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COMMERCIAL HUMAN SYSTEMS INTEGRATION PROCESSES (CHSIP)

CONCURRENCE

MAY 2011

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1.0 INTRODUCTION

1.1 PURPOSE

The purpose of the Commercial Human Systems Integration Processes (CHSIP) document is to provide Commercial Crew Transportation (CCT) companies with the National Aeronautics and Space Administration's (NASA's) procedures and best practices NASA has used to meet human systems and human certification requirements for developing crewed spacecraft. CHSIP contents focus on human-centered design methodologies and processes.

The JSC-65993 Commercial Human-System Integration Requirements (CHSIR) document specifies human-systems integration requirements for crewed commercial space system design. Those program requirements are derived from NASA-STD-3001 NASA Space Flight Human-System Standard Volume 2, which establishes the Agency standards for Human Factors, Habitability, and Environmental Health. The NASA Procedural Requirements (NPR) 8705.2B, Human-Rating Requirements for Space Systems specifies the Agency's human-rating processes, procedures, and requirements.

The CHSIP was written to share with the Commercial Crew Transportation (CCT) Company NASA's compendium of knowledge towards achieving human certification of a spacecraft through implementation of human-systems integration requirements. Although the CHSIP speaks directly to implementation of CHSIR 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 CHSIP is a reference document which may be used during the development of crewed space systems developed by commercial companies in partnership with NASA. The CHSIP can guide the commercial company through all system development phases in the implementation of requirements in CHSIR and NPR 8705.2B Human-Rating Requirements for Space Systems.

1.3 HOW TO USE THE CHSIP

The CHSIP document is a compendium of human- systems design "how-to's," describing the processes, methodologies, and best practices used by NASA as a result of lessons learned and legacy space system standards. Select processes included in the CHSIP are based on NASA's experiences and expertise in spacecraft design; particularly those which are complex processes, have notable lessons learned, or have important considerations. Each CHSIP topic addresses a subset of requirements specified in the CHSIR and/or the NPR 8705.2B. While the CHSIP does not levy program requirements, relevant CHSIR or NPR requirements are referenced in each process along with suggested technical products for insight and assessment throughout the systems engineering lifecycle. In areas where NASA has documented background information or detailed design guidance, references are made to the NASA/SP-2010-

3407 Human Integration Design Handbook (HIDH). The HIDH is a resource document for the NASA-STD-3001 Volume 2, which provides technical information on many aspects of space system design for crew health, habitability, environment, and human factors.

The CHSIP is organized into stand-alone sections, assuming that the CCT developer will reference individual topics, as needed. Relevant information is repeated in various sections and cross-references are provided, as needed.

Chapter 3 provides over-arching information beginning with a discussion of NASA's human-centered design (HCD) philosophy and approach to space system development. The HCD approach has been captured in NASA-STD-3001 Volume 2 as a requirement for each human spaceflight program. Section 3.1.3 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 the CHSIP processes. For each milestone review, relevant technical products (e.g., concepts of operation, analyses and evaluations, design descriptions, etc.) are identified with the intent of minimizing engineering lifecycle development costs through iterative assessment of concepts and designs. Section 3.3 summarizes the generic technical products that would be typical outputs of HCD activities and their associated milestones. Section 3.2 describes the Human-Systems Integration (HSI) Team concept and the role of an HSI Team in the HCD process and development of commercial human space vehicles.

Section 4 contains separate, stand-alone subsections describing different spacecraft design processes related to requirements specified in CHSIR. Each process is explicitly tied to CHSIR and/or NPR 8705.2B requirements and is written with the intent of enabling spacecraft development and requirement verification. 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 lifecycle.

A list of the sections is below. The CCT developer should read sections 3.1, 3.2 and 3.3 as they are a companion to each section. For convenience, each title is a hyperlink to that section.

It is important to note that the processes described in CHSIP do not cover all activities necessary to ensure effective system design. This process document may be used in addition to existing design methods in order 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.

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/system. Throughout CHSIP, 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 B, respectively.

2.0 DOCUMENTS

2.1 APPLICABLE DOCUMENTS

Document Number	Document Revision	Document Title
JSC-65993	Baselined 12/2010	Commercial Human-systems Integration Requirements (CHSIR)
NASA-STD-3001 Volume 2		NASA Space Flight Human-System Standard, Volume 2: Human Factors, Habitability, and Environmental Health
NPR 8705.2B		Human-Rating Requirements for Space Systems

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-CENTERED DESIGN

3.1.1 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-Cented Design Processes for Interactive Systems. Human-centered design (HCD) is an approach to interactive system development that focuses on making systems usable by ensuring that the needs, abilities, and limitations of the human user are met. HCD is a multi-disciplinary activity that involves a range of skills and stakeholders that 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 customer satisfaction.

Engineering lifecycle development costs 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 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. Although not designed, the human user may be viewed as a functional sub-system 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.

Customer satisfaction is increased by involving the user/customer in the HCD process so there is understanding of and participation in design decisions. This is especially important when the human user will have critical control responsibilities over the system or when a positive customer experience is important to business goals.

3.1.2 PRINCIPLES OF HUMAN-CENTERED DESIGN

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

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

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

Users provide valuable knowledge about 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 spaceflight 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.

3.1.2.2 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.

The decision should weigh the relative capabilities and limitations of the human vs. technology and 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. They 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. For further guidance, see ISO 9241-2 and ISO 10075.

3.1.2.3 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 those 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.

3.1.2.4 MULTIDISCIPLINARY DESIGN

Human-centered design involves the application of a range of technical expertise in order to adequately address the human aspects of the design. This means that multi-disciplinary 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, discipline 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. Multi-disciplinary teams do not have to be large but the team should be sufficiently diverse to make appropriate design trade-off decisions.

3.1.3 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 user/crewmember may be NASA or Commercial Crew Transportation (CCT) Company astronauts. The HCD process is comprised of three main activities that are performed iteratively in a feedback loop as represented in Figure 3.1.3-1. The HCD process is conducted and iterated throughout the overall systems engineering lifecycle. The HCD activities are shown in the context of the systems engineering milestones in section 3.3. The CHSIP processes in Section 4 are either structured around or a part of these activities, which are described in paragraphs below.

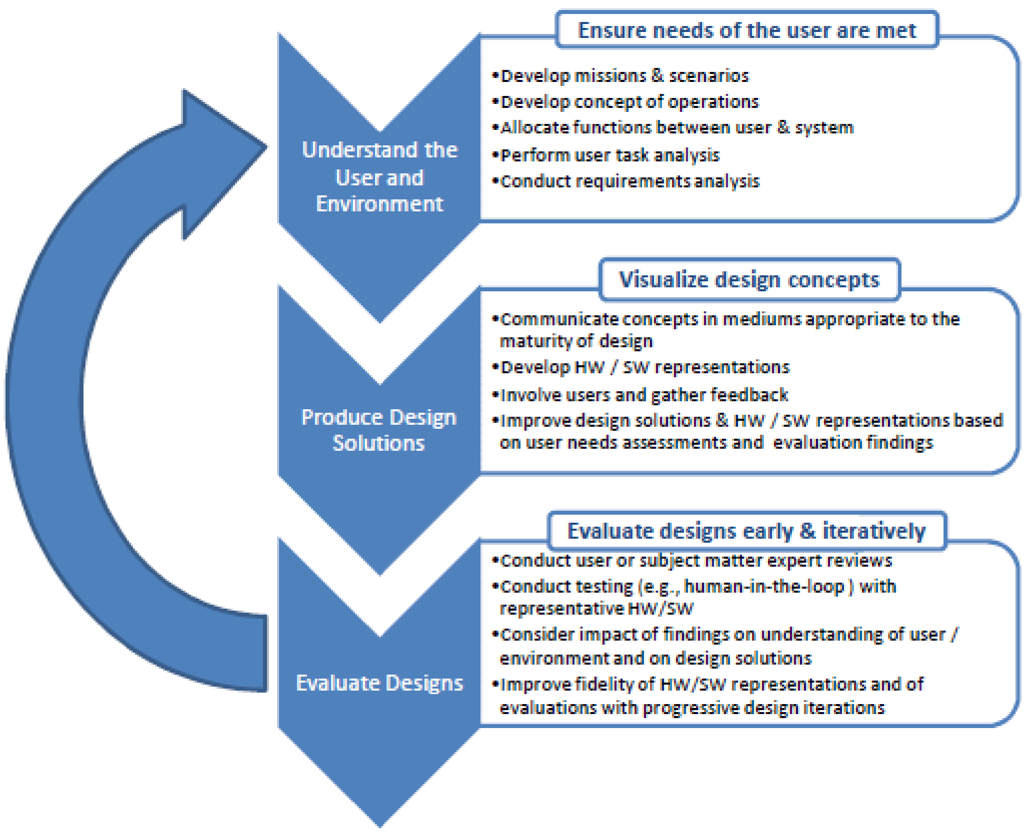

FIGURE 3.1.3-1 HUMAN-CENTERED DESIGN ACTIVITIES

3.1.3.1 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, etc.), 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

3.1.3.1.1 DEVELOP MISSIONS AND SCENARIOS

Per the 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 CHSIR is based upon is to provide ISS increment crew rotation for up to four NASA crewmembers. The nominal scenario includes the following events, which are illustrated in Figure 3.1.3.1.1-1.

- Vehicle maintenance and processing at launch site
- Launch
- Up to 3 day transit to ISS
- Quiescent vehicle-docked phase of up to 210 days
- Less than 2-day return-to-earth from ISS
- Post landing operations no greater than 2 hours

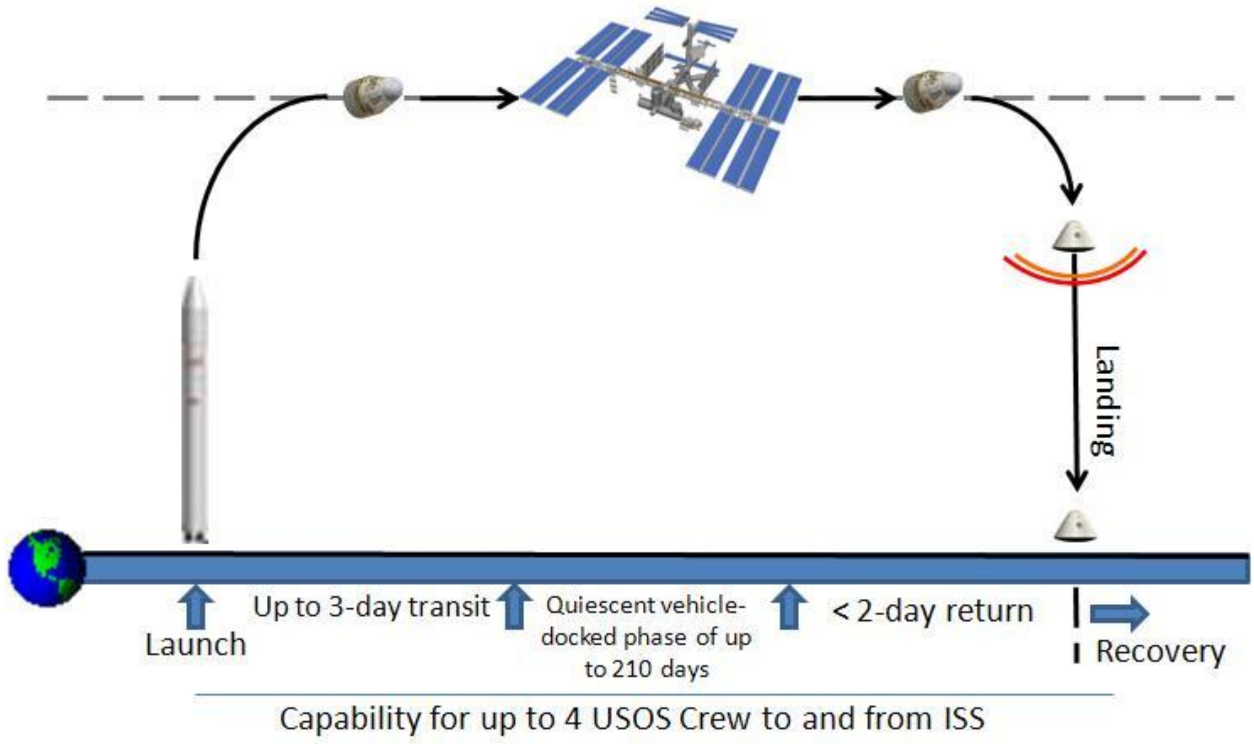

FIGURE 3.1.3.1.1-1 NOMINAL COMMERCIAL CREW TRANSPORT MISSION (ASSUMED FOR CHSIR)

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 four USOS crewmembers

3.1.3.1.2 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 3.1.3.1.2-1. 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 impacted 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 3.1.3.1.2-1 EXAMPLE NOMINAL SCENARIO - TRAVEL TO ISS (NOTIONAL)

Mission Phase	Crew Activities					Subsystems Impacted
	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
Ascent	Checklist procedures	Eat Waste Sleep	Eat Waste Sleep	Eat Waste Sleep	Eat Waste Sleep	ECLSS
Orbit	Eat Waste Sleep	Eat Waste Sleep	Eat Waste Sleep	Eat Waste Sleep	Eat Waste Sleep	ECLSS Hygiene Stowage & Trash
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)

3.1.3.1.3 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 versus 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 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. Task analyses and tests may be useful in evaluating performance to help to determine allocations. Representative users should be involved in these decisions. Per 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.

3.1.3.1.4 PERFORM USER TASK ANALYSIS

The purpose of task analysis is to analyze how the user interacts with the space system and 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, 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. CHSIP 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.

3.1.3.1.5 CONDUCT REQUIREMENTS ANALYSIS

As operating scenarios, function allocations, and tasks are better defined, design requirements should be revisited, refined, and documented. 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.

3.1.3.2 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 *Understanding the User and Environment* activities. 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.

3.1.3.3 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 which contributes to lifecycle development cost control 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 upon Human-in-the-Loop (HITL) evaluation (required per NPR 8705.2B paragraph 2.3.10), or 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. CHSIP sections 4.2 and 4.3 provide additional detail and guidance on usability and workload evaluation, 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., use of computer simulations, mock-ups/prototypes, test scenarios, etc.)
- How the evaluation is to be performed (test set up, methodology, etc.)
- The procedures to be used in the evaluation
- Resources required for evaluation and analysis, including users/test subjects

- Scheduling evaluation activities and resources, including users/test subjects and concrete design proposals (e.g., models, simulations, mock-ups, etc.)
- 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., mock-ups, qualification units, etc.). Intentional design iteration is a fundamental principle of human-centered design which contributes to lifecycle development cost control by helping to identify risks and issues early in the design cycle when they are relatively inexpensive to fix.

3.2 ROLES AND RESPONSIBILITIES

3.2.1 THE HUMAN-SYSTEMS INTEGRATION (HSI) TEAM

The Human-Systems Integration (HSI) Team is the group which 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 which serve to protect crew from hostile or extreme environments. Ensuring effective human-systems integration across the design is particularly important for crewed space system design due to the increased risk 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, including such varied topics as environmental factors, human factors, and safety concerns. 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 lifecycle through operations and decommission.

3.2.2 HSI TEAM BASIS IN NASA REQUIREMENTS

An HSI Team is required for NASA human-rating and 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.*

In the commercial space model, an HSI Team is created as a part of a NASA Program Office managing commercial space projects. This NASA HSI Team is comprised of

NASA members representing various stakeholder disciplines, and includes representation from the CCT Company.

3.2.3 TECHNICAL SCOPE OF THE HSI TEAM

In order to integrate 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. Example areas of technical expertise necessary for proper HSI include, but are not limited to:

- Human Factors/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, etc.)
- 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
- EVA Physiology
- Mission Operations
- Training

3.2.4 THE ROLE OF THE HSI TEAM IN COMMERCIAL SPACE

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 iterative and adequate HSI design considerations are taking place throughout the engineering lifecycle. Appropriate discipline experts from the HSI Team interact with system designers between milestone reviews in order 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 regarding the deliverables provided. It is important that the NASA HSI Team include representation from the CCT Company for effective HCD implementation. Membership on the NASA HSI Team ensures that the CCT Company is involved in discussions of design reviews, stakeholder reviews, evaluations, and other activities such as system analyses and design trades, in order to communicate information to and from appropriate discipline experts within the CCT Company and provide design insight as needed. Note that the CCT Company may also choose to form an internal CCT HSI Team as an interface to the NASA HSI Team. The mechanism by which the CCT Company 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 human-centered design implementation, providing official positions to any and all CCT and NASA oversight boards and panels. This level of authority is necessary for an HSI Team to fulfill its responsibility.

3.2.5 HSI TEAM REVIEW OF DELIVERABLES

The NASA HSI Team is involved in review of all human-rating contract deliverables, as detailed in each company's Human-Rating Certification Plan (HRCP). The deliverables due at each stage of the engineering lifecycle are multiple and varied. The technical products presented in sections 3.3 and 4 of the CHSIP may or may not be contractual deliverables. The determination will be made on a contract by contract basis. 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, CCT companies are referred to NPR 8705.2B Human-rating Requirements for Space Systems.

3.3 SUMMARY OF CHSIP TECHNICAL PRODUCTS

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

3.3.1 GENERIC TECHNICAL PRODUCTS

A summary of generic technical products and the lifecycle review by which they should be provided is presented in Table 3.3.1-1. 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 3.3.1-1 SUMMARY OF GENERIC TECHNICAL PRODUCTS

Technical Products	Responsible Org	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.	NASA	X	---	---	---	---	---
A description of the Human-Systems Integration Team and their authority within the program. Required per NPR 8705.2B paragraph 2.3.8.	NASA	X	---	---	---	---	---
A description of the ConOps, functions allocation, and associated crew task lists.	CCT Company	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.	CCT Company	---	---	I	U	U	---
System architecture drawings (structures, equipment, etc.), material specifications, interface requirements.	CCT Company	---	---	I	U	U	---
Verification plan.	CCT Company	---	---	I	U	U	---
X = one-time release of item I = initial release of item U = updated release of item							

3.3.2 GENERIC TECHNICAL PRODUCTS DEFINITIONS

Reference Missions

Prior to 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 per NPR 8705.2B paragraph 2.3.1, and it is essential as input for CCT Company-developed products such as Concept of Operations and crew task lists.

Human-Systems Integration Team

No later than SRR, NASA will provide a description of the NASA HSI Team and their authority within the program (required per NPR 8705.2B paragraph 2.3.8). The description will also include how the NASA HSI Team will interface with NASA Program boards and CCT Company 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 lifecycle, 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.

Concept of Operations and Crew Task Lists

The ConOps, described in paragraph 3.1.3.1.2 provides information such as identification of crew activities and determination of which subsystems are impacted by crew activities. Functions allocation, described in paragraph 3.1.3.1.3, 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.

Modeling/Analysis/Evaluation Summaries

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 utilize increasingly higher fidelity inputs/mockups, as discussed in paragraph 3.1.3.3 Evaluate Designs and Iterate Solutions. It is important that summaries address how key/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.

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. 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 CHSIP PROCESSES

4.1 USER TASK ANALYSIS

4.1.1 INTRODUCTION

Task analysis is a methodology used to break an event down into individual 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.

The purpose of a spacecraft task analysis is to identify user and system level tasks in order 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 support 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 section 3 of the NASA/SP-2010-3407 Human Integration Design Handbook (HIDH).

This section of the CHSIP 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 JSC-65993 Commercial Human-Systems Integration Requirements (CHSIR) 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 to perform nominal and contingency tasks. CHSIP Section 3.2 discusses the human-centered design approach and activities, highlighting the importance of task analysis throughout the design process.

4.1.1.1 PURPOSE

Task analysis is an essential component of human-centered design, which focuses on providing usable systems for humans throughout a system's entire life cycle. While 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 frequently as design matures. This iterative approach allows for the identification of current and future task demands which can aid in decisions such as which tasks should be allocated to a human versus an automated system or how system components should be used. Task analysis also results in the identification of critical crew tasks, which are those tasks that are absolutely required and necessary for crew to successfully accomplish operations and mission objectives. Critical crew tasks may occur nominally or off-nominally and include tasks which are essential to crew health or, if done incorrectly, may lead to loss of crew, loss of mission, or undesirable vehicle states. By identifying these tasks early, effort can be put forth to implement designs that reduce the probability of mishaps or errors and allow crew 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 the implementation of many CHSIR 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 inspections are recommended to avoid late and costly changes. A single task analysis activity may concurrently address multiple requirements. The following requirements call for task analyses in their verification:

- CH4001 Anthropometry
- CH4002 Range of Motion
- CH4006 Structural Integrity of the Human-Machine Interface
- CH4007 Operational Strength Limit for the Human-Machine Interfaces
- CH4008 Metabolic Loads
- CH6023 Water Dispensing Rate
- CH6025 Hot Food and Beverage Water Temperature
- CH6041 Contamination Responses – Cleanup, Isolation, Removal
- CH6042 Cross-Contamination
- CH6043A Environmental Health Kit
- CH7005 Food System Provisions
- CH7006 Personal Hygiene System Considerations
- CH7007 Body Waste Management System Provisions
- CH7013 Medical Care Provisions
- CH7014 Emergency Return Medical Care Provisions
- CH7015 Stowage Locations
- CH7023 Sleep System Provisions
- CH7024 Clothing System Provisions
- CH7025 Housekeeping System Provisions
- CH7028 Single Crew Operation
- CH8001 Functional Volume Allocation
- CH8010 Assisted Ingress and Egress
- CH8012 Hatch Cover and Door Operation Without Tools
- CH8015 Hatch Size and Shape
- CH8026 Mobility Aids for Ingress and Egress
- CH8030 Window Optical Properties
- CH8035 Interior Lighting
- CH8039 Exterior Lighting
- CH8044 Unassisted Ingress and Egress
- CH9022 Durability
- CH9032 Maintenance Item Location
- CH9033 Check and Service Point Accessibility
- CH9050 Crew Survival Kit

- CH10001 Legibility
- CH10002 Crew Interface Usability
- CH10003 Workload: Off-Nominal
- CH10004 Workload: Nominal
- CH10005 Handling Qualities for Manual – Control Level 1
- CH10006 Handling Qualities for Manual Control – Level 2
- CH10011 State Information
- CH10014 Missing Data Display
- CH10019 Command Feedback
- CH10023 Inadvertent Operation Prevention
- CH10024 Field of View
- CH10028 Reach for Critical Controls
- CH10029 Functionally Related Displays and Controls
- CH10040 Notifications
- CH10046 Emergency Control Coding
- CH10047 Over 3 G
- CH10048 Over 2 G
- CH10049 Supports
- CH10051 Suited Control Operability
- CH10052 Information Management Methods and Tools
- CH10053 Data Rate and Fidelity
- CH10056 Data Distribution System
- CH10064 Automated Functions
- CH10067 Manual Override of Automated Functions
- CH10069 Crew Satisfaction with Interfaces
- CH11015 Ability to Work in Suits
- CH11017 Suited Donning and Doffing
- CH12003 Ventilation Openings
- CH12004 Sharp Objects
- CH12005 Hazards Labeling
- CH12007 Labeling
- CH12010 Illumination
- CH12014 Maintenance Without De-integration
- CH12016 Maintenance Without Damage
- CH12017 Fluid Management
- CH12018 System Safing Controls

4.1.2 TASK ANALYSIS PROCESS OVERVIEW

Task analysis refers to a family of techniques (see Ainsworth, 2004) which involves 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. An initial task definition 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/functional allocation is defined. At later stages, the focus should be on capturing the lower-level crew and system interactions that the vehicle needs to support 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 result in modified designs and knowledge that are 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 that allows the user to perform all necessary tasks and operations during the course of a defined mission is achieved.

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 sub-system such 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 sub-system or component level, considerations need to be made for how crew and system-level tasks with these components may be affected by or have an effect on other components and the fully integrated vehicle. By understanding these inter-dependencies it may be possible to effect the subsequent development of mission related task sequences or concepts of operations, which will be needed throughout the system and hardware design process.

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 crew when needed throughout the mission. The analysis should generally focus upon interfaces (hardware and software) and locations within the craft with which crew have direct interaction during a mission.

4.1.2.1.1 TASK ANALYSIS EXECUTION

The task analysis execution process involves group interviews with SMEs. First, the specific objectives of the task analysis 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 consistent data is captured from session to session.

Following the specification of objectives, the conductors of the task analysis should review appropriate reference documents (requirements, standards, engineering drawings, etc.) 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 operation experts, crewmembers, or other individuals with specialized knowledge about the tasks of interest. Prior to the task analysis session, 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 is 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 for 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 that the objectives of the session are covered (through appropriate queries) 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 not only address the tasks required to perform hygiene such as unstowing crew provisioning items and setting up the hygiene area, but other considerations such as the mission phases where hygiene should occur, how many crewmembers can conduct the hygiene tasks at one time, the type of hardware, restraints and 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:

- Mission objectives
    - Identify tasks that are required to achieve mission objectives
- Mission phases and scenarios
- Identify tasks that are required for each mission phase
    - Nominal and off-nominal crew tasks
- System tasks as they impact crew tasks or crew monitoring activities
- Necessary task sequences (parallel, serial, multiple crew/systems, individual crew/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)
- Integrated human/system tasks and system interactions
- Vehicle, environmental, safety, operational, and crew constraints related to tasks
- All human interfaces (hardware and software) with which the crew will interact to accomplish tasks
    - Including tools and equipment needed to accomplish the task
- Level of crew involvement and required communication with the ground
- Function allocation for manual and automated crew and system tasks
    - Identify required resources and information necessary to perform tasks
- Environmental considerations/constraints for tasks
- Vehicle/system state
- Expected results for task errors or failures in task completion
- Required operator inputs
- Performance expectations
- Time related data (e.g., duration, frequency, limits) for tasks

- Task priority and criticality

The moderator should ensure that the data collected for each scenario and task is complete in respect to these aspects. Any aspects in which there are disagreements between SMEs or in which knowledge is incomplete should be documented.

Upon 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 allow for 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.

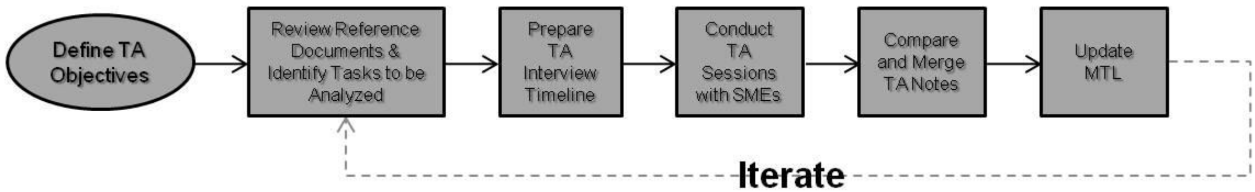

FIGURE 4.1.2.1.1-1 TASK ANALYSIS EXECUTION PROCESS

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. This 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 (via 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 upon tasks requirements identified via task analyses. It 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 they 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 lifecycle. 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 lifecycle, the technical products in Table 4.1.3-1 are recommended for review by the NASA customer.

TABLE 4.1.3-1 TASK ANALYSIS TECHNICAL PRODUCTS

Technical Products	Responsible Org	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.	CCT Company	X	---	---	---	---	---
Completion of "Round 2" of all task analysis sessions and updates to related individual summary reports and task list. MTL Rev B complete.	CCT Company	---	X	---	---	---	---
Completion of "Round 3" of all task analysis sessions and updates to related individual summary reports and task list. MTL Rev C complete.	CCT Company	---	---	X	---	---	---
Task analysis sessions are complete and final versions of individual summary reports and task list complete. Final MTL.	CCT Company	---	---	---	X	---	---
Hardware/ 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.	CCT Company	---	---	---	---	X	---
Final hardware/ vehicle based analysis based on defined critical crew tasks and systems tasks.	CCT Company	---	---	---	---	---	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 Sandom, C., Harvey, R. (Eds.), Human Factors for Engineers (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*. Surry, 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. It has been shown that usability increases efficiency, effectiveness, and user satisfaction. Furthermore, designs with good usability can reduce errors, fatigue, training time, and overall lifecycle costs.

4.2.1.2 HUMAN-CENTERED DESIGN

Usability is a key component of human-centered design. Human-centered design focuses on users’ needs in order 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 lifecycle.

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 lifecycle 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 lifecycle from the earliest stages in order 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 CHSIR section 10.0 Crew Interfaces, with the principal requirements being the two listed below. These requirements limit error rate and set minimum standards for user satisfaction as measured by a system usability scale.

- CH10002 Crew Interface Usability
- CH10069 Crew Satisfaction with Interfaces

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 purposes of conducting a usability study, some of which 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 employed. This section provides a high level, step-by-step approach that may be tailored to fit each usability study.

1. Define purpose of the study
   - Decide what features of the system are to be tested at 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 basis for selecting between two 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 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 sub-set of possible tasks may be selected. It is wise to select tasks that are frequently used, 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 is dependent upon 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 based on the method selected. A minimum of 8-10 subjects is typically recommended. More subjects are needed to find less frequent design issues. Again, subjects should be representative of the user population in terms of experience, training, age, and other factors.

6. Collect data
   - Complete data collection based on 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 are dependent upon the objectives of the study. A quantitative analysis can help compare interfaces, determine if error rates decreased with a new design, or compare efficiency 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) for small sample size data and statistical methods for user testing. Sometimes only descriptive statistics are appropriate (e.g., range, mean, median, standard deviation), while other times it is appropriate to look at pair-wise comparisons of performance measures.

4.2.3 USABILITY EVALUATION METHODS

There are many usability evaluation methods. Some are conducted by human factors experts alone (e.g., heuristic evaluation, cognitive walkthrough) while others are conducted with the participation of users or test subjects (e.g., user testing, knowledge elicitation). Method selection is dependent upon 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, 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 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 performing a heuristic evaluation, 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 involve 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/ETHNOGRAPHIC STUDIES

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 two 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 three-dimensional models of components that users might be asked to arrange in a preferred configuration, or two-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 HITL evaluations are methods that evaluate a system by testing it with its users. The testing consists of asking users to complete high frequency or high criticality 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

There are many usability metrics 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 towards 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 three 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 across all task steps *counts* 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 towards 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 based on severity. These help with identifying 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. This may result in low efficiencies or high error rates, or issue with physical interface design factors such as control sizing or orientation of movement. Use of usability results in furthering the design's maturation can increase the efficiency and effectiveness of the interface while reducing errors and fatigue.

4.2.6 USABILITY VERIFICATION

The methods and metrics described above are industry standard ways of assessing and designing for usability. However, the CHSIR only requires a subset for successful verification of spacecraft usability. CH10002 Crew Interface Usability requires calculation of errors rates (see section 4.2.4.1.1), while CH10069 Crew Satisfaction with Interfaces requires measurement of user satisfaction as measured by the System

Usability Scale (see section 4.2.4.1.3). Each is assessed as part of a HITL usability evaluation.

4.2.7 USABILITY EVALUATION TECHNICAL PRODUCTS

For each of the major milestones of the design lifecycle, the technical products in Table 4.2.7-1 are recommended for review by the NASA customer.

TABLE 4.2.7-1 USABILITY EVALUATION TECHNICAL PRODUCTS

Technical Products	Responsible Org	Phase A		Phase B	Phase C	Phase D	
		SRR	SDR	PDR	CDR	SAR	FRR
A description of the ConOps, functions allocation, and associated crew task lists. Includes identification of potential errors that can be encountered for each task.	CCT Company	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.	CCT Company	---	---	I	U	U	---
Verification plan.	CCT Company	---	---	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 3.1.3.1.2 provides information such as identification of crew activities and determination of which subsystems are impacted by crew activities. Functions allocation, described in paragraph 3.1.3.1.3, 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.

<u>Modeling/Analysis/Evaluation Summaries</u>

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 utilize increasingly higher fidelity inputs/mockups, as discussed in paragraph 3.1.3.3 Evaluate Designs and Iterate Solutions. It is important that summaries address how key/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 metrics for effectiveness, efficiency, and satisfaction as well as subjective data.

<u>Verification Plan</u>

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

4.2.8 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/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 that designers must consider 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 since 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 per 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 spaceflight, the primary concern is avoiding unnecessarily high workload levels, given that spaceflight is generally a high stress environment. Therefore, the requirements in the JSC-65993 Commercial Human-Systems Integration Requirements (CHSIR) and the process described below focus on measuring workload with the goal of keeping workload at a level that does not negatively impact 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 CHSIP sections along with this one, and the reader is strongly recommended to review all three sections. The reader should also review the CHSIP section on task analysis, as task analysis is required for identifying workload verification tasks.

4.3.1.1 APPLICABLE REQUIREMENTS

Workload requirements are specified in the CHSIR section 10.0 Crew Interfaces. The two requirements listed below specify acceptable Bedford Workload Scale ratings for off-nominal and nominal tasks.

- CH10003 Workload Measure: Off-Nominal
- CH10004 Workload Measure: Nominal

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). When the Bedford Workload Scale is used as per CHSIR, this is considered to be a validated method. 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:

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 lifecycle: Testing of those tasks, hardware, and systems that task analysis identified as relevant to workload

3. Component 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 lifecycle 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 lifecycle, 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 pre-Request For Proposal or prior to 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.

Following task definitions, the next stage would be to start assessing crew workload in a series of simulated vehicle tasks. 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 via 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.

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 three 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 based on 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 would select WL7 for that task.

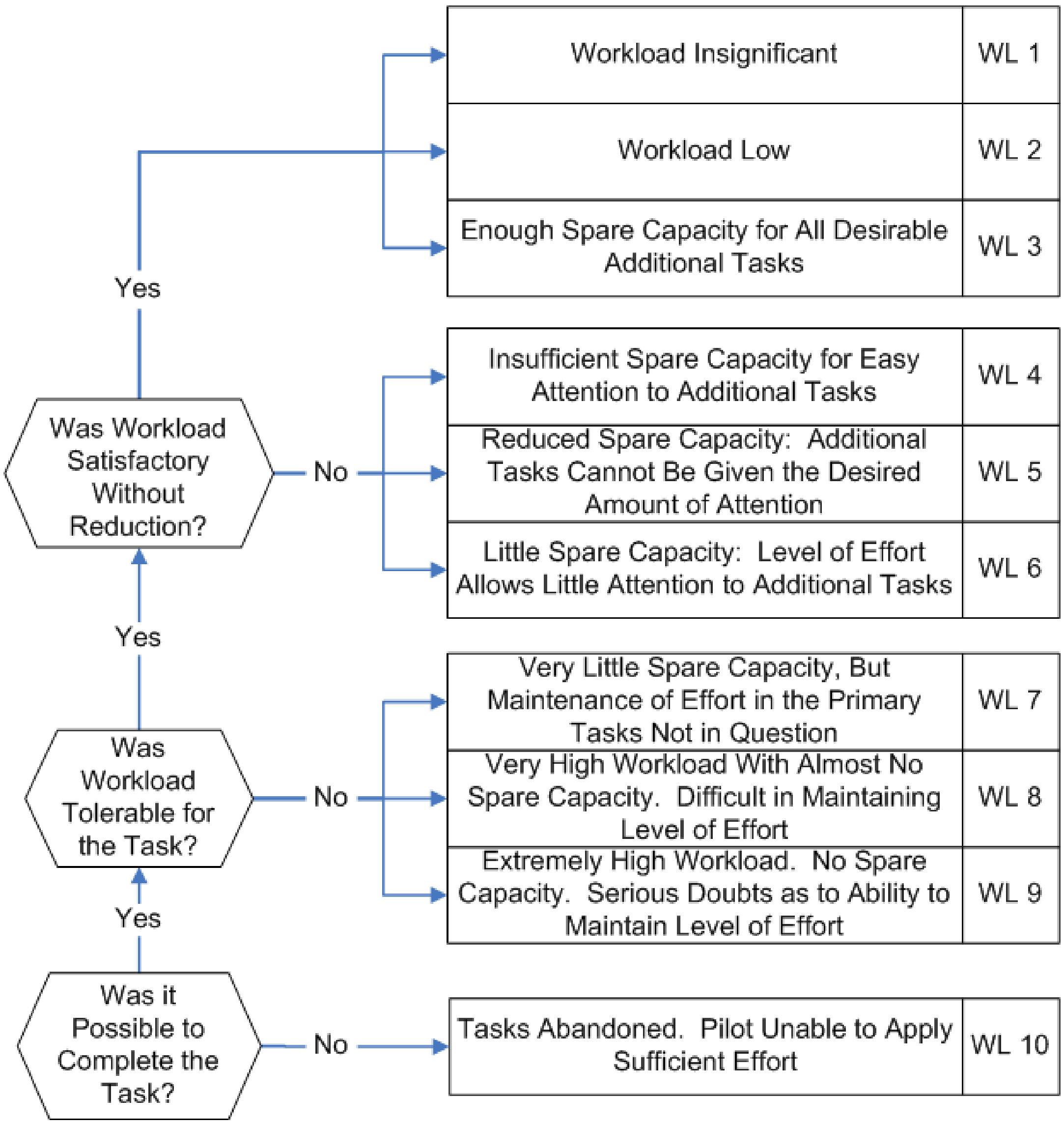

FIGURE 4.3.2-1 THE BEDFORD SCALE

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, where 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 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 is 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 in which to assess the workload of the task: physiological, performance, and subjective measures. Measurement of workload to meet the CHSIR requirement is a subjective means of assessing workload. In a HITL evaluation aimed at assessing workload, each subject will be asked to perform a task, have an identified secondary task (whether mocked-up for the test or just described to the subject), and the Bedford scale will be administered following completion of that task. Paragraph 4.3.2.2.1, below, discusses how to administer the Bedford scale during a HITL evaluation.

It is critically important that prior to 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 set-up, task, and expectations. The definition of a task is important because there are often multiple steps 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 spaceflight 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 there has been task-specific testing (such as dry-run testing or development testing) showing short peaks of high workload, the test conductor may use the results of that testing to advise the subject to use some pre-determined 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 set-up influences the subjects' workload levels, and in order to get a representative measure of workload for a given task, the task set-up must be as representative as possible. This includes using high fidelity hardware, software, test procedures, timelines, environments, and the inclusion of 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, 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 there is not extraneous information that could potentially interfere with the task, 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 set-up, an accurate depiction of the workload induced by a design is contingent on having a high fidelity design.

The CHSIR requirement stipulates that subjects need to **maintain error rates and task completion times** commensurate with the performance requirements of the particular task. Without this requirement, 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. In order to maintain task performance across individuals and get a representative measure of workload, it is important to instruct each subject how long 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 co-pilot, 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 allow 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 spaceflight, **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 spaceflight 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*" (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 crew 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 (crew, ops, hardware designers, human engineering, etc.) prior to 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 that can help determine appropriate secondary tasks.

There are several expected differences 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, etc. All of these off-nominal factors have the potential to increase task workload. Thus, there are two CHSIR workload requirements with different acceptance criteria -- one for a nominal task and one for an off-nominal task. The off-nominal CHSIR verification allows for higher workload ratings for the task (up to and including WL6) than the nominal CHSIR verification (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 is 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 spaceflight, it is unacceptable for the workload to be intolerable for the subject. Even in 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 what 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. Since the Bedford scale does not dictate how those factors are combined, the subject needs to make their own determination as to 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 there is a piece of hardware or part of a procedure that should be given more emphasis/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 may be experienced 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, 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 among 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 for the use of half ratings, even between groups (such as level 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 only be given if the subject cannot determine an answer to the question on the left distinguishing those groups.

Following 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 they decide 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.

Since 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 six 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 level 1 and 2 may not be the same as the difference between level 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. Since the CHSIR requirement calls for ratings of 1, 2, or 3 for nominal tasks and 1, 2, 3, 4, 5, or 6 for off-nominal tasks, the most effective way of describing the data is using frequency tables or plots (e.g., histograms, frequency weighted scatter plots, etc.). For example, an evaluation with six subjects who rated their workload a 1 and two subjects who rated their workload a 2 on the Bedford scale would pass the verification of the requirement. However, if six subjects rated their workload a 1, one subject rated his/her workload a 3, and one subject rated his/her workload a 4, then a consensus report stating that the workload is acceptable to all subjects in the evaluation would be required to pass the verification of the nominal-task requirement. If a consensus report cannot be acquired, then the task/design does not pass the verification of the nominal-task requirement.

4.3.2.2.3 INCORPORATING WORKLOAD THROUGHOUT THE PROJECT LIFECYCLE

In order to identify the tasks that are relevant to the workload requirement, the Commercial Crew Transportation (CCT) Company must perform a task analysis of all tasks the crew will be performing during all mission phases. Once the task analysis is complete, the CCT Company should select representative nominal and off-nominal tasks for NASA review. NASA SMEs are available to assist in the selection of the tasks, secondary tasks, and hardware and software needed for a representative test. The task analysis should begin at the beginning of the program and be refined through CDR. Following SDR, the CCT is expected to begin generation of the verification task list. The verification task list should be provided to NASA at PDR and CDR.

The 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 for a better understanding of the workload associated with a given task, familiarity with the administration of the Bedford scale, potential re-design of hardware or software based on scale ratings and crew feedback for associated tasks.

CCT products associated with workload should always include:

- 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 lifecycle, the technical products in Table 4.3.3-1 are recommended for review by the NASA customer.

TABLE 4.3.3-1 WORKLOAD EVALUATION TECHNICAL PRODUCTS

Technical Product	Responsible Org	Phase A		Phase B	Phase C	Phase D	
		SRR	SDR	PDR	CDR	SAR	FRR
A description of the ConOps, functions allocation, and associated crew task lists.	CCT Company	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.	CCT Company	---	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.	CCT Company	---	---	I	U	U	---
Verification plan.	CCT Company	---	---	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.	CCT Company	---	---	---	---	X (ORR)	---
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 3.1.3.1.2 provides information such as identification of crew activities and determination of which subsystems are impacted by crew activities. Functions allocation, described in paragraph 3.1.3.1.3, 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.

<u>Explanation of Workload Evaluation Plans</u>

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. CHSIR requires the use of the Bedford scale for the evaluation of workload in nominal and off-nominal tasks.

<u>Modeling/Analysis/Evaluation Summaries</u>

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 utilize increasingly higher fidelity inputs/mockups, as discussed in paragraph 3.1.3.3 Evaluate Designs and Iterate Solutions. It is important that summaries address how key/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.

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.

<u>Verification Plan</u>

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

<u>Workload Validation</u>

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. CHSIR requires the use of the Bedford scale for the evaluation of workload in nominal and off-nominal tasks.

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 Human Mental Workload P. A. Hancock & N. Meshkati (Eds.). Amsterdam: North Holland, 139-183.

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)

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.

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 on the behalf of 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/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 Human Error Analysis (HEA) within the framework of human-systems integration (HSI). The use of HSI processes in aviation is well established, as is the implementation of human error analysis. There are many HEA approaches described in the literature and the vehicle, system, or component developer must consider the most appropriate method for any given analysis. There are numerous tools associated with the analysis of human error, 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 CHSIP sections along with this one, and the reader is strongly recommended to review all three 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 JSC-65993 Commercial Human-Systems Integration Requirements (CHSIR) section 4.0 Physical Characteristics and Capabilities includes requirements to ensure 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, body surface area, body volume, body mass, and strength within the design process, and to evaluate the spacecraft design against requirements. The process also details the various factors that will impact successful accommodation of the population within the design and how to account for their effects. The anticipated technical products to assess whether the design is on track during the course of the engineering lifecycle are also discussed within the context of this design process. The purpose of the process for each parameter of anthropometry, range of motion, body surface area, body volume, body mass, and strength 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 section 4 of the NASA/SP-2010-3407 Human Integration Design Handbook (HIDH).

4.5.1.1 HOW TO USE THESE GUIDELINES

The following describes a process for critically evaluating a proposed design by using an approach based in 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 which the Commercial Crew Transportation (CCT) Company can use as a guide to conduct testing and analysis to ensure compliance with the requirements set forth by CHSIR and to outline the expected technical products within the engineering design lifecycle.

4.5.1.2 THE INTEGRATED APPROACH

An integrated approach examines the design across all possible physical characteristics evaluations methodologies at various stages in the design process. It is recommended that the CCT companies employ an integrated approach to understand of how the primary physical characteristics and capability aspects relate together within a design to ensure the entire population for each aspect and across aspects 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 regarding suit design and accommodation for space missions. It is anticipated that CCT companies with commercial designs that include use of Launch, Entry, Abort (LEA) suits for crew may have questions regarding suit implementations and design criteria, specifically, on how to incorporate or account for suit effects in their design. Additionally, there may arise needs for designs to place the crew in postures or dynamic activities not explicitly defined by the CHSIR requirements. For these circumstances or if questions arise on the application of requirements, suit factors, or accommodation due to suit usage, NASA is available to facilitate interpretation and work with CCT companies to assist their successful design efforts.

4.5.2 DESIGN FOR ANTHROPOMETRY

4.5.2.1 INTRODUCTION

The CHSIR requirement CH4001 Anthropometry specifies critical anthropometric dimensions for vehicle and suit design in Tables 4.1-1 and 4.1-2, respectively. These critical dimensions were selected as the measurements integral to the design of a vehicle and suit and are representative of the range of anthropometry within the NASA astronaut corps. Designs are to adhere to the range of anthropometry dimensions established in the CHSIR to ensure accommodation of the crew for both suited and unsuited tasks. The purpose of the design requirements is to ensure that all vehicle, vehicle-suit hardware, and interfaces are operable by the entire NASA-prescribed 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, via analysis, modeling, and physical testing, designs against the requirements set forth in CHSIR requirement CH4001V.

4.5.2.2 ANTHROPOMETRY GENERAL OVERVIEW

The evaluation of designs is a multi-phase process that is dependent on the stages of the design life cycle. In the preliminary stages of design, robust analytical and CAD modeling should be utilized at a minimum, to identify the worst case scenarios, the critical dimensions of interest, and determine accommodation of the design. The assumptions of posture, suit effects, and other human interface variables must be documented in order to verify with future Human-in-the-Loop (HITL) testing. HITL testing will either validate those assumptions or disprove them. If the assumptions are disproven, the analytical/CAD modeling work can be re-analyzed 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 CHSIR must move from the theoretical to the physical using Human-in-the-Loop 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, whether low fidelity analytical analysis or high fidelity HITL testing, contains the same backbone of required steps:

1. Identify test objectives – which include accounting for but not limited to: unsuited/suited operations, gravity condition (1-g, micro-g, hyper-g, etc), group effects, test configuration fidelity etc.
2. Identify the critical measurements that influence the ability of a human to interact with the design and the surrounding environment. These critical measurements can be CHSIR-based, derived dimensions, and/or measurements unique to the design itself.
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 documented in CHSIR and the design is in the final stages of the design cycle.

4.5.2.3 METHODOLOGY

4.5.2.3.1 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 due 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 the seat can fit all crew members and the console can be reached by all crewmembers, both suited and unsuited. Secondary objectives could examine if 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 both the design as an individual piece as well as part of the larger overall vehicle/interface design at all steps of the design cycle.

4.5.2.3.2 IDENTIFY CRITICAL MEASUREMENTS

The selection of anthropometric measurements for an evaluation is not necessarily confined to the CHSIR critical dimensions list. There are measurements outside the scope of the CHSIR measurements that a designer may deem necessary to the evaluation or the design itself. For example, functional measurements used to reconstruct a body posture, unique measurements derived from the combination of two or more established measurements, clearances between the human and hardware, or even standard anthropometry not contained on the CHSIR critical dimension list. Selection of these measurements should include those specifically tailored to the task which incorporates all potential subject body posture configurations, as well as CHSIR critical dimensions, for proper subject classification within the population. At a minimum, one should select from CHSIR Table 4.1-1. Vehicle Design Critical Anthropometric Dimensions: unsuited CHSIR measurements in order to place measurements in context of the population, unsuited task specific measurements to analyze the task at hand and to understand the impact of posture, and suited (as appropriate) task specific measurements to understand the impact of the suit.

Compliance requires that a design meet the CHSIR minimum and maximum for a given design, however there most likely is not a 1-to-1 ratio for every measurement for a 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 a person. The chair itself must still accommodate the maximum to minimum buttock-to-knee distance, however when evaluating the distance of the chair from the console, the hip angle's impact on buttock-to-knee length must be accounted for to accurately predict the clearance between the human and interface.

4.5.2.3.3 ACCOUNTING FOR SUIT, POSTURE, AND MICROGRAVITY FACTORS

4.5.2.3.3.1 SUIT FACTORS

Changes to overall suited body shape due to the suit, called suit factors, have ramifications across all levels of design and must be accounted for, if applicable, when allotting and interpreting the necessary space required to fit the expected population. 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.

Suit factors for a suit like the NASA Advanced Crew Escape Suit (ACES) were used to develop the minimum and maximum anthropometric requirements for vehicle-based, suited unpressurized and suited pressurized values in the CHSIR Table 4.1-1. The evaluation to determine the CHSIR suited values tested small females in a small ACES suit and large males in a large ACES suit. All anthropometric dimensions were collected unsuited, suited unpressurized, and suited pressurized in a recumbent shuttle seat and in a standing posture. The suit factors were determined for both large male and small female subjects. The female suit factors were applied to the minimum unsuited values and the male suit factors were applied to the maximum unsuited values in the CHSIR to determine the suited unpressurized and suited pressurized CHSIR values for all measurements with the exception of hip breadth. For hip breadth the reverse was applied: the maximum value for hip breadth unsuited is the female value and the minimum value is the male value. Therefore, the respective suit factors for hip breadth were applied to the respective gender values.

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, etc. Ideally, these factors are derived for a specific suit, in a specific configuration, in a standardized baseline posture, and are only applicable for instances 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 than the stature suit factor for an ACES suit. Likewise the hardware will impact the suit factors; the suit factor for stature in an ACES suit with a bailer bar will be different than the stature suit factor for ACES suit without bailer bar. A bailer bar is an external locking mechanism of the helmet which 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 suited values in the CHSIR critical dimensions table were formulated from the suit factors and are provided in conjunction with the CHSIR unsuited critical dimensions. These suited dimensions allot a certain amount of clearance for the suit and provide a standard that the suit designers must adhere to and the vehicle/hardware designers must account for within their respective designs. If suit factors are needed for measurements outside of the CHSIR critical dimensions, the CCT Company is advised to contact NASA for support.

Questions have previously arisen regarding how to handle suit factors for subjects falling in the middle range between the maximum and minimum values. These questions are based on scenarios where the worst case body configurations are not in the extremes but rather a middle segment of the population or during human based testing with subjects of varying 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 minimum CHSIR value or the suit factor used to derive the maximum CHSIR 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 CHSIR value. If the subject is female, the analyst should apply the suit factor used to derive the minimum CHSIR value, with the exception of hip breadth where the situation is reversed. For more complicated cases between the minimum and maximum values presented by the CHSIR, the CCT companies are advised to seek support from NASA.

4.5.2.3.3.2 POSTURAL FACTORS

Measurements will also be influenced during testing due to posture effects induced by the hardware that change the standard body position of the human. Essentially posture factors account for the variation between the baseline, unsuited posture of the CHSIR measurements and the unsuited task-specific posture. The measurements used to generate the requirements from the CHSIR anthropometric database were collected in a laboratory environment with distinct, standardized anthropometric data collection postures. Vehicle or system design may necessitate that crew assume postures that differ significantly from the prescribed and standardized measurement postures reflected in the CHSIR requirements Appendix D1. These postural effects need to be quantified and accounted for in order 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. There will be an error 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 the assumptions are valid or to modify the analysis as appropriate. At the stage of HITL testing, the ratio of standard unsuited body measurement to the posture-based unsuited body measurement in the human-interface can be determined, compared to the previous estimated factors, and integrated into the overall analysis in a fashion similar to the suit factors.

4.5.2.3.3.3 COMBINED POSTURAL AND SUIT EFFECTS

As previously discussed, in the preliminary stages of design, the posture and suit factors can be estimated using the CHSIR 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 error inherent which must be verified during HITL testing. As the design process moves into HITL testing, it follows that if there is a combination of posture and suit 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 hardware specific value and the unsuited standard value becomes a combined suit factor, incorporating the effects of both posture and suit effects. When iteratively bringing this factor 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 hardware specific, and suited hardware specific values to quantify each piece of the puzzle.

4.5.2.3.3.4 MICROGRAVITY SPINAL ELONGATION

When analyzing tasks that will be performed in microgravity or which will be impacted by microgravity effects, spinal elongation must be incorporated into the assessment. Spinal elongation is the straightening of the spinal curve due to the lack of vertebral compression, bone loss, and bodily fluid shifts in microgravity. Historically, it has been found that the spine straightens in microgravity resulting in a 3-percent growth in stature. This is the basis of the current requirement in CHSIR which states that any anthropometric measurement involving the spine (such as seated height, eye height, etc.) impacted by microgravity exposure needs to be adjusted for spinal elongation. For example, spinal elongation needs to be included when analyzing fit or accommodation to determine if a crewmember will properly fit within the seat for landing after being exposed to microgravity. To properly determine if the crewmember is accommodated, 3-percent of the stature needs to be added to the seated height or any other measurement that incorporates 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. It cannot be applied mathematically to the maximum/minimum values in the CHSIR, since the values given in CHSIR are percentile values mathematically derived from the entire population. Percentiles are not additive or subtractive from a mathematical perspective, so the maximum CHSIR stature and maximum CHSIR sitting height cannot be input into Equation 1 to derive the maximum sitting height with spinal elongation. It is advised to apply spinal elongation on a per subject basis for the measurement of interest, and then statistically examine the resulting population values to evaluate compliance.

4.5.2.3.3.5 MICROGRAVITY FLUID SHIFT

Crewmembers experience significant changes to their body especially in the regions of hands, legs, torso, and face due to fluid shift. To date, no empirical data exists on the amount of fluid shift in these regions and how they may affect the crew anthropometry.

4.5.2.3.4 IDENTIFY WORST CASE SCENARIOS

Identification of the worst case scenarios essentially focuses the analysis to highlight the segments of the population impacted 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 CHSIR anthropometric database (available upon request) to identify individuals within the population who have issues with the restrictions imposed by design or who are an ‘at risk’ group in regard to anthropometric compliance. The range of anthropometry of those individuals indicates the worst case scenarios. Identification of worst cases is important for three reasons: 1) it quickly highlights the necessary changes that need to be made to the design by examining or accounting for the population as a whole; 2) It identifies those 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. 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 values given in CHSIR are percentile values of specific attributes of the expected user population and therefore, should not 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 those portions of the population that are truly impacted by the design. While modeling a ‘large’ male or ‘small’ female could be useful for visualization purposes, verification should utilize the anthropometric values identified by the worst case analysis to feed into modeling or analytical analyses.

4.5.2.4 EVALUATE THE DESIGN USING POPULATION ANALYSIS

There are several factors that 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:

All anthropometric data should go through a population analysis, which minimally means placing the design factors under consideration within the context of the entire population of interest.

This may consist of defining test subjects based on a percentile analysis, comparisons to the extremes of the expected population, or it may consist of comparing hardware dimensions against a large sample population database of potential users. Whichever approach is employed, the end result is quantification of subject accommodation for the purposes of compliance evaluation. There is no one-size-fits-all population analysis method that 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 benefits of combined usage during various lifecycle phases.

4.5.2.4.1 ANALYTICAL EVALUATION

The analytical evaluation method is the simplistic ‘on paper’ analysis 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 specific focus of the analysis. The benefits of this analysis is that it provides a quick analysis of the data to ensure the design meets the criteria, it identifies the worst case scenarios, and it is relatively quick and simple to do prior to any other analysis. In order to explain this method further, take an example of a basic seat.

For individual measurements with a direct one-to-one match between CHSIR dimensions with an identical posture, the analysis is very simple: meet the CHSIR maximum and minimum for the design for the unsuited/suited conditions, as applicable. Using the example of a seat, the seat pan depth must not exceed the minimum CHSIR buttock to popliteal length, the seat pan width must meet the maximum CHSIR hip breadth sitting value, and the seat back length must meet the maximum CHSIR sitting height in order to fully accommodate the entire population. Thus, the recommended analytical analysis method for a simplistic CHSIR measurement case is to compare the design's measurements against the CHSIR 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 impacted by posture, the analytical method must be adjusted to account for the change in posture relative to the analysis of interest. The measurement must be mathematically adjusted to reflect the change in body posture. The recommended analytical way is to break the body into body planes (sagittal, frontal, and transverse) and mathematically adjust the body posture to the anticipated postural changes using trigonometry 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 CHSIR 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 distance of 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 CHSIR values and the resulting derived measurement can be compared against the design. The caveat to this analytical analysis is the estimation of the actual body angle, which must be verified through HITL testing to achieve confidence in the results.

For multivariate measurements impacted by posture, a whole body posture based analysis (WBPBA) should be utilized (Rajulu, 2010; Gonzalez, 2003). The analysis is employed 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 CHSIR anthropometric database 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 CHSIR 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 employed to determine group effects. Group effects are the impact of the surrounding environment on the ability to accommodate multiple crew members. Ideally, a designer would account for the space multiple crewmembers occupy in a design, but often design constraints are prohibitive.

For example, the minimum spacing between two seats can be set using the maximum suited male CHSIR 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 two males with maximum forearm to forearm breadth will fly together. The quantification of group effects using a Monte Carlo simulation can be utilized 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 two 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 concerning 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 two 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 two people. The design constraints can be compared against the new population to determine what percentiles are not accommodated, how much more space is required to accommodate the majority, and even evaluate the probability that crewmembers will have to be reselected based on the measurement constraints. It is also important to note that while the Monte Carlo can assess accommodation of the population into 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).

4.5.2.4.2 CAD MODELING/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 incredibly useful tool for visualizing a particular scenario and for determining initial limitations of the design. The major drawback of modeling is that it only provides 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; they 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 for modeling of clothing effects, factors, and would account for variations in anthropometry caused by changes in posture. Unfortunately, off-the-shelf CAD modeling programs are not advanced enough at this stage to be the sole tool used for a human factors analysis. Thus, it is important to recognize the limitations of CAD programs and employ 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 of postural changes between the analytical analysis method and the model as well as differences in body measurements.

It is recommended that the analytical analysis method be employed to identify the worst case scenarios and preliminary issues with the design before moving to a CAD based analysis. By the time modeling is employed, 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 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 crew members can also be modeled similar to individual measurements by just adding a second manikin. However, when the analysis involves multivariate measurements impacted by posture, the WBPBA should be used to capture the worst case individual's anthropometry (Rajulu, 2010; Gonzalez, 2003) and use the corresponding values to drive the CAD manikin sizing. In this manner, the modeling will use realistic custom tailored manikins which have been identified as problematic to analyze in 3-D against the design. As previously noted in paragraph 4.5.2.3.4 Identify Worst Case Scenarios, one should not use a 'large' or 'small' manikin, which has all the maximum or minimum CHSIR measurements entered in for all the possible customizable manikin dimensions, for verification purposes. The percentile values are not additive/subtractive and the maximum and minimum manikins do not represent realistic configurations of a human. Relying on one or two erroneous manikins to show that the entire population spectrum is accommodated is not the proper method for evaluation of the design.

By entering the worst case manikins identified from the analytical analysis, the CAD representation of the human-to-design interface can initially be used 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 utilized 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 impacted by the modified design.

This iterative process results in an optimized methodology, where the analytical model is employed 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 one method versus the other, 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 employed 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.

4.5.2.4.3 HITL TESTING

NPR 8705.2B paragraph 2.3.10 requires human-in-the-loop evaluations for human-system interfaces. HITL testing within 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 if the assumptions concerning the posture and/or hardware issues are consistent. The major drawback of HITL testing is the time consumption and limited subject pool availability and the 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 is dependent on the fidelity of the mockup against the proposed design. The lower the mockup fidelity, the more mathematical assumptions will have to be incorporated into the analysis to account for the variability of the mockup to the actual design. HITL testing for anthropometric evaluation requires a concrete plan of what measurements will be collected, quantification of test subjects' anthropometry, and what data analysis will be done to verify the design.

Analytical analysis and modeling should be employed 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 subject selection 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 must be gathered from each subject corresponding to the CHSIR critical dimensions as well as any other task-specific anthropometric variables critical to the analysis.

The data analysis associated with HITL testing for anthropometric evaluation has several basic goals. The first is simply a validation of the assumptions used for analytical and CAD modeling. Facets of this include if the actual posture is the same as the assumed posture, if the actual restrictions/limitations on the dimensions of the human are the same as those previously anticipated based on analytical and modeled scenarios, and if there are any additional issues faced by a person within the human-system interface. If there are differences between the actual and the prior mathematical or modeled work, then the prior 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 knee cap, 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 prior work must then be updated to determine the impact on the population as a whole 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. There will be situations where this is not the case. Thus, a second goal of the data analysis is to identify these unanticipated restrictions and quantify them in regards to the population as a whole to determine the root of the problem, be it subject-specific, posture-specific or design-specific. One method to quantify the subject in terms of the population uses percentile analysis. The basic steps for this analysis are to identify the subject's percentile value within the gender-specific population, evaluate where the subject falls within the population, and then determine how much of the population is impacted 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, a seated individual in a chair. The analytical analysis and CAD modeling all 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 the knee. Upon 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 females ranging from the 1st to the 20th percentile may have a similar issue with the edge of the seat pan. Perhaps the impingement is due to postural differences between small females and the rest of the population, perhaps the ability to conform to the seat pan is different on smaller females, or perhaps the foot rest adjustability dropped the thigh closer than ideal to the seat pan. Regardless, there is now a segment of the population identified as 'at risk' which 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 CHSIR requirements by extrapolating from HITL test subjects that 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 if 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 wearing a suit. Hypothetically speaking, the critical dimensions of interest would be identified as bideltoid breadth and stature and the two 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 appears 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 two 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, there is a group of subjects that range 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 largest males in bideltoid breadth and 1-inch for stature. By collecting unsuited data from the subject pool and comparing each subjects values and the actual observed clearance, the analysis will yield the anticipated postural effects (see paragraph 4.5.2.3.3.2 Postural Factors). In extrapolating by applying the observed postural effects on the 99th percentile male values for both dimensions, the required entryway dimensions can thus be determined and compared 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 function to examine the worst case manikins identified from the analytical analysis and CAD modeling, validate the prior analysis assumptions, and identify any unforeseen issues in the design. If the prior 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 non-compliant with CHSIR, 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 impacted by the modified design. Finally, if the design is CHSIR compliant based on the HITL test, continue conducting HITL testing using higher fidelity level mockups until the final stage of design. 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, where the HITL test is employed to validate design assumptions and identify problem areas, the modeling and analytical analysis is 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 versus the other, 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.

4.5.2.4.4 PERCENTILE ANALYSIS

Percentile analysis can be utilized at all levels of analytical, modeling, and HITL analyses. In the most simplistic terms, CHSIR anthropometric verification and validation is a comparison of the design against the CHSIR 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 CHSIR anthropometric database 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 to use this tool during the design process, utilizing 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.

4.5.2.4.5 USE OF THE MINIMUM AND MAXIMUM CHSIR VALUES

While a design may not specifically require both the maximum and minimum values, care must be taken to account for them both in the context of the overall vehicle design. There must be consideration for both the maximum and minimum values even if a design specifically utilizes only one of the critical values. Using a basic seat example, the seat pan width must meet the CHSIR maximum value to ensure all crew members are supported, however 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 females may shift around on the seat plan, causing discomfort and potential injury. Thus while the seat pan width is driven by the maximum and supports the entire population range, there is a factor of adjustability for that dimension that is driven by the combination of the maximum and minimum. Consideration of this adjustability factor is essential for crew comfort and safety.

4.5.2.4.6 MEASUREMENTS NOT SPECIFIED IN CHSIR

The measurements in CHSIR attempted to account for the critical anthropometry influencing all the physical hardware with which the crew would interface. However, it is highly probable that there are measurements outside the realm of CHSIR that will feed into a design. Questions have arisen in the past concerning how to handle such measurements. While these cannot be specified in CHSIR, it is recommended to simply follow the principle of good human factors design. If there is a scenario where a particular measurement outside of CHSIR Tables 4.1-1 and 4.1-2 is useful to determine the location of an interface, use that measurement's 1st percentile female and 99th percentile male to bound the population. On the other hand if adjustability of a component is limited and tied specifically to a particular measurement outside of CHSIR, utilize population analysis tools such as those described in Section 4.5.2.4 to evaluate what portion of the population is accommodated by that design.

4.5.2.4.7 ADDITIONAL INFORMATION

The analysis methods will require both the ANSUR Handbook for consistency and maintaining the standard anthropometric measurements and landmarks (Gordon et al 1989), and the CHSIR anthropometric database, which is the modified ANSUR database used to generate the NASA requirements.

4.5.2.5 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 CHSIR maximum and minimum ranges on the selected set of critical dimensions. The design must prove through analytical, modeling, and HITL methods that the entire population spectrum between the maximum and minimum CHSIR values have been accounted for within the design. Designs in which multiple critical dimensions interact, such as posture based clearance measurements, must employ the relevant analysis methods to determine the accommodation of the population as a whole. Successful verification for these multi-variable scenarios would mean the design accounts for the entire range between 1st percentile female to 99th percentile male values for the given measurements of interest using the entire CHSIR anthropometric database.

For each of the major milestones of the design lifecycle, the technical products in Table 4.5.2.5-1 are recommended for review by the NASA customer.

TABLE 4.5.2.5-1 ANTHROPOMETRY TECHNICAL PRODUCTS

Technical Products	Responsible Org	Phase A		Phase B	Phase C	Phase D	
		SRR	SDR	PDR	CDR	SAR	FRR
A description of the ConOps, functions allocation, and associated crew task lists. Includes list of tasks considered to be design-driving for anthropometry requirements as well as definition of factors impacting anthropometry.	CCT Company	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.	CCT Company	---	---	I	U	U	---
System architecture drawings (structures, equipment, etc.), material specifications, interface requirements.	CCT Company	---	---	I	U	U	---
Verification plan.	CCT Company	---	---	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 3.1.3.1.2 provides information such as identification of crew activities and determination of which subsystems are impacted by crew activities. Functions allocation, described in paragraph 3.1.3.1.3, 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 anthropometry requirements, it is important to determine what tasks may be design-driving. Tasks or use of hardware that represent challenges for anthropometric extremes will be particularly important for system-level analysis and testing. Factors that may impact anthropometry include variables such as suit conditions, posture, gravity conditions, and group effects.

Modeling/Analysis/Evaluation Summaries

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 utilize increasingly higher fidelity inputs/mockups, as discussed in paragraph 3.1.3.3 Evaluate Designs and Iterate Solutions. It is important that summaries address how key/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 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 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 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 CCT Company Technical Products:

- Overall Plan for meeting anthropometric design compliance
- Define human related major systems and what CHSIR 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 design does not meet requirements

NASA Involvement:

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

System Definition Review (SDR)

Suggested CCT Company Technical Products:

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

NASA Involvement:

- Review reports and mitigation plans, provide feedback

Preliminary Design Review (PDR)

Suggested CCT Company Technical Products:

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

NASA Involvement:

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

<u>Critical Design Review (CDR)</u>

Suggested CCT Company Technical Products:

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

<u>Test Readiness Review (TRR)</u>

Suggested CCT Company 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

<u>System Acceptance Review (SAR)</u>

Suggested CCT Company Technical Products:

- Demonstration of design compliance and all anthropometric requirements met

NASA Involvement:

- Review of design relative to levied CHSIR requirements

4.5.2.6 ANTHROPOMETRY REFERENCES

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).

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.

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

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).

McConville, J and Tillman, B. Year 2015 astronaut population anthropometric calculations for NASA-STD-3000 (1991).

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

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)

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).

4.5.3 DESIGN FOR RANGE OF MOTION

4.5.3.1 INTRODUCTION

The CHSIR requirement CH4002 Range of Motion specifies that CCT companies are to accommodate crew ranges of motion (ROM) as detailed in CHSIR Appendix D1 Range of Motion data. The referenced ROM data in CHSIR Tables D1-1 through D1-3 represent the best available data relevant to operational concepts likely to be performed within the scope of a NASA mission. NASA will update CHSIR tables as additional data are developed from future suit testing for commercial mission scenarios.

The purpose of the mobility design requirements is to ensure that all hardware developed by CCT companies is operable by all potential NASA crewmembers and to provide a common design requirement for multiple companies constructing interacting system components. Accordingly, all designers and developers of CCT technology will need to demonstrate compliance with the verification requirement using a variety of methodologies including analysis, modeling, and HITL testing.

4.5.3.2 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 that conducts progressively more vigorous testing to ensure that a crewmember with worst-case (See Section 4.5.3.3.2 range of motion 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 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 battery 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, etc.)

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

1. State objectives – based 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 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, etc.
4. Recognize critical operations – some comprehensive testing may require testing every possible configuration of the hardware while 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 & redesign as necessary – interpret the results of the test to verify that the design met requirements and improve the design to increase accommodation.

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.

4.5.3.3 METHODOLOGY

4.5.3.3.1 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 while low to high fidelity mockups become available as the design matures and eventually flight hardware is available for testing. Initial objectives should focus on ensuring that the tasks(s) can be successfully performed based on human system interaction with respect to the ROM. They 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 allow for identification of issues associated with a diverse population of test subjects. Human models typically create an idealized test subject while inclusion of live human test subjects introduces idiosyncrasy such as bilateral asymmetry (dominant limbs may have different ROM than non-dominant limbs), subject motivation, training, etc. Use of models may be appropriate to save time early in the design cycle but HITL testing is necessary to verify a mature design satisfies all requirements.

4.5.3.3.2 IDENTIFY CRITICAL METRICS

Before designing an experiment, it is important to consider what the goals of the study are and design the test accordingly. Requirements from CHSIR explicitly state joint angle ROMs believed to be relevant to planned operations; however, well-documented experimentation may prove that that these values are insufficient to complete all planned operations. The requirements, while originally generated to cover as many critical tasks as possible, are not all inclusive. Thus, the goal is to ensure the ROM is relevant to planned operations by performing a task analysis. The results of the task analysis should be compared and aligned with the corresponding ROM requirements from CHSIR. For those items in the task analysis which are not covered by the CHSIR ROM requirements yet are still critical to achieve mission success, it is necessary to demonstrate that the design meets those task-specific ROM needs. Ultimately, the goal is to prove that the design configuration satisfactorily allows a mission to succeed for all tasks rather than verifying that body movements just fall 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.

4.5.3.3.3 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 impact the fidelity of testing.

4.5.3.3.4 HUMAN MODELING

If the goal of the test, for example, is to determine if 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 there are no obvious errors 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, two human models with identical ROM limits but different anthropometry yield a feasible arm position for a larger male (left) but surface penetration of the arm into the chest for a smaller female (right).

FIGURE 4.5.3.3.4-1 EXAMPLE OF SURFACE PENETRATION IN RAMSIS AS DEPENDENT ON SUBJECT ANTHROPOMETRY

While 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 space suits. Some software permits editing of certain parameters that 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 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 is acquired, human modeling may be an appropriate intermediary step following acquisition of preliminary input and before physical fabrication of new hardware.

4.5.3.3.5 HUMAN-IN-THE-LOOP TESTING

Following the initial evaluation of hardware designs with human modeling, generally the next step would be to create physical mockups of the vehicle/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 may be elaborate prototypes constructed of flight-grade materials capable of interfacing with reduced gravity analogs.

Relatively late in the design cycle, as higher fidelity HITL testing is being performed, it may be necessary to utilize a variety of means for simulating altered-gravity states. These simulators, which include NASA's parabolic flight Reduced-Gravity Aircraft, Neutral Buoyancy Lab (NBL), the hydraulically offloading partial gravity simulator

(POGO), 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 may proceed at two 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, however the process of collecting and analyzing the data may be rather involved.

Mobility data can be acquired through a wide variety of methods; each of those methods have differences in markers, analysis techniques, and even principles of physics which influence how motion data is 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, or even accelerometer/inertia based systems. Each system has benefits and limitations depending on the surrounding environment, the test setup, occlusion issues, and on what motion data is output from the specific method. When collecting mobility data, care must be taken to ensure 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 however 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, 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 near impossible to include subjects of extreme dimensions for whom space suit 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 space suit for these extreme test subjects since the metric of performance difference may change based on suit sizing.

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.

4.5.3.3.6 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. While 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 two 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 in order to verify the design.

4.5.3.4 EVALUATE THE DESIGN

In the initial stages of design, the anticipated ROM values from CHSIR 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 crew member'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 the 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 is 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 in the scope of that assessment, because it only applies 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 in comparison 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, it would be a fair first step to apply the same ratio of degradation in mobility 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 pressurizable 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.

4.5.3.4.1 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 prior to 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 hyper- gravity environment (such as on the reduced gravity aircraft or in a centrifuge) in order to assess the performance limitations of a reduced gravity state. Likewise, issues presented with contingency conditions may require extra attention paid to critical operations of the hardware.

4.5.3.4.2 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.

4.5.3.5 RANGE OF MOTION TECHNICAL PRODUCTS

CCT companies must be able to demonstrate that they have satisfactorily met mobility requirements identified through the critical metrics, accounting for the test conditions and recognizing the critical operations at a minimum, as represented in the mobility tables in CHSIR Appendix D1. Initially, the designer may report what mobility was required to operate the hardware based on human modeling while final verification will necessitate high-fidelity HITL tests.

For each of the major milestones of the design lifecycle, the technical products in Table 4.5.3.5-1 are recommended for review by the NASA customer.

TABLE 4.5.3.5-1 RANGE OF MOTION TECHNICAL PRODUCTS

Technical Products	Responsible Org	Phase A		Phase B	Phase C	Phase D	
		SRR	SDR	PDR	CDR	SAR	FRR
A description of the ConOps, functions allocation, and associated crew task lists. Includes list of tasks considered to be design-driving for range of motion requirements as well as definition of test conditions and critical operations impacting range of motion.	CCT Company	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.	CCT Company	---	---	I	U	U	---
System architecture drawings (structures, equipment, etc.), material specifications, interface requirements.	CCT Company	---	---	I	U	U	---
Verification plan.	CCT Company	---	---	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 3.1.3.1.2 provides information such as identification of crew activities and determination of which subsystems are impacted by crew activities. Functions allocation, described in paragraph 3.1.3.1.3, 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 range of motion 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 impact range of motion include variables such as suit conditions, posture, gravity conditions, and group effects.

Modeling/Analysis/Evaluation Summaries

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 utilize increasingly higher fidelity inputs/mockups, as discussed in paragraph 3.1.3.3 Evaluate Designs and Iterate

Solutions. It is important that summaries address how key/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 range of motion 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 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 CCT Company Technical Products:

- Overall plan for meeting human-systems design compliance for mobility
- Define human related major systems and which CHSIR 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 identifies risks of design not meeting requirements for all conditions

NASA Involvement:

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

System Definition Review (SDR)

Suggested CCT Company Technical Products:

- Reports detailing analytical analyses for all major subsystems to prove concept designs meet CHSIR mobility requirements and account for assumptions
- If available, reports detailing preliminary CAD model work or low-fidelity human model work based on prior analytical analyses to prove concept designs meet CHSIR mobility requirements and account for assumptions
- Plans for mitigation efforts if analyses indicate 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

<u>Preliminary Design Review (PDR)</u>

Suggested CCT Company Technical Products:

- Reports on detailed analyses (analytical, human modeling, and HITL) examining the impact of CHSIR mobility requirements on the human-systems interface design, with any limitations and assumptions addressed,
- Plans for mitigation efforts if analyses indicate 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 analyses results for accommodation and issues with integration of results, provide feedback
- Review plans, provide feedback

<u>Critical Design Review (CDR)</u>

Suggested CCT 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 design does not meet requirements
- Reports on updated analyses (analytical and modeling) based on results of HITL testing examining the impact of CHSIR mobility requirements on the human-systems interface design; plans for mitigation efforts if analyses indicate 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

<u>Test Readiness Review (TRR)</u>

Suggested CCT Company 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 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, give feedback
- Review potential contingency plans, give feedback

System Acceptance Review (SAR)
Suggested CCT 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 CHSIR requirements

4.5.3.6 RANGE OF MOTION REFERENCES

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.

4.5.4 DESIGN FOR STRENGTH

4.5.4.1 INTRODUCTION

The CHSIR requirements CH4006 Structural Integrity of the Human-Machine Interface and CH4007 Operational Strength Limit for the Human-Machine Interfaces specifies that CCT companies must accommodate crew member strength as specified in Appendix D4 Strength. The CHSIR strength data have been identified as relevant to operational concepts and tasks assumed likely to be performed within the scope of a commercial mission as defined in the CHSIR section 1.3 Mission Assumptions. The purpose of the human strength requirements is to ensure that all hardware developed by the CCT Company is operable by all potential crewmembers and to provide common design requirements for multiple companies constructing interacting system components. Accordingly, all designers and developers of CCT technology must demonstrate via analysis, modeling, and human-in-the-loop testing that verification and validation of the design has been satisfactorily achieved against the requirements set forth in CHSIR CH4006V and CH4007V.

The intent of this design process is to provide users with methodologies and best practices that should be implemented by the designer to ensure that adherence to the human-systems integration requirements set forth by NASA with respect to strength are satisfactorily met. The hardware design should involve careful consideration for interactions between humans and interfaces when performing tasks, including consideration for the weakest crewmember, hardware integrity, and performance decrements due to physiological adaptations to spaceflight. These considerations can be addressed by adherence to strength standards set forth by NASA for human spaceflight as well as human strength testing when appropriate and applicable for specific tasks and hardware designs.

4.5.4.1.1 DEFINITION OF HUMAN STRENGTH

Strength refers to a person’s ability to generate force. Applying strength requirements will result in a minimum and maximum applied crew load to be used for operational and hardware design. The minimum load pertains to operational strength that accommodates the weakest person while the maximum load represents the force the hardware must be able to withstand without failure. It is important to note that these requirements 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. In the CHSIR Appendix D4 strength tables, values specified for Criticality 1 (Crit 1) operations are to be applied in the design of crew interfaces where the possibility of a single failure could result in loss of life or vehicle. Values specified for Criticality 2 (Crit 2) operations are to be applied in the design of crew interfaces where the possibility of a single failure could result in loss of mission alone. The values pertaining to Criticality 1 and 2 include decrement factors to reflect physiological de-conditioning effects of extended spaceflight on crewmembers that could potentially affect the ability to perform necessary tasks. The criteria for determining whether a task is Criticality 1, Criticality 2, or Other Operation is found in the rationale of CHSIR requirement CH4007.

4.5.4.1.2 APPLICABILITY TO SPACEFLIGHT SCENARIOS

Launch, In-Flight, and Re-Entry

Higher gravitational forces, as would be experienced during launch and re-entry, will affect the successful application of human strength to perform a given task (i.e., higher gravitational forces may result in a decrement in the force a crewmember is able to apply for completion of a given task). Criticality values selection should be carefully considered when designing hardware and tasks for such scenarios of 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 which are performed under microgravity conditions (i.e., in-flight) may be subject to decreased application forces by users. This may be the result of crewmembers being unable to attain a posture which allows compensation for any reaction forces applied back on the human by the tool or interface used (i.e., torque reaction force from a wrench). Therefore, the posture employed as well as available braces or handholds should be taken into consideration and the appropriate criticality level applied to ensure successful completion of tasks performed under microgravity conditions. This subject is further addressed in paragraph 4.5.4.2.2.3.2 Posture Variability.

Criticality Values

Criticalities are implemented in the CHSIR strength tables, D4-1,D4-2, and D4-3, to provide users with a more realistic representation of how strength should be critical to hardware design for mission tasks. The criticality values provide users with a worst-case scenario for a given human posture and force application situation. Criticality values were developed to levy requirements that ensure that the weakest crewmember is able to perform a given task, in nominal and emergency scenarios. In addition to an applied safety factor, the values in the Criticality 1 and 2 columns also include decrement factor(s) to reflect the de-conditioning effects on crewmembers due to space adaptation. These de-conditioning effects are brought about by bone loss, muscle atrophy and other physiological decrements associated with long-duration exposure to micro-gravity conditions, and can potentially have notable effects on a crewmembers' ability to apply the necessary force or torque to complete a given mission task or operation. As de-conditioning will affect each human in different ways, values for muscle strength decrements will vary.

It was determined by subject matter experts and CHSIR developers that a worst-case scenario of a 20-percent decrement in strength, when combined with the appropriate factors of safety, would adequately protect crew, vehicle, and mission. Application of a Criticality 1 or Criticality 2 value to a given task or human-hardware interface will depend on the operation being performed and its impact on crew safety and mission success. Factors of safety, as well as factors for strength loss due to exposure to microgravity, are applied to the "Other Operations" values to arrive at the Criticality 1 and 2 values. For example, a factor of safety of 2, as well as a 20-percent decrement in strength due to de-conditioning effects, is applied to the "Other Operations" value to arrive at a Criticality 1 value to protect against the event of a single failure resulting in a loss of life or vehicle.

It is important to note that the CCT Company should be careful not to implement multiple safety factors. For example, NASA-STD-5017 torque/force margin requirements (4.10.0) levy an extra safety factor on the applied torque/force to a given mechanism. Implementing this requirement along with the already built in safety factor (i.e., Criticality 1 or 2) in the strength tables results in an overly-conservative design.

4.5.4.2 STRENGTH GENERAL OVERVIEW

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

In general, the flow of any design evaluation, whether 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 not limited to, accounting for the following: unsuited/suited operations, gravity condition (1-g, micro-g, hyper-g, etc), postural effects, muscle fatigue effects, test configuration fidelity, etc.
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 de-conditioning 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. Evaluate and make changes to the design to ensure accommodation of those using hardware to perform task/operation
7. Repeat steps 1-6 until the design meets the requirements documented in CHSIR and the design is in the final stages of the design cycle.

4.5.4.3 METHODOLOGY

4.5.4.3.1 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 allows for 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 the lever can be successfully operated by all crew members, from strongest to weakest, and the required force to actuate the lever allows for all de-conditioned crewmembers to still successfully operate it in both nominal and emergency situations. Secondary objectives may examine if 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 both the design as an individual piece as well as part of the larger overall vehicle/human/interface design at all steps of the design cycle.

4.5.4.3.2 IDENTIFY INFLUENCING FACTORS

Using the defined test objectives, the next step would be to match the assumed posture needed to perform the task to corresponding postures in the CHSIR Appendix D4 and resolve the posture into all necessary and applicable strength components (i.e., for an example of a pushing motion at an oblique angle using a handle, hand grip, elbow flexion, and any other applicable postures). 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/operation. Justification for the selection of strength values from the Criticality 1 or 2, or from "Other Operations' categories must be provided using the definitions as specified in CHSIR CH4007. In addition, the corresponding maximum crew operational load must be accounted for, or reasonable justification (i.e., Finite Element Analysis modeling, stress analyses) provided for max loads exceeding put forth in the CHSIR CH4006 to ensure structural integrity of the hardware during operation. These steps will help determine if 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.

4.5.4.3.3 ACCOUNT FOR SUIT, POSTURE, AND GRAVITY EFFECTS

4.5.4.3.3.1 SUIT EFFECTS

CHSIR Appendix D4 in tables D4-1, D4-2, and D4-3, provides strength data for unsuited, suited pressurized, and suited unpressurized conditions. The forces required to operate a given designed human-system interfaces 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).

4.5.4.3.3.2 POSTURE VARIABILITY

Strength measurements will be directly influenced during testing due to the posture effects, and as such, the strength requirements compiled and set forth in the CHSIR 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 were smaller individuals will adopt a different posture as opposed to larger individuals and vice versa, this variability must be accounted for and should be validated separately. While there is limited data for the analytical and modeling stages of design, 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 within the population and determine the strength performance impacts. The assumptions of the impact of posture effects on the human body unequivocally must be verified during HITL testing to ensure the assumptions are valid or to modify the analysis as appropriate.

4.5.4.3.3.3 GRAVITY EFFECTS

Microgravity conditions present the crewmember with an interesting challenge when actuating a hardware interface or performing a task/operation requiring the application of force or torque. In this environment, it is much more difficult to apply the necessary force or torque due to the lack of reaction forces (i.e., the forces acting back on the body when a human force is applied), and therefore tasks performed under such conditions should be evaluated carefully and the appropriate Criticality values should be applied for the other conditions applicable to the situation (e.g., suited or unsuited conditions). For instance, the posture employed by the crewmember, as well as any available braces or handholds, should be accounted for and the appropriate Criticality 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.

Conditions involving hypergravity (e.g., launch, re-entry) should involve the application of worst-case scenarios (e.g., de-conditioning effects, safety factors, weakest crewmember, etc.) to ensure safe operation of human-systems interfaces and the avoidance of any failures that may lead to loss of crew, vehicle, or mission. As such, the task should be carefully analyzed and the appropriate strength Criticality value be applied.

4.5.4.3.4 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 that will be impacted by the design.

4.5.4.4 EVALUATE THE DESIGN

There are several factors that 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 requirements levied in the CHSIR 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 Criticality factors must be considered. A comparison of the force/torque values of the hardware to the Criticality values for a given posture will determine compliance of the design.

4.5.4.4.1 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/torque requirements of the hardware design. These can then be compared to human strength requirements found in the CHSIR to determine if further examination, analysis, and/or testing are warranted.

4.5.4.4.2 MODELING

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

4.5.4.4.3 HITL TESTING

HITL testing within 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 if the assumptions concerning the posture, strength required to perform a task, and/or hardware issues are consistent. Some challenges associated with HITL testing include cost, time consumption, as well as 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 conducting HITL testing for evaluation of strength, multiple subjects will be needed to validate the posture assumptions, if there is a variation the performance improvement/degradation can be determined by comparing subjects. Testing must include a range of subject sizes to properly scope the population. Ideally, a mock-up of the human-system interface would be used with instrumentation capable of measuring human-applied forces/torques. This would allow for a one-to-one comparison of actual hardware forces/torque to those being estimated, as well as to applicable CHSIR strength requirements. Other scenarios, though less than ideal, may include obtaining unsuited strength data of the functional posture in question using a strength dynamometer to see where subjects fall in the population, and compare 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 make comparisons to test 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 changes between the two 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.

4.5.4.4.4 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 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.

4.5.4.4.5 MEASUREMENTS NOT SPECIFIED IN CHSIR

The CHSIR sets forth very specific postures for application of human strength and as such, it is possible that a posture required to perform a specific, as yet to be determined task, may not directly correspond with any one posture in the CHSIR strength data tables. Under such circumstances, CCT companies should consult with NASA for direction on how to apply the appropriate combination of postures and associated strength values or if 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 STRENGTH TECHNICAL PRODUCTS

The reporting of human strength values should involve incorporation of worst-case scenarios (i.e., Criticality values). These should be implemented to ensure the protection of all crewmembers, as well as 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 regarding the strength of a group of individuals, but do not provide end-users with information regarding 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) ensure 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 that may operate a given hardware component/interface. This information will apply to HITL testing as well, and it is crucial for any CCT Company HITL testing to include an appropriate number of subjects so as to provide the necessary statistical confidence in results and testing-derived strength requirements/recommendations.

Reporting maximum strength values for human-system interfaces provides users guidelines for the protection of hardware from strongest crewmembers that may operate a given hardware component/interface.

For each of the major milestones of the design lifecycle, the technical products in Table 4.5.4.5-1 are recommended for review by the NASA customer.

TABLE 4.5.4.5-1 STRENGTH TECHNICAL PRODUCTS

Technical Products	Responsible Org	Phase A		Phase B	Phase C	Phase D	
		SRR	SDR	PDR	CDR	SAR	FRR
A description of the ConOps, functions allocation, and associated crew task lists. Includes list of tasks considered to be design-driving for strength requirements as well as definition of factors impacting strength.	CCT Company	I	U	U	U	---	---
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System architecture drawings (structures, equipment, etc.), material specifications, interface requirements.	CCT Company	---	---	I	U	U	---
Verification plan.	CCT Company	---	---	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 3.1.3.1.2 provides information such as identification of crew activities and determination of which subsystems are impacted by crew activities. Functions allocation, described in paragraph 3.1.3.1.3, 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 use of hardware that represent challenges for weaker individuals will be particularly important for system-level analysis and testing. Factors that may impact strength include variables such as suit conditions, posture, gravity conditions, and group effects.

Modeling/Analysis/Evaluation Summaries

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 utilize increasingly higher fidelity inputs/mockups, as discussed in paragraph 3.1.3.3 Evaluate Designs and Iterate Solutions. It is important that summaries address how key/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 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 human-in-the-loop evaluations. CAD and human-in-the-loop 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 CCT Company Technical Products:

- Overall Plan for meeting human-systems design compliance
- Define human related major systems and what CHSIR 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 analyses results for consistency and methodology, give feedback

System Definition Review (SDR)

Suggested CCT Company Technical Products:

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

NASA Involvement:

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

Preliminary Design Review (PDR)

Suggested CCT Company Technical Products:

- Continued development of overall plan for meeting human-systems design compliance
- Detailed analyses (modeling, etc.) examining the impact of CHSIR strength requirements on the human-systems 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 analyses results for consistency and methodology, provide feedback

Critical Design Review (CDR)

Suggested CCT Company 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 CCT Company 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/validate strength requirements
- Define human related major systems and applicable CHSIR strength requirements to HITL testing to be performed

NASA Involvement:

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

System Acceptance Review (SAR)
Suggested CCT Company Technical Products:

- Demonstration of design compliance

NASA Involvement:

- Review of design relative to levied CHSIR requirements

4.5.4.6 STRENGTH REFERENCES

Chaffin, D.B.; Andersson, G.B.J.; Martin, B.J. Occupational Biomechanics. J. Wiley & Sons, New York, NY 1999.

MIL-STD-1472. Department of Defense Human Engineering Design Criteria for Military Systems, Equipment, and Facilities.(initial, with revisions through F). 1968 and *ff.*

4.5.5 DESIGN FOR MASS PROPERTIES, VOLUME, AND SURFACE AREA

4.5.5.1 INTRODUCTION

While requirements for range of motion, anthropometry, and strength are provided to ensure that any crewmember can safely operate and manipulate the selected human-systems interface of interest, 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, or radiation exposure calculations. The primary goal of the process is to ensure that the entire population has been accounted for within the design to ensure compliance of these primary objectives. This impacts the process to verification and validation and the interpretation of associated data.

4.5.5.1.1 WHOLE-BODY AND BODY-SEGMENT MASS PROPERTIES

Whole-body and body-segment mass properties data are included in CHSIR requirement CH4005 Body Mass Properties and Appendix D3 Body Mass 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 are dependent 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.

4.5.5.1.2 WHOLE-BODY AND BODY-SEGMENT VOLUME

Whole body and body segment volume data are provided in CHSIR requirement CH4004 Body Volume and Appendix D2 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. The volume is also provided to maintain consistency relating to the other anthropometric characteristics in CHSIR when volumetric information is required for an analysis.

4.5.5.1.3 WHOLE-BODY SURFACE AREA

Whole body surface area data are provided in CHSIR requirement CH4003 Body Surface Area 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. The body surface area is also provided to maintain consistency relating to the other anthropometric characteristics in CHSIR when surface area information is required for an analysis.

4.5.5.2 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 via conventional means. Historically, cadaver studies were performed to quantify the exact physical characteristics of mass, volume and surface area (DuBois and DuBois (1916), Martin et al (1984), Gehan et al (1970)). The regression equations utilized 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 in regards 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 in the flow of the design process:

1. Determine the objectives of the analysis
2. Account for any impacts of suit, posture, group, and gravitational effects
3. Identify possible worse-case scenarios for the proposed objectives
4. Evaluate the design: Use the volume, surface area, and mass properties information in the relevant applicable analysis. Evaluate and perform revisions to the design to ensure accommodation of population
5. Repeat steps 1-4 until the design meets the requirements documented in CHSIR and the design is in the final stages of the design cycle.

4.5.5.3 METHODOLOGY

4.5.5.3.1 IDENTIFY ANALYSIS OBJECTIVES

The necessity for an evaluation of the volume, surface area, and/or mass properties of the design is based on the applicability to the design given the relevant vehicle conditions and exposure concerns of the crewmember. Not every human-systems interface design will require such an analysis, so the first step is to identify the relevance of a volume, surface area, or mass properties analysis on 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 and will require a solid understanding of the proposed seat design and structural properties of the seat components in order to perform an evaluation. Similarly, low earth orbit (LEO) scenarios may involve body volume and body surface area characteristics, but may not be required until the layout of the vehicle design has been fully determined.

The second component in the 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 area requirements are applicable in order to ensure crew safety and health.

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

4.5.5.3.2.1 SUIT EFFECTS

There is limited information regarding the suit and its associated impact on the human in relation to volume, surface area, and mass properties 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, etc, will impact the mass and inertia profiles of the analysis. This addition of any mass to the body of the user will adversely impact the mass properties and must be accounted for within 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 for body moment of inertia analyses.

The suit will also impact 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. These are all potential applications of suit effects, if possible, attempt to incorporate aspects of the suit into the analysis when applicable

4.5.5.3.2.2 POSTURE EFFECTS

While volume and body surface area values are, for the most part, independent of posture, the mass properties require posture to perform dynamic calculations. The whole body mass properties as presented in CHSIR only reflect a standing position and deviations from this body position requires re-calculation of the whole body mass properties. A combination of the segment anthropometry and segment position of the user must be accounted and combined with the segmental mass properties to determine the posture-based impacts on whole body mass properties, such as the center of mass and moment of inertia values. If the CCT Company needs to derive posture based mass properties, they are advised to use the CHSIR anthropometric database coupled with the regression equations from McConville (1980) and Young (1983) and follow the methodology outlined in the Blackledge (2010) paper, in which 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. Subsequent to this analysis, the assumptions of posture and associated body angles must be evaluated through HITL testing to ensure the calculations are accurate.

4.5.5.3.2.3 GROUP EFFECTS

The impact of 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 negatively impact the system from meeting compliance.

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 will preclude the ability to take other objects into space, due to restrictions in the total mass that can be flown. Similar to the example provided in the anthropometry section, there is a low likelihood that multiple 99th percentile males in mass will fly simultaneously. Thus weight/mass of the entire CHSIR population can be used with the random sampling of various crew numbers to derive whole body crew mass, the results of this work are seen in CHSIR Table D3-1 Whole Body Mass of a Crewmember and the background to the eventual derivation of those values is given in Margerum and Rajulu (2008). The Monte Carlo 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 all users vary in body size, their body volume also varies and the group effects compound this variation in volume. Volume data of the whole body is available in CHSIR Appendix D2 Table D2-1. Consideration for a multi-sized crew is essential to functional volume calculations, for example, when a crew of four is composed of three large crewmembers and one small crewmember compared to the volume of three medium crewmembers and one small crewmember. The variances apparent in the population will influence these calculations and thus the designer should consider group effects within their analyses.

4.5.5.3.2.4 GRAVITY EFFECTS

While volume, mass properties, and body surface area are impacted by the effects of deconditioning; to date, no empirical data exists on the amount of change in these body parameters.

4.5.5.3.3 IDENTIFY WORST CASE SCENARIOS

For volume and area, the maximum and minimum values are provided in CHSIR because they were deemed the most relevant given the potential uses of the data. Typically for radiation exposure analyses or functional volume design calculations, the worst case whole body values are typically the largest and smallest values. However, it is recommended to critically evaluate the design and the analysis objectives to determine if this is indeed the case. Caution must be used in determining the worst case scenario and it should not be assumed that applying all maximum or minimum values to the given body segments represent the worst case.

It is incorrect to assume the largest mass provided in CHSIR equates to a summation of the largest values for all body segment masses Similar to anthropometric percentiles, the CHSIR requirements for mass are based on percentile values and mathematically the summation of the individual segment masses will yield a total body mass exceeding the requirement. For mass properties, the maximum and minimum values are provided in CHSIR and essentially bound the population, but it is more than likely that these values will not be sufficient for all analyses. For example, examination of the worst case dynamic profiles using mass properties will be impacted by posture and anthropometry, and adding suit or crew survival equipment will impact it further. In order to properly determine a posture specific COM, it is suggested that worst cases be identified by the procedure specified in the Blackledge (2010) paper.

4.5.5.4 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 the designer in evaluating their design in regards to mass properties, volume, and surface area. The end goal is to ensure that the full population has been considered for the design.

4.5.5.4.1 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 the kinetic behavior of the design. 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, crew member 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) analysis 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 on 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 in the analysis as well to ensure that the entire user population is considered in the design.

4.5.5.4.2 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 mass properties, volume, and surface area values 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 it is analysis relating to the evaluation of dynamic loading or estimations of radiation dosimetry as referenced in CHSIR CH4003.

4.5.5.4.3 HITL TESTING

HITL for mass properties, volume, and surface area testing can be used to verify assumptions used in the analytical and CAD modeling analyses. Specifically this pertains to the mass properties work that is dependent on posture. HITL testing can be used to verify the assumed postures utilized 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 prior 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 which utilizes these parameters and all assumptions have been validated. In scenarios where HITL testing is required but unsafe, the use of mannequins/crash test dummies should be used as substitutions for the human body (e.g. mannequin-in-the-loop testing). Mannequin-in the loop testing would follow HITL testing parameters and methodology, with the exception the data would be collected from mannequins instead of humans. For example, flight testing the center of gravity of the manned vehicle using representative mannequins instead of actual crew.

4.5.5.4.4 ADDITIONAL INFORMATION

The analysis methods will require the CHSIR anthropometric database, which is the modified ANSUR database used to generate the requirements. The CCT Company is also advised to acquire copies of the McConville (1980) and 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.

4.5.5.5 MASS PROPERTIES, VOLUME, AND SURFACE AREA TECHNICAL PRODUCTS

Evaluating the design requires unique phases that depend on the varying 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 for 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 lifecycle, the technical products in Table 4.5.5.5-1 are recommended for review by the NASA customer.

TABLE 4.5.5.5-1 MASS PROPERTIES, VOLUME, AND SURFACE AREA TECHNICAL PRODUCTS

Technical Products	Responsible Org	Phase A		Phase B	Phase C	Phase D	
		SRR	SDR	PDR	CDR	SRR	SDR
A description of the ConOps, functions allocation, and associated crew task lists. Includes list of tasks considered to be design-driving for mass properties, volume, and surface area requirements as well as definition of factors impacting these properties.	CCT Company	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.	CCT Company	---	---	I	U	U	---
System architecture drawings (structures, equipment, etc.), material specifications, interface requirements.	CCT Company	---	---	I	U	U	---
Verification plan.	CCT Company	---	---	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 3.1.3.1.2 provides information such as identification of crew activities and determination of which subsystems are impacted by crew activities. Functions allocation, described in paragraph 3.1.3.1.3, 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 impact these properties include variables such as suit conditions, posture, gravity conditions, and group effects.

<u>Modeling/Analysis/Evaluation Summaries</u>

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 utilize increasingly higher fidelity inputs/mockups, as discussed in paragraph 3.1.3.3 Evaluate Designs and Iterate Solutions. It is important that summaries address how key/critical design decisions were assessed. Per the 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 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 CCT Company Technical Products:

- Define 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 analyses method and results for consistency, give feedback

System Definition Review (SDR)

Suggested CCT Company Technical Products:

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

NASA Involvement:

- Review reports, give feedback

Preliminary Design Review (PDR)

Suggested CCT Company Technical Products:

- Reports detailing analytical analyses and/or modeling work (area, volume, mass) for the design, detailing compliance with the specifications given in CHSIR.
- Plans for mitigation efforts if analyses indicate design does not meet requirements
- Plan for verification of requirements

NASA Involvement:

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

<u>Critical Design Review (CDR)</u>
Suggested CCT Company Technical Products:

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

<u>Test Readiness Review (TRR)</u>
Suggested CCT Company 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

<u>System Acceptance Review (SAR)</u>
Suggested CCT Company Technical Products:

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

NASA Involvement:

- Review of design relative to levied CHSIR requirements

4.5.5.6 MASS PROPERTIES, VOLUME, AND SURFACE AREA REFERENCES

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.

Du Bois D, Du Bois EF. 1916. A formula to estimate the approximate surface area if height and weight be known. Arch Intern Med 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. 11:24

Margerum, Sarah; Rajulu, Sudhakar. 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).

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.

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.

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.

4.5.6 BACKGROUND OF CHSIR VALUES

4.5.6.1 ANTHROPOMETRY

The anthropometric measurements selected for inclusion in the 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 database is based on the Natick Anthropometry Survey of Army Personnel (ANSUR), an Army-based anthropometric database (Gordon et al, 1989). This database more closely represents the anticipated body type of the astronaut corps, as opposed to more general population databases available. The database was age-truncated to between 30 and 51 years to encompass the representative age range of the astronaut corps as well as height-adjusted to align with Air Force population height and to correspond to projected growth trends to the year 2015 (NHANES 2004, Churchill et al., 1976, McConville et al, 1991). This truncated database minimizes the anticipated anthropometric ranges while ensuring that the astronaut corps can still be accommodated in comparison to a more generalized population database.

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. While 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 database. Analyses were performed to investigate reducing this 1st percentile female to 99th percentile male range to a smaller range of values; 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 due to the relatively poor correlation among anthropometric dimensions and the large number of dimensions overall. This truncated and height adjusted CHSIR anthropometric database should be the database used by the CCT Company for the majority of population analyses that rely on a database. The 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 tables were generated can be found the 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 values in the CHSIR were developed from extensive review of literature as well as from human strength testing under unsuited, suited unpressurized, and suited pressurized conditions performed at facilities at NASA. The literature review included an extensive collection of journal articles associated with human strength data. In addition, other references were used, such as the MIL-STD-1472 and the Occupational Biomechanics textbook (Chaffin, et al. 1999), 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 relevant and applicable to a wide range of possible mission tasks that may include both suited (e.g., launch, entry, extra-vehicular activities) and unsuited operations.

4.5.6.4 WHOLE-BODY AND BODY-SEGMENT MASS PROPERTIES

In order to calculate whole-body and body-segment mass properties in the CHSIR, regression equations were used based on two anthropometric dimensions, stature and weight. Both anthropometric parameters for stature and weight were used from the CHSIR anthropometric database for both female and male genders. 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 the density of the human flesh was homogeneous having a density value of 1 g/cm^3. With a value of unity for the density, the mass values are numerically equal to their corresponding volume values. The COM and 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 the human flesh was homogeneous and assuming that the center of volume is at the center of mass location. Both McConville et al. (1980) and Young et al. (1983) provided ranges for the location of the center of volume for the male and female gender, respectively in their study. 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 5st percentile stature and weight lower range values.

Whole-body and body-segment moment of inertia 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 within the CHSIR anthropometric database was employed for identifying the lower (i.e., 5th percentile) and upper (i.e., 95th percentile) range values for the MOI locations. However, the moments of inertia presented are about the principal axes, X_P, Y_P, and Z_P.

4.5.6.5 WHOLE-BODY AND BODY-SEGMENT MASS VOLUME

Regressions 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 two 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 value. The maximum whole-body and body-segment values pertain to the acquired maximum value from the male data and the minimum whole-body and body-segment value 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 upon univariate concerns (e.g., just strength, just range of motion, 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 in nature, 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 CCT companies employ an integrated approach, as soon as possible in the design lifecycle in order 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 three primary aspects of anthropometry, strength, and range of motion relate together within a design, since 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 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 a general flaw in the design for use by a certain segment of the population. By evaluating these aspects 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 as opposed 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 utilizes the same methodologies outlined in the strength, range of motion, 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 impacted by the design. For example, a larger individual may fit, anthropometrically speaking, in the seat and reach all the controls; however a small female seated next to a larger male may have a portion of their range of motion blocked due to the bulk of the person sitting next to them. Similarly, a larger individual may be able to articulate a lever at the extreme range of their 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. Essentially, 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/simulation, or in HITL testing, and placing the results within the context of the population for each design variable of interest. This might be thought of as a multi-dimensional evaluation which examines for all relevant design variables for all possible combinations of the population based design factors. For example this could involve examining the suit, posture, gravity and group effects' impact 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 (i.e., 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 following 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 within the framework of human-systems integration (HSI). The use of HSI processes in aviation is well established, as is the implementation of handling qualities (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 as 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.

Note that handling qualities 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 handling qualities. These topics are covered in CHSIP sections 4.2 and 4.3, respectively. Review of all three processes is strongly recommended.

4.6.1.1 APPLICABLE HANDLING QUALITIES REQUIREMENTS

The evaluation of handling qualities 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. Handling qualities requirements are also specified in the JSC-65993 Commercial Human-Systems Integration Requirements (CHSIR) Section 10.0 Crew Interfaces. These requirements set minimum criteria for vehicle handling qualities as measured by the Cooper-Harper Scale.

- CH10005 Handling Qualities for Manual Control- Level 1
- CH10006 Handling Qualities for Manual Control- Level 2

NPR 8705.2B paragraph 2.3.10.1 requires human-in-the-loop 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 handling qualities goes back to the very first flights of the Wright Brothers. From then until now, the evaluation of handling qualities 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 handling qualities by pilots was highly subjective and lacked formality. Efforts to examine aircraft performance characteristics and pilot opinion increased from the 1930’s through the 1960’s, resulting in the development of various tools to standardize the assessment of handling qualities. 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 handling qualities, as embodied by the Cooper-Harper rating scale, was adopted by the US military (MIL-F-8785C). Though there have been efforts to create new scales and derivatives of the Cooper-Harper, the original Cooper-Harper scale continues to be used as the industry standard for handling qualities 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 & displays), and what the pilot touches (input devices) are all factors that impact and are related to handling qualities. 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 revision of engineering design, 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 handling qualities. The scale associates subjective ratings of 1 through 10 on handling qualities to one of three 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 if 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 within the scale.

Since 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.

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

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

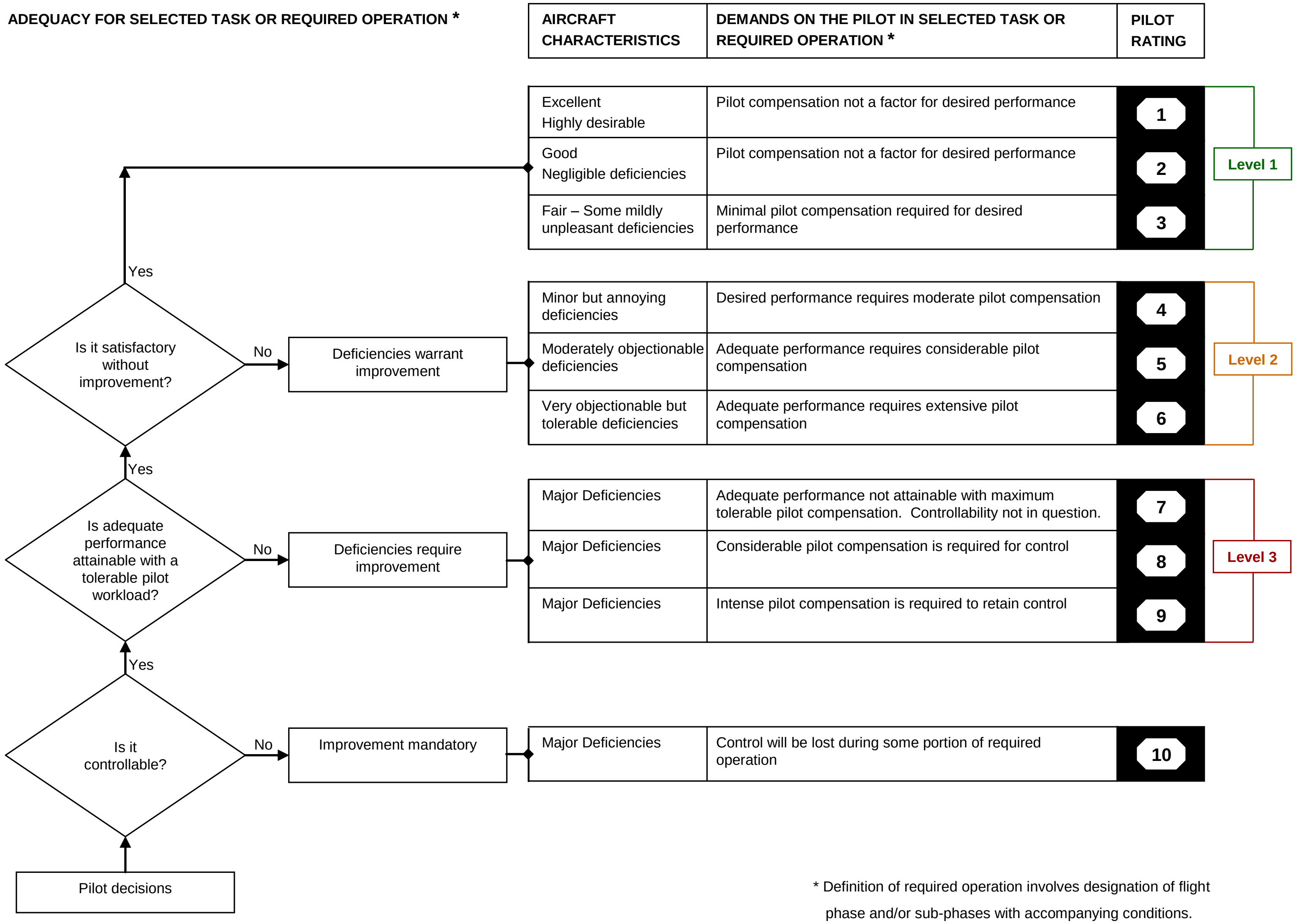


FIGURE 4.6.1.3.2-1 COOPER-HARPER HANDLING QUALITIES RATING SCALE

4.6.2 HANDLING QUALITIES DESIGN PROCESS

4.6.2.1 WHEN TO INTEGRATE HANDLING QUALITIES IN AN HSI ENGINEERING LIFECYCLE

Generally speaking it is easier and more cost effective to correct deficiencies in handling qualities 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 lifecycle so that handling quality related design decisions 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 handling qualities can be done from the very earliest stages of design, though actual evaluation of handling qualities does require a certain minimum level of design maturity. At the earliest stages of the design lifecycle, integration of handling qualities should focus on activities such as:

- defining the various operational flight phases of the vehicle (e.g., what actions will the vehicle be expected to perform, particularly from the stand point of manual control versus automation);
- identification of different control modes (e.g., pulse vs. continuous thrust);
- determination of available pitch/yaw/roll capabilities combined with available translational modes; and
- listing of 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), and associated with the appropriate CHISR handling qualities requirement (i.e., CH10005 or CH10006). These factors will be driven by the vehicle’s intended mission and operational theatres. Many of these considerations can be defined very early on during the vehicle specification stage, even pre-request for proposal or prior to procurement activity.

Following flight definitions, the next stage would be to start testing early aerodynamic or control scheme based prototypes via computer simulation. These simulations may simply be aero models of the craft with rudimentary control algorithms, and benefit the program by exposing any potentially inherent aerodynamic instability that might drive flight control development. This is also a good stage 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 via simulation become more consistent. The value of early and iterative evaluation of handling qualities is realized through direct input to design decisions related to both physical layout/conformation and control methodologies/

algorithms. This also allows for exposure of any flight phases where manual control may not be feasible due to 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 unpractical).

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 crew trained as operators who have also flown in space or rarified atmosphere environments (e.g., shuttle pilots, and extreme altitude reconnaissance aircraft) and trained spacecraft pilots.

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

- Definition of flight phases and specific flight scenarios to be tested
- Definition of adequate versus desired performance criteria for each flight scenario to be tested
- Test conductor selection
- Test subject selection
- 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 handling qualities is the definition of the vehicles' required flight phases, subphases, and scenarios. These will be based upon the design reference mission prescribed by NASA. The detailed identification of flight phases, subphases, and scenarios may occur as part of the development of the overall Concept of Operations and crew task list. The Concept of Operations (ConOps) specifies crew activities for each mission phase and scenario and determines which subsystems are impacted by crew activities.

The term flight phase is commonly used to refer to a portion of an overall 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 since 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 since separate subphases (a) place different degrees of workload or attention upon the pilot, and (b) elicit different performance characteristics from the vehicle based on 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 there are multiple conditions of a subphase that might be evaluated. For example, consider a spacecraft in an "entry" flight phase and the "initial deceleration" subphase where the craft must use aero maneuvers to shed velocity as it re-enters the atmosphere. For this example, there might be several scenarios to be tested: one where the entry profile is flown as a "ballistic" entry; another scenario where 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 pre-set 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 re-enter with additional roll reversals prior to a final landing. All three 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 the exact 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 the exact 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/night), aero properties (density, temperature, humidity), or percent 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 significantly source of variability so as to 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 differing parameter values within the scenario.

4.6.3.2 DEFINING PARAMETERS: ADEQUATE VERSUS DESIRED PERFORMANCE

After selecting scenarios 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 three decision gates, any one of which can direct the test subject to a subset of three potential ***levels***, each of which contains three ***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 which directs him or her to a particular level, they must then choose amongst the three 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 two 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 is able to 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-percent fuel remaining, while desired would be associated with 50-percent fuel remaining) or perhaps accuracy for a docking operation for a capsule rendezvous with ISS (e.g., no more than +/- 3 cm of center-point for desired or within +/- 9 cm for adequate, with those numbers based upon the specifications for the docking mechanism and its design capabilities).

The importance of these terms comes most into play when the test subject is trying to decide between Level 1 versus Level 2 ratings. Within Level 1, there 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 notes that it required **moderate** pilot compensation, while 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 handling qualities 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 handling qualities since 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 where the pilot is on the final approach to the docking mechanism, but is having a difficult time staying "on-center" with the docking mechanism, and has to perform multiple lateral translations to correct the capsule's trajectory. Even if successful docking is achieved, the pilot may give a rating of 6 given the need for extensive control inputs to perform the docking.

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 the vagaries of how to brief and debrief subjects. Whether through the Department of Defense, NASA, or Federal Aviation Administration (FAA), there are several federal organizations that can facilitate the training and mentoring of new test conductors. In addition, there are commercially available centers that specialize in simulations and handling quality evaluation 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 and common basis of knowledge regarding the Cooper-Harper rating scale. Military test pilots are trained at Test Pilot School and have historically been considered as the “gold standard” baseline for the rating of military flight vehicles. The justification for this is that not only do they have extensive classroom training on application of the Cooper-Harper scale, they also have been through training and possibly have operational experience in rating actual flight hardware vehicles. This level of experience, familiarity, and understanding far exceeds any simple briefing given in a 1- to 2-hour window just prior to 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 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 in order 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 handling qualities because of the subject selection based upon the use of 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 utilizing an initial sample size on the order of 10 to 20 pilot subjects for an assessment. This provides a data set of sufficient size that significant variability in the underlying vehicle handling qualities should be revealed, as should any significant consistency or clustering of the data. For requirement verification (CH10005V and CH10006V), at least five crew trained as operators are required.

4.6.3.5 PREPARATION OF BRIEFING MATERIALS

Briefing materials must be generated prior to conducting the handling quality evaluations. 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 there are multiple profiles being tested, each with several scenarios, it is often recommended that a different test session be conducted for each. For example if an organization had both docking and entry flight profiles being tested, there could be a test 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 pilot on 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 from 30- to 90-minutes in length, 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 (e.g., within the past few days or weeks) the Cooper-Harper refresher portion may be more streamlined than for pilots who have not performed a handling qualities assessment in several months or years.

Familiarization

Familiarization runs are simply a set of simulation or flight passes where the pilot is given time to become accustomed to the vehicles 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 'sand-box 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 based upon 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 is comprised of three basic components:

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

The practice runs are an opportunity for the pilot to be sure they fully understand the profile and scenario being tested, and have their piloting methodology figured out. If they spent considerable time with the familiarization runs they may only need or want a single practice run. On the other hand, if there are multiple scenarios being tested for the current flight profile, they may be confused as to which specific scenario they are piloting and want to ensure they are flying the scenario they think they are flying. It may sound overly conservative, but on many occasions pilots have been known to try jumping straight from familiarization time into data runs, only to make incorrect flight stick inputs because they weren't 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 two 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 one is performed with desired performance, while run two is performed with adequate), in these cases a third data run is highly recommended to determine the best performance category to assign for 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 upon the pilot's professional judgment of the vehicle's performance across the two or three 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 pilot that though they may have attained desired performance, this does not limit them to a rating of 1 to 4. However, if they only attained 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 they may have only been a transient effect in a single run. If such a transient response would have caused a major loss of control, it can 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, its controls, displays, or characteristics.

Debrief

Following 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 pilot is encouraged to talk about any items of note 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 due to the non-linear 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 upon (though 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 via graphical methods such as histograms, box and whisker plots, or frequency weighted scatter plots.

Examples of each of graphical method are provided below, taken from those 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). All three of these plots portray the same data set in three different ways (i.e., histogram, box and whisker plot, and frequency weighted scatter plot). Illustrated is data from a set of two 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 following a system error, where 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 four tasks, resulting in a total of eight separate ratings which 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.

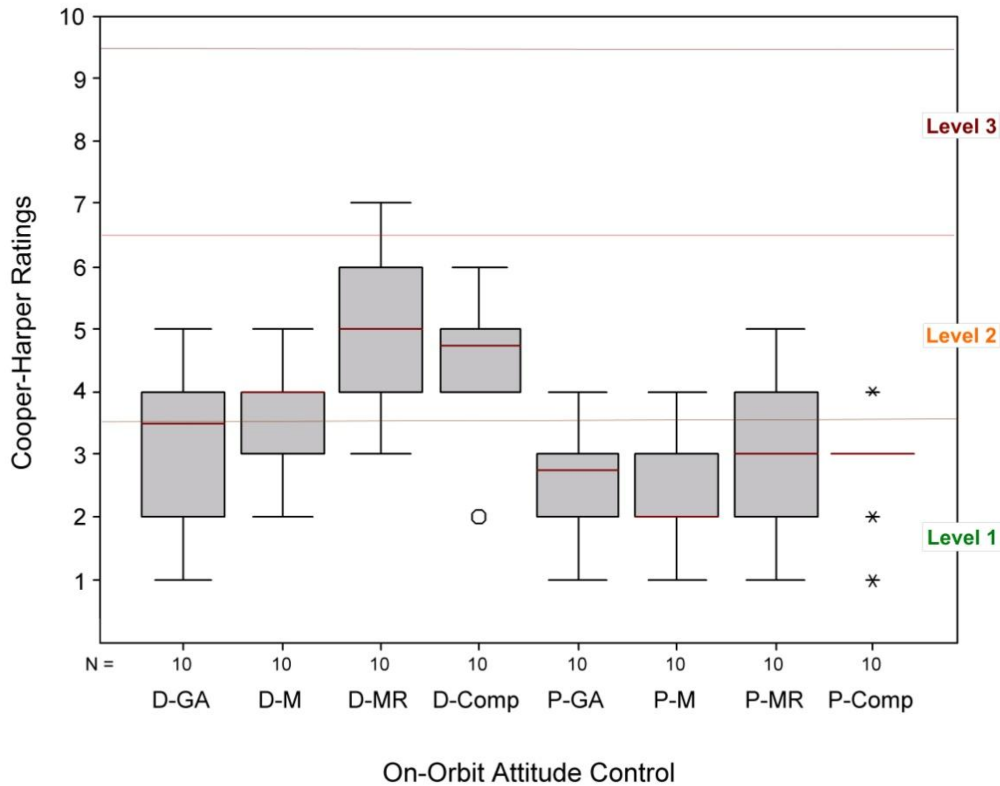


FIGURE 4.6.3.7-1 BOX AND WHISKER PLOTS OF THE ORBIT SCENARIO COOPER-HARPER RATINGS

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 mid-line of each box, while the upper and lower shoulders represent the 75th and 25th ordinal percentiles respectively. Whiskers portray data within 1.5xIQR (inter-quartile range) from the shoulders, with additional values greater than 1.5xIQR and greater than 3.0xIQR 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 for comparison of multiple distributions simultaneously, while histograms are easily generated and understood. The only significant drawback to histograms is illustrating them in such a way as to allow for 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 two figures provide an example of each of these graphical methodologies.

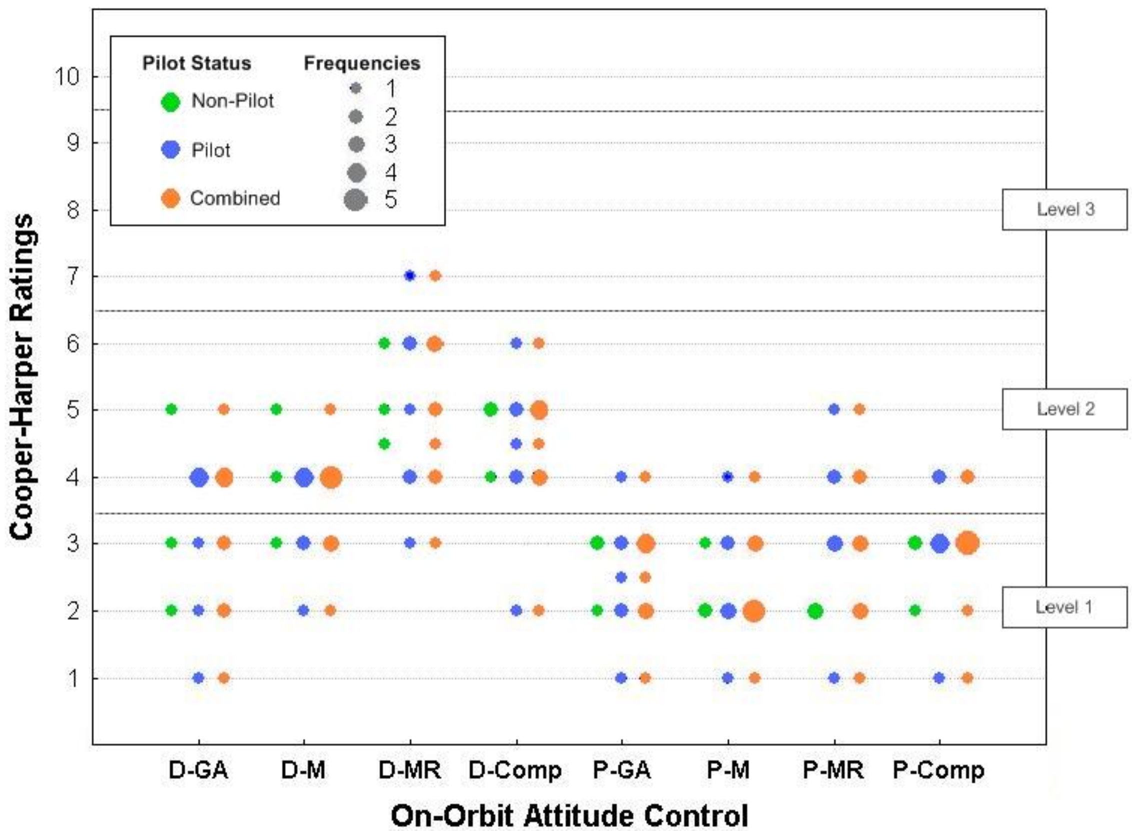


FIGURE 4.6.3.7-2 FREQUENCY SCATTER-PLOTS OF THE ORBIT SCENARIO COOPER-HARPER RATINGS

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).

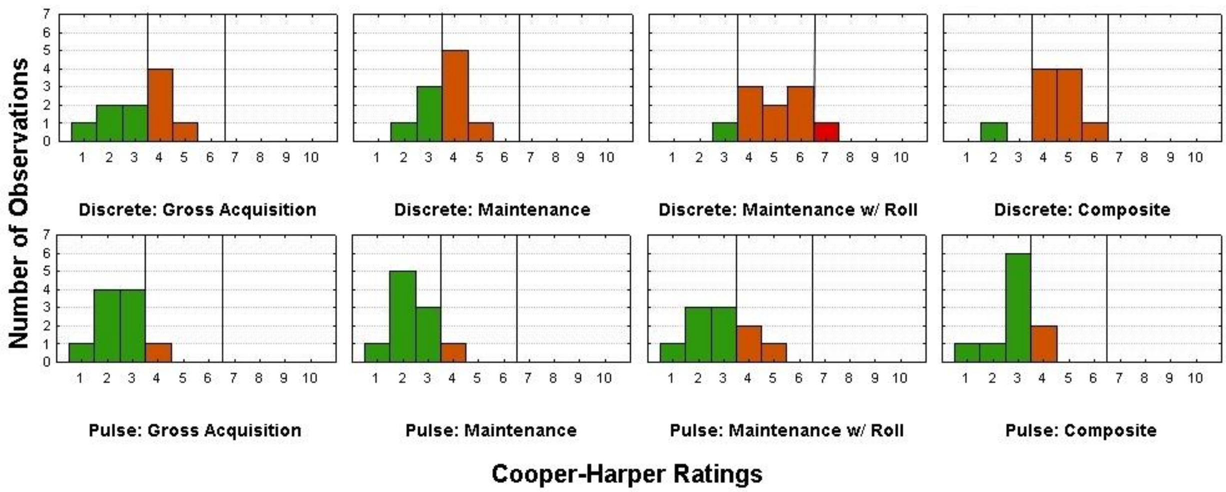


FIGURE 4.6.3.7-3 HISTOGRAMS OF THE ORBIT SCENARIO COOPER-HARPER RATINGS

Ratings colored green indicate Level 1, ratings coded orange indicated Level 2, while ratings coded red indicated 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 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 upon 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 lifecycle, 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	Responsible Org	Phase A		Phase B	Phase C	Phase D	
		SRR	SDR	PDR	CDR	SAR	FRR
A description of the ConOps, functions allocation, and associated crew task lists. Includes details such as identification of all potential flight phases, sub-phases, related scenarios, and pilot tasks for which manual control is provided, as required by the design reference mission and as specified by NASA.	CCT Company	I	U	U	U	---	---
Definition of control modes for each flight phase. Preliminary flight display concepts.	CCT Company		I	U	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. Includes simulation based HQ evaluation of each flight phase based on aero models, preliminary control algorithms and display concepts Required per NPR 8705.2B, and HITL evaluations required per paragraph 2.3.10.	CCT Company	---	---	I	U	---	---
System architecture drawings (structures, equipment, etc.), material specifications, interface requirements.	CCT Company	---	---	I	U	U	---
High-fidelity simulation based evaluation of HQ based on final structural models, control algorithms, and final displays.	CCT Company	---	---		I	U	U
Verification plan.	CCT Company	---	---	I	U	U	---
Final review of any lingering handling quality issues or pilot-ability concerns.	CCT Company	---	---	---	---	I	U
Hardware based evaluation of handling qualities with test pilots. All flight phases should be tested.	CCT Company	---	---	---	---	---	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 3.1.3.1.2 provides information such as identification of crew activities and determination of which subsystems are impacted by crew activities. Functions allocation, described in paragraph 3.1.3.1.3, 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 handling qualities evaluations include the identification of all potential flight phases, sub-phases, related scenarios, and pilot tasks for which manual control is provided. By SRR, definition of flight phases and required handling qualities rating for each phase should be defined. By SDR, control modes for each flight phase should be defined.

Modeling/Analysis/Evaluation Summaries

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 utilize increasingly higher fidelity inputs/mockups, as discussed in paragraph 3.1.3.3 Evaluate Designs and Iterate Solutions. It is important that summaries address how key/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 handling qualities, a simulation based handling qualities evaluation of each flight phase based on aero models, preliminary control algorithms, and display concepts should be performed by PDR. By CDR, a high fidelity simulation based evaluation of handling qualities based on final structural models, control algorithms, and final displays should be performed. Hardware-based evaluations of handling qualities 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 handling qualities, 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 upon the publications of Cooper and Harper, including their seminal 1969 paper on handling qualities, 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 handling qualities from not only aviation but also as it pertains to the assessment of spacecraft. With the burgeoning development of multiple commercial spacecraft, the relevance of handling qualities has only increased in recent years and is set to continue increasing in the near future. The methodology discussed here is mean to provide a sound foundation to facilitate these companies and NASA in ensuring that future craft are safe, reliable, and controllable under all anticipated flight conditions.

4.6.6 REFERENCES

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.

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

NASA-TN-D-5153 The use of pilot rating in the evaluation of aircraft handling qualities (1969)

MIL-F-8785C, Military Specification: Flying Qualities of Piloted Airplanes (05 NOV 1980)

4.7 ACOUSTIC NOISE CONTROL DESIGN

4.7.1 INTRODUCTION

Spacecraft acoustics is 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 the 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 ensure that alarms are audible. Finally, acoustics plays a critical role in the crew's health and stress level. Loud environments 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 the 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 regard to acoustics and thereby attain human-rating certification.

4.7.2 APPLICABLE ACOUSTIC REQUIREMENTS

Acoustic requirements for commercial vehicles during the mission phases in which the vehicle is not attached to the International Space Station (ISS) are specified in the JSC-65993 Commercial Human-Systems Integration Requirements (CHSIR) Section 6.6. Mission phases covered by this document include launch, abort, orbit, entry, and post-landing. ISS docked operations are covered in SSP 50808 "International Space Station (ISS) to Commercial Orbital Transport Services (COTS) Interface Requirement Document (IRD)." Although similar to some of the CHSIR requirements, a discussion of the IRD requirements is beyond the scope of this document.

The first acoustic requirement of the CHISR is the establishment of an Acoustic Noise Control Plan (CH6062), which is to document the plan for achieving spacecraft acoustic requirements.

The acoustic requirements for launch, entry, and abort phases are specified in CHSIR:

- CH6063 Noise Exposure Limits for Launch, Entry, and Abort
- CH6064 Hazardous Noise Level for Launch, Entry, and Abort
- CH6065 Impulse Noise Limits for Launch, Entry, and Abort
- CH6066 Infrasonic Noise Limits for Launch, Entry, and Abort

The acoustic requirements for orbit and post-landing phases are specified in CHSIR:

- CH6067 Impulsive and Intermittent Annoyance Noise Limit During Crew Sleep
- CH6068 Impulse Noise Limits for the Orbit and Post-Landing Phases
- CH6069 Continuous Noise Limits During the Orbit and Post-Landing Phases
- CH6070 Sound Pressure Level (SPL) Limits for Intermittent Noise During the Orbit and Post-Landing Phases
- CH6071 Hazardous Noise Limit for the Orbit and Post-Landing Phases
- CH6072 Tonal and Narrow-Band Noise Limits

Although documented in a separate family of ISS requirements, the requirements for docked operations are similar to the orbit and post-landing requirements in the CHSIR. Additionally, HIDH section 6.6.3 Human Exposure and Acoustic Environment Limits provides guidelines for the limits that ensure 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

CHSIR requirement CH 6062 establishes the requirement for an Acoustic Noise Control Plan (ANCP). The ANCP is a document that contains an acknowledgement of the applicable acoustic requirements, identification of the noise producing systems and components, a development plan for meeting the acoustic requirements (e.g., planned hardware selection criteria, acoustic mitigation efforts that will be employed), 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 acoustic noise control development. 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 analysis 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 towards meeting acoustic requirements. The following paragraphs highlight design steps that should be followed and documented within 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 in order to evaluate the acoustic noise emission scenarios for comparison to 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 in order to develop crew task lists and procedures. Off-nominal situations, such as abort scenarios, must also be considered, and the applicable acoustic requirement applied. See CHSIP sections 3.1.3.1.2 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 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. Structural analysis will be necessary to assess the inputs to the vehicle and the resulting acoustic environment experienced at the crew member’s ear. The insertion loss of the communications gear, space suit, and helmet must also be considered during this mission phase.

- 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, structural analysis will be necessary to assess the inputs to the vehicle and the resulting acoustic environment experienced at the crew member’s ear. The insertion loss of the communications gear, space suit, and helmet must also be considered during this mission phase.

- On-orbit Operations
  The dominant noise sources during this mission phase (prior to docking with the ISS) will need to be assessed based on the specified vehicle and crew configurations. Generally during this mission phase, the dominant noise sources will be inside the pressurized volume of the vehicle. 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
  When docked 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 regarding docked operation.

- Undock/De-orbit/Re-entry/Landing/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 de-orbit engines, aerodynamic interaction between the vehicle and the atmosphere, and vehicle and/or space suit Environmental Control and Life Support (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 should be included in an integrated acoustic model for an accurate representation of individual sources, propagation paths, as well as the overall acoustic environment. 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 in order to address the separate acoustic requirements. 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 measurement 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 two or three of the noted acoustic modeling techniques will need to be applied in order to bridge gaps and address the entire frequency range. A single commercial acoustic modeling software package that combines these three 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 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 static testing and ground test articles are to be incorporated as early in the process as possible to verify assumptions and improve the accuracy of the acoustic model.

4.7.3.2.2 NOISE SOURCE ALLOCATIONS

Major noise sources and acoustic allocations for each mission phase are to be identified and documented in the ANCP. The significant noise sources (e.g., engines, ECLS system, payload, atmosphere interactions, etc.) 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 and mission phase. 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 space suit (again taking into account the provided attenuation). This is an iterative process with the accuracy of the assessment improving as the design matures, major components are selected, 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 noise producing hardware (e.g., pumps, fans, and actuators) that have the lowest acoustic “foot print” and meet the functional requirements. Allocations should be in units of 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 are not dependent 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 in order 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 in order 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 in order to balance the functional requirements with a component’s acoustic emissions. Component over-engineering 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.

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 only at the speed necessary to meet the flow and pressure requirements for its role. This is an iterative process in which trade-offs between performance and acoustics are made between many noise producing systems.

4.7.3.2.5 NOISE SOURCE REDUCTION

Once systems 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 in order to reduce the noise source emissions of the unit to acceptable limits. If noise source treatments cannot be applied, then this should be documented in the ANCP along with rationale. One of the most important design activities for noise source reduction 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 original acoustic model in order 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

Once the hardware acoustic exceedances are identified though testing and trade studies, 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 to the acoustic model, and updated predictions on the overall acoustics of the habitable volume are made. Specific components (i.e., fans, pumps, actuators) may be identified along with required component reductions needed in order to meet the acoustic requirements. 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 a fan that has an overall sound level of 60 dB in the 250 Hz octave band. In order 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 tested 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, either some other counter measure would be needed to reduce the level of the fan to the necessary 50 dB in the 250 Hz octave band, or other system changes would be needed to compensate for the exceedance (e.g., adjustment of the acoustic requirement allocation).

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 in order to meet the noise source’s allocation. Designs for component level reductions may include component mufflers, acoustic covers, etc. Also, trade-offs 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 in order to verify predicted system level compliance with acoustic requirements. The predicted results of these component level noise treatments are to be documented in the ANCP.

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 predictions and treatment testing are applied as inputs to the acoustic model in order 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 in order to verify predictions that were used as inputs to the system level 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 component-level noise treatment performance results 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 loading, etc.) 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 is to be included from pad abort testing, launch abort testing, and unmanned flight testing, and this data is 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 test testing (pad abort tests, aerial abort tests, unmanned flight tests). Validation of pressure shell, blast protective cover, and space suit attenuation of launch and abort acoustic loading must be performed through testing at expected noise levels (as with reverberation chamber or flight testing). Acoustic verification is to include modeling analysis of the interior noise environment and flight test data prior to 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 future development course and expected results. 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	Responsible Org	Phase A		Phase B	Phase C	Phase D	
		SRR	SDR	PDR	CDR	SAR	FRR
A description of the ConOps, functions allocation, and associated crew task lists.	CCT Company	I	U	U	U	---	---
Initial ANCP (requirements, noise sources, initial allocations).	CCT Company	X	---	---	---	---	---
Acoustic model.	CCT Company	---	I	U	U	---	---
Updated ANCP (modeling analyses, component acoustic testing results, forward work).	CCT Company	---	X		---	---	
Updated ANCP (modeling analyses, component testing, external environment definition, verification plan, forward work).	CCT Company	---	---	X	---	---	---
Updated ANCP (modeling analyses, component testing, external environment test results, verification results, forward work).	CCT Company	---	---	---	X	---	---
Final ANCP (updated with final verification results and status, including any remedial actions needed to address requirement non-conformance).	CCT Company	---	---	---		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 3.1.3.1.2 provides information such as identification of crew activities and determination of which subsystems are impacted by crew activities. Functions allocation, described in paragraph 3.1.3.1.3, 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.

System Requirements Review (SRR)

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

NASA will review the ANCP at the SRR and provide feedback. Follow-on technical interchanges or reviews will be scheduled, as needed. Upon successful completion of SRR, the acoustic requirements will be frozen and the program will proceed with preparations for project implementation of acoustic requirements.

System Definition Review (SDR)

In order to understand the proposed system architecture, an acoustic model of the pressurized volume is to be prepared and the ANCP updated to reflect the model assumptions, inputs, findings, and projections. Modeling analyses should demonstrate the progress of the system design towards 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 component noise source acoustic testing (fans, blowers, pumps, etc) and selection criteria for flight hardware are to be included in the ANCP.

NASA will review the updated ANCP and upon successful completion of the SDR, approval will be given to begin development and/or acquisition of system components.

Preliminary Design Review (PDR)

Prior to the PDR, the ANCP is to be updated to reflect further progress in definition of the major noise producing systems. System-level noise treatment preliminary design and effects 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/abort is to be presented, and inputs included in the acoustic model. The acoustic model is to be updated to reflect the results of any completed tests (component, system, and/or flight) prior to the PDR, and the results documented in the ANCP. Necessary acoustic countermeasures 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, authorization will be given 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 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/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 presented.

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

Test Readiness Review (TRR)

A TRR is to be conducted prior to each verification test involving acoustics design. 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 one month prior to 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 completion of the test, a test report is to be provided and attached to the ANCP along with updates 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. It is assumed that the test report documentation has previously been submitted and reviewed, as discussed in section 3.5. 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 non-conformances documented and approved by NASA.

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

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 crew from radiation exposure such that effective dose (tissue averaged) is consistent with As Low As Reasonably Achievable (ALARA) principles, as specified in SSP 50005 International Space Station Flight Crew Integration Standard section 5.7.2.2.2 Ionizing Radiation Protection Design Requirements.

The following process is intended to guide the Commercial Crew Transportation (CCT) Company 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 based on assessments of projection models and a reasonable “worst-case” space environment to be encountered on specific missions. Although specific exposure limits are identified based on mortality risk, all decisions concerning vehicle, habitat, and mission design are made such that resulting crew radiation exposures are ALARA. Additional information regarding 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 to radiation exposure varies with age and gender of the astronaut and throughout the approximately 11-year solar cycle. The likelihood of SPEs is higher near solar maximum while the GCR doses are higher at solar minimum. Shielding against radiation can substantially reduce SPE doses and provide modest protection for GCR. Career exposure to radiation is limited to not exceed 3 percent Risk of Exposure-Induced Death (REID) for fatal cancer. NASA assures that this risk limit is not exceeded at a 95-percent confidence level using a statistical assessment of the uncertainties in the risk projection calculations to limit the cumulative effective dose 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 current 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

JSC-65993 Commercial Human-System Integration Requirements (CHSIR) CH6054 Radiation Design Requirement specifies that the CCT Company is to design the spacecraft to protect crew from radiation exposure in compliance with ALARA. A mitigation plan to protect crew 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 vehicle. See CHSIP sections 3.1.3.1.2 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., chemopreventive 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 by 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 spaceflight. 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 distinct physically and biologically damaging properties compared to terrestrial radiation, and the spectrum and energy of concern for humans differs from that 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 CCT Company and NASA. Throughout the iterative process of vehicle design, evaluation of the vehicle radiation shielding is to be performed by the commercial company using standard analysis tools and an integrated set of models. These models will be initially provided by NASA or the CCT Company at SRR. Those models provided by the CCT Company should be approved by NASA prior to use. The integrated set of models used to perform analysis of the vehicle design includes components such as design environment, biological, transport code, and vehicle geometry, as specified in CHSIR CH6054V.

As materials are selected and design solutions are implemented, 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 CCT Company findings. Input data includes CAD models, mass distributions, and material compositions. NASA insight to developmental analyses can be beneficial for checking assumptions and assessing progress towards 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. Although the major phases of the vehicle design have been completed prior to 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. Monitoring, per CHSIR 6079 Passive Radiation Monitoring, will also continue into 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.

The CCT Company provides locations for no fewer than six radiation area monitors, as required per CHSIR 6079, to be mounted within the vehicle. NASA provides the dosimeters and uses the results of radiation exposure analyses provided by the CCT Company to help determine the ideal quantity and best locations for the monitors within the vehicle. The CCT Company 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 prior to launch. The ground operations Interface Requirement Document (IRD) reflects installation and recovery of dosimeters immediately before/after mission. NASA supports post-landing collection and analysis of samples.

4.8.3 RADIATION SHIELDING DESIGN TECHNICAL PRODUCTS

For each of the major milestones of the design lifecycle, 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	Responsible Org	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.	CCT Company	I	U	U	U	U	---
Integrated set of models used to perform analysis of radiation shielding vehicle design.	NASA or CCT Company	X	U	U	U	---	---
Radiation instruments specifications and drawings.	NASA	I	U	U	U	U	---
Verification approach and plans for radiation shielding and area monitoring.	CCT Company	I	U	U	U	U	---
System architecture drawings (structures, equipment, etc.), material specifications, interface requirements.	CCT Company	---	I	U	U	U	---
Specifications for vehicle construction/shielding.	CCT Company	---	I	U	U	U	---
Radiation shielding tests and analyses.	CCT Company	---	I	U	U	U	--
IRDs for vehicle and portable equipment and cargo, vehicle and ground systems, vehicle and mission systems, vehicle and ISS.	CCT Company	---	I	U	U	U	---
Dosimeter and radiation area monitor mounting and recovery procedures.	CCT Company	---	---	I	U	U	U
Flight plan, flight rules, space weather environment, projected radiation dose, flight data file procedures, system operations data file procedures.	NASA	--	---	---	---	---	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 3.1.3.1.2 provides information such as identification of crew activities and determination of which subsystems are impacted by crew activities. Functions allocation, described in paragraph 3.1.3.1.3, 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)
- JSC-65994 CMORD
- JSC-65993 CHSIR
- NASA-STD-3001 Volumes 1 and 2
- NPR 8705.2B

Suggested CCT Company Technical Products:

- Initial ConOps addressing radiation requirements
- Preliminary analysis plan/verification & validation (V&V) approach for shielding analyses.
- Preliminary analysis plan/V&V approach for radiation area monitor installation

NASA or CCT Company 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
- Radiation instrumentation specifications

Suggested CCT Company Technical Products:

- Revisions of ConOps
- System architecture (structures, portable equipment, cargo) definition
- IRDs for vehicle/equipment/cargo, vehicle/ground systems, vehicle/mission systems, vehicle/ISS
- Specs for vehicle construction/shielding
    - Final analysis plan/V&V approach
    - Preliminary analysis results
    - Input data/calculations used in shielding analysis.
    - Preliminary mitigation plan if shielding is inadequate
- Methods for dosimeter mounting to vehicle
    - Updated analysis plan/V&V approach
    - Preliminary assessment of maximum loads

NASA or CCT Company 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 CCT Company Technical Products:

- Revisions of ConOps
- Updates to system architecture (structures, portable equipment, cargo) definition
- 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
- Specs for vehicle construction/shielding
    - Updated analysis results
    - Input data/calculations used in shielding analysis.
    - Updated mitigation plan if shielding is inadequate
- Methods for dosimeter mounting to vehicle
    - Updated load assessment

NASA or CCT Company Technical Products:

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

<u>Critical Design Review (CDR)</u>

NASA Technical Products:

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

Suggested CCT Company 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 shielding analyses
- Final analysis plan/V&V approach for radiation area monitor installation
- Specs for vehicle construction/shielding
    - Final analysis results
    - Input data/calculations used in shielding analysis.
    - Final mitigation plan
- Methods for dosimeter mounting to a minimum of 6 locations in vehicle
    - Final load assessment

NASA or CCT Company Technical Products:

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

<u>System Integration Review (SIR) (if scheduled)</u>

NASA Technical Products:

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

Suggested CCT Company Technical Products:
- Final ConOps, IRDs.

Test Readiness Review (TRR)
NASA Technical Products:
- Changes to radiation instrumentation specifications, as available
- Operational constraints for hardware

Suggested CCT Company Technical Products:
- Specs/drawings for vehicle
  - Updates to shielding analysis, as available
  - Input data/calculations used in shielding analysis, as available.
  - Changes to shielding mitigation plan, as required
  - Testing results
- Mounting locations for a minimum of 6 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 CCT Company Technical Products:
- Documentation that vehicle will provide adequate shielding
- Documentation that no fewer than six 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 CCT Company Technical Products:
- Specs for vehicle construction/shielding
  - Final analysis results
  - Input data/calculations used in shielding analysis.
  - Final mitigation plan as required
- Methods for dosimeter mounting 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 CCT Company 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 crew 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 crew are provided adequate volume within which to perform these tasks and optimally function in their environment. There are several methods and processes 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. For example, considerations need to be made as to how crew 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 crew 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 requirement for functional volume design and evaluation is specified in the JSC-65993 Commercial Human-Systems Integration Requirements (CHSIR) requirement CH8001 Functional Volume Allocation, which specifies that the system provide defined and sufficient functional volumes for crew to perform tasks. CH8001, and its associated verification statement, describes the functional volume allocation NASA expects a Commercial Crew Transportation (CCT) Company to provide. The intent of this requirement 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 allocation 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 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 has 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 lifecycle.

HIDH describes three spacecraft volumes which 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 crew member’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 amount 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 regarding determination of the habitability of a given volume.

Volumes are 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 a 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

*Volumes are **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/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 lifecycle. 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 CHSIP Section 3.1.

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 crew of a range of anthropometric sizes, and evaluate body positions within static physical volumes (also see paragraph 4.5.2 Anthropometry). Physical testing, in mock-ups of increasing fidelity, allows for human-in-the-loop (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 they should both be preformed 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, etc.), overall vehicle or habitat configuration, interior module design, and facility design (windows, hygiene area, etc.). 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, there are three major activities involved in designing for and assessing functional volume allocation:

- **Task analysis**: Define the tasks that crew will perform both nominally and off-nominally and the context of how they will perform them (mission phase, vehicle configuration, time constraints, number of crew members, etc.)
- **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 mock-ups 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 crew need to perform, potential postures for crew of a range of anthropometric sizes, and acceptable volume for dynamic tasks and translations. Each component of the functional volume process also informs the other. 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 three 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

Tasks analysis is used to produce a list of tasks that crew 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 function 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 impact the volume available to the crew. For example, some tasks may require rearrangement of hardware (e.g., seats) or stowage; other tasks may require keep-out-zones, due to privacy, contamination, or safety issues. When critical tasks need to be performed in a short amount of time, faster task performance may take priority over vehicle re-arrangement for additional volume.

To illustrate the selection of volume-driving scenarios, consider an event involving four crew members 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 crew member to don a suit. A task analysis may help determine if all crewmembers will need to don suits at the same time or if they can assist one another, the expected configuration of the vehicle interior (including interfaces used to accomplish the task), and whether there is time to relocate stowage to provide more volume. Thus, the task analysis is used to identify the task which requires the greatest amount of volume (e.g., four suits donned at the same time) and the context of that task so that appropriate volume is allocated for it and all related tasks which require less volume. At other times there may be multiple crew members 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.

There are several scenarios that have shown to be volume-driving for NASA vehicles. There include, but are not limited to:

- 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. 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, etc.) 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 non-functional 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.

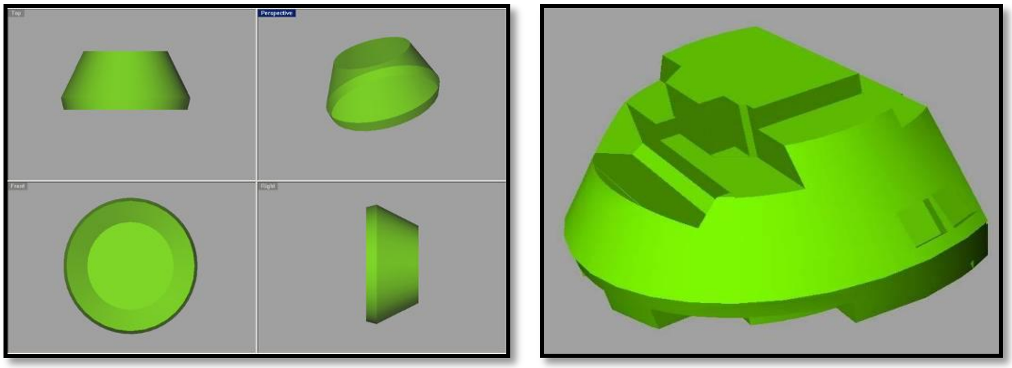


FIGURE 4.9.2.2.2-1 INITIAL CAD MODELING OF NHV

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 tables in CHSIR Tables 4.1-1 and 4.1-2, and Appendices D1 and D2. These tables will help define the volume needs of the tasks (Figure 4.9.2.2.2-2). Bodies can be modeled such that they assume expected positions for accomplishing the task, as determined by historic systems or HITL evaluations. For example in determining ways that two crew members could fit into a volume designed for radiation shielding, several possible configurations for two large males 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.

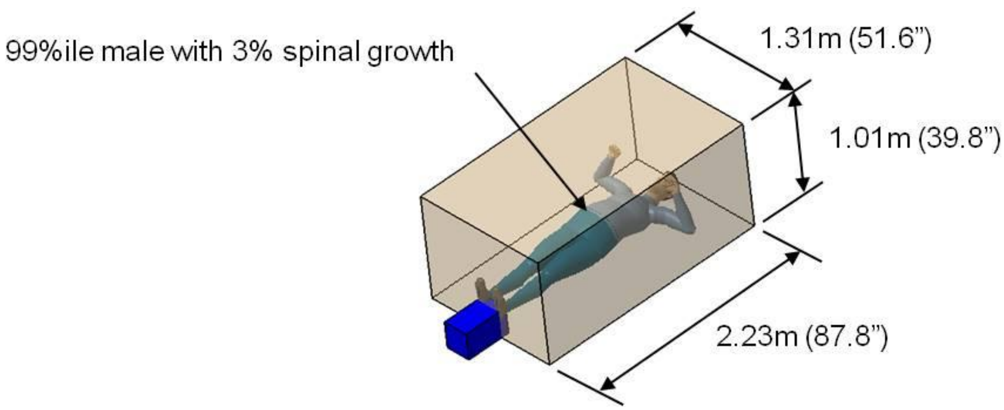


FIGURE 4.9.2.2.2-2 HYPOTHETICAL CAD MODEL OF TASK VOLUME NEEDED BASED ON ANTHROPOMETRY AND RANGE OF MOTION REQUIREMENTS

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 amongst 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 for 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 mock-up upgrades have been made.

Although CAD modeling provides critical information about the available versus needed functional volume for various vehicle configurations and body positions, it does have some limitations, which HITL evaluations can supplement. CAD analysis may not be able to capture the adaptability and flexibility of the human body to obtain 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 in order 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 such that assessments of the task across the anthropometric distribution can be performed. This has a two-fold purpose: (1) to provide evidence that the required range of crew sizes are accommodated, not just the sizes of the subjects in the HITL evaluation, and (2) to integrate and measure volume from the physical mock-up into the CAD model. Take for example, a hypothetical capsule designed to seat two crewmembers. The capsule program may require that the capsule be able to seat two fully-suited males side-by-side with 99^{th} percentile bi-deltoid breadth. A HITL evaluation is performed using two males, one with an 84^{th} percentile bi-deltoid breadth and another with a 90^{th} percentile bi-deltoid 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 two males with 99^{th} percentile bi-deltoid 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 mock-ups 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 MOCK-UPS

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.

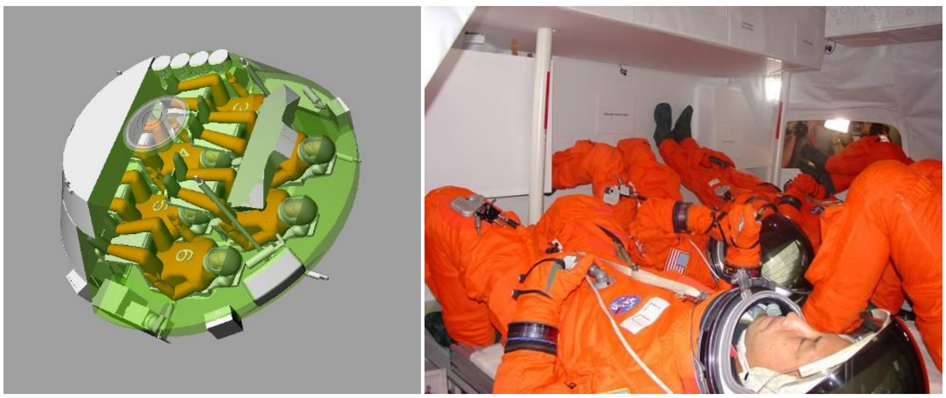


FIGURE 4.9.2.2.3.1-1 CAD MODELING AND LOW-FIDELITY MOCKUP EVALUATION

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. Note the foam-core boxes representation the display panel and the poly-vinyl chloride pipes for struts (Kallay et al., 2006).

This type of physical mockup is key in 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 crew.

In order 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, etc. to document the available volume, as well as feed future CAD models
- Interferences: The evaluator should document when a subject bumps/hits an interface, when there is a protrusion that interferes with the task, when there is not adequate fit, 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 of 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, choreography, etc.

4.9.2.2.3.2 CAD MODELING AND HITL WITH MEDIUM-FIDELITY MOCK-UPS

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 mock-up. The medium-fidelity mock-up 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, etc. The designers and test subjects get a presentation of how hardware use may affect the interior habitable volume and drive crew interactions.

Factors that increase task and mock-up fidelity include, but are not limited to:

- Hardware: Inclusion of as high-fidelity hardware as possible increases the realism and allows for 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, acceptability, etc.
- 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 where subjects spend their days and nights working a simulated mission timeline, including activities such as exercising, sleep, or meal preparation, may reward the design team with higher quality volumetric data than previous mock-ups 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 there is adequate functional volume provided to perform all identified tasks. Functional volume allocation is a key component of the system design lifecycle.

4.9.3 DESIGN DRIVERS

When evaluating the functional volumes of space environments several unique considerations should be taken into account. These drivers may be associated with the number of crew, the number of mission and contingency days, the crews' behavioral health, body dimensions, postural factors, movement capabilities, gravity, environment 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 three-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 upon another crew member'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 necessary functions 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

Design of the functional volume required for medical tasks is unique because the commercial crewed vehicle medical kit will be provided by NASA JSC and will include items to ensure Level of Care One medical care is provided for the transport phases of the mission (to and from ISS), as specified in CH7013. In addition, NASA-specified components of ISS Crew Health Care System (CHeCS) hardware from the Health Maintenance System (HMS) will be used onboard the CCT vehicle for ISS emergency evacuation and medical return capability, as specified in CH7027. 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 three-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 non-medical (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 for stabilization of the crewmember’s head, neck, and spine in a fully supine position from the 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 needed or so the caregiver can access or move around the patient from any side. See CHSIR CH9004 Interior Item Restraint. 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, etc.) and stowage restraint. See CHSIR CH7015 Stowage Locations and CH7017 Stowage Restraints.

4.9.4 EXAMPLES FROM NASA PROGRAMS AND PROJECTS

Several specific examples of how NASA projects have addressed functional volume allocation exist, and 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 functional volume allocation and are an excellent demonstration of how CAD and HITL testing concepts are integrated within their respective engineering lifecycles. 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 allocation can be performed, and CCT companies 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 broken down into cycles, called design and analysis cycles (DACs). The first cycle, DAC1, begun the three 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 based on hardware needs. For example, one task analysis session would be devoted to assessing the operational needs and tasks associated with the food warmer, while another session would be devoted to assess 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 / Docking
- EVA Preparation / Contingency EVA

The identified driving scenarios were further developed in CAD, in order 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 four crew 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 compared 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 in order to check whether cubic feet/meters was a valid way of measuring NHV. Formal HITL evaluations were not conducted in DAC1, since further analytical work was identified before mock-ups were to be built.

FIGURE 4.9.4.1-1 CAD MODEL SIMULATING FOUR CREW 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 during, and the design changes that were made in 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 provide an updated model to feed HITL mock-up 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 on 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 / Docking
  - EVA Preparation / 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 the 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.

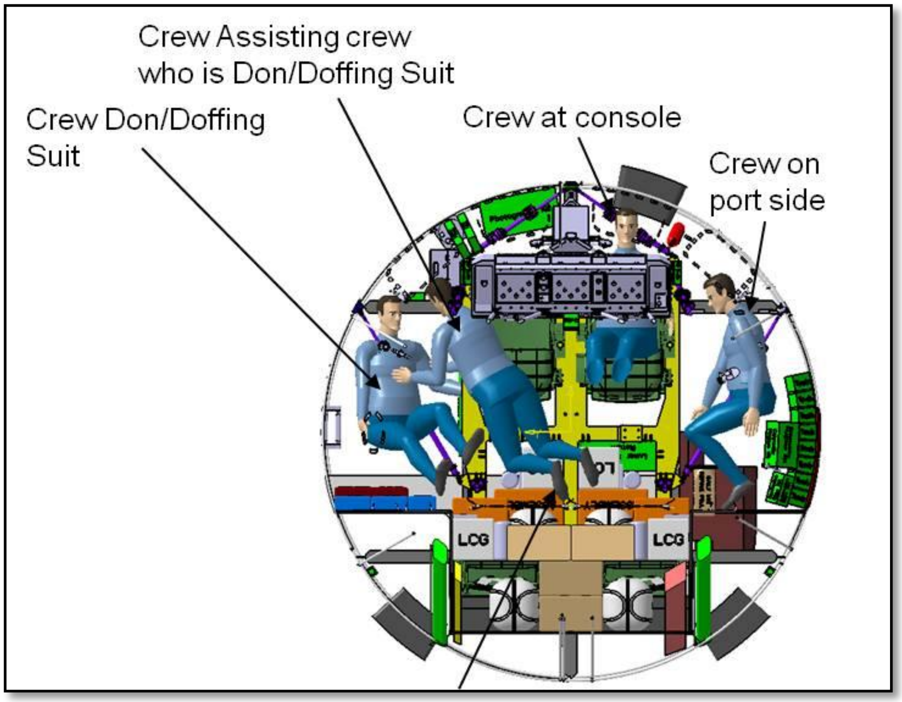


FIGURE 4.9.4.1-2 DAC2 CAD MODEL SIMULATING FOUR CREW PERFORMING THE VOLUME DRIVING SUIT DONNING AND DOFFING TASK

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 within the baseline configuration
- Review System and Subsystem concepts with scripts generated to best approximate context and fidelity within the mockup
- Determine value of HITL as part of a verification process
- Identify activities unable to perform in 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/iterative process, the data was not to be used to update any requirements, there was no crew performance/time measures 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:

- Post Insertion Cabin Configuration (crew of 6)
    - Crewmembers performing in-space stowage of seats, suits, set up and usage of Waste Management System (WMS) and access to stowed items.

- Group Meet/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 as follows:

- Pallet interference with WMS operations
- Potential strut interference in area of food preparation activity
- Strut interference with windows viewing (for Earth, vehicle photo ops) and armrests
- D&C view not available unless floating into that space
- D&C 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 D&C related issues were unavoidable at this time based on other design constraints. Through 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 mock-up physical measurement) and phase 2 including verifying that NHV is usable space through task analysis and demonstration. Phase 2 should include both CAD model analyses of tasks difficult to perform in 1-G and allow for more frequent analysis as well as task analysis and task demonstration performed by human subjects in a physical mock-up.

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 net habitable volume with a crew of four for ISS and Lunar missions and identify NHV impacts of volume-intensive tasks within 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:

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

Vehicle ingress and egress were evaluated during DAC3 in a separate evaluation, not as part of the NHV assessment. Additionally rendezvous/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 mock-up was complemented with volumetric mockups to represent suits, seats, suit stowage bags, 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 the volume was deemed adequate to perform the key driving tasks in the evaluation. 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 lifecycle, and using the results of task analysis, CAD, and HITL evaluations to iterate the design.

4.9.4.2 LUNAR SURFACE SYSTEMS

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

The low-fidelity mock-up 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 is illustrating connecting an umbilical to a mock-up space suit. The image on the right is the full crew eating dinner in the vehicle’s volume. Note the foam-core boxes on the walls around the crew representing all the subsystem hardware (Litaker et al., 2008; Thompson et al., 2010).

The Lunar Rover has gone through two different configurations since its inception. Figure 4.9.4.2-2 shows the low-fidelity mock-up of the first configuration considered, built based on a CAD model. Human factors engineers conducted an initial NHV HITL evaluation of sixteen tasks in this low-fidelity mock-up 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 due to 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 mock-up. 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 sixteen 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 is showing test subjects discussing the visibility of the front window with the side displays. Note the blue taped box on 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 in 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 two 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 two worked and lived in the functional mockup for three days interfacing with all the interior and exterior systems. Human factor 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 three day field trial. The bottom left image shows Cabin 1A cockpit interior with functional system computers and controls. The bottom right image shows Cabin 1A from the perspective of the suit ports 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 three 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 space suits, 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 (see 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 affect the crews' behavioral health (see Figure 4.9.4.2-6). The increased fidelity and representative timeline allows for 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 collected at 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 is showing a crewmember using both 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 back is doing exercises while the crewmember up front is having a snack. Both images are in the Cabin 1B mockup vehicle and show how various dynamic tasks are 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 amount of iterative testing considerably. In fact, through this NHV process, the rover design team (at the time of this writing: September, 2010) feels confident pushing forward to develop a next generation vehicle to bring the project closer to a pressure-like flight vehicle with realistic on-line subsystems. This will allow for 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 TECHNNICAL PRODUCTS

For each of the major milestones of the design lifecycle, 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	Responsible Org	Phase A		Phase B	Phase C	Phase D	
		SRR	SDR	PDR	CDR	SAR	FRR
A description of the ConOps, functions 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.	CCT Company	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. Includes analysis of volume-driving tasks based on CAD and human-in-the-loop.	CCT Company	---	---	I	U	---	---
System architecture drawings (structures, equipment, etc.), material specifications, interface requirements. Includes provision of vehicle CAD for use in analyses.	CCT Company	---	---	I	U	U	---
Verification plan.	CCT Company	---	---	I	U	U	---
X = one-time release of item I = initial release of item U = updated release of item							

<u>Concept of Operations (ConOps) and Crew Task Lists</u>

The ConOps, described in paragraph 3.1.3.1.2 provides information such as identification of crew activities and determination of which subsystems are impacted by crew activities. Functions allocation, described in paragraph 3.1.3.1.3, 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.

Modeling/Analysis/Evaluation Summaries

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 utilize increasingly higher fidelity inputs/mockups, as discussed in paragraph 3.1.3.3 Evaluate Designs and Iterate Solutions. It is important that summaries address how key/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 functional volume, analysis of volume-driving tasks should occur in CAD and human-in-the-loop 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). *Crew exploration vehicle (CEV) net habitable volume assessments for 6-crew missions.* NASA TDS CEV-05-002, NASA/Johnson Space Center, August 2006.

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.

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.

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.

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.

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.

NASA (2008a). *Net Habitable Volume Verification Method*. JSC 63557 Draft, October 30, 2008. Internal NASA Document.

NASA (2010a). *Human Integration Design Handbook (HIDH).* NASA/SP-2010-3407. January 27, 2010. NASA: Washington, DC.

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.

4.9.7 BIBLIOGRAPHY

Bond, R. and Campbell, P. (1995). “Operational monitoring of MIR habitability,” (PIPS Database #810530). Internal NASA Document.

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.

ISO (1999). *International Standard for Human-Centred Design Processes for Interactive Systems.* ISO 13407:1999(E). International Organization for Standardization. Geneve: Switzerland.

Mount, F.E. (1999). Space human factors engineering challenges in long duration flight. *NASA/Johnson Space Center Document #20000096524.*

NASA (1966). *Gemini Program Mission Report of Gemini VII*. NASA-TM-X-62892, N79-76319. National Aeronautics and Space Administration Manned Spacecraft Center, Houston, Texas.

NASA (2008b). *NASA Procedural Requirements for Human-Rating Requirements for Space Systems.* NPR 8705.2B. May 6, 2008. Office of Safety and Mission Assurance.

NASA (2009). *NASA Space Flight Human-System Standard Volume 2: Human Factors, Habitability, and Environmental Health.* NASA-STD-3001Draft 5, November 2, 2009. Internal NASA Document.

NASA (2010b). *Commercial Human-Systems Integration Requirements.* JSC-65993 Baseline, December 2010.

4.10 CREW SURVIVABILITY ASSESSMENT

4.10.1 INTRODUCTION

Per the 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 lifecycle, 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	Responsible Org	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.	NASA	X	---	---	---	---	---
A description of the ConOps, functions allocation, and associated crew task lists.	CCT Company	I	U	U	U	---	---
Establishment of scenarios to be used for hazard analysis and risk assessments.	CCT Company	I	U	---	---	---	---
A description of the design philosophy which will be followed to develop a system that utilizes the crew's capabilities to execute the reference missions, prevent aborts, and prevent catastrophic events. Required per NPR 8705.2B paragraph 2.3.3 Documenting the Design Philosophy for Utilization of the Crew.	CCT Company	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.	CCT Company	---	I	U	U	U	U
A description of the implementation of the crew survival capabilities and a clear traceability to the highest level program documentation. Required per NPR 8705.2B paragraph 2.3.4 Incorporating Capabilities into the System Design.	CCT Company	---	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.	CCT Company	---	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 in order to provide and maintain atmospheric cabin conditions necessary to ensure the health and human performance of the crewmembers. Taking the human-centered approach to spacecraft design will help the designer to achieve required environmental conditions needed to sustain crew 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 spaceflight 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 JSC-65993 Commercial Human-Systems Integration Requirements (CHSIR) requirement relevant to metabolic loads and ECLS design include:

- CH4008 Metabolic Loads
- CH6001 Total Pressure Tolerance Ranges for Crew Exposure
- CH6003 O_2 Partial Pressure Tolerance Ranges for Crew Exposure
- CH6004 CO_2 Partial Pressure Tolerance Ranges for Crew Exposure
- CH6006 Contingency Control of Heat Stored by Crewmembers
- CH6005 Nominal Atmospheric Temperature
- CH6007 Relative Humidity Tolerance Ranges for Crew Exposure

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

In order 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 CHSIP sections 3.1.3.1.2 Develop Concept of Operations and 4.1 User Task Analysis).

Metabolic rate profiles can then be developed using NASA established crewmember metabolic loads provided in CHSIR Appendix D. CHSIR Table D5-1 provides crewmember metabolic loads for standard day, sleep, and nominal activity; Table D5-2 provides crewmember metabolic loads for peak activity; and Table D5-3 provides crewmember metabolic loads for suited operations. Total heat output from a single crewmember is the sum of sensible (i.e., dry) heat and latent (i.e., wet) heat outputs.

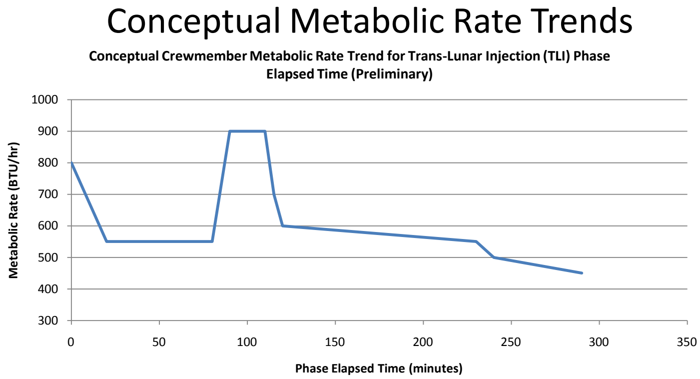
Comprehensive analysis of crew activities in establishing metabolic rate profiles is critical for ensuring the ECLS system is designed to accommodate nominal and peak, transient thermal loads and metabolic byproducts without compromising the cabin environment. Figures 4.11.2.1-1 and 4.11.2.1-2 provide 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 Commercial Crew Transportation (CCT) Company with a tool to determine the system's efficiency in managing human metabolic loads early in the design process. The CCT Company 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 as specified in the CHSIR. 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)

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FIGURE 4.11.2.1-2 EXAMPLE METABOLIC RATE PROFILE

Metabolic load values provided in CHSIR are based on a set of environmental conditions and crewmember assumptions, which are detailed in CHSIR Appendix D5 Metabolic Loads. If the spacecraft conditions or crewmember characteristics vary from the assumptions, metabolic loads will differ from values in CHSIR Appendix D5and should be captured in the metabolic rate profile. For example, if pressurized suits are worn instead of shirt-sleeves, insulation and convection properties must be adjusted accordingly.

For metabolic rate data not available in the CHSIR, the CCT Company should employ 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, spaceflight analogue data or applicable ground based data from NASA laboratories, or other aerospace physiology laboratories. NASA can provide assistance with adjusting metabolic loads values 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, i.e., CO_2 production, O_2 consumption, water production, etc. Historically, NASA has utilized the 41-Node Man or Wissler models as a validated means of ascertaining the human physiological response to flight environments.

By SDR, the CCT Company should identify the validated model that will be utilized to perform analyses throughout the design process. Input data needed for each model may vary from the information provided in the CHSIR document. In these cases, NASA will work with the CCT Company 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 Section 6.1.1 of the CHSIR. 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 CHSIR requirements:

- CH6001 Total Pressure Tolerance Ranges for Crew Exposure
- CH6003 O_2 Partial Pressure Tolerance Ranges for Crew Exposure
- CH6004 CO_2 Partial Pressure Tolerance Ranges for Crew Exposure
- CH6005 Nominal Atmospheric Temperature
- CH6007 Relative Humidity Tolerance Ranges for Crew Exposure

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 to developmental analyses can be beneficial for checking assumptions and assessing progress towards 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 lifecycle, 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	Responsible Org	Phase A		Phase B	Phase C	Phase D	
		SRR	SDR	PDR	CDR	SAR	FRR
A description of the ConOps, functions allocation, and associated crew task lists.	CCT Company	I	U	U	U	---	---
Metabolic load timelines/profiles.	CCT Company	---	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.	CCT Company	---	I	U	U	---	---
Integrated analysis of all subsystems demonstrating design capacity to manage human metabolic loads throughout all mission phases.	CCT Company	---	---	I	U	U	---
Verification plan.	CCT Company	---	---	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 3.1.3.1.2 provides information such as identification of crew activities and determination of which subsystems are impacted by crew activities. Functions allocation, described in paragraph 3.1.3.1.3, 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.

Modeling/Analysis/Evaluation Summaries

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 utilize increasingly higher fidelity inputs/mockups, as discussed in paragraph 3.1.3.3 Evaluate Designs and Iterate Solutions. It is important that summaries address how key/critical design decisions were assessed. Per the 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 featuring 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. There is rarely a wealth of tried and true design solutions 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 graphical and textural, readily understood, 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 multi-disciplinary 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 spaceflight 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. It should be a collaboration where 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. While 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, procedures developers, etc.

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/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
- Human-System Integration Requirements document – requirements to ensure human-rating, and safe and productive integration of the human and the system
    - JSC-65993 Commercial Human-Systems Integration Requirements (CHSIR)
- Display Format Standards document – describes the design standards, templates, software component “look and feel”, colors, fonts, etc., 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 within a spacecraft.

Section 3.1 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 as to the functionality they will be able to provide through the display formats since often system design is still immature early in the lifecycle. 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 to be crew needs and understanding the variety of ways in which the system may be used by crew. 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 when designing usability evaluations. At minimum, scenarios should be developed that address: nominal/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:

- What will be accomplished via 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 crew interact with the display formats and how will control of a format be shared or not?
- Are multiple instances of a display format possible? If so, how will real-time data updates/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 regarding 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 the different categories of formats that 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 via 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 there are many documented methods 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 some of the more standard hardware task analyses, documenting many of the software-driven tasks may require prediction since as previously mentioned, the planned tasks and capabilities may have never before have existed; “experts” may have to make educated guesses.

4.12.4.4 CONCEPT PROTOTYPING

The human-centered design activities outlined in section 3.1.3 describes 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 get multiple ideas down 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, since their purpose is short-lived and there will be many changes 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 to perfect these early prototypes, or build in interactivity or system models, is time wasted since 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 stakeholders for review and comment throughout the process. This helps ensure there will be early buy-in, and no surprises late in the development lifecycle that could result in costly redesigns.

When a custom software platform is being used, prototyping and display standards development must often develop 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 out 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 prior to any crew-in-the-loop testing since 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, as opposed to 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 time-line 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 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 insure that they are semi-realistic and formatted correctly. It will not be possible to test all components, functions, options, etc., so it is important to work within the multi-disciplinary team to select the subset of functions to be tested. While procedures should be somewhat realistic, it is more important that the procedures require the crewmember to work through/exercise all of the pre-selected display components, functions, or operations. While this may result in an impact to realism, and you may receive some comments from subjects about this, it is more important that all of the key functions be exercised. A decision will have to be made regarding 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 over or simulated. It is sometimes useful to time sessions, but it 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 a lot 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 time-lining. 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.

Following the task, crew 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 fluctuations in attention, frustration, confusion, or verbal comments during 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 for 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 3.1.3 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 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 implemented in the spacecraft, a plan should be developed for post-deployment evaluation. This is 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 insuring 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. In addition, the creation of display standards is a requirement in the Commercial Human-Systems Integration Requirements document (CH10009 Display Standards).

4.12.5.1 STANDARDS DEVELOPMENT PROCESS

Display standards development 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 display standards document and use iterative process to refine and update standards
- Perform stakeholder review
- Implement standards and perform checks to verify 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 if 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 non-compliance.

4.12.5.3 CREATE A DISPLAY STANDARDS COMMITTEE WITH APPROPRIATE STAKEHOLDERS

A display standards committee is responsible for making decisions on 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. This 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/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., 2/3rds 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 based on 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; documented standards should be easily accessible by them. 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 upon.

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/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, there may be symbols, colors, or terminologies that have familiar meaning to users based on their cockpit experience or other display interactions (e.g., ISS). There may be other standards documents (Federal Aviation Administration, Department of Transportation, Military Standards, Institute of Electrical and Electronics Engineers, etc.) or general human factors principles to draw upon.

It is critical to understand the tasks that users will be asked to perform via 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 non-dynamic 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 should be collected on vehicle hardware and software 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 on-going 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 there is evidence, 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, there will likely need to be less information 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 crew that 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 a common language between all display teams and software developers. 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 crew will interact with displays. For example, how crew 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 crew 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 upon 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 crew input/action areas. The standards document should specify how display elements that are dynamic (e.g., telemetry of vehicle states/data values) are distinguished from those that are static (e.g., reference information or labels). The document should specify how display elements, that crew can manipulate or change, are distinguished visually from elements that cannot be changed by crew.

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, due to 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 exists, which should be followed unless there is significant rationale for not following them. Some example conventions include:

- Yellow - caution or cautionary state
- Red - warning/emergency
- Blue or cyan - advisory
- Gray - unavailable function
- White - available/dynamic information
- Green - available information or normal state (non-cautionary)

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 standard issues or need for clarifications may arise. An iterative process should be used to incorporate any updates, changes, or clarifications to 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 if designs comply with the standards. Verification by inspection should be performed on all displays prior to 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 lifecycle, 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 since 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	Responsible Org	Phase A		Phase B	Phase C	Phase D	
		SRR	SDR	PDR	CDR	SAR	FRR
A description of the ConOps, functions allocation, operational use scenarios, and associated crew task lists.	CCT Company	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.	CCT Company	---	---	I	U	---	---
Software Development Plan	CCT Company	I	U	U	---	---	---
Display Format Standards Document, including icon library and display dictionaries	CCT Company	I	U	U	---	---	---
Verification plan.	CCT Company	---	---	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 3.1.3.1.2 provides information such as identification of crew activities and determination of which subsystems are impacted by crew activities. Functions allocation, described in paragraph 3.1.3.1.3, 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.

Modeling/Analysis/Evaluation Summaries

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 utilize increasingly higher fidelity inputs/mockups, as discussed in paragraph 3.1.3.3 Evaluate Designs and Iterate Solutions. It is important that summaries address how key/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.

Verification Plan

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

Pre- System Requirements Review (SRR)

- Draft of Software Development Plan
- Concept(s) of Operation
- Operational/ Use Scenarios
- Early Task Lists/ Task Flows
- User/ 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 following 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/ Use Scenarios
- Updated Task Lists/ 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/ 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

- Update 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., and Thronesbery, C. (1998). Guide to Designing Usable Software Systems in Advanced Technology Environments, JSC Technical report: JSC-28517.

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 for providing identifying or instructional information to the operator for activities such as finding items, following procedures, avoiding hazards, locating emergency equipment, or 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 on 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 with the implementation of JSC-65993 Commercial Human-Systems Integration Requirements (CHSIR) requirements CH10010 Labeling, CH7022 Labeling of Hazardous Waste, CH9029 Cable Identification, and CH10008 Operations Nomenclature for labeling. This overview is to serve as a guide for Commercial Crew Transportation (CCT) companies to facilitate user interface labeling design through the use of human-centered design process and ISS labeling examples.

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, the commercial 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 CHSIP sections 3.1.3.1.2 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/placement on equipment/system, and orientation with respect to 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, etc. Text size should be in accordance with CHSIR CH10010 and be sans serif style for optimum readability. The preferred font styles used on ISS are Helvetica or 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 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 has unique design considerations that are described in the following paragraphs. For commonality with 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 trash containing toxic or otherwise hazardous waste that may be exposed to crew, biohazards, and electrical shock hazards. 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 CH7022 Labeling of Hazardous Waste.

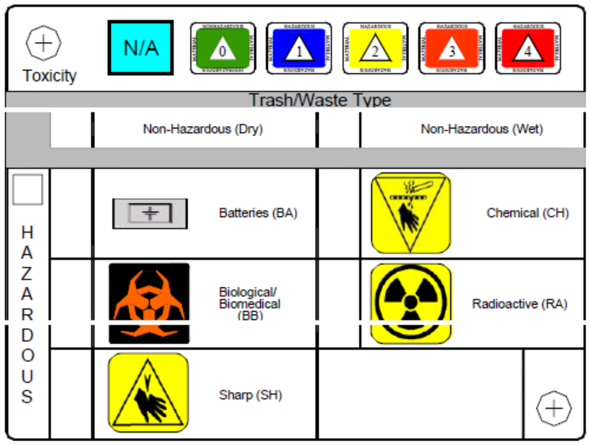


FIGURE 4.13.2.2.2.1-1 ISS HAZARDOUS TRASH IDENTIFICATION LABEL (SDG32105751)

Caution and warning labels should be used to indicate special circumstances such as, an unprotected hot surface that may cause startle reaction, keep out zones, reduced clearance, sensitivity to electrostatic discharge, or stored energy. Generally, caution and warning labels are distinguished by the use of yellow and black diagonal striping for intra-vehicular activity (IVA) applications. Gold and black are used for extra-vehicular 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 and fire ports, fire extinguishers, emergency exits, or connectors that are to be disconnected in 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 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 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 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 utilized on ISS and available from DDPF.

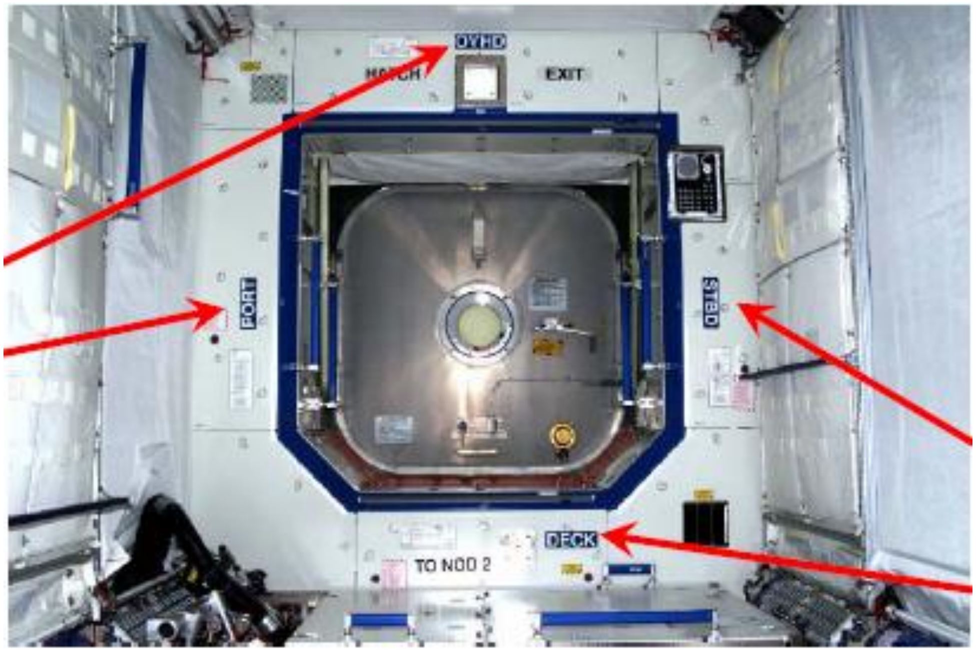


FIGURE 4.13.2.2.2.2-1 ISS CREW PREFERENCE LOCATION MARKING LABELS (SDG32106315)

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 crew 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 intended operations should be employed 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.

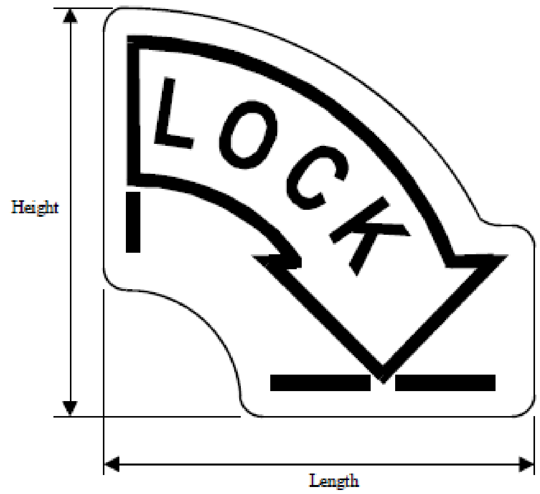
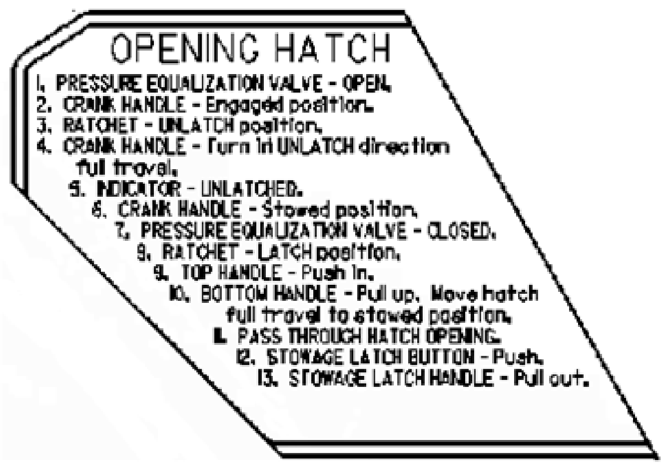


FIGURE 4.13.2.2.2.3-1 SAMPLE "LOCK" INSTRUCTION LABEL



EVA Side (Rib Side) IVA Side (Dome Side)

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 crew 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, etc.) 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/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/displays.

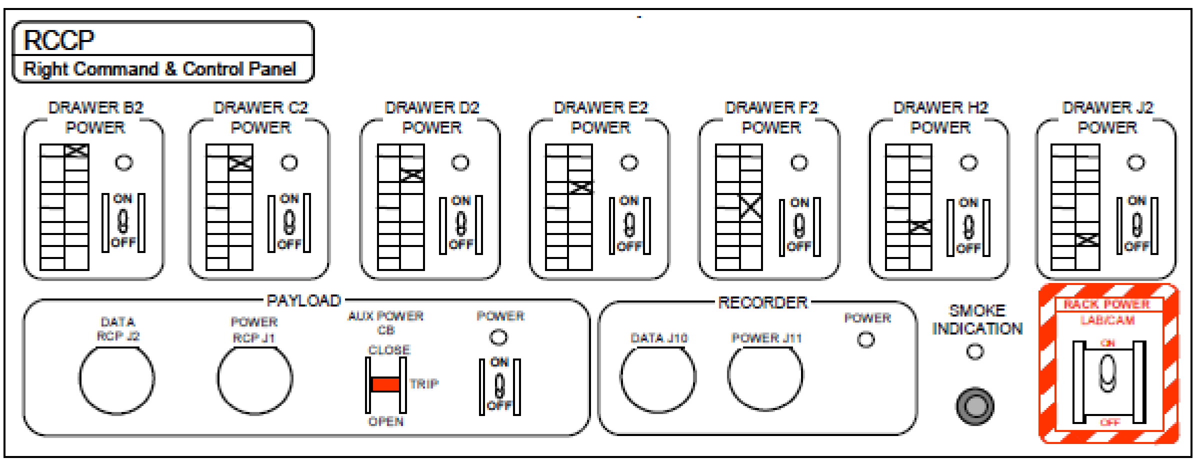


FIGURE 4.13.2.2.2.4-1 SAMPLE ISS CONTROL PANEL LABELING

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 crew 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 crew 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.

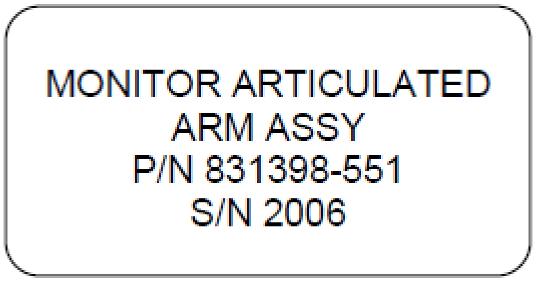


FIGURE 4.13.2.2.2.5-1 ISS HARDWARE IDENTIFICATION LABEL (SDG32107015)

4.13.2.2.2.6 INVENTORY MANAGEMENT SYSTEM BARCODE LABLING

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 ISS. The IMS is also used to catalog and track items that are on-board ISS. Therefore, items that are transferred to 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.

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 crew 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 crew.

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 connectors-ends that crew will operate regularly/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 non-emergency use or operated infrequently, such as utility cables installed behind equipment racks that may be operated only when equipment is replaced.

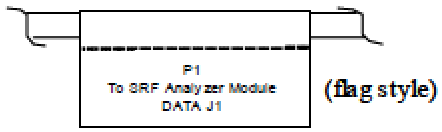


FIGURE 4.13.2.2.2.7-1 SAMPLE ISS FLAG-STYLE LABEL

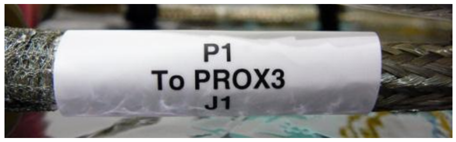


FIGURE 4.13.2.2.2.7-2 SAMPLE ISS BAND-STYLE LABEL

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, three lines of text are used.

Line 1: Identifies either the hardware name that the cable/hose is part of or a connector identification code. Use of the hardware name is recommended on long cables/hoses where the connector-end may be far from the base hardware, such as long utility cables connecting equipment to power. When 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 matching number. Electrical connector gender (pins/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 with electrical connectors and receptacles, only.

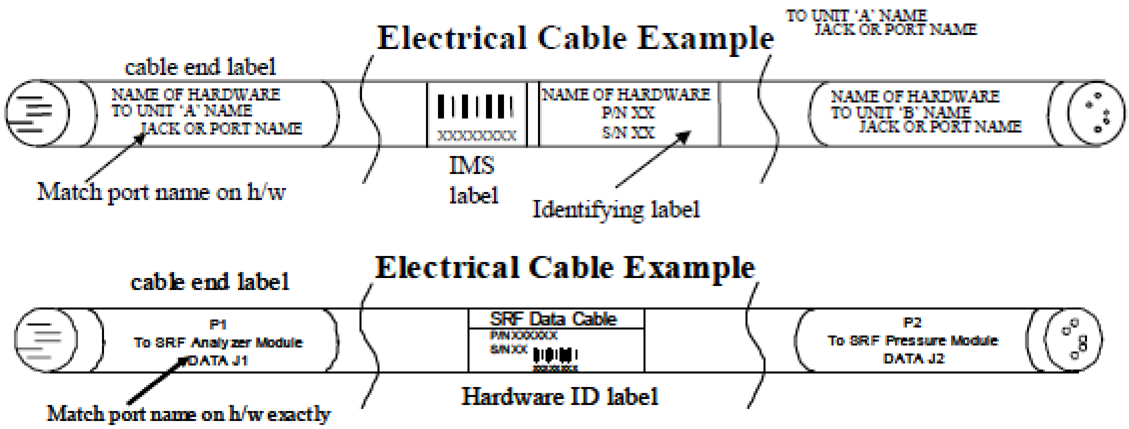


FIGURE 4.13.2.2.2.7-3 SAMPLE ISS ELECTRICAL CABLE LABELING

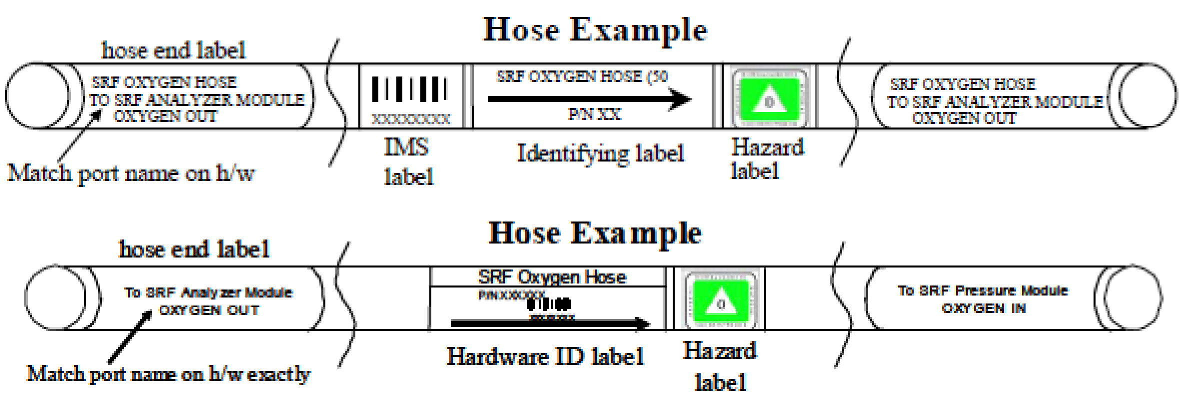


FIGURE 4.13.2.2.2.7-4 SAMPLE ISS FLUID HOSE LABELING

4.13.2.2.3 OPERATIONAL NOMENCLATURE

For operational consistency, NASA and the International Space Station 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 acronyms and abbreviations. If needed, NASA will assist the CCT Company in obtaining OpNom through the OpNom process. Registered OpNom is used on ISS labels for identifying hardware/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 CCT Company chooses to request DDPF production of flight labels, the labels must either 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 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 intra-vehicular labels. To be approved for flight to ISS, labeling materials must meet requirements/restrictions for flammability, odor, toxic off-gassing, fungus, and polyvinyl chloride. Refer to JSC-27260 for material specifications.

If the CCT Company 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 ISS per 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 due to environment 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 utilized 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 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 lifecycle, 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	Responsible Org	Phase A		Phase B	Phase C	Phase D	
		SRR	SDR	PDR	CDR	SAR	FRR
A description of the ConOps, functions allocation, and associated crew task lists.	CCT Company	I	U	U	U	---	---
User interface Labeling Design Plan.	CCT Company	I	U	U	U	---	---
Operational nomenclature proposals/requests.	CCT Company	I	U	U	U	---	---
Operational nomenclature approvals/registration.	NASA		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.	CCT Company	---	---	I	U	---	---
Verification plan.	CCT Company	---	---	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 3.1.3.1.2 provides information such as identification of crew activities and determination of which subsystems are impacted by crew activities. Functions allocation, described in paragraph 3.1.3.1.3, 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.

Modeling/Analysis/Evaluation Summaries

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 utilize increasingly higher fidelity inputs/mockups, as discussed in paragraph 3.1.3.3 Evaluate Designs and Iterate Solutions. It is important that summaries address how key/critical design decisions were assessed. Per the NPR 8705.2B, updated summaries are to be provided at each design review through SAR. Per the requirements in NPR 8705.2B 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.

4.14 OCCUPANT PROTECTION DESIGN

4.14.1 INTRODUCTION

Occupant protection as described in JSC-65993 Commercial Human-Systems Integration Requirements (CHSIR) focuses on those crewed spacecraft features designed to control hazards and limit injury risks presented by excessive crew loads due to high accelerations or insufficient crew restraint, during dynamic phases of the mission. It is important that the occupants be protected from injury without excessive protections 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 commercial crewed spacecraft requires modification to meet the CHSIR requirements.

4.14.1.1 DEFINITION OF OCCUPANT PROTECTION

Proper support and restraint of the body components can reduce the risk of injury and needs to be addressed by both the vehicle and the flight suit system (if included). Many parameters affect the likelihood of injury during dynamic flight events, including extrinsic factors such as g-loading, velocity change, rate of acceleration onset, acceleration rise time, load paths and load distribution, deflection of spacecraft structure and collapse of habitable volume, bone and soft tissue compression, tension, extension, flexion, shear force magnitudes and directions, deflections of the body components, etc., as well as intrinsic factors of the crew such as age, gender, physical condition, deconditioning due to spaceflight, 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.

4.14.1.2 APPLICABLE REQUIREMENTS

Occupant protection requirements are specified in CHSIR Section 6.4.6. 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.

- CH6048 Brinkley Dynamic Response Model
- CH6049 Limitation of Crew Injury
- CH6050 Spinal Alignment

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 due to the varying environments they must withstand during the ascent, descent, and landing phases of flight. During all phases of flight, the crew will be exposed to accelerations of varying intensity, duration, and orientation. Therefore, simple adoption of standardized methodologies of injury assessment from other industries (like commercial aircraft) is not possible for any spacecraft. This section is intended to provide a guide to the process that may be used to assess occupant injury, but is not an exhaustive description of the methods needed to implement the process.

4.14.2.1 RECOMMENDED BEST PRACTICES

During nominal, off-nominal, and contingency landing scenarios and aborts, crewmembers are subjected to forces and accelerations that may cause serious injury if not adequately mitigated. By utilizing a variety of analysis tools and methods for assessing different occupant protection system designs, predictions of injuries for a range of acceleration load cases, seat designs and seat locations can be developed. Combining these simulations with existing research and information from current impact injury databases, recommendations may be made for improvements to the spacecraft to prevent or mitigate these injuries.

Best practices include:

- Design the system such that accelerations are concentrated in directions most easily tolerated by the human body (for example +Gx eyeballs back)
- Identify the set of certified landing cases (nominal, off-nominal, and contingency) for which the system performance will be analyzed and certified. This should include abort cases, failed conditions of parachutes, control systems, or other landing system elements, as well as off-nominal environments (wind, wave state, or surface conditions) as defined by hazard analysis and statistical probability.
- Perform analysis to determine which landing cases are the drivers for Brinkley Low criteria
- Mitigate the driving Brinkley Dynamic Response Model cases with additional controls as necessary including design features such as crushable structure, airbags, retro-rockets, or stroking seat pallets
- Analyze the load case and modify the design iteratively to minimize statistical energy risk for all cases, adding operational controls such as launch and landing environment placards only as a final option
- Simplify the interface between the occupant and seat, eliminating rigid points in the suit, and providing direct interface between the body and restraint systems.
- Apply conformal seating to distribute loads as evenly as possible along the back and buttocks for x-axis and z-axis load.
- Provide shoulder and head lateral support to maintain spinal alignment for y-axis loading
- Ensure that the limbs are restrained such that flail under off-nominal or unexpected acceleration does not result in hyperextension, hyperflexion, or impact with structure or other crew members. Note that the degree of restraint must be balanced with other operational impacts such as reaching displays and controls and performing unassisted egress in off-nominal landing scenarios. Perform structural analysis to ensure that a survivable volume is provided in excess of loads for all certified off-nominal and contingency landing scenarios, including prevention of structural collapse, stroking of the seats into structure, or structural failure of any equipment that may become a projectile and strike the crew.

4.14.2.2 DEFINE LANDING CONDITIONS AND LANDING LOADS

Due to the complexity and cost of manufacturing a new spacecraft, much of the design work for assessing and controlling accelerations and the 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 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

To accurately predict landing probabilities, parameters that affect landing orientation and velocity are to be included in landing probability analysis. Some of the parameters that factor into the analysis include reentry attitude, parachute performance, hang angle, wind speed, and sea state (e.g., wave height, frequency, angle, shape, direction, etc.) or terrain (e.g., slope, soil conditions, etc). 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 would describe 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, 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. The off-nominal and contingency landing environments may include parachute out conditions, loss or guidance or roll control, failure of air bags or other landing systems, off-target landing locations, pad- and ascent-abort landing conditions, etc.

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. There are many methods 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 based on 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 splits the acceptable and unacceptable landing cases for factors such as system failures, horizontal and vertical landing velocity, impact angle, wave state, or soil condition. An initial boundary is defined that includes the wide majority of landing conditions based on a probabilistic distribution, with variable assessed either independently (such as the case for random failures) or dependently (for conditions 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 such 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 via operational controls on flight operations (i.e., placards) or accepted as risk. Additional analysis must be conducted to show that the cases within the boundary satisfactorily meet the occupant protection requirements, else either the design must be modified or the offending environmental conditions controlled via placards to prevent the system from operating outside of the certified conditions within acceptable risk.

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. Following 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 then modeled as described below in the following sections. The results of these analyses are then used to estimate the injury response of all of the landing cases using a response surface. See NASA/TM-2009-215704 for additional information on the method. Once this analysis is conducted, addition critical landing cases can be selected near areas where cases may be near the threshold of failing the requirements 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 are selected, landing simulations of the entire vehicle are conducted. This simulation provides the necessary loads and dynamics information needed to drive the crew interface sub-system model which includes the crew, seats, and restraints as well as anything in the direct load path such as pressure suits, as well as the accelerations the crew experiences considering the effects of impact, vehicle structural deformation, and impact attenuations systems such as landing gear, airbags, retrorockets, and stroking crew pallet or struts. This model may have increasing levels of fidelity based on the design phase, allowing for more detailed results in each subsequent design phase.

4.14.2.2.4 CREW-INTERFACE AND CREW RESPONSE MODELING

When the time histories of the vehicle dynamics from landing are estimated, the next step is to model the crew-interface (i.e., crew positions). As before this is an evolutionary process where 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 allow evaluation of the Brinkley Dynamic Response criteria at a minimum. To accomplish this, the model must account for gross accelerations at the vehicle level, and simulation of energy attenuation to accurately predict the accelerations at each crew location. Ideally, this level of analysis occurs between SRR and PDR.

Once the gross performance of the vehicle accelerations is known, modeling of the crew interface is needed including the seat and any energy attenuation systems. This fidelity model also requires a human surrogate model to be restrained in the seat. Models of the suit, if applicable, should be included, but may be of a low fidelity nature. At this stage, initial developmental testing using an Anthropomorphic Testing Device (ATD) and human subjects may be used to refine predictions of load distributions on the crew, and validate the simulations and analysis. This level of simulation should inform the design between PDR and CDR.

4.14.2.2.5 MODEL VALIDATION TESTING

Because the above analysis is highly dependent of responses of Finite Element (FE) models, physical testing is required to support the validity of the analysis. These simulations must be validated with physical test data 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 to 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 system testing is of flight-like systems and subsystems, and test results match predicted, simulated data.

4.14.2.3 INJURY ASSESSMENT

An injury assessment is completed 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 in 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 in CH6048, 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; the design and assessment of an escape system concept for the National Aerospace Plane; development, test, and evaluation of the X-38 assured crew recovery system; development, test, and evaluation of the Soyuz TMA crew module; and advanced development, test, and evaluation of the K-36D-3.5A ejection seat.

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 encapsulated ejection seats for the B-58 and XB-70 aircraft and the cockpit crew escape system for the F/B-111 aircraft for the U.S. Air Force, the established acceleration limits specified 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 upon 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.

4.14.2.3.1.2 ASSUMPTIONS FOR THE BRINKLEY DYNAMIC RESPONSE MODEL

The Brinkley Dynamic Response Model will only be accurate for systems meeting the following criteria:

- Accelerations of less than 0.5 sec (e.g., during liftoff, launch abort, landing impacts, and parachute deployments)
- Seated crewmembers where any seat padding or cushions preclude amplification of transient linear accelerations transmitted to the occupant (excessive padding will result in dynamic overshoot, amplifying rather than attenuating accelerations)
- Crewmembers 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 that might require application of the Brinkley Dynamic Response Model Criteria.
- Crewmembers restrained by a system that is adequately pre-tensioned to eliminate slack (during the experimental efforts used to derive the Brinkley Dynamic Response Model , pyrotechnically powered inertial reels were used to position escape system occupants and to eliminate slack in the restraint during the operation ejection cases that were used)
- Crewmember fit and restraint such that the gap between the subject and the seating support surfaces is minimal (any significant 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 +x axis limits presume that the seat occupant's head is protected by a flight helmet with a liner adequate to pass the test requirements of American National Standards Institute (ANSI) Z-90 (latest edition) or equivalent.

  Note: 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).These must be eliminated from the design as a component of CH6049 Limitation of Crew 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 listed in paragraph 4.14.1.3.1 are met. If these criteria are met, the Brinkley Dynamic Response Model is valid to apply and the injury risk criterion, β, is calculated according to CH6048 Brinkley Dynamic Response Model with Dynamic Response Limits, DR_{lim}, as given in Appendix E2 of the CHSIR.

The appropriate risk level will be determined in coordination with NASA and the Program. The desired Dynamic Response limits are low (approximately 0.5%) for all cases. The Brinkley very low category, which included modified DR limits, developed for ill/injured/unconscious crewmembers, may not be applicable to commercial vehicles, which do not have the medical return mission design mandate. If occupant protection principles are not properly applied and/or multiple off-nominal failures occur, loads could impart risks in the medium risk (approximately 5%) and high risk categories (approximately 50%) for risk of sustaining a serious or incapacitating injury.

To determine the injury risk criterion, Beta, as a function of time:

1. Find the acceleration at the critical point in each axis at time (t),
2. Solve the second order differential equation for the displacement (x) of the occupant,
3. Determine the dynamic response (DR(t)) for each axis at time (t), and
4. Determine Beta at time (t).

Using this process, increment the elapsed time and repeat until the maximum Beta is found.

In this model, it is assumed that the total body mass that acts upon the vertebrae to cause deformation can be represented by a single mass. Using the Dynamic Response model limits for accelerations of less than 0.5 sec (e.g., during nominal liftoff, launch abort, landing impact, and parachute deployment) provides the proper margins of safety for a healthy deconditioned crewmember. Prediction of injury risk for deconditioned crew can be achieved by applying the model with the modified Dynamic Response Limits from table E2.2-2 from Appendix E of the CHSIR. For either condition, the Dynamic Response Model will provide an injury risk assessment for either nominal or off-nominal failure or multiple failures given an input acceleration profile.

For further detail, the Brinkley Dynamic Response Model is documented in the Advisory Group for Aerospace Research and Development (AGARD), CP-472, "Development of Acceleration Exposure Limits for Advanced Escape Systems" as well in NASA TM-2008-215198.

4.14.2.3.2 LIMITATION OF CREW INJURY

CH6049 requires protection from blunt force trauma, point loads, flail injury, and injurious loads to the head and neck. These can be achieved in a variety of ways, and verification that this requirement is met is achieved by a combination of inspection of the design and analysis, supported by test data

Blunt force trauma is one of the leading injury modes in terrestrial accidents including aviation and automotive crashes. Trauma occurs when the structural failure associated with acceleration and resulting forces causes either 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. In order to prevent this injury mode, designers need to ensure that the volume surrounding the occupant is sufficient to prevent crew from impacting the structure when subjected to accelerations, including consideration of uncontrolled flailing of limbs. Further, structural designers and analysts must ensure that there are sufficient factors of safety such that the structure does not yield and deform into the survivable volume or fail and strike the occupants, including lose equipment.

Accelerations are tolerated by the human body best when distributed evenly over a large area. To prevent point loads in the seat and restraint design, seats should be conformal to the human body to the extent possible in any direction that is designed to provide support, particularly at the buttocks, back, legs, 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 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 loads in the x and z axes for nominal loads, 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 due to any rigid part of the flight suit (if applicable).

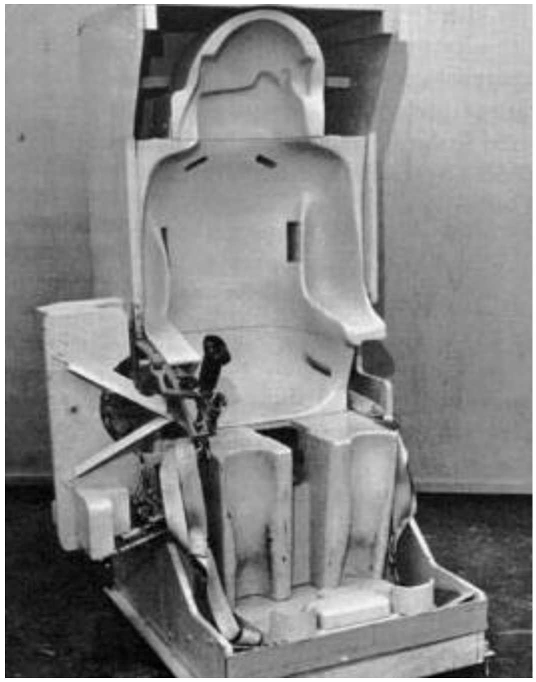


FIGURE 4.14.2.3.2-1 NASA/NACA PROJECT MERCURY CONFORMAL COUCH

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 to crew due to impact with structure or impact to crew by other crew limbs and may also result in hyper-extension or hyper-flexion, injuring joints. System designers should consider the effects of limb flail in the design, and provide design countermeasures. To the degree possible, structure 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 position, and elbow or wrist restraint to prevent arm flail beyond the design reach area. Additionally, inserts within the helmet should prevent the crew from experiencing head and neck flail within the helmet itself. Care should be provided to ensure that any restraints do not preclude unassisted egress or prevent crew from reaching critical controls.

The following criteria are given as best practices for meeting the intent of CH6049 Limitation of Crew Injury.

4.14.2.3.2.1 HEAD INJURY CRITERIA

To calculate the Head Injury Criteria (HIC) with a 15 msec window, Equation 4.14.2.3.2.1 is applied to the ATD resultant head acceleration. The resulting maximum HIC15 value may not exceed the values in Table 4.14.2.3.2.1-1 for the respective dummy size and risk level.

Equation 4.14.2.3.2.1 Head Injury Criteria Formula

TABLE 4.14.2.3.2.1-1 HIC15 IARVS

	0.5%			5.0%		
	Small Female	50^{th} % Male	Large Male	Small Female	50^{th} % Male	Large Male
HIC15	278	250	239	779	700	670

4.14.2.3.2.2 BRAIN ROTATIONAL INJURY CRITERIA

Reserved

4.14.2.3.2.3 NECK INJURY CRITERIA

Using the upper neck load cell z-axis force, calculate the maximum force and compare to the tension values listed in Table 4.14.2.3.2.3-1 for the respective dummy size and risk level. For compression, calculate the minimum (negative peak) force and compare to the compression values in Table 4.14.2.3.2.3-1 for the respective dummy size and risk level. Non-deconditioned values are only applicable to dynamic phases of flight that take place before deconditioning of the crew due to microgravity occurs.

TABLE 4.14.2.3.2.3-1 NECK IARVS

	0.5%			5.0%		
	Small Female	50^{th} % Male	Large Male	Small Female	50^{th} % Male	Large Male
Peak neck (cervical spine) axial tension (N) (Deconditioned)	1,635	2,595	3,137	1,780	2,830	3,970
Peak neck (cervical spine) axial tension (N) (Non-deconditioned)	1,901	3,017	3,647	2,070	3,290	3,970
Peak neck (cervical spine) compression (N) (Deconditioned)	596	946	1,142	2,167	3,440	4,154
Peak neck (cervical spine) compression (N) (non-deconditioned)	693	1,100	1,328	2,520	4,000	4,830

4.14.2.3.2.4 LOWER EXTREMITY INJURY CRITERIA

Femur and tibia axial compression values calculated from the ATD may not exceed the values given in Table 4.14.2.3.2.4-1 for the respective dummy size and risk level. Non-deconditioned values are only applicable to dynamic phases of flight that take place before deconditioning of the crew due to microgravity occurs.

TABLE 4.14.2.3.2.4-1 PEAK LOWER EXTREMITY AXIAL COMPRESSION IARVS

	0.5%			5.0%		
	Small Female	50th % Male	Large Male	Small Female	50th % Male	Large Male
Peak femur axial compression (N) (deconditioned)	3,867	5,670	7,212	4,640	6,803	8,653
Peak femur axial compression (N) (non-deconditioned)	5,156	7,560	9,616	6,186	9,070	11,537
Peak tibia axial compression (N) (deconditioned)	1,914	3,000	3,690	3,825	6,000	7,380
Peak tibia axial compression (N) (non-deconditioned)	2,552	4,000	4,920	5,100	8,000	9,840

4.14.2.3.2.5 CHEST COMPRESSION

After calculating sternal compression per SAE J211/1, the compression may not exceed the values in Table 4.14.2.3.2.5-1 for the respective dummy size and risk level.

TABLE 4.14.2.3.2.5-1 CHEST STERNAL TO SPINE DEFLECTION IARVS

	0.5%			5.0%		
	Small Female	50th % Male	Large Male	Small Female	50th % Male	Large Male
Chest Sternal to Spine Deflection (mm)	33	41	45	39	48	53

4.14.2.3.2.6 DERIVATION OF DECONDITIONING FACTOR

Several of the Occupant Protection Requirements such as the Biodynamic Response Model include a Deconditioning. Deconditioning factor is a function of measured physiological changes of the human body associated with dwell time away from the earth's surface (reduced gravitational environment). The deconditioning factor can be multiplied by the able-bodied loading estimates in order to account for the Bone Mineral Density (BMD) loss that occurs in space. For purposes of this analysis, the deconditioning factor is assumed to be a proportionality factor relating the allowable pre-flight skeletal loading to the allowable post-flight skeletal loading after deconditioned BMD loss. It can be further assumed that the same probability of injury should exist in both pre-flight and post-flight cases.

4.14.2.3.3 SPINAL ALIGNMENT

One key injury mode due to high onset rate, high magnitude accelerations is the failure of the seat and restraint system to maintain spinal alignment under acceleration. Without proper support, one part of the body such as the head and neck is free to move relative to the rest of the body, generating shear and axial loads at the spine. Proper seat and restraint design supports the whole body including the head, shoulders, chest, and pelvis and prevents movement of any one body segment relative to the others. Ideal displacements are listed in Table 4.14.2.3.3-1 Restrained Body Movement IARVs.

Body movement measures under acceleration are made in two ways depending on whether a physical test or numerical simulation is used. For physical testing, video tracking of fiducial markers on the ATD is used to determine body movement as shown in Figure 4.14.2.3.3-1. For numerical simulations, reference points associated with joints and key points on the head, limbs and torso can be selected from the finite element model in lieu of fiducial markers to evaluate spinal alignment under simulated acceleration pulses.

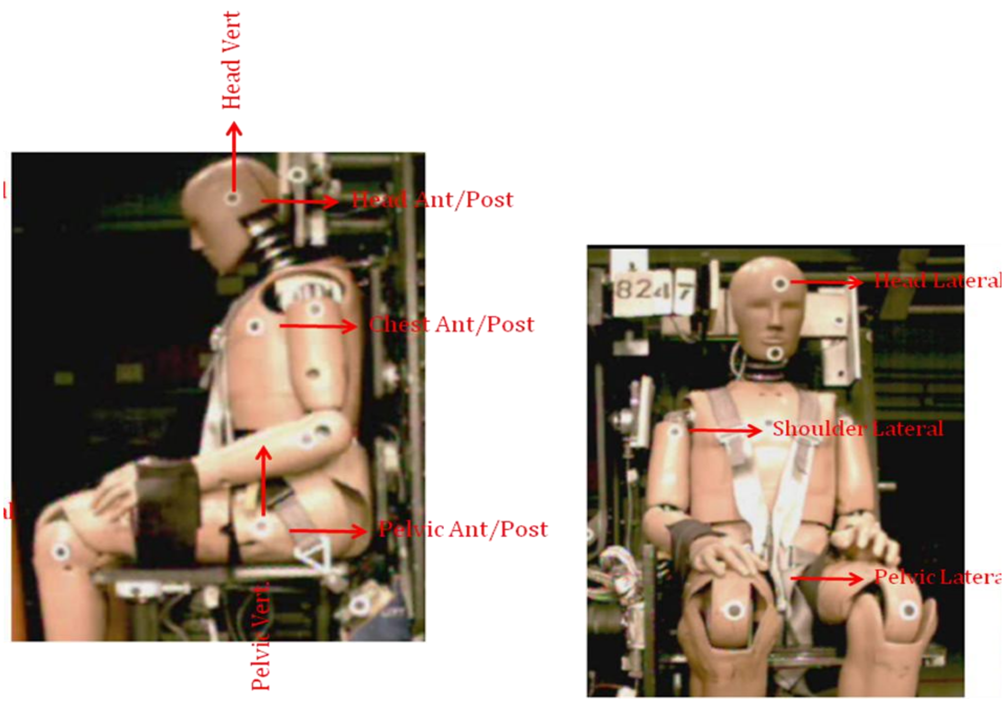


FIGURE 4.14.2.3.3-1 FIDUCIAL MARKER LOCATIONS FOR TRACKING ATD BODY MOVEMENT

TABLE 4.14.2.3.3-1 RESTRAINED BODY MOVEMENT IARVS

	Lateral *($\pm G_y$)*	*Anterior* *($+G_x$)*	*Posterior* *($-G_x$)*
Head Movement (mm)	75	125	25
Chest Movement (mm)	N/A	63	25
Pelvic Movement (mm)	37	50	25
Shoulder Movement (mm)	50	N/A	N/A
Caudal Pelvic Movement ($+G_z$) (mm)	50	N/A	N/A
Upward Head Movement ($-G_z$) (mm)	75	N/A	N/A

4.14.3 OCCUPANT PROTECTION DESIGN TECHNICAL PRODUCTS

For each of the major milestones of the design lifecycle, the technical products in Table 4.14.3-1 are recommended for review by the NASA customer.

TABLE 4.14.3-1 OCCUPANT PROTECTION DESIGN TECHNICAL PRODUCTS

Technical Products	Responsible Org	Phase A		Phase B	Phase C	Phase D	
		SRR	SDR	PDR	CDR	SAR	FRR
A description of the ConOps, functions allocation, and associated crew task lists. Includes identification of potential errors that can be encountered for each task.	CCT Company	I	U	U	U	---	---
Environmental conditions definitions	CCT Company	I	U	U	U	---	---
Landing probabilities Monte Carlo distribution for nominal and off-nominal landings	CCT Company	---	I	U	U	---	---
Boundary cases for landing defined and full landing FE model ran for each case	CCT Company	---	I	U	U	---	---
Finite element sub-system models with ATD including seat and energy attenuation system. Model fidelity should increase for each milestone review.	CCT Company	---	I	U	U	---	---
Sled Testing & Modeling							
Model correlation sled testing	CCT Company	---	---	I	---	---	---
Coarse Model Correlation Analysis	CCT Company	---	---	I	---	---	---
Model Correlation within 10% of tests	CCT Company	---	---	---	U	---	---
Biodynamic Results from FE modeling							
Initial Biodynamic Results of FE modeling	CCT Company	---	---	I	---	---	---
Final Design Results of FE modeling	CCT Company	---	---	---	U	---	---
Results of FE Modeling Following Verification Testing	CCT Company	---	---	---	---	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.	CCT Company	---	---	I	U	---	---
System architecture drawings (structures, equipment, etc.), material specifications, interface requirements.	CCT Company	---	---	I	U	U	---
Verification plan	CCT Company	---	---	I	U		---
Biodynamic Response, Crew Injury Limitation, and Spinal Alignment verification Report						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 3.1.3.1.2 provides information such as identification of crew activities and determination of which subsystems are impacted by crew activities. Functions allocation, described in paragraph 3.1.3.1.3, 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. 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.

Modeling/Analysis/Evaluation Summaries

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 utilize increasingly higher fidelity inputs/mockups, as discussed in paragraph 3.1.3.1.3 Evaluate Designs and Iterate Solutions. It is important that summaries address how key/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 occupant protection considerations, the usability testing and human-in-the-loop evaluations should include crew 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 human-in-the-loop testing may also include tests of the seat and restraints with volunteer human subjects under simulated landing and abort acceleration pulses.

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.

4.14.4 REFERENCES

National Aeronautics and Space Administration. *Commercial Human-Systems Integration Requirements (CHSIR).* JSC 65993. December 2010.

Brinkley, J.W., Specker, L.J. *Development of Acceleration Exposure Limits for Advanced Escape Systems*. AGARD NATO Conference Proceedings No. 472, April 1989.

Horta, L.G., Mason, B.H., Lyle, K.H. *A Computational Approach for Probabilistic Analysis of Water Impact Simulations*. NASA/TM-2009-215704. April 2009.

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-2008-215198. April 2008.

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	
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 six 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 spaceflight 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 spaceflight on crewmembers
Crew	Human onboard the spacecraft or space system during a mission. This includes USOS crewmembers and CCT company employees 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 utilize 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 spaceflight 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 two adjoining environments and allows physical passage of people and/or material from one environment to the other (such as between two 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 two 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 if 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 three 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 utilizes 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 upon 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)
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)