMANCE

After scenarios have been selected for testing, it is necessary to define the minimal level of vehicle performance. The Cooper-Harper scale (as shown in Figure 4.6.1.3.2-1) is used by cognitively working through a series of 3 decision gates, any one of which can direct the test subject to a subset of 3 potential ***levels***, each of which contains 3 ***ratings***. Each rating is associated with certain ***aircraft characteristics*** as well as a set of ***demands on the pilot***. Once the test subject makes a selection in the decision gates that directs him or her to a particular level, the subject must choose among the 3 ratings associated with that level. A key differentiating concept used in the *demands on the pilot* component of the ratings is the subject’s objective **performance** in the simulation or flight test. The 2 adjectives associated with performance are ***adequate*** versus ***desired***.

Within these words lies a subtlety of the Cooper-Harper scale. As previously mentioned, desired performance refers to the best possible objective performance attainable in a flight phase or in a specific flight-related task. Adequate performance describes a level of success within the needs of the flight phase or specific task for successful completion, though better performance might have been possible had the vehicle handled better. The lack of desired or adequate performance suggests that the flight phase or task was not completed successfully. The key is that these classes of performance are associated with some metric of the flight phase or task that can be assessed objectively, perhaps even quantitatively.

For example, performance might be based on the percentage of fuel left when a certain maneuver is completed (e.g., adequate would be associated with at least 30% fuel remaining, whereas desired would be associated with 50% fuel remaining), or performance might be based on accuracy of a capsule rendezvous (a docking operation) with the International Space Station (e.g., no more than ± 3 cm of center-point for desired or within ± 9 cm for adequate, with those numbers based on the specifications for the docking mechanism and its design capabilities). Performance criteria should be established ahead of time in collaboration with subject matter experts such as pilots, operators, and ground control.

The importance of these terms comes most into play when the test subject is trying to decide between Level 1 and Level 2 ratings. Within Level 1 are 3 ratings, all of which include desired performance and are fairly easy to attain. Level 2, however, has 3 ratings of which the first (Rating 4) is associated with desired performance, but note that it requires **moderate** pilot compensation, whereas ratings of 5 and 6 are associated with adequate performance and considerable or extensive pilot compensation. The key here lies in marrying the performance attained with the level of pilot compensation required to get there. Again, a fundamental concept of this scale is that the pilot is highly adaptable and can compensate for less than ideal HQ in the vehicle, but that this adaptability has its limits. In other words, the pilot can compensate when needed, but only so much—place too many demands on the pilot and the flight phase objectives may not be met, or worse, an accident may occur.

Note that a test subject can attain desired performance but still provide a poor rating for HQ because the pilot’s required degree of compensation is the driving factor to be considered for the rating. Even if desired performance is attained, ratings are not limited to the range of 1-4. Desired performance does not prohibit selection of a poor (numerically higher) rating, though adequate or poor performance does prohibit selection of a better (numerically lower) rating than the performance warrants. An example might include a docking maneuver for which the pilot is on the final approach to the docking mechanism, but is having a difficult time staying “on-center” with the mechanism and has to perform multiple lateral translations to correct the capsule’s trajectory. Even if successful docking is achieved, the pilot may give HQ a rating of 6, given the need for extensive control inputs to perform the docking. The test conductor should keep track of whether the test subject achieves desired performance. The test conductor can advise the test subject when a rating cannot be selected because of not meeting performance criteria, but cannot advise on what rating to pick.

4.6.3.3 TEST CONDUCTOR SELECTION

Critically important to the validity of the evaluations are the credentials of the test conductors. It is essential that the test conductors are familiar with the intricacies of the Cooper-Harper scale and have been mentored on proper application of a handling-quality evaluation through past assessments with experienced professionals. It is not enough to simply understand the scale; an effective test conductor must also understand testing and evaluation as an applied science, how to administer evaluations with human subjects, and how to brief and debrief subjects. Several federal organizations, including the Department of Defense, NASA, and the Federal Aviation Administration (FAA), can facilitate the training and mentoring of new test conductors. In addition, commercially available centers exist that specialize in simulations, handling-quality evaluations, and are available to conduct testing.

4.6.3.4 TEST SUBJECT SELECTION

One of the key driving factors of the evaluation is an understanding of and common basis of knowledge about the Cooper-Harper rating scale. Military test pilots are trained at Test Pilot School and have historically been considered the “gold standard” baseline for the rating of military flight vehicles. The justification for this is that not only do military test pilots have extensive classroom training on application of the Cooper-Harper scale, they also have been through training and may have operational experience in rating actual flight hardware vehicles. This level of experience, familiarity, and understanding far exceeds the result of any simple briefing given in a 1- to 2-hour window just before a simulation. For this reason, current or former military test pilots are the gold standard by which most if not all handling-quality evaluations are conducted. This has also been true in most NASA settings, where most NASA pilots are former military test pilots of either fixed-wing or rotary-wing aircraft. It is recommended that handling-quality assessments conducted in future space programs continue this tradition and use current or former test pilots in evaluation of their vehicles. In the circumstance where this is not possible, it is highly recommended that test subjects go through extensive training in use of the scale and are shown real-world examples of how past operational craft were rated under various conditions and settings to calibrate them on proper application of the scale.

An additional topic related to test subject selection is the number of subjects to recruit for testing. Generally, a sample size of 30 or more subjects is considered an adequately large sample. However, recruiting of 30 test pilots is unlikely to be practical for handling-quality evaluation. On the other hand, sample populations that have less inherent variability can be characterized with a smaller number of samples, which is relevant to HQ because the preferred subjects are experienced test pilots (a population with far less variability in piloting skill than the larger population of general aviators). A sound compromise is to propose using an initial sample size of 10 to 20 pilot subjects for an assessment. This provides a data set of sufficient size that significant variability in the underlying vehicle HQ should be revealed, as should any significant consistency or clustering of the data. For requirement verification, NASA recommends testing with at least 8 crewmembers trained as operators. This sample size is acceptable because of the homogeneity of the subject population (highly trained crew, many with test pilot backgrounds). By the time verification of HQ is conducted, the crew operator population ought to have been regularly engaged in iterative handling-quality evaluations focused on systems design and manual control scenario down-selection, ensuring desired or adequate handling-quality performance with known and quantified flight performance characteristics.

4.6.3.5 PREPARATION OF BRIEFING MATERIALS

Briefing materials must be generated before the handling-quality evaluations are conducted. These materials should introduce the subjects to multiple topics, including

- The purpose of the evaluation
- The specific aspects of the vehicle that will be assessed
- Details of each flight phase and scenario to be tested
- The metrics to be used for determinations of desired, adequate, or failed performance
- A refresher on the Cooper-Harper handling-quality rating scale

The level of detail for each of the above may vary from one evaluation to the next, but generally all components listed should be present for any assessment. In particular, the desired versus adequate performance metrics are critical for the test subject to understand, as well as the details of what is expected of them for the assessment.

4.6.3.6 TEST EXECUTION AND DATA COLLECTION

Testing is a multi-stage process that includes a briefing session, a collection of familiarization runs, data runs and collection of ratings, and finally debriefing the pilot, as noted in Figure 4.6.3.6-1. Note that when multiple profiles are being tested, each with several scenarios, it is often recommended that a different test session be conducted for each. For example, if an organization were testing both docking and entry flight profiles, a test could be conducted in the morning with a briefing, familiarization period, testing, and debrief just for the docking profile and the various scenarios associated with it. The entry test session could be done that afternoon with its own specific briefing, familiarization, testing, and debrief. This separation of flight profiles is highly recommended to prevent confusion of the pilots about what is being tested and what the performance metrics are for each flight profile.

Briefing →	**Familiarization** →	**Testing** 1) Practice Run(s) 2) Data Runs (2-3) 3) Rating and comments collection →	**Debrief**
30-60 min	30-90 min	60-120 min	30-60 min

FIGURE 4.6.3.6-1 PRIMARY COMPONENTS OF A HANDLING-QUALITIES TESTING SESSION

Briefing

The briefing session may vary in length from 30 to 90 minutes, and should include both a refresher on the use of the Cooper-Harper scale, a presentation of the overall vehicle capabilities and control methods as related to the testing, and details of the planned test itself. For pilots who have gone through handling-quality tests recently (i.e., within the past few days or weeks), the Cooper-Harper refresher portion may be more streamlined than for pilots who have not performed an HQ assessment in several months or years.

Familiarization

Familiarization runs are simply a set of simulation or flight passes in which the pilot is given time to become accustomed to the vehicle's control schema and general handling characteristics, and perform several iterations of the flight profiles to be tested, but without the collection of any data and without rating the vehicle. This may be thought of as "sandbox time" for the pilot to simply become familiar with the vehicle and the tasks he or she is expected to perform during the test. Generally it is recommended that the pilot be given ample time to fly through all expected tasks and scenarios associated with each profile being tested. Times for this component may vary, usually ranging from 30 to 90 minutes, depending on the number of profiles and scenarios being tested or the complexity of the vehicle controls. A minimum time should be planned for familiarization to ensure valid results.

Testing

The testing session has 3 basic components:

- Practice run(s)
- Data runs
- Collection of ratings and comments

The practice runs are an opportunity for the pilots to be sure they fully understand the profile and scenario being tested, and have their piloting methodology figured out. If they have spent considerable time with the familiarization runs, they may need or want only a single practice run. On the other hand, if multiple scenarios are being tested for the current flight profile, the subjects may be confused about which specific scenario they are piloting and want to ensure that they are flying the scenario they think they are flying. It may sound too conservative, but on many occasions pilots have tried jumping straight from familiarization time into data runs, only to make incorrect flight stick inputs because they were not flying the scenario they thought they were. A minimum number of practice runs should be planned to ensure valid results.

For data runs, the test conductor should ensure that the pilot understands which scenario is being tested. Often, the pilot will fly 2 runs with the ability to go ahead and provide their ratings and comments at the end of the second run, or proceed with a third data run. For these runs it is important to pay close attention to the performance criteria for adequate versus desired performance. Frequently the data runs may attain different levels of performance (e.g., run 1 is performed with desired performance, but run 2 is performed with adequate performance). In these cases a third data run is highly recommended to determine the best performance category to assign to the collection of runs. The rating by the pilot should be a mental integration of all their data runs.

Once the data runs are complete, the pilot should provide the Cooper-Harper ratings and verbal commentary. The rating should take into consideration all of the pilot’s data runs, and is essentially a mental integration of those runs to provide a single rating. This rating is not an average of the runs, nor is it a separate rating for each run; instead it should rely on the pilot’s professional judgment of the vehicle’s performance across the 2 or 3 data runs. It is extremely important to properly administer the Cooper-Harper scale according to its published methodology. For this, the pilot must have a visual representation of the scale in front of them, and they are asked to verbalize their thoughts as they proceed through the decision gates to the various levels, and then on to select a specific rating. They should be reminded of the performance attained (adequate versus desired), and they must resist the temptation to jump directly to a rating number (a tendency more prevalent in highly experienced pilots). The test conductor may remind the pilots that although they may have attained desired performance, this does not limit them to a rating of 1 to 4. However, if they attained only adequate performance, they are not allowed to provide a rating of 1 to 4. So desired performance does not prohibit selection of a poor rating, though adequate or poor performance does prohibit selection of a better rating than the performance warrants. The rating by the pilot should be a mental integration of all their data runs. This does not mean "average," as that would imply a measure of central tendency or blind drift to the median rating of the data runs. Instead, the mental integration is supposed to consider the significance of unexpected behaviors in the handling of a craft, even though these behaviors may have been only a transient effect in a single run. If such a transient response caused a major loss of control, it could drive the overall rating more than the other data runs. Along with the rating, the pilot should be prompted to verbally comment on any noted deficiencies or things that should be improved regarding the vehicle or its controls, displays, or characteristics.

Debrief

After completion of testing for all scenarios in the flight profile of interest, it is important to regroup in a nearby office or conference room to debrief the pilot on his or her experience in the test. The pilots are encouraged to talk about any items of note that they found or experienced, and they may also be provided with a more detailed questionnaire or survey where they may provide additional ratings on items such as the physical flight displays, flight stick design, cockpit layout, software design, or any other component of the vehicle that they may have interacted with.

4.6.3.7 DATA ANALYSIS AND INTERPRETATION

Once testing is completed, the data must be treated as a non-parametric data set because of the nonlinear and categorical nature of the Cooper-Harper scale, compounded by the lack of any single and specific continuous latent trait that it might be based on. (Although cognitive or physical workload may be a reasonable underlying cognitive trait for pilot compensation, the dynamics of the vehicle may simply create poor handling characteristics, ones unrelated to workload and simply related to uncontrollability, making any final selection of latent traits difficult.) Because of this, the simplest and often best way to examine and communicate the data is by means of graphical methods such as histograms, box-and-whisker plots, or frequency-weighted scatter plots.

Examples of each graphical method are provided below, taken from the Constellation Program's Orion pre-PDR Handling Qualities Evaluation led by NASA in 2008 (Figures 4.6.3.7-1, -2, and -3). These 3 plots portray the same data set in 3 different ways (i.e., histogram, box-and-whisker plot, and frequency-weighted scatter plot). Illustrated are data from a set of 2 different scenarios tested for an on-orbit attitude correction maneuver performed using a rotational hand controller (RHC) to reset the guidance system's star-tracker after a system error. Each scenario was associated with a specific type of RHC control mode. The first mode was *RHC Discrete Rate* mode and the second was *RHC Pulse* mode. One of the goals of this particular test was to determine which mode would be most appropriate for piloting the craft. Each scenario tested included 4 tasks, resulting in a total of 8 separate ratings that needed to be documented. The following figures allowed the team to determine that *pulse mode* was the preferred and more controllable way to pilot the vehicle for this flight profile and suggested a design decision in development of the control schema for Orion.

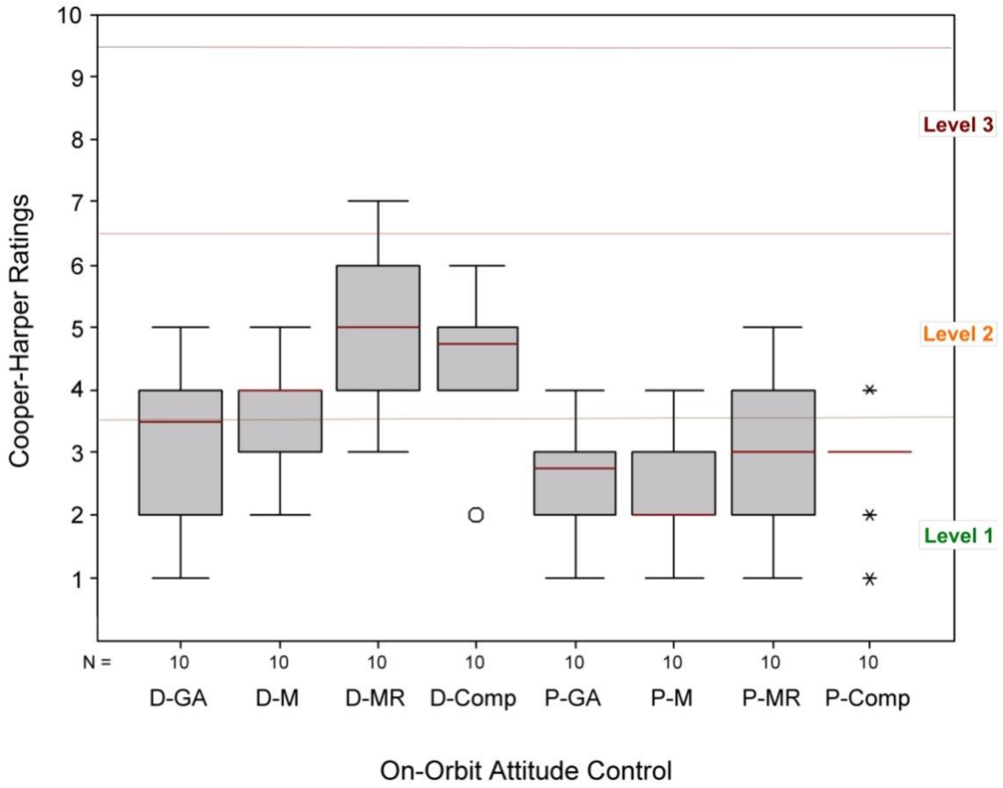


FIGURE 4.6.3.7-1 BOX-AND-WHISKER PLOTS OF THE ORBIT SCENARIO COOPER-HARPER RATINGS

Ratings for gross acquisition (GA), maintenance (M), maintenance while rolling (MR), and the composite (Comp) score, for both discrete rate (D) and pulse (P) cases. Median values are represented by the midline of each box, and the upper and lower shoulders represent the 75th and 25th ordinal percentiles respectively. Whiskers portray data within 1.5 x IQR (inter-quartile range) from the shoulders, with additional values greater than 1.5 x IQR and greater than 3.0 x IQR illustrated by circles and asterisks.

Ordinal box-and-whisker plots are content-rich and allow a very detailed simultaneous review of data for multiple distributions. However, they may be misinterpreted by audiences that are less familiar with this method of data presentation. Thus, their use in handling-quality evaluations can be a great benefit in the analysis of findings, but is not advised for communicating results to a larger audience.

On the other hand, frequency scatter plots are readily communicated in a fashion that also allows comparison of multiple distributions simultaneously, whereas histograms are easily generated and understood. The only significant drawback to histograms is determining how to present them in such a way as to allow comparison of multiple distributions. Histograms are a frequently used methodology for illustrating Cooper-Harper ratings and their use is strongly encouraged in final presentation of results. The following 2 figures provide an example of each of these graphical methodologies.

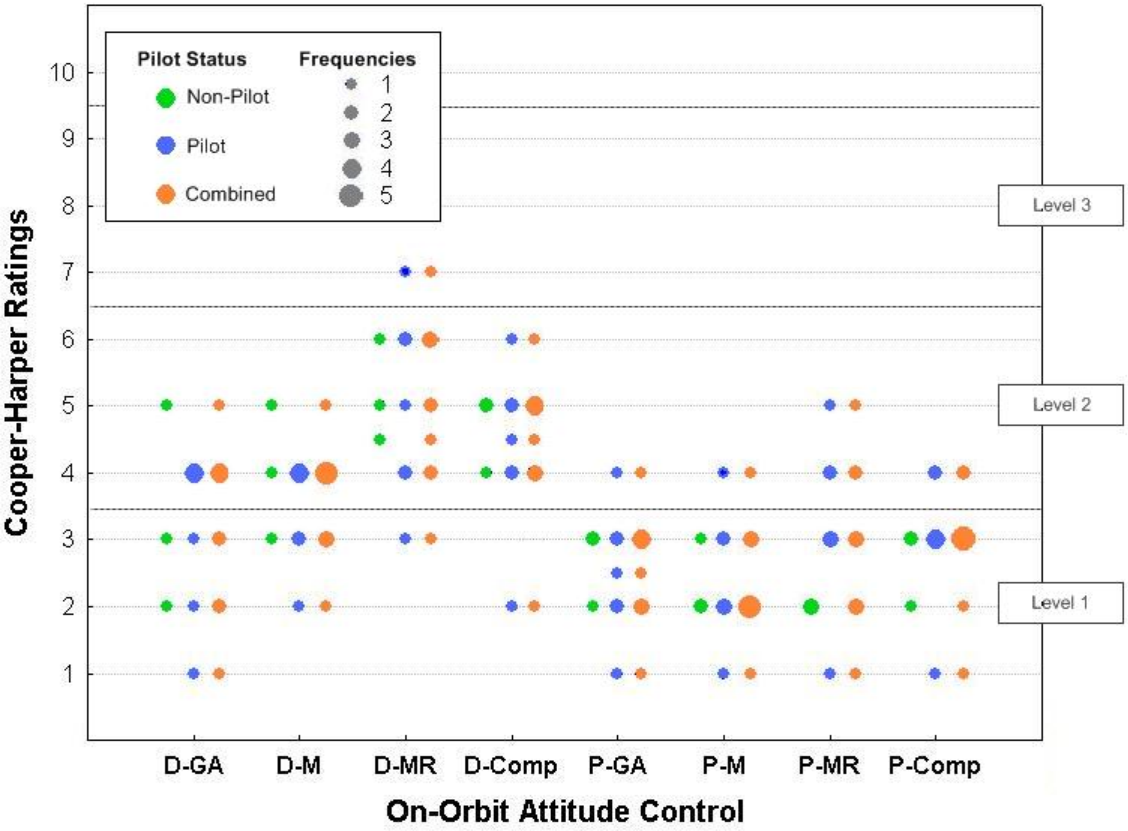


FIGURE 4.6.3.7-2 FREQUENCY SCATTER PLOTS OF THE ORBIT SCENARIO COOPER-HARPER RATINGS

Ratings for gross acquisition (GA), maintenance (M), maintenance while rolling (MR), and the composite (Comp) score, for both discrete rate (D) and pulse (P) cases. Results are color coded for non-pilot data, pilot data, and the combined dataset (both pilots and non-pilots).

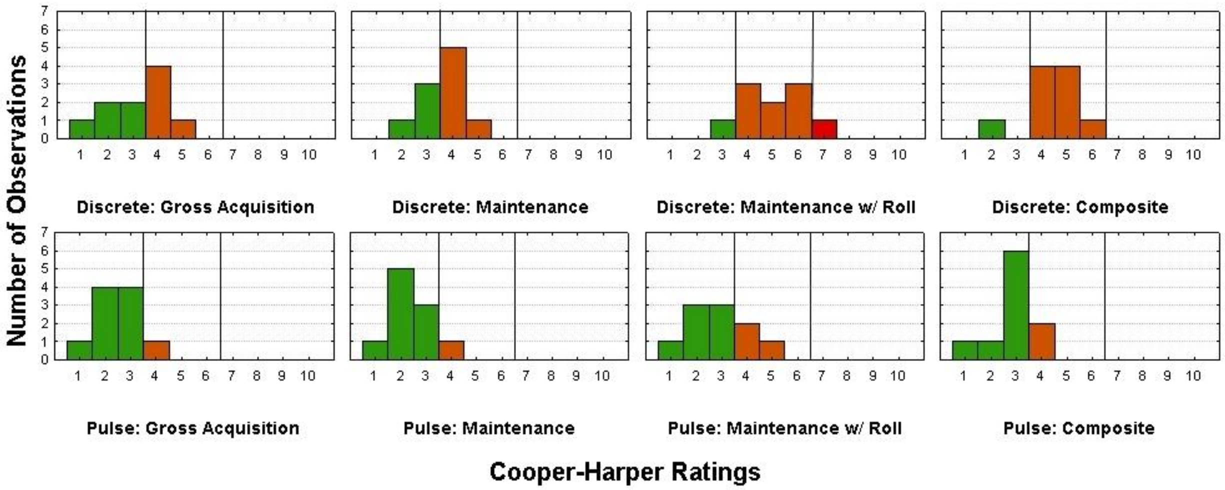


FIGURE 4.6.3.7-3 HISTOGRAMS OF THE ORBIT SCENARIO COOPER-HARPER RATINGS

Ratings colored green indicate Level 1, ratings colored orange indicate Level 2, and ratings colored red indicate Level 3 or higher.

In circumstances where significant variability is seen in the results, likely causes that should be examined include the background of the test subject population (e.g., were all subjects military test pilots with similar backgrounds, did subjects have significant differences in their histories such as rotary-wing versus fixed-wing experience?), differences in piloting strategies, and simulation deviations. Piloting strategies can explain some variability in performance and ratings and should be elicited in the debrief for comparative assessment. Simulation deviations or off-nominal boundary conditions may explain variant ratings if deviations are experienced by some, but not all, of the subjects. Note that these are often some of the most important data points, as they may illustrate previously unconsidered flight conditions or scenarios on which more scrutiny may need to be focused. In such circumstances, additional testing may be warranted.

4.6.4 HANDLING-QUALITIES EVALUATION TECHNICAL PRODUCTS

For each of the major milestones of the design life cycle, the technical products in Table 4.6.4-1 are recommended for review by the NASA customer.

TABLE 4.6.4-1 HANDLING QUALITIES EVALUATION TECHNICAL PRODUCTS

Technical Products	Phase A		Phase B	Phase C	Phase D	
	SRR	SDR	PDR	CDR	SAR	FRR
A description of the ConOps, function allocation, and associated crew task lists. Includes details such as identification of all potential flight phases, subphases, related scenarios, and pilot tasks for which manual control is provided, as required by the design reference mission and as specified by NASA.	I	U	U	U	---	---
Definition of control modes for each flight phase. Preliminary flight display concepts.		I	U	U	U	U
A summary of modeling/analysis/evaluation performed to date and their influence on system design, with links to the detailed analysis results. Includes simulation-based HQ evaluation of each flight phase, based on aerodynamic models, preliminary control algorithms, and display concepts. Required per NPR 8705.2B, and HITL evaluations required per paragraph 2.3.10.	---	---	I	U	---	---
System architecture drawings (structures, equipment, etc.), material specifications, interface requirements.	---	---	I	U	U	---
High-fidelity simulation-based evaluation of HQ based on final structural models, control algorithms, and final displays.	---	---		I	U	U
Verification plan.	---	---	I	U	U	---
Final review of any lingering handling-quality issues or pilot ability concerns.	---	---	---	---	I	U
Hardware-based evaluation of handling qualities with test pilots. All flight phases should be tested.	---	---	---	---	---	X

X = one-time release of item
I = initial release of item
U = updated release of item

Concept of Operations and Crew Task Lists

The ConOps, described in paragraph 3.2.3.1.2, provides information such as identification of crew activities and determination of which subsystems are affected by crew activities. Function allocation, described in paragraph 3.2.3.1.3, establishes the extent to which an activity is to be automated or assigned to humans. The crew task list, described in section 4.1 User Task Analysis, documents details including allocation of function between crew and systems, definition of crew activities sequence, and identification of critical tasks. As the crew task list evolves through the design cycle, its final iteration should become crew procedures.

Crew task list development details specific to HQ evaluations include the identification of all potential flight phases, subphases, related scenarios, and pilot tasks for which manual control is provided. By SRR, definition of flight phases and required HQ rating for each phase should be defined. By SDR, control modes for each flight phase should be defined.

Summaries of Modeling, Analyses, and Evaluations

Iterative summaries of modeling, analyses, and evaluations provide NASA with insight into human-system integration technical details throughout the design process. As designs mature, modeling, analyses, and evaluations should use inputs and mockups of increasingly higher fidelity, as discussed in paragraph 3.2.3.3 Evaluate Designs and Iterate Solutions. It is important that summaries address how key and critical design decisions were assessed. According to NPR 8705.2B, updated summaries are to be provided at each design review through SAR. Also in paragraph 2.3.10, the use of human-in-the-loop evaluation is a required method to progressively demonstrate that the operational concept meets system requirements for operational safety, efficiency, and user interface design.

For HQ, a simulation-based HQ evaluation of each flight phase, based on aerodynamic models, preliminary control algorithms, and display concepts, should be performed by PDR. By CDR, a high-fidelity simulation-based evaluation of HQ, based on final structural models, control algorithms, and final displays, should be performed. Hardware-based evaluations of HQ with test pilots, testing all flight phases, should occur no later than SRR.

Architecture, Materials, and Interface Specifications

Drawings, materials, and interface specifications provide NASA with insight into human-system integration technical details throughout the design process. For HQ, this includes providing preliminary flight display concepts at SDR.

Verification Plan

The verification plan is a formal document describing the specific methodologies to be used to show compliance with each requirement.

4.6.5 CONCLUSION

The procedures and processes listed here are based on the publications of Cooper and Harper, including their seminal 1969 paper on HQ, the numerous follow-up publications they have released, military standards, common industry practice, the mentorship of experienced handling-quality experts from both the Ames and Langley Research Centers, and the testimony of numerous military test pilots and test pilot instructors who were also Space Shuttle pilots and commanders. These sources tie together the use of the Cooper-Harper scale in the assessment of HQ as it pertains to not only aviation but also the assessment of spacecraft. With the burgeoning development of multiple commercial spacecraft, the relevance of HQ has only increased in recent years and is set to continue increasing in the near future. The methodology discussed here is meant to provide a sound foundation to facilitate spacecraft development by these companies as well as NASA and its contractors. Building on this foundation should ensure that future craft are safe, reliable, and controllable under all anticipated flight conditions.

4.6.6 REFERENCES

Cooper, G. E., & Harper, R. P., Jr. (1969). The use of pilot rating in the evaluation of aircraft HQ (NASA-TN-D-5153). Washington, DC: National Aeronautics and Space Administration.

Hart, S. G., & Staveland, L. E. (1988). Development of NASA-TLX (Task Load Index): Results of empirical and theoretical research. In P. A. Hancock & N. Meshkati (Eds.), *Human mental workload* (pp. 139-183). Amsterdam: North Holland.

International Organization for Standardization. (1998). Ergonomic requirements for office work with visual display terminals (VDTs). Part 11: Guidance on usability (ISO/IEC 9241-11). Geneva (Switzerland): ISO.

U.S. Military Specification: Flying qualities of piloted airplanes (MIL-F-8785C). (1980, November 5).

4.7 ACOUSTIC NOISE CONTROL PLAN DEVELOPMENT

4.7.1 INTRODUCTION

Spacecraft acoustics are a critical design consideration from the standpoint of crew safety, health, and mission performance. The first and foremost concern is the risk of temporary and permanent hearing damage caused by exposure to high noise levels over a relatively long duration. Also, the crew must be able to communicate among themselves, hear and respond to communication from the ground, and be altered by alarms. Finally, acoustics play a critical role in the crew's health and stress level. Loud, annoying, or intermittent noise can be disruptive of restful sleep and can stimulate the human "fight or flight" reflex, which can contribute to the overall anxiety level of the crew. For further discussion of the effects of noise on human performance, see NASA/SP-2010-3407 Human Integration Design Handbook (HIDH) section 6.6.2 Human Response to Noise.

The acoustic environment of a spacecraft is a critical design consideration and must be addressed from the outset of the design process. This extreme environment is discussed further in HIDH section 6.6.1 The Acoustic Environment of Spacecraft. Incorporating acoustic design concepts for noise control into the early stages of hardware development will reduce or eliminate costly re-work, design changes, mitigations, and associated schedule slippage, as well as potential operational constraints. A human-centered approach to spacecraft design is essential for achieving required acoustic conditions needed to ensure the safety of the crew with respect to acoustics and thereby attain human rating of the spacecraft.

4.7.2 APPLICABLE ACOUSTIC REQUIREMENTS

Acoustic requirements are specified in NASA-STD-3001 Volume 2, section 6.6. Mission phases covered by this document include launch, abort, orbit, entry, and post landing. ISS docked operations are covered in a separate family of SSP documents. Although acoustic requirements for ISS are similar to some of the NASA-STD-3001 Vol. 2 requirements, discussion of ISS-specific requirements is beyond the scope of this document.

The first acoustic requirement of NASA-STD-3001 Vol. 2 is the establishment of an Acoustic Noise Control Plan (V2 6071), which specifies documenting the plan for achieving spacecraft acoustic requirements.

The following are the acoustic requirements for launch, entry, and abort phases:

- V2 6073 Launch, Entry, and Abort Noise Exposure Limits
- V2 6074 Hazardous Noise Levels for Launch and Entry
- V2 6075 Hazardous Noise Levels for Launch Abort
- V2 6076 Launch, Entry, and Abort Impulsive Noise Limits
- V2 6085 Infrasonic Sound Pressure Limits

The following are the acoustic requirements for orbit and post-landing phases:

- V2 6077 Hazardous Noise Limits for All Phases Except Launch, Entry, and Abort
- V2 6078 Continuous Noise Limits
- V2 6079 Crew Sleep Continuous Limits
- V2 6080 Intermittent Noise Limits
- V2 6084 Narrow-Band Noise Limits
- V2 6082 Impulse Annoyance Limit
- V2 6083 Impulse Noise Limit
- V2 6086 Ultrasonic Noise Limits

Additionally, V2 6072 establishes the requirement for Acoustic Requirement Verifications, and V2 6087 & V2 6088 require mission acoustic monitoring and individual crew exposure monitoring, respectively.

Additionally, HIDH section 6.6.3 Human Exposure and Acoustic Environment Limits provides guidelines for the limits that ensure that a spacecraft provides the crew with an acoustic environment that will not cause injury or hearing loss, interfere with voice communications, cause fatigue, or degrade overall human-machine system effectiveness.

4.7.3 ACOUSTIC NOISE CONTROL DESIGN PROCESS

NASA-STD-3001, Vol. 2 requirement V2 6071 establishes the requirement for an Acoustic Noise Control Plan (ANCP). The ANCP is a document that contains an acknowledgment of the applicable acoustic requirements, identification of the noise-producing systems and components, a development plan for meeting the acoustic requirements (e.g., criteria for planned hardware selection, efforts that will be used for acoustic mitigation), and a summary of the project’s acoustic requirement verification plan. The ANCP is a “forward-looking” plan and serves as a guide for addressing development of acoustic noise control. In the later stages of development, the ANCP becomes comprehensive documentation of the rationale behind design decisions affecting the acoustic environment of the vehicle. It also serves as a summary of the requirement verification testing and analyses performed. The ANCP is to be updated as subsystem designs are developed, subsystem components are selected, and analysis and test data are applied to improve the accuracy of the initial acoustic projections. Identified challenges to meeting acoustic requirements should also be documented in the ANCP. The ANCP is to be provided to NASA at each design review (i.e., program milestone) and will be assessed for progress toward meeting acoustic requirements. The following paragraphs highlight design steps that should be followed and documented in the ANCP.

4.7.3.1 DEVELOP CREW TASK LIST

Crew task lists are necessary for identifying crew locations and positions with respect to noise sources, potential combinations of hardware that may be operated concurrently (for evaluation of intermittent acoustic noise emission requirements), and configurations of the crew (suited, unsuited, helmeted, visor up, visor down). All of these factors are important for evaluating the acoustic noise emission scenarios to compare them with the acoustic requirements. Vehicle design for acoustic noise control should begin with development of the concept of operations and scenarios for nominal, off-nominal, and emergency operations. For each mission phase and relevant scenario, crew roles and activities should be specified for the purpose of developing crew task lists and procedures. Off-nominal situations, such as abort scenarios, must also be considered, and the applicable acoustic requirement applied. See HIDP sections 3.2.3.1.2 and 4.1 for discussion of developing concept of operations and crew task lists.

The following general mission phases and crew configurations should be separately considered and compared to the applicable acoustic requirements (note that this list is not exhaustive and should not be considered as such):

- Launch
  At launch the dominant noise sources will be the vehicle engines and the air interaction between the vehicle and the atmosphere, and the dominant acoustic path will be the vehicle structure. Vibro-acoustic analysis and testing will be necessary to assess the inputs to the vehicle and the resulting acoustic environment experienced at the crewmember’s ear. The noise reduction of the communications gear, spacesuit, and helmet must also be considered during this mission phase. Insertion loss is the decrease in sound pressure level, measured at the location of the receiver, when a sound insulator or a sound attenuator is inserted in the transmission path between the source and the receiver.

- Pad Abort and Launch Abort
  In the event of either a pad or launch abort situation, the dominant noise sources will be the abort engines and atmosphere interaction with the vehicle. As with launch, vibro-acoustic analysis and testing will be necessary to assess the inputs to the vehicle and the resulting acoustic environment experienced at the crewmember’s ear. The noise reduction of the communications gear, spacesuit, and helmet must also be considered during this mission phase.

- On-orbit Operations
  The dominant noise sources during the free-flight mission phase will need to be assessed according to the specified vehicle and crew configurations. Generally during this mission phase, the dominant noise sources will be inside the pressurized volume of the vehicle, including vehicle and/or spacesuit Environmental Control and Life Support (ECLS) systems. Acoustic transmission paths will be a combination of structure-born and airborne paths. Particular consideration must be paid to the crew configuration. It must be specified whether the crew is seated or free to move inside the pressurized volume, suited with visors down inside pressurized suits, suited with visors up and suit unpressurized, or unsuited. The differing noise sources and acoustic transmission paths for each configuration must be considered and compared to the applicable acoustic requirements.

- Docked Operations
  If the visiting-vehicle will be docking to the ISS, the visiting-vehicle requirements will apply and must be considered. A complete discussion of this mission phase

is beyond the scope of this document. Refer to SSP 50808 for more information about ISS commercial visiting vehicle docked requirements.

- Undocking, Deorbit, Reentry, Landing, and Post Landing
  As with launch and on-orbit operations, the configuration of the crew during different phases of post-docked operations must be considered. Applicable noise sources may include deorbit engines, aerodynamic interaction between the vehicle and the atmosphere, and vehicle and/or spacesuit ECLS systems. Acoustic transmission paths will include both structural and airborne paths. Different noise sources and acoustic paths may be dominant at different points of the mission and must be considered and compared to the applicable acoustic requirements. Note that acoustic requirements are applicable until the crew is recovered from the vehicle.

4.7.3.2 DEVELOP DESIGN SOLUTIONS

4.7.3.2.1 ACOUSTIC MODELING

The major noise-generating systems and components should be included in an integrated acoustic model for an accurate representation of individual sources and propagation paths, as well as reverberation effects. In recent years, computerized acoustic modeling techniques have improved, especially with respect to modeling complex geometries. The ANCP is to include a description of the selected acoustic modeling approach, noting the engineering assumptions made in the construction of the acoustic model. Different modeling strategies may be needed to address the separate acoustic requirements or frequency ranges. Finite Element Analysis (FEA) and Boundary Element Analysis (BEA) approaches are acceptable modeling techniques for low-frequency noise prediction; however, these methods can become complex and computationally intensive as the frequencies of interest increase. Statistical Energy Analysis (SEA) has been shown to be an effective and accurate analysis approach for mid-frequency and high-frequency predictions; however, the accuracy of SEA estimates may decrease in the low frequencies, where the fundamental assumptions of this method may not be applicable. It is expected that a hybrid acoustic modeling approach utilizing 2 or 3 of the noted acoustic modeling techniques will need to be applied to bridge gaps and address the entire frequency range. A single commercial acoustic modeling software package that combines these 3 modeling techniques may be used, or separate acoustic modeling packages may be selected and combined into a coherent overall model result. As component, system, and vehicle designs are developed and modeling analyses are performed, results and design decisions are to be documented in the ANCP. Any acoustic issues or areas of concern and the forward plans for addressing, mitigating, and resolving these issues and concerns are to be documented for each design review. Although modeling is used to make predictions, data from component acoustic testing, flight testing, and ground test articles are to be used as inputs to the models and incorporated as early in the process as possible to verify assumptions and improve the accuracy of the acoustic model. Empirical and analytical models and techniques can also be very useful and are often necessary. These can be used along with acoustic modeling or alone if needed. An example is the use of empirical data for first estimates of launch rocket noise.

4.7.3.2.2 NOISE SOURCE ALLOCATIONS

Acoustic allocations for each major noise source and each mission phase are to be identified and documented in the ANCP. The significant noise sources (e.g., engines, ECLS components, payload, boundary layer noise) either within or penetrating the crew pressurized volume should be identified and broken down into component noise allocations. Each noise source should then be allocated with an allowable acoustic emission level based on the appropriate requirement using acoustic analysis. For example, launch noise can be divided into (1) external noise environment, (2) interior vehicle noise (taking into account the attenuation provided by the vehicle), and (3) noise inside the spacesuit (again taking into account the attenuation provided by the spacesuit). This is an iterative process with the accuracy of the assessment improving as the design matures, major components are tested, and acoustic mitigation efforts are developed and implemented. The ANCP is to be updated as the design matures and should include summaries of how modeling and analyses influenced system design.

4.7.3.2.3 NOISE SOURCE SELECTION

Using the acoustic requirement allocations, a test-based strategy should be used to select or design noise-producing hardware (e.g., pumps, fans, and actuators) that have the lowest acoustic levels and meet the functional requirements. Allocations should be expressed in Sound *Power* Level (as opposed to sound pressure level) for the highest accuracy. Sound power levels indicate the total propagating acoustic energy created by the source, and do not depend on source directivity or the distance from the noise source (as with sound pressure levels). Preliminary acoustic testing results should also be used as model inputs to make early estimates of the integrated hardware acoustic noise levels. These results should be compared to the acoustic allocations and the overall acoustic requirements to verify that the vehicle will be able to meet the acoustic requirements and to identify where acoustic mitigation efforts will need to be developed.

4.7.3.2.4 DESIGN ITERATION OF NOISE SOURCES

Trade studies should be conducted to balance the functional requirements with a component’s acoustic emissions. Selection of components that have capabilities in excess of functional requirements or extra engineering margin should not come at the expense of elevated acoustic emissions that put the overall acoustic requirements at risk. The results of these trade studies and the resulting design decisions are to be documented in the ANCP. Operating fans and pumps at reduced speeds is effective at lowering noise levels while maintaining performance margin for contingencies.

Consider an example trade study for a fan, which is a typical spacecraft noise source. Generally, higher fan speeds lead to higher acoustics emissions. Therefore, one should design or select fans that operate most efficiently at the speed necessary to meet the flow and pressure requirements for its role. This is an iterative process in which tradeoffs between performance and acoustics are made between many noise-producing systems. One important consideration when selecting and designing “prime mover” fans is to include an estimate of pressure loss from inline mufflers (as necessary). See 4.7.3.2.7 on component-level noise controls.

4.7.3.2.5 FURTHER NOISE SOURCE REDUCTION

Once components are optimized for required performance and acoustics, the remaining noise sources must be addressed individually for noise source reduction measures. Applying the previous example of a fan, once the fan speed is selected based on the functional requirements, it may be necessary to look at noise source treatments such as optimized balancing of the fan or vibration isolation to reduce the noise source emissions of the unit to acceptable limits. If noise source treatments cannot be applied, this fact should be documented in the ANCP along with the rationale.

One of the most important design activities for reduction of noise sources is early testing of noise sources and measurements of radiated noise levels at realistic installed conditions. For example, a flow restrictor may be used to impose the right pressure loss for measuring fan noise. The measured sound power levels for early testing of noise source data should be input into the acoustic model to update the accuracy of the model predictions. Early testing will give an early indication of possible problems; this is extremely important. These updates should be noted and documented in the ANCP.

4.7.3.2.6 DESIGN OF SYSTEM-LEVEL NOISE TREATMENTS

Meeting the acoustic requirements is not just the responsibility of the noise-making system, but is an integrated vehicle design endeavor. To incorporate more broadly applied noise controls, system-level treatments such as barriers, gap-sealing elements, and absorbers, as part of the hardware or inside the crew pressurized volume (for vehicles), may be applied and incorporated in the acoustic model. The needed insertion loss of system-level noise treatments are to be documented in the ANCP as well as model results showing the acoustic impacts of proposed mitigation efforts.

An example is the case of a fan that has a sound pressure level of 60 dB in the 250-Hz octave band. To meet the acoustic requirement allocation, assume that the required acoustic emissions for the fan in the 250 Hz octave band must not exceed 50 dB. In this simple example, the “needed insertion loss” would be 10 dB in the 250 Hz octave band in order to meet the requirement. Assume further that a muffler is designed for the fan, and when the fan and muffler are tested together, the insertion loss in the 250-Hz octave band is only 7 dB. This would result in an exceedance to the acoustic requirement allocation of 3 dB, and the exceedance could roll up to the overall vehicle acoustic requirement. In this case, a possible solution could be application of absorption treatments inside the cabin to reduce the reverberation and resulting noise levels by 3 dB.

Note that this iterative analysis process is necessary over the entire frequency range of the acoustic requirements and all the associated operating conditions for each of the defined mission phases. The use of an acoustic model will greatly simplify the analysis process, assist in the identification of acoustic challenges, and allow the virtual evaluation of potential acoustic mitigation efforts to be performed quickly and efficiently.

4.7.3.2.7 DESIGN OF COMPONENT-LEVEL (END-ITEM) NOISE TREATMENTS

Once the noise source levels have been measured and the system-level noise treatments are designed (at least preliminarily), the noise-reduction requirements for component-level treatments can be determined to meet the noise source's allocation. Designs for component-level reductions may include such items as component mufflers and acoustic covers. Also, tradeoffs between the component-level noise treatments and system-level noise treatments can be addressed when the projected component-level reductions are predicted and applied to the global model to predict system-level compliance with acoustic requirements. The predicted results of these component-level noise treatments are to be documented in the ANCP.

Also note that consideration of structure-born noise is very important and the use of vibration isolation as component noise control can be very effective at reducing this effect. Broader control of structure-born noise or identification of structural resonance may need to be approached as system-level noise control efforts.

4.7.3.3 TEST AND EVALUATION

Iterative tests and evaluations should be performed to assess the acoustic emission characteristics of the hardware selected for use in the vehicle. The results of the initial component-level noise and treatment testing are applied as inputs to the acoustic model to assess progress in meeting the acoustic requirements. Additionally, data from spacecraft external noise sources are applied, as needed. As the system design matures, the ANCP is to be updated and include summaries of how tests and evaluations influenced design decisions.

4.7.3.3.1 TESTING OF COMPONENT-LEVEL NOISE TREATMENTS

Component-level treatments are to be mocked up, fabricated, and tested so that their performance is known. Integrated treatments are tested at component level to be used as inputs to the acoustic model. Examples of methods to use include 1) insertion-loss measurements for mufflers and silencers (or components that act as such), and 2) impedance tube absorption and transmission-loss measurements for acoustic materials and layups. Actual measured results of component-level noise treatment performance are to be documented in the ANCP.

4.7.3.3.2 TESTING OF SPACECRAFT EXTERNAL ENVIRONMENTS

Test data from spacecraft external noise sources (e.g., engines, aerodynamic boundary layer noise) are to be applied as inputs to acoustic modeling. External noise sources should be characterized through all mission phases including launch, abort, and descent, and testing must be used as the basis for estimates. For this, static rocket firings, wind- tunnel tests, and flight tests are to be used. Data are to be included from pad abort testing, launch abort testing, and unmanned flight testing, and these data are essential for the human rating of the space vehicle.

4.7.3.3.3 VERIFICATION TEST PLAN

The ANCP is to include, or point to, a complete acoustic verification plan and schedule with pass/fail criteria for component verification testing (sound power, acoustic emissions testing), static system verification testing (ground test article test plan), and development flight testing (pad abort tests, aerial abort tests, unmanned flight tests). Validation of pressure shell, blast protective cover, and spacesuit attenuation of launch and abort acoustic loading must be performed through testing at expected noise levels. Acoustic verification is to include modeling analysis of the interior noise environment and flight-test data before the first manned test flight. The ANCP is to include all verification results.

4.7.4 ACOUSTIC NOISE CONTROL DESIGN TECHNICAL PRODUCTS

An updated version of the ANCP is to be provided at each program milestone for review. It is important to emphasize that the ANCP is a "living document" that will evolve over the project design life to reflect the current project strategy at each review phase. The ANCP will both document the overall process and update NASA on the course and expected results of future development. Recommended activities and products for each program milestone review are outlined in the following paragraphs. A summary table of technical products is provided in Table 4.7.4-1.

TABLE 4.7.4-1 ACOUSTIC NOISE CONTROL DESIGN TECHNICAL PRODUCTS

Technical Products	Phase A		Phase B	Phase C	Phase D	
	SRR	SDR	PDR	CDR	SAR	FRR
A description of the ConOps, function allocation, and associated crew task lists.	I	U	U	U	---	---
Acoustic model.	---	I	U	U	---	---
An Acoustic Noise Control Plan (ANCP) that includes statement of applicable acoustic requirements, identification of noise sources, external environment definition, modeling analyses, component acoustic testing results, external environment test results, verification plan, verification results, and any remedial actions needed to address requirement non-conformance).	---	---	I	U	U	---

X = one-time release of item
I = initial release of item
U = updated release of item

<u>Concept of Operations and Crew Task Lists</u>

The ConOps, described in paragraph 3.2.3.1.2, provides information such as identification of crew activities and determination of which subsystems are influenced by crew activities. Function allocation, described in paragraph 3.2.3.1.3, establishes the extent to which an activity is to be automated or assigned to humans. The crew task list, described in section 4.1 User Task Analysis, documents details including allocation of function between crew and systems, definition of the sequence of crew activities, and identification of critical tasks. As the crew task list evolves through the design cycle, its final iteration should become crew procedures.

Preliminary Design Review (PDR)

The initial ANCP is to be prepared for PDR and provided to NASA for review. It is to contain restatement of the applicable acoustic requirements, identification of the major noise-producing systems (e.g., ECLS, Payload), and an initial allocation of the acoustic requirements to appropriate systems.

To understand the proposed system architecture, an acoustic model of the pressurized volume is to be prepared and the model assumptions, inputs, findings, and projections documented in the ANCP. Modeling analyses should demonstrate the progress of the system design toward meeting acoustic allocations for all mission phases. Areas of concern are to be identified and documented in the ANCP with forward plans for addressing the issues. Plans for acoustic testing of component noise sources (such as fans, blowers, and pumps) and selection criteria for flight hardware are to be included in the ANCP.

Preliminary design and effects of system-level noise treatments are to be documented. Components are to be specified along with sound power level allocations that meet the overall acoustic requirements previously specified. The acoustic model is to be updated to reflect the component-level acoustic contributions to the applicable systems and the overall acoustic environment. An initial definition of the spacecraft external environments for launch, descent, and abort is to be presented, and inputs are to be included in the acoustic model. The acoustic model is to be updated to reflect the results of any completed component tests before the PDR, and the results are to be documented in the ANCP. Necessary component noise controls and their expected contributions are also to be accounted for in the model and documented in the ANCP.

The initial acoustic verification plan is to be prepared for the PDR. The acoustic verification plan is to include a schedule and pass/fail criteria for component verification testing (sound power, acoustic emissions testing), static system verification testing (ground test article test plan), and development flight testing (pad abort tests, aerial abort tests, unmanned flight tests).

NASA will review the updated ANCP and upon successful completion of the PDR, will give authorization to proceed into implementation and final design.

Critical design review (CDR)

At the CDR stage, the ANCP is updated to reflect the results of already completed component qualification testing, and a comprehensive plan and schedule for incomplete qualification testing are to be presented. Component-level noise treatment design requirements are to be specified. The acoustic model is updated to reflect the results of the completed component acoustic qualification testing. In addition, the ANCP is updated to reflect the results of ground and flight testing completed to date and the spacecraft exterior launch, descent, and abort environments. Risks to the overall acoustic requirements identified by the acoustic model are to be highlighted in the ANCP as well as a comprehensive forward plan for mitigation.

The acoustic requirement verification plan is to be updated with the results of completed tests and analyses, and the schedule for remaining tests is to be identified. Flight test objectives for acoustic requirement verification are to be defined clearly, and a forward plan for acquisitions activities is to be presented.

NASA will review the updated ANCP, and upon successful completion of the CDR, will give authorization to proceed with system qualification testing and integration activities.

Test Readiness Review (TRR)

A TRR is to be conducted before each verification test involving acoustics design requirements. An updated ANCP is not a necessary input for the TRR; however, a formal acoustic test plan is to be submitted for review at least 1 month before the scheduled TRR. The acoustic test plan is to include a summary of the applicable acoustic requirements that the test is intended to verify, a list of measurement locations with instrumentation details (transducer type and traceable calibration record, placement of transducer, data acquisition parameters), intended post-processing analysis planned for the measurement data, and expected results relating to the acoustic requirements.

The acoustic test plan is to be reviewed by NASA and inputs submitted to the flight article team. Upon successful completion of the TRR, approval will be given to conduct the test. After the test is completed, a test report is to be provided. Updates should be made to the ANCP with the findings of the test and a forward plan to address any acoustic requirement exceedances identified in the test results.

System Acceptance Review (SAR)

A SAR is to be conducted upon the successful completion of all acoustic verification testing, submittal of the respective test reports, and the ANCP updated to reflect the results of all testing. Verification documentation will be reviewed for requirement closure. Therefore, it is not necessary to include all verification documentation in its entirety. It is expected that a synopsis statement for each verification test conducted, as well as a cross-reference to the test documentation, will be included in the ANCP. All acoustic requirements are to be met or their nonconformances documented and approved by NASA.

Upon successful completion of the SAR, acoustic flight certification of the vehicle will be granted for crewed space flight.

4.8 RADIATION SHIELDING DESIGN

4.8.1 INTRODUCTION

Radiation shielding is an important aspect of vehicle design that is incorporated during the various design phases of a spacecraft. Radiation shielding is designed to protect the crew from radiation exposure so that effective dose (tissue averaged) is consistent with the “as low as reasonably achievable” (ALARA) principle, as specified in NASA-STD-3001 Volume 2 section 6.8.1 Ionizing Radiation.

The following process is intended to guide the spacecraft developer by describing the NASA radiation shielding design process to facilitate successful design verifications and support achievement of spacecraft human rating.

4.8.1.1 BACKGROUND

Radiation sources in space consist of galactic cosmic rays (GCR), trapped radiation, and solar particle events (SPEs). Limits for both short-term and career exposure are established on the basis of assessments of projection models and a reasonable “worst-case” space environment to be encountered on specific missions. Although specific exposure limits are identified according to mortality risk, all decisions concerning vehicle, habitat, and mission design are made such that resulting crew radiation exposures are ALARA. Additional information about ionizing and non-ionizing radiation can be found in the NASA/SP-2010-3407 Human Integration Design Handbook (HIDH) sections 6.8 and 6.9, respectively.

Crewmembers’ mission risk of radiation exposure varies with age and gender of the astronaut, and the variation of solar activity during the approximately 11-year solar cycle. The likelihood of SPEs is higher near solar maximum and the GCR doses are higher at solar minimum. Shielding against radiation can substantially reduce SPE doses and provide modest protection from GCR. Career exposure to radiation is limited to not exceed 3% risk of exposure-induced death (REID) for fatal cancer. NASA ensures that this risk limit is not exceeded at a 95% confidence level by using a statistical assessment of the uncertainties in the risk projection calculations to limit the cumulative effective dose received by an astronaut throughout his or her career. Refer to NASA-STD-3001 Volume 1 for more information on dose limits, and HIDH section 6.8.3 Physiological Effects of Ionizing Radiation Exposure for information on the physiological effects of radiation exposure.

The ALARA principle is both a legal and a recognized NASA 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 “tolerance values.” Mission programs resulting in radiation exposures to astronauts are required to find cost-effective approaches to implement ALARA. At the present time, acute risks are a concern with SPEs; therefore, protection against these events must be incorporated into the vehicle design. The impracticalities involved in shielding for the higher GCR energies, as well as the large uncertainties in GCR risk projections, must be considered in exposure projections and mitigation. Risk uncertainties for SPEs are smaller than for

GCR; therefore, application of the ALARA principle through shielding design and related mass distributions is more practical.

4.8.1.2 RADIATION SHIELDING DESIGN APPLICABLE REQUIREMENTS

NASA-STD-3001 Volume 2 requirement [V2 6097] Design Approach specifies that the vehicle shall be designed using the ALARA principle to limit crew radiation exposure. A mitigation plan to protect crewmembers in the event that shielding is inadequate should also be provided.

4.8.2 RADIATION SHIELDING DESIGN PROCESS

4.8.2.1 DEVELOP CONCEPT OF OPERATIONS AND CREW TASK LIST

Vehicle design for radiation shielding should begin with development of the concept of operations and scenarios for nominal, off-nominal, and emergency operations. For each mission phase and relevant scenario, crew roles and activities need to be specified and crew task lists developed. Crew task lists are necessary for identifying crew locations and positions with respect to radiation sources and/or varying levels of shielding within the vehicle. See HIDP sections 3.2.3.1.2 and 4.1 for discussion of developing concept of operations and crew task lists.

4.8.2.2 DEVELOP DESIGN SOLUTIONS

Methods of protection from radiation exposure include development of effective shielding materials, provision for radiation safe haven, solar proton event warning systems, scheduling of missions and tasks to reduce exposure, and development of dietary or pharmaceutical countermeasures (e.g., chemopreventives and radioprotectants). For more information see HIDH section 6.8.5 Protection from Ionizing Radiation.

Achievement of ALARA is an iterative process of integrating radiation protection into the design process and ensuring optimization of the design to afford the most protection possible, within other constraints of the vehicle systems. The protection from radiation exposure is ALARA when the expenditure of further resources would be resource prohibitive relative to the reduction in exposure that would be achieved. Radiation protection for humans in space differs from that on Earth because of the distinct types of radiation, the small population of workers, and the remote location of astronauts during space flight. The National Council on Radiation Protection and Measurements (NCRP) has set a limit for crew exposure in Low-Earth Orbit (LEO) as defined in NCRP Report No. 132, Radiation Protection Guidance for Activities in Low-Earth Orbit. The definition of the worker population (i.e., NASA astronaut population) is incorporated into the design limit. The radiation sources in space—GCR, trapped particles, and SPEs— have physically and biologically damaging properties different from those of terrestrial radiation, and the spectrum and energy of concern for humans differ from those for electronics. Radiation protection for the crew must consider this environment and these concerns. Nominal mission exposure will be covered by the legal limit as established in NCRP Report No. 132.

4.8.2.3 DESIGN EVALUATION AND VALIDATION

Design evaluations will be a collaborative effort between the spacecraft developer and NASA. Throughout the iterative process of vehicle design, evaluation of the vehicle radiation shielding is to be performed by the developer using standard analysis tools and an integrated set of models. These models will be initially provided by NASA or the developer at SRR. Those models provided by the developer should be approved by NASA before use. The integrated set of models used to perform analysis of the vehicle design includes components such as design environment, biological components, transport code, and vehicle geometry. These models should be specified in program-level requirements, as in Commercial Human-Systems Integration Requirements (CHSIR) CH6054V, for example.

As materials are selected, design solutions are implemented, and vehicle system configuration layouts are determined, models are updated for iterative analyses. All elements of the radiation shielding analyses, to include input data and calculations, are to be provided to NASA to confirm the developer’s findings. Input data includes CAD models, mass distributions, and material compositions. NASA insight into developmental analyses can be beneficial for checking assumptions and assessing progress toward meeting adequate radiation shielding.

To validate that the ALARA principle has been met, monitoring with passive radiation area monitors is included during vehicle flight tests and crewed missions. Although the major phases of the vehicle design have been completed before the flight tests, the data obtained from these monitors are used to validate the shielding provided, verify model results, and identify areas that have a relatively high exposure rate (e.g., avoidance areas) by providing a spatial distribution of radiation exposure within the spacecraft. Spacecraft design must accommodate passive radiation monitoring, which continues during the operational flight phase of the vehicle. Levels of exposure rate will continue to vary with solar activity and vehicle stowage configuration changes, and must be continuously monitored and assessed. Continual monitoring and assessment, using real time or near-real-time data, are important for enabling crew health and should be part of a mission plan.

The spacecraft developer provides locations for no fewer than 6 radiation area monitors to be mounted within the vehicle. NASA provides the dosimeters and uses the results of radiation exposure analyses provided by the developer to help determine the ideal quantity and best locations for the monitors within the vehicle. The developer verifies that the attachment method for the passive radiation monitors is sufficient to withstand anticipated loads to the vehicle structure during all mission phases, including launch and landing. The concept of operations document includes the installation of radiation area monitors inside the vehicle just before launch. The ground operations Interface Requirement Document (IRD) contains requirements for installation and recovery of dosimeters immediately before and after a mission, respectively. NASA supports post-landing collection and analysis of samples. . The data obtained from these passive radiation area monitors will be used to evaluate total mission ioniziong radiation exposure from the various locations within the vehicle. It may also be used as part of the individual crewmember exposure results, if the individual crewmember worn passive dosimeter becomes lost or misplaced.

4.8.3 RADIATION SHIELDING DESIGN TECHNICAL PRODUCTS

For each of the major milestones of the design life cycle, the technical products in Table 4.8.3-1 are suggested for review by the NASA customer.

TABLE 4.8.3-1 RADIATION SHIELDING DESIGN TECHNICAL PRODUCTS

Technical Products	Phase A		Phase B	Phase C	Phase D	
	SRR	SDR	PDR	CDR	SAR	ORR/FRR
A description of the ConOps, function allocation, and associated crew task lists.	I	U	U	U	U	---
Integrated set of models used to perform analysis of vehicle design with radiation shielding.	I	U	U	U	---	---
Radiation instrument specifications and drawings.	I	U	U	U	U	---
Verification approach and plans for radiation shielding and area monitoring.	I	U	U	U	U	---
System architecture drawings (structures, equipment, etc.), material specifications, interface requirements.	---	I	U	U	U	---
Specifications for vehicle construction w/ shielding.	---	I	U	U	U	---
Radiation shielding tests and analyses.	---	I	U	U	U	--
IRDs for vehicle and portable equipment and cargo, vehicle and ground systems, vehicle and mission systems, vehicle and ISS.	---	I	U	U	U	---
Mounting and recovery procedures for dosimeters and radiation area monitors.	---	---	I	U	U	U
Flight plan, flight rules, space weather environment, projected radiation dose, flight data file procedures, system operations data file procedures.	--	---	---	---	---	X

X = one-time release of item
I = initial release of item
U = updated release of item

Concept of Operations and Crew Task Lists

The ConOps, described in paragraph 3.2.3.1.2, provides information such as identification of crew activities and determination of which subsystems are influenced by crew activities. Function allocation, described in paragraph 3.2.3.1.3, establishes the extent to which an activity is to be automated or assigned to humans. The crew task list, described in section 4.1 User Task Analysis, documents details including allocation of function between crew and systems, definition of crew activities sequence, and identification of critical tasks. As the crew task list evolves through the design cycle, its final iteration should become crew procedures.

Architecture, Materials, and Interface Specifications

Drawings, materials, and interface specifications provide NASA with insight into human-system integration technical details throughout the design process.

Verification Plan

The verification plan is a formal document describing the specific methodologies to be used to show compliance with each requirement.

System Requirements Review (SRR)

NASA technical products:

- Desired design reference mission (DRM)
- Program Medical Operations Requirement Document
- Program Human-Systems Integration Requirements Document
- NASA-STD-3001 Volumes 1 and 2
- NPR 8705.2B
- Radiation instrumentation specifications

Suggested developer technical products:
- Initial ConOps addressing radiation requirements
- Preliminary analysis plan and verification & validation (V&V) approach for shielding analyses
- Preliminary analysis plan and V&V approach for radiation area monitor installation

NASA or Developer Technical Products:
- Integrated set of models used to perform analysis of vehicle design

System Definition Review (SDR)

NASA technical products:
- Updates to previous documentation, as available
- Changes to radiation instrumentation specifications

Suggested developer technical products:
- Revisions of ConOps
- Definition of system architecture (structures, portable equipment, cargo)
- IRDs for vehicle/equipment/cargo, vehicle/ground systems, vehicle/mission systems, vehicle/ISS
- Specifications for vehicle construction and shielding
    - Final analysis plan/V&V approach
    - Preliminary analysis results
    - Input data and calculations used in shielding analysis
    - Preliminary mitigation plan if shielding is inadequate
- Methods for mounting dosimeter to vehicle
    - Updated analysis plan/V&V approach
    - Preliminary assessment of maximum loads

NASA or Developer technical products:
- Updates to integrated set of models used to perform analysis of vehicle design

Preliminary Design Review (PDR)

NASA technical products:
- Updates to previous documentation, as available
- Changes to radiation instrumentation specifications, as available

Suggested developer technical products:

- Revisions of ConOps
- Updates to definition of system architecture (structures, portable equipment, cargo)
- IRDs for vehicle/equipment/cargo, vehicle/ground systems, vehicle/mission systems, vehicle/ISS
- Updated analysis plan/ V&V approach for shielding analyses
- Updated analysis plan/V&V approach for radiation area monitor installation
- Specifications for vehicle construction and shielding
  - Updated analysis results
  - Input data and calculations used in shielding analysis
  - Updated mitigation plan if shielding is inadequate
- Methods for mounting dosimeter to vehicle
  - Updated load assessment

NASA or developer technical products:

- Updates to integrated set of models used to perform analysis of vehicle design

Critical Design Review (CDR)

NASA technical products:

- Updates to previous documentation, as available
- Changes to radiation instrumentation specifications, as available

Suggested developer technical products:

- Final ConOps
- System architecture (structures, portable equipment, cargo)
- Final IRDs for vehicle/equipment/cargo, vehicle/ground systems, vehicle/mission systems, vehicle/ISS
- Final analysis plan/V&V approach for analyses of shielding
- Final analysis plan/V&V approach for installing radiation area monitor
- Specifications for vehicle construction and shielding
  - Final analysis results
  - Input data and calculations used in shielding analysis
  - Final mitigation plan
- Methods for mounting dosimeters to a minimum of 6 locations in vehicle
  - Final load assessment

NASA or developer technical products:

- Updates to integrated set of models used to perform analysis of vehicle design

System Integration Review (SIR) (if scheduled)

NASA technical products:

- Updates to previous documentation, as available
- Changes to radiation instrumentation specifications, as available

Suggested developer technical products:
- Final ConOps, IRDs.

Test Readiness Review (TRR)

NASA technical products:
- Changes to radiation instrumentation specifications, as available
- Operational constraints for hardware

Suggested developer technical products:
- Specifications and drawings for vehicle
    - Updates to shielding analysis, as available
    - Input data and calculations used in shielding analysis, as available
    - Changes to shielding mitigation plan, as required
    - Testing results
- A minimum of 6 dosimeter mounting locations in vehicle
    - Updates to analyzed maximum loads, as available
    - Testing results

System Acceptance Review (SAR)

NASA technical products:
- Changes to radiation instrumentation specifications, as available
- Operational constraints for hardware

Suggested developer technical products:
- Documentation that vehicle will provide adequate shielding
- Documentation that no fewer than 6 dosimeters will be mounted to vehicle

Operational Readiness Review (ORR)

NASA technical products:
- Preliminary flight plan
- Preliminary flight rules (vehicle specific and ISS/vehicle, Space Environment section)
- Preliminary flight data file procedures
- Preliminary system operations data file procedures
- Final specifications for radiation instrumentation
- Operational constraints for hardware

Suggested developer technical products:
- Specifications for vehicle construction and shielding
    - Final analysis results
    - Input data and calculations used in shielding analysis.
    - Final mitigation plan as required
- Methods for mounting dosimeters to a minimum of 6 locations in vehicle
    - Final assessment of maximum loads

Flight Readiness Review (FRR)

NASA technical products:

- Final flight plan
- Final flight rules (vehicle specific and ISS/vehicle, Space Environment section)
- Current and expected space weather environment
- Projected crew radiation dose
- Final flight data file procedures
- Final system operations data file procedures

Suggested developer technical products:

- Plan to attach and recover radiation area monitors

4.9 FUNCTIONAL VOLUME DESIGN

4.9.1 INTRODUCTION

Functional volume, also referred to as net habitable volume (NHV), is the accessible volume available to crewmembers in which they can perform required mission tasks. The use of a structured iterative design and evaluation process to define, calculate, and preserve functional volume helps to ensure that crewmembers are provided adequate volume within which to perform these tasks and optimally function in their environment. Several methods and processes are used to drive designs and assess the functional volume of systems and vehicles. Although the specific methods may vary, proper assessment requires careful consideration of human operational needs during the mission.Some of the questions to consider are how crewmembers will move or translate from task to task throughout the course of a mission, as well as how multiple crewmembers may perform simultaneous tasks. Functional volume design is thus a core component of a system’s iterative human-centered design process. Additional information on how to ensure that crewmembers have enough room to safely and effectively perform mission tasks can be found in section 8.2.4 of the NASA/SP-2010-3407 Human Integration Design Handbook (HIDH), Internal Size and Shape of Spacecraft.

4.9.1.1 APPLICABLE REQUIREMENTS

The following requirements for functional volume design and evaluation are specified in NASA-STD-3001, Volume 2:

- Volume Allocation [V2 8001]
- Volume for Crewmember Accommodation [V2 8002]
- Volume for Mission Accommodation [V2 8003]
- Volume for Behavioral Health [V2 8004]

Collectively, these requirements specify that the system provide defined and sufficient functional volumes for crew to perform tasks, for the expected number of crewmembers and mission days.

The intent of these requirements is for the system to provide sufficient volume for the crew to work, sleep, eat, ingress, egress, and perform all other necessary tasks safely and effectively.

The purpose of this section is to elaborate on the processes and methodologies used for functional volume design assessments. Additional reference materials on functional volume design are listed in Table 4.9.1.1-1.

TABLE 4.9.1.1-1 REFERENCE MATERIALS FOR FUNCTIONAL VOLUME DESIGN

Document Number	Document Revision	Document Title
JSC 63557	10/2008	Net Habitable Volume Verification Method
NASA-STD-3001	4/2009	NASA Space Flight Human-System Standard Volume 2: Human Factors, Habitability, and Environment Health
NASA/SP-2010-3407	1/2010	Human Integration Design Handbook (HIDH)
ISO 13407	6/1999	International Standard for Human-Centred Design Processes for Interactive Systems
NPR 8705.2B	5/2008	NASA Procedural Requirements for Human-Rating Requirements for Space Systems

NPR 8705.2B, paragraph 2.3.10.1, requires human-in-the-loop (HITL) evaluations for human-system interfaces. NPR-required deliverables at PDR and CDR include summaries of how these evaluations were used to influence system design.

4.9.1.2 FUNCTIONAL VOLUME DEFINITION

Providing adequate and appropriate functional volume in a vehicle or habitat is necessary for ensuring mission success. Historically, mass and volume constraints associated with factors such as vehicle lift capability, structural requirements, environmental support, and other required technical equipment have defined the amount of space left over and allocated to the crew. Redefining the human as a system has allowed vehicles and habitats to be designed to fit the needs of the crew rather than forcing the crew to fit the design. To protect against the mass and volume of various systems encroaching into the mass and volume needed by the crew, it is important to consider the functional volume required by the crew from the earliest phases in the spacecraft design life cycle.

HIDH describes 3 spacecraft volumes that the vehicle designer must consider:

- **Pressurized volume** – the total volume within the pressure shell.
- **Habitable volume** – the volume remaining within the pressurized volume after accounting for all installed hardware and systems (sometimes known as “sand volume”).
- **Net habitable volume (NHV)** – the functional volume made available to the crew after accounting for the loss of volume due to deployed equipment, stowage, trash, and any other structural inefficiencies and gaps or unusable volume that decrease the functional volume. Items such as the crewmember’s body volume or temporarily deployed equipment required for a task are not considered a deduction to NHV.

Any space vehicle design will have a certain number of cavities and voids, which are deducted from the overall habitable volume. JSC-63557, Net Habitable Volume Verification Method, defines cavities as “regions extending off the main volume that are too small or poorly shaped to count as habitable.” Voids, on the other hand, are defined as “empty volumes completely separated from the habitable volume” (NASA, 2008a). An example of a void might be a volume behind a bulkhead or wall that is totally inaccessible by the crew. The following lists provide some additional guidance for determining the habitability of a given volume.

A volume is considered habitable if

- A human body can be placed completely inside it
- It consists of cavities that are touching or connected to the vehicle’s main volume and are nominally accessible
- A human body cannot completely fit inside the volume (e.g., it is too small), but a human limb can be placed in that volume while the rest of the body is contained within a contiguous, adjacent volume

*A volume is **not** considered habitable if*

- It is unreasonable for a crewmember to nominally place a body part inside a volume produced by cavities between stowage, equipment, etc., during the execution of a nominal task
- It is taken up by physical systems or hardware (e.g., seats, structure, electrical or electronic systems, hygiene systems, waste management systems)
- It consists of voids
- It is within stowage volumes
- It is inaccessible inside a gravity field (e.g., lunar gravity)

4.9.2 FUNCTIONAL VOLUME DESIGN PROCESS

4.9.2.1 HUMAN-CENTERED DESIGN APPROACH

A human-centered design (HCD) process supports development of an effective, efficient, productive, and safe design by linking task, crew, and design requirements. Consistent with core HCD philosophy, the consideration of functional volume should be done from the very earliest stages of the design life cycle. As the design matures, functional volume assessments should be performed iteratively to drive design decisions, understand changes to crew functional volume, and compare design volumes with task-required volumes. Performing assessments throughout the design process ensures that required functional volumes are preserved. Further information on HCD can be found in HIDP section 3.2.

The HCD approach to functional volume design includes both computer-aided design (CAD) modeling and testing with physical mockups. CAD modeling is used to define volumes, visualize concepts, investigate volume with crewmembers of a range of anthropometric sizes, and evaluate body positions within static physical volumes (also see paragraph 4.5.2 Anthropometry). Physical testing, in mockups of increasing fidelity, allows designers to conduct HITL evaluations involving dynamic tasks, translations, and coordination between crewmembers. HITL evaluations are critical for providing information on how volumes affect crew task efficiency, effectiveness, and satisfaction. CAD analyses and HITL evaluations each provide important information about the sufficiency of functional volume; thus both of them should be performed iteratively as the design matures. This approach can save time and money by catching potential volumetric issues early in the design cycle.

4.9.2.2 TASK ANALYSIS, MODELING, AND EVALUATION

The functional volume design process begins with understanding the vehicle and mission. This includes understanding mission requirements (objectives and associated crew tasks, duration, crew size, location, and so on), overall vehicle or habitat configuration, interior module design, and facility design (e.g., windows, hygiene area). Information can be obtained from requirements, design reference mission documentation, and concept of operations. Existing and historic systems can provide information on how similar missions were accomplished in the past and the lessons learned from those missions. More information about the architecture analysis process and development of the vehicle configuration and mission requirements can be found in the HIDH section 8.2.5, Module Layout and Arrangement.

Throughout the vehicle design process, 3 major activities are involved in designing for and assessing functional volume design:

- **Task analysis**: Define the tasks that crewmembers will perform, both nominally and off-nominally, and the context in which they will perform them (mission phase, vehicle configuration, time constraints, number of crewmembers, and so on)
- **Modeling**: Use CAD models to represent and assess static crew body positions for the various tasks identified in the task analysis. Modeling should be driven by anthropometric and biomechanical requirements.
- **HITL evaluation**: Use physical mockups with crew subjects to simulate tasks and evaluate provided volume under mission-like circumstances (as per NPR 8705.2B paragraph 2.3.10).

Task analyses, modeling, and HITL evaluations each provide unique information about the tasks that crewmembers need to perform, potential postures for crewmembers of a range of anthropometric sizes, and acceptable volume for dynamic tasks and translations. Each component of the functional volume process also informs the others. For example, tasks and scenarios identified in a task analysis may be modeled using CAD software to provide guidance on how much volume is needed per task, which may then be validated with crew subjects in a HITL evaluation, or vice versa. Thus, it is crucial that all 3 components—task analysis, modeling, and HITL evaluations—be used throughout the functional volume design and analysis process. More detailed information about each is provided below.

4.9.2.2.1 TASK ANALYSIS

Task analysis is used to produce a list of tasks that crewmembers will need to perform and the relevant information about those tasks, such as mission phase, vehicle configuration, task criticality, time for tasks, concurrent tasks, crew interfaces, and crew clothing. Section 4.1 User Task Analysis provides information about the general task analysis process. For functional volume design, these tasks are examined to determine which of them are expected to have the greatest effects on required volume. It is important to consider mission phase and interior vehicle configuration, as these will affect the volume available to the crew. For example, some tasks may require rearrangement of hardware (such as seats) or stowage; other tasks may require keep-out zones because of privacy, contamination, or safety issues. When critical tasks need to be performed in a short time, faster task performance may take priority over vehicle rearrangement for additional volume.

To illustrate the selection of volume-driving scenarios, consider an event involving 4 crewmembers who need to don suits in a short period of time. The amount of volume required for this activity will likely be more than that needed for a single crewmember to don a suit. A task analysis may help determine whether all crewmembers will need to don suits at the same time or if they can assist one another, determine the expected configuration of the vehicle interior (including interfaces used to accomplish the task), and determine whether enough time is available to relocate stowage to provide more volume. The task analysis is used to identify the task that requires the greatest amount of volume (e.g., 4 suits donned at the same time) and the context of that task, so that appropriate volume is allocated for it and all related tasks that require less volume. At other times multiple crewmembers may be performing concurrent smaller tasks, such as reviewing procedures, preparing food, and performing hygiene activities. The volume allocated for these tasks would need to be considered all at once because the volume required for one activity (e.g., hygiene) may limit the amount available for another activity (e.g., food preparation). Additionally, crewmembers may need to be given functional volume that allows them to translate between the areas where these tasks occur.

Several scenarios have proved to be volume-driving for NASA vehicles. These include, but are not limited to, the following:

- Suit donning and doffing
- Cabin reconfiguration
- Separating meal and hygiene areas
- Vehicle ingress and egress
- Exercise operations
- Medical event operations

Section 2.5 of JSC 63557 provides additional information on how to determine volume-driving tasks.

4.9.2.2.2 MODELING

After the volume-driving tasks have been identified, CAD modeling can be used to assess the amount of available volume, given current or proposed designs, and the bounding volume required for these tasks across a range of anthropometric sizes. Determining net habitable volume is not as simple as subtracting the volume of components in the vehicle from the full volume of the vehicle. First, simple solids (spheres, cones, cylinders) are used to represent and calculate, by summing all these solids, the gross amount of volume available (Figure 4.9.2.2.2-1). Using Boolean or equivalent operations, the model is refined to remove nonfunctional volumes that intersect or are completely enclosed within the full volume. This includes removing volumes taken up by mechanical, electric, or life-support systems, architectural components such as struts, hardware such as seats and display units, stowage, and volumes that are too small to be considered habitable. Several models may need to be developed to account for various vehicle interior configurations or competing design concepts. The final model should represent the overall available volume in an accurate shape (not just the volume of a simple solid or rectangular prism). Additional information on how to calculate functional volume, using cubic feet or meters, can be found in JSC 63557 Appendix A.1.

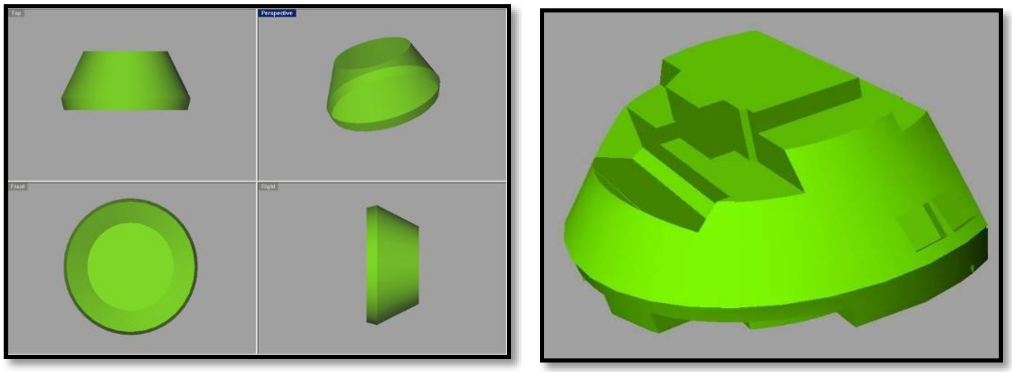


FIGURE 4.9.2.2.2-1 INITIAL CAD MODELING OF NHV

The image on the left shows the first step of defining the simple solids. The image on the right shows a compilation of many simple solids, used to create an Orion model.

Models of the human body within the overall available volume can be used to generate functional volume needs for each workstation and associated tasks. Modeling the human body should be based on the anthropometric dimensions, range of motion, and body volume (Figure 4.9.2.2.2-2). Bodies can be modeled so that they assume expected positions for accomplishing the task, as determined by historic systems or HITL evaluations. For example in determining ways that 2 crewmembers could fit into a volume designed for radiation shielding, several possible configurations for 2 large male crewmembers may be explored (e.g., back to back, both sitting with legs crossed, or one laying and one sitting). The amount of required functional volume can be estimated again by using simple solids to represent and calculate the minimum amount of volume needed for the task. This modeling can be used to further develop HITL scenarios or suggest design changes to hardware.

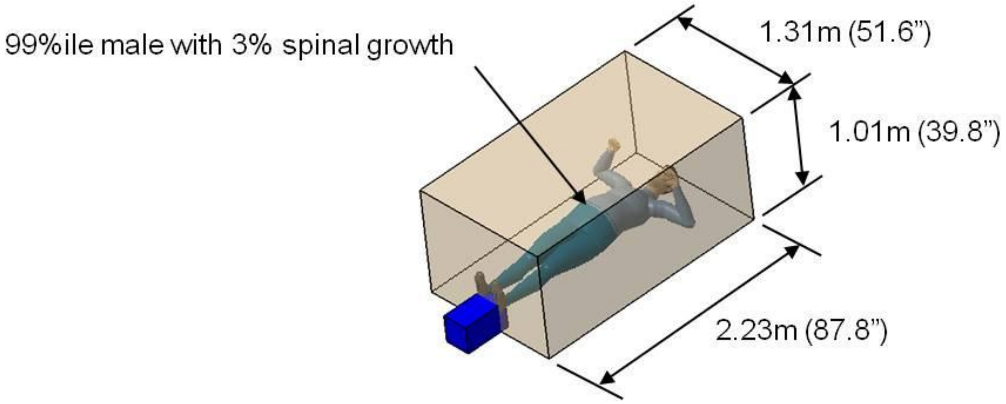


FIGURE 4.9.2.2.2-2 HYPOTHETICAL CAD MODEL OF TASK VOLUME NEEDED BASED ON ANTHROPOMETRY AND RANGE OF MOTION REQUIREMENTS

When modeling the functional volume of related or simultaneous tasks, it is important to note that these volumes cannot be simply added together to yield a total functional volume, as it is expected that a volume might be shared among several workstations.

CAD modeling is also useful for analyzing volumes required for tasks that are difficult to perform in 1*g*, such as docked operations. Task analysis and HITL evaluations can be used to drive the scenarios, but the posture and accommodation will have to be analyzed using a model.

Another benefit of modeling is that it allows frequent analysis. Often small design changes can be checked for feasibility using modeling, much faster and cheaper than performing a HITL evaluation. A HITL evaluation should still be performed in conjunction with the modeling, but may need to be postponed until several design changes are complete and mockup upgrades have been made.

Although CAD modeling provides critical information about the available versus needed functional volume for various vehicle configurations and body positions, CAD does have some limitations, which HITL evaluations can make up for. CAD analysis may not be able to capture the adaptability and flexibility of the human body to attain various postures and orientations. In a HITL evaluation, crew subjects may come up with alternative body positions and orientations not anticipated by biomechanics engineers, designers, or CAD developers, to accomplish a given task. Additionally, HITL evaluations may reveal comfort levels, pain, or fatigue associated with various body positions or orientations and how these positions and orientations are related to the ability to accomplish the task effectively and efficiently. Results of HITL evaluations may be integrated into the next iterative phase of CAD modeling by introducing new possible body or hardware placements or eliminating ones that are unacceptable.

CAD modeling should be used after a HITL evaluation to capture the postures and motions used by the HITL test subjects, so that assessment of the task across the anthropometric distribution can be performed. This assessment has a 2-fold purpose: (1) to provide evidence that the required range of crew sizes is accommodated, not just the sizes of the subjects in the HITL evaluation, and (2) to integrate and measure volume from the physical mockup into the CAD model. Take, for example, a hypothetical capsule designed to seat 2 crewmembers. The capsule program may require that the capsule be able to seat, side by side, 2 fully suited men with 99th-percentile bideltoid breadth. A HITL evaluation is performed using 2 men, one with an 84th-percentile bideltoid breadth and another with a 90th-percentile bideltoid breadth, and both subjects are able to accomplish all expected mission tasks within the volume provided. An analysis could then be performed with CAD modeling in which 2 men with 99th-percentile bideltoid breadth and a set of other critical dimensions are modeled in the seats through the volume-driving tasks to confirm that the HITL findings extrapolate to the expected anthropometric distribution.

4.9.2.2.3 HUMAN-IN-THE-LOOP EVALUATIONS

Task analysis and CAD modeling can both be used to develop HITL evaluation scenarios and parameters, which are used to judge the acceptability and adequacy of the provided volume for a task. HITL evaluations involve having human subjects perform the identified volume-driving tasks in a representative mockup. HITL evaluations with low- and medium-fidelity mockups are discussed below. High-fidelity testing would take place in a qualification or flight vehicle.

4.9.2.2.3.1 CAD MODELING AND HITL WITH LOW-FIDELITY MOCKUPS

To help validate and refine CAD analysis, a physical mockup should be constructed to evaluate movements, dynamic tasks, translations, and coordination between crewmembers during HITL evaluations. A low-fidelity mockup can be constructed from simple materials such as wood or foam-core, with printed faceplates, volumetrically representing all the subsystems (see Figure 4.9.2.2.3.1-1). This will aid the test subjects in visualizing the volume and interacting with the required hardware while acting out the task. Data should be collected on obstructions to the task, major reconfigurations, whether the hardware is configured to support task flow, whether the subjects have the required volume to perform the task, whether that volume is sufficient to successfully accomplish the task, and anything else identified as relevant.

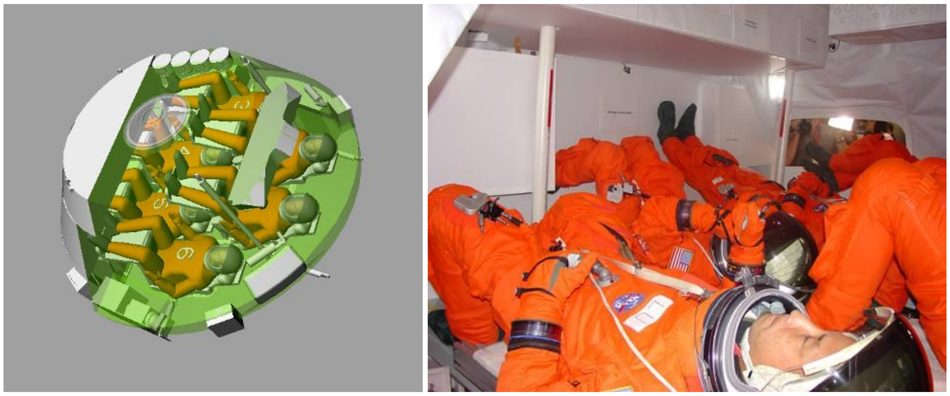


FIGURE 4.9.2.2.3.1-1 CAD MODELING AND LOW-FIDELITY MOCKUP EVALUATION

The image on the left is a CAD representation of the Orion Crew Exploration Vehicle (CEV). The image on the right is the low-fidelity physical mockup of the CAD model with human participants (Kallay et al., 2006).

This type of physical mockup is key to determining which human task(s) absorb the largest amount of habitable volume and which vehicle configuration best supports successful completion of the volume-driving tasks. Simulating the tasks in a physical mockup can also help in defining the driving tasks that require simultaneous operations and/or choreography among all or some crewmembers.

To assess the adequacy of the functional volume during a HITL evaluation, an evaluator (i.e., test conductor) should plan to collect the following data:

- Real-time measurements: Real-time measurements may be collected on range of motion, joint angles, anthropometry, distance from the body to a surface, clearances, and so on to document the available volume as well as feed future CAD models
- Interferences: The evaluator should document when a subject bumps or hits an interface, when a protrusion interferes with the task, when fit is not adequate, and anything related to the subjects’ ability to successfully accomplish the tasks.
- Subjective measures: Subjective measures such as acceptability, fatigue, and workload should be collected during or after a task. Subjective feedback from the subject is important in making design decisions and identifying areas for improvement.

Comments: Subject comments during and after a task should be documented to better understand the operations of the task and subject requirements, such as effort, avoiding obstacles, and choreography.

4.9.2.2.3.2 CAD MODELING AND HITL WITH MEDIUM-FIDELITY MOCKUPS

Leveraging the data and lessons learned from HITL testing using a low-fidelity mockup, designers should integrate any redesign decisions into the project’s CAD models. Once the CAD models are updated, the design can be tested again in a medium-fidelity mockup. The medium-fidelity mockup should represent the baseline functional vehicle, and may contain some limited functionality in the human interaction components. Incorporation of subsystem prototypes is encouraged. A functional mockup that is as realistic as possible will aid the test subject in providing quality data. The subject will be able to effectively simulate hardware interactions, obstacles, necessary volume, timeline, and so on. The designers and test subjects are shown how hardware use may affect the interior habitable volume and drive crew interactions.

Factors that increase task and mockup fidelity include but are not limited to the following:

- Hardware: Inclusion of hardware with as high a fidelity as possible increases the realism and allows the identification of representative issues. Also, having hardware present that was not available during previous HITL testing is important. For example, incorporation of increasingly higher fidelity suits into the suit-doffing task increases the quality of data such as time on task, difficulty, obstructions, and acceptability.

- Environmental Conditions: Simulating the task under the anticipated environmental conditions (e.g., noise levels) will provide realism and increase the potential for identifying NHV-related issues.
- Timeline: Performing a simulated mission in which subjects spend their days and nights working a simulated mission timeline, including activities such as exercising, sleep, and meal preparation, may reward the design team with higher quality volumetric data than previous mockups or CAD modeling. Behavioral assessments of how the crew perceives the volume while working and living in the vehicle, under a representative timeline, can focus the task analysis, human performance, and movement within the vehicle mockup. This type of testing is usually rare, but definitely beneficial.

As mission tasks and crew expectations are refined, design or volume changes are made, and the design cycles advance, it is important to repeat the steps in this process—task analysis, CAD modeling, and HITL testing—to ensure that adequate functional volume is provided to perform all identified tasks. Functional volume design is a key component of the system design life cycle.

4.9.3 DESIGN DRIVERS

When the functional volumes of space environments are being evaluated, several unique design drivers should be taken into account. These drivers may be associated with the number of crewmembers, the number of mission and contingency days; the crewmembers' behavioral health, body dimensions, postural factors, and movement capabilities; gravity; environmental factors; and tasks associated with both nominal and off-nominal (e.g., emergency) operations. Table 4.9.3-1 provides some specific examples of these unique design drivers.

TABLE 4.9.3-1 UNIQUE SPACECRAFT ARCHITECTURAL DRIVERS

Drivers	Description
The gravity environment	Crews in 0*g* are not constrained in any one orientation and they have the ability to move about freely in 3-dimensional space.
Mission objectives	The mission objectives are all affected by the reference mission, crew size, duration of mission, and the operational gravity environment of the crew and vehicle.
Size and number of crew	The design will have to accommodate the maximum number of expected crew, the range of physical dimensions, and the range of motions. Crew interaction during planned mission tasks should be addressed, so that infringement on another crewmember's volume is avoided to the best extent possible.
Limitations of mass and volume	The internal volume must ensure the safety, efficiency, and effectiveness of the crew to perform the functions necessary for a successful mission.

Mission duration	As the duration of a mission increases, so does the physical volume required to accommodate the personal needs of the crew and the mission tasks. Long-duration missions can affect the crews' behavioral health, due to the confinement, stress, and isolation. The psychological needs of a long-duration mission may drive additional space and privacy requirements.

4.9.3.1 MEDICAL CAPABILITIES

An example spacecraft design driver includes design for medical capabilities. The vehicle design needs to accommodate operations associated with use of the medical kit and use of NASA-specified HMS hardware for specific medical conditions. NASA identifies space medical conditions and prioritizes each by likeliness to occur and treatability in NASA/TP-2010-216118 Space Medicine Exploration Medical (ExM) Condition List. Diagnosis and treatment procedures associated with each condition are described in JSC 65973 Medical Conditions Concept of Operations.

Design to accommodate the volume required for medical tasks involves the same iterative 3-step process described above: task analysis, CAD modeling, and HITL evaluations. The difference is the incorporation of government-furnished equipment (GFE) and procedures for diagnosis and treatment. Design solutions to accommodate crew tasks for addressing medical conditions involves incorporating considerations for the medical treatment area, patient and caregiver area and volume, and needed equipment and resources (e.g., oxygen, power). For example, diagnosis of most conditions calls for measurement of crewmember vital signs including temperature, blood pressure, pulse, respiratory rate, oxygen saturation, and auscultation along with verbal intake of medical history and symptoms. To supplement the content below, refer to NASA/SP-2010-3407 Human Integration Design Handbook (HIDH) section 7.6 Medical for additional information on the design and layout of a medical area in a spacecraft, including the overall size, medical interfaces, and stowage.

Identifying the area(s) of the vehicle where medical care will be provided is one of the first steps in accommodating functional volume for the medical system. When designing functional volume for patient and caregiver, ensure that task analysis has considered the number of crewmembers involved, the equipment needed including interface location and size constraints, and any nonmedical (e.g., vehicle system operations) tasks that may be occurring in adjacent or overlapping volumes or areas. The medical care area needs to have adequate volume and surface area to provide care to a patient and allow access for the medical care provider and medical equipment.

For in-flight medical diagnosis and treatment, restraint of the patient is needed to prevent motion of the patient's arms and legs, and allow stabilization of the crewmember's head, neck, and spine in a fully supine position from hips to head. In addition, the capability to restrain the caregiver and medical equipment needed for diagnosis and treatment is to be provided. The medical restraints design should consider multiple and/or moveable restraints so that equipment can be positioned where it is needed or so the caregiver can access or move around the patient from any side. Furthermore, electrical isolation capability may be built into the patient restraint system for treatment involving advanced life support (ALS) procedures.

The vehicle needs to accommodate NASA-defined medical hardware and procedures in locations that are easily accessible to the medical care area or point of use. All required vehicle medical resources (e.g., power, data, potable water, pressurized oxygen), specified in JSC 65973 Medical Conditions Concept of Operations document (according to medical condition), should be easily accessible within the medical care area. NASA will provide NASA medical hardware specifications upon request.

Design activities for medical equipment stowage and accessibility should be performed in conjunction with design of overall stowage needs (food, crew equipment) and stowage restraint.

4.9.4 EXAMPLES FROM NASA PROGRAMS AND PROJECTS

Several specific examples exist of how NASA projects have addressed functional volume design, and they are given in the following paragraphs. These include examples from the Orion project and the Lunar Surface Systems project of the Constellation Program. These examples describe how specific projects chose to pursue iterative functional volume design at different design phases and are an excellent demonstration of how CAD and HITL testing concepts are integrated into their respective engineering life cycles. These examples are provided as guides, and by no means imply that these are the only ways to execute the process. There is a great deal of flexibility in how functional volume design can be performed, and developers are encouraged to be innovative while taking advantage of the lessons learned at NASA over the course of many programs and projects.

4.9.4.1 THE ORION PROJECT

DAC1

Orion’s design process is divided into cycles, called design and analysis cycles (DACs). The first cycle, DAC1, began the 3-step NHV process of task analysis, CAD modeling, and HITL evaluations for the vehicle. The task analysis sessions in DAC1 were initialized using the current DRM and ConOps, and were organized according to hardware needs. For example, one task analysis session would be devoted to assessing the operational needs and tasks associated with the food warmer, and another session would be devoted to assessing the tasks associated with the hatch. The assumptions and critical driving tasks were identified for all crew systems’ hardware, and some associated hardware such as hatches (structures) that the crew is required to interact with for a successful mission.

The DAC1 task analysis identified several volume-driving tasks:

- Nominal ingress
- Post-insertion operations
- Post-sleep operations

- Rendezvous and docking
- EVA preparation and contingency EVA

The identified driving scenarios were further developed in CAD, to identify the volume needs based on the anthropometry and range-of-motion data provided in the requirements tables (of the HSIR). The CAD model was used to represent performing these tasks to identify any design or volume issues. Figure 4.9.4.1-1 shows a CAD model of 4 crewmembers performing post-insertion cabin reconfiguration tasks. Additionally, CAD modeling was used to assess the amount of NHV in cubic feet/meters, to determine how much NHV Orion was providing relative to the NHV requirement. Note, at that time the requirement for NHV was quantified in cubic feet/meters. The Lockheed Martin and NASA teams each performed a CAD analysis measuring NHV, and then compared their measurements to check whether cubic feet/meters was a valid way of measuring NHV. Formal HITL evaluations were not conducted in DAC1, as a need for further analytical work was identified before mockups were to be built.

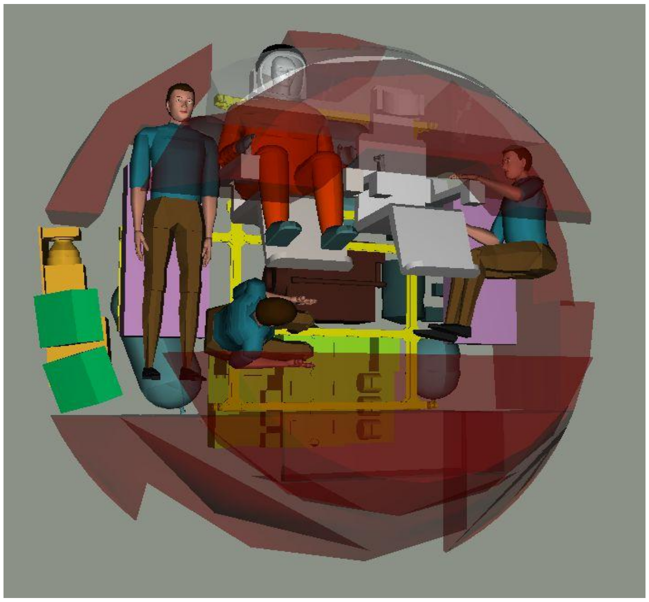


FIGURE 4.9.4.1-1 CAD MODEL SIMULATING 4 CREWMEMBERS PERFORMING POST-INSERTION CABIN RECONFIGURATION TASKS

DAC2

The task analysis sessions in DAC2 were similar to those in DAC1 in that they were hardware based, but they expanded on the information gathered, the knowledge gained, and the design changes made during DAC1. CAD modeling was used to ensure that the recommended design changes from DAC1 did not impinge on the NHV allocated for volume-driving tasks, and to provide an updated model to feed HITL mockup refinements. DAC2 HITL evaluations resulted in important design changes intended to increase crew operability.

The DAC2 task analysis identified several additional volume-driving tasks to be evaluated in CAD and HITL evaluations. For example, increased knowledge about the operations associated with the exercise device, such as an outstretched elbow motion, added the exercise task as a potential volume driver.

- DAC1 list:
    - Nominal ingress
    - Post-insertion operations
    - Post-sleep operations
    - Rendezvous and docking
    - EVA preparation and contingency EVA (suit donning and doffing)
- DAC2 additions:
    - Exercise
    - Suit donning and doffing for ISS and lunar missions

The increased fidelity of the CAD modeling in DAC2 (Figure 4.9.4.1-2) increased confidence in the results of the simulation, increased the probability of identifying obstructions to the task, and helped scope the protocol for the HITL testing.

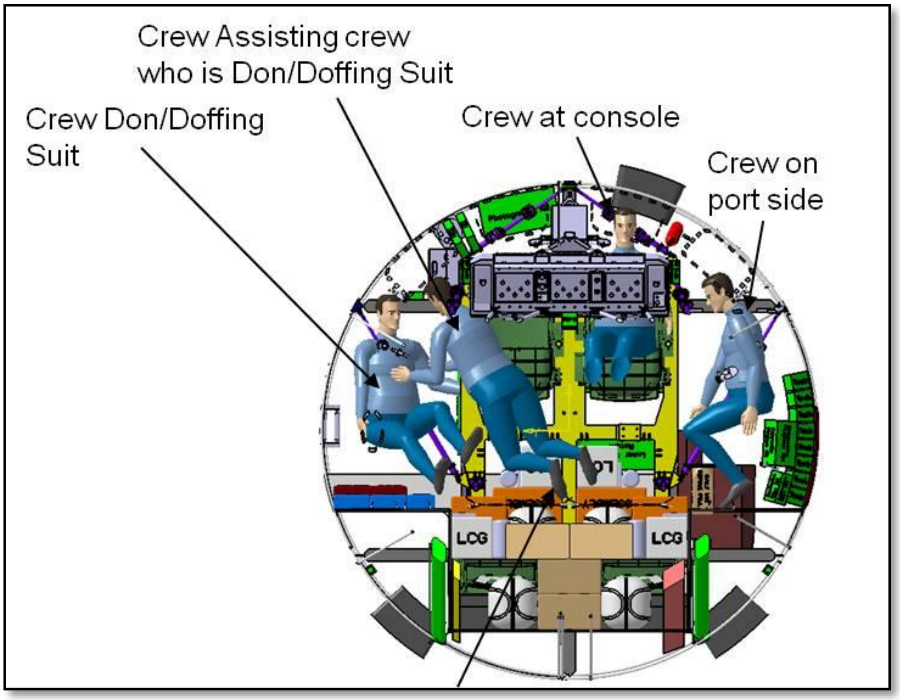


FIGURE 4.9.4.1-2 DAC2 CAD MODEL SIMULATING 4 CREWMEMBERS PERFORMING THE VOLUME-DRIVING TASK OF SUIT DONNING AND DOFFING

An NHV HITL evaluation was performed during DAC2 to examine performing the NHV volume-driving tasks within the CEV Crew Module low-fidelity mockup. The objectives of the test were to

- Identify NHV impacts of volume-intensive tasks in the baseline configuration
- Review system and subsystem concepts with scripts generated to best approximate context and fidelity within the mockup
- Determine the value of HITL as part of a verification process

- Identify activities that could not be performed in the mockup, for future evaluations in higher fidelity mockups or microgravity environments, and future watch items

The caveats were that this testing was being performed early in the design cycle, the data were not to be used to update any requirements, no crew performance/time measures were taken at this level of fidelity, and the full anthropometric range was not represented. Within the CEV mockup, subjects enacted scripted scenarios with volumetric representations of suits, seat stowage, and other crew cabin equipment, performing tasks to the level of available fidelity. The tasks included these:

- Post-insertion cabin configuration (crew of 6)
    - Crewmembers performing in-space stowage of seats and suits, setup and use of Waste Management System (WMS), and access to stowed items.
- Group meet and eat, galley food preparation (crew of 6)
- Medical event with use of medical seat (crew of 6)
- Exercise activity (crew of 4)
- Radiation event – no activity, discussion only (crew of 4)
- Suit donning
- Suit doffing
- Vehicle ingress
- Vehicle egress

The evaluators collected video, audio, still images, real-time human engineering observations, real-time subject comments, and comments on a post-evaluation questionnaire. The main findings of the evaluation were these:

- Pallet interference with WMS operations
- Potential strut interference in area of food preparation activity
- Strut interference with window viewing (of Earth, vehicle photo opportunities) and armrests
- Display console view not available unless floating into that space
- Display console keypad protrusion consistently bumped
- HITL evaluation of tasks can be used as both a validation of CAD analysis and as an independent method to demonstrate that volume-driving crew tasks can be performed in the available NHV.

The design issues identified in this evaluation resulted in changes to the pallet to reduce interference with WMS operations and relocation of the struts to prevent interferences. The other displays and controls related issues were unavoidable at this time because of other design constraints. As a result of these evaluations, additional recommendations on cabin stowage and space management were recorded and applied to ConOps, specifications, and later to mission planning.

The CAD and HITL activities of DAC2 shifted the focus of the NHV requirement from a cubic feet/meters-based verification to include a task-based verification. The HITL evaluations highlighted that the NHV measurement should not only meet a number, but also constitute a volume that is usable space for all the NHV-driving tasks the crew must perform. The creation of JSC 63557 established a dual-phased verification method, with phase 1 including calculation of the vehicle's NHV (CAD model volume measurement and mockup physical measurement) and phase 2 including verification that NHV is usable space through task analysis and demonstration. Phase 2 should include CAD model analyses of tasks difficult to perform in 1*g* and allow more frequent analysis as well as task analysis and task demonstration performed by human subjects in a physical mockup.

DAC3

DAC3 task analysis and CAD modeling followed the same process as DAC2 by expanding the knowledge base and incorporating design changes. An Orion DAC3 NHV evaluation was conducted to evaluate the NHV with a crew of 4 for ISS and lunar missions and identify NHV impacts of volume-intensive tasks in the baseline configuration. The evaluation took place in an updated CEV low-fidelity mockup, simulating hardware to the current configuration. The evaluation focused on specific suited and unsuited volume-driving tasks, acted out by the subjects to exercise the volume configuration. The volume-driving tasks included these:

- Suit doffing and stowage
- Contingency suit donning
- On-orbit stowage including umbilical stowed layout
- WMS and hygiene tasks
- Sleep layout
- Exercise operations
- Medical event operations
- Radiation shelter setup and inhabitance

Vehicle ingress and egress were evaluated during DAC3 in a separate evaluation, not as part of the NHV assessment. Also, rendezvous and docking was removed from the list of volume-driving tasks. It was determined that the tasks in the list above were larger volume drivers than ingress/egress and rendezvous/docking.

The CEV low-fidelity mockup was complemented with volumetric mockups to represent suits, seats, suit stowage bags, and emergency medical kits. Every attempt was made to acquire the highest fidelity possible. These items were used to facilitate discussion of potential volume impacts. Oral and written comments, anthropometric data, and audio and video were collected for analysis.

Overall in the evaluation the volume was deemed adequate to perform the key driving tasks. The changes to the pallet and WMS area from DAC2 led to satisfactory ratings during the DAC3 evaluation. Design changes were identified for

- Stowage restraints
- Seat removal
- Restraints to perform medical procedure on patient
- Radiation shelter, ventilation, lighting, and communication

Work followed the evaluation to mature the detailed component operations and crew procedures, particularly with respect to the EVA suit interfaces and choreography to develop the operational timelines.

The efforts of DAC1-3 highlighted the importance of including HITL evaluation of volume-driving tasks in the design life cycle, and using the results of task analysis, CAD, and HITL evaluations to iterate the design.

4.9.4.2 LUNAR SURFACE SYSTEMS

After task analysis sessions, the Lunar Surface Systems team built a low-fidelity mockup of the Altair Lunar Lander and the Lunar Rover.

The low-fidelity mockup of the Altair was developed with simulated foam-core boxes and representative volume to simulate the identified volume-driving tasks, such as suit donning and meal preparation. The HITL evaluation identified the driving tasks that required “choreography” among crewmembers and helped to refine hardware and configurations affecting the tasks (see Figure 4.9.4.2-1).

FIGURE 4.9.4.2-1 MOCKUP EVALUATION FOR DRIVING TASKS

Using a low-fidelity mockup of the Altair Lunar Lander, both suited and unsuited tasks were tested in the proposed design volume. The image on the left illustrates connecting an umbilical to a mockup spacesuit. The image on the right is the full crew eating dinner in the vehicle’s volume. Note the foam-core boxes, representing all the subsystem hardware, on the walls around the crew (Litaker et al., 2008; Thompson et al., 2010).

The Lunar Rover has gone through 2 different configurations since its inception. Figure 4.9.4.2-2 shows the low-fidelity mockup of the first configuration considered, built based on a CAD model. Human factors engineers conducted an initial NHV HITL evaluation of 16 tasks in this low-fidelity mockup using simple subjective scales, subjects’ comments, field analysis, frequency of movement, reconfiguration patterns and frequencies, and anthropometric analysis, using dynamic tasks that were baselined by the Program. After the analysis of the NHV data, as well as other dynamic data, it was concluded that a new cabin design was needed because of excessive reconfiguration and a change in the vehicle’s center of gravity (CG).

FIGURE 4.9.4.2-2 MOCKUP EVALUATION FOR DYNAMIC TASKS

The first configuration of the Lunar Rover as a low-fidelity mockup. The image on the left is the cabin mockup with investigators collecting NHV data. The image on the right shows test subjects reconfiguring for sleeping (Litaker et al., 2008).

This initial HITL evaluation was able to identify volume limitations during the cabin reconfiguration task, not identified by the CAD model. Taking the knowledge gained about the rover's NHV during the initial HITL test, the designers updated the cabin configuration in the model and then built another mockup. Figure 4.9.4.2-3 shows the low-fidelity mockup used for the NHV testing of the updated design. Human factors investigators asked the test subjects to perform the same 16 tasks used in the initial HITL test to judge the required functional volume.

FIGURE 4.9.4.2-3 MOCKUP EVALUATION OF REDESIGNED CONFIGURATION

The left image was the new redesigned-configuration, low-fidelity mockup that was used for testing the NHV. The image on the right shows test subjects discussing the visibility of the front window with the side displays. The blue-taped box at the far right of the photo represents a side window (Litaker et al., 2008).

The lunar rover's second configuration benefited from iterative NHV analyses and evaluations, which provided the project team an enhanced ability to make an informed decision on how to mature the design and create a medium-fidelity mockup of the second configuration. Figure 4.9.4.2-4 shows the functional Cabin 1A medium-fidelity mockup.

The medium-fidelity mockup has been used in 2 field trials during the Desert Research and Technology Studies (DRATS) at the Black Point Lava Flow in Arizona. During the first field trial in 2008, a crew of 2 worked and lived in the functional mockup for 3 days, interfacing with all the interior and exterior systems. Human factors engineers, along with vehicle design engineers, collected data on the volumetric acceptability of the vehicle, the acceptability of the task accomplished, and the engineering data associated with operating such a prototype vehicle in a real-world simulation (Litaker, Thompson, Howard, Szabo, Conlee, & Twyford, 2008).

FIGURE 4.9.4.2-4 MEDIUM-FIDELITY MOCKUP EVALUATION

The top image shows the medium-fidelity functional rover Cabin 1A during engineering test runs before the 3-day field trial. The bottom left image shows the Cabin 1A cockpit interior with functional system computers and controls. The bottom right image shows Cabin 1A from the perspective of the suitports in the aft section of the vehicle. With the front seats in the down position, the cabin is being configured for crew sleep.

The data gathered during the 3-day test proved to be invaluable to the vehicle designers. Several modifications to the design were made, including adding stowage areas, adding an environment enclosure for the spacesuits, and redesigning the cockpit layout for increased efficiency. Using these HITL lessons learned from the Cabin 1A mockup, another medium-fidelity functional mockup was built with the added modifications (Figure 4.9.4.2-5).

FIGURE 4.9.4.2-5 MEDIUM-FIDELITY MOCKUP ITERATION EVALUATION

The left image is the modified Cabin 1B with suit enclosure and added side hatch. The right image shows the modified Cabin 1B cockpit display arrangement and added overhead stowage.

With the earlier data showing confidence in the vehicle’s NHV, a 14-day simulated mission was planned with Cabin 1B during the 2009 DRATS field trials. Using the same tasks as in the earlier test, but with more mission fidelity added, investigators collected data not only on the vehicle’s volumetric and habitability design configuration but also on how the volume affected the crewmembers’ behavioral health (Figure 4.9.4.2-6). The increased fidelity and representative timeline allows increased confidence in the results of the volumetric assessment, and possibly validation of some functional volume allocations in the vehicle (depending on the phase of the design process). Data of this caliber gives the design team stronger knowledge of the characteristics of the vehicle’s habitable volume, which in turn becomes a valuable asset in updating the design.

FIGURE 4.9.4.2-6 ENHANCED MEDIUM-FIDELITY MOCKUP ITERATION EVALUATION

The image on the left shows a crewmember both using the control stick and interacting with edge keys on the display during a 14-day mission. The image on the right shows both crewmembers during off-working hours. The crewmember in the background is doing exercises while the crewmember in the foreground is having a snack. Both images were made in the Cabin 1B mockup vehicle and show how various dynamic tasks were testing the NHV (Litaker et al., 2010).

For the rover team, the lessons learned from these simulated missions, the quantity and quality of data collected, and the use of multiple mockups of varying fidelity reduced the needed amount of iterative testing considerably. In fact, through this NHV process, the rover design team (at the time of this writing: September, 2010) felt confident about pushing forward to develop a next-generation vehicle to bring the project closer to a pressurized flight-like vehicle with realistic online subsystems. This will allow flight-like vehicle testing of all volumetric parameters of the configuration, and provide interface interaction data that will facilitate finalization of the design as well as evaluation of other factors such as workload and usability.

4.9.5 FUNCTIONAL VOLUME DESIGN TECHNICAL PRODUCTS

For each of the major milestones of the design life cycle, the technical products in Table 4.9.5-1 are recommended for review by the NASA customer.

TABLE 4.9.5-1 FUNCTIONAL VOLUME DESIGN TECHNICAL PRODUCTS

Technical Products	Phase A		Phase B	Phase C	Phase D	
	SRR	SDR	PDR	CDR	SAR	FRR
A description of the ConOps, function allocation, and associated crew task lists. Includes identification of volume-driving tasks and identification of equipment and configurations that will be present in crew work and habitation areas.	I	U	U	U	---	---
A summary of modeling/analysis/evaluation performed to date and their influence on system design with links to the detailed analysis results. Required per NPR 8705.2B, and HITL evaluations required per paragraph 2.3.10. Includes analysis of volume-driving tasks based on CAD and human-in-the-loop.	---	---	I	U	---	---
System architecture drawings (structures, equipment, etc.), material specifications, interface requirements. Includes provision of vehicle CAD for use in analyses.	---	---	I	U	U	---
Verification plan.	---	---	I	U	U	---

X = one-time release of item
I = initial release of item
U = updated release of item

Concept of Operations (ConOps) and Crew Task Lists

The ConOps, described in paragraph 3.2.3.1.2, provides information such as identification of crew activities and determination of which subsystems are influenced by crew activities. Function allocation, described in paragraph 3.2.3.1.3, establishes the extent to which an activity is to be automated or assigned to humans. The crew task list, described in section 4.1 User Task Analysis, documents details including allocation of function between crew and systems, definition of crew activities sequence, and identification of critical tasks. As the crew task list evolves through the design cycle, its final iteration should become crew procedures.

ConOps and crew task list development for functional volume includes the identification of expected volume-driving tasks such as work, sleep, eating, medical care, translation, egress, ingress, pressure-suit donning, and other tasks. In addition, they include the identification of equipment and configurations that will be present in crew work and habitation areas.

Summaries of Modeling, Analyses, and Evaluations

Iterative summaries of modeling, analyses, and evaluations provide NASA with insight into human-system integration technical details throughout the design process. As designs mature, modeling, analyses, and evaluations should use inputs and mockups of increasingly higher fidelity, as discussed in paragraph 3.2.3.3 Evaluate Designs and Iterate Solutions. It is important that summaries address how critical design decisions were assessed. According to NPR 8705.2B, updated summaries are to be provided at each design review through SAR. Also in paragraph 2.3.10, the use of HITL evaluation is a required method to progressively demonstrate that the operational concept meets system requirements for operational safety, efficiency, and user interface design.

For functional volume, analysis of volume-driving tasks should occur in CAD and HITL evaluations, with increasing fidelity of models beginning at SDR and continuing to SAR.

Architecture, Materials, and Interface Specifications

Drawings, materials, and interface specifications provide NASA with insight into human-system integration technical details throughout the design process.

Verification Plan

The verification plan is a formal document describing the specific methodologies to be used to show compliance with each requirement.

4.9.6 REFERENCES

Kallay, A., Harvey, C., Byrne, V., DeSantis, L., Maida, J., Szabo, R., & Whitmore, M. (2006, August). *Crew exploration vehicle (CEV) net habitable volume assessments for 6-crew missions* (NASA TDS CEV-05-002). Houston, TX: Johnson Space Center.

Litaker, H. L., Jr., Howard, R., Ferrer, M., & Young, K. (2008, January). *Lunar rover habitability volume evaluation on configuration one.* Houston, TX: Johnson Space Center. Internal NASA Document.

Litaker, H. L., Jr., Thompson, S., Howard, R., Szabo, R., Baldwin, T., Conlee, C., Twyford, E., Nguyen, A., & Ward, M. (2008, February). *Suited and unsuited habitable volume evaluation for Altair lunar lander DAC-2 configuration.* Houston, TX: Johnson Space Center. Internal NASA Document, September 2008.

Litaker, H. L., Jr., Thompson, S., Howard, R., Szabo, R., Conlee, C., & Twyford, E. (2008). *Habitable volume evaluation for the lunar sortie habitat Altair: Configuration one.* NASA/Johnson Space Center. Internal NASA Document.

Litaker, H. L., Thompson, S., Howard, R., Szabo, R., Conlee, C., & Twyford, E. (2008, December). *Small Pressurized Rover (SPR) three day desert trial: A human factors assessment.* Houston, TX: Johnson Space Center. Internal NASA Document.

Litaker, H. L., Jr., Thompson, S., Howard, R., Szabo, R., Conlee, C., Green, S., & Twyford, E. (2010, February). *A human factors assessment of the Lunar Electric Rover (LER) during a 14-day desert trial.* Houston, TX: Johnson Space Center. Internal NASA Document.

National Aeronautics and Space Administration. (2008a, October). *Net habitable volume verification method* (JSC 63557 Draft, October 30, 2008). Internal NASA Document.

National Aeronautics and Space Administration. (2010a, January 27). *Human integration design handbook (HIDH)* (NASA/SP-2010-3407). Washington, DC: Author.

Thompson, S., Litaker, Jr., H.L., Szabo, R., Howard, R., & North, D. (2010, January). *Evaluation of the Altair lunar lander DAC-3 interior volume configuration.* Houston, TX: Johnson Space Center. Internal NASA Document.

4.10 CREW SURVIVABILITY ASSESSMENT

4.10.1 INTRODUCTION

According to NPR 8705.2B Human-Rating Requirements for Space Systems, one of the key elements to be included in a human-rating certification plan is the system's implementation of crew survival strategies for each phase of the reference mission. For each reference mission it is important to identify potential operational risks and accompanying mitigation strategies to enhance crew survival. The risks should include system failures and emergencies (such as fire, collision, toxic atmosphere, decreasing atmospheric pressure, and medical emergencies) with specific mitigation capabilities (such as abort, safe haven, rescue, emergency egress, emergency systems, and emergency medical equipment or access to emergency medical care) identified to protect the crew. Crew survivability assessment is the process of identifying potential crew survivability methods for all potential catastrophic hazards expected to occur during each phase of the reference mission. This process should be integrated throughout system design and be iteratively performed as missions, operations, and tasks mature.

4.10.2 PROCESS

Reserved

4.10.3 CREW SURVIVABILITY ASSESSMENT TECHNICAL PRODUCTS

For each of the major milestones of the design life cycle, the technical products in Table 4.10.3-1 are suggested for review by the NASA customer.

TABLE 4.10.3-1 CREW SURVIVABILITY TECHNICAL PRODUCTS

Technical Products	Phase A		Phase B	Phase C	Phase D	
	SRR	SDR	PDR	CDR	SAR	FRR
A description of each reference mission for which human rating is being pursued. Required per NPR 8705.2B paragraph 2.3.1.	X	---	---	---	---	---
A description of the ConOps, function allocation, and associated crew task lists.	I	U	U	U	---	---
Establishment of scenarios to be used for hazard analysis and risk assessments.	I	U	---	---	---	---
A description of the design philosophy that will be followed to develop a system that utilizes the crew's capabilities to execute the reference missions, prevent aborts, and prevent catastrophic events. Required per NPR 8705.2B paragraph 2.3.3 Documenting the Design Philosophy for Utilization of the Crew.	X	---	---	---	---	---
A description of the crew survival strategy for all phases of the reference missions and the system capabilities required to execute the strategy. A description of the implementation of the identified survival capabilities. Required per NPR 8705.2B paragraph 2.3.2 Identifying System Capabilities for Crew Survival.	---	I	U	U	U	U
A description of the implementation of the crew survival capabilities and a clear traceability to the highest level of program documentation. Required per NPR 8705.2B paragraph 2.3.4 Incorporating Capabilities into the System Design.	---	I	U	U	---	---
A summary of how the safety analysis activities related to loss of crew were used to understand the relative risks and uncertainties within the design and subsequently influence decisions related to the system design and application of testing. Required per NPR 8705.2B paragraph 2.3.6 Designing to Control Hazards and Reduce Risk.	---	I	U	U	U	---
X = one-time release of item I = initial release of item U = updated release of item						

4.11 METABOLIC LOADS AND ENVIRONMENTAL CONTROL LIFE SUPPORT SYSTEM DESIGN

4.11.1 INTRODUCTION

Crewmembers' metabolic loads are one important contributor to the design and sizing of the spacecraft Environmental Control and Life Support (ECLS) system capacity. An effective ECLS system is critical to provide and maintain cabin atmospheric conditions necessary to ensure the health and performance of the crewmembers. Taking the human-centered approach to spacecraft design will help the designer to achieve required environmental conditions needed to sustain crews and attain human-rating certification.

Although human response to physical and environmental stimuli is individual and variable, NASA has developed data and requirements that reflect the best knowledge to date regarding space flight physiological response. Integrated analysis of crew system metabolic loads in conjunction with other vehicle system loads early in the vehicle design process will ensure that the ECLS system design is adequate to meet the vehicle environmental limits. The NASA-STD-3001 requirements relevant to metabolic loads and ECLS design include the following::

- V2 6003 O2 Partial Pressure Range for Crew Exposure
- V2 6006 Total Pressure Tolerance Range for Crew Exposure
- V2 6010 Relative Humidity
- V2 6011 Suited and Post-Landing Relative Humidity
- V2 6012 Comfort Zone
- V2 6013 Temperature Range
- V2 6014 Crewmember Heat Storage

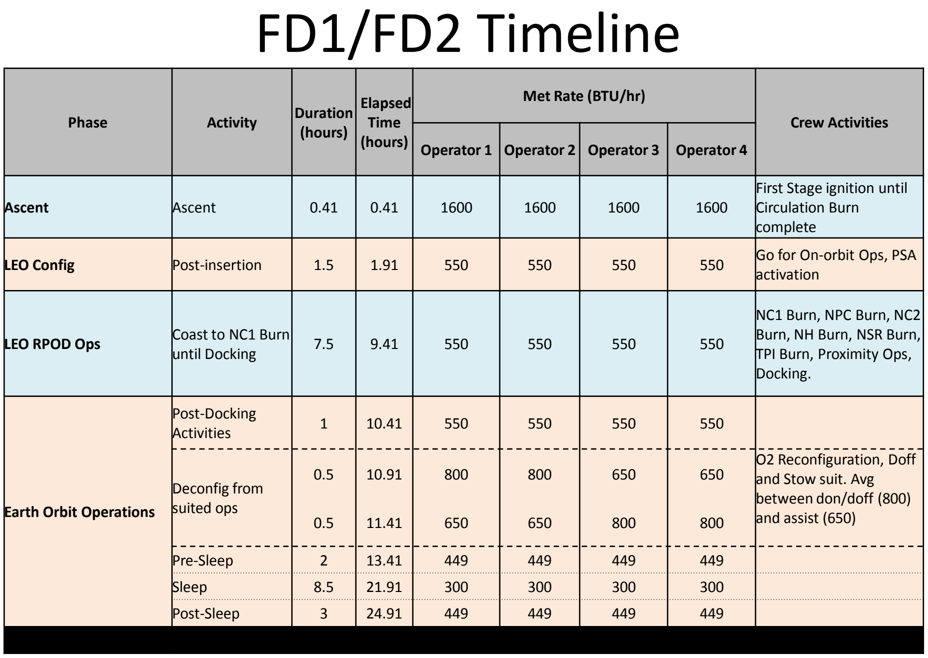
The contributions of metabolic loads are one important aspect of ECLS design that is discussed in this section. The following process describes the "how to," assumptions, critical components, and data that are relevant to the development and utilization of an appropriate representation of crew-induced metabolic loads. Additional discussion can be found in NASA/SP-2010-3407 Human Integration Design Handbook (HIDH) section 6.2.3.1.4 Expected Metabolic Loads.

4.11.2 METABOLIC LOADS DESIGN PROCESS

4.11.2.1 DEVELOP CREW ACTIVITIES LIST AND METABOLIC RATE PROFILES

To maintain required spacecraft internal temperature range, relative humidity, and air composition, crewmember metabolic rate profiles are necessary to quantify the crewmember contributions to total vehicle heat load and metabolic gas exchange during the mission phases. Establishing crew metabolic rate profiles for a given design reference mission should begin with development of the concept of operations and scenarios for nominal, off-nominal, and emergency operations. For each mission phase and relevant scenario, specify and sequence crew roles and activities (see HIDP sections 3.2.3.1.2 Develop Concept of Operations and 4.1 User Task Analysis).

Comprehensive analysis of crew activities in establishing metabolic rate profiles is critical for ensuring that the ECLS system is designed to accommodate nominal and peak transient thermal loads and metabolic byproducts without compromising the cabin environment. Figures 4.11.2.1-1 and 4.11.2.1-2 provide examples for developing metabolic rate profile. Figure 4.11.2.1-1 illustrates the breakdown of metabolic rates for each crewmember by mission phase and activity for a nominal scenario that includes spacesuit doffing. The contributions of each crewmember must be considered, especially if crewmember activities differ significantly during a given mission phase.

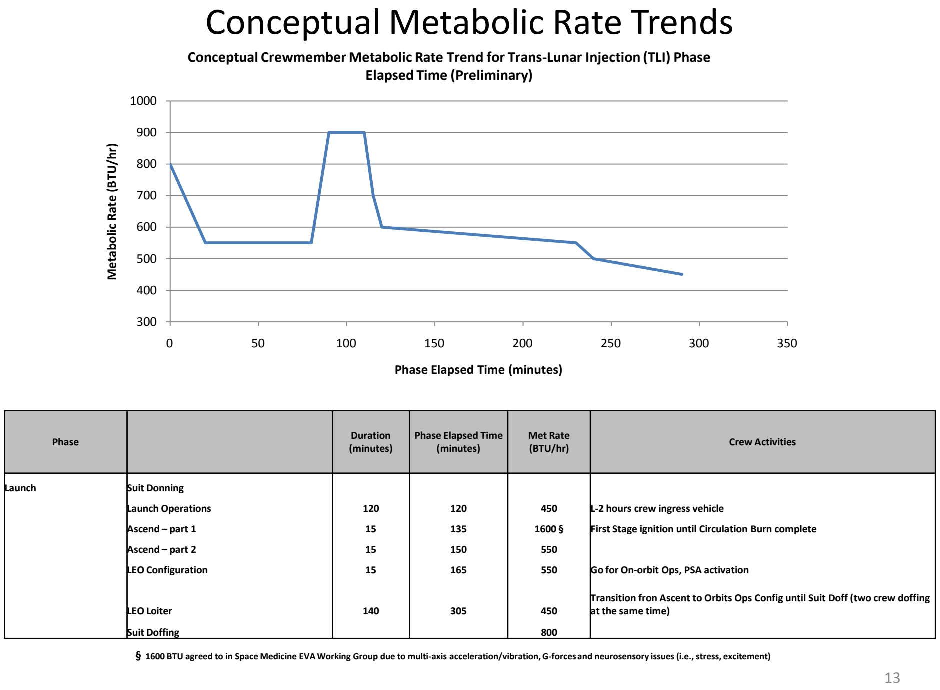


FD1/FD2 Timeline

Phase	Activity	Duration (hours)	Elapsed Time (hours)	Met Rate (BTU/hr)				Crew Activities
				Operator 1	Operator 2	Operator 3	Operator 4	
Ascent	Ascent	0.41	0.41	1600	1600	1600	1600	First Stage ignition until Circulation Burn complete
LEO Config	Post-insertion	1.5	1.91	550	550	550	550	Go for On-orbit Ops, PSA activation
LEO RPOD Ops	Coast to NC1 Burn until Docking	7.5	9.41	550	550	550	550	NC1 Burn, NPC Burn, NC2 Burn, NH Burn, NSR Burn, TPI Burn, Proximity Ops, Docking.
Earth Orbit Operations	Post-Docking Activities	1	10.41	550	550	550	550	
	Deconfig from suited ops	0.5	10.91	800	800	650	650	O2 Reconfiguration, Doff and Stow suit. Avg between don/doff (800) and assist (650)
		0.5	11.41	650	650	800	800	
	Pre-Sleep	2	13.41	449	449	449	449	
	Sleep	8.5	21.91	300	300	300	300	
	Post-Sleep	3	24.91	449	449	449	449	

FIGURE 4.11.2.1-1 EXAMPLE OF MISSION TIMELINE WITH METABOLIC RATES

Metabolic rate timelines will provide the spacecraft developer with a tool to determine the system’s efficiency in managing human metabolic loads early in the design process. The developer must also determine the ability of the system to support peak loads while maintaining the 24-hour and 1-hour limits for atmospheric constituents during the different phases of the mission. For example, ascent and entry phases are expected to induce increased metabolic rates due to vibration, *g*-loads, and excitatory state of the crew. Figure 4.11.2.1-2 illustrates cumulative crew metabolic rate breakdown for launch phase and the use of a time-elapsed chart to show a representative metabolic rate timeline.



Phase		Duration (minutes)	Phase Elapsed Time (minutes)	Met Rate (BTU/hr)	Crew Activities
Launch	Suit Donning				
	Launch Operations	120	120	450	L-2 hours crew ingress vehicle
	Ascend – part 1	15	135	1600 §	First Stage ignition until Circulation Burn complete
	Ascend – part 2	15	150	550	
	LEO Configuration	15	165	550	Go for On-orbit Ops, PSA activation
	LEO Loiter	140	305	450	Transition fron Ascent to Orbits Ops Config until Suit Doff (two crew doffing at the same time)
	Suit Doffing			800	

§ 1600 BTU agreed to in Space Medicine EVA Working Group due to multi-axis acceleration/vibration, G-forces and neurosensory issues (i.e., stress, excitement)

13

FIGURE 4.11.2.1-2 EXAMPLE OF METABOLIC RATE PROFILE

For the Commercial Crew and Multi-Purpose Crew Vehicle Programs, NASA provides metabolic load values for unsuited and suited activities in Appendix tables. Those values are based on a set of environmental conditions and crewmember assumptions, which are detailed in each Appendix. If the spacecraft conditions or crewmember characteristics vary from the assumptions, metabolic loads will differ from values in the tables and should be captured in the metabolic rate profile. For example, if pressurized suits are worn instead of shirtsleeves, insulation and convection properties must be adjusted accordingly.

Where metabolic rate data are not available, the developer should use an evidence-based approach in determining values that accurately represent the crew's physiological response during a particular mission phase. Resources available for this process include published in-flight data, space flight analog data, or applicable ground-based data from NASA laboratories or other aerospace physiology laboratories. NASA can provide assistance with adjusting values for metabolic loads or developing metabolic profiles. Failure to reassess metabolic loads may result in potential shortfalls of the ECLS system, thereby increasing the risk for loss of mission and/or loss of crew.

4.11.2.2 DEVELOP DESIGN SOLUTIONS

4.11.2.2.1 MODEL THERMAL LOADS

Throughout ECLS system design, human thermal response modeling should be performed to assess the interactive effects of the spacecraft cabin environment on the crew. A validated human thermal model must allow variable input for key parameters that include crewmember metabolic rate, crewmember size, cabin gas temperature, cabin gas pressure, wall temperature, dew point, cabin gas free-stream velocity, and gravitational forces. The output of the model must represent the crewmembers' reaction to the environmental cabin conditions and the impact that it will have on the cabin's environment, including CO_2 production, O_2 consumption, and water production. Historically, NASA has used the 41-Node Man or Wissler models as a validated means of ascertaining the human physiological response to flight environments.

By SDR, the developer should identify the validated model that will be used to perform analyses throughout the design process. Input data needed for each model may vary from the Commercial Human-Systems Integration Requirements example. In these cases, NASA will work with the developer to adjust assumptions and metabolic loads data for use as input to the model.

4.11.2.2.2 CABIN ATMOSPHERE QUALITY

Cabin atmosphere quality limits are identified and described in NASA-STD-3001 Volume 2. As mentioned in the preceding paragraph, metabolic loads are affected by these cabin conditions. It is important that these parameters be used as inputs to the thermal models in order for the predicted outputs to be representative of acceptable cabin atmosphere. For cabin atmosphere specifications, refer to the following NASA-STD-3001 requirements:

- V2 6006 Total Pressure Tolerance Ranges for Crew Exposure
- V2 6003 O_2 Partial Pressure Tolerance Ranges for Crew Exposure
- V2 6013 Temperature Range
- V2 6010 Relative Humidity

4.11.2.3 ITERATIVE AND INTEGRATED ANALYSES

Modeling analyses should be performed iteratively, as design concepts and crew activities are defined or modified. NASA insight into developmental analyses can be beneficial for checking assumptions and assessing progress toward meeting cabin atmosphere requirements. By CDR, an integrated analysis should be performed to include other life support hardware and actual metabolic loads.

4.11.3 METABOLIC LOADS DESIGN TECHNICAL PRODUCTS

For each of the major milestones of the design life cycle, the technical products in Table 4.11.3-1 are recommended for review by the NASA customer.

TABLE 4.11.3-1 METABOLIC LOADS DESIGN TECHNICAL PRODUCTS

Technical Products	Phase A		Phase B	Phase C	Phase D	
	SRR	SDR	PDR	CDR	SAR	FRR
A description of the ConOps, function allocation, and associated crew task lists.	I	U	U	U	---	---
Metabolic load timelines/profiles.	---	I	U	U	---	---
A summary of modeling/analysis/evaluation performed to date, including human thermal modeling analyses and integrated metabolic loads analyses, and the influence on system design with links to the detailed analysis results. Required per NPR 8705.2B. The validated metabolic model should be identified by SDR.	---	I	U	U	---	---
Integrated analysis of all subsystems demonstrating design capacity to manage human metabolic loads throughout all mission phases.	---	---	I	U	U	---
Verification plan.	---	---	I	U	U	---

X = one-time release of item
I = initial release of item
U = updated release of item

Concept of Operations and Crew Task Lists

The ConOps, described in paragraph 3.2.3.1.2, provides information such as identification of crew activities and determination of which subsystems are influenced by crew activities. Function allocation, described in paragraph 3.2.3.1.3, establishes the extent to which an activity is to be automated or assigned to humans. The crew task list, described in section 4.1 User Task Analysis, documents details including allocation of function between crew and systems, definition of crew activities sequence, and identification of critical tasks. As the crew task list evolves through the design cycle, its final iteration should become crew procedures.

Summaries of Modeling, Analyses, and Evaluations

Iterative summaries of modeling, analyses, and evaluations provide NASA with insight into human-system integration technical details throughout the design process. As designs mature, modeling, analyses, and evaluations should use inputs and mockups of increasingly higher fidelity, as discussed in paragraph 3.2.3.3 Evaluate Designs and Iterate Solutions. It is important that summaries address how critical design decisions were assessed. According to NPR 8705.2B, updated summaries are to be provided at each design review through SAR.

Architecture, Materials, and Interface Specifications

Drawings, materials, and interface specifications provide NASA with insight into human-system integration technical details throughout the design process.

Verification Plan

The verification plan is a formal document describing the specific methodologies to be used to show compliance with each requirement.

4.12 DISPLAY FORMAT DESIGN

4.12.1 INTRODUCTION

Designing a spacecraft that features a glass cockpit presents many challenges, such as determining appropriate information architecture for limited display real estate; allocating functions to hardware versus software controls; and finding intuitive ways to manage a variety of input devices (e.g., cursor control devices, keypads, edge keys, or other console-based controls). These spacecraft cockpits often involve many unknowns: systems that have never before existed, hardware and software functions that have yet to be defined, and only a very small population of users and experts who have the experience to address design questions. Only rarely does a wealth of tried and true design solutions exist that can be mimicked. The designer is faced with developing software to meet the user's needs, when it is unclear what those needs are and which design solutions are even possible. All of these challenges pose a risk to information availability in the cockpit, which can result in errors and ultimate threats to mission success and crew safety.

Software displays, also referred to as "display formats," provide the primary interface for a crewmember in a glass cockpit to command subsystems and monitor subsystem health and status data. Display formats must provide situational awareness, reduce crew workload, and enhance crew safety by providing readily understood graphical and textual subsystem information in a timely manner. This chapter describes the processes and activities that should be undertaken in the development of display formats and display standards to ensure human rating of vehicles and habitats.

The term "display standards" is used here to mean a set of user-interface specifications and guidelines developed and implemented to ensure a common design framework for all computer interfaces (i.e., all flight and system displays) used by crewmembers. These standards establish a consistent look and feel across all interfaces and specify consistent behaviors across all user-interface components of the same type. The purpose of the standards is to promote ease of learning, crew productivity, and mission safety by supporting a simple and consistent user environment. It is expected that crew transportation companies will develop, modify, and enforce display standards throughout the display development process.

4.12.2 ESTABLISHING A DISPLAY FORMAT DESIGN AND STANDARDS TEAM

Designing usable software systems requires multiple areas of expertise. The display format design team should be a multidisciplinary team, including individuals who (1) have content or domain expertise—e.g., vehicle subsystems experts, (2) have process and design expertise—e.g., human factors specialists, (3) have technical implementation expertise—e.g., software developers, or (4) are users or representative users—ideally crewmembers with space flight experience. It is important that all participants are able to openly offer their ideas and concerns, and that no one team member owns all the decision-making power. The work of the team should be a collaboration in which all team members' viewpoints are valued and respectfully considered. The size of this team is an important consideration. A team that is too small may not have the relevant representation and will not have the breadth of community buy-in of a larger team. A larger team can be difficult to manage and inefficient. Although the display format design team should perform the core display format design work, the process should ensure proper review and participation by other stakeholders as well—e.g., management, vehicle integration groups, safety, training, procedure developers.

The development of display formats involves multiple phases, including definition of the display format layout and behavior, implementation of the formats, and final verification of the formats in flight software. These activities may be performed by the same or different organizations.

4.12.3 DOCUMENTS SUPPORTING THE DISPLAY FORMAT DESIGN EFFORT

The efforts of the display format design team should be supported by the following types of documents:

- Display development process document – a project-specific process document describing activities, including flows and timelines, roles and responsibilities of the various parties, review milestones, and final technical products.
    - Some of the information in this document could be used to create a process document
- Program-level requirements document – requirements to ensure human rating, and safe and productive integration of the human and the system
    - Derived from NASA-STD-3001
- Display format standards document – describes the design standards, templates, software component “look and feel,” colors, fonts, and so on, to promote consistency, ease of learning, and ease of use.
- Display format definition document (“dictionary”) – describes the detailed layout and behavior of each display format.
- Software requirements specification – detailed specifications for developing display formats; may contain the format dictionaries; points to the display standards document.
- Software development plan – describes the method of implementation of the display formats
- Other resources – human factors design guidelines documents, standard templates, icon libraries

4.12.4 HUMAN-CENTERED DESIGN ACTIVITIES FOR DISPLAY FORMAT DESIGN

Working within a design space where there are many unknowns means that iteration, revision, and refocusing are a necessary part of the process. Project goals, functions, designs, and standards may need to be revisited throughout the process as more information becomes available. Thus, special processes, methods, and policies are required when applying human-centered design to software user interfaces in a spacecraft.

Section 3.2 describes the Human-Centered Design process that should be followed in the development of all hardware or software products for human-rated vehicles and habitats. The subsections that follow elaborate this process as applied to display format design.

4.12.4.1 FUNCTIONAL REQUIREMENTS DEFINITION

Given the unique nature of designing display formats for new spacecraft, functional requirements are not likely to be complete at the beginning of a project. Potential users/crew may assist in this definition process, but sometimes they themselves have had no previous experience in using this unique software. Software developers may be unsure about the functionality they will be able to provide through the display formats, as system design often is still immature early in the life cycle. Thus, efforts to define functional requirements must begin early.

Requirements should evolve throughout the design process, particularly once prototypes are built. When crewmembers are able to see the capabilities in a concrete format within a scenario, they can see the potential of the system. They can begin to think of functions that may have been left out or need to be modified. Functional requirements should be allowed to mature throughout design instead of being locked in for implementation too early.

Task analyses should progress throughout the design cycle, and the outcomes should be used to establish requirements for the displays. During requirements development, the focus should be crew needs and understanding the variety of ways in which the system may be used by crewmembers. The development and use of scenarios can be helpful in discussing and defining these requirements.

4.12.4.2 SCENARIO DEVELOPMENT

Scenario development often begins with an operational concept definition. This describes the working environment and typical activities involved in performing the tasks planned for various missions. Scenarios can begin as simple narratives, and evolve to include embedded display designs. Scenarios can be important and useful for designing usability evaluations. At a minimum, scenarios should be developed that address nominal or frequent operations, particularly difficult or troublesome tasks, and expected emergency or contingency situations. Make sure all members of the display format design team review and concur with the scenarios developed, as it is not uncommon for team members working in different domains to have very different ideas about expected scenarios.

4.12.4.2.1 EXAMPLE QUESTIONS TO CONSIDER

With respect to display formats, examples of some challenging questions that might be considered during task analysis, scenario development, and concepts of operation include these:

- What will be accomplished by means of software versus hardware controls?
- How much automation is involved and what role does the crew play?
- Will all display formats be available on each display device?

- Will there be default configurations (i.e., predefined sets of formats) for different tasks?
- How will crewmembers interact with the display formats and how will control of a format be shared, if it is shared?
- Are multiple instances of a display format possible? If so, how will real-time data updates and commands be handled?
- What insight will the crew have into system states and faults?
- How will system cautions and warnings be handled?

4.12.4.2.2 NUMBER AND TYPES OF DISPLAY FORMATS

Once decisions have been made about display device hardware, input devices, and software platform, it is important to scope the display format design effort by determining how many display formats will be needed and which categories of formats will be needed (e.g., summary formats, detailed subsystem formats, electronic procedures). Again, it will be important to first understand basic concepts of operation, i.e., how the crewmembers will work independently or in teams to monitor and command by means of display formats. It is prudent to begin work on a small subset of display formats that provide basic capabilities. Much will be learned from the initial design effort that can be applied to all remaining efforts for greatest efficiency.

4.12.4.3 TASK ANALYSIS

Section 4.1 describes task analysis, and many documented methods are available to accomplish this activity. Task analysis results become critical for interpreting many requirements and for developing procedures to be used in evaluations and in real-time operations. The challenge with display formats is that unlike in some of the more standard hardware task analyses, documenting many of the software-driven tasks may require prediction because, as previously mentioned, the planned tasks and capabilities may have never before existed; “experts” may have to make educated guesses.

4.12.4.4 CONCEPT PROTOTYPING

The human-centered design activities outlined in section 3.2.3 describe concept prototyping as part of the Visualize and Produce Design Solutions activity. Early concept prototyping is a method for visualizing, exploring, or demonstrating aspects of a software system. One of the initial goals of prototyping is to capture multiple ideas in a visual form so that they can be reviewed and discussed. The greatest benefit of prototypes is that they are concrete and tangible, thus making design discussions much easier.

Important aspects of early concept prototyping are (1) iteration and (2) increasing fidelity of prototypes over time. Large amounts of time should not be spent on initial prototypes, because their purpose is short-lived and many changes will be made early on. For this reason, it is good practice to develop early prototypes with a rapid prototyping tool or a tool such as Microsoft PowerPoint. The first goal is to get the concept on paper so that it can be discussed and evolved. Time spent by developers on perfecting these early prototypes, or on building in interactivity or system models, is time wasted as the designs may quickly become obsolete. It is important to select prototyping tools that can be used to make changes rapidly and easily. It is also beneficial if the prototyping tool can produce usable code, which saves software implementation time.

Prototypes should progress in fidelity from early concept prototypes to integration prototypes as described below:

- Early concept prototype (“paper” prototype): static sketch used to illustrate design layouts and basic functions. These are often fragmentary, illustrating representative display formats or portions of formats.
- Interactive prototype: dynamic prototype with the ability for key functions to be demonstrated through user interaction. Still typically incomplete in functionality.
- Operational prototype: highly interactive prototype that may have some system models running in the background to enhance realism.
- Integration prototype: suite of high-fidelity, interactive prototype display formats integrated into an operational environment. Often used in high-fidelity simulations for training or verification.

Prototypes should be made available to all members of the design team and to stakeholders, for review and comment throughout the process. This helps ensure early buy-in, and no surprises late in the development life cycle that could result in costly redesigns.

When a custom software platform is being used, prototyping and display standards development must often occur somewhat in parallel. Standards should define the basic template and high-level standards. A standard template is important for ensuring a consistent approach to display format design. Prototypes should demonstrate and prove the standards; and finally, prototyping and evaluation results will lead to the need to document new standards or modify existing ones. In addition to a standard, documented template, an icon library should be established for the collection and use of a single, standard set of icons and symbols. This will avoid time being wasted by developers recreating common display objects, and will ensure a consistent “look and feel.”

4.12.4.5 HEURISTIC EVALUATION

Once prototypes are mature enough for evaluation to begin, a heuristic evaluation should be performed. This type of evaluation involves a human factors specialist reviewing the display format with respect to established program display format standards, and usability guidelines and principles. The result of this evaluation is a list of issues and redesign recommendations. Ideally, a heuristic evaluation should be performed before any crew-in-the-loop testing, as crew time is typically limited and should be reserved for feedback related to operational concerns, rather than obvious design issues and standards violations. Once the recommendations from a heuristic evaluation have been incorporated into the prototype, crew evaluations can proceed.

4.12.4.6 HUMAN-IN-THE-LOOP EVALUATION

The purpose of these evaluations is to determine the usability of the display formats in terms of the following: (1) Does the format support task performance? (2) Does it promote efficiency? (3) Does it optimize workload and minimize errors? This part of the process is intended to be highly iterative. The design-evaluate-redesign approach ensures that problems are identified early, when the design is more changeable.

Human-in-the-loop evaluations, required per NPR 8705.2B paragraph 2.3.10.1, should be conducted in much the same way as a standard usability test. This testing is the core of the development process – an opportunity for the display formats to be used and evaluated within the context of a real-world task, and the opportunity to collect objective data in a structured way, instead of relying on subjective opinions. This testing can also be used to discover any issues with the concept of operations, written procedures, or the hardware involved in the task. It may also offer some preliminary task timeline information.

4.12.4.6.1 SCENARIO-BASED TESTING

Test sessions should be set up for one crewmember at a time. With very mature, simulation-level prototypes, crew-in-the-loop testing can involve teams. Testing should be scenario-based, whereby the subject completes a list of procedures designed to “exercise” all of the key human interface components and functions. Testing should include nominal, contingency, and/or particularly problematic scenarios.

4.12.4.6.2 PROCEDURES

Procedures should be developed specifically for the purpose of the test. Relevant team members should contribute to development of these test procedures to ensure that they are semi-realistic and formatted correctly. It will not be possible to test all components, functions, options, and so on, so it is important to work within the multidisciplinary team to select the subset of functions to be tested. Although procedures should be somewhat realistic, it is more important that the procedures require the crewmember to work through or exercise all of the preselected display components, functions, or operations. This may have a negative impact on realism, and you may receive some comments from subjects about this, but it is more important that all of the key functions be exercised. A decision will have to be made about use of paper versus electronic procedures, depending on the concept of operations, scenarios tested, and maturity of the electronic procedures.

4.12.4.6.3 TEST METHODOLOGY

A standard usability testing approach should be used. The goal in the test plan should be to have the crewmember/subject work through the display formats to perform semi-realistic tasks. The evaluation should focus on all aspects of the format, including spatial layout, use of icons, proper terminology, consistency, and methods of interaction. Everything may not be functional, and inoperable functions can be skipped or simulated. Timing sessions is sometimes useful, but its usefulness may depend on the level of maturity of the prototypes. Tests of immature prototypes using subjects who are not familiar with the display formats will result in much more interaction between the test conductor and the subject, thus making completion times invalid. Later sessions with trained subjects and more mature prototypes can be timed. This information may help with mission planning and timelining. Completion times can also serve as meaningful data if they can be compared to task completion times from previous vehicle designs. Automated data collection should be used where possible to capture errors during the session.

After completing the task, crewmembers should be asked to complete a questionnaire or rating scale about various aspects of their experience with the interface. Subjects are often videotaped to capture frustration, confusion, fluctuations in their attention, and verbal comments during their participation. A technique called “Verbal Protocol Analysis” (or “think aloud” method) is useful for collecting additional data. In this technique, subjects are asked to verbalize (i.e., speak their thoughts), while they are performing the task. This allows identification of points of confusion and frustration in the format or procedures. Once a crew-in-the-loop evaluation has been completed, the problems identified should be addressed through design iteration, as discussed in section 3.2.3 Human-Centered Design Activities. Results and recommendations for display format or prototype redesign will be documented in a report, and provided to the design team for use in the next iteration of the prototype. Comments or results related to standards will be forwarded to the format standards team or committee.

4.12.4.6.4 FREQUENCY OF TESTING

Crew-in-the-loop-testing should be done in an iterative fashion, with multiple tests being completed during development. As formats and scenarios mature, testing can become more structured, and error rates and completion times should begin to be calculated and tracked. Assessments of the path to compliance should be made with early checks regarding ability to meet the Human-Systems Integration Requirements and the Display Standards with the display formats designed. Testing should be performed on individual display formats early in the design process, and then testing should be done on integrated suites of display formats as the designs mature. A final “run for the record” test will need to be performed for verification of many of the requirements related to display formats. Once the display formats have been implemented in the spacecraft, a plan should be developed for post-deployment evaluation. This plan is to be developed to enable identification of any issues in the real-time operations environment that may be able to be addressed for the next vehicle block upgrade.

4.12.5 DISPLAY FORMAT STANDARDS

The key to ensuring consistency within and among display formats is the creation and use of display format standards. Consistency in display formats can increase usability (see section 4.2 Usability Evaluation), reduce workload (see section 4.3 Workload Evaluation), decrease learning time for users, and increase mission safety. For display designers and developers, the development of standards can reduce work time by providing a common set of templates and widgets.

4.12.5.1 STANDARDS DEVELOPMENT PROCESS

The development of display standards uses an iterative process that begins before any design work is started; standards are updated and revised as displays are being developed. The display standards process consists of the following steps:

- Determine the purpose of the standards
- Create a display standards committee with appropriate stakeholders
- Perform research and task analyses
- Develop standards and evaluate them
- Draft a display standards document and use an iterative process to refine and update standards
- Perform a stakeholder review
- Implement standards and perform checks to verify that displays comply with standards

4.12.5.2 DETERMINE THE PURPOSE OF THE STANDARDS

The first step in developing display standards is to determine the purpose of the standards and their scope. Display standards can provide general guidelines based on good design and human factors principles, or they can explicitly call out rules and requirements that ensure absolute consistency among displays. In general, the larger the design team and number of displays, the more specific the display standards should be. Furthermore, it should be determined whether the standards will be specified at the user interface level for display designers, or at the programming (code) level for display programmers. Display standards without a clear purpose and audience may suffer from an unmanageable amount of information, leading to noncompliance.

4.12.5.3 CREATE A DISPLAY STANDARDS COMMITTEE WITH APPROPRIATE STAKEHOLDERS

A display standards committee is responsible for making decisions about display standards, and for documenting, disseminating, and enforcing these standards. A committee creates a single point of contact for the determination and interpretation of standards. Having a single point of contact can minimize confusion and allow standards updates to flow down to design teams. Thus, it is important for all stakeholders to be represented on the display standards committee. The committee should include the following representatives:

- Crew
- Human factors experts
- Safety experts
- Software developers
- Mission control and operations
- Procedure writers

Committee members need to be fully committed to the display standards process. Support of the process may include attending standing meetings, bringing standards issues to the committee for decisions to be made by the committee, helping with documentation and review, assisting with producing templates and common widgets, and disseminating information to design teams. Ideally, committee members will also be part of a design team, giving them an opportunity to record any problems with the current standards and to enforce standards.

Once the display standards committee is formed, the members should decide the methods for establishing standards, including how disagreements between committee members will be handled (e.g., two-thirds vote). The committee should also determine how new, recommended standards will be flowed to the committee, and then flowed down to design teams. For example, the committee can decide to create a master spreadsheet of all known standards issues that is updated according to feedback from design team leads. The committee can create and maintain a shared network folder that includes all standards documentation and templates. The method chosen by the committee for determining standards should be transparent to display designers; they should have easy access to documented standards. Committee members should decide how standards will be enforced. For example, the committee can hold standard compliance checks at various points in the display design process. During these checks, the design of displays can be compared against the standards, and any mismatches can be fed back to the designers. Lastly, the committee should establish goal dates for draft completion. This will ensure that the standards will be available when needed for display development. These and other process decisions of the committee should be documented and agreed on.

4.12.5.4 PERFORM RESEARCH AND TASK ANALYSIS

The process of developing new standards should begin by gathering information about users and their tasks, existing standards and guidelines, and hardware. It is important to understand users' existing knowledge and experience because standards that conflict with user expectations may reduce the usability of displays. For example, certain symbols, colors, or terminologies may have familiar meanings to users that are based on their cockpit experience or other display interactions (e.g., the International Space Station). Users may be familiar with other standards documents from, for example, the Federal Aviation Administration, Department of Transportation, Military Standards, Institute of Electrical and Electronics Engineers, or other organizations, or the committee may draw on general human factors principles.

It is critical to understand the tasks that users will be asked to perform using the displays, and the environmental or situational requirements of those tasks. For example, displays that crewmembers need to interact with during dynamic phases of flight may need to have a larger font size than those used during nondynamic phases. Results from a task analysis (see section 4.1 User Task Analysis) should be used to make reasonable predictions as to how many displays will be needed and the type of information needed on each.

Finally, information about vehicle hardware and software should be collected to understand the capabilities and limitations of the system. At a minimum, the size of the display device and software processing speed should be gathered.

4.12.5.5 DEVELOP STANDARDS AND EVALUATE

After initial task analyses, the next step is to start developing and documenting standards. Of course, task analysis should be ongoing as standards are developed and evaluated. Any updated knowledge about the vehicle, tasks, and crew should be incorporated into iterations of the standards, as appropriate. As a reminder, the purpose of display standards is to ensure consistency between display formats used by crewmembers, by providing a common design framework. At a minimum, standards should specify a common template or templates, common design elements, and common methods of interaction. The intent of standards is not to provide rigid rules that reduce the usability of displays; rather, standards should provide regularity in how display elements are shown and interacted with to reduce learning time and errors. Standards can and should be updated if evidence becomes available, from task analysis, evaluation, or display development, that better implementations are available.

A standards document should be developed hand-in-hand with development of prototype templates and widgets. These prototypes help to communicate the implementation and intent of standards. Widgets that can be duplicated and reused (i.e., copy-and-paste) provide display designers an easy method to replicate common design elements and maintain consistency.

The appropriateness of novel display standards (e.g., new symbols) should be evaluated to ensure that they contribute to the usability of displays, and do not lead to user errors (see section 4.2 Usability Evaluation for information on how to calculate error rates).

4.12.5.5.1 DISPLAY FORMAT STANDARDS DOCUMENT CONTENT

Once a set of standards is established, the standards should be officially documented to ensure a single source of written information on standards decisions. The following is a suggested list of what should be included in the standards document.

Interaction with hardware. The standards document should include an overview of how hardware (e.g., physical buttons, cursor control devices, keypads, and other input devices) interface with display formats. Typically this section is intended to provide sufficient foundational information to document how users’ interaction with hardware affects software. The level of detail in this section will likely correspond to the “newness” of the hardware device. For example, if a standard computer mouse and keyboard are used, less information will likely need to be included than the information needed for a new type of control or interaction device. If different types of hardware are used during different phases of flight (e.g., dynamic phases above 3*g* versus on-orbit phases), this should be documented as well.

Cockpit configuration. An overview of how the cockpit is configured should be included in the display standards document. This will provide display design teams with information such as the number of displays available, their size and orientation, and the number of crewmembers who can interact with the displays at any one time.

Definitions and common terms. All terms related to display components and modes of operation should be clearly defined to ensure that all display teams and software developers use a common language. Definitions may include names and descriptions of different types of keys or buttons, title bars, cursors, display regions, focus areas, and input/command-able areas.

Interaction with displays. It is important to provide a description of how crewmembers will interact with displays. For example, how crewmembers will input values or commands (e.g., through data entry fields, popups, or virtual keypads) should be documented. Other standards may describe cursor movement, navigation between displays, and error handling.

Automation and procedures. Documentation should be provided describing how automation (e.g., electronic procedures) interacts with display elements, if applicable. If crewmembers are able to control the level of automation or are able to inhibit automatic processes, this should be documented as well.

Common template. To have a unified look and feel, display formats should be built on one or a few related common templates. Elements in templates can include the appearance and location of display format titles, time, navigational menus, and system health and status items.

Static versus dynamic information, and areas for crew input or action. The standards document should specify how display elements that are dynamic (e.g., telemetry of vehicle states and data values) are distinguished from those that are static (e.g., reference information or labels). The document should specify how display elements that crewmembers can manipulate or change are distinguished visually from elements that cannot be changed by crewmembers.

Colors. The display standards document should specify available colors, the use of which should be limited to a small set of highly distinguishable values. Color should not be used as the sole indicator of a state, because of potential issues with perception of color under different lighting conditions or crew visual abilities. Redundant information can be provided to supplement color (e.g., symbols, text, or other design features), and the standards document can specify these. A color table with a clear description of uses of color, and a method to produce the colors (e.g., red/green/blue values) is recommended. Existing color standards and conventions exist and should be followed unless there is a significant rationale for not following them. Example conventions include

- Yellow – caution or cautionary state
- Red – warning or emergency
- Blue or cyan – advisory
- Gray – unavailable function
- White – available / dynamic information
- Green – available information or normal state (noncautionary)

Icons. Icons are a common set of symbols that represent vehicle components (e.g., valves, switches, batteries, and tanks). The display standards document should specify common icons and their definitions. An icon table with images of icons and their meanings is recommended. Industry standard and conventional icons should be used wherever possible.

Graphical elements. Standards should include specifications for available graphical elements and their behaviors, if applicable. Examples include line widths, the look and behavior of virtual buttons, and graphics used to group common elements together.

Time. A standard way to display and/or enter time values should be specified.

Data Display. Standards should specify how data are displayed; for example, units of measure, significant digits, and rate of change. Human-factors principles should be followed. For example, numerical data should be decimal aligned, units of measure displayed, and leading zeros suppressed for numbers greater than one. There should also be standards for displaying missing information.

Additional standards. The above items are not an exhaustive list of possible standards. All applicable standards that support consistency of displays should be included in the display standards document.

General rules for a well-written standards document:

- Write in simple and concise language
- Provide examples through images
- Provide a clear organization to the document

4.12.5.6 USE AN ITERATIVE PROCESS TO REFINE AND UPDATE STANDARDS DOCUMENT

As displays are being designed, new standards issues or need for clarifications may arise. An iterative process should be used to incorporate any updates, changes, or clarifications into the standards document and supporting materials such as prototype templates and widgets.

4.12.5.7 PERFORM STAKEHOLDER REVIEW

All relevant stakeholders should be given an opportunity to review and comment on the display standards draft document before it is released as an official document.

4.12.5.8 IMPLEMENT STANDARDS AND PERFORM CHECKS TO VERIFY THAT DISPLAYS COMPLY WITH STANDARDS

After an official display standards document is released, all displays should be designed to comply with the standards set forth in the document. A checklist that lists all display standards can be a helpful tool in determining whether designs comply with the standards. Verification by inspection should be performed on all displays before their implementation on a spacecraft. Any inconsistencies between a display design and display standards will need to be resolved by a redesign of the display, or a waiver with appropriate rationale.

4.12.6 DISPLAY FORMAT DESIGN TECHNICAL PRODUCTS

For each of the major milestones of the design life cycle, the technical products in Table 4.12.6-1 are recommended for review by the NASA customer.

NASA personnel can assist with any or all of these activities, as facilities, expertise, and recent vehicle design experience are all in place (e.g., rapid prototyping lab, library of display components and templates, display standards, preliminary flight system designs, data collection tools, and human engineering expertise).

TABLE 4.12.6-1 DISPLAY FORMAT DESIGN TECHNICAL PRODUCTS

Technical Products	Phase A		Phase B	Phase C	Phase D	
	SRR	SDR	PDR	CDR	SAR	FRR
A description of the ConOps, function allocation, operational use scenarios, and associated crew task lists.	I	U	U	U	---	---
A summary of modeling/analysis/evaluation performed to date and the influence on system design with links to the detailed analysis results. Required per NPR 8705.2B, and HITL evaluations required per paragraph 2.3.10.	---	---	I	U	---	---
Software Development Plan	I	U	U	---	---	---
Display Format Standards Document, including icon library and display dictionaries	I	U	U	---	---	---
Verification plan.	---	---	I	U	U	---

X = one-time release of item
I = initial release of item
U = updated release of item

Concept of Operations and Crew Task Lists

The ConOps, described in paragraph 3.2.3.1.2, provides information such as identification of crew activities and determination of which subsystems are influenced by crew activities. Function allocation, described in paragraph 3.2.3.1.3, establishes the extent to which an activity is to be automated or assigned to humans. The crew task list, described in section 4.1 User Task Analysis, documents details including allocation of function between crew and systems, definition of crew activities sequence, and identification of critical tasks. As the crew task list evolves through the design cycle, its final iteration should become crew procedures.

Summaries of Modeling, Analysis, and Evaluation

Iterative summaries of modeling, analyses, and evaluations provide NASA with insight into human-system integration technical details throughout the design process. As designs mature, modeling, analyses, and evaluations should use inputs and mockups of increasingly higher fidelity, as discussed in paragraph 3.2.3.3 Evaluate Designs and Iterate Solutions. It is important that summaries address how critical design decisions were assessed. According to NPR 8705.2B, updated summaries are to be provided at each design review through SAR. Also in paragraph 2.3.10, the use of human-in-the-loop evaluation is a required method to progressively demonstrate that the operational concept meets system requirements for operational safety, efficiency, and user interface design.

Verification Plan

The verification plan is a formal document describing the specific methodologies to be used to show compliance with each requirement.

Before the System Requirements Review (SRR)

- Draft of Software Development Plan
- Concept(s) of Operation
- Operational and Use Scenarios
- Early task lists and task flows
- User and system function allocation tables
- Commercial trade studies
- Preliminary “paper” prototypes
- Preliminary templates
- Prototype reviews
- White papers
- Draft of display format development process document, referenced by the Software Development Plan
- Early draft of display format standards document, including plans for an icon library
- Report on proof-of-concept / pathfinder display format design effort after draft process plan
- Draft requirements verification strategies

SRR through Preliminary Design Review (PDR)

- Final Software Development Plan
- Updated draft of display format standards document
- Icon library
- Updated Concepts of Operation
- Revised operational and use scenarios
- Updated task lists and task flows
- Updated function allocation tables
- Interactive prototypes
- Draft procedures
- Prototype reviews
- Commercial trade studies
- White papers
- Reports from human-in-the-loop evaluations of single interactive display formats
- Draft display dictionaries

PDR through Critical Design Review (CDR)

- Updated Concepts of Operation
- Task lists and task flows
- Updated function allocation tables
- High-fidelity prototypes
- Evaluation reports
- White papers
- Reports from human-in-the-loop evaluations of integrated suites of mature display formats
- Reports from phase-based human-in-the-loop evaluations of integrated suites of operational display formats
- Final display dictionaries

CDR

- Updated Concepts of Operation
- Vehicle display formats
- Verification activities related to display formats

Post Delivery

- In situ surveys and Reports
- Post-mission questionnaires, debriefs and interviews
- Lessons learned

4.12.7 REFERENCES

Holden, K. L, Malin, J. T., & Thronesbery, C. (1998). Guide to designing usable software systems in advanced technology environments (JSC Technical Report JSC-28517). Houston, TX: Johnson Space Center.

Turner, S., Bockman, M. Cain, L., Morgan, J., & Barber, D. (2009). CEV Display Format Development Process (Draft).

4.13 USER INTERFACE LABELING DESIGN

4.13.1 INTRODUCTION

Labels are an essential component of a user interface. They provide identifying or instructional information to the operator for activities such as finding items, following procedures, avoiding hazards, locating emergency equipment, and orienting to their environment. It is important that labels support recognition, identification, and operation; provide operationally relevant and consistent information; and be readable to the intended user in the design environment. Additional information about labeling can be found in NASA/SP-2010-3407 Human Integration Design Handbook (HIDH) section 10.7 Labels.

4.13.1.1 PURPOSE

This section provides an overview of the International Space Station (ISS) crew interface labeling process and is intended to aid the implementation of labeling requirements in NASA-STD-3001. This overview is to serve as a guide for spacecraft and equipment developers to facilitate design of labeling for user interfaces, through the use of the human-centered design process and ISS labeling examples. Additional examples from the Constellation Program can be found in CxP 70152 Constellation Program Crew Interface Labeling Standard.

4.13.1.2 BACKGROUND

The ISS crew interface labeling process is a collaborative effort between the hardware developers, procedure writers, mission operations personnel, crew office, and Flight Crew Integration. ISS standards have been established to promote consistency in labeling style, content, and operational nomenclature. To facilitate usability by NASA crewmembers, the developer is encouraged to use the ISS standards described in this process.

4.13.2 USER INTERFACE LABELING PROCESS

4.13.2.1 DEVELOP CONCEPT OF OPERATIONS AND CREW TASK LIST

Crew task lists are necessary for identifying crew operational interfaces and related labeling needs. Spacecraft crew interface designs should begin with development of the concept of operations and scenarios for nominal, off-nominal, and emergency operations. For each mission phase and relevant scenario, specify crew roles and activities and develop crew task lists. See HIDP sections 3.2.3.1.2 and 4.1 for description of concept of operations and developing crew task lists.

4.13.2.2 DEVELOP DESIGN SOLUTIONS

4.13.2.2.1 LABELING DESIGN PLAN

As crew tasks and equipment/system interfaces are defined, labeling designs should be planned and documented in a Labeling Design Plan. The Labeling Design Plan should contain detailed descriptions and illustrations or photos of all necessary user interface labels. Descriptions are to include label information such as text content, text size and font style, colors, dimensions, materials, location and placement on the equipment or system, and orientation with respect to the equipment/system and expected user working orientation. Label design for user interfaces should consider the item being labeled, the task at hand, adjacent or concurrent tasks and interfaces, and any need to distinguish interfaces. Equipment and system labels must also be consistent with operational procedures that identify controls to be operated, displays to be monitored, and so on. Text size should be in accordance with NASA-STD-3001, Volume 2 and be sans serif style for optimum readability. The preferred font styles used on the ISS are Helvetica and Arial.

The content of the Labeling Design Plan depends on the size of the hardware project. Information for a single piece of hardware may be contained on a single label drawing, or on one single top-level assembly drawing. For larger hardware projects, such as an entire vehicle, the information may be a consolidated package of several label drawings and charts identifying label locations, orientations, content, and design, or could be a document that details where the label information is depicted in a hardware project’s drawing package.

4.13.2.2.2 CREW INTERFACE LABEL TYPES

An approach for organizing a Labeling Design Plan is to organize by label types. To facilitate implementation, NASA categorizes labels into types based on their function:

- Hazard, Caution and Warning, Emergency Use
- Location Coding and Orientation
- Instructional
- Control and Display Panel
- Equipment Identification
- Inventory Management System (IMS) Barcode
- Cable and Hose Connector-end

By virtue of the intended label function, each type of label has unique design considerations that are described in the following paragraphs. For commonality with the ISS, and to minimize training and risk of error, NASA standards for panel labeling and operational nomenclature are recommended. Refer to SSP 50783 Labeling of Intravehicular International Space Station Hardware: Design Development Process, SSP 50005 International Space Station Flight Crew Integration Standard section 9.5 for NASA labeling standards, and SSP 50254 Operations Nomenclature.

4.13.2.2.2.1 HAZARD, CAUTION AND WARNING, EMERGENCY USE LABELING

Hazard, caution and warning, and emergency use labels are intended to convey critical information in an appropriate context. Hazard labels should be applied to equipment or components that may be hazardous to crew or equipment. Examples of hazards include biohazards, electrical shock hazards, and trash containing toxic or otherwise hazardous waste to which crewmembers may be exposed. Space vehicles designed for NASA crew use should comply with ISS label design standards for hazard, caution and warning, and emergency use. The commonality reduces training time and minimizes confusion or error because NASA crewmembers are familiar with the design. Figure 4.13.2.2.2.1-1 is an example hazardous waste label that can be found in JSC 27260 Decal Process Document and Catalog and satisfies the requirement in V2 7069 Labeling of Hazardous Waste.

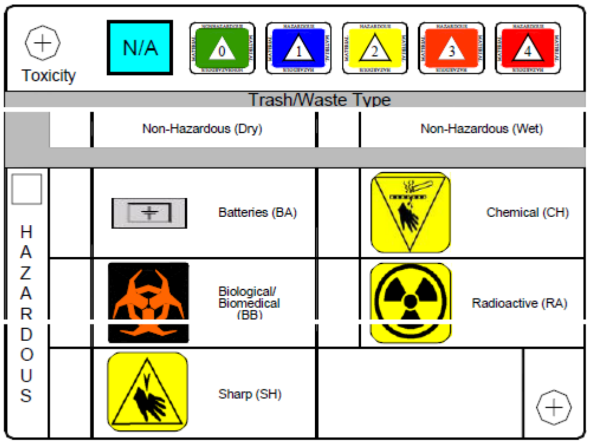


FIGURE 4.13.2.2.2.1-1 ISS HAZARDOUS TRASH IDENTIFICATION LABEL (SDG32105751)

Caution and warning labels should be used to indicate special circumstances, such as keep-out zones, reduced clearance, sensitivity to electrostatic discharge, stored energy, or an unprotected hot surface that may cause startle reaction. Generally, caution and warning labels are distinguished by the use of yellow and black diagonal striping for intravehicular activity (IVA) applications. Gold and black are used for extravehicular activity (EVA) applications. Specifications for the striping pattern can be found in SSP 50005 ISS Flight Crew Integration Standards paragraph 9.5.3.1.13 Caution and Warning Labels Design Requirements. Figure 4.13.2.2.2.1-2 is an example caution/warning label that can be found in JSC 27260 Decal Process Document and Catalog.

FIGURE 4.13.2.2.2.1-2 ISS CAUTION/WARNING PINCH POINTS LABEL (SDG32105057)

Emergency use labels should be used to identify special-use items such as fire extinguishers, fire ports, emergency exits, and connectors that are to be disconnected in an emergency. Emergency-use labels are distinguished by the use of red and white diagonal striping. Specifications for the striping pattern can be found in SSP 50005 ISS Flight Crew Integration Standards paragraph 9.5.3.1.13 Caution and Warning Labels Design Requirements. Figures 4.13.2.2.2.1-3, -4, and -5 are example emergency-use labels that can be found in JSC 27260 Decal Process Document and Catalog.

FIGURE 4.13.2.2.2.1-3 ISS FIRE PORT LOCATION CODE (SDG32108589)

FIGURE 4.13.2.2.2.1-4 ISS PORTABLE FIRE EXTINGUISHER PANEL DOOR LABELS (SDG32107729)

FIGURE 4.13.2.2.2.1-5 ISS EMERGENCY DISCONNECT LABEL (SDG32106342)

For commonality with ISS to minimize training and risk of error, NASA standard or conventional hazard labels or icons are recommended. Refer to JSC-27260 Decal Process Document and Catalog for NASA standard labels that can be produced by the Decal Design and Production Facility (DDPF).

4.13.2.2.2.2 LOCATION AND ORIENTATION LABELING

Location coding and orientation labels are intended to provide location and direction information. On the ISS, location coding is an alphanumeric coding system used to uniquely identify internal locations to facilitate identification of equipment location, stowage areas, or emergency-use equipment location. See SSP 30575 Space Station Interior and Exterior Operational Location Coding System for guidance on location coding. Orientation labels provide needed position cues to crew in the absence of gravity. When attached to the ISS, interior visiting vehicle orientation should correspond with the ISS reference orientation, which can be found in applicable Interface Requirement Documents or in SSP 30575. Figure 4.13.2.2.2.2-1 is an example of orientation placards used on the ISS and available from DDPF.

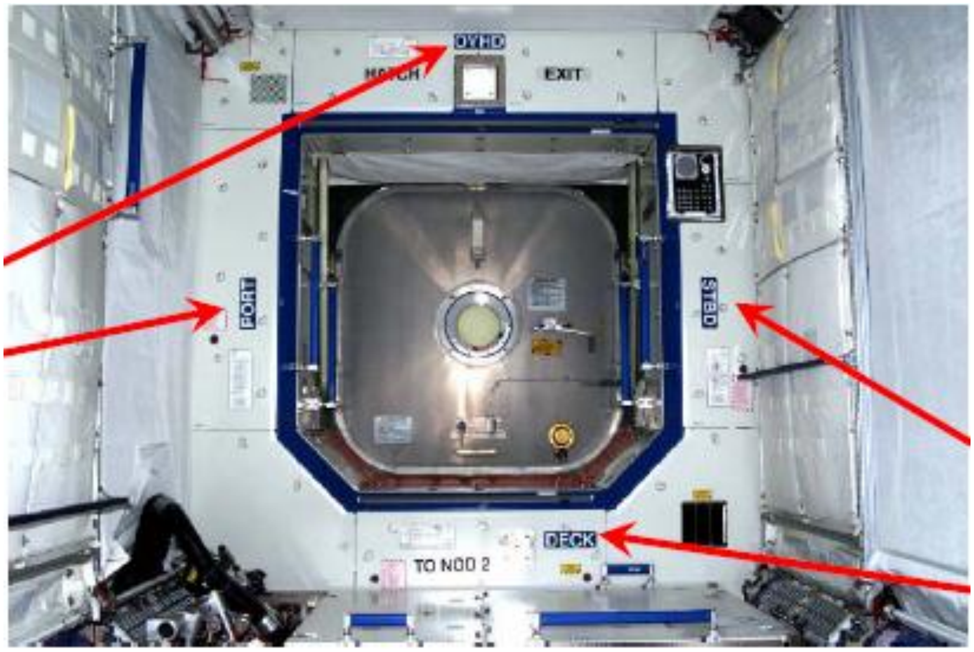


FIGURE 4.13.2.2.2.2-1 ISS CREW PREFERENCE LOCATION MARKING LABELS (SDG32106315)

4.13.2.2.2.3 INSTRUCTIONAL LABELING

Instructional labels are useful for providing cues on how to operate hardware, or augmenting operational procedures to which crewmembers have been trained or that must be performed quickly in an emergency situation. Instructional labels range from one-line cues, such as “Lock” or “Press to Activate,” to step-by-step instructions for hatch operation. Iterative design and evaluation by representative users performing the intended operations should be used in developing instruction labels. Figure 4.13.2.2.2.3-1 shows a sample “Lock” cue and Figure 4.13.2.2.2.3-2 shows a sample ISS hatch instruction label.

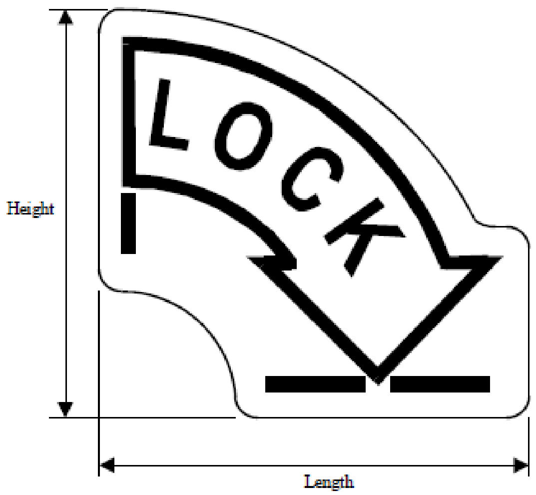
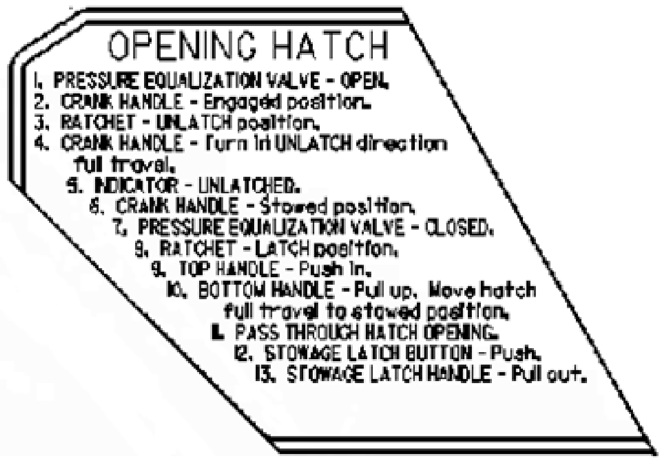


FIGURE 4.13.2.2.2.3-1 SAMPLE "LOCK" INSTRUCTION LABEL



OPENING HATCH

1. PRESSURE EQUALIZATION VALVE - OPEN.
2. CRANK HANDLE - Engaged position.
3. RATCHET - UNLATCH position.
4. CRANK HANDLE - Turn in UNLATCH direction full travel.
5. INDICATOR - UNLATCHED.
6. CRANK HANDLE - Stowed position.
7. PRESSURE EQUALIZATION VALVE - CLOSED.
8. RATCHET - LATCH position.
9. TOP HANDLE - Push in.
10. BOTTOM HANDLE - Pull up. Move hatch full travel to stowed position.
11. PASS THROUGH HATCH OPENING.
12. STOWAGE LATCH BUTTON - Push.
13. STOWAGE LATCH HANDLE - Pull out.

EVA Side (Rib Side)

OPENING HATCH

1. PRESSURE EQUALIZATION VALVE - OPEN.
2. CRANK HANDLE - Engaged position.
3. RATCHET - UNLATCH position.
4. CRANK HANDLE - Turn in UNLATCH direction full travel.
5. INDICATOR - UNLATCHED.
6. CRANK HANDLE - Stowed position.
7. PRESSURE EQUALIZATION VALVE - CLOSED.
8. RATCHET - LATCH position.
9. TOP HANDLE - Pull out.
10. STOWAGE LATCH HANDLE - Pull up. Move hatch full travel to stowed position.
11. STOWAGE LATCH BUTTON - Push.
12. STOWAGE LATCH HANDLE - Pull up.

IVA Side (Dome Side)

OPENING HATCH

1. PRESSURE EQUALIZATION VALVE - OPEN.
2. CRANK HANDLE - Engaged position.
3. RATCHET - UNLATCH position.
4. CRANK HANDLE - Turn in UNLATCH direction full travel.
5. INDICATOR - UNLATCHED.
6. CRANK HANDLE - Stowed position.
7. PRESSURE EQUALIZATION VALVE - CLOSED.
8. RATCHET - LATCH position.
9. TOP HANDLE - Pull out.
10. STOWAGE LATCH HANDLE - Pull up. Move hatch full travel to stowed position.
11. STOWAGE LATCH BUTTON - Push.
12. STOWAGE LATCH HANDLE - Pull up.

FIGURE 4.13.2.2.2.3-2 SAMPLE ISS HATCH OPENING INSTRUCTION LABEL

4.13.2.2.2.4 CONTROL AND DISPLAY PANEL LABELING

Control and display panel labels are intended to convey operationally relevant information about function or usage. All input and output devices that crewmembers may operate or monitor are to be clearly and succinctly labeled. Figure 4.13.2.2.2.4-1 is a sample control panel illustrating how power switches are to be labeled with the equipment/system controlled and the “ON” and “OFF” positions, and how connector ports are to be labeled with the connecting cable type (e.g., power, 1553 data, Ethernet) and port identification code (e.g., J11). The sample also illustrates the ISS convention for labeling circuit breakers using the acronym “CB” and the positions “OPEN,” “CLOSE,” and “TRIP” to provide clear indication of the circuit breaker status. One power switch is reserved for emergency use, as indicated by the red and white striping around the control and labeling. One indicator light display is labeled with its function for smoke indication. Note that labels are typically located above and centered with respect to the control or display and that all text is consistently oriented with respect to the operator’s expected working orientation. Grouping lines are used to visually distinguish related and unrelated controls and displays.

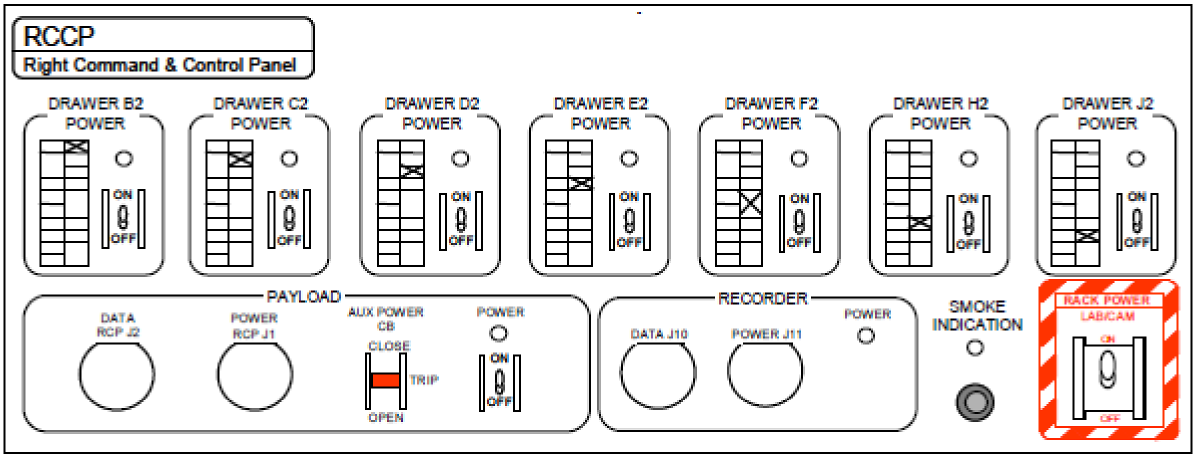
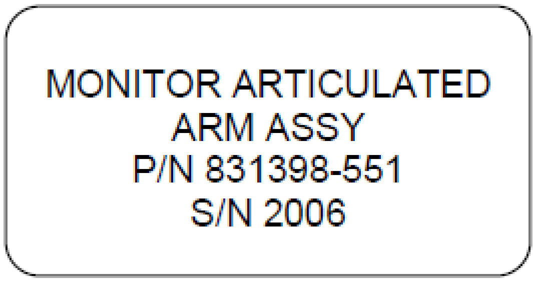


FIGURE 4.13.2.2.2.4-1 SAMPLE ISS CONTROL-PANEL LABELING

4.13.2.2.2.5 EQUIPMENT IDENTIFICATION LABELING

Equipment labels are intended to identify operationally and functionally relevant pieces of hardware, equipment, subsystems, or components that crewmembers may operate. Registered operational nomenclature should be used to identify hardware and equipment; see paragraph 4.13.2.2.3 Operational Nomenclature. Equipment labeling should be sized and located so that crewmembers can easily see, recognize, and distinguish items when they are needed. Identification labeling is used to identify control panels (such as in Figure 4.13.2.2.2.4-1), cables and hoses (such as in Figures 4.13.2.2.2.7-1, -2, and -3), and equipment, as shown in Figure 4.13.2.2.2.5-1. For hardware and equipment, including cables and hoses, identification labeling includes part number and serial number to further identify the item.



MONITOR ARTICULATED
ARM ASSY
P/N 831398-551
S/N 2006

FIGURE 4.13.2.2.2.5-1 ISS HARDWARE IDENTIFICATION LABEL (SDG32107015)

4.13.2.2.2.6 INVENTORY MANAGEMENT SYSTEM BARCODE LABELING

Typically, items that are transferred to the ISS are registered in the established ISS inventory management system (IMS) for inventory and/or on-orbit tracking purposes. The IMS is used to track items that may be replaced, resupplied, or temporarily stored on the ISS. The IMS is also used to catalog and track items that are on board the ISS. Therefore, items that are transferred to the ISS are registered in the ISS IMS system for a unique tracking number and have an IMS barcode label applied. IMS barcode labels can be separate from or combined with equipment identification labeling. Figure 4.13.2.2.2.6-1 shows a combination identification and IMS barcode label that is available from the DDPF.

Waste Gas Line Shutoff Valve
P/N 2310-320 100A00C
S/N 11
00001198E

FIGURE 4.13.2.2.2.6.-1 SAMPLE ISS COMBINATION IDENTIFICATION AND BARCODE LABEL (SDG32108325)

4.13.2.2.2.7 CABLE AND HOSE CONNECTOR-END LABELING

Connector-end labels are intended to provide clear and succinct information needed by crewmembers to correctly match mating connector ends. Connector-end labels are to be implemented on all cables and hoses that may be connected or disconnected by crewmembers. Flag-style labels, as shown in Figure 4.13.2.2.2.7-1, are easier to see and read and are preferred, especially for use on connector ends that crewmembers will operate regularly or nominally, or will need to locate, identify, and operate during emergencies. Alternatively, band-style labels (shown in Figure 4.13.2.2.2.7-2) which completely wrap around, are acceptable on cables and hoses that are for non-emergency use or are operated infrequently, such as utility cables installed behind equipment racks that may be operated only when equipment is replaced.

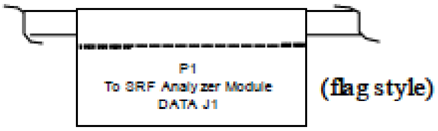


FIGURE 4.13.2.2.2.7-1 SAMPLE ISS FLAG-STYLE LABEL

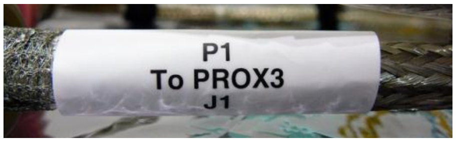


FIGURE 4.13.2.2.2.7-2 SAMPLE ISS BAND-STYLE LABEL

Figures 4.13.2.2.2.7-3 and 4.13.2.2.2.7-4 illustrate ISS connector-end labeling conventions for an electrical cable and a fluid hose, respectively. Generally, 3 lines of text are used.

Line 1: Identifies either the name of the hardware that the cable or hose is part of or a connector identification code. Use of the hardware name is recommended on long cables or hoses where the connector end may be far from the base hardware, such as long utility cables connecting equipment to power. When a connector identification code is used with electrical cables, the cable end plugs are coded with “P” and a number, and the hardware receptacles are coded with “J” and a matching number. Electrical connector gender (pins or sockets) is immaterial to connector coding. Within a given hardware system, ensure that unique connector identification code numbers are used for each connector. Hose connectors are coded with “F” on the female end and “M” on the male end.

Line 2: Identifies the hardware that the connector end will connect to. Registered operational nomenclature should be used to identify the hardware; see paragraph 4.13.2.2 Operational Nomenclature.

Line 3: Identifies the receptacle on the hardware that the connector end will connect to. The connect-to text is to match the labeling text on the hardware receptacle. Electrical connector receptacles are coded with “J” and a number that matches the connector end number. “P” and “J” coding are to be used only with electrical connectors and receptacles.

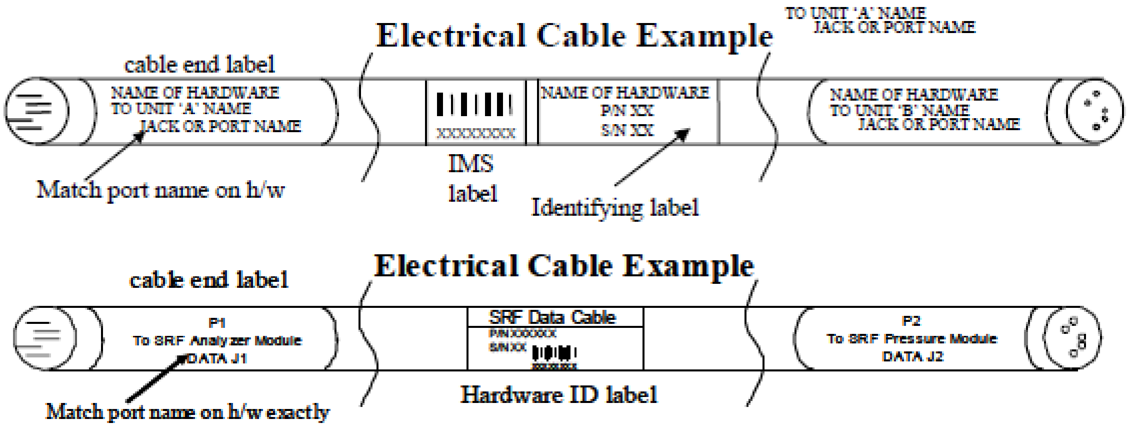


FIGURE 4.13.2.2.2.7-3 SAMPLE ISS ELECTRICAL CABLE LABELING

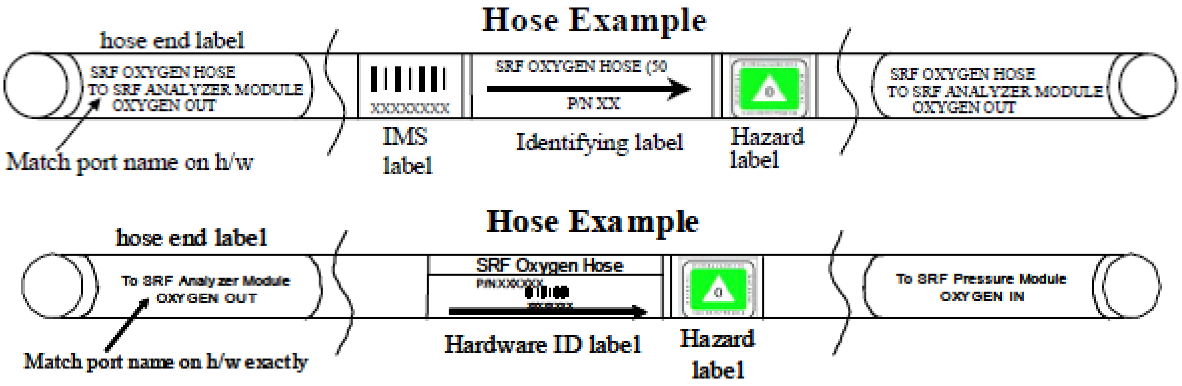


FIGURE 4.13.2.2.2.7-4 SAMPLE ISS FLUID HOSE LABELING

4.13.2.2.3 OPERATIONAL NOMENCLATURE

For operational consistency, NASA and the ISS use a managed set of operational nomenclature and a defined process to assign operationally relevant nomenclature to equipment and systems. The OpNom process also manages standardized abbreviations, including acronyms. If needed, NASA will assist the developer in obtaining OpNom through the OpNom process. Registered OpNom is used on ISS labels for identifying hardware and software, in procedures, on displays, and in communications between flight crew and ground support. Equipment, controls, and displays with which the NASA crew will interface are to be identified in accordance with SSP 50254 Operations Nomenclature (CH10008).

4.13.2.2.4 LABEL DRAWINGS

The NASA DDPF produces flight-certified labels for the ISS. If the developer chooses to request DDPF production of flight labels, the labels must be ordered from the JSC-27260 Decal Process Document and Catalog or engineering drawings of labels must be provided with the DDPF request. The engineering drawings for DDPF label production must contain the information in Table 4.13.2.2.4-1. Drawings for custom labels to be produced by DDPF should be provided to NASA for inspection at design reviews. Engineering drawings of labels in the decal catalog may be requested from NASA. If needed, NASA will assist with preparation and submittal of NASA DDPF label orders on JSC Form 733 Decal Design and Production Facility Support Request.

TABLE 4.13.2.2.4-1 DDPF LABEL DRAWING DETAILS

Label Drawing Details	Notes
Material	See JSC-27260 paragraph 5.2.1.1 Recommended Decal or Placard Base Material for IVA Applications or 5.2.1.2 Recommended Decal or Placard Base Material for EVA Applications
Adhesive	DDPF uses 3M #966 or NASA-approved equivalent
Color	Specified per FED-STD-595
Character Style and Size	Specify font style (Helvetica or Arial preferred), size
Dimensions	Specify in drawing
Text and/or Graphics Details	Specify in drawing

4.13.2.2.5 LABELING MATERIALS

The JSC-27260 Decal Process Document and Catalog paragraph 5.1 provides material safety requirements and recommended flight-certified material for intravehicular labels. To be approved for flight to the ISS, labeling materials must meet requirements and restrictions for flammability, odor, toxic off-gassing, fungus, and polyvinyl chloride. Refer to JSC-27260 for material specifications.

If the developer chooses to request label production from DDPF, the materials in Table 4.13.2.2.5-1 are available and approved for flight use and on the ISS in accordance with SSP 30233 Space Station Requirements for Materials and Processes as implemented by JSC 27301 Materials Control Plan for JSC Space Station GFE. Note that there may be restrictions on use of some materials because of environmental or other use considerations.

TABLE 4.13.2.2.5-1 NASA-APPROVED LABELING MATERIALS

Materials	Notes
Aluminum, photosensitive	Metalphoto, Dye-N-Seal
Nomex	HT 90-40, HT10-41 When using Nomex labels with adhesive backing (non-sewn labels) the DDPF will cut the labels using a laser or heat knife to prevent fraying of edges. In the event that the laser or heat knife is not available, approved fray-check material will be applied to prevent fraying of edges. DDPF customers should include this information as a note on new engineering drawings for Nomex labels (non-sewn).
Polycarbonate	Lexan 8A35-112, 8A13-112
Polycarbonate laminated photosensitive polyester	3M or NASA-approved equivalent with label guard 3M # 821
Polycarbonate (Lexan) laminated paper	Hammermill or Canon laser color, or Cardstock/K-10, etc., laminated with ID Mark Polycarbonate P/N 8794
Vinyl	Gerber Scotchcal 220, Starliner
Polyester	Brady, Intermec, and Tedlar
Polyolefin	Cryo-Babies

If the DDPF is not used for label production, materials used to fabricate flight decals and placards must be certified for flammability, toxic off-gassing, odor, fungus resistance, and thermal vacuum stability for uses with short-term low Earth orbit (LEO) exposure, and for thermal vacuum stability, atomic oxygen and ultraviolet resistance, and thermal cycling for uses with long-term LEO exposure.

Decal materials typically used on the ISS include paper stocks, vinyl (2 - 4 mil), polyester film, photosensitive films, and Nomex cloth. Placard materials include Lexan, acrylic, and polyester-based transparent films. Aluminum, sheet metals, stainless steel, and various plastics can also be used to manufacture placards for more harsh environments.

4.13.2.3 ITERATE DESIGNS, TEST, AND EVALUATE

Labeling designs should be evaluated by representative users performing representative operations and in conjunction with related usability evaluations, workload assessments, task analyses, or error analyses. Labeling evaluations are primarily subjective and should focus on assessing clarity and accuracy of the labels for their intended operational purpose. Operational procedures should be evaluated along with labeling to ensure consistency where labeled items are referenced. Evaluation results should be used to iteratively improve designs, and changes should be updated in the Labeling Design Plan.

4.13.3 USER INTERFACE LABELING DESIGN TECHNICAL PRODUCTS

For each of the major milestones of the design life cycle, the technical products in Table 4.13.3-1 are suggested for review by the NASA customer.

TABLE 4.13.3-1 USER INTERFACE LABELING DESIGN TECHNICAL PRODUCTS

Technical Products	Phase A		Phase B	Phase C	Phase D	
	SRR	SDR	PDR	CDR	SAR	FRR
A description of the ConOps, function allocation, and associated crew task lists.	I	U	U	U	---	---
User interface Labeling Design Plan.	I	U	U	U	---	---
Operational nomenclature proposals/requests.	I	U	U	U	---	---
Operational nomenclature approvals/registration.		I	U	U	---	---
A summary of modeling/analysis/evaluation performed to date and the influence on system design with links to the detailed analysis results. Required per NPR 8705.2B, and HITL evaluations required per paragraph 2.3.10.	---	---	I	U	---	---
Verification plan.	---	---	I	U	U	---

X = one-time release of item
I = initial release of item
U = updated release of item

Concept of Operations and Crew Task Lists

The ConOps, described in paragraph 3.2.3.1.2, provides information such as identification of crew activities and determination of which subsystems are influenced by crew activities. Function allocation, described in paragraph 3.2.3.1.3, establishes the extent to which an activity is to be automated or assigned to humans. The crew task list, described in section 4.1 User Task Analysis, documents details including allocation of function between crew and systems, definition of crew activities sequence, and identification of critical tasks. As the crew task list evolves through the design cycle, its final iteration should become crew procedures.

Summaries of Modeling, Analyses, and Evaluations

Iterative summaries of modeling, analyses, and evaluations provide NASA with insight into human-system integration technical details throughout the design process. As designs mature, modeling, analyses, and evaluations should use inputs and mockups of increasingly higher fidelity, as discussed in paragraph 3.2.3.3 Evaluate Designs and Iterate Solutions. It is important that summaries address how critical design decisions were assessed. According to NPR 8705.2B, updated summaries are to be provided at each design review through SAR. In accordance with the requirements in NPR 8705.2B paragraph 2.3.10, the use of human-in-the-loop evaluation is a method required for progressively demonstrating that the operational concept meets system requirements for operational safety, efficiency, and user interface design.

Verification Plan

The verification plan is a formal document describing the specific methodologies to be used to show compliance with each requirement.

4.14 OCCUPANT PROTECTION DESIGN

4.14.1 INTRODUCTION

Occupant protection focuses on crewed spacecraft features designed to control hazards and limit injury risks presented by excessive loads to crewmembers due to transient accelerations (≤0.5 second) or insufficient crew restraint during dynamic phases of the mission such as ascent abort and Earth landing. It is important that the occupants be protected from injury without excessive design implementations that lead to unnecessary vehicle weight and complexity. Approaches to ensure safety, such as those used in the commercial aviation and automotive industries, provide a foundation for occupant protection in human-rated space vehicles; however, their application to crewed spacecraft requires modification to meet NASA human-systems standards (NASA-STD-3001) that are applicable to all NASA human space flight (HSF) programs.

Proper support and restraint of body components can reduce the risk of injury and must be addressed by designers of the vehicle and the pressure suit system (if included). Many factors affect the likelihood of injury during dynamic flight events. Extrinsic factors include vehicle-specific factors (G-loading, velocity change, rate of acceleration onset, acceleration profile, load paths, load distribution, deflection of spacecraft structure, and collapse of habitable volume) and crew factors (bone and soft-tissue compression, tension, joint extension, flexion, shear-force magnitudes and directions, deflections of body components). Intrinsic factors relating to the crew include age, gender, physical condition, deconditioning due to space flight, and degree of muscle tension. Reliable injury-predictive tools and injury criteria are required to ensure that human-rated spacecraft be designed with the appropriate level of occupant protection.

4.14.1.1 APPLICABLE REQUIREMENTS

Occupant protection requirements are specified in NASA-STD-3001 Volume 2, section 6.5. These requirements are in place to control hazards and limit injury risk presented by excessive crew loads due to high accelerations or insufficient crew restraint, particularly during abort and landing scenarios.

- Acceleration Injury Prevention [V2 6069]
- Injury Risk Criterion [V2 6070]

Additional information that supports system design for occupant protection is provided by section 6.5 of the NASA Human Integration Design Handbook (HIDH), NASA/SP-2010-3407.

4.14.2 OCCUPANT PROTECTION DESIGN PROCESS

Designing a spacecraft to carry humans into low Earth orbit or beyond and returning them safely to Earth presents unique challenges because of the varying environments they must withstand during the ascent, descent, and landing phases of flight. Vehicle design solutions may range from a winged to lifting body, a biconic to a capsule shape with a wide range of nominal and off-nominal trajectories, cross-range capabilities, deceleration means, and landing modes (e.g., land, water, rocket, airbag). Ascent abort methods include puller and pusher rockets that may be used at various points from the launch pad to high atmospheric altitudes. During all phases of flight, the crew will be exposed to accelerations of widely varying intensity, duration, and orientation. Therefore, simple adoption of standardized methodologies of injury assessment from other industries (such as commercial aircraft) is not feasible for many spacecraft. Each vehicle's design solution results in a unique set of transient acceleration loadings on the flight crew, and thus necessitates unique methods to achieve occupant protection to NASA's human-systems standards. This section is intended to provide a guide to the process that may be used to evaluate compliance with NASA standards on occupant protection, but it is not an exhaustive description of the methods needed to implement the process.

4.14.2.1 RECOMMENDED BEST PRACTICES

The reader should identify industry best practices to use during design and testing. A list is provided by NASA in the HIDH.

Crewmembers may be subjected to forces and accelerations during mission scenarios such as nominal, off-nominal, and contingency landing and ascent aborts, that may cause serious injury if not adequately mitigated. By utilizing methods for evaluating occupant protection system designs, predictions of injuries for acceleration load cases, seat designs, and seat locations can be developed. These predictions can be used to formulate recommendations to improve the spacecraft design to prevent or mitigate these injuries to the acceptable levels described by NASA human-systems standards.

4.14.2.2 DEFINE LANDING CONDITIONS AND LANDING LOADS

Because of the complexity and cost of manufacturing a new spacecraft, much of the design work for assessing and controlling accelerations and determining the effects on structural integrity and crew safety during contingency, nominal and off-nominal landing scenarios, and aborts may be based on analytical methods. As a result of the inherent uncertainty and natural variation of environmental factors affecting impact conditions, landing assessments are often performed using a probabilistic approach, including consideration of vehicle-specific worst-case scenarios. This section provides a high-level overview of the process that may be used to establish landing conditions due to environmental factors and the subsequent down-selection process to a subset of cases for detailed crew injury assessment.

4.14.2.2.1 ENVIRONMENTAL CONDITIONS AND LANDING DISTRIBUTION DEFINITION

Parameters that affect vehicle landing orientation and relative velocity should be included in landing probabilistic analysis to accurately predict landing probabilities. Some of the parameters that factor into the analysis are parachute performance, hang angle, wind speed, and sea state (e.g., wave height, frequency, angle, shape, direction) or terrain (e.g., slope, soil conditions). Because some of the parameters are correlated (i.e., horizontal wind speed and sea state), a probabilistic approach may be preferable to reduce the number of possible conditions for landing. The output of this analysis describes the initial conditions of the vehicle orientation and dynamics in relation to the water or land surface. These parameters should include normal velocity; relative angle of impact; roll, pitch, and yaw angles; and horizontal and vertical velocities. This process will need to be conducted for all nominal and for select off-nominal and contingency landing environments and vehicle landing conditions based on program-specific requirements for design and verification. The off-nominal and contingency landing environments may include parachute-out conditions, loss of guidance or roll control, failure of air bags or other landing systems, off-target landing locations, pad- and ascent-abort landing conditions, and so on.

4.14.2.2.2 CRITICAL LANDING CASE SELECTION METHODOLOGY

Once a distribution of landing parameters is generated, a systematic method for selecting critical landing cases for further analysis is necessary. Many methods exist for determining the selected cases. Two methods will be discussed here: the Boundary Selection Method and the Response Surface Selection Method. For either method, success criteria will be developed on the basis of the probability of occurrence and acceptance of risk under each condition.

4.14.2.2.2.1 BOUNDARY SELECTION METHOD

The intention of this selection method is to define a boundary along the distribution that defines the acceptable and unacceptable landing cases for factors such as system failures, horizontal and vertical landing velocity, impact angle, wave state, and soil condition. An initial boundary is defined that includes the majority of landing conditions based on a probabilistic distribution, with variables assessed either independently (such is the case for random failures) or dependently (for conditions such as wave state, wind, and horizontal velocity, which are highly correlated). Typically, goals such as 3-sigma dispersions are established to define the certified boundary. The system will then be designed in such a way that all cases on one side of the boundary will be acceptable and meet all the crew injury requirements and the cases on the other side will not be certified cases and may be controlled by means of operational controls on flight operations (i.e., placards) or accepted as residual risk. Additional analysis must be conducted to show that the cases inside the boundary satisfactorily meet the occupant protection requirements, else either the design must be modified or the offending environmental conditions controlled through placards to prevent the system from operating outside of the certified conditions.

Once this boundary is defined satisfactorily, cases near the boundary on each side are selected for further analysis. The method for selecting the cases should be justified and the number of cases should be justified statistically. After analysis, the boundaries may have to be modified to capture a broader distribution of landing cases based on injury criteria. The conditions defining the certified landing distribution may then be used to refine the design or be used as derived requirements for conditions such as landing velocity or flight environment placards.

4.14.2.2.2.2 RESPONSE SURFACE SELECTION METHOD

An alternate approach to selecting cases to analyze may be used separately or may be used to define the boundary in the previous method. In this method, a statistically significant number of cases are selected uniformly from the entire distribution. These cases are modeled as described below in the following sections. The results of these analyses are used to estimate the injury response of all of the landing cases, using a response surface. See NASA/TM-2009-215704 for additional information about the method. Once this analysis has been conducted, additional critical landing cases can be selected that may be near the threshold of failing the requirements. This procedure may be used to more accurately define the certified landing condition boundary. The conditions defining the certified landing distribution may then be used to refine the design or be used as derived requirements for conditions such as landing velocity or flight environment placards.

4.14.2.2.3 LANDING DYNAMICS MODELING

Once critical landing cases have been selected, landing simulations of the entire vehicle are conducted by numerical analysis (e.g., by dynamic finite element modeling). These simulations provide the necessary information about loads and dynamics that is needed to drive the crew interface subsystem model, which includes the crew, seats, and restraints, as well as anything in the direct load path, such as pressure suits, and the accelerations the crew experiences. The designers consider the effects of impact, vehicle structural deformation, and impact attenuation systems such as landing gear, airbags, retrorockets, and seat support structures and mechanisms. The numerical analysis and the subsystem model may have increasing levels of fidelity with increasing levels of design maturity, allowing more detailed results to be obtained in each subsequent design phase.

4.14.2.2.4 CREW INTERFACE AND CREW RESPONSE MODELING

After the vehicle landing dynamics are estimated, the next step is to model the crew interfaces (i.e., crew positions). As before, this is an evolutionary process in which low-fidelity models may be used early in the design process and are then replaced by higher fidelity models as the design matures. Using these models, crew responses will be simulated by driving the model using information from the loads and dynamics obtained from the critical landing cases.

Initial low-fidelity models should, at a minimum, allow evaluation of the Brinkley Dynamic Response criteria. To accomplish this evaluation, the model must account for gross accelerations at the vehicle level and simulate energy attenuation, to accurately predict the accelerations at each crewmember location. Ideally, this level of analysis occurs no later than between SRR and PDR.

Once the gross performance of the vehicle accelerations is known, more detailed modeling of the crew-vehicle interface is needed, including the seat and any additional energy-attenuation systems inherent to the crew-seat interface. This fidelity model also requires a human surrogate (i.e., Anthropomorphic Testing Device [ATD]) finite element model to be restrained in the seat. Models of the suit, if applicable, should be included, even if they may have low fidelity at this point. This level of simulation should inform the design no later than between PDR and CDR.

4.14.2.2.5 MODEL VALIDATION TESTING

Because the above analysis is only of Finite Element (FE) models, physical testing is required to support the validity of the analysis. The physical test data are obtained to correlate the model responses with the real performance of the system. Testing should begin as early as possible in the developmental cycle to inform the design, build confidence in the FE models, and reduce cost of the ultimate verification events. Developmental and validation testing potentially includes parachute testing to validate deceleration onset rate and landing velocity, drop testing of full and subscale vehicles in various wave conditions and soil types as applicable to determine vehicle-level impact accelerations, drop testing of load attenuation subsystems such as crew pallet and stroking seat or strut assemblies, and finally drop or sled testing of seat assemblies and restraints, including ATDs or human (volunteer or post mortem) test subjects. Developmental testing transitions into validation testing when the tested system moves toward flight-like systems and subsystems. Test data can therefore be used to validate the analytical modeling results.

4.14.2.3 INJURY ASSESSMENT

An initial overall injury assessment can be performed after the modeling activities described above are completed. All injury metrics except the Brinkley Dynamic Response Criteria are to be calculated as described in SAE J211/1. The results are then compared with the Injury Assessment Reference Values (IARV) detailed below.

4.14.2.3.1 BRINKLEY DYNAMIC RESPONSE MODEL

4.14.2.3.1.1 HISTORY OF THE BRINKLEY DYNAMIC RESPONSE MODEL

The multi-axial dynamic response criteria, referred to by NASA as the Brinkley Dynamic Response Model, have been used in numerous research and development applications. These include the investigation of the Challenger accident; the development, test, and evaluation of the Crew Escape Technologies (CREST) escape system demonstration ejection seat, among others.

The Brinkley Dynamic Response criteria were developed as a result of an evolutionary process to define the human dynamic response to and exposure limits for short-duration accelerations associated with spacecraft landing and emergency escape system performance. During the development of the NASA Mercury, Gemini, and Apollo crew modules (as well as the B-58, XB-70, and F/B-111 aircraft escape systems), the established acceleration limits specified the acceleration rate of onset, acceleration amplitude, and duration for areas known to be within voluntary tolerance and those known to cause moderate to severe injury. These acceleration limits were based on the research of John P. Stapp and his contemporaries using military volunteers, animal surrogates, and the results of accidental exposures of humans. Additional information related to the Brinkley Dynamic Response Criteria can be found in AGARD CP-472, Development of Acceleration Exposure Limits for Advanced Escape Systems and in the HIDH Chapter 6.5.

4.14.2.3.1.2 ASSUMPTIONS AND LIMITATIONS FOR THE BRINKLEY DYNAMIC RESPONSE MODEL

As with any model, the Brinkley Dynamic Response Model has assumptions and limitations. The model will be accurate only for systems meeting the following criteria:

- Accelerations must be less than or equal to 0.5 seconds (e.g., during liftoff, launch abort, landing impacts, and parachute deployments).
- Seat padding or cushions should preclude amplification of transient linear accelerations transmitted to the occupant. Excessive padding will result in dynamic overshoot, amplifying rather than attenuating accelerations.
- Crewmembers must be restrained by a system that includes, at a minimum, pelvic restraints, torso restraints, and anti-submarining restraints that provide occupant restraint no less than that of a conventional 5-point harness during all events.
- The restraint system must be adequately pre-tensioned to eliminate slack.
- Proper crewmember fit and restraint must be ensured such that there is no gap between the subject and the seating support surfaces Any gap between the seat and subject, including gaps created by rigid elements within suits (if applicable), will increase the risk of injury and cannot be predicted by the Brinkley Dynamic Response Model.
- The suit may not change the natural frequency or damping of the body.
- The G_X axis limits presume that the seat occupant's head is protected by a flight helmet weighing less than 2.3 kg, with a liner adequate to pass the test requirements of American National Standards Institute (ANSI) Z-90 (latest edition) or equivalent.
- All crewmembers are similarly restrained during all events that require the application of the Brinkley model.

Resulting qualifications and uncertainties on the valid use of this model include the following:

- The Brinkley model predicts risk of generic “injury” but not the severity or location of injury. This inability to predict the severity and location of an injury limits the ability to assess the integrated medical consequences of different injuries under different landing operation conditions. For example, a post-mortem human subject study of the placement of rigid suit elements proved that the Brinkley was inefficient in predicting injury (McFarland, 2011). The addition of the elements drastically increased the probability of injury, but the increase was not predicted using the Brinkley.

- The model does not predict risk of injury based on subject's gender, age, weight, or space flight deconditioning.
- In the development of the original model, a generic seat was used along with the assumptions listed above. Another seat configuration would need the development of a new model. Thus, the probability of crew injury may be lesser or greater than the prediction given by the Brinkley.
- The dynamic response model cannot predict injury caused by localized blunt trauma or localized point loading (i.e., point loading due to rigid suit elements or interference with restraints). Blunt trauma due to rigid suit elements invalidates the risk prediction.
- The model assumes a minimally supported head mass in the risk estimate. Heavier space flight helmets may increase risk of neck injury but may not be predicted by the model.
- The natural frequency of the body could be changed by the suit and helmet. The model was originally developed without the use of a pressure suit. The additional mass from the suit and helmet, along with the fact that the mass would not be evenly distributed, would have an effect on the dampening parameters of the human.
- The Dynamic Response Index (DRI) was developed for a defined single-axis pulse shape, which may not apply to landing pulses of complex spacecraft. For example, the DRI primarily predicts thoracolumbar spine injury in the $+G_Z$ axis. Other axis limits are not well defined with the model.
    - NATO recommends using the Brinkley model only for the $+G_Z$ axis. The U.S. Army, on the other hand, does not use the Brinkley Model due because of its limitations.
- Along with the defined pulse, valid application requires the spine to be aligned within 5° of the load vector. An application greater than 5° drastically increases the risk of injury.

4.14.2.3.1.3 BRINKLEY DYNAMIC RESPONSE MODEL APPLICATION

The Brinkley Dynamic Response model may be applied only if all of the assumptions are met and the limitations are accepted. If these criteria are met, the Brinkley Dynamic Response Model is valid to apply and the injury risk criterion, β, is calculated according to the Brinkley Dynamic Response Model with Dynamic Response Limits, DR_{lim}.

The appropriate risk level for the Brinkley assessment will be determined in coordination with NASA Health and Medical Technical Authority (HMTA) and the specific HSF vehicle development program. The desired Dynamic Response limits are low (about 0.5%) for all cases. If occupant protection principles are not properly applied and/or multiple off-nominal failures occur, loads could impart risks in the medium risk (about 5%) and high risk (about 50%) categories for risk of sustaining a serious or incapacitating injury.

To calculate the injury risk criterion, β, see HIDH section 6.5.

In this model, it is assumed that the total body mass that acts on the vertebrae to cause deformation can be represented by a single mass. Using the Dynamic Response Model limits for accelerations of less than or equal to 0.5 second (e.g., during nominal liftoff, launch abort, landing impact, and parachute deployment) provides the proper margins of safety for a healthy conditioned crewmember. Prediction of injury risk for deconditioned crewmembers with 6-month space flight exposures can be achieved by applying the model with modified Dynamic Response Limits. For either crew condition, the Dynamic Response Model will provide a general injury risk assessment for either nominal or off-nominal failure or multiple failures, given an input acceleration profile.

Appropriately used, the Brinkley Dynamic Response Model can provide an early assessment of general injury potential for a new vehicle design. More specific evaluation of injury likelihood and consequence is expected to require physical Anthropomorphic Test Device (ATD) testing in conjunction with Finite Element (FE) modeling.

For further detail, the Brinkley Dynamic Response Model is documented in the Advisory Group for Aerospace Research and Development (AGARD) publication CP-472, "Development of Acceleration Exposure Limits for Advanced Escape Systems" as well as in NASA TM-2008-215198.

4.14.2.3.2 LIMITATION OF SPECIFIC CREW INJURY TYPES

NASA-STD- 3001 V2 6069 requires protection from injury caused by accelerations, including blunt-force trauma, point loads impact, and flail injury, and injurious loads to the head and neck. Protection can be achieved in a variety of ways, and verification that this requirement is met can be achieved by inspection of the design and the analysis, supported by test data.

Blunt-force trauma is one of the leading impact injury modes in terrestrial accidents, including aviation and automotive crashes. Trauma occurs when the structural failure associated with acceleration and resulting forces causes the occupant to strike surrounding structure, the structure itself to fail resulting in a collapse of the occupant’s survivable volume or in impingement into the volume from structures deforming or becoming ballistic. To prevent this injury mode, designers need to ensure that the volume surrounding the occupant is sufficient to prevent crewmembers from impacting the structure when they are subjected to accelerations, including consideration of uncontrolled flailing of limbs. Further, structural designers and analysts must ensure that safety factors are such that the structure does not yield and deform into the survivable volume or fail and strike the occupants.

Accelerations are best tolerated by the human body when they are distributed evenly over a large body surface area. To prevent point loads in the design of seats and restraints, seats should conform to the human body to the extent possible in any direction that is designed to provide support, particularly at the buttocks, back, legs, shoulders, and head, and should provide large, uniform surfaces to distribute the loads in these directions. A variety of design approaches exist, including individually molded seat liners as provided by the Russian Soyuz or United States Mercury vehicles (shown in Figure 4.13.2.3.2-1); taut fabric seat back, seat, and leg pan as provided by the United States Apollo; as well as rigid metal seat back with minimal padding as provided by the United States Gemini and Orion vehicles and common to many aircraft ejection seats. Conformal supports should be considered for both the nominal and off-nominal load directions of seats. For instance, many capsule designs concentrate nominal loads in the x and z axes, but provide lateral support to prevent injury in the case of unexpected off-nominal loads in the y axis. Any locations on the seats or restraints where the load is supported unevenly by only a small area will concentrate the loads and increase the injurious effects of accelerations. The occupant protection crew interfaces system should be free of any such points, including those generated by interference with restraints and the flight suit, or by any rigid part of the flight suit (if applicable).

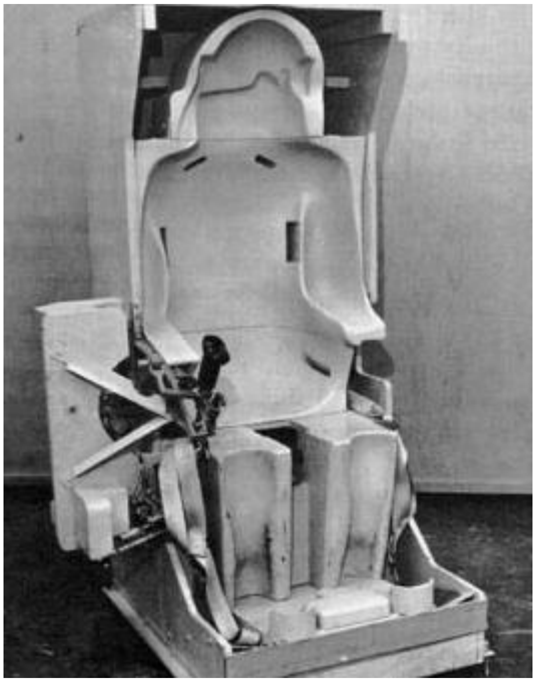


FIGURE 4.14.2.3.2-1 NASA/NACA PROJECT MERCURY CONFORMAL COUCH (SEAT)

During high-acceleration phases with rapid onset rates, the human body, and in particular the limbs and extremities, may be unable to resist the accelerations and will consequently flail relative to the cabin without design features to act as flail countermeasures. Limb flail can cause injury when flailing limbs collide with structures or when a limb of one crewmember collides with the body of another crewmember. Limb flail may also result in hyperextension or hyperflexion, injuring joints of the limb. System designers should consider the effects of limb flail in the design, and provide design countermeasures. To the degree possible, structures should be kept away from the occupant with the exception of controls. Additionally, designers may limit the magnitude of crew flail by providing limb restraints for all dynamic mission phases. Limb restraints include boot clips to fully restrain the foot, and elbow or wrist restraints to prevent arm flail beyond the designed reach area. Additionally, inserts within the helmet should prevent the crew from experiencing head and neck flail within the helmet itself. Care should be taken to ensure that any restraints do not preclude unassisted egress or prevent crewmembers from reaching critical controls.

To evaluate specific injury types, in terms of both likelihood and consequence, NASA is developing a suite of tools and measures. The Operationally Relevant Injury Scale (ORIS) describes injuries in terms of their relation to space flight crew tasking and functional needs that may be negatively affected by injuries.

A standard for acceptable risk of injury from transient acceleration is also being defined, on the basis of flight crew injury data from historically acceptable space flight systems and by comparison to acceptable risk in other relevant human transportation systems. In addition to the Brinkley Dynamic Response Model, recent advances in the automotive industry have provided additional tools for assessing injury risk during impact and dynamic loads. In determining what NASA's posture on injury risk should be, NASA has found it is helpful to review the risk postures of other industries.

Currently, NASA is using human surrogate data and additional data mining to develop injury risk functions. A set of Injury Assessment Reference Values (IARV) are being derived that specify loading limits on various portions of the human body that correspond to acceptable risk of injury. These IARVs are expected to focus on load limits such as these, for both conditioned and deconditioned crewmembers in both nominal and off-nominal situations:

- Head Injury Criteria (HIC)
- Rotational Brain Injury Criteria (BRIC)
- Peak upper neck axial tension force [N]
- Peak upper neck axial compression force [N]
- Maximum chest compression displacement [mm]
- Lateral shoulder force [N]
- Lateral shoulder deflection [mm]
- Lumbar axial compression force [N]
- Peak ankle dorsiflexion moment [Nm]
- Peak ankle inversion/eversion moment [Nm]
- Contact force [N]

Once they have been established, the IARVs must not be exceeded in any dynamic phase of flight. For additional information on the application and derivation of these values, see Somers, et al. (2012).

In addition, a deconditioning factor must be added for cases when the crew has been exposed to reduced gravity. See HIDP section 4.15 Deconditioned Crewmember for a description of space flight deconditioning effects. Each injury metric was evaluated at each injury class at the specified risk level, and the lowest IARV was chosen so as to be conservative.

Refer to the HIDH section 6.5 for more information about calculating the IARVs. These descriptions will be updated as NASA human research provides new information to inform the IARVs. This proposed method is currently under development, but other methods, with approval by NASA, may be used to evaluate and verify a minimal probability of risk to the crewmembers.

4.14.3 OCCUPANT PROTECTION DESIGN TECHNICAL PRODUCTS

For each of the major milestones of the design life cycle, the technical products in Table 4.14.3-1 are recommended for review by the NASA customer.

TABLE 4.14.3-1 TECHNICAL PRODUCTS OF OCCUPANT PROTECTION DESIGN

Technical Products	Phase A		Phase B	Phase C	Phase D	
	SRR	SDR	PDR	CDR	SIR	FRR
A description of the ConOps, function allocation, and associated crew task lists. Includes identification of potential errors that can be encountered for each task.	I	U	U	U	---	---
Definitions of environmental conditions	I	U	U	U	---	---
Monte Carlo distribution of probabilities for nominal and off-nominal landings	---	I	U	U	---	---
Definition of boundary cases for landing, and full landing FE model run for each case	---	I	U	U	---	---
Finite element subsystem models with ATD, including seat and energy attenuation system. Model fidelity should increase for each milestone review.	---	I	U	U	---	---
Brinkley Analysis						
Perform Brinkley Dynamic Response Model analysis	---	I	U	U	U	---
ATD Testing						
ATD testing	---	---	I	---	---	---
ATD verification testing	---	---	---	---	I	---
Biodynamic Results from FE Modeling						
Model correlation with ATD testing results	---	---	I	---	---	---
Assessment of finite element (FE) model	---	---	I	---	---	---
Initial biodynamic results of FE modeling	---	---	I	---	---	---
Final design results of FE modeling	---	---	---	U	---	---
Results of FE modeling after verification testing	---	---	---	---	U	---
A summary of modeling/analysis/evaluation performed to date and their influence on system design, with links to the detailed analysis results Required per NPR 8705.2B, and HITL evaluations required per paragraph 2.3.10	---	---	I	U	---	---
System architecture drawings (structures, equipment, etc.), material specifications, interface requirements.	---	---	I	U	U	---
Verification plan	---	---	I	U		---
Report on biodynamic response, crew injury limitation, and spinal alignment verification					X	

X = one-time release of item
I = initial release of item
U = updated release of item

4.14.3.1 CONCEPT OF OPERATIONS AND CREW TASK LISTS

The ConOps, described in paragraph 3.2.3.1.2, provides information such as identification of crew activities and determination of which subsystems are influenced by crew activities. Function allocation, described in paragraph 3.2.3.1.3, establishes the extent to which an activity is to be automated or assigned to humans. The crew task list, described in section 4.1 User Task Analysis, documents details including allocation of function between crew and systems, definition of the sequence of crew activities, and identification of critical tasks. For occupant protection considerations, the Concept of Operations should address such factors as seat deployment, restraint don and doff for both nominal and off-nominal situations, a description of critical tasks to be performed during restrained or partially restrained operations including reach to critical controls, and any manual tasks associated with activating the occupant protection system such as tightening restraints at key mission phases, or activating, arming, or disarming aspects of the crew impact attenuation system, parachutes, or landing system. Designers should ensure their conops and tasks lists are used to help define tasks that need to be modeled in the occupant protection systems.

4.14.3.2 SUMMARIES OF MODELING, ANALYSES, AND EVALUATIONS

Iterative summaries of modeling, analyses, and evaluations provide NASA with insight into human-system integration technical details throughout the design process. As designs mature, modeling, analyses, and evaluations should use inputs and mockups of increasingly higher fidelity, as discussed in paragraph 3.2.3.3 Evaluate Designs and Iterate Solutions. It is important that summaries address how critical design decisions were assessed. In accordance with NPR 8705.2B, updated summaries are to be provided at each design review through System Integration Review (SIR). Also in NPR 8705.2B paragraph 2.3.10, the use of human-in-the-loop (HITL) evaluation is a required method to progressively demonstrate that the operational concept meets system requirements for operational safety, efficiency, and user interface design. For occupant protection considerations, the HITL evaluations should include crew seated tasks and ingress and egress from seats including don and doff of restraints, to demonstrate that the occupant protection system does not prevent successful activation of critical controls or crew egress in emergency scenarios, and to demonstrate seat fit and function for the design population in the suited configuration (if applicable). The HITL testing may also include tests of the seat and restraints with volunteer human subjects under simulated landing and abort acceleration pulses.

4.14.3.3 ARCHITECTURE, MATERIALS, AND INTERFACE SPECIFICATIONS

Drawings, materials, and interface specifications provide NASA with insight into human-system integration technical details throughout the design process.

4.14.3.4 VERIFICATION PLAN

The verification plan is a formal document describing the specific methodologies to be used to show compliance with each requirement.

4.14.4 REFERENCES

Association for the Advancement of Automotive Medicine. (2005). *Abbreviated Injury Scale 2005*. Barrington, IL.

Brinkley, J. W., & Specker, L. J. (1989). *Development of Acceleration Exposure Limits for Advanced Escape Systems (Proceedings No. 472)*. Presented at the meeting of AGARD NATO Conference.

U.S. Department of Transportation, Research and Innovative Technology Administration, (2007). *Trends in Personal Income and Passenger Vehicle Miles*. (Bureau of Transportation Statistics Publication No. SR-006).

Dub, M. O., & McFarland, S. M. (2010). *Suited Occupant Injury Potential during Dynamic Spacecraft Flight Phases*. NASA Johnson Space Center. Houston, TX:

Duma, S., Boggess, B., Bass, C., & Crandall, J. (2003). Injury Risk Functions for the 5th percentile Female Upper Extremity. In D. Holt (Ed.), *Recent Developments in Automotive Safety Technology* (pp. 93-101). Warrendale, Pennsylvania: Society of Automotive Engineers.

Duma, S., Schreiber, P., McMaster, J., Crandall, J., Bass, C., & Pilkey, W. (1999). Dynamic injury tolerances for long bones of the female upper extremity. *Journal of Anatomy*, 194, 463-471.

Horta, L. G., Mason, B. H., & Lyle, K. H. (2009). *A Computational Approach for Probabilistic Analysis of Water Impact Simulations.* (NASA TM-2009-215704). Houston, TX: NASA Johnson Space Center.

Lawrence, C., Fasanella, E. L., Tabiei, A., Brinkley, J. W., & Shemwell, D. M. (2008). *The Use of a Vehicle Acceleration Exposure Limit Model and a Finite Element Crash Test Dummy Model to Evaluate the Risk of Injuries During Orion Crew Module Landings.* (NASA-TM-2008-215198). Houston, TX: NASA Johnson Space Center.

Kuppa, S., Wang, J., Haffner, M., & Eppinger, R. (2001). Lower Extremity Injuries and Associated Injury Criteria. 17th ESV Conference Paper No. 457.

United States Air Force. (2006). *Mapes, P. USAF Helicopter Mishap Data*. (The Human Effectiveness Directorate No. AFRL-WS 06-2221).

McFarland, S. M. (2011). Injury Potential Testing of Suited Occupants during Dynamic Spaceflight Phases. American Institute of Aeronautics and Astronautics.

Mertz, H. J., Prasad, P., & Irwin, A. L. (1997). *Injury Risk Curves for Children and Adults in Frontal and Rear Collisions (SAE 973318)*. (pp. 13-30)Presented at the Forty-First Stapp Car Crash Conference.

National Highway Traffic Safety Administration. (2012). *Motorcycle Helmets* (Federal Motor Vehicle Safety Standard No. 218).

National Aeronautics and Space Administration. NASA Space Flight Human-System Standard Volume 2: Human Factors, Habitability, and Environmental Health, January 2011.

National Aeronautics and Space Administration, Human Integration Design Handbook, NASA/SP-2010-3407, January 2010.

National Center for Statistics and Analysis. (2009). Motor Vehicle Traffic Crash Fatality Counts and Estimates of People Injured for 2007. DOT HS 811 034, U.S. Department of Transportation, National Highway Traffic Safety Administration, Washington, D.C.
National Highway Traffic Safety Administration. (1995). Final Economic Assessment, FMVSS No. 201, Upper Interior Head Protection.

Nightingale, R. W., McElhaney, J. H., Richardson, W. J., & Myers, B. S. (1996). Dynamic responses of the head and cervical spine to axial impact loading. *Journal of Biomechanics*, 29 (3), 307-318.

Federal Aviation Administration. (2011). Philippens, M., Forbes, P., Wismans, J., DeWeese, R., & Moorcroft, D. *Neck Injury Criteria for Side Facing Aircraft Seats.* (Federal Aviation Administration Final Report No. DOT/FAA/AR-09/41).

Somers, J., Granderson, B., & Scheuring, R. (2010). *Occupant Protection at NASA*. JSC-CN-21380, Houston, TX: NASA Johnson Space Center.

Somers, J., Lawrence, C., Granderson, B., Jones, J., Scheuring, R., Ridella, S., et al. (2012). Recommended changes to NASA's occupant protection standards and requirements. In Press.

Somers, J., Melvin, J., Tabiei, A., Lawrence, C., Ploutz-Snyder, R., Granderson, B., et al. (2011). Development of head injury assessment reference values based on NASA injury modeling. *Stapp Car Crash Journal*, 55.

Takhounts, E., Hasija, V., Ridella, S., Rowson, A., & Duma, S. (2011). *Kinematic Rotational Brain Injury Criterion (BRIC) (11-0263)*. Presented at the 22nd International ESV Conference.

4.15 DESIGN FOR DECONDITIONED CREWMEMBER

4.15.1 INTRODUCTION

Deconditioning refers to the decreased performance capacity of crewmembers who have been exposed to space flight. The effects of deconditioning are measurable and observable in decrements to sensorimotor function, aerobic capacity, and orthostatic tolerance, and in loss of muscle and bone strength. The occurrence of deconditioning and reduced abilities of the deconditioned crewmember must be considered in the design of spacecraft and space systems. Additionally, countermeasures must be incorporated into the concept of operations for use during space flight and post landing to effectively mitigate or manage the effects of deconditioning and ensure the health and performance of the crewmembers. Although individual responses to space flight vary, all organ systems are affected to some degree by the space flight environment. NASA has gathered data and developed requirements that reflect the best knowledge to date about responses to space flight.

Many tasks are affected by crew deconditioning. This chapter will highlight some of those areas, but will focus the design process considerations on post-landing unassisted (emergency) egress. The act of emergency egress includes, but is not limited to, rapid motor control tasks (including fine motor tasks such as object manipulation, and gross motor tasks such as opening a hatch), visual acuity tasks, and ambulation, as well as maintenance of spatial orientation and postural stability to escape safely.

4.15.2 APPLICABLE REQUIREMENTS

NASA standards for protecting the health and performance of crewmembers are captured in NASA Standard 3001 Volume 1 (Crew Health) and Volume 2 (Human Factors, Habitability, and Environmental Health). Deconditioning effects have implications for designs based on the following standards:

- For the musculoskeletal system: V2 8022, V2 8025, V2 8040, and V2 8041
- For the cardiovascular system: V2 7042
- For the sensorimotor system: V2 8015, V2 8016, V2 8018, V2 8019, V2 8020, V2 8021, V2 8024, and V2 11002, and Volume 1, section 4.2.4

These standards are based on the best available scientific and clinical evidence as well as operational experience acquired during Apollo, Skylab, Shuttle, Shuttle-Mir, and International Space Station (ISS) programs.

4.15.3 BACKGROUND

Two key factors play into crewmember deconditioning: gravity unloading and gravity transitions. With direct exposure to space flight, crewmembers experience changes in anatomy and physiology. Initially upon entering the space flight environment, crewmembers experience sensorimotor dysfunction and space motion sickness (SMS) due to a mismatch between vestibular and visual signals. The normal gravity cues sensed by the vestibular system (providing terrestrial humans with a spatial orientation) are misinterpreted once the gravitational vector is removed. The sensorimotor system will adapt to the new cues, but until that adaptation has fully taken place, a mismatch in cues leads to sensorimotor dysfunction and SMS. Sensorimotor disturbances typically resolve within the first few days of flight. Additionally, gravitational unloading leads to a cephalad fluid shift and loss of load-bearing forces on the body. Over time, this leads to progressive changes in the cardiovascular and musculoskeletal systems. Crewmembers experience bone demineralization and decreased strength and aerobic capacity due to gravity unloading. Even though countermeasures are used, they are not yet fully protective.

On landing, crewmembers experience new sensorimotor disturbances (gait dysfunction, decreased visual acuity, and postural stability disturbances), motion sickness, impaired strength and aerobic capacity, and orthostatic intolerance (which is characterized by a variety of symptoms that occur on standing, including lightheadedness, increase in heart rate, altered blood pressure, and in some cases fainting). Because of these physiological disturbances, careful consideration should be given to the deconditioned crewmember specifically during vehicle egress. The result of space flight adaptation on the human body, if not mitigated in full or in part by countermeasures, includes muscle atrophy, reduced orthostatic tolerance, reduced aerobic capacity, sensorimotor dysfunction (including gait instability and altered dynamic visual acuity), decreased bone mineral density, and changes in bone architecture. The following sections describe deconditioning and what should be considered in spacecraft design with respect to the sensorimotor, musculoskeletal (muscle and bone), and cardiovascular (aerobic capacity and orthostatic intolerance) systems.

4.15.4 SENSORIMOTOR ADAPTATION

4.15.4.1 BACKGROUND

The occurrence of sensorimotor dysfunction varies by individual, but is most prominent within the first 72 hours of space flight after gravitational transitions (entry into microgravity and landing). The spacecraft designer must consider the impacts of gravitational transitions on human performance when developing the concept of operations, crew tasks, and crew interfaces. The plasticity of the human central nervous system allows individuals to adapt to altered stimulus conditions encountered in space flight. However, until some level of adaptation is achieved, many astronauts experience space motion sickness (SMS), disturbances in gait and eye-hand coordination, unstable vision, and illusory motion of the self, the visual scene, or both (Reschke et al., 1998; Clement and Reschke, 2008).

Sensorimotor impairments can present as sudden performance decrements or failures, such as diminished visual acuity, decreased strength, impaired gait, symptoms of SMS, transient illusions, impaired gaze control, oscillopsia, or disturbances in postural equilibrium. See Paloski et al., 2008 for a complete description of the sensorimotor performance disturbances. The NASA Standard 3001, Volume 1 section 4.2.4 Fitness for Duty Sensorimotor Standards should be used to mitigate decrements in sensorimotor function, so that successful performance of all required duties is possible, including egress.

A common sensorimotor difficulty encountered upon entering the space flight environment is SMS. Symptoms of SMS can vary from mild to moderate nausea, headaches, and disorientation, to vomiting and intense discomfort. Although the symptoms are similar to terrestrial motion or sea sickness, the mechanisms are different. Current NASA countermeasures for SMS on the ISS include pharmaceuticals and minimization of crew tasks during ascent and the first few days of flight, and before reentry. The drug promethazine is part of the ISS medical kit and is prescribed either prophylactically or within the first 72 hours of flight as treatment for SMS. Additionally, since many sensorimotor disturbances are caused by mismatched visual-vestibular cues (which happens when individuals make independent eye, head, and trunk movements), a reduced or minimized list of tasks is often prescribed for crewmembers affected by SMS until adaptation takes place and SMS symptoms resolve.

Upon reentry and landing on Earth, crewmembers encounter a unique set of neurovestibular symptoms with functional consequences that must be considered in the design of crew egress procedures and interfaces (e.g., seat egress, translation paths, mobility aids, and emergency equipment). The probability and the duration of the impairment after any gravity transition will be related to both the magnitude of the gravitational transition and mission duration. Missions of longer duration typically require longer recoveries.

Water landings present additional environmental challenges to sensorimotor deconditioned crewmembers. For safety and operational reasons, returning crewmembers may need to egress the vehicle within a few minutes after a water landing under various sea state conditions. Exposure to even low frequency motions (0.2-2.0 Hz) induced by sea conditions surrounding a vessel can cause significant fine and gross motor control problems that can affect critical tasks. Furthermore, the modulation of otolith-mediated responses are frequency dependent, in that low-frequency linear acceleration may be misinterpreted as tilt and high-frequency acceleration may be misinterpreted as translation. The ambiguity of otolith-mediated information is greatest in the mid-frequency region where tilt and translation otolith mediated responses cross over. This frequency range is also the common frequency range of wave action. The minimum wave periods corresponding to different sea states (Sea States 1-7) indicate frequencies ranging from 0.125-0.5 Hz. The ambiguity of inertial motion cues is greatest in the frequency region where tilt and translation responses cross over (0.1-0.5 Hz).

Full sensorimotor recovery is expected within 15-30 days after landing. Recent data indicate that astronauts returning from long-duration space flight (6 months) experience altered locomotor function with a 48% increase in the time to complete an obstacle course on the day after landing (or return, R+1). These data indicate that a typical subject would recover to 95% of his/her pre-flight level at about 15 days post-flight (Mulavara et al. 2010). Similar recovery curves for posturography during pitch head movements have been observed after 6-month expeditions on the ISS (Wood et al. 2011).

4.15.4.2 IMPACT ON DESIGN

Physiological changes have a significant effect on crewmember ambulation during egress, and such changes should be considered and accounted for in the design of new vehicles. It is likely that crewmembers will experience impaired ability to control the spacecraft during landing and impaired ability to immediately egress after a landing on a planetary surface (Earth or other). Additionally, astronauts may (1) experience the sensation of turning while attempting to walk a straight path, (2) encounter sudden loss of postural stability, especially when rounding corners, (3) perceive exaggerated pitch and roll of head movements when walking, (4) experience sudden loss of orientation in unstructured visual environments, and/or (5) experience significant oscillopsia (a visual disturbance in which objects in the visual field appear to oscillate) during locomotion. Muscle activation patterns around heel strike and toe-off are altered after flight (Layne et al., 1998), and head pitch and vertical trunk movements are significantly reduced (Bloomberg et al., 1997). Returning crewmembers compensate for the potential loss of stability by adopting a wide base of support, taking shorter strides, and using their arms more than they did before flight. These adaptations serve to maintain stability, but walking speed is reduced and more steps are needed to cover a specified distance. The altered muscle activation patterns can mean a failure to achieve the proper toe clearance and result in tripping, which increases the risk of post-flight injury.

Hatch openings and egress pathways should be designed so that a space flight-adapted crewmember would be able to egress safely from a vehicle while meeting NASA Standard 3001, Volume 2 requirements. These requirements include configuration of egress pathways so that the adapted crewmember can egress within the time required (V2 8013 and 8014) and while in a suit (V2 8015). Since postural stability is compromised and crewmembers may be disoriented, egress pathways should be large enough to tolerate sway without injury to the crewmembers, contain handholds for balance, free of interference (V2 8016), and designed to prevent exposure to hazards or obstacles (V2 8018; e.g., crewmembers should not have to step over large objects). Additionally, since visual acuity is diminished and oscillopsia is usually present, markings and interfaces should be prominently displayed for egress tasks such as restraint release, egress pathways, and egress equipment location and operations (V2 8019).

In the challenging situation that a water egress will demand, space flight-adapted, deconditioned crewmembers will need additional time to resolve the ambiguity of inertial motion cues. These motion frequencies coupled with the varying sea state conditions (e.g., Sea State 6 results in wave heights of 4-6 meters) could cause performance deficits by affecting the efficacy of skills that depend on motor and visual acuity in tasks critical to emergency egress activities, such as visual monitoring of displays, actuating discrete controls, operating auxiliary equipment, and communicating with Mission Control and recovery teams.

Egress activities can also be impaired by post-flight motion sickness. The probability will increase with moderate to large wave activity. Thus, the sensorimotor disturbances caused by crewmembers' adaptation to space flight may disrupt the ability to perform emergency egress tasks during the initial introduction to Earth's gravity after long-duration space flight. Therefore, tasks should be designed to be as simple as possible, with ample performance time planned for the adapted crew. Additionally, crew access to motion-sickness bags without requiring ambulation or excessive head motion is essential.

4.15.5 ORTHOSTATIC INTOLERANCE

4.15.5.1 BACKGROUND

Orthostatic intolerance is an abnormal response to standing upright that results from decreased blood pressure (an inability to maintain arterial pressure) and inadequate blood flow to the brain (inadequate cerebral perfusion), and it is frequently seen in crewmembers returning from space flight. It is also one of the most important physiological changes that have a negative impact on flight operations and crew safety, especially if it progresses to presyncope or syncope. Symptoms of orthostatic intolerance are elevated heart rate, decreased stroke volume, pallor, sweating, and a drop in blood pressure or *orthostatic hypotension*. All of the orthostatic intolerance symptoms are acceptable to some degree provided orthostatic hypotension does not occur. Due to this fact, orthostatic intolerance countermeasures are geared toward preventing orthostatic hypotension. Symptoms and consequences of orthostatic hypotension include dizziness, confusion, and loss of consciousness. Without proper mitigation of orthostatic hypotension, a crewmember suffering from the effects of this condition post flight could not achieve safe and successful descent and landing (if in an upright posture), or post-landing tasks. These effects may result in an inability to operate controls, complete required tasks (such as landing the vehicle), and egress from the vehicle unassisted.

Orthostatic hypotension affects about 20%-30% of crewmembers who fly short-duration (4-18 days) missions (Fritsch-Yelle et al., 1996; Waters et al., 2002; Meck et al., 2004) and 83% of astronauts who fly long-duration (129-190 days) missions (Meck et al., 2001). The etiology of orthostatic hypotension is complicated and not completely understood. Factors include a decrease in plasma volume secondary to the cephalad fluid shift that occurs in space. Additional impacts may arise from dysfunction of the sympathetic nervous system, the renin-angiotensin-aldosterone system, and/or cardiac atrophy resulting in decreased stroke volume. A description of these mechanisms can be found in the Human Research Program Evidence Book on the *Risk of Orthostatic Intolerance During Re-exposure to Gravity* (HRP-47072).

4.15.5.2 IMPACT ON DESIGN

Mitigation strategies are required in accordance with NASA-STD-3001, V2 7042. Those used during Space Shuttle and ISS missions included

- Fluid- and salt-loading regimens before reentry to partially counteract space flight-induced losses of plasma volume
- Compression garments to prevent blood pooling in the lower body and abdomen
- Liquid cooling garments to prevent heat stress-induced orthostatic hypotension and to maintain crewmember comfort
- Recumbent crewmember seating to minimize the effects of acceleration along the long axis of the body

A fluid-loading protocol is used to partially counteract space flight-induced losses of blood plasma volume. NASA Space Shuttle flight rules stipulated that for each deorbit attempt, crewmembers must consume 48 oz of water with 12 salt tablets, or an alternate approved isotonic drink solution, during the 2-hour period before landing (Space Shuttle Operational Flight Rules, NSTS 12820 Vol A, section 13: Aeromedical: 13-57, 1996). If one orbit wave-off occurred and the fluid-loading protocol was completed, one half (24 oz) of the protocol was repeated. If the wave-off was greater than one orbit, the entire protocol (48 oz) was repeated.

Orthostatic hypotension is also counteracted by use of graduated pressure compression garments from the feet to the thorax to improve venous blood return. The mean compression provided by these countermeasure garments should be between 40 and 80 mmHg. These levels are similar to pressures provided by the NASA Anti-Gravity Suit and the Russian Kentavr, which are donned for reentry, and have been efficacious during Space Shuttle and Soyuz landings. Compression should be provided during reentry and during the period immediately post landing. Graded compression garments may be advantageous and, if used, must apply the highest pressure at the foot and ankle, lower pressures up the leg, and the lowest pressure over the abdomen to the level of the diaphragm.

Heat load (increased core temperature) and the resultant skin vasodilation can exacerbate orthostatic hypotension by causing a decrease in blood pressure. Therefore, control of body temperature through cooling or other means of dissipating metabolic heat loads is a key component of orthostatic protection. NASA crewmembers currently wear liquid cooling garments to prevent heat stress-induced orthostatic hypotension and to maintain crewmember comfort.

Another method for minimizing lower-body blood pooling during reentry is the use of recumbent seating to position crewmembers in the feet-up orientation to minimize the effects of acceleration along the long axis of the body. Note that if crewmembers reenter in feet-up orientation, lower-body compression is contraindicated until post landing when crewmembers attempt to move to a vertical, head-up orientation on the ground.

Because the greatest risk of hypotension is to the deconditioned crewmember, countermeasures are not required early in a mission, and do not apply before the start of ISS docked operations. Moreover, judging by existing NASA data, it should be assumed that most crewmembers on future exploration missions will experience post-flight orthostatic hypotension, and appropriate countermeasure garments should be allocated for all crewmembers.

Given that orthostatic hypotension produces dizziness, confusion, and/or loss of consciousness, the following factors should be considered in the design:

- Reliance on automation during descent and landing, to counter the crew's potential inability to operate controls
- If a crewmember is unconscious, provisions need to be made for safe egress of that crewmember. This may include placing appropriate handholds on the suit, allowing other crewmembers to easily grab the unconscious crewmember, or providing slide paths for dragging the incapacitated crewmember out of the vehicle.
- Clearly outlined procedures or diagrams posted near required equipment, to counter confusion and avoid errors.
- A clear egress pathway, free of obstacles and/or obtrusions that may cause injury.

Refer to HRP-47072 Human Research Program Evidence Book: Risk of Orthostatic Intolerance During Re-exposure to Gravity, and NASA/SP-2010-3407 Human Integration Design Handbook (HIDH) paragraphs 6.5.2.2 and 6.5.2.4, for information on cardiovascular deconditioning and orthostatic intolerance caused by space flight, and for details of extensive research performed by NASA on protective garments.

4.15.6 MUSCLE, BONE, AND AEROBIC CAPACITY DECONDITIONING

4.15.6.1 MUSCLE DECONDITIONING

4.15.6.1.1 BACKGROUND

Successful egress in an emergency scenario requires that designers of egress interfaces take muscle deconditioning into consideration. Muscle deconditioning decreases crewmember strength, or the ability to generate force. Skeletal muscle adaptations to space flight affect both the structure and function of the muscle. The muscles involved in maintenance of posture (antigravity muscles) in terrestrial gravity are the most susceptible to space flight-induced adaptations, as these muscles endure nearly continuous levels of self-generated and environmentally generated mechanical loading on Earth and are not extensively used during space flight. NASA-STD- 3001, Volume 1 section 4.2.8 Fitness for Duty Muscle Strength Standards provides the standards for pre-, in-, and post-flight muscle strength, which are required so that successful performance of all duties is achievable, including egress. Section 4.5.4 of this document addresses the design process for operational strength to ensure that space flight equipment and interfaces are operable by all potential crewmembers.

Long-duration space flight results in a loss of muscle strength that poses both safety and performance risks, particularly during emergency egress. The risks associated with the loss of skeletal muscle mass, strength, and endurance depend not only on the level of loss but also on the starting fitness of the individual crewmember. Thus, an operational need exists to determine the amount of strength needed to perform a task, and then attempt to maintain that strength during flight as much as possible. The goal is to prevent functional strength from falling below the level needed to complete critical mission tasks after deconditioning occurs on orbit. Crewmembers' physical requirements for the completion of tasks should be known and within strength limits specified for crewmembers.

Space flight crewmember operational force limits were developed by NASA for Constellation (now MPCV) and Commercial Crew Programs on the basis of post-flight measurements and estimated strength decrement due to deconditioning. Minimum and maximum operational load limits, based on average estimated post-flight strength decrement, were established for these programs and can be found in MPCV 70024 Human-Systems Integration Requirements (HSIR), JSC-65993 Commercial Human-Systems Integration Requirements (CHSIR), and as reference in the HIDH (Appendix B).

The performance and medical risks associated with deconditioning stem from decreases in skeletal muscle size and function, which have been reported since the beginning of human space flight (Kakurin et al., 1971). Space flight results in the loss of lean body mass as determined by body composition measurements and decreased lower-limb circumference. Data from space flight studies indicate significant loss of muscle mass/volume and strength despite use of exercise countermeasures, even on short-duration missions. After an 8-day Shuttle mission, LeBlanc et al. (2000) showed significant losses in muscle volume relative to pre-flight levels in the soleus/gastrocnemius (-6%), hamstrings (-8%), quadriceps (-6%), back (-10%), and anterior calf (-4%). After longer missions of 16-28 weeks on Mir, quadriceps (-12%), hamstrings (-16%), back (-20%), gastrocnemius (-24%), soleus (-20%), and anterior calf (-16%) muscle volumes were reduced. Reduced muscle strength accompanies the loss in muscle volume, but the magnitude of changes seems to be greater than can be explained by muscle volume alone. Greenisen et al. (1999) showed a 12% reduction in knee extensor strength and a 23% reduction in trunk flexor strength after Space Shuttle missions lasting up to 16 days. Knee extensor and flexor strength losses in long-duration (greater than 30 days) crewmembers after flights on board Mir and the ISS were 23% and 25% respectively (S. Lee, personal communication). Additionally, recent data from ISS crewmembers show that mean isokinetic strength declined 8-17% after space flight of 163 ± 38 days (mean ± SD; unpublished data). Finally, the majority of losses occur in the lower body, as these muscles are highly active in 1*g* posture and ambulation and less active in 0*g*. Upper-body strength losses are generally much less than lower-body losses.

4.15.6.1.2 COUNTERMEASURES

Mitigation strategies for strength loss include both physiological and engineering countermeasures. Resistance exercise using high-load protocols are an effective mitigation strategy to protect against loss of muscle mass and function during unloading conditions like bed rest (Alkner & Tesch, 2004; Trappe et al., 2004; Trappe et al., 2007; Trappe et al., 2007; Trappe et al., 2008). NASA-STD-3001 requires that the space system provide countermeasures to mitigate muscle loss (V2 7038).

Exercise countermeasures should provide sufficient stimuli to help mitigate the effects of microgravity on the human body. For optimal and generalizable results, resistive exercise hardware should be able to accommodate performance of a variety of exercises to protect against muscle atrophy and loss of strength, and to protect postural muscles. These exercises may include squats, deadlift, calf raise, hip flexor/extensor, hip abduction/adduction, upright row, bent-over row, lateral raise, front raise, rear raise, shoulder press, biceps curl, triceps extension, side bend, side bend (neck), neck extension, neck flexion, and bench-press capabilities.

A needs analysis should be performed to determine the hardware capabilities required as well as the exercise regime. After the needs analysis is completed, the developer should review current literature, current ISS hardware, and current available technology to devise a new concept. Some design features to address include

- Type of muscle movement – It is recommended that the hardware provide both concentric (muscle shortening under tension) and eccentric (muscle lengthening under tension) capabilities to most closely emulate terrestrial resistance exercise. Eccentric exercise training is important, as it results in greater strength gains than concentric exercise alone (Hilliard-Robertson et al., 2003).
- Load increments – Load increments should be adjustable to accommodate various crewmember capabilities.
- Minimum and maximum loads – The load levels should be determined during the needs analysis to accommodate various crewmember capabilities.
- Speed of movement – The literature suggests that speed of exercise movement has an effect on muscle strength and bone mineral density (BMD). Therefore, moderate loads at high speed (power training) may provide similar or better effects than high loads at slow speeds (von Stengel et al., 2007).
- Crew usage – If a crewmember will be exercising alone, then the hardware should be designed so that a single crewmember can perform all configurations, load setting adjustments, and exercises without assistance.

Currently NASA ISS protocols provide for resistance exercise countermeasures on all space flight missions that last longer than 7 days and include the core set of squat, deadlift, and heel-raise exercises. The primary device used for these exercises is the Advanced Resistive Exercise Device (ARED). The ARED uses vacuum cylinders to provide concentric loading up to 272 kg (600 lb), an eccentric-concentric ratio of ~90%, constant force throughout the range of motion, and inertial flywheels. The flywheels require the subject to overcome inertia to initially move the load. Strength losses have been reduced, but not eliminated, in crewmembers who have flown after ARED was deployed as the primary in-flight resistance exercise hardware. Two hours of exercise is built into the crewmember daily schedule for the un-stowing of hardware, performance of resistive and aerobic exercise (based on whatever is prescribed that day by the ASCR, or Astronaut Strength, Conditioning and Rehabilitation staff), stowing of hardware, and crewmember hygiene and clean-up.

4.15.6.2 BONE DECONDITIONING

4.15.6.2.1 BACKGROUND

Bone mineral loss occurs in space flight primarily because of unloading of the skeletal system. The average loss rates are about 1.0%-1.5% per month, according to the results of pre- and post-flight evaluations. Bone resorption (demineralization or bone loss) targets weight-bearing skeletal sites and results in deficits in areal bone mineral density (aBMD) that can range from 3 to 9% of pre-flight BMD over a typical 180-day mission. LeBlanc et al. (2000) conducted dual-energy x-ray absorptiometry (DXA) BMD measurements of crewmembers (n=16 to 18) before and after they served on the Mir spacecraft (mission duration varied from 4 to 14 months) and reported a BMD change over an entire mission. However, because of the wide range of mission lengths during this data collection period, BMD losses were normalized as percentage change per month to report an average loss of 1.0 to 1.5% on a monthly basis. BMD losses were greater in the lower limbs and the weight-bearing sites of the central skeleton. These sites included the hip and spine, sites that have a high incidence of osteoporotic fractures. It is unclear whether BMD stabilizes at a lower level early in space flight, or if it continues to diminish throughout the entire expedition. It is unknown whether fractional gravity, present on the moon and Mars, would mitigate the loss. Evidence from crewmembers flown on space missions greater than 30 days suggests that the adaptations of the skeletal system to mechanical unloading (i.e., bone mineral loss during flight) predisposes crewmembers to accelerated premature onset of osteoporosis after they return to Earth. Refer to section 4.14 Occupant Protection of this document for more information on this risk. In those calculations, a deconditioning factor is applied to account for crewmember bone deconditioning.

Declines in volumetric BMD in the proximal femur significantly reduce compressive strength, bending strength, and hip strength. In the event of a post-flight emergency vehicle egress, reduced muscular strength and endurance, and sensorimotor adaptation increase the risk of fall. This increased risk combined with reduced bone strength increases the risk of bone fracture during this critical task.

Understanding whether any bone is at risk for fracture requires evaluating its strength, that is, its capacity to resist failure under an applied mechanical loading (such as landing and vehicle egress). For the human skeleton, the measurement of areal bone mineral density [aBMD, g/cm^2] by DXA is a widely applied surrogate for bone strength. It is used clinically as a surrogate endpoint for “fragility fractures” and for the diagnosis of osteoporosis. However, in recognition that DXA measures reflect only bone density and not bone strength, NASA is working on development of new bone strength measures using finite element analysis of QCT (quantitative computerized tomography) hip scans to better estimate bone changes caused by space flight. Additionally, the Bone Fracture Risk Module [BFxRM] of the Integrated Medical Model [IMM] is a predictive model developed at the NASA Glenn Research Center. In the absence of any fracture incidence data, this model uses biomechanical algorithms, knowledge of mission operations and tasks, and the declines in astronaut BMD in space to estimate fracture probability. This module can be used to increase the understanding of bone injury and fracture risk during design for egress. The model supplies data that can be important for designing egress tasks within strength and time limits to reduce bone fracture risk.

4.15.6.2.2 COUNTERMEASURES

Attempts should be made to maintain bone mass during flight. Several factors pertaining to the development and capabilities of exercise countermeasures are important to maintaining bone mass: (1) high magnitude and rate of strain (higher strain rates provide greater bone formation responses), (2) diverse strain distributions (bone formation is specific to muscle activation and applied external loads), (3) repetition (the minimal number of repetitions depends on the load, and higher loads require fewer repetitions), and (4) rest intervals (bone sensitizes to mechanical loading stimuli, so rest intervals allow restoration of the mechanosensitivity). Newly designed exercise hardware for exploration missions should be developed on the basis of these factors, to properly maintain bone and reduce fracture risk during egress.

NASA is currently researching 2 countermeasures to bone demineralization: exercise protocols and pharmaceuticals. Exercise protocols use resistive exercise hardware to impart a load on the bone across various body segments and at varying intensities, and it is primarily this loading that assists in the maintenance of bone and bone formation. NASA is investigating a high-intensity-interval training protocol to be used during flight to determine the efficacy of the exercise for helping to maintain bone mass during long-duration missions. Design features to enhance usability, increase loading, and increase speed greatly improve the effectiveness of exercise countermeasures at preserving bone mass. Additionally, NASA is testing the effectiveness of an anti-resorptive pharmaceutical to prevent bone demineralization by inhibiting osteoclast-mediated bone resorption. The pharmaceutical (alendronate) is being tested as a prophylactic countermeasure to bone loss during flight. Further work is required to validate this drug as an effective bone countermeasure.

4.15.6.3 AEROBIC DECONDITIONING

4.15.6.3.1 BACKGROUND

Crewmember aerobic capacity decreases during space flight. This phenomenon is known as aerobic deconditioning, and is the result of reduced daily activity and cardiac stress. Aerobic deconditioning results in a diminished ability to perform strenuous physical tasks, and this condition affects the capability of a crewmember to perform an egress. Therefore, design of unassisted egress procedures and aids must take into account a decrease in crewmember aerobic capacity.

The impact of aerobic deconditioning on crewmembers needs to be minimized by having crewmembers maintain upright exercise capability during missions, in full or partial gravity. Maintaining upright exercise capability is operationally important to the success of a mission and perhaps to crew survival (Lee et al., 2007; Watenpaugh et al., 2000). Emergency egress represents a significant metabolic (>2.5 l•min$_{-1}$) and cardiovascular (>160 beats•min$_{-1}$) stress in normal ambulatory subjects (Bishop et al., 1999) and is a much greater challenge after long-duration missions of 6 months or more.

The gold standard measure of aerobic capacity is maximum oxygen uptake (VO$_2$max), which is directly related to the physical working capacity of an individual (ACSM, 2009; Astrand, 2003). VO$_2$max is the maximal level of oxygen utilization that can be attained during exercise requiring a large muscle mass (McArdle et al., 2004). Many physiological factors influence aerobic capacity. Decreased plasma volume seems to have a strong influence on aerobic capacity (Stegemann et al.; 1997), and is the most rapidly occurring adaptation to space flight. Convertino (1997) reported that 70% of the variability in VO$_2$max after bed rest deconditioning, which is an analog of space flight, can be explained by a decreased plasma volume. Reduced circulating plasma volume may negatively affect exercise stroke volume, the delivery of oxygen and nutrients to working muscles, and the removal of metabolic waste products. After landing, a reduced plasma volume is even more problematic, as upright exercise or activity can cause increased pooling of blood in the abdomen and lower body, thus degrading crewmembers' ability to perform demanding tasks such as suit donning or doffing and vehicle egress.

The NASA-STD-3001, Volume 1, section 4.2.3 Fitness for Duty Aerobic Capacity Standard requires that aerobic capacity be maintained to support successful performance of all required duties, including egress. Recent data from ISS crewmembers shows that aerobic capacity decreases initially during flight, but then increases toward pre-flight levels during the mission with exercise. Crewmembers had their aerobic capacity measured before and after flight, and performed graded exercise tests during flight approximately every 30 days. Results showed elevated heart rate early in flight during each exercise stage, and reduced oxygen pulse relative to pre-flight levels (unpublished data). Additionally, an elevated heart rate response and reduced oxygen pulse occurred soon after landing. Aerobic capacity declined in the early post-flight period and then recovered to pre-flight levels by 30 days after landing. These data show that aerobic deconditioning likely occurs in the initial in-flight period, but moderates as flight duration increases, presumably because of the use of exercise countermeasures. The elevated heart rate and reduced oxygen pulse in the early post-flight period is likely due to a combination of relative hypovolemia and cardiac atrophy but recovers within 30 days after landing. These data indicate that crewmembers have compromised aerobic capacity in the early in-flight and early post-flight timeframe.

Total crewmember deconditioning depends on the initial fitness level of the crewmember at launch, the overall capabilities of the exercise hardware (whether the hardware can provide adequate load and speed), the motivation or ability of the crewmember to complete prescribed exercise protocols (taking into consideration interruptions in exercise due to docked operations, visiting vehicles, EVA, and so on), and the capability of the food system to provide adequate calories and nutrients for crewmember health during flight.

4.15.6.3.2 COUNTERMEASURES

Mitigation strategies for aerobic deconditioning include both physiological and engineering countermeasures. High-intensity aerobic exercise, such as treadmill running and cycling, or rowing ergometry, can be used to partially mitigate the loss of aerobic capacity during space exploration. Mitigation has been demonstrated during flight analog bed rest studies (that impair aerobic performance), as well as during space flight missions (Guinet et al., 2009; Lee et al., 2007; Lee et al., 2009).

The current exercise hardware suite on the ISS that is used to mitigate decreased aerobic capacity is the second-generation treadmill (T2) and the Cycle Ergometer with Vibration Isolation and Stabilization (CEVIS) ergometer. The equipment supports continuous exercise for 30 minutes at 75% of the crewmember’s aerobic capacity for each crewmember, for several days each week, as well as high-intensity interval training, with maximal aerobic efforts for at least 30 seconds and up to 4 minutes.

4.15.6.4 IMPACTS ON DESIGN

Even with current exercise countermeasures, strength losses of 5-25% can occur, and aerobic capacity is compromised early in the post-flight timeframe. Therefore, the design of the egress tasks, markings, and interfaces, such as restraint release, egress pathways, and egress equipment location and operation, need to (1) adhere to strength limits, such as those specified in HIDH Appendix B for the deconditioned crewmember, and (2) provide support functions for the egressing crewmember. Support functions for crew egress include clear egress pathways (NASA-STD-3001, V2 8014), hand-holds, foot-steps and ladders to aid egress, and optimized mechanisms. Crew survival equipment should be operable within the strength requirements for a deconditioned crewmember, in the expected posture (e.g., lightweight, easily deployable life raft).

Egress pathways need to be free of obstructions (e.g., snags, protrusions, stowed items), clearly marked, and illuminated for emergency operations, and the number of the operations required for passage should be minimized (such as awkward turns or multiple hatch operations; V2 8014). Hatch coverings and door-opening mechanisms should also be designed so that the force required to open the mechanism is within the range of a deconditioned crewmember (that is, minimal; NASA-STD-3001, V2 8025) and the crew can egress safely within the time required (NASA-STD-3001, V2 8014 and V2 8024).

The combination of decreased strength, endurance, and sensorimotor adaptation puts the crew at increased risk of falling. This increased risk of falling, combined with reduced BMD and decreased bone strength, puts the crew at increased risk of fracture post landing. As the exact amount of bone loss, and thus the functional implications, cannot be predicted ahead of the flight, the design must attempt to reduce the probability of falling and the occurrence of fracture. This involves removing egress obstacles, not requiring crewmembers to perform strenuous tasks or tasks that put them in awkward postures, and preventing heavy loading on the bone. Utilizing the same support functions outlined for muscle and aerobic deconditioning should also prevent loss of bone strength.

Consideration must be given to the design and scheduling of crew tasks. In terms of muscle deconditioning, this is important to ensure that (1) crewmembers have reserve capacity to perform contingency or emergency response procedures, and (2) the composite task can be completed safely and effectively. For example, it is possible that a crewmember can complete any given task, nominal or off-nominal, individually, but the composite task combined with deconditioning may exceed the capabilities of the deconditioned crewmember.

4.15.7 SUMMARY

This chapter addressed some of the major physiological changes induced by space flight deconditioning. The effects of deconditioning are measurable and observable in decrements to sensorimotor function, aerobic capacity, and orthostatic tolerance, and in loss of muscle and bone strength. The result of space flight adaptation by the human body at landing, if not mitigated in full or in part by in-flight countermeasures, includes muscle atrophy, reduced orthostatic tolerance, reduced aerobic capacity, sensorimotor dysfunction (including gait instability and altered dynamic visual acuity), decreased bone mineral density, and changes in bone architecture. Table 4.15.7-1 provides an overview of crewmember deconditioning symptoms, effects, and design impacts during flight and during the descent and landing mission phases.

TABLE 4.15.7-1 OVERVIEW OF CREWMEMBER DECONDITIONING

	In-flight			**Descent & Landing**		
	Symptoms	Effects	Design Impacts	Symptoms	Effects	Design Impacts
Sensorimotor	SMS (early in flight) Nausea or vomiting, malaise, headache	Restricted movements, reduced activity	Minimize activity; provide easy access to sickness bags and medical kit; provide mobility aids	SMS Nausea or vomiting, malaise, headache	Decreased dynamic visual acuity, nausea or vomiting, gait and/or eye-hand coordination disturbances, ataxia, reduced performance	Openings and walkways that accommodate unsteady, deconditioned crewmembers; assisted egress; provide hand-holds, minimize activity and whole-body and head movements; increased task time
Muscle	Reduced strength	N/A	Exercise hardware	Fatigue, exhaustion	Decreased muscle mass, strength, and endurance; reduced performance	Openings and walkways that accommodate unsteady, deconditioned crewmembers; provide hand-holds and ladders for stability; minimize lifting; minimize force required of mechanisms; assisted egress
Bone	N/A	N/A	Exercise hardware	None	Decreased bone density, altered bone architecture, increased fracture risk	Remove obstructions to egress; provide hand-holds and ladders for stability; provide assisted egress
Orthostatic Hypotension	N/A	N/A	Compression garments and exercise hardware	Presyncope or syncope, swelling of the lower extremities	Incapacitated crewmember	Provide compression garments for egress; provide fluids and salt for fluid-loading reentry protocol; provide cooling; provide recumbent seating; provide assisted egress
Aerobic Capacity	Reduced endurance, fatigue	N/A	Exercise hardware	Fatigue, exhaustion	Decreased endurance, reduced performance	Openings and walkways that accommodate unsteady, deconditioned crewmember; provide hand-holds and ladders for stability; minimize force required of mechanisms; assisted egress

In general, crewmembers should not be required to egress their seats unassisted for any reason post landing. In the event of an emergency, such as an unassisted egress, the crew should not be required to make sudden movements, lift heavy objects, or assume awkward postures. Egress pathways need to be clear of obstructions (with appropriate toe clearances, and free of snags, protrusions, stowed items, and other obstructions), clearly marked, illuminated for emergency operations, and the number of the operations required for passage should be minimized. Several design countermeasures should be in place throughout the flight and/or before landing to reduce the effects of deconditioning on post-landing operations, including exercise hardware and protocols, compression garments, and fluid loading.

For complete scientific summaries of the space flight-induced physiological changes, see the Human Research Program's Evidence Books (http://humanresearchroadmap.nasa.gov/evidence/). The evidence books provide the current record of the state of knowledge from research and operations for each of the defined human health and performance risks for future NASA exploration missions.

4.15.8 TECHNICAL PRODUCTS

For each of the major milestones of the design life cycle, the technical products in Table 4.15.8-1 are recommended.

TABLE 4.15.8-1 DECONDITIONING TECHNICAL PRODUCTS

Technical Product	Phase A		Phase B	Phase C	Phase D	
	SRR	SDR	PDR	CDR	SAR	FRR
A description of the ConOps.	I	U	U	U	---	---
A description and justification of chosen deconditioning mitigation strategies and/or countermeasures for the defined ConOps and scenarios.	---	I	U	U	---	---
A summary of how deconditioning has been accommodated in the design.	---	---	I	U	U	---
An assessment of efficacy of the deconditioning countermeasures in appropriate flight analogs.	---	---	I	U	U	---
Verification plan, including how deconditioning mitigations will be assessed.	---	---	I	U	U	---
Validation of efficacy of selected deconditioning countermeasures.	---	---	I	U	U	---

X = one-time release of item
I = initial release of item
U = updated release of item

Concept of Operations

The ConOps, described in paragraph 3.2.3.1.2, provides information such as identification of the mission objectives, mission duration, and number of intended EVAs.

Justification for Proposed Mitigation Strategy

The developer is expected to consider all mitigation strategies and propose the method most suitable to the design reference mission. Justification of why this method is the most suitable is required.

Summaries of Modeling, Analyses, and Evaluations

Iterative summaries of modeling, analyses, and evaluations provide NASA with insight into human-system integration technical details throughout the design process. As designs mature, modeling, analyses, and evaluations should use inputs and mockups of increasingly higher fidelity, as discussed in paragraph 3.2.3.3 Evaluate Designs and Iterate Solutions. It is important that summaries address how critical design decisions were assessed. Modeling, analysis, and/or evaluation are required to progressively demonstrate that the operational concept meets system requirements for operational safety, efficiency, and user interface design.

Verification Plan

The verification plan is a formal document describing the specific methodologies to be used to show compliance with each requirement.

Validation of Method

A summary of the validation performed is required, to determine that the selected mitigation strategy will ensure crew safety and efficiency.

4.15.9 REFERENCES

Alkner, B. A., & Tesch, P. A. (2004). Efficacy of a gravity-independent resistance exercise device as a countermeasure to muscle atrophy during 29-day bed rest*. Acta Physiologica Scandinavica,* 181, 345-57.

American College of Sports Medicine (2009). *ACSM's Guidelines for Exercise Testing and Prescription*, 8th edition. Baltimore, Maryland: Lippincott Williams and Wilkins.

Astrand, P. O. (2003). *Textbook of Work Physiology*. Champaign, Illinois: Human Kinetics.

Bishop, P. A., Lee, S. M., Conza, N. E., Clapp, L. L., Moore, A. D., Jr., Williams, W. J., Guilliams, M. E., & Greenisen, M. C. (1999) Carbon dioxide accumulation, walking performance, and metabolic cost in the NASA launch and entry suit*. Aviation Space and Environmental Medicine*, 70, 656-65.

Bloomberg, J. J., Peters, B. T., Smith, S. L., Huebner, W. P., & Reschke, M. F. (1997). Locomotor head-trunk coordination strategies following spaceflight. *Journal of Vestibular Research,* 7(2-3), 161-77.

Carpenter, R. D. (2006). *Mechanobiology of Bone Cross-Sectional Development, Adaptation, and Strength.* (Unpublished doctoral dissertation). Stanford University, Stanford, CA.

Clement, G., & Reschke, M. F. (2008). *Neuroscience in Space*, New York, New York: Springer.

Cody, D. D., Gross, G. J., Hou, F. J., Spencer, H. J., Goldstein, S. A., & Fyhrie, D. P. (1999). Femoral strength is better predicted by finite element models than QCT and DXA. *Journal of Biomechanics*, 32(10), 1013-1020.

Convertino, V. A. (1997). Cardiovascular consequences of bed rest: effect on maximal oxygen uptake*. Medicine and Science in Sports and Exercise*, 29, 191-6.

Edgerton, V. R., Zhou, M-Y., Ohira, Y., Klitgaard, H., Jiang, B., Bell, G., Harris, B., Saltin, B., Gollnick, P. D., Roy, R. R., Day, M. K., Greenisen, M. (1995). Human fiber size and anymatic properties after 5 and 11 days of spaceflight. *Journal of Applied Physiology*, 78, 1733-1739.

Fitts, R. H., Trappe, S. W., Costill, D. L., Gallagher, P. M., Creer, A. C., Colloton, P. A., Peters, J. R., Romatowski, J. G., Bain, J. L., & Riley, D. A. (2010). Prolonged spaceflight-induced alterations in the structure and function of human skeletal muscle fibres. *Journal of Physiology*, 588, 3567-3592.

Fritsch-Yelle, J. M., Whitson, P. A., Bondar, R. L., & Brown, T. E. (1996). Subnormal norepinephrine release relates to presyncope in astronauts after spaceflight. *Journal of Applied Physiology*, 81(5), 2134-2141.

Greenisen, M., Hayes, J., Siconolfi, S., & Moore, A. Functional performance evaluation. In: Sawin, C. F., Taylor, G. R., Smith, W. L. (Eds*.). Extended Duration Orbiter Medical Project Final Report 1989-1995*. NASA SP-1999-534, 3.1-3.24. Houston, TX: NASA Johnson Space Center.

Guinet, P., Schneider, S. M., Macias, B. R., Watenpaugh, D. E., Hughson, R. L., Le Traon, A. P., Bansard, J. Y., & Hargens, A. R. (2009). WISE-2005 Effect of aerobic and resistive exercises on orthostatic tolerance during 60 days bed rest in women. *European Journal of Applied Physiology*, 106(2), 217-27.

Hilliard-Robertson, P., Schneider, S. M., Bishop, S. L., & Guilliams, M. E. (2003). Strength gains following different combined concentric and eccentric exercise regimens. *Aviation Space and Environmental Medicine*, 74, 342-347.

Kakurin, L. I., Cherapakhin, M. A., Ushakov, A. S., Senkevich, I*. A. (1971) Functional insufficiency of the neuromuscular system caused by weightlessness and hypokinesia*. Presented at the 14th Plenary Session, Life Sciences and Space Research X. Seattle, WA. Berlin: Akademia-Verlag, 61-4.

Layne, C. S., McDonald, P. V., & Bloomberg, J. J. (1997). Neuromuscular activation patterns during treadmill walking after spaceflight. *Experimental Brain Research*, 113(1), 104-16.

Layne, C. S., Lange, G. W., Pruett, C. J., McDonald, P. V., Merkle, L. A., Mulavara, A. P., Smith, S. L., Kozlovskaya, I. B., & Bloomberg, J. J. (1998). Adaptation of neuromuscular activation patterns during treadmill walking after long-duration spaceflight. *Acta Astronautica*, 43(3-6), 107-19.

LeBlanc, A., Lin, C., Shackelford, L., Sinitsyn, V., Evans, H., Belichenko, O., Schenkman, B., Kozlovskaya, I., Oganov, V., Bakulin, A., Hedrick, T., & Feeback, D. (2000). Muscle volume, MRI relaxation times (T2), and body composition after spaceflight. *Journal of Applied Physiology*, 89, 2158-2164.

LeBlanc, A., Schneider, V., Shackelford, L., West, S., Oganov, V., Bakulin, A., & Voronin, L. 2000. Bone mineral and lean tissue loss after long duration spaceflight. *Journal of Musculoskeletal Neuronal Interactions*, 1(2), 157-160.

Lee, S. M., Schneider, S. M., Boda, W. L., Watenpaugh, D. E., Macias, B. R., Meyer, R. S, & Hargens, A. R. (2007). Supine LBNP exercise maintains exercise capacity in male twins during 30-d bed rest. *Medicine and Science in Sports and Exercise*, 39, 1315-26.

Lee, S. M., Schneider, S. M., Boda, W. L., Watenpaugh, D. E., Macias, B. R., Meyer, R. S., & Hargens, A. R. (2009). LBNP exercise protects aerobic capacity and sprint speed of female twins during 30 days of bed rest. *Journal of Applied Physiology*, 106, 919-28.

McArdle, W. D., Katch, F. I., Katch, V. L. (2004). Exercise Physiology: Energy, Nutrition, and Human Performance. Baltimore, Maryland: Lippincott Williams and Wilkins.

Meck, J. V., Reyes, C. J., Perez, S. A., Goldberger, A. L., & Ziegler, M. G. (2001). Marked exacerbation of orthostatic intolerance after long- vs. short-duration spaceflight in veteran astronauts. Psychosomatic Medicine, 63(6), 865-873.

Meck, J. V., Waters, W. W., Ziegler, M. G., deBlock, H. F., Mills, P. J., Robertson, D., & Huang, P. L. (2004). Mechanisms of post-spaceflight orthostatic hypotension: low alpha1-adrenergic receptor responses before flight and central autonomic dysregulation postflight. American Journal of Physiology - Heart *and Circulatory* Physiology, 286(4), H1486-H1495.

Mulavara, A. P., Feiveson, A., Fiedler, J., Cohen, H. S., Peters, B. T., Miller, C. A., Brady, R., & Bloomberg, J. J. (2010). Locomotor function after long-duration spaceflight: Effects and motor learning during recovery. *Experimental Brain Research*, 202(3), 649-59.

NASA (2007). *NASA Space Flight Human System Standard Volume 1: Crew Health*. NASA-STD 3001.

NASA (2009). *NASA Space Flight Human System Standard Volume 2: Human Factors, Habitability, and Environmental Health*. NASA-STD 3001.

Paloski, W. H., Oman, C. M., Bloomberg, J. J., Reschke, M. F., Wood, S. J., Harm, D. L., Peters, B. T., Mulavara, A. P., Locke, J. P., & Stone, L. S. (2008). Risk of sensory-motor performance failures affecting vehicle control during space missions: A review of the evidence. *Journal of Gravitational Physiology*, 15(2), 1-29.

Reschke, M. F., Bloomberg, J. J., Harm, D. L., Paloski, W. P., Layne, C. S., & McDonald, P. V. (1998). Posture, locomotion, spatial orientation, and motion sickness as a function of spaceflight. *Brain Research. Brain Research Reviews,* 28(1-2), 102-17.

Stegemann, J., Hoffmann, U., Erdmann, R., & Essfeld, D. (1997). Exercise capacity during and after spaceflight. *Aviation Space and Environmental Medicine*, 68, 812-7.

Trappe, S., Trappe, T., Gallagher, P., Harber, M., Alkner, B., & Tesch, P. (2004). Human single muscle fibre function with 84 day bed-rest and resistance exercise. *Journal of Physiology*, 557, 501-513.

Trappe, T. A., Burd, N. A., Louis, E. S., Lee, G. A., & Trappe, S. W. (2007). Influence of concurrent exercise or nutrition countermeasures on thigh and calf muscle size and function during 60 days of bed rest in women. *Acta Physiologica Scandinavica*, 191, 147-159.

Trappe, S., Creer, A., Slivka, D., Minchev, K., & Trappe, T. (2007b) Single muscle fiber function with concurrent exercise or nutrition countermeasures during 60 days of bed rest in women. *Journal of Applied Physiology*, 103, 1242-1250.

Trappe, S., Creer, A., Minchev, K., Slivka, D., Louis, E., Luden, N., & Trappe, T. (2008). Human soleus single muscle fiber function with exercise or nutrition countermeasures during 60 days of bed rest. American Journal of *Physiology - Regulatory, Integrative and Comparative Physiology*, 294, R939-947.

Trappe, T. (2009). Influence of aging and long-term unloading on the structure and function of human skeletal muscle. *Applied Physiology, Nutrition, and Metabolism*, 34(3), 459-464.

Watenpaugh, D. E., Ballard, R. E., Schneider, S. M., Lee, S. M., Ertl, A. C., William, J. M., Boda, W. L., Hutchinson, K. J., & Hargens, A. R. (2000). Supine lower body negative pressure exercise during bed rest maintains upright exercise capacity. *Journal of Applied Physiology*, 89, 218-27.

Waters, W. W., Ziegler, M. G., & Meck, J. V. (2002). Post-spaceflight orthostatic hypotension occurs mostly in women and is predicted by low vascular resistance. *Journal of Applied Physiology*, 92, 586-594.

Wood, S. J., Loehr, J. A., & Guilliams, M. E. (2011). Sensorimotor reconditioning during and after spaceflight. *NeuroRehabilitation*, 29, 185-195.

4.16 DESIGN FOR MITIGATION OF DECOMPRESSION SICKNESS RISK

4.16.1 INTRODUCTION

Life on Earth exists under Earth-normal atmospheric pressure (14.7 psia, 101.3 kPa, 760 mmHg) and Earth-normal gravity (1*g*). Earth-normal atmospheric pressure is just one pressure in a range of higher and lower pressures at which humans can comfortably exist. It is the rapid transition from a high to a low pressure that is the concern for decompression sickness (DCS). These transitions occur at different stages for diving and space flight. A diver experiences DCS after completing tasks at depth (higher pressure) and then returning to the Earth-normal atmospheric pressure at the surface. By contrast, an astronaut performing an extravehicular activity (EVA) in a spacesuit is afflicted with DCS because of the decrease in pressure from the spacecraft cabin to the spacesuit. Although DCS is a significant health risk in both settings, it is space flight DCS that can compromise crew health, EVA success, and ultimately the success of a mission. DCS in astronauts is both a medical and a productivity concern, and both aspects must be considered in the definition of an acceptable risk level and development of a mitigation process.

Preventing DCS is preferred over treating the resulting signs and symptoms. Complete prevention is possible, but at significant cost, whereas management of DCS risk is often the practical approach used by a mitigation process. The overall scope of this section is to discuss DCS mitigation for planned decompressions. Decompression occurs most commonly during an EVA, but some of the mitigation strategies described are also applicable when the vehicle cabin is depressed as part of a staged decompression strategy to reduce the overall risk of DCS in preparation for phases of operations that have a higher frequency of EVAs.

4.16.2 DCS SIGNS AND SYMPTOMS

DCS signs and symptoms are historically classified as Type I, Type II, and skin bends. At JSC, Type I symptoms are described as “pain only” DCS symptoms localized in muscle(s) or joint(s) and can include localized paresthesia and simple skin bends. Type I symptoms can result in an EVA termination or abort and jeopardize mission success. If not treated, Type I symptoms can eventually become incapacitating and jeopardize recovery of an EVA crewmember.

Type II symptoms are systemic, generally neurological, involving the central nervous system; or cardiopulmonary, resulting in pulmonary “chokes,” circulatory collapse, shock, and even death; and may include multiple site paresthesias. Type II symptoms require immediate EVA abort and jeopardize both mission success and crewmember health. Type II symptoms may or may not be preceded by Type I symptoms and may be life-threatening, especially in the EVA environment, if not abated by an increase in pressure and adjunctive treatment.

Cutis marmorata is a type of skin bends, more serious than Type I skin bends, in which the skin has a marbled or mottled appearance. At JSC, this serious type of skin bends is categorized separately from Type I and Type II DCS.

DCS is also associated with gas embolism (the presence of gas bubbles in the vascular system), both venous gas emboli (VGE) and arterial gas emboli (AGE). Most physicians prefer not to allow for circulating VGE, with or without a patent foramen ovale (PFO), which is a hole in the wall separating the right and left atria of the heart. A PFO is a remnant of life in the womb, where oxygenated blood from the placental circulation is shunted away from the pulmonary circulation of the fetus. This connection closes in most newborns, but about 25% of the adult population has some small patency (hole) that allows oxygenated and deoxygenated blood to mix, potentially putting them at greater risk for DCS. If denitrogenation is not effective, either because of inadequate vehicle design or inadequate operational prebreathe (PB) protocols, then the resulting presence of VGE during an EVA could cross through a patient PFO under particular conditions and become arterialized. A high number of VGE entering the pulmonary circulation can put astronauts at high risk of arterializing VGE that are normally filtered out by a healthy lung. AGE put the astronaut at risk of vascular blockages and resulting ischemic damage to the brain or other organs.

4.16.3 BACKGROUND

Space flight DCS can occur as a result of moving from a higher atmospheric pressure to a lower pressure. This pressure change most often happens during an EVA, but could happen during a reduction in cabin pressure in preparation for EVA activities, or during an emergency. A fundamental axiom of DCS is that a transient gas supersaturation, also called over-pressure or pressure difference (ΔP), exists in a tissue region. The sum of all gas partial pressures in that region is greater than the ambient pressure, causing the release of the gas. Expressed as an equation, supersaturation exists when ΔP is positive:

$$\Delta P = \sum_{i=1}^{n} (P_i - P2), \qquad \text{Eq. 1}$$

where P_i = the summed dissolved gas tensions of oxygen (O_2), carbon dioxide (CO_2), nitrogen (N_2), and water vapor (H_2O) in the tissue; and P2 = the ambient pressure after depressurization. The potential for bubble nucleation and rate of bubble growth are a function of supersaturation.

Gas supersaturation in the tissue is not in itself harmful, but it is a thermodynamically unstable condition between the tissue and the surrounding environment. The difference between tissue gas partial pressure and ambient pressure is easily resolved with a phase transition, and some of the excess mass (moles) of gas in the form of bubbles may be accommodated by the tissue and cause no symptoms. However, when a gas space is formed because of partial or complete desaturation of a supersaturated tissue, there is a probability of DCS (P(DCS); Weathersby, Homer, & Flynn, 1984). A necessary but insufficient condition for DCS is the formation of a gas phase in the tissue, which may result in pain. The assumption that due to evolved gas, pain results from the deformation of tissue past a critical point may not account for symptoms other than pain-only DCS, but evolved gas is certainly the primary insult for all subsequent signs and symptoms. It is not the presence or even the volume of evolved gas in the tissue that is important in pain-only DCS; it is the pressure difference between the gas space and the tissue that is important. The pressure difference is termed “deformation pressure” (Nims, 1951).

Multiple strategies can be used to prevent DCS. The first strategy would be to prevent a change in the atmospheric pressure. This could be done by providing sufficient ambient gas pressure around the body by means of a mechanical structure. The use of Earth-normal atmospheric pressure (14.7 psia) inside the spacecraft, habitat, or spacesuit eliminates DCS risk.

A second strategy exposes the body to a hypobaric (lower pressure) environment but reduces ambient pressure at a rate that avoids or limits the formation of bubbles in the tissues, as denitrogenation occurs during the slow depressurization. However, when an astronaut transitions to a hypobaric environment, the amount of inert (nonphysiological) gas in excess of what can be held in solution at the new, lower pressure has the potential to come out of solution to form gas spaces that can displace or otherwise damage tissues.

Displacement of tissue by trapped gas spaces or disruption of metabolic function by embolic obstruction of blood flow can cause a wide range of signs and symptoms. To avoid this, an effective third strategy is to perform an O_2 PB, either resting or during exercise, before a transition to a hypobaric environment. Current suit technology, especially in the design of gloves, limits operation at higher suit pressures without an increase in crew fatigue and reduced mobility. So, reducing the risk of DCS by operating at a higher suit pressure during EVA has significant operational limitations. Therefore, NASA’s current primary mitigation strategy is through denitrogenation, which can be achieved in several ways, dictated by the constraints of EVA operations. Denitrogenation is the process of removing inert tissue nitrogen from the body and is most often accomplished through breathing 100% O_2 (an O_2 PB or PB). O_2 PB can be accomplished through a tight-fitting oronasal mask or in the EVA suit. Both methods have some associated difficulties. Using a mask requires a break in PB to don the EVA suit, and performing O_2 PB in the EVA suit requires extending the time in the suit. Denitrogenation protocols are effective in reducing VGE and AGE, as well as the P(DCS). After denitrogenation, an astronaut has reduced tissue N_2. The amount of dissolved N_2 that transforms into evolved gas under a modest supersaturation after a PB is very small, but is significant because of volume expansion (Boyle’s Law) at the new lower pressure. The denitrogenization strategy is not as safe as maintaining Earth-normal atmosphere, but increases the efficiency of a PB protocol to perform EVAs.

4.16.4 APPLICABLE REQUIREMENTS

The following NASA-STD-3001, Volume 2 requirements are related to the mitigation of DCS:

- Decompression Sickness Risk Identification [V2 6008]
- Decompression Sickness Capability [V2 6009]
- Suit Decompression Sickness Treatment Capability [V2 11008]

4.16.5 DEVELOPMENT OF A DCS MITIGATION PROCESS

New space flight programs will need to either select and modify an existing DCS mitigation strategy or develop a new strategy, in conjunction with vehicle design. It is wise to consider the strategy options early in the design life cycle to save potential redesign costs later. Several of the strategies outlined below have significant impacts on design, requiring consideration of EVA frequency and the mitigation of DCS risk early in the design life cycle.

4.16.5.1 DEFINE LEVEL OF ACCEPTABLE RISK

In future revisions of NASA-STD-3001, Volume 1, a standard will define the acceptable risk for space flight DCS for nominal EVAs. Nominal EVAs shall be performed using validated protocols that allow crewmembers to perform an EVA with a total risk of DCS $\leq 15\%$ and Grade IV VGE $\leq 20\%$ per person with 95% statistical confidence, and no reports of Type II DCS. The rationale is that when Type I DCS is reported at $\leq 15\%$, there have been no reported cases of Type II DCS. Beyond this standard, the P(DCS) may need to be reduced further to ensure mission success. Considerations include the importance of a successful EVA for a particular mission scenario, the available crew to perform EVA in the event DCS removes an astronaut from the EVA rotation, the association between the P(DCS) and the severity of symptoms (Allen, Maio, & Bancroft, 1971), and the availability of effective DCS treatment capability in a remote location. It is forward work to establish the level of acceptable risk for vehicle planned decompressions, but until then all decompressions should meet the limits established for EVAs.

4.16.5.2 DEVELOP CONCEPT OF OPERATIONS AND CHARACTERIZE EVA

An evaluation of the Concept of Operations (ConOps) should including a clear understanding of the mission objectives, cabin atmosphere, number of intended EVAs, frequency of EVAs, time to prepare for EVA, the activities required during EVAs, and the goals of each EVA. EVAs are the primary driver for selection of a DCS mitigation strategy. It is unlikely that the current protocols for ISS will be sufficient to support anticipated exploration mission EVAs, as they require significant crew time and consumable usage. For exploration missions, it is expected that the time to prepare for EVA will need to be minimized, especially if EVA durations are short and frequent. The physical activity on the surface of an asteroid, planet, or moon must be understood since the type, intensity, and duration of exercise during an EVA significantly influences the P(DCS). Also, a mitigation strategy for contingency EVA operations must be defined.

As described below, if the frequency of EVAs is high for a mission, then a staged decompression combined with an EVA suit that is both easy to don and doff and a quick-access entrance/exit from the vehicle will be the best design solution, given current knowledge. If the EVA preparation time is minimal, then multiple EVAs are possible within 1 day, taking advantage of the physiology of intermittent recompression. However, if EVAs will be relatively infrequent (e.g., once per month, or even once per week), a staged decompression is advantageous, but a PB protocol and an airlock entrance/exit strategy may be sufficient to prevent DCS. Preferable mitigation strategies cannot be determined solely on the basis of the frequency of EVAs. There must be an appropriate balance between cost, consumable usage (and weight), crew workload, and other factors.

4.16.5.3 DEVELOP MITIGATION SOLUTIONS

Once acceptable risk is determined and the EVA and overall mission objectives are understood, the next step is to develop a DCS mitigation strategy. DCS mitigation can be accomplished through engineering design solutions in concert with operational procedures. The 4 protocols currently available for use on the ISS all rely primarily on operational procedures. The Space Shuttle staged protocol is a good example of a combined design solution using a partial decompression of the shuttle cabin in conjunction with a reduced operational in-suit PB time.

It is assumed that a nominal vehicle cabin atmosphere is 14.7 psia. Therefore, transitions from this atmosphere require consideration of a DCS risk mitigation strategy. However, even lower nominal cabin pressures (e.g., 10.2 psia) will require mitigation of DCS if the crew will be transitioning to another pressure, such as that supported by an EVA suit. The Extravehicular Mobility Unit (EMU) currently operates at 4.3 psia, but other suit pressures are possible. For example, the Apollo suit operated at 3.75 psia, which was determined to be as low as possible with a safety margin to prevent hypoxia. Considerations for selection of a nominal suit pressure include several factors. Crewmember effort to overcome the stiffness of the suit is considered to decrease as the suit pressure decreases, but the lowest achievable suit pressure is bounded by hypoxia mitigation. The length and complexity of the denitrogenation process is based on the difference between the cabin atmosphere and the suit pressure. To minimize this difference, an EVA suit that operates at higher pressure or a staged decompression protocol, which lowers the nominal cabin pressure, can be used. Lowering cabin pressure to reduce ambient N_2 partial pressure likely includes an increase in O_2 concentration to mitigate hypoxia and to further reduce N_2 partial pressure. This approach certainly has an impact on vehicle design, as reducing tissue N_2 partial pressure to minimize the final in-suit PB time introduces a new risk of increased flammability and the cost of selection of compatible materials.

The following sections will detail several mitigation strategies to reduce P(DCS). The selective use of any or all of these strategies depends on the EVA and mission objectives in combination with the available resources.

4.16.5.3.1 MINIMIZE PRESSURE REDUCTION

Avoiding or minimizing transition to a hypobaric (lower pressure) environment avoids or limits the formation of bubbles in the tissues. Therefore, the first logical mitigation approach is to minimize pressure reduction. However, if an EVA must be performed, the crew will need to transition to a hypobaric environment because high-pressure suits, operating between 8 and 10 psia, that minimize the need for a PB are not yet practical, due to restricted mobility. However, higher pressure EVA suits may be used in the future to achieve the approximate threshold pressure to eliminate DCS (about 9.0 psia). Even a modest increase from the current EMU pressure of 4.3 psia reduces the PB (denitrogenation) time significantly. For instance, the Russian Space Agency uses the *Orlan* suit at 5.8 psia after an effective PB of about 60 min, so a higher pressure suit is a possible solution.

4.16.5.3.2 DEVELOP PREBREATHE PROTOCOL

If an EVA must be performed, then a denitrogenation protocol must be used. A PB protocol at 14.7 psia is an advantageous option for missions requiring a low frequency of EVAs. In general, PBs take several hours to complete, and thus may not be operationally efficient for missions requiring a higher frequency of EVAs.

The first step in defining a new PB protocol is to justify the operational need for a new protocol. At present 4 PB protocols are used on the International Space Station (ISS), each with advantages and disadvantages depending on the planned EVA. Mission managers and crewmembers weigh several factors, such as availability of consumables and crew time, functionality of available equipment (exercise equipment, PB masks, O_2 monitors), and crew preference, when making a choice of PB protocol. The protocols are acceptable for use because ground testing and analysis and operational implementation have shown the protocols to be safe and reliable.

The following are PB considerations:

- It is important to define the minimum PB durations that protect the greatest number of EVA astronauts, whether they are male or female and given a reasonable range of body types. In general, the amount of N_2 in the fat tissues of women is greater than in men, and the amount of N_2 in lean tissues of men is slightly greater than in lean tissues of women. Given enough PB time, the same total volume of N_2 would be removed from both genders. As PB time is always limited, the kinetics of N_2 elimination and the relative contributions of N_2 from the fat and lean tissues during a limited PB must be considered.
- Given that PB time is limited, it is possible to reduce the DCS risk by limiting the exposure time and physical activity after the decompression. Although these methods are effective, they are not acceptable as mitigation approaches for most applications that require EVA.

- Some evidence exists that certain people may be resistant to DCS (Kumar, Waligora, & Gilbert, 1992; Weathersby, 1989; Webb, Pilmanis, Balldin, & Fischer, 2005). Certain factors have been evaluated including age (Conkin, Klein, & Acock, 2003; Eckenhoff, Olstad, & Carrod, 1990; Cameron, Olstad, Clark, Gelfand, Ochroch, & Eckenhoff, 2007; Sulaiman, Pilmanis, & O'Connor, 1997; Carturan, Boussuges, Vanuxem, Bar-Hen, Burnet, & Gardette, 2002), gender (Vann, Denoble, Emmerman, & Corson, 1993; Webb, Kannan, & Pilmanis, 2003; Conkin, 2010; Thompson, Chhikara, & Conkin, 2003), aerobic fitness (Dujic, Duplancic, Marinovic-Terzic, Bakovic, Ivancev, Valic, Eterovic, Petri, Wisloff, & Brubakk, 2004; Dujic, Valic, & Brubakk, 2008; Carturan, Boussuges, Burnet, Fondaral, Vanuxem, & Gardette, 1999), hydration (Fahlman & Dromsky, 2006) and patent foramen ovale (PFO; Saary & Gray, 2001; Foster, Boriek, Butler, Gernhardt, & Bove, 2003). Selecting for natural resistance is problematic and is not required if efficient denitrogenation protocols are available. Therefore, denitrogenation is a practical means of including the greatest number of astronauts in an EVA program.
- Denitrogenation time can be reduced by incorporating exercise during the PB. Sequencing, duration, and intensity of the exercise are factors that need to be considered and merit further investigation.
- Denitrogenation through staged decompression is also practical (see below). Although it takes a longer time, a significant portion of denitrogenation can occur while the astronaut sleeps, which reduces impact on operational activities.
- The mechanism for delivering the O_2 during a PB and minimizing a break in PB need to be considered. Delivery options include a tight-fitting facemask, the EVA suit, or possibly an airlock certified to operate with enriched O_2. Use of the EVA suit is currently the only way to ensure that there is no break in PB. Any mask-based PB will eventually require some break in PB to transition into the EVA suit and knowledge about the consequences of a break in PB is inadequate. An airlock that supports 100% O_2 is an unlikely option for PB delivery as there are flammability concerns as well as a large amount of unused O_2 that might be wasted if it was not reclaimed with another system. An airlock compatible with partial O_2 enrichment may be a viable option to mitigate concerns with break in PB.

4.16.5.3.2.1 CONTROL OF TISSUE MICRONUCLEI INTO GROWING BUBBLES

In addition to reducing the amount of tissue N_2, DCS prevention also includes hindering the transformation of tissue micronuclei into growing bubbles (Tikuisis & Gerth, 2003; Blatteau, Sourauld, Gempp, & Boussuges, 2006). The presence of gaseous micronuclei in the tissues permits DCS to occur under modest depressurizations (Weathersby, Homer, & Flynn, 1982). Application of a short-duration high-pressure spike while breathing 100% O_2 is an accepted means to reduce the number and size of micronuclei (or change the distribution), as is evident from fewer bubbles or cases of DCS after a subsequent depressurization (Evans & Walder, 1969; Ikles, 1970; Vann, Grimstad, & Neilson, 1980). A high-pressure spike before EVA, possibly during the PB, is one possible intervention to reduce the size distribution of micronuclei in the tissue.

However, the difficulty of providing the technology to create the pressure spike may prohibit the application of this mitigation strategy. Also, normal physical activity establishes a size distribution of micronuclei within tissues that can be modified by changing activity or by adaptation to microgravity. Operationally, NASA handles this by recognizing that the timing of exercise countermeasures will be important for frequent EVA missions. On days when both EVAs and exercise sessions are required, exercise should be performed after the day's EVAs have been completed. Also, if an exercise PB is used, the high-intensity phase should be done early in the PB protocol.

4.16.5.3.2.2 AIR BREAK DURING PREBREATHE

Oxygen PB can be accomplished by means of either a tight-fitting oronasal mask or an EVA suit. If a mask is used, eventually a transition from the mask to the suited environment must be accomplished. A lengthy break in PB is an operational reality that could compromise an otherwise safe denitrogenation procedure and jeopardize a scheduled EVA. Current NASA Aeromedical Flight Rules define O_2 payback time on the basis of the phase and duration of a simple air break during a PB. Payback time is the number of minutes of additional PB time needed to compensate for an interruption in the original PB time. For air breaks during resting PB, the payback time on 100% O_2 is 2 times the duration of the air break. For an air break that occurs early in an exercise PB protocol, the payback time is 4 times the duration of the air break. A break in PB that lasts longer than 10 min requires that the PB be repeated from the start, or that the crew switch to an alternative PB.

Various methods to preserve the quality of, and confidence in, the PB during the transition from mask to suit have been evaluated at JSC, and all were found to be inadequate (Bateman, 1951; Clarke, Humm, & Nims, 1945; Cooke, 1976; Adams, Theis, & Stevens, 1977; Horrigan, Wells, Hart, & Goodpasture, 1979; Dixon, Adams, Olson, & Fitzpatrick, 1980; Barer, Vakar, Vorob'yev, Iseyev, Filipenkov, & Chadov, 1983; Pilmanis, Webb, Balldin, Conkin, & Fischer, 2010). Thus, payback time is required. In effect, the inability to avoid a potentially long air break in PB at 14.7 psia and uncertainty of the consequences of an air break during PB were responsible for the development of the staged denitrogenation protocols on the Shuttle and the ISS (Powell, Horrigan, Waligora, & Norfleet, 1994; Horrigan & Waligora, 1980). Use of a mitigation strategy other than, or in conjunction with, a PB is necessary if a long air break is anticipated. Any design of an EVA system should minimize the chance of an interrupted PB, an interruption that renitrogenates tissues. For example, removing the O_2 mask while at 10.2 psia and breathing a 26.5% O_2 atmosphere during the Shuttle staged protocol, the ISS campout, and ISLE PB protocols is an acceptable break in PB since denitrogenation, and not renitrogenation, continues albeit at a reduced rate. The crew can take the required time to complete suit donning without rushing to reestablish the final in-suit denitrogenation.

4.16.5.3.3 STAGED DECOMPRESSION

For mission phases that have a high-frequency EVA requirement, a staged decompression strategy is the most efficient solution since it minimizes in-suit PB time, minimizes the impact of an air break during PB, and provides the opportunity to partially denitrogenate without interfering with crew activities. A staged decompression involves reducing the overall cabin pressure (e.g., from 14.7 to 10.2 psia) for a predetermined amount of time (such as 24 hours) and then completing the O_2 PB required for suit donning. Since the cabin pressure was decreased before suit donning, the final in-suit PB time is also reduced (allowing more frequent EVAs). Once the EVAs are complete, the cabin pressure is returned to normal operating pressure (e.g., 14.7 psia).

The Shuttle staged protocol is a successful example. The orbiter cabin was maintained at a setpoint of 10.2 psia and 26.5% O_2 until all the EVAs for the mission were completed. Recent discussions have proposed a cabin environment of 8.0 psia and 32% O_2 (NASA, 2010) and more recently 8.2 psia and 34% O_2 (for new vehicle/habitat designs). Once the blood is saturated with O_2 at this environment for 24-36 hours, the O_2 PB requirements are reduced to only what is required to complete the suit-donning process. When this environment is coupled with a rapid suit-donning process, such as the use of a rear-entry EVA suit with a suitport, the transition from the cabin to EVA could be as short as 15 min.

One challenge with a staged decompression protocol is the cost-benefit trade process. Reduction of the ambient pressure reduces the DCS risk, by decreasing the inspired partial pressure of N_2 (PIN_2) from the initial Earth-normal PIN_2 (Maio, Allen, & Bancroft, 1970; Allen, Maio, Beard, & Bancroft, 1969; Cook & Robertson, 1974; Horrigan & Waligora, 1980; Waligora, Horrigan, Hadley, & Conkin, 1983). To minimize hypoxia, the staged depressurization approach requires an increase in O_2 concentration, which further reduces PIN_2. However, O_2 can be enriched only to a certain point before flammability concerns may limit any further increase. Therefore, a balance must be achieved between the increased risk of fire at higher O_2 concentration and the decreased risk of DCS as PIN_2 is reduced. The concentration of O_2 and, therefore, the risk of fire for a given ambient pressure, can be reduced further if PIO_2 is less than 150 mmHg, but not so low as to cause significant hypoxia (Conkin & Wessel, 2008). Denitrogenation may be effective to reduce the P(DCS), but even effective PB protocols may be associated with an incidence of VGE; many more subjects have VGE than report DCS, even in protocols with low DCS incidence. Significant VGE insult of the lungs at 4.3 psia increases the chance of transporting VGE through the pulmonary vasculature or through a PFO (Foster, Boriek, Butler, Gernhardt, & Bove, 2003; Moon, 2000; Pilmanis, Meissner, & Olson, 1996). Designers of a future habitat atmosphere should consider a low PIN_2 to shorten or eliminate the PB time. One practical approach to reduce the PIN_2 is to increase the PIO_2 while also reducing the ambient pressure (Allen, Maio, Beard, & Bancroft, 1969; Cooke, 1974; Horrigan & Waligora, 1980). The atmosphere for Skylab achieved a working balance between risk and reward. The science and medical community accepted 70% O_2 at 5.0 psia, since the Earth-equivalent PIO_2 would be 150 mmHg, and the risk of atelectasis was minimized because the atmosphere was 30% N_2. Scientists on Earth did not have to provide a hypoxic or hyperoxic environment as part of their ground-based control studies, so μ*g* was the only experimental variable. No dedicated PB was needed before EVAs were undertaken from Skylab in spacesuits pressurized to 3.7 psia since the tissues would eventually equilibrate to a PIN_2 of no more than 1.2 psia, far below the suit pressure. Various restrictions, such as uncomfortable flame-retardant polybenzimidazole clothing, were imposed because of the serious risk of fire in a 70% O_2 atmosphere. Skylab was a success, and the need to confront several technical issues early in the mission showed that an effective EVA capability is critical to the success of long-duration missions.

Another concern with a staged decompression protocol is that the initial pressure reduction likely transforms a subpopulation of tissue micronuclei into “silent” (asymptomatic) bubbles in some astronauts, so a 60-min PB with a mask was performed before the initial modest reduction in ambient pressure to 10.2 psia for the Shuttle staged protocol occurred (Degner, Ikels, & Allen, 1965; Waligora, Horrigan, Conkin, & Hadley, 1984; Damato, Highly, Hendler, & Michel, 1963; Vann & Torre-Bueno, 1984; Hills, 1985). Some form of this initial PB would also take place with a staged decompression to an 8.0-psi cabin pressure.

Staged decompression is the preferred strategy for missions requiring frequent EVAs (e.g., more than once per week), because of concern over the PB time required and the length of the break in PB for suit donning. A staged decompression protocol requires that the vehicle be designed (from early in the design life cycle) to ensure compatibility with the lower pressure and the O_2-enriched environment, and to accomplish these transitions in a controlled manner so that DCS risk can be minimized during the first transition from 14.7 psia to the incremental pressure. The hardware and systems must be designed to function safely at the various predetermined pressures and oxygen concentrations. Designers must also consider how the EVA crewmember will enter and exit the vehicle, as the benefit of a reduced PB will not be realized if the EVA suit preparation process takes an excessive amount of time.

4.16.5.3.4 INTERMITTENT RECOMPRESSION

Intermittent recompression is a technique that reverses the growth of bubbles during a staged decompression or even during future exploration EVAs by an exposure to a higher pressure for a short period. A recompression step while the EVA crewmember is in the suit is more effective because the crewmember is breathing 100% O_2, but it is also effective when the crewmember is returning to the vehicle/habitat pressure and breathing environment. The intermittent recompression pressure is an increase in pressure, but is smaller and longer than the “spike” pressure discussed above. The rationale for the maneuver is based on the physics of gas exchange between tissue and bubbles when pressure is applied during the time of bubble growth (Gernhardt, 1991; Abercromby, Gernhardt, & Conkin, 2008; Conkin, Gernhardt, Abercromby, & Dervay, 2008). During this recompression, the increased O_2 window (Van Liew, Conkin, & Burkard, 1993) and the benefit of surface tension on very small bubbles temporarily reverse the N_2 diffusion gradient so that N_2 leaves the bubble and is transported in a dissolved state. When the decompression resumes, less N_2 is available to move into a smaller size distribution of bubbles. The net effect is to reduce the opportunity for evolved gas in silent bubbles to reach a threshold that initiates signs and symptoms of DCS. This technique is already part of the operational PB protocols on the ISS and may be used in future exploration EVAs.

Examples of intermittent recompression in the existing ISS protocols include the return to 14.7 psia after a short suit-donning period at 10.2 psia in both the Exercise and the In-suit Light Exercise (ISLE) PB protocols and 2 returns to 14.7 psia over the course of the longer campout PB. These intermittent recompressions likely reduced the subsequent P(DCS) by removing silent bubbles. These bubbles have the potential to form from a limited number of large-radius micronuclei during the initial depressurization to 10.2 psia. After the bubbles are formed and then reabsorbed during the repressurization to 14.7 psia while breathing 100% O_2, tissues are temporarily left with a smaller range of micronuclei radii from which to grow bubbles during the final depressurization to 4.3 psia. Research showed that cumulative DCS was not a concern in repetitive hypobaric depressurizations (Conkin, Edwards, Waligora, Stanford, Gilbert, & Horrigan, 1990; Cooke, Bollinger, & Richardson, 1975; Pilmanis, Webb, Kannan, & Balldin, 2002).

Intermittent recompression might be used even more frequently if the PB time and EVA suit preparation time were reduced so that EVAs could be done as required, which is the expectation for exploration missions with the Multi-Mission Space Exploration Vehicle (MMSEV) (see below), which combines the 8.2 psia / 34% O_2 environment with a rear-entry suit and suitport operations for rapid suit and vehicle egress and ingress. Intermittent recompression is a bonus companion to the staged decompression protocol, needed when multiple EVAs are planned within a 24- to 48-hour period. Instead of one long daily EVA, as currently performed on the ISS, an astronaut could perform several short EVAs, undergoing several recompressions throughout the day and an overall reduction in P(DCS). The design of the vehicle would optimize methods for ingress and egress from the EVA suit into the vehicle.

4.16.5.3.5 PROTOCOL CONSIDERATIONS

Designers must consider several factors before selecting a DCS mitigation strategy and beginning vehicle design:

- What are the EVA needs from the vehicle? – When frequent EVAs are part of the mission architecture, then a DCS mitigation strategy that minimizes crew time and especially the PB time and break in PB time is the preferred strategy.
- What is the vehicle exit strategy? – The design of the vehicle will be greatly affected by the choice of an airlock, suitlock, suitport, or depressurizable cabin. Airlocks are well understood and were the choice for the Shuttle program and the ISS. A depressurizable cabin was the method used by the Apollo program because it had low mass requirements and a low-pressure habitat, but it offers minimal dust mitigation and planetary protection. A suitport offers direct access from the vehicle to the EVA suit and is the most rapid ingress/egress solution, but it relies on an EVA suit that can be pressurized nominally to the cabin pressure. There also is a suitlock, a hybrid of a suitport and airlock, which keeps the suit isolated from the cabin, but protected in a closed environment when it is not in use.

- How fast does the crew need to get out of the vehicle? – For missions requiring single-person, frequent, or unplanned EVAs, the crew may need to exit the vehicle in a relatively fast, efficient manner. If the crew needs to exit the vehicle quickly, a solution that has no break in PB and that minimizes PB time, suit-donning time, and habitat gas loss is the preferred strategy.
- Reclamation of gas – For efficiency purposes, consideration should be given to the reclamation of gases expelled during the pressure transition and suit-purging process. The most efficient strategy is to reclaim the gas in the vehicle environment. However, the size of the vehicle has an impact on how much gas can be reclaimed, as the overall O_2, N_2, and CO_2 concentrations must be relatively stable and within human health limits.
- Target work efficiency index – A target work efficiency index (WEI) is useful in planning for EVAs. Currently, the index NASA uses is: EVA time (out of the vehicle) / EVA preparation time. ISS-based work efficiency is currently less than 0.5. Architectures for which a higher WEI of 2-3 is desired would need a combination of a staged denitrogenation protocol with efficient suit donning/doffing and vehicle ingress/egress.
- Suit donning – Suits should be designed to be donned quickly. The break in PB is a serious concern for cases where the mask PB is the primary method of denitrogenation. Additionally, missions requiring frequent EVAs will require efficient suit donning and doffing procedures.
- Pressure and O_2 concentration – A robust, high-frequency EVA program will likely need to use a staged denitrogenation strategy that has the crew live in a lower pressure, O_2-enriched environment during the EVA stages of a mission. All vehicle elements will need to be compatible with or isolated from this environment. Examples of this include the Shuttle operating at 10.2 psia and 26.5% O_2, and the more recent environments discussed, including 8 psia and 32% O_2 (NASA, 2010), which was adjusted to 8.2 psia and 34% O_2 (HMTA memo).

The Exploration Atmospheres Working Group final report (NASA, 2010) provides a good example of a trade study conducted for an alternative to an Earth-normal atmosphere, including all of the factors for designers to consider. Refer to this report, in addition to this HIDP section, when selecting a DCS mitigation strategy or conducting an atmospheric trade analysis.

4.16.5.3.5.1 EXAMPLE VEHICLE

The MMSEV is an example of a vehicle that had DCS mitigation and high EVA capability as key initial drivers for the vehicle design. The MMSEV will be designed to operate at environments known to be compatible with other space flight vehicles. Characteristics of these environments include cabin atmospheres at 14.7 psia (21% O_2) and 10.2 psia (26.5% O_2). In addition, the MMSEV will be designed to operate at 8.2 psia / 34% O_2 during the EVA stages of a mission. The MMSEV has multiple entry points including 2 suitports and 2 hatches, and is capable of a full depressurization during an emergency, if needed. The MMSEV uses suitports as the nominal ingress/egress strategy. The combination of suit ingress, operation checkout, suitport operation, and PB is expected to be about 15 min. The EVA suit used with the MMSEV will be a variable-pressure suit, compatible with the cabin environment up to 8.2 psia, but nominally expected to be used around 4.3 psia. The variable-pressure suit can be quickly repressurized to 8.2 psia in the case of a DCS incident, allowing near-immediate treatment and quick resolution of any DCS symptoms.

4.16.5.4 PROTOCOL VALIDATION

The traditional standard approach is to validate any protocol that affects crew health, performance, and safety. Empirical validation through testing is preferred over validation through analysis. Until high confidence is attained through mathematical modeling of DCS, there will always be a requirement to empirically validate a new PB protocol.

4.16.5.4.1 PROBABILISTIC DCS MODELING

NASA uses a suite of DCS prediction models for different scenarios, but no combination of these models is currently considered robust enough for validation of a new PB protocol. These models are used as tools to generate potential PB protocol options, but these protocols then require a ground-based hypobaric chamber validation test. Models are excellent tools for evaluating subtle changes in parameters critical to P(DCS) such as depressurization time or O_2 PB time. Therefore, a small proposed operational change can be evaluated by modeling in conjunction with expert opinion and may not require ground validation testing. A more thorough discussion of DCS probabilistic modeling can be found in a recent review by Conkin (2011).

Statistical descriptions of DCS and VGE outcomes from hypobaric exposures, using logistic regression and survival analysis as well as biophysical modeling of tissue bubble dynamics, have made significant advances in the last 20 years. The integration of the 2 approaches has produced sophisticated probabilistic models. Simple descriptions of decompression dose, such as tissue ratio (TR) or ΔP, approximate the true dose (Conkin, 1994; Weathersby, Homer, & Flynn, 1982) whereas models concerning tissue bubble dynamics strive to define true dose through diffusion-based physics and consideration of mass-balance (Srinivasan, Gerth, & Powell, 2003; Epstein & Plesset, 1950; Van Liew & Hlastala, 1969; Gernhardt, 1991; Gerth & Vann, 1997; Thalmann, Parker, Survanshi, & Weathersby, 1997; Srinivasan, Gerth, & Powell, 2002; Nickolaev, 2008). Those referenced, and many others as well (Ball, Himm, Homer, & Thalmann, 1995; Tikuisis, Gault, & Nishi, 1994; Vann, 1982; Wienke, 1991), may contribute to a single evolving model to describe the P(DCS), in both diving and altitude depressurizations, by invoking multiple tissue compartments, multiple finitely diffusible gases, and a distribution of bubble nuclei that begin to grow at different times during depressurization.

4.16.5.4.2 EMPIRICAL TESTING

Prospective, sequential, statistically driven ground testing using subjects that represent the physical characteristics of astronauts is the optimal approach. Integral to this approach are accept and reject criteria for a PB protocol. Advancement in denitrogenation protocol selection is contingent on establishing *a priori* success criteria for validation trials. Validation trials should be aimed at assessment of the protocol for incidence of DCS.

A sequential design was used to good effect by Kumar et al. (Kumar, Powell, & Waligora, 1994) as a means by which to discontinue a trial when statistical significance was achieved, thus minimizing risk to research subjects. A sequential design concept was applied to the PB protocol selection for the ISS. First, an assessment of the maximum impact that a case of DCS would have on the completion of ISS assembly, balanced with an ability to effectively treat DCS on orbit, created 3 “accept” conditions for validation trials. A PB protocol was acceptable in validation trials for ISS EVA operations if no serious case (Type II) of DCS was observed, if the incidence of pain-only DCS was ≤15%, and if the incidence of Grade IV VGE was ≤20% (Gernhardt, Conkin, Foster, Pilmanis, Butler, & Fife, 2000). Second, the “accept” region during sequential trials was set at 95% statistical confidence with the “reject” region set at 70% statistical confidence, which avoided continued testing of ineffective protocols. Figure 4.16.6.4.2-1 is a visual example of how one particular prospective, sequential, statistical design was implemented. The area between the 70% reject and 95% accept regions defines a zone where continued testing is valid. As testing continues, the results trend toward the true incidence of Type I DCS. After 40 exposures and 2 cases of DCS the protocol was validated, but testing continued so as to reduce the chance of type II statistical error. The testing was stopped after 47 tests and the protocol was validated for mitigating DCS.

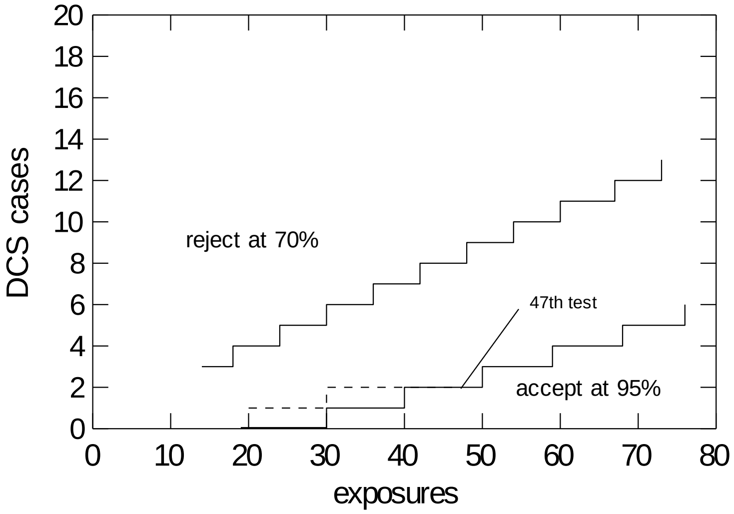


FIGURE 4.16.6.4.2-1 VISUAL EXAMPLE OF A PROSPECTIVE, SEQUENTIAL, STATISTICAL DESIGN. It can be used to limit the true incidence of Type I DCS to ≤ 15% at 95% statistical confidence. Two cases in 47 trials means that one is confident that P(DCS) is ≤ 15% at 95% confidence.

For the exercise-enhanced PB protocols, in 50 exposures the observed DCS could not exceed 3 cases (6%) and the observed Grade IV VGE could not exceed 5 cases (10%) to meet the accept conditions. One of these trials (the current Exercise PB protocol on the ISS) met accept criteria with no DCS and only 3 occurrences of Grade IV VGE in 45 exposures. Another trial (the current ISLE exercise protocol on the ISS) met accept criteria with 2 cases of Type I DCS and did not meet either accept or reject criteria with 8 occurrences of Grade IV VGE in 48 exposures. These protocols were considered acceptable for flight after extensive peer review of the research and with the realization that operational implementation of an operational PB has always included more PB than during ground testing. This will not necessarily be the case for exploration-class missions.

4.16.5.5 POST VALIDATION

Once a PB protocol is validated and approved by NASA for operational use, a significant effort is expended to operationalize the protocol. This includes documenting the detailed steps, procuring and certifying any special equipment, establishing a crew training protocol for the PB, developing a treatment response in the event DCS occurs, updating Aeromedical Flight Rules, and educating flight surgeons and mission managers about the new protocol.

For any approved and validated PB protocol, pre-flight crew training needs to be completed. The steps to execute a PB are documented, trained, and simulated before the first operational use. PB protocols based on individual characteristics, like aerobic fitness in the case of the Exercise PB, require that the crew train on the exercise devices and that a pre-flight exercise prescription be developed and provided to the crew. Information about DCS symptom recognition, levels of impact, and how to respond to a case of DCS are also provided to the crew during pre-flight training.

Training is often conducted in space flight analog environments. Policies and procedures are followed that minimize the P(DCS) after hyperbaric suited exposures in the U.S. Neutral Buoyancy Laboratory (NBL) and the Russian Space Agency's Hydrolab, during suited exposures in hypobaric chambers, and after diving activities from the NASA Extreme Environment Mission Operations (NEEMO) underwater habitat. Objectives of an EVA are choreographed on flight-like hardware submerged in 40 feet of fresh water (FFW) at the NBL. Training emulates actual EVA scenarios and can last for 6 hours. To avoid DCS after long exposures to a maximum physiological depth of 50 FFW (pool depth plus suit pressure), astronauts breathe nitrox, a mixture of 46% O_2 and 54% N_2. At this extreme, the equivalent air depth is 23 FFW. Breathing nitrox eliminates the need for staged depressurization at the end of a long training session (Fitzpatrick & Conkin, 2003). Astronauts also train and maintain proficiency in operating the spacesuit by exposure to vacuum in various altitude chambers at JSC. In some cases, astronauts are required to fly in the T-38 aircraft to complete another training activity or may fly on a commercial aircraft for personal reasons shortly after a hyperbaric or hypobaric exposure. In these cases, specific directives, based on best available research (Horrigan, LaPinta, & Conkin, 1989; Vann, Denoble, Emmerson, & Corson, 1993; Pollock & Fitzpatrick, 2004), dictate the proper surfacing intervals and PB procedures that minimize the P(DCS) on a subsequent hypobaric exposure.

Procedures and equipment are available to treat DCS on orbit and after training activities, and a disposition policy returns astronauts to flight status after they undergo a successful treatment regimen. Adherence to these policies, procedures, and Aeromedical Flight Rules, which undergo periodic review and update, minimizes the chance that DCS will become a medical concern to the astronaut or hinder the completion of training or safe execution of an EVA.

4.16.6 CURRENT DCS MITIGATION PROCESSES

Knowledge of ISS and Shuttle operational PB protocols is helpful to appreciate the complexity that even simple notions of denitrogenation achieve when they are implemented. This section outlines the techniques NASA uses to mitigate the risk of DCS when an astronaut transitions from an Earth-normal 14.7 psia spacecraft or habitat to the low-pressure EVA environment, which is conducive to evolved gas.

4.16.6.1 PROCESS 1: 4 HOURS IN SUIT

Shuttle astronauts had the option of an in-suit denitrogenation strategy, for which the astronaut simply donned the suit and breathed 100% O_2 for 3.5 - 4 hours before an EVA. The type and amount of work done in the suit and the duration of decompression set the final PB time to achieve an acceptable risk of DCS (Conkin, Waligora, Horrigan,

& Hadley, 1987). The operational challenge was to balance the length of the PB with an acceptable low incidence of DCS (Waligora, Horrigan, & Conkin, 1987). Waligora, Horrigan, Conkin, and Hadley (1984) describe tests of 3.5- and 4-hr PBs at JSC. The first of several PB protocols were evaluated with male volunteers in August 1982, and DCS was reported after the first 3.5-hr PB in one subject and one Doppler technician (Conkin, Powell, & Gernhardt, 2003; Conkin, Edwards, Waligora, Stanford, Gilbert, & Horrigan, 1990). A 4-hr PB while resting compared to a 3.5-hr resting PB reduced the incidence of DCS from 42% to 21% and the incidence of VGE from 71% to 46% in men who ambulated as part of exercise at 4.3 psia (Waligora, Horrigan, Conkin, & Hadley, 1984; Conkin, Edwards, Waligora, Stanford, Gilbert, & Horrigan, 1990).

4.16.6.2 PROCESS 2: SHUTTLE STAGED

The protocol that ultimately became the preferred PB for the Shuttle was achieved in 3 steps as follows. The first step was an initial 60-min PB by mask, of which 45 min were completed before the Shuttle atmosphere was depressurized from 14.7 to 10.2 psia and the air was enriched to 26.5% O_2 to provide an inspired partial pressure of O_2 (PIO_2) of 127 mmHg. The second step was a minimum stay of 12 hr at this intermediate pressure. And the third was an in-suit PB before a final depressurization to 4.3 psia, lasting 40 to 75 min depending on the time spent at 10.2 psia. Astronauts donned their suits at 10.2 psia and performed a final 40- to 75-min in-suit PB before final depressurization to 4.3 psia. For Shuttle missions, the cabin was typically depressurized on flight day 2 from 14.7 psia to 10.2 psia, and the cabin remained at 10.2 psia until the last EVA was completed.

Optimization of the final Shuttle 10.2 psia staged depressurization protocol took months of planning and years of validation. The first critical step was to certify the Shuttle for operations at a reduced pressure with an enriched O_2 atmosphere, as the vehicle was not planned to operate under these conditions. Several interacting variables were evaluated in isolation or combination: rate of ascent to intermediate pressure, the intermediate pressure itself (equipment cooling issues; Horrigan, Waligora, & Nachtwey, 1985), the partial pressure of O_2 (ppO_2) and ppN_2 at the intermediate pressure, hypoxia and flammability issues (Waligora, Horrigan, Bungo, & Conkin, 1982), length of stay (Waligora, Horrigan, Hadley, & Conkin, 1983; Damato, Highly, Hendler, & Michel, 1963), likelihood of silent bubbles, final suit pressure, duration of EVA, work performed in the suit, final in-suit PB time before final ascent, and balancing the acceptable risk of DCS during EVA with limited treatment options (Waligora, Horrigan, Conkin, & Hadley, 1984; Adams, Dixon, Olson, Bassett, & Fitzpatrick, 1981).

4.16.6.3 PROCESS 3: ISS CAMPOUT

A modification of the Shuttle staged decompression protocol, which is called the campout protocol, is now used on the ISS. Because the entire atmospheric pressure in the ISS cannot be reduced to 10.2 psia and enriched to 26.5% O_2, 2 astronauts must “camp out” at 10.2 psia and 26.5% O_2 in the ISS airlock. For various operational reasons, the time at 10.2 psia is limited to 8 hr and 40 min, most of which is spent sleeping. The lack of food preparation and restroom facilities in the airlock means that a repressurization to 14.7 psia is needed so that crewmembers can use the bathroom and prepare food. During this break, the astronauts breathe 100% O_2 by means of hose and mask for a minimum of 70 min. On return to 10.2 psia the masks are removed, the crewmembers eat, and the suit-donning process is completed. The airlock is then re-pressurized to 14.7 psia, after the astronauts don their spacesuits to allow an assistant to exit at 14.7 psia, and then the astronauts complete a 50-min in-suit PB before final depressurization of the airlock to the vacuum of space. After extensive review, the similarity of the campout PB to the Shuttle staged PB, along with good operational experience with the Shuttle PB, negated an empirical validation (ground testing) of the campout PB.

4.16.6.4 PROCESS 4: EXERCISE PB AND ISLE PB

After the ISS airlock was delivered on STS-104.7A in July 2001 and before the campout protocol was available in September 2006, an option to perform exercise-enhanced denitrogenation on the ISS became available. Because the elimination and uptake of N_2 is a perfusion-limited process, the use of exercise during the PB allows accelerated denitrogenation. An exercise PB protocol was needed to avoid scheduling constraints on EVAs performed from the ISS, in addition to the ambitious goal of reducing the 4-hr in-suit PB by about half. Before the delivery of the Quest airlock, EVAs to support ISS construction were performed with hatches closed between ISS and Shuttle so that Shuttle staged 10.2-psia PB could be used. The first use of exercise PB was to complete the installation of the ISS airlock. The complexity of adding an effective interval of exercise during PB must be balanced with the rewards (less total PB time and greater reduction in the P(DCS) from an alternative resting PB), or the option is not acceptable to the astronaut. In addition, although exercise is an effective denitrogenation enhancement, it is also problematic in that exercise is known to affect tissue micronuclei. Therefore exercise has both positive and negative effects on the P(DCS) and should be properly managed if used during O_2 PB.

Two exercise PB protocols that are deemed acceptable for operations on the ISS are briefly described. The first of these is the Exercise PB protocol, which uses the cycle ergometer with vibration isolation and stabilization (CEVIS) device; and the second is the In-suit Light Exercise (ISLE) PB protocol, which uses the Extravehicular Mobility Unit (EMU) as a resistive exercise device.

<u>Exercise PB (CEVIS)</u>
For the Exercise PB protocol an astronaut, months before launch, performs a peak O_2 consumption test (VO_2 peak test) using cycle ergometry, and a linear regression of VO_2 vs. watts (workload) is created. An exercise prescription is produced that distributes the appropriate workload between the upper body (12%) and the lower body (88%). Before performing an EVA, the astronaut breathes O_2 from a mask and performs 3 min of incremental exercise on the CEVIS at about 75 rpm using a prescription that increases work from 37.5% to 50.0% and then to 62.5% of VO_2 peak while also rhythmically pulling against elastic surgical tubing to include upper body activity. The exercise prescription is completed after 7 min at 75% of VO_2 peak. After waiting an elapsed time of 50 min while still breathing 100% O_2 from the mask, the astronauts and an assistant

depressurize to 10.2 psia for 30 min in the ISS airlock. During this depressurization, the astronauts don the liquid cooling garment and the lower portion of the spacesuit. Once the airlock O_2 concentration stabilizes at 26.5%, the astronauts and the assistant remove the masks and finish donning the upper torso of the spacesuit. Thus, for a good portion of the PB time, the astronaut is actively engaged in the suit-donning process. A leak check and then purge with 100% O_2 to remove N_2 from the suit completes the suit-donning procedure. In-suit PB starts in conjunction with a 5-min airlock repressurization back to 14.7 psia, where the remaining 55 min of in-suit PB are performed and the assistant exits the airlock. The final depressurization to 4.3 psia in the suit and to the vacuum of space takes 30 min.

ISLE

For the ISLE PB protocol, the astronaut does not engage in a short bout of intense PB exercise on the CEVIS before suit donning at 10.2 psia but instead performs a longer bout of mild exercise in the EMU. The ISLE PB protocol shares many steps with the Exercise PB protocol but differs from the latter in that 40 min are spent breathing 100% O_2 by mask followed by a 20-min depressurization to 10.2 psia. Once the astronaut has completed suit donning, arm and leg motions are performed in segments of 4 min followed by 1 min of rest, in conjunction with a 5-min airlock repressurization back to 14.7 psia. This mild exercise pattern continues for 50 min and achieves a minimum VO_2 of 6.8 $ml \bullet kg^{-1} \bullet min^{-1}$. An additional 50 min of resting in-suit PB completes the protocol, followed by a 30-min depressurization of the airlock to vacuum (Gernhardt & Pollock, 2006).

4.16.7 SUMMARY

DCS occurs as a result of changing from a higher to a lower pressure. For astronauts, the primary concern is transitioning from the cabin atmosphere to the suit. Because space flight DCS can compromise EVA success and ultimately the success of a mission, prevention of DCS is crucial. Multiple strategies can be used to prevent DCS. The first strategy would be to prevent a change in the atmospheric pressure. A second strategy exposes the body to a hypobaric (lower pressure) environment but reduces ambient pressure at a rate that avoids or limits the formation of bubbles in the tissues. Third, to avoid emboli or embolic obstruction of blood flow, transitions to a hypobaric environment are most often coupled with O_2 PB to initiate the denitrogenation process before depressurization occurs. Four PB protocols are currently available to use on the ISS. Development of a new mitigation strategy, such as a PB protocol, involves assessment of the level of acceptable risk and the concept of operations, development of the mitigation strategy (as described above), validation, operationalization, and training.

4.16.8 TECHNICAL PRODUCTS

For each of the major milestones of the design life cycle, the technical products in Table 4.16.8-1 are recommended.

TABLE 4.16.8-1 DCS MITIGATION TECHNICAL PRODUCTS

Technical Product	Phase A		Phase B	Phase C	Phase D	
	SRR	SDR	PDR	CDR	SAR	FRR
A description of the ConOps, cabin atmosphere, and number and frequency of EVAs.	I	U	U	U	---	---
A description of DCS mitigation strategies for the defined ConOps and scenarios, including cabin depressurization (nominal and contingency) and EVA.	---	I	U	U	---	---
A summary of the DCS mitigation strategy analyses performed to date.	---	---	I	U	U	---
Verification plan.	---	---	I	U	U	---
A description of how the selected DCS mitigation strategy for the reference mission was validated and determined to be acceptable.	---	---	---	I	U	---

I = initial release of item
U = updated release of item

Concept of Operations

The ConOps, described in paragraph 3.2.3.1.2, provides information such as identification of the mission objectives, cabin atmosphere, number of intended EVAs, frequency of EVAs, and the goals of the EVA. It is unlikely that the current protocols for the ISS will be sufficient to support anticipated exploration-mission EVAs, as they all require significant crew time and consumable usage. For exploration missions, it is expected that the time to prepare for EVA will need to be minimized, especially if EVA durations are short and frequent. The physical activity on the surface of an asteroid, planet, or moon must be understood because the type, intensity, and duration of exercise during an EVA significantly influences the P(DCS). Also, a mitigation strategy for contingency EVA operations must be defined.

Justification for Proposed Mitigation Strategy

The developer is expected to consider all mitigation strategies and propose the method most suitable to the design reference mission. Justification of why this method is the most suitable is required.

Summaries of Modeling, Analyses, and Evaluations

Iterative summaries of modeling, analyses, and evaluations provide NASA with insight into human-system integration technical details throughout the design process. As designs mature, modeling, analyses, and evaluations should use inputs and mockups of increasingly higher fidelity, as discussed in paragraph 3.2.3.3 Evaluate Designs and Iterate Solutions. It is important that summaries address how critical design decisions were assessed. Modeling, analysis, and/or evaluation are required to progressively demonstrate that the operational concept meets system requirements for operational safety, efficiency, and user interface design.

Verification Plan

The verification plan is a formal document describing the specific methodologies to be used to show compliance with each requirement.

Validation of Method

A summary of the validation performed is required, to determine that the selected mitigation strategy will ensure crew safety and efficiency.

4.16.9 REFERENCES

Abercromby, A. F. J., Gernhardt, M. L., & Conkin, J. (2008, May). *Potential benefit of intermittent recompression in reducing decompression stress during lunar extravehicular activities [abstract no. 425]*. Proceedings of 79th Annual Scientific Meeting of the Aerospace Medical Association, Boston, MA, p. 306.

Adams, J. D., Dixon, G. A., Olson, R. M., Bassett, B. E., & Fitzpatrick, E. L. (1981, May). *Preventing of bends during space shuttle EVAs using staged decompression.* Proceedings of the 1981 Aerospace Medical Association Annual Scientific Meeting, San Antonio, TX, pp. 55-56.

Adams, J. D., Theis, C. F., & Stevens, K. W. (1977, May). *Denitrogenation/renitrogenation profiles: interruption of oxygen prebreathing.* Proceedings of the 1977 Aerospace Medical Association Annual Scientific Meeting. Las Vegas, NV, pp. 42-43.

Allen, T. H., Maio, D. A., & Bancroft, R. W. (1971). Body fat, denitrogenation and decompression sickness in men exercising after abrupt exposure to altitude. *Aerospace Medicine*, *42*, 518-524.

Allen, T. H., Maio, D. A., Beard, S. E., & Bancroft, R. W. (1969). Space-cabin and suit pressures for avoidance of decompression sickness and alleviation of fire hazard. *Journal of Applied Physiology, 27*, 13-17.

Ball, R., Himm, J., Homer, L. D., & Thalmann, E. D. (1995). Does the time course of bubble evolution explain decompression sickness risk? *Undersea & Hyperbaric Medicine, 22*, 263-280.

Barer, A. S., Vakar, M. I., Vorob'yev, G. F., Iseyev, L. R., Filipenkov, S. N., & Chadov, V. I. (1983). Influence of addition of nitrogen to inhaled oxygen on efficacy of two-hr denitrogenation before decompression from 760 to 220 mm Hg [in Russian]. *Space Biology and Aerospace Medicine, 17*, 66-69.

Bateman, J., B. (1951). Preoxygenation and nitrogen elimination. Part I: Review of data on value of preoxygenation in prevention of decompression sickness. In: J. F. Fulton (Ed.), *Decompression sickness* (pp. 242-277). Philadelphia, PA: WB Saunders.

Blatteau, J.-E., Souraud, J.-B., Gempp, E., & Boussuges, A. (2006). Gas nuclei, their origin, and their role in bubble formation. *Aviation, Space, and Environmental Medicine, 77,* 1068-1076.

Cameron, B. A., Olstad, C. S., Clark, J. M., Gelfand, R., Ochroch, E. A., & Eckenhoff, R. G. (2007). Risk factors for venous gas emboli after decompression from prolonged hyperbaric exposures. *Aviation, Space, and Environmental Medicine*, *78,* 493-499.

Carturan, D., Boussuges, A., Burnet, H., Fondaral, J., Vanuxem, P., & Gardette, B. (1999). Circulating venous bubbles in recreational diving: relationship with age, weight, maximum oxygen uptake, and body fat percentage. *International Journal of Sports Medicine*, *20*, 410-414.

Carturan, D., Boussuges, A., Vanuxem, P., Bar-Hen, A., Burnet, H., & Gardette, B. (2002). Ascent rate, age, maximal oxygen uptake, adiposity, and circulating venous bubbles after diving. *Journal of Applied Physiology*, *93*, 1349-1356.

Clarke, R. W, Humm, F. D., & Nims, L. F. (1945). The efficacy of preflight denitrogenation in the prevention of decompression sickness. (National Research Council, Committee on Medical Research, Report 472). New Haven, CT: Yale Aeromedical Research Unit, Yale University.

Conkin, J. Diver and aviator decompression sickness and gender. (2010). In: C. E. Fife & M. St. Leger Dowse (Eds.) *Women and pressure* (pp. 27-40). Flagstaff, AZ: Best Publishing Co.

Conkin, J. (2011, June). Preventing decompression sickness over three decades of extravehicular activity (NASA Technical Publication 2011-216147). Houston, TX: NASA Johnson Space Center.

Conkin, J. (1994). *Probabilistic modeling of hypobaric decompression sickness* [dissertation]. Buffalo, NY: State University of New York at Buffalo.

Conkin, J., Edwards, B. F., Waligora, J. M., Stanford, J., Jr., Gilbert, J. H., III, & Horrigan, D. J., Jr. (1990, October). Updating empirical models that predict the incidence of aviator decompression sickness and venous gas emboli for shuttle and space station extravehicular operations (NASA Technical Memorandum 100456 Update). Houston, TX: NASA Johnson Space Center.

Conkin, J., Gernhardt, M. L., Abercromby, A.F.J., & Dervay, J. P. (2008). Delaying venous gas emboli formation with oxygen prebreathe and intermediate recompression [abstract no. 52]. 79th Annual Scientific Meeting of the Aerospace Medical Association, Boston, MA, pp. 219, May 11-15, 2008.

Conkin, J., Klein, J. S., & Acock, K. E. (2003, July). Description of 103 cases of hypobaric decompression sickness from NASA-sponsored research (1982 to 1999) (NASA Technical Publication 2003-212052). Houston, TX: NASA Johnson Space Center.

Conkin, J., Powell, M. R., & Gernhardt, M. L. (2003). Age affects severity of venous gas emboli on decompression from 14.7 to 4.3 psia. *Aviation, Space, and Environmental Medicine, 74,* 1142-1150.

Conkin, J., Waligora, J. M., Horrigan, D. J., Jr., & Hadley, A. T., III. (1987). *The effect of exercise on venous gas emboli and decompression sickness in human subjects at 4.3 psia* (NASA Technical Memorandum 58278). Houston, TX: NASA Johnson Space Center.

Conkin, J., & Wessel, J. H., III. (2008). Critique of the equivalent air altitude model. *Aviation, Space, and Environmental Medicine, 79,* 975-982.

Cooke, J. P. (1976). Denitrogenation interruptions with air. *Aviation, Space, and Environmental Medicine 47*, 1205-1209.

Cooke, J. P., Bollinger, R. R., & Richardson, B. (1975). Prevention of decompression sickness during a simulated space docking mission. *Aviation, Space, and Environmental Medicine*, *46*, 930-933.

Cooke, J. P., & Robertson, W. G. (1974). Decompression sickness in simulated Apollo-Soyuz space missions. *Aerospace Medicine*, *45*, 297-300.

Damato, M. J., Highly, F. M., Hendler, E., & Michel, E. L. (1963). Rapid decompression hazards and prolonged exposure to 50 percent oxygen – 50 percent nitrogen atmosphere. *Aerospace Medicine*, *34*, 1037-1040.

Degner, E. A., Ikels, K. G., & Allen, T. H. (1965). Dissolved nitrogen and bends in oxygen-nitrogen mixtures during exercise at decreased pressures. *Aerospace Medicine*, *36*, 418-425.

Dixon, G. A., Adams, J. D., Olson, R. M., & Fitzpatrick, E. L. (1980, May). Validation of additional prebreathing times for air interruptions in the shuttle EVA prebreathing profile. *Proceedings of the 1980 Aerospace Medical Association Annual Scientific Meeting*. (pp. 16-17). Anaheim, CA.

Dujić, Z., Duplancic, D., Marinovic-Terzic, I., Bakovic, D., Ivancev, V., Valic, Z., Eterovic, D., Petri, N. M., Wisløff, U., & Brubakk, A. O. (2004). Aerobic exercise before diving reduces venous gas bubble formation in humans. *Journal of Physiol*ogy 555:637-642.

Dujić, Z., Valic, Z., & Brubakk, A. O. (2008). Beneficial role of exercise on scuba diving. *Exercise and Sport Sciences Reviews*, *36*,38-42.

Eckenhoff, R. G., Olstad, C. E., & Carrod, G. E. (1990). Human dose-response relationship for decompression and endogenous bubble formation. *Journal of Applied Physiology*, *69*, 914-918.

Epstein, P. S., & Plesset, M. S. (1950). On the stability of gas bubbles in liquid-gas solutions. *Journal of Chemical Physics, 18*, 1505-1509.

Evans, A., & Walder, D. N. (1969). Significance of gas micronuclei in the aetiology of decompression sickness. *Nature*, *222*, 251-252.

Fahlman, A., & Dromsky, D. M. (2006). Dehydration effects on the risk of severe decompression sickness in a swine model. *Aviation, Space, and Environmental Medicine*, *77*,102-106.

Fitzpatrick, D. T., & Conkin, J. (2003). Improved pulmonary function in working divers breathing nitrox at shallow depths. *Aviation, Space, and Environmental Medicine*, *74*, 763-767.

Foster, P. P., Boriek, A. M., Butler, B. D., Gernhardt, M. L., & Bové, A. A. (2003). Patent foramen ovale and paradoxical systemic embolism: a bibliographic review. *Aviation, Space, and Environmental Medicine*, *74*(suppl), B1-B64.

Gernhardt, M. L. (1991). *Development and evaluation of a decompression stress index based on tissue bubble dynamics [dissertation]*. Philadelphia: University of Pennsylvania.

Gernhardt, M. L., Conkin, J., Foster, P. P., Pilmanis, A. A., Butler, B. D., & Fife, C. E. (2000). Design of a 2-hr prebreathe protocol for space walks from the international space station [abstract no. 43]. *Aviation, Space, and Environmental Medicine*, *71*, 49.

Gernhardt, M. L., & Pollock, N. W. (2006, April). *Prebreathe reduction program V-4 status report and options for protocol V-5*. Houston, TX: NASA Johnson Space Center. Contact authors for copy of report.

Gerth, W. A., & Vann, R. D. (1997). Probabilistic gas and bubble dynamics models of DCS occurrence in air and nitrogen-oxygen diving. *Undersea & Hyperbaric Medicine*, *24*, 275-292.

Hills, B. A. (1985). Compatible atmospheres for a space suit, space station, and shuttle based on physiological principles. *Aviation, Space, and Environmental Medicine*, *56*, 1052-1058.

Horrigan, D. J., Jr., LaPinta, C. K., & Conkin, J. (1989, December). NASA requirements for underwater training and surface intervals before flying. In P. J. Sheffield (Ed.) *Flying after diving. Proceedings of the 39th Undersea and Hyperbaric Medical Society Workshop* (UHMS Report 77). (pp. 11-27). Bethesda, MD: Undersea and Hyperbaric Medical Society.

Horrigan, D. J., Jr., & Waligora, J. M. (1980, May). The development of effective procedures for the protection of space shuttle crews against decompression sickness during extravehicular activities. *Proceedings of the 1980 Aerospace Medical Association Annual Scientific Meeting*. *(*pp. 14-15). Anaheim, CA.

Horrigan, D. J., Jr., Waligora, J. M., & Nachtwey, D. S. (1985, July). *Physiological considerations for EVA in the space station era* (SAE Technical Series No. 851313)*.* Paper presented at 15th International Conference on Environmental Systems. San Francisco, CA.

Horrigan, D. J., Jr., Wells, C. H., Hart, G. B., & Goodpasture, J. E. (1979, May). The uptake and depletion of inert gases in muscle and subcutaneous tissues of human subjects. *Proceedings of the 1979 Aerospace Medical Association Annual Scientific Meeting* (pp. 264-265). Washington, DC.

Ikles, K. G. (1970). Production of gas bubbles in fluid by tribonucleation. *Journal of Applied Physiology*, *28*, 524-527.

JSC CMO Health and Medical Technical Authority (HMTA) (2012, August). Level II position on potential atmospheres for exploration (HMTA Memo SA-12-067). Houston, TX: Johnson Space Center.

Kumar, K. V., Powell, M. R., & Waligora, J. M. (1994). Early stopping of aerospace medical trials: application of sequential principles. *Journal of Clinical Pharmacology*, *34*, 596-598.

Kumar, K. V., Waligora, J. W, & Gilbert, J. H., III. (1992). The influence of prior exercise at anaerobic threshold on decompression sickness. *Aviation, Space, and Environmental Medicine*, *63*, 899-904.

Loftin, K. C., Conkin, J., & Powell, M. R. (1997). Modeling the effects of exercise during 100% oxygen prebreathe on the risk of hypobaric decompression sickness. *Aviation, Space, and Environmental Medicine*, *68*, 199-204.

Maio, D. A., Allen, T. H., & Bancroft, R. W. (1970). Decompression sickness and measured levels of exercise on simulated Apollo missions. *Aerospace Medicine*, *41*, 1162-1165.

Moon, R. E. (2000). Patent foramen ovale (PFO) and decompression illness (DCI) in space [abstract no. 380]. *Aviation, Space, and Environmental Medicine*, *71*,125.

National Aeronautics and Space Administration. (2010, October). *Recommendations for exploration spacecraft internal atmospheres: The final report of the NASA Exploration Atmospheres Working Group* (NASA Technical Publication 2010-216134). Houston, TX: NASA Johnson Space Center.

Nikolaev, V. P. (2008). Simulation of cumulative risk of developing altitude decompression sickness. *Aviation, Space, and Environmental Medicine*, *79*, 21-29.

Nims, L. F. (1951). Environmental factors affecting decompression sickness. Part I: Physical theory of decompression sickness. In J. F. Fulton (Ed.), *Decompression sickness* (pp. 192-222). Philadelphia, PA: WB Saunders.

Pilmanis, A. A., Meissner, F.W, & Olson, R. M. (1996). Left ventricular gas emboli in six cases of altitude induced decompression sickness. *Aviation, Space, and Environmental Medicine, 67*, 1092-1096.

Pilmanis, A. A., Webb, J. T., Balldin, U. I., Conkin, J., & Fischer, J. R. (2010). Air break during preoxygenation and risk of altitude decompression sickness. *Aviation, Space, and Environmental Medicine*, *81*, 944-950.

Pilmanis, A. A., Webb, J. T., Kannan, N., & Balldin, U. I. (2002).The effect of repeated altitude exposures on the incidence of decompression sickness. *Aviation, Space, and Environmental Medicine*, *73*, 525-531.

Pollock, N. W, & Fitzpatrick, D. T. (2004). NASA flying after diving procedures. In P. J. Sheffield & R. D. Vann (Eds.) *DAN flying after diving workshop proceedings* (pp. 59-64). Durham, NC: Divers Alert Network.

Powell, M. R., Horrigan, D. J., Jr., Waligora, J. M., & Norfleet, W. T. (1994). Extravehicular activities. In A. E. Nicogossian, C. Leach Huntoon, & S. L. Pool (Eds.), *Space physiology and medicine*, 3rd ed. (pp. 128-140). Philadelphia, PA: Lea & Febiger.

Saary, M. J., & Gray, G. W. (2001). A review of the relationship between patent foramen ovale and type II decompression sickness. *Aviation, Space, and Environmental Medicine*, *72*, 1113-1120.

Srinivasan, R. S., Gerth, W. A., & Powell, M. R. (2003). Mathematical model of diffusion-limited evolution of multiple gas bubbles in tissue. *Annals of Biomedical Engineering, 31*, 471-481.

Srinivasan, R. S., Gerth, W. A., & Powell, M. R. (2002). A mathematical model of diffusion-limited gas bubble dynamics in unstirred tissue with finite volume. *Annals of Biomedical Engineering, 30*, 232-246.

Sulaiman, Z. M., Pilmanis, A. A., & O’Connor, R. B. (1997). Relationship between age and susceptibility to altitude decompression sickness. *Aviation, Space, and Environmental Medicine*, *68,* 695-698.

Thalmann, E. D., Parker, E. C., Survanshi, S. S., & Weathersby, P. K. (1997). Improved probabilistic decompression model risk predictions using linear-exponential kinetics. *Undersea & Hyperbaric Medicine*, *24*, 255-274.

Thompson, L. A., Chhikara, R. S., Conkin, J., & Cox. (2003, March). Proportional hazards models for modeling the time to onset of decompression sickness in hypobaric environments (NASA Technical Publication 2003-210791). Houston, TX: NASA Johnson Space Center.

Tikuisis, P., Gault, K. A., & Nishi, R. Y. (1994). Prediction of decompression illness using bubble models. *Undersea & Hyperbaric Medicine, 21*, 129-143.

Tikuisis, P., & Gerth, W. A. (2003). Decompression theory. In A.O. Brubakk & T. S. Neuman (Eds.) *The physiology and medicine of diving*, 5th ed. (pp. 419-454). New York, NY: Saunders.

Van Liew, H. D., Conkin, J., & Burkard, M. E. (1993). The oxygen window and decompression bubbles: estimates and significance. *Aviation, Space, and Environmental Medicine*, *64,* 859-865.

Van Liew, H. D., & Hlastala, M. P. (1969). Influence of bubble size and blood perfusion on absorption of gas bubbles in tissues. *Respiratory Physiology, 7*, 111-121.

Vann, R. D. (1982). Decompression theory and applications. In P. B. Bennett & D. H. Elliott (Eds.), *The physiology and medicine of diving,* 3rd ed. (pp. 366-370). San Pedro, CA: Best Publishing.

Vann, R. D., Denoble, P., Emmerman, M. N., & Corson, K. S. (1993). Flying after diving and decompression sickness. *Aviation, Space, and Environmental Medicine*, *64*, 801-807.

Vann, R. D., Grimstad, J., & Nielsen, C. H. (1980). Evidence for gas nuclei in decompressed rats. *Undersea Biomedical Research*, *7,* 107-112.

Vann, R. D., & Torre-Bueno, J. R. (1984). A theoretical method for selecting space craft and space suit atmospheres. *Aviation, Space, and Environmental Medicine*, *55*, 1097-1102.

Waligora, J. M., Horrigan, D. J., Jr., Bungo, M. W., & Conkin, J. (1982). Investigation of combined effects of bedrest and mild hypoxia. *Aviation, Space, and Environmental Medicine, 53*, 643-646.

Waligora, J. M., Horrigan, D. J., Jr., & Conkin, J. (1987). The effect of extended oxygen prebreathing on altitude decompression sickness and venous gas bubbles. *Aviation, Space, and Environmental Medicine*, *58*(suppl 9), A110-A112.

Waligora, J. M., Horrigan, D. J., Jr., Conkin, J., & Hadley, A. T., III. (1984, June). *Verification of an altitude decompression sickness protocol for shuttle operations utilizing a 10.2 psi pressure stage* (NASA Technical Memorandum 58259). Houston, TX: NASA Johnson Space Center.

Waligora, J. M., Horrigan, D. J., Jr., Hadley, A. T., III, & Conkin, J. (1983, May). Evaluation of a stage decompression protocol to prevent altitude decompression sickness. *Proceedings of the 1983 Aerospace Medical Association Annual Scientific Meeting* (pp. 124-125). Houston, TX.

Weathersby, P. K. (1989). Individual susceptibility to DCS. In: Vann R. D., ed. *The Physiological Basis of Decompression*. 38th Undersea and Hyperbaric Medical Society Workshop, Bethesda, Md, June 1, 1989. 1989:372-373. Reproduces data from J.S. Gray. (1947). Studies on altitude decompression sickness. IV. Attempts to avoid decompression sickness by selection of resistant personnel. *Journal of Aviation Medicine, 18*, 88-95.

Weathersby, P. K., Homer, L. D., & Flynn, E. T. (1984). On the likelihood of decompression sickness. *Journal of Applied Physiology*, *57*, 815-825.

Weathersby, P. K., Homer, L. D., & Flynn, E. T. (1982). Homogenous nucleation of gas bubbles in vivo. *Journal of Applied Physiology*, *53*, 940-946.

Webb, J. T., Kannan, N., & Pilmanis, A. A. (2003). Gender not a factor for altitude decompression sickness risk. *Aviation, Space, and Environmental Medicine*, *74*, 2-10.

Webb, J. T., Pilmanis, A. A., Balldin, U. I., & Fischer, J. R. (2005). Altitude decompression sickness susceptibility: influence of anthropometric and physiologic variables. *Aviation, Space, and Environmental Medicine*, *76*, 547-551.

Wienke, B. R. (1991). *Basic decompression theory and application*. Flagstaff, AZ: Best Publishing Co.

4.17 SPACE FOOD SYSTEM DESIGN

4.17.1 INTRODUCTION

The space food system must provide food that is safe, nutritious, and acceptable to the crew, to maintain crew health and performance during space flight. Provisioning of a space food system begins with qualified personnel, facilities, and equipment. The food system must be developed according to the requirements outlined in the NASA-STD-3001. The food system is complex, and consideration must be given to multiple factors including menu development, suitability in microgravity, acceptability, packaging, safety, and stowage. This section describes how to consider these factors when developing a food system and provides examples and lessons learned from NASA's food system. More detail on factors that must be considered during food system development can be found in the NASA Human Integration Design Handbook (HIDH) section 7.2.

4.17.2 APPLICABLE REQUIREMENTS

The following requirements from NASA-STD-3001, Volume 2 are applicable to the space food system:

- Spacecraft maximum allowable concentrations (SMAC) for airborne contaminants [V2 6004; V2 6005; V2 6050]
- Food Quality [V2 7001]
- Food Acceptability [V2 7002]
- Food Caloric Content [V2 7003]
- EVA Food Caloric Content [V2 7004]
- Food Macronutrients [V2 7005]
- Food Micronutrients [V2 7006]
- Food Microorganism Levels [V2 7007]
- Food Preparation [V2 7008]
- Food Preparation and Cleanup [V2 7009]
- Food Contamination Control [V2 7010]
- Food and Beverage Heating [V2 7011]

4.17.3 FOOD DEVELOPMENT

Foods must be developed to be safe, nutritious, and acceptable, and to meet mission requirements. To do this, food scientists choose a variety of foods to develop that are commonly eaten on Earth, meet the daily caloric needs of the astronauts (per NASA-STD-3001), and provide a variety of macronutrients and micronutrients. The current space food system contains more than 200 foods, comprising commercially available products and foods developed specifically to meet space flight requirements, which include meats, side dishes, vegetables, fruits, breads, snacks, and drinks. Currently, foods are shipped and stored at room temperature, so they are thermostabilized, irradiated, freeze-dried, or low-moisture foods to ensure shelf stability. As processing methods in industry advance, other methods may be used to increase food quality in the future. Provisioning of condiments such as mayonnaise, mustard, ketchup, and hot sauce reduces the monotony of the restricted food variety. Fresh foods also may be provided on a limited basis for consumption within the first few days after a resupply mission. Fresh food provisioning depends on the ability to stow these foods immediately before launch (and the length of transit time to the crew). More information about the various types of foods can be found in the NASA Human Integration Design Handbook (HIDH) section 7.2.3.4.

4.17.3.1 MISSION REQUIREMENTS

Before food development, mission and system requirements need to be determined. These mission requirements include generic information found in the concept of operations, such as mission duration, and information more specific to the food system, such as menu cycle length and considerations and limitations of system and infrastructure. Often the food system-specific requirements are derived from the mission requirements, by relying on historical lessons learned and expertise.

Mission duration is a key factor in food development. During missions up to 3 days in length the resources required to support certain types of foods, such as rehydratables and heated foods, may not be available because of mass and power constraints. Shelf-stable commercially available foods may be provided if they meet space food system requirements, including complete nutrition requirements. However, these foods may require repackaging for suitability in a microgravity environment. For missions longer than 3 days the resources required to rehydrate and heat foods in various packaging sizes must be provided to support crew health throughout the mission. As mission length increases, more foods that meet requirements will need to be developed, as variety promotes healthy eating habits and maintains crew health and performance.

Menu cycle length is another key factor in food development. Currently on the ISS, NASA provides an 8-day menu cycle for 3 crewmembers and Russia provides an 8-day menu cycle for 3 crewmembers. The current NASA food system contains over 200 foods, but the number of foods needed increases as mission length increases (to be greater than the typical ISS mission) and more variety is required to maintain consumption. Crews have commented that the current menu cycle is not adequate for 6-month ISS missions, but the ability to share food (e.g., between astronauts and cosmonauts) at crewmembers’ discretion increases the variety and acceptability of the cycle length. As mission length increases over 6 months, menu cycle length must increase (to be greater than 8 days) to provide variety, which promotes consumption.

System and infrastructure considerations and limitations must be assessed for food development. Rehydration (both hot and cold water) and heating abilities are required for missions longer than 3 days. Without rehydration and heating, the variety of food is reduced, which decreases consumption, which can lead to health problems. The ability to rehydrate and heat foods requires mass, power, and volume. Providing both hot and cold water to rehydrate foods allows preparation of freeze-dried foods, powdered beverages, and coffees. Providing the ability to heat foods increases the palatability of many thermostabilized and irradiated foods that may not be acceptable cold.

On missions up to 3 days, the capability to rehydrate and heat foods may not be provided because of mass, volume, and power constraints. The current food system supplies 1.83 kg (0.00472 m^3; data determined by measurement) of food and packaging per crewmember per day. This amount, which provides 3000 kcal per day, meets the nutritional requirements in NASA-STD-3001. These numbers do not include the mass and volume of stowage containers or protective materials, which are determined when stowage configuration is determined (see below) because the required number of containers and number and type of protective materials varies with the vehicle's stowage configuration.

4.17.3.2 DEVELOPMENT OF FOOD PRODUCTS

Once mission requirements are determined, food products are developed with consideration for nutritional content, safety, and acceptability. The food system typically contains a mixture of commercial off-the-shelf foods and foods developed specifically for space flight by a food scientist. After foods are developed to meet the nutritional requirements and are determined to be safe, they are analyzed for sensory acceptability (e.g., palatability). Foods that meet safety, nutritional, and acceptability standards are included in the space food system.

The food system must provide the full caloric and nutritional complement outlined in the NASA- STD-3001 V2 7003-7006. Currently, foods are tested for macronutrients and a few micronutrients through laboratory testing (currently at the NASA JSC Water and Food Analysis Laboratory (WAFL), but can be outsourced). Most micronutrients are determined through a computer program that uses a food database. Food Processor SQL (ESHA Research, Salem, OR) is one of several food programs that will provide nutritional estimates. For long-duration missions it will be important to select foods that will maintain their macro- and micronutrient content throughout the mission. This may require empirical measurement of nutritional content throughout shelf life to ensure that food system requirements are continually met, although this may be financially difficult for large food systems.

Each food production lot (each time the food is produced), including commercial foods repackaged in flight-approved packaging, must be tested for microbiological safety in accordance with SD-T-0252 Microbiological Specification and Testing Procedure for Commercially Sterile Foods and SD-T-0251 Microbiological Specification and Testing Procedure for Foods Which Are Not Commercially Sterile, as described in NASA-STD-3001 V27007 and the NASA Human Integration Design Handbook (HIDH) section 7.2.3.1.2.

To ensure that the crew consumes the nutrition and calories required to maintain optimum physical and cognitive performance, the food must be acceptable and usable during space missions (NASA-STD-3001 V2 7002). Provisioning of nutritious foods that are unacceptable will lead to underconsumption, nutritional deficiencies, weight loss, reduced cognitive function, reduced physical performance, and even illness (Friedl and Hoyt, 1997).

After they are tested for nutritional content and microbiological safety, all potential flight foods must be evaluated for acceptability by volunteer panelists in a food evaluation session (as described in the NASA Human Integration and Design Handbook (HIDH) section 7.2.2.1). A quantitative 9-point hedonic scale, ranging from (9) “like extremely” to (1) “dislike extremely,” is used to evaluate multiple food quality factors, such as appearance and flavor. Given that statistical power changes with the number of panelists (Meilgaard, Civille, & Carr, 1999), it is best to use a large subject sample when testing acceptability. Currently 30 panelists are used to evaluate each new food. Items that receive an overall score of 6.0 or higher are included in the space food system (6 is the lowest “like” score). After a food is included in the space food system, each production lot for all internally produced and commercial foods needs to be evaluated by at least 4 panelists, generally space food system laboratory personnel, before space flight. Crewmembers similarly evaluate all flight food options before their missions. This information may be used during menu development, described below.

In addition to nutritional content, safety, and acceptability of food items, other factors are important to consider during food development. The first of these additional factors is the storage duration (based on mission duration plus the time required to process, test, and ship the foods for launch) and shelf life (based on each food’s composition and preparation method). When selecting and developing foods, the food scientist must consider the mission duration and whether resupply will be available. For long-duration missions, foods with a long shelf life should be developed and selected. The methods used to provide shelf-stable foods either process the foods to commercial sterility (thermostabilized and irradiated foods) or reduce the water activity to the extent that microorganisms are not able to proliferate (freeze-dried and low-moisture foods). These foods deteriorate in quality over time, so shelf-life testing is needed to determine their nutritional content and acceptability after various durations. The foods should remain safe to consume unless the package is damaged.

The second additional factor to be considered is food packaging. Use of an appropriate packaging type is essential for maintaining the safety, nutritional quality, and acceptability of a food throughout its shelf life. Food packaging must meet safety and gaseous pollutant specifications (NASA-STD-3001 V26004; V2 6005; V2 6050). Packaging contributes significant mass and volume to the food system, and must be considered for stowage, launch mass, and waste disposal mass and volume. Flexible packaging (which may be compressed) provides savings in mass, volume, stowage, and waste over rigid packaging. Packaging must be easy to open, while not allowing contents to escape or leak in reduced-gravity environments. Foods that need to be rehydrated need packaging that is compatible with the rehydration equipment. More information on the types of food packaging currently used can be found in the NASA Human Integration and Design Handbook (HIDH) section 7.2.3.4.

The third factor is suitability for use in microgravity. Foods that are easily broken (such as potato chips) are difficult to eat in space and should be avoided. Foods that produce crumbs (such as crackers) should be provided in bite-sized pieces to minimize debris. Meal items should contain enough moisture to stay in the package or on a utensil through surface tension. Foods should be packaged in single-serving sizes to eliminate the need to transfer food and the need for additional tableware. Consideration should be given to variety, food familiarity, preparation time, meal scheduling, galley location, flavor changes in microgravity, and other human factors that affect food acceptability (as described in the HIDH section 7.2.2.1). This information has been mostly determined through experience and crew debriefs from previous missions.

4.17.4 MENU DEVELOPMENT

Menus can be developed in multiple ways. Two types of menu systems have been used in the NASA Space Food Systems Laboratory at Johnson Space Center: personal-preference menus and standard menus. Both types of menus require a preapproved list of flight foods.

Personal-preference menus are developed individually for each crewmember using scores from food evaluation sessions. Foods on which a crewmember scores 6.0 or higher on the hedonic scale are entered into a nutrient database program (such as the Food Processor SQL; ESHA Research, Salem, OR) by a dietitian. The computer program includes a database with nutritional information for individual foods and ingredients. This information is necessary for menu development to ensure adequate amounts of required nutrients. A dietitian may add foods necessary to fulfill the nutritional requirements if crewmember preferences are limiting. Personal-preference menus are popular with crewmembers but have proven unfeasible for the ISS due to variable resupply schedules. Resupply schedules for ISS are so variable that sometimes crewmembers’ preferred food items cannot be delivered in time to coincide with their increments. Personal-preference menus could be considered again for missions that do not involve crew rotation and/or food resupply.

To generate a standard menu, a registered dietitian enters the flight foods into a nutrient database program, which (1) has a database of commercial food products and ingredients, (2) can calculate the nutritional content of the formulated food, and (3) uses these calculations of nutritional content to determine the daily nutritional content for a given crewmember. The dietitian selects foods with the proper balance of macro- and micronutrients to meet the nutritional requirements of each crewmember. This leads to a menu that all crewmembers use that provides the required level of nutrition for the mission. The length of the menu cycle should be adjusted for mission duration, with longer menu cycles for missions of longer duration. Menus may be supplemented with bonus containers that include crewmember-requested shelf-stable commercial foods or food items developed for space flight that the crew selects during acceptability evaluations before flight. Currently, each crewmember receives 0.11 m^3 of bonus food storage for a 6-month ISS mission.

4.17.4.1 FOOD STOWAGE

Food may be stowed in various configurations, as long as the packages are protected from puncture or damage. Two types of stowage that may be used are (1) stowage by type of food and (2) stowage by meal. When food is stowed by type (e.g., meats, side dishes, drinks, snacks), also known as pantry style, crewmembers can assemble their own meal choices according to what food is available and are not restricted to the menu cycle. When food is stowed by meal, crewmembers eat meals in a predetermined menu cycle. Historically, for longer missions pantry style has been preferred. For shorter missions, either stowage configuration can be used and is decided on by the food system designer in collaboration with the stowage team or the crew. Stowage by meal requires that all foods required for a given meal be stowed together or in close proximity to one another to ease mealtime preparations.

4.17.5 EXPERTISE, FACILITIES, AND EQUIPMENT

To provide a food system suitable for use in microgravity, specific expertise, facilities, and equipment are necessary.

4.17.5.1 EXPERTISE

Food scientists are needed to develop specifications for food items, including ingredients, formulations, and processing conditions; develop new foods and determine food processing methods; determine sensory acceptability, confirm food safety, determine storage conditions, confirm shelf life, and confirm suitability for use in microgravity. Registered dietitians are needed to develop menus and confirm nutritional content. Packaging engineers are needed to determine the functionality of food packaging, confirm the suitability of packaging for use in microgravity, develop packaging parameters (including sealing and vacuum), and test the package integrity of packaged foods. Logistics specialists are needed to develop stowage procedures and monitor food inventory. A programmer is needed to develop and maintain database specifications for foods, and a food system engineer is required in the event that food processing equipment is designed in-house, including equipment to rehydrate and heat food.

4.17.5.2 FACILITIES AND EQUIPMENT

An analytical laboratory should provide a texture analyzer for assessing food texture profiles and the physical properties of packaging materials, a moisture analyzer and water activity analyzer for assessing the water properties of the food, a moisture sorption isotherm analyzer to estimate shelf life, a viscometer to determine fluid behavior, and a headspace analyzer to determine the oxygen content remaining in packaged foods.

A food processing pilot plant or test kitchen includes a freeze-dryer, a retort, a blast freezer, and general food production pilot plant equipment, such as a steam-jacketed kettle.

A sensory facility is used for acceptability testing and includes evaluation booths and a computerized sensory analysis program.

The packaging room includes vacuum sealers with gas flush capability and packaging equipment for specialty microgravity packaging, such as sealing of a septum into a pouch to enable rehydration of food in the package.

The stowage room should include areas to perform stowage and controlled storage for food until it is shipped for launch.

Office space is also needed for use by the members of the food laboratory for development of formulas, development of menus, computerized nutrition analysis, and other logistics, such as maintenance of inventory and specifications.

4.17.6 TECHNICAL PRODUCTS

For each of the major milestones of the design life cycle, the technical products in Table 4.17.6-1 are recommended for review by the NASA customer.

TABLE 4.17.6-1 SPACE FOOD SYSTEMS TECHNICAL PRODUCTS

Technical Products	Phase A		Phase B	Phase C	Phase D	
	SRR	SDR	PDR	CDR	SAR	FRR
Concept of Operations	X	---	---	---	---	---
Mission menu	---		X	---	---	---
Rehydration and warming hardware capability	---	---	I	U	U	U
Food hardware testing results	---	---	I	U	U	U
Food safety and testing procedures	---	---	X	---	---	---
Evidence of adequate stowage volume for food	---	---	I	U	U	U

X = one-time release of item
I = initial release of item
U = updated release of item

Concept of Operations
The ConOps, described in paragraph 3.2.3.1.2, provides information such as identification of crew activities and determination of which subsystems are influenced by crew activities. The ConOps is required to determine the type of food that will need to be flown for a given mission duration and the menu cycle length.

Mission Menu
The mission menu must be delivered, showing compliance with the nutritional and acceptability standards in NASA-STD-3001.

Rehydration and Warming Hardware Capability
If the mission duration requires rehydratable and hot food, evidence must be shown that the hardware is compatible with the food packaging.

Food Safety and Testing Procedures
Evidence that proper food safety and testing procedures are in place for all production lots needs to be delivered for NASA review at PDR. NASA expects that all foods to be delivered for the mission comply with the procedures specified in the evidence report.

Stowage Volume
Evidence is required that stowage volume for the food and packaging required for a given mission duration are adequate.

4.17.7 REFERENCES

Friedl, K. E, & Hoyt, R. W. (1997). Development and biomedical testing of military operational rations. *Annual Review of Nutrition*, *17*, 51-75.

Meilgaard, M., Civille, G. V., & Carr, B. T. (1999). Sensory evaluation techniques (3rd ed.) Boca Raton, FL: CRC Press.

4.18 LEGIBILITY EVALUATION

4.18.1 INTRODUCTION

Legibility is a key component of interface usability. Interfaces should be designed so that crewmembers can easily and quickly recognize and read text, numbers, and any labels. During space flight, many tasks involve prompt responses and commands that require quick identification of display elements. Without legible fonts, numbers, and symbols, task times will be longer and the chance of error will increase, causing delays and, in extreme cases, task failure.

4.18.2 BACKGROUND

4.18.2.1 DEFINITION OF LEGIBILITY

Legibility refers to the perceptual clarity of visual elements that allows discrimination of the details of a visual stimulus to such a degree that it can be recognized (Sheedy, Subbaram, Zimmerman, Hayes, 2005). Legibility is influenced by the method of display generation, application of human factors guidelines for correct depiction of the object in relation to the task requirements, the environmental conditions, and eyesight standards. Legibility of text is often defined in terms of readability: the relative ease with which text can be read and understood when characters are arranged in words, sentences, and paragraphs.

4.18.2.2 APPLICABLE REQUIREMENTS

The following requirements from NASA-STD-3001, Volume 2 are applicable to legibility:

- Visual Display Legibility [V2 10047]
- Visual Display Parameters [V2 10048]
- Visual Display Character Parameters [V2 10049]
- Display Font [V2 10050]
- Label Display Standards [V2 10062]
- Label Font Height [V2 10066]

4.18.2.3 FACTORS AFFECTING LEGIBILITY

The most important factors affecting legibility are related to the font used, such as type and size. However, environmental factors such as lighting conditions, vibration, and wearing a suit or helmet, which change visibility and the visual field, are also relevant.

Font characters are complex graphic elements that vary in width and height. The size of a character is usually given by the height of the uppercase letter H. In a comprehensive series of studies, Legge and colleagues (Legge, Pelli, Rubin, & Schleske, 1985) investigated reading rate as a function of letter size, contrast, font, color, and other variables. They varied character width and letter size of a fixed-width font. Maximum reading rates were achieved for characters of 0.3-2° of visual angle. There was a relatively rapid decline in reading rate for letters smaller than 0.3°. Furthermore, there was a gradual decline for letters larger than 2° (Legge *et al*., 1985). NASA-STD-3001, Volume 2, requires that font height be 0.4° or greater for labels and a minimum of 0.25°

for visual display characters (with 0.4 degrees preferred). In addition to type and size, stroke width, character spacing, line spacing, and other characteristics of fonts also need to be considered for legibility (McNeese & Katz, 1987).

4.18.2.4 MEASURING LEGIBILITY

In practice, legibility is often defined by the criteria and methodologies that are used to investigate it. In his review of legibility research, Pyke (1926) surveyed more than 100 studies published between 1825 and 1926, and discovered 15 different methods used by researchers for measuring legibility. The methods described were speed of reading (by the time threshold and amount read), the distance threshold (direct and peripheral), “eye-span,” “illumination threshold,” focus threshold, fatigue, number of eye pauses, number of eye re-fixations, regularity of eye movements, reading rhythm, “legibility coefficient,” “specific legibility,” size of letters, “judgment of the trained human eye,” and aesthetic merits.

In *Legibility of Print,* published in 1963, Tinker presented a more condensed list of investigative criteria, representative of those most commonly used:

1. *Speed of perception:* The speed and accuracy with which characters can be perceived in a short period of exposure.
2. *Perceptibility at a distance:* The distance from the eyes at which characters can be accurately perceived.
3. *Perceptibility in peripheral vision:* The distance from a given “fixation point” at which a character can be accurately perceived in the periphery.
4. *Visibility:* A measure of the point at which characters can be perceived when viewed through a visual apparatus that uses rotating filters to obscure and clarify those characters.
5. *The reflex blink technique:* Frequency of blinking when reading text with different typographical characteristics.
6. *Rate of work,* includes such measures as “speed of reading, amount of reading completed in a set time limit, time taken to find a telephone number, time taken to look up a power or root in mathematical tables, and work output in a variety of situations which involve visual discrimination.” It is a measure of the speed of reading, controlling for comprehension.
7. *Eye movements:* Measure of the movements of the eyes when reading, using methods such as corneal reflection and electrical signals.
8. *Fatigue in reading:* Measures of fatigue in reading. This measure has not been demonstrated to be a valid method for measuring legibility.

However, no single one of these methods (or criteria, depending on how they are described) is adequate for measuring legibility in all of its aspects. Each has to be understood and considered on its own merits as contributing to a broader notion of legibility.

Based on the listed criteria, 3 major categories can be used to group the legibility methods , as follows:

1. Size thresholds (visual acuity) for letter identification, measured with 5-letter strings presented on a video monitor, using an up-down staircase method (Levitt, 1971) with 0.05 log unit size steps. Size (or, inversely, distance) thresholds are probably the most common method for assessing text legibility (Tinker, 1963), and are widely used in applied settings such as highway signage, with lower size thresholds indicating higher legibility. Studies may use different kinds of stimuli: random strings of all lowercase, all uppercase, and randomly selected case; and 5-letter words, all upper- or all lowercase, randomly selected from the 2110 most frequent 5-letter words in English (Francis, Kucera, & Mackie, 1982).

2. Reading speeds using Rapid Serial Visual Presentation (RSVP). Higher legibility, by this criterion, allows faster reading. RSVP involves presenting a stimulus (word, letter) one at a time for a brief time interval. Reading speed is a less common measure of legibility but it is perhaps more representative of ordinary reading than is size threshold. Because RSVP can support extremely high rates of reading, it has the potential to be more sensitive to subtle differences in legibility. RSVP reading was tested with individual sentences, whose speed was varied to determine the speed that supported a 50% (of words) correct reading rate.

3. Reading speeds using continuous reading of text passages taken from standardized tests (9th-grade level).

The ergonomic requirements for office work with visual display terminals (VDTs) - Part 11 (ISO 9241-11) also describes an approach recommended to measure legibility: Ask users to read system messages and instructions displayed on a screen using a range of illumination levels from 50 lux to 5000 lux. At a normal viewing distance (typically 20″ from eye to screen), 98% of words used in system messages and instructions should be read correctly.

4.18.3 LEGIBILITY EVALUATION AND VERIFICATION PROCESS WITH RSVP

The following section describes a process of measuring and verifying legibility, given the following assumptions:

- The display viewing distance is 20″ measured from the eyes of the participant to the display
- There may be several viewing angles defined based on task analysis that need to be considered. For example, if 3 displays are used, and 2 of these are canted, 3 viewing angles would be evaluated.
- The design complies with the general human factors standards and guidelines for workstations, such as font size, brightness, and contrast (e.g., NASA-STD-3001). Standards and guidelines provide information for a good baseline design; however, they do not replace usability and legibility testing in representative conditions with representative tasks.
- The font size, spacing, and other properties of the design are based on recommendations and requirements from vibration and acceleration studies and

take into account the minimal font size, contrast, and other specifications for these conditions. Again, these guidelines provide a good baseline, but do not replace assessments and evaluations.

The recommended legibility evaluation process is completed in 3 phases:

1. Iterative, brief legibility assessments during the development phase in the context of iterative usability testing
2. Integrated, in-depth legibility evaluations using RSVP during development phase
3. Final legibility verification

The first 2 phases—assessing legibility as part of a usability study and integrated legibility evaluation—are complementary and are usually completed in an iterative fashion. The last phase—final legibility verification—is done at the end of the design process together with other verifications. The next sections will describe these phases in more detail.

This legibility evaluation process is specific to software interfaces. However, it can be applied to hardware labels and placards with slight modifications, such as measuring reading time instead of using RSVP. This method may be applied to evaluate legibility under other environmental conditions as well, such as during exposure to vibration and acceleration. To increase efficiency and save time, when it is feasible a legibility evaluation may be combined with other assessments and verifications, such as usability and workload (see HIDP section 4.2, Usability and 4.3, Workload) in integrated testing conditions.

The selected process and verification method are easy to implement because they do not need special equipment or specialized software, and it can be used in applied settings and various environments.

4.18.3.1 ITERATIVE BRIEF LEGIBILITY ASSESSMENT DURING DEVELOPMENT ALONG WITH USABILITY TESTING

Iterative usability testing (see HIDP section 4.2, Usability) is usually completed on a large number of interfaces during the design and development phase. As part of usability testing, the test conductor should ask questions about the legibility of specific interface elements (e.g., during the familiarization phase). The legibility of the following interface elements should be queried: text, numbers, symbols, icons, and graphics.

Comments and observations regarding legibility of interface elements should be recorded and analyzed. Changes to improve legibility should be made according to the feedback received. This will help ensure that if there are legibility issues in the early phases of design, they will be identified early and corrected by the time of requirement verification. If there are questions or concerns about the legibility of a particular interface, the usability test should include a legibility performance test similar to that described for legibility verification.

4.18.3.2 INTEGRATED LEGIBILITY EVALUATION USING RSVP DURING DEVELOPMENT

An integrated legibility evaluation is performed on integrated interface suites as designs mature. In the case of interfaces that are one of many similar in a set, (e.g., display formats) the test planner should define a number of categories they can be grouped in, such as: mostly text based formats, schematic based formats, and flight display formats. Several formats that are representative of each category should be selected for testing. If the interface is one-of-a-kind, it should be selected for testing.

Testing should be accomplished for a reasonable number of possible lighting conditions and viewing angles. These conditions have to be defined based on task analysis conducted during the development phase to make sure that they cover the most relevant combinations of conditions. The test procedure should involve having the test conductor ask the participant to identify selected portions of each interface, querying text, numbers, symbols, icons, and graphics.

Identification accuracy should be collected for all or the most relevant combinations of factors as illustrated in the Table 4.18.3.2-1 example.

TABLE 4.18.3.2-1 EXAMPLE OF COMBINATIONS OF FACTORS TO TEST LEGIBILITY OF DISPLAY ELEMENTS

	Display type		
	Text display (test text)	Schematic display (test object)	Flight display (test symbol)
Lighting 1	Viewing angle 1 Viewing angle 2 Viewing angle 3	Viewing angle 1 Viewing angle 2 Viewing angle 3	Viewing angle 1 Viewing angle 2 Viewing angle 3
Lighting 2	Viewing angle 1 Viewing angle 2 Viewing angle 3	Viewing angle 1 Viewing angle 2 Viewing angle 3	Viewing angle 1 Viewing angle 2 Viewing angle 3
Lighting 3	Viewing angle 1 Viewing angle 2 Viewing angle 3	Viewing angle 1 Viewing angle 2 Viewing angle 3	Viewing angle 1 Viewing angle 2 Viewing angle 3

The method used for the testing should be based on rapid presentations of the items to the participants and asking them to identify a cued/highlighted element on the screen (see Figure 4.18.3.2-1 for an example). Presentation times for the highlighted item on the display should be 1 second for simple items such as words, numbers, or symbols. This timing is based on the cognitive psychology literature: simple stimuli, such as common words presented alone on a display are perceived in about 200 - 250 ms (Becker, 2011). In a cluttered display, such as an electronic procedures display shown in Figure 1, to perceive an element, one needs to do a visual search as well; therefore, the time needed to identify an element increases. Nevertheless, within 1 second, one should be able to identify an element on a cluttered display. In this brief amount of time, accuracy should be around 98% for all elements using the ISO 9241-11 criterion.

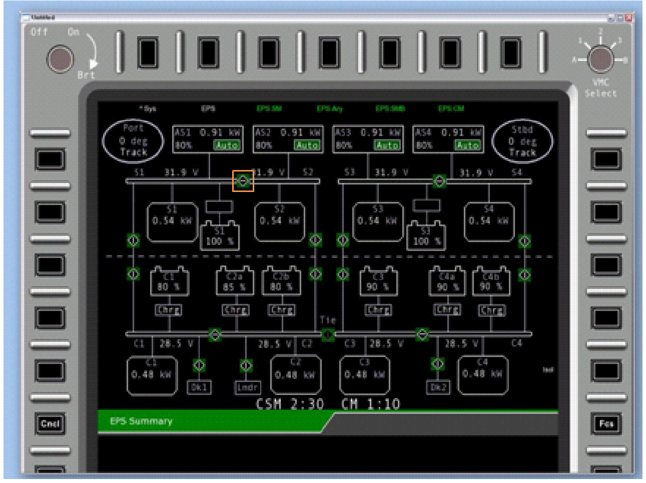


FIGURE 4.18.3.2-1 SYMBOL HIGHLIGHTED WITH AN ORANGE BOX ON AN ELECTRONIC PROCEDURES SCREEN IS THE CUED ELEMENT THE SUBJECT IS ASKED TO IDENTIFY.

The display elements should be presented with the rest of the display covered or the area of interest highlighted. The subject should be prompted to look at the highlighted area for the item to be identified. Responses can be called out and recorded by the evaluator or entered on the computer by the subject. If the interface elements are legible, accuracy should be 98%.

4.18.3.3 LEGIBILITY VERIFICATION

For verification, the RSVP method using the criterion of 98% accuracy should be applied, as described in the previous section. A limited set of representative displays and display elements in a limited set of worst-case conditions (e.g., reduced visibility, small viewing angle) should be selected. The sets should be determined based on task analysis taking into account criticality, representativeness, and frequency of use.

The 3-phased iterative approach for measuring and verifying legibility described in this document will help ensure that problems are caught and corrected early, and that a standard, time-efficient, and objective method is followed for formal verification of legibility.

4.18.3.3.1 LEGIBILITY VERIFICATION EVALUATION USING READING TIMES

The RSVP methodology can be modified to fit evaluation conditions when RSVP cannot be used, such as legibility of hardware labels or when modifying the software to accommodate RSVP is not feasible. In these cases, overall reading time can be measured and used to calculate how long it takes to read the individual elements on the display. In this case, participants are asked to read all the words, symbols, and numbers line-by-line, top to bottom displayed on the screen as they would read a book. Reading time for each element is calculated by dividing total reading time for the part of the display by the number of elements in that part. Reading times for each element should be under 1s and accuracy above 98%, just as in the case of RSVP, to pass verification.

4.18.4 LEGIBILITY TECHNICAL PRODUCTS

For each of the major milestones of the design life cycle, the technical products in Table 4.18.4-1 are recommended.

TABLE 4.18.4-1 LEGIBILITY TECHNICAL PRODUCTS

Technical Products	Phase A		Phase B	Phase C	Phase D	
	SRR	SDR	PDR	CDR	SAR	FRR
A description of the ConOps, function allocation, and associated crew task lists and crew interfaces.	I	U	U	U	---	---
A summary of modeling/analysis/evaluation performed to date showing legibility of displays at 98%.	---	---	I	U	U	---
Verification plan.	---	---	I	U	U	---
X = one-time release of item I = initial release of item U = updated release of item						

Concept of Operations and Crew Task Lists

The ConOps, described in paragraph 3.2.3.1.2 provides information such as identification of crew activities and determination of which subsystems are impacted by crew activities. Function allocation, described in paragraph 3.2.3.1.3, establishes the extent to which an activity is to be automated or assigned to humans. The crew task list, described in section 4.1 User Task Analysis, documents details including allocation of function between crew and systems, definition of crew activities sequence, and identification of critical tasks. As the crew task list evolves through the design cycle, its final iteration should become crew procedures.

For legibility testing, task analysis must include an analysis of the possible conditions under which displays should be legible.

Summaries of Modeling, Analyses, and Evaluations

Iterative summaries of modeling, analyses, and evaluations provide insight into human-system integration technical details throughout the design process. As designs mature, modeling, analyses, and evaluations should use increasingly higher fidelity inputs and mockups, as discussed in paragraph 3.2.3.3 Evaluate Designs and Iterate Solutions. It is important that summaries address how critical design decisions were assessed. Per the NPR 8705.2B, updated summaries are to be provided at each design review through SAR. Also in paragraph 2.3.10, the use of human-in-the-loop evaluation is a required method to progressively demonstrate that the operational concept meets system requirements for operational safety, efficiency, and user interface design.

For usability, this should include the evaluation of displays, and results showing that elements on the displays are legible with 98% accuracy.

Verification Plan

The verification plan is a formal document describing the specific methodologies to be used to show compliance with each requirement.

4.18.5 BIBLIOGRAPHY

ASTM D 7298. *Standard Test Method for Measurement of Comparative Legibility by Means of Polarizing Filter Instrumentation.*

Becker SI (2011) Determinants of Dwell Time in Visual Search: Similarity or Perceptual Difficulty? PLoS ONE 6(3)

Francis. W. N., Kucera, H., & Mackie, A. W. (1982). *Frequency Analysis of English Usage: Lexicon and Grammar.* Houghton Mifflin, Boston, MA.

ISO 9241-11. Ergonomic requirements for office work with visual display terminals (VDTs) **–** Part 11- Guidance on Usability

Legge, Pelli, Rubin, & Schleske, (1985). Psychophysics of reading. Normal vision. *Vision Res,* 25(*2*), 239-252.

Levitt, H. (1971). *Transformed Up-Down Methods in Psychoacoustics.* The Journal of the Acoustical Society of America, 49, 467.

McNeese, M. D., & Katz, L. (1987). *Legibility evaluation of a large screen display system under medium ambient illumination. Proceedings of the Society for Information Display*, 28 (*1*), 59-65.

Pyke, R. L. (1926). *Report on the legibility of print,* Medical Research Council, Special Research Series. London, UK.

Sheedy, J. E., Subbaram, M., V., Zimmerman, A. B., Hayes, R. J. (2005). Text legibility and the letter superiority effect. *Human Factors: The Journal of the Human Factors and Ergonomics Society, (47)4*, 797–815.

Tinker, M.A. (1963). *Legibility of print*. Iowa State University Press, Ames, IA.

APPENDIX A ACRONYMS AND DEFINITIONS

ABF	Anthropometry and Biomechanics Facility	NASA's Space and Life Sciences Directorate, Habitability and Human Factors Branch, Anthropometry and Biomechanics Facility
ACES	Advanced Crew Escape Suit	
ACLS	Advanced Cardiac Life	
AGARD	Advisory Group for Aerospace Research and Development	
ALARA	As Low As Reasonably Achievable	
ANCP	Acoustic Noise Control Plan	
ANSI	American National Standards Institute	
ANSUR	Anthropometry Survey of Army Personnel	NATICK document
ATD	Anthropomorphic Testing Device	
BEA	Boundary Element Analysis	
BMD	Bone Mineral Density	
BTE	Barrier Thickness Evaluator	
CAD	Computer Aided/ Assisted Design	
CCT	Commercial Crew Transportation	
CDR	Critical Design Review	Review during project life cycle Phase C Final Design and Fabrication. Follows PDR and precedes SIR. May be conducted with PRR.
CEV	Crew Exploration Vehicle	
CG	Center of Gravity	
CHSIP	Commercial Human Systems Integration Processes	JSC-65995
CHSIR	Commercial Human-Systems Integration Requirements	JSC-65993
CMORD	Commercial Medical Operations Requirements Document	JSC-65994
COM	Center of Mass	
ConOps	Concept of Operations	
COTS	Commercial Orbital Transport Services	
CREST	Crew Escape Technologies	
dB	decibels	

DDPF	Decal Design and Production Facility	NASA label design and production facility
DRATS	Desert Research and Technology Studies	
DRM	Design Reference Mission	End-to-end description of reference mission including # crew, # days, nominal and emergency, recovery, aborts, medical, etc.
ECLSS	Environmental Control and Life Support Systems	
EMU	Extravehicular Mobility Unit	
ESPO	Extravehicular Activity Systems Project Office	
EVA	Extra-Vehicular Activity	
ExMC	Exploration Medical Capability	
FAA	Federal Aviation Administration	
FAST	Functional Analysis Systems Technique	
FCI	Flight Crew Integration	NASA's Space and Life Sciences Directorate, Habitability and Human Factors Branch, Flight Crew Integration
FE	Finite Element	
FEA	Finite Element Analysis	
FMEA	Failure Mode Effect Analysis	
FRR	Flight Readiness Review	Review at end of project life cycle Phase D System Assembly, Integration & Test, Launch. Follows ORR.
g	Gravity	Gravitational Force
GCR	Galactic Cosmic Rays	
GFE	Government Furnished Equipment	
H&M	Health and Medical	
HCD	Human-Centered Design	
HEA	Human Error Analysis	
HIC	Head Injury Criteria	
HIDH	Human Integration Design Handbook	NASA/SP-2010-3407 Human Integration Design Handbook (HIDH)
HITL	Human-in-the-Loop	Human-in-the-Loop usability evaluation is required per NPR 8705.2B paragraph 2.3.10 for the human-system interfaces and integrated human-system performance testing, with human performance criteria, for critical system and subsystem operations involving human performance
HRCP	Human Rating Certification Plan	
HQ	Handling Qualities	
HSI	Human Systems Integration	
HZ	hertz	

IARV	Injury Assessment Reference Values	
IMS	Inventory Management System	
IRD	Interface Requirements Document	
ISO	International Standards Organization	
ISS	International Space Station	
IVA	Intra-Vehicular Activity	
JSC	Johnson Space Center	
LEA	Launch, Entry, Abort	A type of astronaut suit worn during launch, entry, and abort mission phases.
LEO	Low Earth Orbit	
LET	Linear Energy Transfer	
MOI	Moment of Inertia	
MPCV	Multi Purpose Crew Vehicle	
MTL	Master Task List	
NASA	National Aeronautics and Space Administration	
NASA-TLX	NASA Task Load Index	
NBL	Neutral Buoyancy Lab	
NCRP	National Council on Radiation Protection and Measurements	
NHV	Net Habitable Volume	
NPR	NASA Procedural Requirements	
OpsCon	Operations Concept	
OpNom	Operational Nomenclature	Review during project life cycle Phase D System Assembly, Integration & Test, Launch. Follows SAR and precedes Flight Readiness Review.
ORR	Operational Readiness Review	Review during project life cycle Phase D System Assembly, Integration & Test, Launch.
PABF	Precision Air-Bearing Floor	
PDR	Preliminary Design Review	Review during project life cycle Phase B Preliminary Design and Technology Completion. Follows SDR and precedes CDR.
PEPC	Portable Equipment Payload and Cargo	
POGO	Hydraulically offloading partial gravity simulator	
PRA	Probabilistic Risk Assessment	

PRR	Production Readiness Review	Review during project life cycle Phase C Final Design and Fabrication. Follows PDR and precedes SIR.
RAMSIS		3D CAD manikin RAMSIS is a simulation software program used for design and construction analyses.
REID	Risk of Exposure-Induced Death	
RHC	Rotational Hand Controller	
RID	Review Item Discrepancy	
ROM	Range of Motion	
RPOD	Rendezvous Proximity Operations & Docking	
SAINT	Systems Analysis of Integrated Network of Tasks	
SAR	System Acceptance Review	Review during project life cycle Phase D System Assembly, Integration & Test, Launch. Follows TRR and precedes ORR.
SDR	System Definition Review	Review during project life cycle Phase A Concept and Technology Development. Follows SRR and precedes PDR.
SEA	Statistical Energy Analysis	
SIR	System Integration Review	Review during project life cycle Phase C Final Design and Fabrication. Follows CDR/PRR and precedes TRR.
SME	Subject Matter Expert	
SMEMCL	Space Medicine Exploration Medical Condition List	
SPE	Solar Particle Events	
SRAG	Space Radiation Analysis Group	NASA Space Radiation Analysis Group
SRR	System Requirements Review	Review during project life cycle Phase A Concept and Technology Development. Follows MCR and precedes SDR.
S&MA	Safety and Mission Assurance	
TA	Technical Authority	
THC	Translational Hand Controller	
TLX	Task Load Index	NASA Task Load Index (TLX) is a diagnostic or multi-dimensional workload scale that can be used along with the Bedford. NASA-TLX provides an estimate of overall workload based on a weighted average of 6 subscale ratings: Mental Demand, Physical Demand, Temporal Demand, Own Performance, Effort, and Frustration (Hart & Staveland, 1988)
TRR	Test Readiness Review	Review during project life cycle Phase D System Assembly, Integration & Test, Launch. Follows CDR/PRR & SIR and precedes SAR.
V&V	Verification and Validation	
WBPBA	Whole Body Posture Based Analysis	

APPENDIX B GLOSSARY

Term	Definition
Abort	Early termination of the mission or mission phase before reaching the mission destination due to a failure or other condition that endangers the crew. At the moment an Abort is declared, the focus of the operation switches from flying the planned mission to saving the crew. A successful Abort ultimately places the crew in the portion of the space flight system normally used for reentry, and in a safe situation suitable for successful return and rescue. Aborts include scenarios where the vehicle is damaged or not recovered.
Accessible	An item is considered accessible when it can be operated, manipulated, serviced, removed, or replaced by the suitably clothed and equipped user with applicable body dimensions conforming to the anthropometric range and database specified by the procuring activity. Applicable body dimensions are those dimensions that are design-critical to the operation, manipulation, removal, or replacement task.
Advisory	A message that indicates a safe or normal configuration, operation of essential equipment, or imparts information for routine action purposes.
Analysis	Determination that requirements have been satisfied and results documented through the use of analytical techniques and tools. These techniques and tools may include computer and hardware simulations, analog and digital modeling, similarity and heritage assessments, validation of records, and the evaluation of results of multiple tests and analyses at a lower level applied to a higher level of assembly.
Anthropometry	The science of measuring the human body and its parts and functional capabilities. Includes lengths, circumferences, body mass, etc.
Assembly	A testable functional item that is viewed as a complete and separate entity for purposes of requirement allocation, manufacturing, maintenance, and record keeping. Examples: Large electronics box consisting of a chassis within which are housed separate smaller electrical/electronic units or a large docking ring attached to which are other discreet units, wire harnesses, or subassemblies. An assembly is testable as-configured item against its own development specification. It contains families of units, slices or subassemblies where all the lower-level units are individually qualified and electronically stressed screened that meet, at a minimum, the unit test requirements
Automatic	Pertaining to a function, operation, process, or device that, under specified conditions, functions without intervention by the crew.
Capability	Having attributes (such as physical or cognitive) required for performance.
Catastrophic Hazard	A condition that may cause the loss of life, permanently disabling injury, or a loss of flight assets.
Caution	An event that needs attention, but not immediate action.
Contamination	The act of rendering unfit for use by the introduction of unwholesome or undesirable elements.
Countermeasures	A means to offset undesirable physical, physiological, and psychological effects of space flight on crewmembers
Crew	Human onboard the spacecraft or space system during a mission. This includes USOS crewmembers and CCT company users or commercial customers (space tourists).
Crew Interface	Any part of a vehicle through which information is transferred between the crew and the vehicle, whether by sight, sound, or touch. Usable, well-designed crew interfaces are critical for crew safety and productivity, and minimize training requirements.

Crew-In-The-Loop	An evaluation that includes a crewmember, whether in an active or passive capacity in the subject role. The active crew-in-the-loop means that the crewmember's actions are being evaluated in some capacity. The crewmember as subject means that the human is providing the data in which case human performance can be captured.
Crew Survival	Ability to keep the crew alive using capabilities such as abort, escape, safe haven, emergency egress, and rescue in response to an imminent catastrophic condition
Criticality 1	Involve tasks where the possibility of a single failure could result in loss of life or vehicle.
Criticality 2	Involve tasks where the possibility of a single failure could result in loss of mission alone.
Critical Dimensions	A key characteristic that establishes critical fit tolerances between other components or assemblies.
Data Accuracy	The degree to which information in a digital database matches true or accepted values. Accuracy is an issue pertaining to the quality of data and the number of errors contained in a dataset.
Data Fidelity	Data qualities that include accuracy, precision, reliability, latency (data freshness), resolution, and completeness.
Data Precision	The level of measurement and exactness of description in a database. Precise location data may measure position to a fraction of a unit. Precise attribute information may specify the characteristics of features in great detail. Note that precise data, no matter how carefully measured, may be inaccurate.
Data Reliability	The degree to which data is the same when sampled repeatedly.
Deconditioned Crew	Decreased functionality of physiological systems, for example, musculoskeletal, cardiovascular, vestibular and nervous systems, related to adaptation to reduced gravity.
Demonstration	Determination that qualitative or Boolean (Y/N) requirements have been satisfied by exhibition of functional performance (for example, serviceability, accessibility, transportability or human engineering features) usually accomplished with only instrumentation and equipment inherent in the item evaluated.
Display	A display is anything that provides visual, auditory and/or haptic information to crewmembers (for example, label, placard, tone, or display device). The term "display" includes text-based user interfaces, as well as Graphical User Interfaces (GUIs).
Display Device	The hardware used to present visual, aural, and tactile information to the crew or ground operations personnel. Display devices include computer monitors and Personal Digital Assistants (PDAs).
Emergency	Time critical warning event that requires immediate action and crew survival procedures. Each type of emergency requires a unique aural tone.
Emergency Equipment	A set of components (hardware and/or software) used to mitigate or control hazards, after occurrence, which present an immediate threat to the crew or crewed spacecraft. Examples include fire suppression systems and extinguishers, emergency breathing devices, and crew escape systems (NPR 8705.2, Human-Rating Requirements for Space Systems).
Emergency Evacuation	The scenario in which ISS becomes uninhabitable and all crewmembers are forced to evacuate.
Emergency Return	The scenario in which a crewmember becomes ill and/or injured and the condition is life-threatening, time-critical, and/or beyond the medical capabilities of ISS
Error	Either an action that is not intended or desired by the person or a failure on the part of the person to perform a prescribed action within specified limits of accuracy, sequence, or time that does not produce the expected result and has led or has the potential to lead to an unwanted consequence.

Escape	In-flight removal of crew from the portion of the space system normally used for reentry, due to rapidly deteriorating and hazardous conditions, thus placing them in a safe situation suitable for survivable return or recovery Escape includes, but is not limited to, those capabilities that use a portion of the original space system for the removal (for example, pods, modules, or foreign bodies). (NPR 8705.2A, Human-Rating Requirements for Space Systems)
EVA	Operations performed by suited crew outside the pressurized environment of a flight vehicle or habitat (during space flight or on a destination surface).
Flight-like	Non-flight component built, inspected and tested to flight component specifications used in flight operating conditions and built with manufacturing processes that are identical to those used for flight equipment.
Ground	Human team of one or more members supporting a mission from the ground during pre-flight, in-flight, surface, and post-flight operations.
Habitability	The state of being fit for occupation or dwelling. Meeting occupant needs of health, safety, performance, and satisfaction.
Hardware	Individual components of equipment including but not limited to, fasteners, panels, plumbing, switches, switch guards, and wiring.
Hatch	An opening with an operable, sealable cover that separates 2 adjoining environments and allows physical passage of people and/or material from one environment to the other (such as between 2 separate pressurized spacecraft when they are mated or from the inside to the outside of a spacecraft or vice versa). A hatch is composed of 2 components: a hatchway (the opening itself) and a hatch cover (the piece that closes the hatchway and provides structural support to the spacecraft). A pressure hatch is one in which the atmospheric pressure on one side of the hatch can be different from that on the opposite side of the hatch when the hatch cover is closed. Sometimes, the term “hatch” is used in place of hatch cover. In this document, however, the word “hatch cover” is used.
Housekeeping	Actions performed by the crew during a mission to maintain a healthy and habitable environment within the spacecraft. Examples of housekeeping activities include biocide wiping of spacecraft interior surfaces, cleaning or servicing of food preparation or hygiene facilities, and trash management.
Human-centered Design	The certification that a system has been developed and is capable of being operated in a manner appropriate for use by human crews at minimal risk. Human-rated certification includes: (1) human safety; (2) human performance (both nominal and degraded states of operation); and (3) human health management and care as applicable.
Impulse Noise	A burst of noise that is at least 10 dB above the background noise, which exists for one second or less.
Information Management	The act of performing functions with electronic data, including data input, organization, internal processing, storage, distribution, saving, and disposal of information about the system. Information management functions are typically performed by crew and ground personnel using displays on display devices.
Inspection	A method of verification of physical characteristics that determines compliance of the item with requirements without the use of special laboratory equipment, procedures, test support items, or services. Inspection uses standard methods such as visuals, gauges, etc., to verify compliance with requirements. Hardware may be inspected for the following: (1) Construction; (2) Workmanship; (3) Physical condition; (4) Specification and/or drawing compliance.
Integrated	The merger or combining of one or more components, parts, or configuration items into a higher level system for ensuring that the logical and physical interfaces can be satisfied and the integrated system satisfies its intended purpose.

Ionizing Radiation	Radiation that converts impacted items wholly or partly into ions (electrically charged particles). The particulate radiation component includes all subatomic particles, such as protons, neutrons, electrons, atomic nuclei stripped of orbital electrons, mesons, etc.
Intravehicular Activity (IVA)	Operations performed by crew within the pressurized environment of a spacecraft during a mission.
Legibility	The extent to which alphanumeric characters and symbols are sufficiently distinct to be easily perceived, deciphered, or recognized.
Linear Acceleration	The rate of change of velocity of a mass, the direction of which is kept constant.
Maintenance	All actions necessary for retaining material in (or restoring it to) a serviceable condition. Maintenance includes servicing, repair, modification, modernization, overhaul, inspection, condition determination, corrosion control, and initial provisioning of support items. Reference - from MIL-HDBK-1908B, Definitions of Human Factors Terms
Monitoring	Includes checking for quality or fidelity; testing to determine whether a signal comes within limits; watching and observing for a specific signal or purpose; keeping track of, regulating, or controlling.
Operator	A crewmember serving the role of pilot or commander.
Net Habitable Volume	The functional volume left available to on a spacecraft after accounting for the loss of volume caused by deployed equipment, stowage, trash, and any other items that decrease the functional volume.
Nominal	Within operational limits or in accordance with planned operational concepts
Noise	Sound in the auditory range (15 Hz to 20,000 Hz) that is hazardous, undesired, and/or inappropriate to the intended use of the space. The word "noise" is used interchangeably with “sound” and is not intended to convey any relative or absolute degree of hazard or other acoustical characteristic.
Non-Ionizing Radiation	Includes 3 categories of electromagnetic radiation: radio frequency (RF) radiation, lasers, and incoherent electromagnetic radiation.
Off-Nominal	Outside of expected, acceptable operational limits or not in accordance with planned operational concepts; anomalous, unsatisfactory (aerospace usage).
Override	To halt, manually or automatically, operation of a function in progress.
Placard	In the context of occupant protection, placards are operational controls on flight operations. For example, if a design is not certified to launch or abort in certain conditions such as wave state, or winds that would blow an abort capsule back toward land, placards would prevent the vehicle from launching in those conditions. Placards allow a design to be certified, even if it cannot meet requirements for all conditions, by accepting the impact to operations.
Population Analysis	Population analysis uses statistical or mathematical tools to interpret results of the testing of a representative sample of subjects. Measures such as fit, reach, and strength are extrapolated or interpolated for comparisons against the entire range of potential crewmembers to ensure an adequate selection test of subjects has been made, and to determine whether the design successfully accommodates the extremes of the crew population.
Provision	The ancillary flight component provided for the CCT company. This includes pyrotechnic devices and equipment (spacesuits, camera systems, tools, clothing and food) primarily for crew provisioning and use. GFE is also any hardware/software (including documentation) provided as a finished product to a contractor for the contractor's use in meeting contractual requirements.
Privacy	Having an acceptable level of control over the extent of sharing oneself (physically, behaviorally, or intellectually) with others. Acceptable level is dependent on an individual’s background and training.
Readily Accessible	Immediately visible and accessible without being blocked or constrained by other equipment. Unimpeded Access is important for Emergency Systems and other critical items.

Recovery	Generally, a recovery is a nominal post-landing operation involving the crew in the crew module.
Rotational Acceleration	The rate of change of angular velocity.
Subject	A subject is an individual about whom an investigator conducting research or evaluations obtains data such as identifiable private information, physical measurements, responses, preferences, and/or whose performance is measured. A subject may be inclusive of a participant.
Suited	Wearing clothing that is designed to protect the crewmember from differences in environment, such as pressure, atmosphere, acceleration, or temperature. “Suited” can refer to both a pressurized and unpressurized pressure suits.
System	Physical entities that have functional capabilities allocated to them necessary to satisfy Architecture-level mission objectives. Systems can perform all allocated functions within a mission phase.
Task Analysis	Task analysis is an activity that breaks a task down into its component levels. It involves 1) the identification of the tasks and subtasks involved in a process or system, and 2) analysis of those tasks (for example, who performs them, what equipment is used, under what conditions, the priority of the task, dependence on other tasks). The focus is on the human and how they perform the task, rather than the system. Results can help determine the displays or controls that should be developed/used for a particular task, the ideal allocation of tasks to humans vs. automation, and the criticality of tasks, which will help drive design decisions.
Test	Determination that requirements have been satisfied through measurement of parameters during and/or after the controlled application of functional and environmental stimuli using laboratory equipment, recorded data, procedures, test support items, or services beyond that provided by the tested unit itself.
Transient Acceleration	Acceleration event, linear or rotational, with a duration of less than or equal to 0.5 seconds.
Unsuited	Wearing the type of clothing that is ordinarily worn in the interior of a spacecraft, especially a habitat, and as might be worn on Earth.
User	A user is any person who directly (physical contact) or indirectly (command, control, communication) interacts with the flight vehicle.
Vehicle	A mobile or static environment with a pressurized atmosphere appropriate for sustained, unsuited survival and crew operations. The vehicle is a container, which is generally composed of multiple elements, used to transport persons or things to/from a location outside of Earth’s atmosphere and includes all hardware and equipment within or attached to the pressurized environment.
Warning	An event that requires immediate action.
Window	A non-electronic means for direct through-the-hull viewing using a transparent material; the same as and used interchangeably with window port and window assembly.
Workload	The amount of work expected in a unit of time. Physical workload refers to the number of individual physical activities that are conducted simultaneously or in close succession. Similarly, mental or cognitive workload refers to the number of mental operations or activities that are conducted simultaneously or in close succession.
Workstation	A place designed for a specific task or activity from where work is conducted or operations are directed. Workstations include cockpits, robotics control stations, or any work area that includes work surfaces, tools, equipment, or computers.

APPENDIX C REFERENCE DOCUMENTS

Document Number	Document Revision	Document Title
AFAMRL-TR-80-119		McConville, J. et al. (1980). *Anthropometric Relationships of Body and Body Segment Moments of Inertia.* Air Force Aerospace Medical Research Laboratory, Aerospace Medical Division, Air Force Systems Command, AFAMRL-TR-80-119. Wright-Patterson Air Force Base, Ohio.
AGARD CP-472	April 1989	Brinkley, J. W., and Specker, L.J., "Development of Acceleration Exposure Limits for Advanced Escape Systems"
ISO/IEC 9241-11	1998	Ergonomic requirements for office work with visual display terminals (VDTs), *Part 11: Guidance on Usability*.
ISO 13407	1999(E)	International Standard for Human-Centered Design Processes for Interactive Systems
JSC-27260		Decal Process Document and Catalog
JSC-27301		Materials Control Plan for JSC Space Station GFE
JSC-28517		Holden, K.L, Malin, J.T., and Thronesbery, C. (1998). Guide to Designing Usable Software Systems in Advanced Technology Environments, JSC Technical report: JSC-28517
JSC-63557	2008	Net Habitable Volume Verification Method
JSC-65994	Draft August 2010	Commercial Medical Operations Requirements Document (CMORD)
MIL-STD-1472	Revision G	Department of Defense, Design Criteria Standard for Human Engineering
MIL-F-8785 B/C		Flying Qualities of Piloted Airplanes (28 AUG 1996)
MPCV 70024	Baseline	Orion Multi Purpose Crew Vehicle Program Human-Systems Integration Requirements
NASA/SP-2007-6105	Rev 1	NASA Systems Engineering Handbook
NASA/SP-2010-3407		Human Integration Design Handbook

NASA-TM-2008-215198	April 2008	Lawrence, C., Fasanella, E.L., Tabiei, A., Brinkley, J.W., Shemwell, D.M. *The Use of a Vehicle Acceleration Exposure Limit Model and a Finite Element Crash Test Dummy Model to Evaluate the Risk of Injuries During Orion Crew Module Landings*
NASA/TM-2009-215704	April 2009	Horta, L.G., Mason, B.H., Lyle, K.H. *A Computational Approach for Probabilistic Analysis of Water Impact Simulations*
NASA-STD-3001		Space Flight Human-systems Standard, Volume 1: Crew Health, and Volume 2: Habitability and Environmental Health
NASA-STD-5017		Design and Development Requirements for Mechanisms, section 4.10 Torque/Force Margins
NASA TN D-5153		“The Use of Piloted Rating In The Evaluation Of Aircraft Handling Qualities,” National Aeronautics and Space Administration, Washington, D.C., April, 1969.
NASA-TM-X-62892, N79-76319		NASA (1966). *Gemini Program Mission Report of Gemini VII*. National Aeronautics and Space Administration Manned Spacecraft Center, Houston, Texas.
NATICK/TR-89/044		1989 U.S. Army Anthropometry Survey of U.S. Army Personnel: Methods and Summary Statistics (Database Section only)
No Number		Ainsworth, L. K. (2004). Task analysis. In C. Sandom & R. Harvey (Eds). *Human Factors for Engineers* (pp. 81–112). London, England: Institution of Engineering and Technology.
No Number		Bangor, A., Kortum, P. T., & Miller, J. A. (2008). An empirical evaluation of the System Usability Scale (SUS). *International Journal of Human-Computer Interaction, 24*(6), 574-594.
No Number		Blackledge, C., Margerum, S., Ferrer, M., Morency, R., and Rajulu, S., (2010). Modeling the Impact of Space Suit Components and Anthropometry on the Center of Mass of a Seated Crewmember. Applied Human Factors and Ergonomics.
No Number		Bond, R. and Campbell, P. (1995). “Operational monitoring of MIR habitability,” (PIPS Database #810530). Internal NASA Document.
No Number		Celentano, J.T., Amorelli, D. and Freeman, G.G. (1963). “Establishing a habitability index for space stations and planetary bases,” *American Institute of Aeronautics and Astronautics Manned Space Laboratory Conference*, May 2, 1963, Los Angeles, CA, pp. 63-139
No Number		Chaffin, D.B.; Andersson, G.B.J.; Martin, B.J. Occupational Biomechanics. J. Wiley & Sons, New York, NY 1999

No Number		Churchill, E. and McConville, J. Sampling and Data Gathering Strategies for Future USAF Anthropometry, Appendix II-A. Air Force Systems Command, Wright Patterson Air Force Base, (1976).
No Number		DuBois D, DuBois EF. 1916. A formula to estimate the approximate surface area if height and weight be known. Arch Intern Med 17:863–871
No Number		England, Scott A; Benson, Elizabeth A.; and Rajulu, Sudhakar L. Functional Mobility Testing: Quantification of Functionally Utilized Mobility among Unsuited and Suited Subjects. NASA/TP-2010-216122, May 2010.
No Number	Draft JSC document	Exploration Medical Conditions Concept of Operations
No Number		Gehan, E.A., George, S.L. (1970). Estimation of human body surface area from height and weight. Cancer Chemotherapy Reports Part I, 54(4), 225-235. 11:24
No Number		Gonzalez, L.J., Rajulu, S.L.. “Posture-Based Whole Body Anthropometric Analysis – A Case Study,” Digital Human Modeling For Design And Engineering Conference And Exhibition, June 2003, Montreal, Canada.
No Number		Hart, S. G. & Staveland, L. E. (1988) Development of NASA-TLX (Task Load Index): Results of empirical and theoretical research. In Human Mental Workload P. A. Hancock & N. Meshkati (Eds.). Amsterdam: North Holland, 139-183.
No Number		Hornbæk, K., & Law, E. L.-C. (2007). *Meta-analysis of correlations among usability measures.* Paper presented at the Proceedings of the SIGCHI conference on Human factors in computing systems, April 28-May 03, 2007, San Jose, CA, USA.
No Number		Kallay, A., Harvey, C., Byrne, V., DeSantis, L., Maida, J., Szabo, R., & Whitmore, M. (2006). *Crew exploration vehicle (CEV) net habitable volume assessments for 6-crew missions.* NASA TDS CEV-05-002, NASA/Johnson Space Center, August 2006
No Number		Kirakowski, J., & Corbett, M. (1993). SUMI: the Software Usability Measurement Inventory. *British Journal of Educational Technology, 24*(3), 210-212.
No Number		Leiden, K., Laughery, K.R., Keller, J., French, J., Warwick. W., and S. Wood. A Review of Human Performance Models for the Prediction of Human Error. 2001.

No Number		Litaker, Jr. H.L., Thompson, S., Howard, R., Szabo, R., Conlee, C., & Twyford, E. (2008). *Habitable volume evaluation for the lunar sortie habitat Altair: Configuration one.* NASA/Johnson Space Center. Internal NASA Document, February 2008.
No Number		Litaker, Jr., H.L., Thompson, S., Howard, R., Szabo, R., Baldwin, T., Conlee, C., Twyford, E., Nguyen, A., & Ward, M. (2008). *Suited and unsuited habitable volume evaluation for Altair lunar lander DAC-2 configuration.* NASA/Johnson Space Center. Internal NASA Document, September 2008.
No Number		Litaker, Jr., H.L., Howard, R., Ferrer, M., & Young, K. (2008). *Lunar rover habitability volume evaluation on configuration one.* NASA/Johnson Space Center. Internal NASA Document, January 2008
No Number		Litaker, Jr. H.L., Thompson, S., Howard, R., Szabo, R., Conlee, C. & Twyford, E. (2008). *Small Pressurized Rover (SPR) three day desert trial: A human factors assessment.* NASA/Johnson Space Center. Internal NASA Document, December 2008
No Number		Litaker, Jr. H.L., Thompson, S., Howard, R., Szabo, R., Conlee, C. Green, S., & Twyford, E. (2009). *A human factors assessment of the Lunar Electric Rover (LER) during a 14-day desert trial.* NASA/Johnson Space Center. Internal NASA Document, February 2010.
No Number		Loukopoulos, L. D., Dismukes, R. K., & Barshi, I. (2009). *The Multitasking Myth: Handling Complexity in Real-World Operations*. Surry, England: Ashgate Publishing Limited.
No Number		Margerum, S.; Rajulu, S. Human Factors Analysis of Crew Height and Weight Limitations in Space Vehicle Design. Human Factors and Ergonomics Society Annual Meeting Proceedings, Volume 52, Number 1, 2008 , pp. 114-118(5)
No Number		Martin, A. D., Drinkwater, D. T., Clarys, J. P., (1984). Human Body Surface Area: Validation of Formulae Based on Cadaver Study. Human Biology, Vol. 56, No. 3, 475-485
No Number		McConville, J and Tillman, B. Year 2015 astronaut population anthropometric calculations for NASA-STD-3000 (1991).
No Number		*Mount, F.E. (1999).* Space human factors engineering challenges in long duration flight. *NASA/Johnson Space Center Document #20000096524.*

No Number		Nielsen, J. (1993). *Usability Engineering*. San Francisco, CA: Morgan Kauffman Publishers Inc.
No Number		Ogden, C. L., Fryar, C. D., Carroll, M. D., & Flegal, K. M. (2004). Mean body weight, height, and body mass index, United States 1960–2002. *Advance data from vital and health statistics*, No 347. Hyattsville, MD: National Center for Health Statistics.
No Number		Rajulu, S., Margerum, S., Young, K, Blackledge, C. Anthropometric Processes for Population Analysis, Suit Factor Generation, and a NASA Recommended set of Practices Essential for Data Collection and Analysis for Verification and Validation of Vehicle, Suit, and Vehicle-Suit Interface Requirements. JSC 65851. (2010)
No Number		Reason, J., Human Error. Cambridge: University Press. 1990
No Number		Roscoe, A H. (Ed.). (1987). In A. H. Roscoe (Ed.) Inflight assessment of workload using pilot ratings and heart rate. In The Practical Assessment of Pilot Workload (AGARD-AG-282, Neuilly-sur-Seine, France: Advisory Group for Aerospace Research and Development, 78-82).
No Number		Roscoe, A.H., & Ellis, G.A. (1990). A subjective rating scale for assessing pilot workload in flight: A decade of practical use (No. Technical Report TR 90019). Farnborough, UK: Royal Aerospace Establishment.
No Number		Sauro, J., & Lewis, J. R. (2005). *Estimating completion rates from small samples using binomial confidence intervals: Comparisons and recommendations.* Paper presented at the Human Factors and Ergonomics Society Annual Meeting, Orlando, FL.
No Number		Sauro, J., & Lewis, J. R. (2009). *Correlations among Prototypical Usability Metrics: Evidence for the Construct of Usability.* Paper presented at the Computer Human Interaction (CHI), Boston, MA
No Number		Sheridan, T. (2002). Humans and automation: Systems design and research issues. New York: Wiley.
No Number		Thaxton, Sherry; Rajulu, Sudhakar. Population Analysis: Communicating About Anthropometry in Context. Human Factors and Ergonomics Society Annual Meeting Proceedings, Volume 52, Number 1, 2008 , pp. 119-123(5)
No Number		Thompson, S., Litaker, Jr., H.L., Szabo, R., Howard, R., & North, D. (2010). *Evaluation of the Altair lunar lander DAC-3 interior volume configuration.* NASA/Johnson Space Center. Internal NASA Document, January 2010.

No Number		Turner, S., Bockman, M. Cain, L., Morgan, J., Barber, D. (2009). CEV Display Format Development Process (Draft)
No Number		Wiegmann, D.A. and S.A. Shappell. A Human Error Approach to Aviation Accident Analysis: The Human Factors Analysis and Classification System. 2003
No Number		Woolford, B. J., & Bond, R. L. (1999). Human Factors of Crewed Spaceflight. In W. J. Larson, & L. K. Pranke, (Eds.). *Human Spaceflight: Mission Analysis and Design* (Chapter 6). New York, NY: McGraw Hill.
No Number		Young, J.W. et al. (1983). *Anthropometrics and Mass Distribution Characteristics of the Adult Female*. FAA Civil Aeromedical Institute, Federal Aviation Administration, AD-A143096. Oklahoma City, Oklahoma
NPR 8715.3		NASA General Safety Program Requirements
NPR 8705.5		Probabilistic Risk Assessment Procedures for NASA Programs and Projects
SSP 30233		Space Station Requirements for Materials and Processes
SSP 30512		Space Station Ionizing Radiation Design Environment
SSP 30575		Space Station Interior and Exterior Operational Location Coding System
SSP 50005		International Space Station Flight Crew Integration Standard section 9.5 for NASA labeling standards and section 5.7 for radiation protection standards
SSP 50254		Operations Nomenclature
SSP 50783		Labeling of Intravehicular International Space Station Hardware: Design Development Process
SSP 50808	Revision B	International Space Station (ISS) to Commercial Orbital Transport Services (COTS) Interface Requirements Document (IRD)

Appendix D Potential Future HIDP Chapters

Alignment with NASA-STD-3001, Volume 2	Chapter Topic
Chapter 3	How to determine whether a verification should be analysis, demonstration, test, or inspection
Chapter 3	How to plan/perform human-in-the-loop evaluations.
Chapter 3	How to plan a human-in-the-loop (HITL) type verification event, verifying multiple requirements in one event.
Chapter 3	Function allocation
Chapter 3	Iterative conceptual design and prototyping
Chapter 5	Design for Team performance/cohesion
Chapter 5	Evaluation of situational awareness
Chapter 6	Accounting for vibration in crew performance.
Chapter 6	Water sampling and analysis
Chapter 6	Toxicology and microbial analysis
Chapter 6	Design for heat storage
Chapter 7	Design for a stowage system and inventory management system
Chapter 7	Medical system selection
Chapter 7	Design for countermeasures
Chapter 7	Waste management design
Chapter 8	Habitat conceptual design
Chapter 9	Design for Training
Chapter 9	Design for control of human hazards, such as electrical hazards
Chapter 9	Design for long duration sustainability
Chapter 9	Equipment training
Chapter 10	Human Robotics Interaction
Chapter 10	Design for autonomy
Chapter 10	Design for HCI
Chapter 10	Design for sharing of information between crewmembers/cock-pit resource management
Chapter 10	Precluding inadvertent operation
Chapter 10	Human Automation Interaction
Chapter 11	Human accommodation in suit design
Chapter 12	Mission Operational Assessment process (e.g., ISS OpsHab process)
Chapter 12	Procedures Design
Chapter 12	Concepts of operations development
Chapter 12	How to design an integrated mission plan to accommodate the human

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave Blank)*

2. REPORT DATE
September 2014

3. REPORT TYPE AND DATES COVERED
Technical Publication

4. TITLE AND SUBTITLE
Human Integration Design Processes (HIDP)

5. FUNDING NUMBERS

6. AUTHOR(S)
Human Health and Performance Directorate

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Lyndon B. Johnson Space Center
Houston, Texas 77058

8. PERFORMING ORGANIZATION REPORT NUMBERS
S-1169

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

National Aeronautics and Space Administration
Washington, DC 20546-0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
TP-2014-218556

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Unclassified/Unlimited
Available from the NASA Center for AeroSpace Information (CASI)
7115 Standard
Hanover, MD 21076-1320 Category: 18

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

The purpose of the Human Integration Design Processes (HIDP) document is to provide human-systems integration design processes, including methodologies and best practices that NASA has used to meet human systems and human rating requirements for developing crewed spacecraft. Content is framed around human-centered design methodologies and processes in support of human-system integration requirements and human rating. NASA-STD-3001, Space Flight Human-System Standard, is a two-volume set of NASA Agency-level standards directed at minimizing health and performance risks for flight crews in human space flight programs. Volume 1 sets standards for fitness for duty, space flight permissible exposure limits, permissible outcome limits, levels of medical care, medical diagnosis, intervention, treatment and care, and countermeasures. Volume 2 focuses on human physical and cognitive capabilities and limitations and defines standards for spacecraft, internal environments, facilities, payloads, and related equipment, hardware, and software with which the crew interfaces during space operations. NASA Procedural Requirements (NPR) 8705.2B specifies the Agency's human-rating processes, procedures, and requirements. Although HIDP speaks directly to implementation of NASA-STD-3001 and NPR 8705.2B requirements, the human-centered design, evaluation, and design processes described in this document can be applied to any set of human-systems requirements and are independent of reference missions.

14. SUBJECT TERMS

space systems; spacecraft design; operations; design process; systems engineering

15. NUMBER OF PAGES
308

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT
Unclassified

18. SECURITY CLASSIFICATION OF THIS PAGE
Unclassified

19. SECURITY CLASSIFICATION OF ABSTRACT
Unclassified

20. LIMITATION OF ABSTRACT
Unlimited